AN EXAMINATION OF RADIATION INDUCED TENSILE FAILURE OF STRESSED AND UNSTRESSED POLYMER FILMS FLOWN ON MISSE 6

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ABSTRACT

Thin film polymers are used in many spacecraft applications for thermal control (multilayer insulation and sunshields), as lightweight structural members (solar array blankets, inflatable/deployable structures) and have been proposed for propulsion (solar sails). Polymers in these applications are often under a tensile load and are directly exposed to the space environment, therefore it is important to understand the effect of stress in combination with the environment on the durability of these polymer films. The purpose of the Polymer Film Tensile Experiment, flown as part of Materials International Space Station Experiment 6 (MISSE 6), was to expose a variety of polymer films to the low Earth orbital environment under both relaxed and tension conditions. This paper describes the results of post flight tensile testing of these samples.

1. INTRODUCTION

Thin film polymers in low Earth orbit (LEO) are vulnerable to degradation by solar ultraviolet radiation, solar flare X-rays, solar wind electrons and protons trapped in Earth's magnetic field, temperature and orbital thermal cycling, and LEO atomic oxygen [1]. In applications where the polymer film is under tension while exposed to these environmental factors, it is important to understand the effect of stress in combination with the environment on the durability of thin polymer films. Polymer films were flown previously in the Polymer Film Thermal Control Experiment and the Gossamer Materials Experiment as part of Materials International Space Station Experiment (MISSE) 1 as well as on MISSE 3, MISSE 4, and MISSE 5 [2, 3]. The MISSE 6 exposure is different from prior such experiments in that it was designed such that a number of the samples were exposed while under tension to better simulate their use in space and determine if the stress level affects the durability. The dog-bone shaped tensile samples of polymers were flown on both the ram (17 samples) and wake (24 samples) facing sides of the MISSE 6 Passive Experiment Containers (PECs). A detailed description of all of the samples flown as part of Polymer Film Tensile Experiment (PFTE) is contained in reference [4]. This paper compares the post flight tensile strength and percent elongation of tensile samples exposed on the ram and wake faces, both under tension and relaxed, with control samples from the same lot that were kept on the ground.

2. FLIGHT EXPERIMENT DESCRIPTION AND PROCEDURE

2.1. MISSE-6 Environment

MISSE 6 was composed of two PECS, 6A and 6B. Both PECS had one side of the suitcase style containers facing ram and the other side facing wake. They were both installed on the European Columbus module of the International Space Station (ISS) on March 22, 2008 during the flight of STS-123. They were retrieved on September 1, 2009 by the crew of STS-128 after slightly over 17 months in low Earth orbit (LEO) [4]. The atomic oxygen arrival fluence was calculated for the ram side of 6A and 6B to be approximately 2×10^{21} atoms/cm^2, and for the wake side approximately 1.2-1.4×10^{20} atoms/cm^2 [4-6]. This indicates that the wake side of MISSE 6, which was to have received very low atomic oxygen exposure was oriented in the ram direction long enough to have received an atomic oxygen dose about 6.5 percent that of the ram oriented side. Estimates of the UV radiation exposure in equivalent sun hours (ESH) were 2600 ESH for the ram sides of 6A and 6B and 1950 ESH for the wake sides of 6A and 6B [7]. Temperature, thermal cycling, and ionizing radiation estimates were not available at this time.

2.2. Experiment Design

The flight experiment was designed to allow some of the polymer dog-bone type samples to be exposed under a tensile load typical of expected conditions for the James Webb Space Telescope sunshield. The tensile load of approximately ~2.22 N (0.5 lb) was applied by mounting the sample in a holder similar to that shown on the left side of the photo in Fig. 1 and then compressing a spring with a spring constant of ~385 N/m (2.2 lbs/in) by approximately ~0.0058 m (0.227 inches) to put the sample under an approximately constant tensile load. The drawing in Fig. 1 shows a double sample holder where the sample on the left did not have an applied tensile stress and the one on the right did. For the samples exposed under stress, the resulting stress was dependent on the polymer film thickness per equation 1 with an average gage width of approximately 0.0032 m (0.126 inches). Two thicknesses of polymer films were exposed under stress. The applied stress was ~2.76×10^7 N/m^2 (~4000 psi) for 2.54×10^{-5} m (0.001 inch), and ~1.38×10^7 N/m^2 (~2000 psi) for $5.08x10^{-5}$ m (0.002 inch) thick films.

