JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 43, No. 2, March–April 2006

Effects of Vacuum Ultraviolet Radiation on DC93-500 Silicone

Joyce A. Dever* and Bruce A. Banks†
NASA John H. Glenn Research Center at Lewis Field, Cleveland, Ohio 44135
and
Li Yan‡
University of Nebraska at Lincoln, Lincoln, Nebraska 68588-0511

Vacuum ultraviolet radiation is among the space environment elements that can be hazardous to DC93-500 silicone film, which has been proposed for use on spacecraft exterior surfaces. Investigations have been conducted to examine vacuum ultraviolet effects on DC93-500 film. Laboratory exposure tests were used to determine the effectiveness of various wavelength ranges in causing optical and mechanical degradation and to determine intensity-dependence of optical and mechanical properties degradation. Results indicated that wavelengths between 185 and 200 nm were significantly more effective in causing degradation than wavelengths between 140 and 185 nm. These findings were consistent with results of vacuum ultraviolet ellipsometric optical measurements, which provided data on depth of penetration in DC93-500 as a function of wavelength. Wavelengths between 185 and 200 nm penetrate to depths between 1 and 3 μm in DC93-500, depths where bulk degradation is likely, whereas the penetration of shorter wavelengths is much more shallow and more likely to result in only surface degradation. Results of exposures of DC93-500 film samples to vacuum ultraviolet radiation of intensities between 1.5 and 5.5 times the sun's intensity indicated no intensity-dependence of optical and mechanical property degradation.

Nomenclature

D_p = depth into a surface at which a propagating light beam is attenuated to $1/e$ of its original intensity
e = base of natural logarithms
k = extinction coefficient
n = index of refraction
R_p = complex Fresnel reflection coefficient for the parallel component of the electric field
R_s = complex Fresnel reflection coefficient for the perpendicular component of the electric field
S = light intensity expressed as number of equivalent suns
Δ = relative phase change for light reflection from a surface
λ = wavelength of light
ρ = ratio of complex Fresnel reflection coefficients R_p and R_s
τ = transmittance
ψ = relative amplitude change for light reflection from a surface

I. Introduction

DOW Corning DC93-500 is a space-grade silicone elastomer that is commonly used as an adhesive for spacecraft components such as solar cells and optical solar reflectors and as a general encapsulant or potting material for spacecraft electronic components. Its wide service-temperature range (−115 to +200°C), flexibility, and low outgassing properties make it desirable for spacecraft applications.[1] Recently, DC93-500, in freestanding film form, has been incorporated into the design of a refractive Fresnel lens solar concentrator for a patented spacecraft solar-cell array referred to as the Stretched Lens Array (SLA).[2] Simulated space environment testing of the DC93-500 material has shown that it is susceptible to ultraviolet (UV)-radiation degradation.[3] Such degradation requires that DC93-500 surfaces be protected from ultraviolet radiation for long-duration durability for space power applications. As part of ongoing studies examining vacuum ultraviolet (VUV) radiation effects on polymer films for spacecraft applications,[4–6] this paper describes laboratory investigations on DC93-500 for VUV penetration depth, and wavelength dependence and intensity dependence of VUV degradation.

The air-mass zero solar (AM0) spectrum contains UV radiation of wavelengths extending down to the Lyman-alpha emissions of hydrogen at 121 nm (Ref. 7). The high-energy portion of the UV spectrum containing wavelengths below approximately 200 nm is generally referred to as VUV radiation. Polymer surfaces on spacecraft are vulnerable to degradation due to incident solar radiation in this wavelength region, which contains short-enough wavelengths and thus high-enough energies to break bonds in organic molecules.[8] Photochemical reactions within organic molecules may result in effects such as discoloration of the material, which can result in increased solar absorptance or loss of mechanical properties due to chemical changes in the material. The depth within which degrading effects occur depends upon the depth of penetration of the VUV light. In general, organic polymers absorb VUV within a shallow depth on the order of micrometers or less, although the depth is dependent upon the polymer.[9] Only surface degradation can occur for wavelengths that penetrate a shallow layer of the polymer, whereas for wavelengths that are more penetrating, bulk degradation is possible.

Ground testing is important for predicting long-duration durability of spacecraft materials, especially for materials or components that have not been previously tested for long-duration exposure in space. However, differences between the space environment and the ground laboratory environment lead to complexities in interpreting the ground test results. Two important differences between space and laboratory VUV exposure conditions are light intensity and irradiance spectra. It is desirable to be able to conduct accelerated testing, or testing at intensities greater than those in space, especially for long-duration mission durability predictions. However, there is no conclusive information on the maximum acceleration factor that will produce damage that is realistic compared to the space environment. It is likely that the acceleration factors are material specific,

---

Received 3 January 2005; revision received 9 June 2005; accepted for publication 25 August 2005.

*Senior Materials Engineer, M.S. 309-2, Electro-Physics Branch, 21000 Brookpark Road. Senior Member AIAA.

†Chief, M.S. 309-2, Electro-Physics Branch, 21000 Brookpark Road.

