Evaluation of Low Earth Orbit Environmental Effects on International Space Station Thermal Control Materials

Joyce A. Dever and Sharon K. Rutledge
Lewis Research Center, Cleveland, Ohio

Mark M. Hasegawa
Boeing Space and Defense Systems, Huntington Beach, California

Charles K. Reed
Lockheed Martin Vought Systems, Dallas, Texas

National Aeronautics and
Space Administration

Lewis Research Center

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EVALUATION OF LOW EARTH ORBIT ENVIRONMENTAL EFFECTS ON INTERNATIONAL SPACE STATION THERMAL CONTROL MATERIALS

JOYCE A. DEVER
SHARON K. RUTLEDGE
NASA Lewis Research Center
Cleveland, OH 44135

MARK M. HASEGAWA
Boeing Space and Defense Systems
Huntington Beach, CA 92647

CHARLES K. REED
Lockheed Martin Vought Systems
Dallas, TX 75265

ABSTRACT

Samples of International Space Station (ISS) thermal control coatings were exposed to simulated low Earth orbit (LEO) environmental conditions to determine effects on optical properties. In one test, samples of the white paint coating Z-93P were coated with outgassed products from Tefzel® (ethylene tetrafluoroethylene copolymer) power cable insulation as may occur on ISS. These samples were then exposed, along with an uncontaminated Z-93P witness sample, to vacuum ultraviolet (VUV) radiation to determine solar absorptance degradation. The Z-93P samples coated with Tefzel® outgassing products experienced greater increases in solar absorptance than witness samples not coated with Tefzel® outgassing products. In another test, samples of second surface silvered Teflon® FEP (fluorinated ethylene propylene), SiO_x (where $x \approx 2$)-coated silvered Teflon® FEP, and Z-93P witness samples were exposed to the combined environments of atomic oxygen and VUV radiation to determine optical properties changes due to these simulated ISS environmental effects. This test verified the durability of these materials in the absence of contaminants.

1. Introduction

In low Earth orbit (LEO), solar ultraviolet (UV) radiation and atomic oxygen can cause changes to the solar absorptance of many thermal control coatings. UV radiation can cause darkening, indicated by an increase in solar absorptance, of some polymers and oxides commonly used in thermal control materials. Atomic oxygen can cause erosion of polymer materials, but may reverse the UV-darkening effect on oxides. Maintenance of low solar absorptance and high thermal emittance of thermal control coatings is important to assure the proper operating temperature of thermal control systems. Thermal control coatings to be used on radiator surfaces of the International Space Station (ISS) were evaluated for their performance upon exposure to simulated LEO environments of solar vacuum ultraviolet (VUV) radiation (wavelength range 115-200 nm) and VUV combined with atomic oxygen (AO). Solar absorptance measurements were made in vacuum in order to eliminate the "bleaching effect," or reversal of degradation due to ambient oxygen exposure, on VUV-induced degradation. For comparison, solar absorptance measurements were also made in air before and after the exposure tests. For some samples, thermal emittance was also measured in air. The objectives of these experiments were to determine changes in optical properties for various thermal control materials due to exposure to simulated LEO conditions similar to those expected for ISS. In one test, samples of the white paint thermal control coating Z-93P (zinc oxide pigment in potassium silicate binder) were coated with outgassed products from a radiation crosslinked Tefzel® (ethylene tetrafluoroethylene copolymer) to simulate possible on-orbit contamination from power cable insulation. Samples were then exposed to VUV radiation to determine the solar absorptance degradation that would be expected due to VUV-induced darkening of both the Z-93P and the contaminant layer. This test represented a worst-case scenario for Z-93P solar absorptance degradation because AO, which may remove some of the contaminants and may reverse the darkening due to

vacuum ultraviolet radiation, was not present during testing. In another set of tests, samples of silvered Teflon® FEP (fluorinated ethylene propylene), SiO_x (where x ≈2)-coated silvered FEP Teflon®, and white paint Z-93P coatings were exposed to AO combined with VUV radiation in order to verify the solar absorptance and thermal emittance durability of these thermal control materials selected for use on the ISS. These samples were not exposed to contamination prior to AO-VUV testing.