Stress=(Force/Area)=
(Force)/((Gage width)(Thickness))* (1)

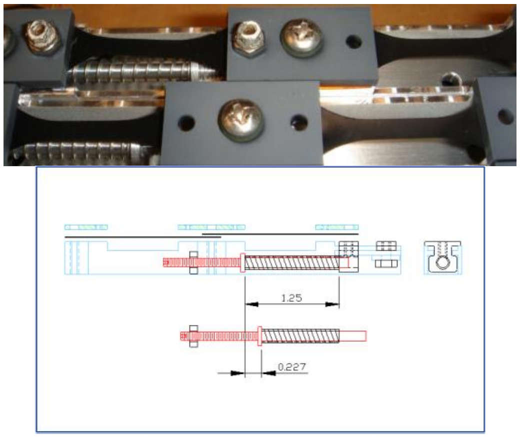

Figure 1. Photo of stressed (left) and unstressed (right) sample holders from above, and a side view drawing of a holder showing the unstressed sample position on the left and the stressed on the right. (Dimensions are in inches.) The stressed sample is fixed on the left side and allowed to move to the right by having the mount hole on the right slotted. Tension is supplied by compression of the spring.

2.3. Sample Description

All of the samples, both for flight and for ground controls, were punched from polymer sheets using a die manufactured according to specimen "Type V" under the American Society for Testing and Materials (ASTM) Standard D-638 [8]. The dog-bone shaped die had a gage length of 7.62 mm (0.3") and an average gage width of 3.21 ± 0.02 mm (0.126"). Polymers tested on MISSE-6 PFTE included 50.8 micron and 127 micron thick FEP Teflon with vapor deposited aluminum (VDA) on one side manufactured by Sheldahl Inc.; an alloyed silicon coating (600 Å)/Kapton E/VDA (550 Å)/Inconel (700 Å)/VDA (900 Å) supplied by NASA Goddard Space Flight Center; Kapton XC 100XC10E7 manufactured by DuPont, Kapton HN/VDA manufactued by DuPont; SiO_x coated Kapton HN manufactured by Sheldahl Inc., and VDA/CP1 manufactured by SRS.

2.4. Tensile Testing

A DDL Inc. Model 200Q bench-top tensile tester manufactured by Test Resources Inc. was used to test the MISSE-6 flight and control samples post retrieval. All of the samples were kept in the same controlled room environment with the tensile tester 48 hours prior to testing to eliminate variation due to change in the environment as recommended by ASTM Standard Test Method for Tensile Properties of Thin Plastic Sheeting D882-02 and ASTM D-638 [9 and 8]. Tensile tests were conducted according to ASTM D-638 [8], using a 444.8 N load cell and a strain rate of 12.7 mm/min. Each sample when loaded into the tensile holder was mounted in the grips with minimum slack and then moved slightly with the motor drive to eliminate the slack without introducing initial tension on the sample. The initial grip separation was kept constant for all samples at 25.4 ± 0.5 mm. Tests were conducted to obtain load versus displacement data for each sample. The tensile strength was calculated from this data as well as the percent elongation at failure.

Tensile Strength = (Maximum load at break/
Original minimum cross sectional area) = N/m^2 (2)

Percent Elongation = (Change in grip distance at break/
*Initial grip distance)*100* (3)

3. RESULTS AND DISCUSSION

The tensile strength, percent loss in tensile strength in comparison to the control sample of the same material, percent elongation at break and percent loss in the elongation at break for each material is contained in Table 1. The sample numbers in the table are pre-fixed with "AO" for samples flown on the ram side of MISSE-6 and "UV" for those flown on the wake side of MISSE-6. Next to the sample number is a notation indicating if the sample was under a tensile load during flight (stressed) or if the sample was pulled tight in the holder but not spring loaded (taut). The thickness of each polymer film is also indicated under the sample description. Ground control data is the average of typically three tensile tests made on tensile samples that were cut from the same material as the flight samples but held on the ground for comparison testing with the flight samples post flight. The standard deviation of these measurements is also listed along with the average. Since each material is unique in its behaviour, the results will be discussed for each material separately.