‡Postdoctoral Research Associate, Department of Electrical Engineering.

depending on material chemistry. It is important to determine the maximum intensity that can be used to produce realistic damage in a reasonable amount of time. Differences between the AM0 irradiance spectrum and that of a laboratory VUV radiation source, when considered along with a materials spectral absorption curve, can also lead to complexities in interpreting results of ground tests. For example, a typical laboratory VUV source is a deuterium lamp with a magnesium fluoride window. This source has a peak at approximately 160 nm, which does not exist in the AM0 spectrum. If a material is highly absorbing in this wavelength region, the laboratory source might produce damage that is unrealistic compared to space, especially for high intensity levels.

This paper describes results of testing to investigate wavelength dependence and intensity dependence of VUV degradation for DC93-500 silicone. The goals of this work were to determine the wavelength ranges that are most damaging to silicone DC93-500 and to determine whether accelerated testing of up to six times the sun's intensity (i.e., six VUV suns) produces realistic degradation by comparing results to those obtained using lower intensity levels. To best interpret the results relative to the properties of DC93-500 silicone, spectral measurements were made of VUV penetration depth.

II. Experimental Methods

A. Preparation of DC93-500 Film Samples

Dow Corning® (DC) 93-500 Space-Grade Encapsulant two-part silicone elastomer was cast and cured by ENTECH into a film of approximately 150-μm thickness following a proprietary process for mixing, casting, and curing via a proven temperature/time schedule in an environment free of cure inhibitors. Samples tested were cut from this "stock" film.

B. Optical Properties Characterization

Total transmittance of the silicone films was measured using a Perkin-Elmer Lambda-19 ultraviolet-visible-near-infrared spectrophotometer equipped with a Labsphere reflectance accessory, which includes an integrating sphere 150 mm in diameter. Measurements were made over a wavelength range of 210–2500 nm.

C. Mechanical Properties Characterization

Tensile testing was conducted using a DDL Model 200Q Electromechanical Test System. Tensile test specimens were punched using a die fabricated to the specifications defined in American Society for Testing and Materials (ASTM) Standard D-638 for type V tensile specimens.[10] Whereas the tensile die produces an overall sample length of 63.5 mm, samples for these experiments were trimmed to an overall length of 44.5 mm to better accommodate the VUV exposure chamber dimensions. The trimmed length was simply the excess material that would fall outside the grips of the tensile tester. Sample width is 9.52 mm with a narrow section 3.18 mm wide and 7.62 mm long. The initial grip separation distance was 25.4 mm. Samples were tested using a speed of 63.5 mm/min, and load vs displacement data were obtained. From the load vs displacement data, ultimate tensile strength (UTS) and elongation at failure were obtained. Elongation was based on the change in grip distance from test start to sample failure.

D. Vacuum Ultraviolet Variable-Angle Spectroscopic Ellipsometry

Spectroscopic ellipsometry is a surface-sensitive, nondestructive optical technique widely used to determine film thickness and optical constants. Reflection ellipsometry measures the change in the polarization state of light upon reflection from a sample surface. Measurement results are expressed as psi (Ψ) and delta (Δ), relative amplitude change and relative phase change for light reflected off of a surface, respectively. These measured parameters are related to the complex Fresnel reflection coefficients R_p and R_s as shown in Eq. (1):

$$\rho \equiv \tan(\psi)\, e^{i\Delta} = R_p/R_s \tag{1}$$

In this work, the optical constants of index of refraction n and extinction coefficient k of DC 93-500 silicone in the UV, including VUV, were determined using variable-angle spectroscopic ellipsometry (VASE®). Theory and methods of determining optical constants for materials using VASE have been described in detail elsewhere.[11] A commercial VUV-VASE® system (J. A. Woollam Co.), covering the spectral range 140–1100 nm, was used. Measurements were performed at two angles of incidence (60 and 70 deg) and over spectral range 140–400 nm. Prior to measurement, the silicone film was backside abraded to eliminate back surface reflections, and the sample was then placed on a glass slide for measurement.

Raw VUV-VASE data were fitted to optical models for a 200-μm (nominal) silicone film to determine the optical constants. Silicone was represented in the optical model by a sum of four Gaussian oscillators to account for interband absorptions. Surface roughness was modeled by a Bruggeman effective medium approximation (BEMA) layer, assuming 50% material and 50% void.

The penetration depth D_p for a material at a given wavelength is a measure of how far a beam of light of that wavelength will penetrate into the material. A propagating beam will be attenuated to $1/e$ of its original intensity after propagating a distance equal to the penetration depth. Penetration depth is related to the optical constant k as indicated in Eq. (2):

$$D_p = \lambda/4\pi k \tag{2}$$

Using Eq. (2), UV light penetration depth in silicone DC93-500 was determined as a function of wavelength of 140–400 nm.