2. Experimental Procedures

2.1 VUV AND COMBINED AO-VUV EXPOSURE FACILITY

The facility that was used in these experiments for VUV exposure and combined AO-VUV exposure is described in [1] and [2]. Four samples of maximum size 2.5 cm diameter and 0.635 cm thickness can be exposed to atomic oxygen and VUV radiation concurrently or to the individual environmental effects. These four samples can be measured, in vacuum, for total hemispherical reflectance. A schematic diagram of the facility is given in Figure 1.
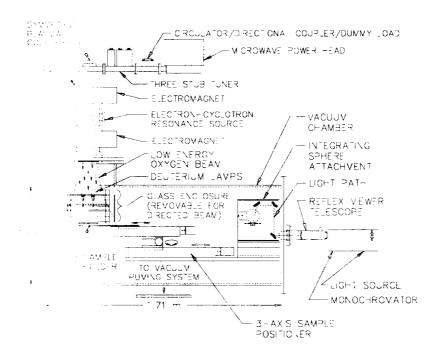

Figure 1: Atomic oxygen-vacuum ultraviolet radiation exposure facility.

An ECR (electron cyclotron resonance) source is used to provide thermal energy atomic oxygen. To avoid direct line-of-sight to the samples from the ECR source, which also provides intense VUV at the 130 nm oxygen resonance line, a fixture consisting of glass surfaces and an aluminum foil liner are used to scatter and redirect the atomic oxygen. Mass change of Teflon® FEP , whose in-space erosion yield has been characterized as 3.64×10^{-25} cm^3/atom [3], was used to determine equivalent atomic oxygen flux and fluence during each AO-VUV exposure test. A pair of deuterium lamps was used for VUV exposure. These lamps are described in section 2.2. The in-vacuum reflectance measurement capability is described in section 2.3.2. Facility pressure was approximately 4×10^{-6} to 10^{-5} torr during VUV exposure of samples without AO, and approximately 4×10^{-4} torr during combined VUV and AO exposure.

2.2 VUV LAMP AND DETECTOR CALIBRATION PROCEDURES

For each test, a pair of 30 watt deuterium lamps (Hamamatsu model L879-01) with magnesium fluoride windows were used to illuminate samples in a 4-sample holder located inside the vacuum chamber as shown in Figure 1. The distance between the lamp's anode and the center of the sample holder was approximately 49.5 cm where distance was measured along the axis of the lamp nose. The bodies of the lamps were located outside of the vacuum chamber with their end-tubes pushed through o-ring compression fittings to provide a vacuum seal. The lamps' end-tube windows were thus located inside the vacuum chamber. Lamp bodies were cooled with forced air.

Prior to and following each test, the output of the pair of lamps was measured in vacuum using a cesium iodide (CsI) phototube (Hamamatsu Model R1187) with a magnesium fluoride window. The CsI phototube was attached to the 4-sample holder with its axis along the lamp nose axis with the sensor at the level of the sample surfaces. The phototube was then placed at each of the four sample sites to obtain signal at that position. This phototube is sensitive in the wavelength range between 115 and 200 nm, the range of primary output of the deuterium lamps.

Prior to measuring the output of the exposure lamps, the CsI phototube was calibrated at 25.4 cm distance with a Hamamatsu L879-01 lamp used as a reference standard. This lamp had been calibrated at 25.4 cm distance by the National Institute of Standards and Technology (NIST). The intensity obtained by NIST was divided by the CsI phototube-measured signal for the reference standard lamp to determine a calibration factor for the detector for the wavelength range of 115-200 nm. Detector calibration data is shown in Table 1.

TABLE 1. VUV Detector Calibration Data

Parameter	Value
Intensity of NIST-calibrated VUV lamp, 25.4 cm distance, 115-200 nm	3.39×10^{-4} W/cm^2
Intensity of the sun, air mass zero, 115-200 nm	1.0378×10^{-5} W/cm^2
Signal of NIST-calibrated VUV lamp measured with CsI detector, 25.4 cm distance	1.68×10^{-6} A
Calibration factor for CsI detector	201.79 W/(cm$^2 \cdot$A)

For each pair of lamps measured using the calibrated CsI detector, the signal obtained in amps was multiplied by the detector's calibration factor to give the lamp intensity in the wavelength range 115-200 nm. Dividing the lamps' intensity by the sun's intensity in the same wavelength range provided the number of suns in the 115-200 nm range. For each VUV exposure test, equivalent sun hours (ESH) of VUV exposure in the 115-200 nm wavelength range were obtained using the following equation:

$$(\text{ESH VUV})_{115\text{-}200 \, \text{nm}} = (\text{No. of Suns})_{115\text{-}200 \, \text{nm}} \times (\text{Exposure duration, hrs.}) \qquad (1)$$

Measured lamp intensity data and ESH for each of the exposure tests will be given in sections 3.1 and 3.2.