3.1. FEP Teflon

Two thicknesses (50.8 microns and 127 microns) of FEP Teflon/VDA were exposed on MISSE-6 to determine if the damage caused by exposure to the environment was limited in depth. The load vs displacement curves for both thickness materials followed the same general shape, with all samples reaching a similar yield point beyond which the material became plastic in nature. All of the samples exposed on MISSE-6 broke at a lower load level and displacement than the control material as shown in Fig. 2. As can be observed from the curve, the unexposed control FEP/VDA samples had a much cleaner break point as the sample material became thinner as stretched and then broke, while the exposed FEP/VDA samples

Table 1. Tensile Strength and % Elongation at Break for MISSE-6 Flight and Ground Control Samples

SAMPLE DESCRIPTION	Sample Number	Tensile Strength (MPa)		ELONGATION (%)	
		Value	%Loss	Value	% Loss
Teflon FEP/VDA (50.8 microns)	Ground Controls	28.4 ± 1.6	-------	229.3 ± 1.4	-------
	UV-U-9	14.7	48.2	35.0	84.7
	UV-U-10	14.1	50.3	111.4	51.4
	UV-S-9	16.6	41.7	85.8	62.6
	AO-S-7 (taut)	12.3	56.8	77.6	66.2
	AO-U-8	15.3	46.0	83.5	63.6
Teflon FEP/VDA (127 microns)	Ground Controls	20.4 ± 2.4	-------	229.8 ± 35.2	-------
	UV-U-11	13.2	35.1	91.3	60.3
	UV-U-12	13.4	34.4	84.3	63.3
	UV-S-10	13.5	34.0	83.5	63.7
	AO-S-8 (taut)	13.0	36.3	65.0	71.7
	AO-U-9	13.0	36.2	71.7	68.8
Si/Kapton E/VDA/Inconel/VDA (50.8 microns)	Ground Controls	296.9 ± 17.7	-------	27.4 ± 2.6	-------
	UV-S-3 Stressed	280.1	5.7	23.4	14.5
	UV-S-4 Stressed	282.5	4.9	25.5	7.1
	UV-S-5 Stressed	290.5	2.2	26.1	4.6
	UV-U-3	286.8	3.4	25.1	8.4
	UV-U-4	278.9	6.1	23.0	16.0
	UV-U-5	275.2	7.3	23.2	15.3
	AO-S-2	129.9	56.2	3.1	88.8
	AO-S-3	128.5	56.7	3.6	86.9
	AO-U-4	137.9	53.6	4.2	84.6
	AO-U-5	80.9	72.8	1.9	93.1
Kapton XC (Black Kapton) (25.4 microns)	Ground Controls	156.1 ± 17.3	-------	28.9 ± 3.1	-------
	AO-U-1 - Broke at edge of holder	-------	-------	-------	-------
	AO-S-1 Stressed - Broke in Flight	-------	-------	-------	-------
	UV-S-1 Stressed	121.1	22.4	22.0	23.8
	UV-S-2 Stressed	110.3	29.3	15.4	46.9
	UV-U-1	134.8	13.6	21.4	26.0
	UV-U-2	124.0	20.5	13.2	54.4
Kapton HN/VDA (50.8 microns)	Ground Controls	102.3 ± 6.3	-------	38.9 ± 4.8	-------
	UV-S-11	78.6	23.2	27.6	29.2
	UV-U-13	84.5	17.4	33.0	15.1

Table 1. Continued

SAMPLE DESCRIPTION	Sample Number	Tensile Strength (MPa)		ELONGATION (%)	
		Value	%Loss	Value	% Loss
SiOx/Kapton HN (50.8 microns)	Ground Controls	106.4 ± 5.6	-------	34.1 ± 0.5	-------
	AO-S-6 Stressed - Broke in Flight	-------	-------	-------	-------
	AO-U-2	57.7	45.8	5.7	83.3
	AO-U-3	64.7	39.2	7.3	78.5
	UV-S-8 Stressed	92.7	12.8	23.0	32.6
VDA/CP1 (25.4 microns)	Ground Controls	80.1 ± 10.5	-------	12.3 ± 5.1	-------
	AO-S-4 Stressed - Broke in Flight	-------	-------	-------	-------
	AO-S-5 Stressed - Broke in Flight	-------	-------	-------	-------
	AO-U-6	86.1	-7.5	6.0	51.2
	AO-U-7	81.3	-1.5	4.7	61.5
	UV-S-6 Stressed	67.2	16.1	2.9	76.7
	UV-S-7	73.5	8.2	6.6	46.4
	UV-U-6	84.7	-5.8	7.2	40.9
	UV-U-7	91.0	-13.6	6.0	51.2
	UV-U-8 CP1/VDA	68.6	14.3	9.6	21.9

developed notch defects along the edge and failed by tearing across rather than breaking. This caused a slight reduction in load prior to break. There was no noticeable difference, however, in tensile strength between the samples flown on the ram and wake sides. The post-flight tensile strength appeared to also be independent of the FEP thickness. There was not a significant difference in percent elongation at break between the two thicknesses of exposed material, and also not a significant difference in percent elongation between samples exposed on the ram versus the wake sides as shown in Table 1.