E. Vacuum Ultraviolet Exposure

The facility used for VUV exposure has been described in detail elsewhere.[6] The facility uses a cryogenic vacuum pumping system. The test chamber contains four individual VUV exposure areas separated by water-cooled copper walls to minimize cross interactions between compartments. Each exposure area contained a 30-W VUV deuterium lamp with a magnesium fluoride end window (Hamamatsu Model L7293), which provided broad spectrum VUV with a lower cutoff wavelength of 115 nm. Sample stages, one per area, were motor controlled so that the intensity of VUV light could be adjusted by changing the distance between the VUV light source and the sample. Each exposure area was equipped with a cesium iodide (CsI) phototube, calibrated to a NIST-measured deuterium source, to make measurements of lamp intensity (in the wavelength range of sensitivity of the detector, 115–200 nm) at the sample distance. Lamp-intensity measurements were used to determine the number of VUV suns, defined as the ratio of lamp intensity to AM0 intensity in the 115–200-nm wavelength range. For reference, the AM0 intensity in the 115–200-nm-wavelength range is 1.073E-5 W/cm^2 (Ref. 7). Multiplying the number of suns by test exposure hours provides the number of equivalent sun hours, or ESH, which is the equivalent time for direct AM0 exposure. Additionally, multiplying the lamp intensity (in units of watts per square centimeter) by test exposure duration (in seconds) provides incident energy fluence (in units of joules/centimeter^2). These exposure conditions are reported with material degradation results.

Prior to exposure, samples were installed in the facility, and the chamber was brought to high vacuum. An operating pressure of approximately 4×10^{-6} torr was achieved within 24 h of establishing high vacuum before commencing ultraviolet exposure. The test chamber was brought to atmosphere using nitrogen to remove or replace samples. Separate from the sample exposure tests, thermocouple temperature measurements were made, which indicated that the VUV lamps did not cause the temperature of the sample stage at the testing distances to rise above room temperature.

A comparison of the AM0 irradiance spectrum and the deuterium lamp irradiance spectrum is shown in Fig. 1.[12] The lamp irradiance spectrum was obtained by the National Institute of Standards and Technology using a distance of 25.4 cm from the source to the detector. For the results described in this paper, the VUV exposure facility used distances that were significantly greater than 25.4 cm, between 50 and 92 cm, and so the absolute irradiance values shown

Table 1 VUV exposure conditions for wavelength dependence of DC93-500 degradation

Filter peak wavelength, nm	Filter wavelength range at half-maximum transmittance, nm	Test duration, h	Avg. intensity, μW/cm^2	Cumulative incident energy fluence, J/cm^2	Avg. number of suns	Total equivalent sun hours
151	143–159	74	2.7 ± 0.5	0.76	17 ± 3	1360
		408		4.0		7190
170	157–184	74	3.9 ± 0.8	1.1	2.0 ± 0.4	150
		408		5.7		800
182	171–193	74	6.2 ± 1	0.17	0.14 ± 0.03	11
		408		0.92		57
188	179–197	74	4.0 ± 0.8	0.11	0.07 ± 0.01	5.7
		408		0.6		30

Table 2 VUV exposure conditions for intensity dependence of DC93-500 degradation

Test area	Source to sample distance, cm	Exposure duration, h	Avg. intensity, μW/cm^2	Cumulative incident energy fluence, J/cm^2	Avg. number of suns	Cumulative equivalent sun hours
1	51.3	118	64 ± 5.4	27	6.0 ± 0.5	700
		356	59 ± 6	75	5.5 ± 0.6	1900
		238	56 ± 4	47	5.2 ± 0.4	1200
2	71.6	118	34 ± 2	14	3.2 ± 0.2	370
		379	32 ± 3	43	3.0 ± 0.2	1100
		262	30 ± 2	29	2.8 ± 0.15	740
4	91.6	117	18 ± 1	7.6	1.7 ± 0.1	200
		379	16 ± 2	22	1.5 ± 0.2	570
		262	15 ± 0.7	14	1.4 ± 0.1	370

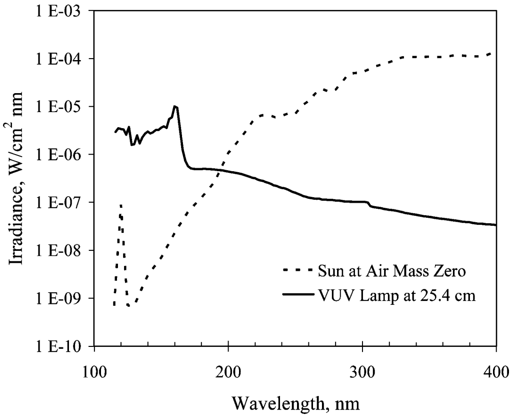

Fig. 1 Air mass zero solar irradiance compared to deuterium VUV lamp irradiance at a 25.4-cm source-to-detector measurement distance.

in Fig. 1 are much higher than would be used for typical test conditions. However, from Fig. 1 it is evident that the spectral shapes are very different between the AM0 sun and the deuterium lamp. For example, the deuterium lamp shows a peak around 160 nm that is absent in the solar spectrum. Additionally, beyond approximately 170 nm, the deuterium lamp irradiance is much less than that of the sun. Test conditions using this facility for wavelength dependence and intensity-dependence studies for silicone DC93-500 degradation are described in the following sections.

1. VUV Exposure Methods: Wavelength Dependence of Silicone Degradation

Samples of DC93-500 silicone films approximately 152 μm thick were exposed to VUV using narrow bandpass filters to isolate various wavelength bands provided by a broad-spectrum deuterium lamp in the VUV exposure facility. For each of four DC-93-500 film samples, a magnesium fluoride window was placed over the silicone samples, and the narrow bandpass filter was placed over the magnesium fluoride window with the coating surface of the filter facing the magnesium fluoride window. This configuration was used so that organic contaminants would not have a view of the coating on the filter. Samples were located at a distance of 50.4 cm from the deuterium lamp source.