2.3 OPTICAL PROPERTIES CHARACTERIZATION PROCEDURES

2.3.1 In-air Solar Absorptance Measurements

Prior to and following VUV or AO-VUV exposure tests, samples were measured for total hemispherical reflectance in air between 250 and 2500 nm using a Perkin-Elmer Lambda-9 spectrophotometer equipped with a 15 cm integrating sphere. A Labsphere Spectralon reference standard was used. Solar reflectance, ρ_s, was obtained by integrating spectral reflectance over the air mass zero solar spectral irradiance distribution using standard procedures [4]. Because samples were opaque, solar absorptance, α_s, was obtained using the following equation:

$$\alpha_s = 1 - \rho_s \qquad (2)$$

Error in repeatability of α_s measurements with the Lambda-9 instrument is expected to be approximately ± 0.005.

2.3.2 In-vacuum Reflectance Measurement System: Calibration and Use

The reflectance measurement system, Optronic Laboratories Model 746 (OL 746), is described in detail in [2]. This system measures total hemispherical spectral reflectance in the wavelength range from 280 to 2500 nm. Calculations of solar absorptance were made in this wavelength range using standard procedures [4] and solar absorptance was calculated using Equation 2.

Because the OL 746 is a single beam instrument, a known reference is measured in order to calibrate the system prior to measuring test samples. Calibration factors as a function of wavelength, λ, are obtained in the form of

$$(\text{Cal. factor})_\lambda = (\text{Reference Reflectance})_\lambda / (\text{measured detector signal})_\lambda. \tag{3}$$

The reference sample used for these experiments was a sample of YB-71 (white paint thermal control coating comprised of zinc orthotitanate pigment in a potassium silicate binder) on aluminum, which was located in the integrating sphere attachment of the OL 746 and protected from VUV and AO exposure. The absolute reflectance of this sample was previously measured in air using the Perkin-Elmer Lambda-9 instrument as described in section 2.3.1. These in-air data were used in Equation 3 as the (Reference Reflectance)$_\lambda$ values.

Samples in the 4-sample holder are transported from the AO-VUV exposure end of the chamber to the measurement end of the chamber using a three-axis positioner to which the sample holder is mounted, as shown in Figure 1. Because samples slide into place under the integrating sphere for measurement, a small gap is needed between the integrating sphere port and the sample surface. This can introduce error in the measurement of reflectance due to loss of light from this gap. In order to reduce this error, the pre-test, in-air reflectance measurement of each sample obtained with the OL 746 was compared to an in-air measurement obtained with the Perkin-Elmer Lambda-9 where samples were in intimate contact with the integrating sphere. For these in-air data, a set of correction factors was generated for each sample so that the reflectance at each wavelength measured with the OL 746 instrument was corrected to the value given by the Lambda-9. These spectral correction factors were applied to each subsequent reflectance spectrum obtained with the OL 746 instrument. Error in repeatability of α_s measurements with the OL 746 instrument is expected to be approximately ± 0.01.

2.3.3 In-air Thermal Emittance Measurements

A Gier-Dunkle model DB-100 portable emissometer was used to measure room temperature total emittance, ε, normal to sample surfaces. The instrument provides an integrated value of normal emittance over the wavelength range of 5 to 25 μm. Error in repeatability of measurement of ε is expected to be approximately ± 0.005.