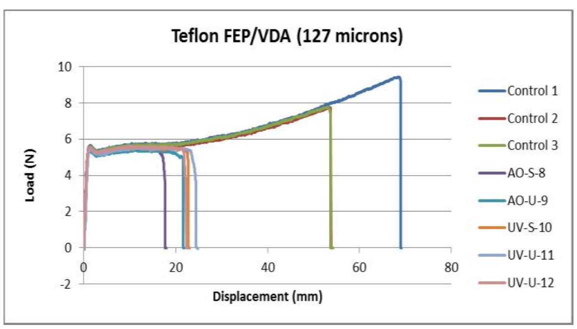

Figure 2. Load versus displacement curve for 127 micron thick FEP/VDA

It appears that the space environment significantly affected the full thickness of both 50.8 micron and 127 micron FEP/VDA and that the reduction in tensile strength and percent elongation was independent of the atomic oxygen level since there was over an order of magnitude difference in the atomic oxygen fluence between the ram and wake sides. The roughly 30 percent difference in UV radiation level between the ram and wake sides also did not appear to be enough to cause a significant difference in the tensile strength or percent elongation.

3.2. Si/Kapton E/VDA/Inconel/VDA

Tensile testing of exposed and ground control Si/Kapton E/VDA/Inconel/VDA samples produced the load versus displacement curve shown in Fig. 3. All samples exhibited a clean break with no tearing. There was a significant difference in the load required to break the samples and the sample elongation to break for samples exposed on the ram side compared to those on the wake side. As shown in Table 1, the tensile strength for those samples exposed on the ram side of MISSE-6 was less than half that of the samples exposed on the wake side and over a factor of 7 less in percent elongation to break. The wake samples were comparable in tensile strength and percent elongation to the samples that remained on the ground as a control. Half of the samples on the wake side were exposed while under a tensile stress of approximately 13.8 MPa simulating a typical blanket loading, but there was no significant difference in either tensile strength or percent elongation between the samples that were exposed under stress and those that were not.

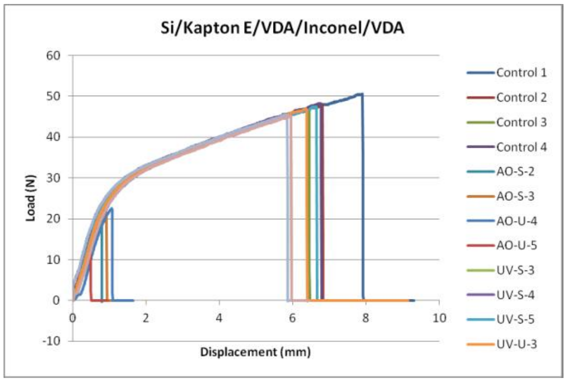

Figure 3. Load versus displacement curve for Si/Kapton E/VDA/Inconel/VDA

The tensile properties for this material appear to be degraded more by atomic oxygen arrival. The Si top coating appears to have small scratches and defects in it that can create a pathway for atomic oxygen to erode the underlying Kapton E causing small voids that may initiate failure under load.

3.3. Kapton XC

Kapton XC (Black Kapton) has been found to have a stress dependence on erosion by atomic oxygen [10]. The left side of Fig. 1 contains Kapton XC samples that were flown on the wake side of MISSE-6 under a tensile load of approximately 25.4 MPa, while the Kapton XC samples on the right were not tensile loaded. Even with the low level of atomic oxygen on the wake side there was surface texturing and higher erosion of the samples that were under stress compared to those that were not. Sample AO-S-1 on the ram side which was accidentally stressed pre-flight eroded through and broke at the highest stress point during flight [10]. Sample AO-U-1 was flown unstressed, but it was suspended between two clamps. Where the sample sagged between the clamps, at the edge of the clamps, it created a stress point and the atomic oxygen eroded through the sample at each edge. There was not enough of the grip area left on either sample to allow these samples to be tensile tested. These samples do illustrate that there is a strong dependence between atomic oxygen erosion and stress for Kapton XC.