Samples were measured for total transmittance in the 210–2500-nm-wavelength range. Filter wavelength ranges and exposure conditions are provided in Table 1. Intensity was measured approximately every 24 to 72 h of exposure. Whereas Table 1 indicates the time-average intensity and number of suns, additional error exists because of the intensity variation across the sample area, which is approximately ±15% of the measured value.

2. VUV Exposure Methods: Intensity Dependence of Silicone Degradation

Samples of DC 93-500 silicone film approximately 152 μm thick were exposed to VUV above a 115-nm wavelength using three different intensity levels to determine rates of transmittance degradation and of mechanical properties degradation. Three exposure compartments in the VUV exposure facility were used to obtain the various intensity levels using different source-to-sample distances. These source-to-sample distances include the maximum and minimum distances achievable with the VUV exposure facility and one additional distance in between. Tensile samples were exposed for three exposure durations. Exposure conditions, measured in the VUV wavelength range of 115–200 nm, are shown in Table 2. Whereas the deuterium lamp also provides radiation above 200 nm, it is a small fraction of the AM0 intensity above 200 nm and is not accounted for here.

Approximately every 24 h of testing, intensity values were measured, lamp windows were cleaned, intensity was remeasured, and exposure resumed. It is necessary to frequently clean lamp windows because even trace amounts of organic contaminants in the test chamber can be easily deposited and fixed on surfaces in the presence of high-intensity UV light, and the highest intensity UV light is at the lamp output window. Because the VUV lamps are located on ports that can be isolated from the main sample chamber, lamp maintenance was conducted while the samples remained under high-vacuum conditions. Whereas Table 2 indicates the time-average intensity and number of suns, there is an intensity variation across the sample area, which is approximately ±15% of the measured value.

III. Results and Discussion

A. Wavelength Dependence of DC93-500 Optical Properties Degradation

Figure 2 shows the total transmittance spectra of 152-μm-thick DC93-500 film samples that were exposed to VUV from beneath

Table 3 Effect of VUV exposure of various wavelength ranges on transmittance at 250 nm of 152-μm DC93-500 film

VUV exposure conditions				
Filter peak wavelength, nm	VUV exposure wavelength range, nm	Cumulative incident energy fluence, J/cm^2	Equivalent sun hours in filter wavelength range	Transmittance measured at 250 nm
151	143–159	0.76	1360	85.80
		4	7190	75.71
170	157–184	1.1	150	87.61
		5.7	800	78.55
182	171–193	0.17	11	87.56
		0.92	57	75.87
188	179–197	0.11	5.7	86.97
		0.6	30	79.42
Pristine sample		0	0	87.51

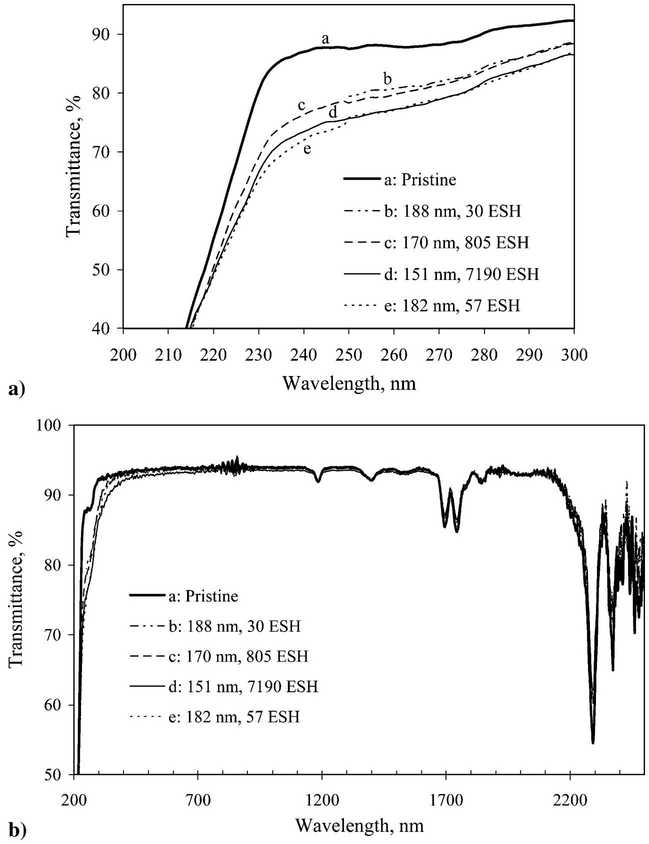

Fig. 2 Effect of VUV exposure of various wavelength ranges on spectral transmittance of 152-µm DC93-500 silicone film for a) the wavelength range of 200–300 nm in which the most significant degradation occurred and b) the overall spectral measurement range of 210–2500 nm.