2.4 TEFZEL®-CONTAMINATED Z-93P EXPOSED TO VUV WITHOUT AO

2.4.1 Samples

The white paint coating Z-93P was applied to aluminum substrates of 2.38 cm diameter. Coating thickness was approximately 0.10-0.13 mm. Samples of Z-93P were coated with approximately 100 nm of outgassed products from a radiation crosslinked Tefzel® as described fully in [5]. Samples of Tefzel® were heated to approximately 149°C under vacuum (10^{-6} to 10^{-7} torr) to drive off contaminant products. Z-93P samples were mounted on a water-cooled sample plate approximately 15.2 cm from the contamination source along with a quartz crystal microbalance (QCM) used to measure thickness of the deposited contaminants. A low pressure mercury near ultraviolet (NUV) lamp illuminated the sample plate, including the QCM, during and after the deposition for a total NUV exposure of 16 hours. It was expected that NUV would fix the contaminants and reduce re-evaporation of the contaminants from the sample plate. Samples purposely contaminated with Tefzel® outgassing products in this manner were labeled 365-1, 365-2, and 365-3. A sample of Z-93P labeled A-100 was not exposed to Tefzel® outgassing products and was used as a witness sample during VUV exposure testing. Although this sample was prepared from a different Z-93P paint batch than those which were coated with Tefzel® outgassing products, it was expected to be a typical Z-93P sample comparable in VUV-durability to the 365-1, -2, and -3 samples in order to determine the effects of the Tefzel® contamination.

2.4.2 VUV Exposure and Sample Characterization Procedures

The three Tefzel®-contaminated Z-93P samples and one witness Z-93P sample were exposed in vacuum to four increments of VUV exposure. Total test duration was 234 hours. In addition to in-air reflectance data obtained before and after the test, in-vacuum reflectance data were obtained prior to VUV exposure and immediately after each increment. The VUV lamp pair used to illuminate the four sample holder was calibrated prior to the first exposure increment and after the final increment. VUV intensity and equivalent sun hours (ESH) for each sample will be provided in section 3.1.

2.5 AO-VUV EXPOSURE OF SILVERED TEFLON® AND SIO$_x$-COATED SILVERED TEFLON®

2.5.1 Samples

Two separate tests were conducted to evaluate uncoated and SiO$_x$ (where x ≈ 2)-coated silvered Teflon® FEP. In AO-VUV Test 1, three samples of SiO$_x$-coated silvered Teflon® FEP labeled SST-1, SST-2 and SST-4 and one Z-93P sample labeled ZPLM-1 were tested. In AO-VUV Test 2, three samples of uncoated silvered Teflon® FEP labeled UST-2, UST-3 and UST-4 and one Z-93P sample labeled ZPLM-5 were exposed. Table 2 shows the composition of each sample including the thickness of each layer. All samples were 2.38 cm diameter.

TABLE 2. Samples for AO-VUV Exposure

Test	Sample Position	Sample Label	Layer 1 on Al substrate	Layer 2	Layer3	Layer 4	Layer 5
AO-VUV Test 1	1	SST-1	acrylic adhesive	Inconel® 27.5 nm	Silver 100 nm	Teflon® FEP 0.140 mm	SiO$_x$ 115 nm
	2	SST-2	acrylic adhesive	Inconel® 27.5 nm	Silver 100 nm	Teflon® FEP 0.140 mm	SiO$_x$ 115 nm
	3	ZPLM-1	Z-93P 0.10 to 0.13 mm	--	--	--	--
	4	SST-4	acrylic adhesive	Inconel® 27.5 nm	Silver 100 nm	Teflon® FEP 0.140 mm	SiO$_x$ 115 nm
AO-VUV Test 2	1	UST-3	acrylic adhesive	Inconel® 27.5 nm	Silver 100 nm	Teflon® FEP 0.254 mm	--
	2	UST-2	acrylic adhesive	Inconel® 27.5 nm	Silver 100 nm	Teflon® FEP 0.254 mm	--
	3	ZPLM-5	Z-93P 0.10 to 0.13 mm	--	--	--	--
	4	UST-4	acrylic adhesive	Inconel® 27.5 nm	Silver 100 nm	Teflon® FEP 0.254 mm	--

2.5.2 Exposure Procedures

In AO-VUV Test 1, the samples described in Table 2 were exposed to AO and VUV radiation simultaneously in four increments. Total test duration was 260.2 hours. In AO-VUV Test 2, the samples described in Table 2 were exposed to AO and VUV radiation simulatneously in three increments. Total test duration was 250.7 hours. In addition to in-air reflectance data obtained before and after each test, in-vacuum reflectance data were obtained prior to AO-VUV exposure and immediately after each increment. The VUV lamp pair used to illuminate the four sample holder was calibrated before and after Test 1. Test 2 was conducted immediately following Test 1; therefore the calibration data following Test 1 is valid for the pre-test calibration prior to Test 2. VUV lamp output following Test 2 was not measured due to equipment problems; however, it was estimated. VUV intensity, VUV ESH, AO flux and AO fluence for each test will be provided in section 3.2.