The load versus displacement curve for the wake side and control samples of Kapton XC is shown in Fig. 4. The two samples flown under stress had a slightly lower yield point than the unstressed samples which more closely followed the profile of the unexposed controls. This may be due to the greater surface erosion on these samples by atomic oxygen. In spite of the additional erosion on the surface, the bulk tensile properties of tensile strength and percent elongation at break are within error of each other and roughly 20 and 30 percent respectively below that of the control sample. The stress effect on this material appears to be limited to enhancing atomic oxygen erosion at the surface. The bulk properties, however are still affected by the environment and appear to be independent of atomic oxygen arrival.

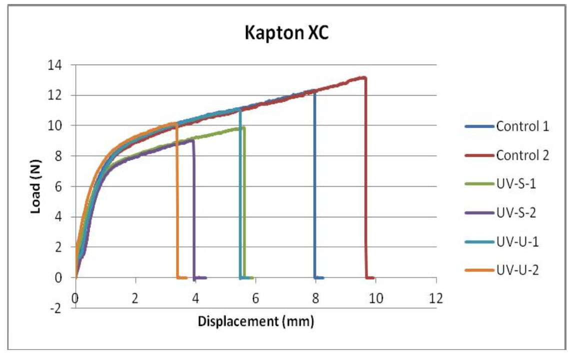

Figure 4. Load versus displacement curve for Kapton XC

3.4. Kapton HN/VDA

The Kapton HN/VDA samples were only flown on the wake side of MISSE-6. Both samples were not under stress but were textured and eroded slightly on the surface by atomic oxygen arrival on the wake side as described in Section 2.1. The load versus displacement curve shown in Fig. 5 looks similar to that for Kapton XC. The two textured samples have a slightly lower yield point than the unexposed controls.

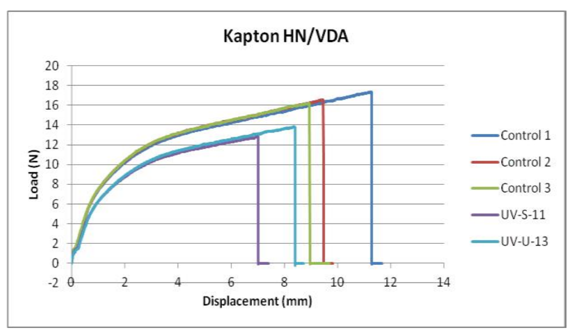

Figure 5. Load versus displacement curve for Kapton HN/VDA

Both the tensile strength for these samples and the percent elongation was reduced by roughly 20 percent as a result of the exposure on the wake side of MISSE-6 as shown in Table 1.

3.5. SiOx/Kapton HN

One SiOx/Kapton HN sample was flown on the wake side of MISSE-6 under a tensile load of approximately 13.8 MPa while three samples, one under approximately the same load and two not under stress were flown on the ram side of MISSE-6. The sample under stress flown on the ram side broke during flight. The surface looked heavily defected and undercut by atomic oxygen erosion and appeared to have defects across the sample at the point where the sample broke. The remaining samples were intact and used for tensile testing. The load versus displacement for these SiO_x/Kapton HN samples is shown in Fig. 6. All of the samples broke cleanly without tearing and followed the same load vs displacement curve as the control except that the stressed sample on the wake side and the ram exposed samples broke at earlier points in the curve. The stressed sample on the wake side experienced an approximately 13 percent reduction in tensile strength and approximately 33 percent reduction in percent elongation at break due to exposure as shown in Table 1. The two unstressed samples on the ram side experienced ~40 percent reduction in tensile strength and ~80 percent reduction in percent elongation at break. This is most likely due to atomic oxygen erosion at coating defect and scratch sites causing localized weakening of the samples.

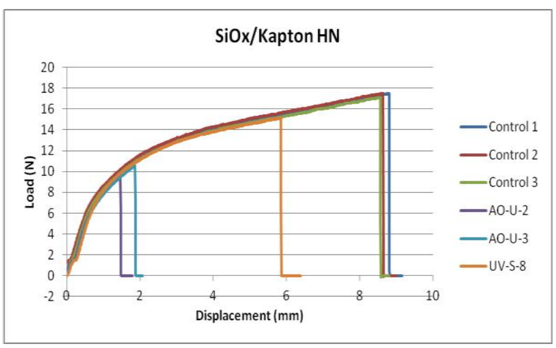

Figure 6. Load versus displacement curve for SiOx/Kapton HN.