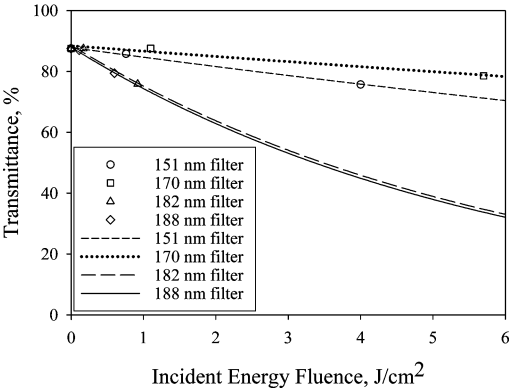

Fig. 3 Transmittance of 152-µm DC93-500 silicone film at 250 nm as a function of incident VUV energy fluence provided by exposure to various wavelength ranges through narrow-bandpass filters.

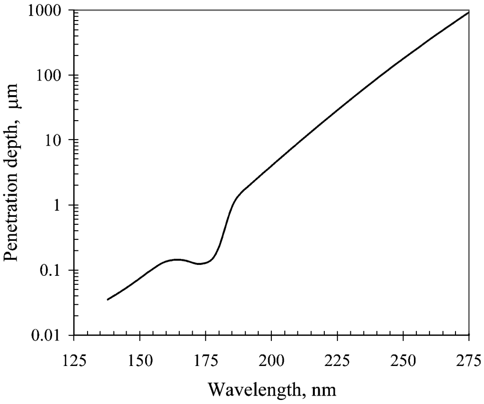

Fig. 4 Depth of penetration of VUV in pristine DC93-500 silicone film.

various narrow bandpass filters (test conditions are fully described in Table 1). Data in Fig. 2 are shown only for samples exposed to VUV for 408 h, because spectra for samples exposed for 74 h were difficult to distinguish from the spectrum of the pristine sample. The legend for Fig. 2 indicates the filter peak wavelength and equivalent space exposure, in units of ESH, for each wavelength band from the exposure conditions listed in Table 1. The most significant changes to the spectra are in the UV wavelengths below 300 nm as shown in Fig. 2a. Significant degradation was observed for all four exposure wavelength ranges. This indicates that degradation is not exclusively caused by exposure to an individual wavelength or narrow wavelength band. However, data can be further analyzed to establish the effectiveness of these wavelength bands in causing degradation. Table 3 shows data for transmittance at 250 nm obtained from the spectral data shown in Fig. 2. Figure 3 shows a plot of transmittance at 250 nm vs incident energy fluence (listed in Table 1) for all exposures. It is evident from Fig. 3 that the VUV filters providing longer VUV wavelengths cause a higher rate of transmittance degradation than the shorter VUV wavelengths. The most likely explanation for this is that the longer wavelengths are more deeply penetrating into DC93-500 and, therefore, affect more of the bulk of the material.

B. VUV Variable-Angle Spectroscope Ellipsometry (VASE) Results

Figure 4 shows VUV penetration depth as a function of wavelength for DC93-500 film. Because radiation must be absorbed to cause degradation, wavelength dependence of VUV degradation, observed in Fig. 3, can be related to the depth to which VUV can penetrate as a function of wavelength. Below 175 nm, penetration is limited to tenths of micrometers, but it increases rapidly with increasing wavelength above 175 nm. Based on the very shallow penetration depth for wavelengths below 175 nm, it is evident that optical degradation caused by VUV below 175 nm would be limited to surface degradation.

Table 1 indicates the wavelength bands for the narrow bandpass filters through which DC93-500 film samples were exposed to VUV radiation. As shown in Table 1, the 151- and 170-nm filters transmit

VUV wavelengths no greater than 185 nm. Based on the data in Fig. 3, indicating the slow rate of degradation for DC93-500 exposed beneath filters that transmit up to 185 nm and the significantly more rapid rate of degradation for samples exposed beneath filters that transmit up to approximately 200 nm, it can be concluded that the wavelengths between approximately 185 and 200 nm are more effective in causing DC93-500 transmittance degradation. These wavelengths can penetrate from 1 to 3 μm in depth in DC93-500.

C. Intensity-Dependence of DC93-500 Optical and Mechanical Properties Degradation

Figure 5 shows the total transmittance spectra of 152-μm-thick DC93-500 film samples exposed to VUV of various intensity levels and for various equivalent sun hours. Samples were exposed to the unfiltered deuterium lamp output, wavelengths above 115 nm, and output is reported in the 115–200-nm-wavelength range, which contains the majority of lamp output as shown in Fig. 1. It is evident that the most significant degradation occurred in the ultraviolet wavelengths, below 400 nm, as shown in Fig. 5a. It is also evident that degradation increases with increasing equivalent sun hours of exposure.

Table 4 and Fig. 6 show transmittance at 300 nm (a wavelength at which significant transmittance degradation of DC93-500 is evident, based on Fig. 5) as a function of exposure, represented by thousands of ESH, for various intensities (number of equivalent suns). In Fig. 6, symbols indicate the measured data points, and lines indicate exponential decay curve fits. In addition to examining data for individual intensities, data were considered all together, independent of intensity, as one of the curves shown in Fig. 6.