3. Results And Discussion

3.1 TEFZEL®-CONTAMINATED Z-93P EXPOSED TO VUV WITHOUT AO

3.1.1 VUV Lamp Calibration

The measured number of VUV suns for each sample position, before and after VUV exposure testing, are shown in Table 3. It is evident that the VUV lamps experienced a significant loss of intensity due to the total 234 hours of use. It is likely that contaminants present in the facility, probably due to perfluorinated polyether vacuum pump oil, were deposited onto the MgF_2 windows of the VUV lamps and were "fixed" onto the windows due to the intense VUV radiation formed inside the lamp.

TABLE 3. Measured Number of VUV Suns at Each Sample Exposure Position

Exposure Position	Sample Type	Sample Label	No. VUV Suns Pre-test	No. VUV Suns Post-test, 234 hrs
1	Tefzel®-contaminated Z-93P	365-1	8.8	1.1
2	Tefzel®-contaminated Z-93P	365-2	10.5	1.7
3	Z-93P witness	A-100	13	1.2
4	Tefzel®-contaminated Z-93P	365-3	10.6	2.0

It was assumed that the lamp intensity degraded following an exponential decay function as shown in Figure 2. The number of suns before and after each of the four exposure increments was interpolated from the exponential decay curve fit of the data for each exposure position. Then the average number of suns for each increment was obtained from these data. Table 4 shows the curve fit equations and the calculated average number of suns for each exposure increment.
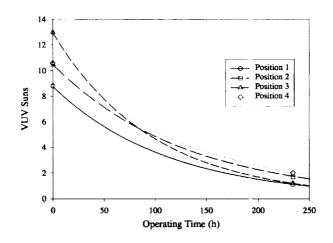

Figure 2: VUV lamp intensity as a function of operating time

TABLE 4. Calculated Number of VUV Suns

Sample Holder Position Sample Label	1 365-1	2 365-2	3 A-100	4 365-3
Exponential decay curve fit, x=operating hours, y=no. of VUV suns	y= exp(2.2- 0.0088x)	y= exp(2.3- 0.0077x)	y= exp(2.6-0.010x)	y= exp(2.4- 0.0071x)
Avg. no. VUV suns Inc. 1	7.2	8.9	10.4	9.0
Inc. 2	4.7	6.1	6.4	6.4
Inc. 3	3.1	4.2	3.9	4.6
Inc. 4	1.8	2.6	2.1	2.9

3.1.2 Solar Absorptance Measurements

The solar absorptance values in the wavelength range 280-2500 nm measured in vacuum at each VUV exposure increment are shown in Figure 3. Table 5 shows solar absorptance values before and after VUV exposure and the overall change in solar absorptance for each sample. Also shown are changes in solar absorptance per ESH of VUV exposure.

As indicated in Table 5, the change in solar absorptance per ESH for Tefzel®-contaminated Z-93P is 1.9 to 2.7 times that of the uncontaminated Z-93P witness sample. Therefore, it can be concluded that deposition of the outgassed products of Tefzel® onto Z-93P will cause degradation in solar absorptance of Z-93P to occur at a faster rate than solar absorptance degradation of Z-93P which has not been exposed to Tefzel® outgassing products. Equivalent ISS radiator VUV exposure years are shown for reference. However, it is not valid to assume that these would be the actual changes in solar absorptance for the equivalent ISS radiator LEO exposure duration, because other LEO environmental effects to which ISS radiators will be exposed were not simulated here. This test provides a worst-case scenario for solar absorptance degradation of Tefzel®-contaminated Z-93P, particularly because atomic oxygen, to which many of the thermal control surfaces on ISS will be exposed, was not present during these tests. Other testing has shown that, following VUV exposure of Tefzel®-contaminated Z-93P samples, atomic oxygen exposure causes reversal of solar absorptance degradation [5].