3.6. VDA/CP1

There were four samples of VDA/CP1 flown on the wake side of MISSE-6, one of the samples was under a tensile stress of approximately 25.4 MPa. An additional sample was flown in reverse (CP1/VDA) to determine if the VDA afforded any protection to the polymer from the environment. There were also four samples flown on the ram side of MISSE-6, two of which were also under a 25.4 MPa tensile load. The two VDA/CP1 samples flown on the ram side under stress broke during flight. It is possible that atomic oxygen erosion at defect sites in the VDA while under stress weakened the material causing it to fail. The load versus displacement curve for the remaining samples is shown in Fig. 7. All of the samples except for the stressed sample on the wake side followed the same load versus displacement curve as the ground control samples that were not exposed. The stressed sample had a slightly lower yield point. The wide variation in performance of the control samples made it more difficult to draw conclusions from this data. The control samples failed in more of a tearing mode while the exposed samples had a more brittle form of failure as evidenced by the shape of the curves in Fig. 7.

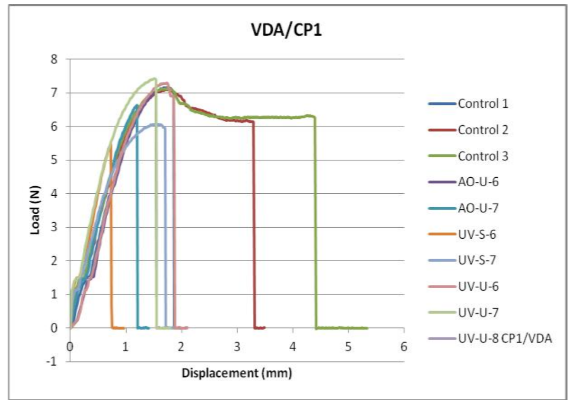

Figure 7. Load versus displacement curve for CP1/VDA

Both unstressed samples on the ram side and the unstressed samples on the wake side had similar tensile strength to the unexposed control samples. The stressed sample on the wake side and the sample with CP1 directly exposed to the environment on the wake side had a reduced tensile strength by roughly 14-16 percent. The percent elongation at break ranged from ~40-60 percent lower for the ram and wake side exposed VDA/CP1 than for the unexposed control samples. The stressed sample had a ~77 percent reduction in percent elongation, while the CP1/VDA had the lowest reduction in % elongation of approximately 22 percent. All of the exposed samples looked more cracked on the surface with the stressed sample having the most cracking present. Stress during environment exposure appears to have a negative effect on the tensile strength and percent elongation of VDA/CP1. Direct exposure of CP1 to the environment also has roughly the same negative effect on tensile strength but appears to help reduce the drop in percent elongation.

4.0. CONCLUSIONS

Exposure to the space environment caused some level of degradation in tensile strength and percent elongation at break for all of the materials that were exposed on the PFTE. For FEP/VDA, the reduction in both tensile strength and percent elongation was independent of the level of atomic oxygen present, and was not dependent on thickness of the polymer indicating that the reduction in tensile properties was not caused by surface degradation but more of a bulk material degradation. Coated Kapton like Si/Kapton E/VDA/Inconel/VDA and SiO_x/Kapton can have defects in the surface coating that develop under stress or are naturally present that when exposed to atomic oxygen can enable localized erosion of the material under the coating at defect sites that can lead to a significant loss in tensile strength and percent elongation. Some materials like Kapton XC are eroded by atomic oxygen at a faster rate while under stress. Although this is a surface effect and does not affect the tensile strength and percent elongation initially, rapid erosion at stress points can result in preferential removal of material at these sites resulting in failure of the film. VDA/CP1 performed well in terms of tensile strength but had a greater loss in tensile strength when under stress and had a significant loss in percent elongation under all conditions. All of these materials are typically used on spacecraft, but each are unique in their durability to the space environment. Proper selection of materials for missions and mitigation techniques to prevent failure will require understanding of each material's limitations with regard to environmental durability and durability under typical use conditions such as tensile loading.

5.0 ACKNOWLEDGEMENTS

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