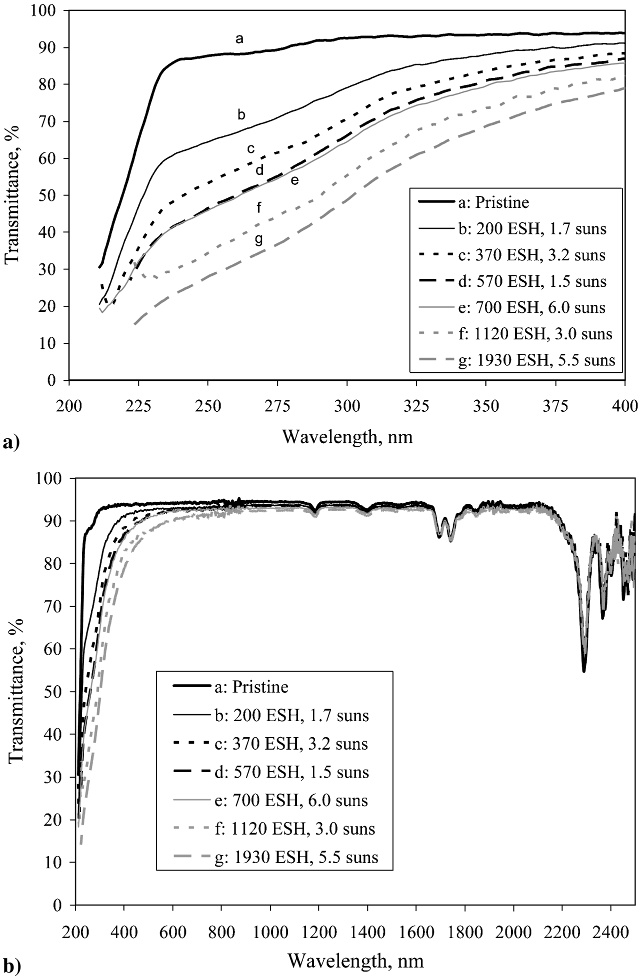

Fig. 5 Effect of VUV exposure of various intensities on spectral transmittance of 152-μm DC93-500 silicone film for a) the 200–400-nm spectral range and b) the 210–2500-nm spectral range.

Table 4 Effect of VUV exposure (>115 nm) of various intensities on transmittance at 300 nm of 152-μm DC93-500 film

Intensity, number of VUV suns	Exposure level, thousands of ESH	Transmittance at 300 nm, %
1.5	0.2	79.10
	0.37	70.77
3	0.57	66.24
	0.7	64.50
5.5	1.12	55.43
	1.93	48.76
0	0	92.50

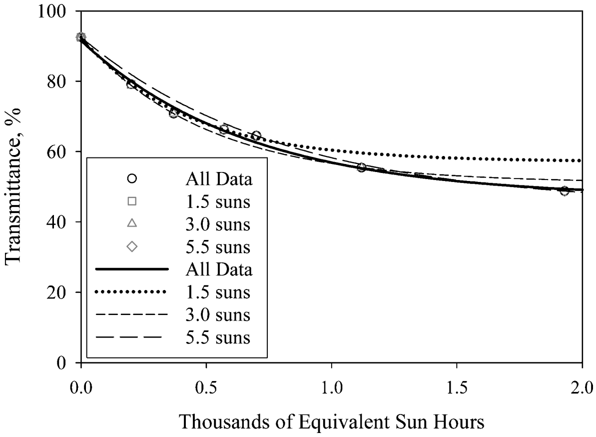

Fig. 6 DC93-500 film transmittance at 300-nm wavelength as a function of VUV exposure duration expressed in thousands of equivalent sun hours.

When transmittance data for all intensites are considered together, the best-curve-fit equation for transmittance τ is given in the format shown in Eq. (3):

$$\tau = y_0 + a \exp(-kx) \tag{3}$$

where x is VUV exposure, in thousands of equivalent sun hours, and y_0, a, and k are constants. Equation (3) represents an exponential decay reaching an asymptotic value, which is evident from examination of Fig. 6. We can further determine the expression for transmittance of unexposed materials, or τ_0, by setting $x = 0$:

$$\tau_0 = y_0 + a \tag{4}$$

Using the expression for a as a function of y_0 and τ_0 from Eq. (4) and by expressing x as the product of S and h, equivalent suns intensity and thousands of exposure hours, respectively, Eq. (3) can be rewritten as

$$\tau = y_0 + (\tau_0 - y_0)\exp(-kSh) \tag{5}$$

To determine whether the rate of transmittance decay shows a dependence upon intensity, Eq. (5) is solved for k to give

$$k = -(1/Sh)\ln[(\tau - y_0)/(\tau_0 - y_0)] \tag{6}$$

The curve fit for all measured transmittance data at 300 nm (Fig. 6) produces a value of $y_0 = 46.7$, which is the asymptote being approached by the decay in transmittance and which is assumed to be constant, independent of intensity. If we examine transmittance data at 300 nm for all intensities and plot k vs S, it is possible to determine whether k is actually constant, which would mean it is independent of intensity, or whether it varies as a function of intensity, indicating intensity dependence. The values for S and h are obtained from the VUV exposure conditions (Table 2), and τ and τ_0 values are the measured transmittance data (shown in Table 4). The plot of k vs S is shown in Fig. 7. Based on the data shown in Fig. 7,