TABLE 5. In-Vacuum Measurements: Effect of VUV on Solar Absorptance of Tefzel®-Contaminated Z-93P and Z-93P Witness Sample

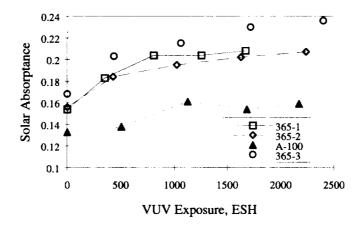| Sample	Total VUV Exposure, ESH	Equivalent ISS Radiator VUV Exposure, years	Solar Absorptance, α_s		$\Delta\alpha_s$	$\Delta\alpha_s$/ESH
			Before Exposure	After Exposure		
Tefzel®-contam., 365-1	1670	4.9	0.154	0.208	0.054	3.2×10^{-5}
Tefzel®-contam., 365-2	2234	6.5	0.156	0.207	0.051	2.3×10^{-5}
Tefzel®-contam., 365-3	2397	7.0	0.168	0.236	0.068	2.8×10^{-5}
uncontaminated, A-100	2167	6.3	0.133	0.159	0.026	1.2×10^{-5}

Figure 3: Solar absorptance of Tefzel®-contaminated Z-93P samples (365-1, -2, and -3) compared to an uncontaminated Z-93P witness sample (A-100).

Table 6 shows solar absorptance values for the wavelength range 250-2500 nm measured in air for the Tefzel®-contaminated Z-93P samples and the Z-93P witness sample before and after VUV exposure.

TABLE 6. In-air Measurements: Effect of VUV on Solar Absorptance of Tefzel®-Contaminated Z-93P and Z-93P Witness Sample

Sample	Total VUV Exposure, ESH	Solar Absorptance, α_s Before Exposure	After Exposure	$\Delta\alpha_s$	$\Delta\alpha_s$/ESH
Tefzel⁺-contam., 365-1	1670	0.144	0.182	0.038	2.3×10^{-5}
Tefzel⁺-contam., 365-2	2234	0.147	0.183	0.036	1.6×10^{-5}
Tefzel⁺-contam., 365-3	2397	0.146	0.188	0.042	1.8×10^{-5}
uncontaminated, A-100	2167	0.111	0.132	0.021	0.96×10^{-5}

A comparison of the $\Delta\alpha_s$ values between the in-air data (Table 6) and in-vacuum data (Table 5) indicate that the in-air values are lower. This difference is likely due to bleaching, or reversal, of VUV-induced darkening upon exposure of the samples to ambient conditions. Such bleaching would cause a reduction in the solar absorptance upon removal of samples from the vacuum chamber. The initial (before exposure) in-vacuum α_s values for the samples are higher than the in-air values indicating an increase upon exposure to the vacuum environment. While instrument error may account for some of the deviation, the consistency of an increase in α_s suggests another effect, possibly facility contamination.

3.2 AO-VUV EXPOSURE OF SILVERED TEFLON® AND SIO$_x$-COATED SILVERED TEFLON®

3.2.1 VUV Intensity and AO Flux Calibration

Table 7 provides VUV lamp calibration data for the AO-VUV exposure tests. As indicated, the lamp intensity after AO-VUV Test 1 was higher than that prior to the test by approximately 10-20%. In general, VUV lamp output does not increase with use as was observed here. Instead, lamp output has been observed to degrade. Degradation is minimal when lamps are used in the presence of AO, because contaminants are removed by AO as fast as they can be UV-fixed onto the lamp windows. The increase in output observed during AO-VUV Test 1 is expected to be due to AO-removal of contaminants that may have been present on the lamp windows prior to use. Because only two data points were obtained, it was not possible to determine whether the increase in lamp output occurred immediately or gradually. Because the change in output was fairly small, it was assumed to follow a linear increase with time for purposes of calculating the average number of suns for each exposure increment as shown in Table 7. It was further assumed that by the conclusion of Test 1 all contaminants were removed from the lamp window surfaces and that further use during Test 2 would cause lamp output to degrade following typical observations of 5% intensity loss

during a 250 hour test. Because facility problems prevented VUV intensity calibrations from being conducted following Test 2, the average number of suns for this test were calculated using this assumption. Calculated values for the average number of suns during Test 2 are shown in Table 7.

TABLE 7. Number of VUV Suns at Each Sample Position for AO-VUV Tests

Sample Position	No. VUV Suns Before AO-VUV Test 1	No. VUV Suns After AO-VUV Test 1	Percent Increase in No. Suns, AO-VUV Test 1	Avg. No. of Suns, AO-VUV Test 1	Avg. No. of Suns, AO-VUV Test 2
1	3.0	3.6	19.4	3.3	3.5
2	3.9	4.5	16.5	4.2	4.4
3	4.9	5.4	9.7	5.1	5.2
4	3.7	4.0	9.6	3.9	3.9

The effective atomic oxygen flux values during AO-VUV Test 1 and Test 2 were obtained by measuring the mass of Teflon® FEP witness samples before and after each test. Test 1 flux was measured to be 4.73×10^{15} atoms/cm^2s, and Test 2 flux was measured to be 4.62×10^{15} atoms/cm^2s.

3.2.2 Optical Properties Measurements

Results of in-vacuum solar absorptance measurements for samples exposed in AO-VUV Test 1 and Test 2 are shown in Table 8 and Table 9, respectively. In-air measurements for both tests are shown in Table 10. The purpose of these tests was to determine the effects of combined AO and VUV on SiO_x-coated silvered Teflon and uncoated silvered Teflon® as compared to Z-93P. Because each sample received a somewhat different ratio of AO fluence/VUV ESH, for simplicity in interpreting data, results are displayed in tabular form and not in graphical form. Based on the $\Delta\alpha_s$ values, there are no consistent increases or decreases in solar absorptance with increasing AO-VUV exposure. The values of $\Delta\alpha_s$, indicate changes that are within experimental error of the measurement throughout the tests. For the coated and uncoated silvered Teflon® materials and Z-93P, it was verified that at AO and VUV fluences representative of 2.5 to 4 years for ISS radiators, there are no significant changes in solar absorptance. In-air measurements also indicate changes within experimental error of the measurements.

TABLE 8. In-vacuum Measurements: Effect of AO and VUV on Solar Absorptance of SiO_x-coated Silvered Teflon® (SST) and
Z-93P (ZPLM) Samples

Sample	VUV ESH	AO Fluence (atoms/cm^2)	ISS Radiator Equivalent VUV years	ISS Radiator Equivalent AO years	α_s	$\Delta\alpha_s$ from t_0
SST-1	0	0	0	0	0.092	
	156	8.12×10^{20}	0.45	0.74	0.081	-0.011
	462	2.40×10^{21}	1.34	2.18	0.088	-0.004
	465	2.41×10^{21}	1.35	2.19	0.091	-0.001
	853	4.43×10^{21}	2.48	4.03	0.087	-0.005
SST-2	0	0	0	0	0.093	
	201	8.12×10^{20}	0.58	0.74	0.081	-0.012
	593	2.40×10^{21}	1.72	2.18	0.091	-0.002
	597	2.41×10^{21}	1.73	2.19	0.083	-0.010
	1095	4.43×10^{21}	3.18	4.03	0.089	-0.004
SST-4	0	0	0	0	0.102	
	184	8.12×10^{20}	0.53	0.74	0.090	-0.012
	544	2.40×10^{21}	1.58	2.18	0.094	-0.008
	547	2.41×10^{21}	1.59	2.19	0.096	-0.006
	1004	4.43×10^{21}	2.92	4.03	0.086	-0.016
ZPLM-1	0	0	0	0	0.148	
	245	8.12×10^{20}	0.71	0.74	0.150	0.002
	724	2.40×10^{21}	2.10	2.18	0.160	0.012
	728	2.41×10^{21}	2.12	2.19	0.151	0.003
	1337	4.43×10^{21}	3.89	4.03	0.151	0.003

TABLE 9. In-vacuum Measurements: Effect of AO and VUV on Solar Absorptance of Silvered Teflon® (UST) and Z-93P (ZPLM) Samples