Table 5 Effect of VUV exposure of various intensities on mechanical properties degradation of DC93-500

Avg. number of VUV suns	Exposure duration, h	Cumulative VUV equivalent sun hours	No. test samples	Avg. UTS, MPa	Avg. elongation, %
5.5	118	700	2	5.9 ± 0.1	79.0 ± 2.8
	356	1900	3	3.8 ± 2.0	65.3 ± 2.0
	238	1200	3	3.6 ± 0.4	69.3 ± 2.1
3	118	370	2	6.2 ± 0.8	86.0 ± 2.8
	379	1100	3	4.3 ± 0.6	69.0 ± 0
	262	740	3	5.3 ± 0.9	76.3 ± 2.1
1.5	117	200	3	6.2 ± 0.4	91.3 ± 2.5
	379	570	3	5.0 ± 1.0	75.0 ± 4.4
	262	370	3	5.6 ± 1.6	82.3 ± 6.1
0 (Pristine)	0	0	5	9.2 ± 0.5	139 ± 6.9

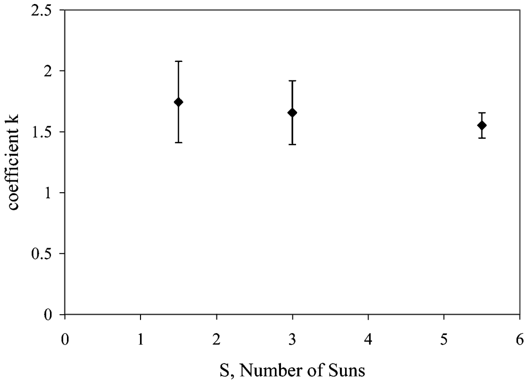

Fig. 7 Coefficient *k*, described by Eq. (6), as a function of VUV equivalent suns for DC93-500 film samples.

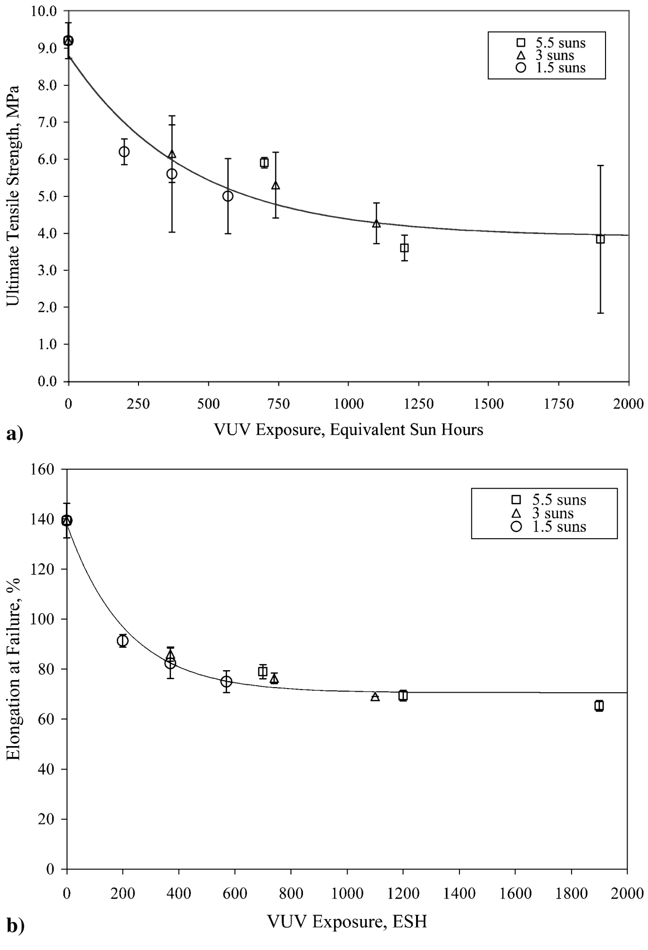

Fig. 8 Mechanical properties of a) tensile strength and b) elongation at failure for 152-μm DC93-500 silicone as a function of VUV exposure equivalent sun hours.

it is evident that there is no statistically significant dependence upon exposure intensity between approximately 1.5 and 5.5 VUV suns.

Table 5 and Figs. 8a and 8b show mechanical properties of 152-μm DC93-500 silicone film samples as a function of exposure (ESH). Both ultimate tensile strength (Fig. 8a) and elongation at failure (Fig. 8b) decrease with increasing exposure and indicate the approach of an asymptotic value near the 2000 ESH exposure level. An exponential decay curve fit is shown in each figure. Based on these data, especially because of similar degradation for similar ESH, regardless of intensity, there is no clear trend indicating an intensity dependence upon the rate of mechanical properties degradation.

IV. Conclusions

DC93-500 silicone has been found to undergo degradation in optical and mechanical properties upon exposure to a laboratory deuterium lamp providing VUV radiation of wavelengths greater than 115 nm. In one experiment, samples of DC93-500 films were exposed to narrow bands of VUV radiation (~20 nm) in wavelength ranges between approximately 140 and 200 nm by using a broad-spectrum deuterium lamp as the VUV source and narrow-bandpass filters over the DC93-500 samples. Results indicated that each wavelength range used for the exposures produced degradation in DC 93-500 optical properties. However, degradation per incident energy fluence indicated the highest rate of degradation for samples exposed from beneath filters that included wavelengths above 185 nm. VUV ellipsometric optical measurements were made on DC93-500 silicone to determine the depth of penetration of VUV light as a function of wavelength. Data showed that VUV of wavelengths below 185 nm penetrate DC 93-500 to depths no greater than 1 μm, indicating that VUV degradation of these wavelengths can only occur in a shallow layer compared to typical spacecraft polymer-film applications, which use films on the order of tens to more than a hundred micrometers in thickness. Compared to VUV exposures to wavelengths below 185 nm, a significantly more rapid rate of transmittance degradation was observed in DC93-500 for VUV exposures that included wavelengths between 185 and 200 nm, which correspond to depths of VUV penetration between 1 and 3 μm.

In another experiment, the rates of optical and mechanical properties degradation for DC93-500 films were examined for exposures to broad spectrum VUV (above 115 nm) of various intensities. It was found that for both transmittance degradation and mechanical properties (ultimate tensile strength and elongation at failure) degradation, loss of these properties followed exponential decay functions approaching asymptotic values. Examination of the data indicated no clear dependence of degradation on the intensity of exposure within a range of intensities between 1.5 and 5.5 VUV suns. The lack of intensity dependence in these data indicates that DC93-500 can be tested using VUV intensities as high as about 5.5 suns without causing significantly different degradation rates compared to near-real-time exposure rates. It remains to be determined whether these rates of degradation are similar to those caused by actual space exposure, especially considering the significantly different spectra between the sun and the laboratory VUV source.

It is hoped that space exposure data will eventually be available to make such comparisons.

Acknowledgments

The authors gratefully acknowledge the technical support of Frank Lam and James Mazor (Akima), Michael DePauw (NASA), Scott Panko and Edward Sechkar (QSS Group, Inc.), Michael Piszczor (NASA), and Mark O'Neill, Don Spears, and A. J. McDanal (ENTECH, Inc.).

References

[1] Dow Corning Corp., "Product Information for Dow Corning® Space-Grade Silicone Sealants," 2001.

[2] O'Neill, M. J., Piszczor, M. F., Eskenazi, M. I., McDanal, A. J., George, P. J., Botke, M. M., Brandhorst, H. W., Edwards, D. L., and Hoppe, D. T., "Ultra-Light Stretched Fresnel Lens Solar Concentrator for Space Power Applications," SPIE Paper 5179-17, Aug. 2003.

[3] Edwards, D. L., and Finckenor, M. M., "Optical Analysis of Transparent Polymeric Material Exposed to Ultraviolet Radiation," 8th International Symposium on "Materials in a Space Environment" and 5th International Conf. on "Protection of Materials and Structures from the LEO Space Environment," Centre National d'Etudes Spatiales, Toulouse, France, June 2000.

[4] Dever, J., Messer, R., Powers, C., Townsend, J., and Wooldridge, E., "Effects of Vacuum Ultraviolet Radiation on Thin Polyimide Films," *High Performance Polymers*, Vol. 13, No. 3, 2001, pp. S391–S399.

[5] Dever, J., Semmel, C., Edwards, D., Messer, R., Peters, W., Carter, A., and Puckett, D., "Radiation Durability of Candidate Polymer Films for the Next Generation Space Telescope Sunshield," AIAA Paper 2002-1564, April 2002.

[6] Dever, J., and McCracken, C., "Effects of Various Wavelength Ranges of Vacuum Ultraviolet Radiation on Teflon® FEP Film," *High Performance Polymers*, Vol. 16, No. 2, 2004, pp. 289–302.

[7] American Society for Testing and Materials, "Solar Constant and Air Mass Zero Solar Spectral Irradiance Tables," ASTM-E 490-73a, Jan. 1974 (reapproved 1992).

[8] Dever, J. A., "Low Earth Orbital Atomic Oxygen and Ultraviolet Radiation Effects on Polymers," *Flight-Vehicle Materials, Structures, and Dynamics—Assessment and Future Directions*, Vol. 2, Advanced Metallics, Metal-Matrix and Polymer-Matrix Composites, American Society of Mechanical Engineers, New York, 1994, pp. 422–433.

[9] Adams, M. R., "The Degradation of Polymeric Spacecraft Materials by Far-UV Radiation and Atomic Oxygen," UMI Dissertation Services, Ann Arbor, MI, 1993, p. 138.

[10] American Society for Testing and Materials, "Standard Test Method for Tensile Properties of Plastics," ASTM D 638-95, Dec. 1995.

[11] Herzinger, C. M., Snyder, P. G., Johs, B., and Woollam, J. A., "InP Optical Constants Between 0.75 and 5.0 eV Determined by Variable-Angle Spectroscopic Ellipsometry," *Journal of Applied Physics*, Vol. 77, No. 4, 1995, pp. 1715–1724.

[12] Dever, J. A., Pietromica, A. J., Stueber, T. J., Sechkar, E. A., and Messer, R. K., "Simulated Space Vacuum Ultraviolet (VUV) Exposure Testing for Polymer Films," AIAA Paper 2001-1054, Jan. 2001.

D. Edwards
Associate Editor