Sample	VUV ESH	AO Fluence (atoms/cm²)	ISS Radiator Equivalent VUV years	ISS Radiator Equivalent AO years	α_s	$\Delta\alpha_s$ from t_0
UST-2	0	0	0	0	0.050	
	287	1.08×10^{21}	0.83	0.99	0.064	0.014
	785	2.97×10^{21}	2.28	2.70	0.052	0.002
	1103	4.17×10^{21}	3.21	3.79	0.056	0.006
UST-3	0	0	0	0	0.057	
	228	1.08×10^{21}	0.66	0.99	0.067	0.010
	624	2.97×10^{21}	1.81	2.70	0.056	-0.001
	878	4.17×10^{21}	2.55	3.79	0.053	-0.004
UST-4	0	0	0	0	0.050	
	254	1.08×10^{21}	0.74	0.99	0.064	0.014
	695	2.97×10^{21}	2.02	2.70	0.057	0.007
	978	4.17×10^{21}	2.84	3.79	0.055	0.005
ZPLM-5	0	0	0	0	0.119	
	339	1.08×10^{21}	0.98	0.99	0.121	0.002
	927	2.97×10^{21}	2.69	2.70	0.124	0.005
	1304	4.17×10^{21}	3.79	3.79	0.118	-0.001

TABLE 10. In-air Measurements: Effect of AO and VUV on Solar Absorptance of SiO_x-coated Silvered Teflon®, uncoated Silvered Teflon® and Z-93P.

Sample	VUV ESH	AO Fluence (atoms/cm²)	ISS Radiator Equivalent VUV years	ISS Radiator Equivalent AO years	α_s	$\Delta\alpha_s$ from t_0
SST-1	0	0	0	0	0.072	
	853	4.43×10^{21}	2.48	4.03	0.070	-0.002
SST-2	0	0	0	0	0.072	
	1095	4.43×10^{21}	3.18	4.03	0.074	0.002
SST-4	0	0	0	0	0.069	
	1004	4.43×10^{21}	2.92	4.03	0.062	-0.007
UST-2	0	0	0	0	0.064	
	1103	4.17×10^{21}	3.21	3.79	0.060	-0.004
UST-3	0	0	0	0	0.065	
	878	4.17×10^{21}	2.55	3.79	0.060	-0.005
UST-4	0	0	0	0	0.064	
	978	4.17×10^{21}	2.84	3.79	0.061	-0.003
ZPLM-1	0	0	0	0	0.132	
	1337	4.43×10^{21}	3.89	4.03	0.125	-0.007
ZPLM-5	0	0	0	0	0.117	
	1304	4.17×10^{21}	3.79	3.79	0.110	-0.007

Thermal emittance values for samples exposed in AO-VUV Tests 1 and 2 were measured as shown in Table 11. Samples were measured following AO-VUV exposure and values were compared with emittances measured for pristine samples.

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Joyce A. Dever, Sharon K. Rutledge, Mark M. Hasegawa, and Charles K. Reed

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13. ABSTRACT (Maximum 200 words)

Samples of International Space Station (ISS) thermal control coatings were exposed to simulated low Earth orbit (LEO) environmental conditions to determine effects on optical properties. In one test, samples of the white paint coating Z-93P were coated with outgassed products from Tefzel® (ethylene tetrafluoroethylene copolymer) power cable insulation as may occur on ISS. These samples were then exposed, along with an uncontaminated Z-93P witness sample, to vacuum ultraviolet (VUV) radiation to determine solar absorptance degradation. The Z-93P samples coated with Tefzel® outgassing products experienced greater increases in solar absorptance than witness samples not coated with Tefzel® outgassing products. In another test, samples of second surface silvered Teflon® FEP (fluorinated ethylene propylene), SiO_x (where x≈2)-coated silvered Teflon® FEP, and Z-93P witness samples were exposed to the combined environments of atomic oxygen and VUV radiation to determine optical properties changes due to these simulated ISS environmental effects. This test verified the durability of these materials in the absence of contaminants.

14. SUBJECT TERMS

Environmental effects; International Space Station; Thermal control materials

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TABLE 11. In-air Measurements: Effect of AO and VUV on Thermal Emittance of SiOₓ-coated Silvered Teflon®, uncoated
Silvered Teflon® and Z-93P.

Sample	VUV ESH	AO Fluence (atoms/cm²)	ISS Radiator Equivalent VUV years	ISS Radiator Equivalent AO years	ϵ	$\Delta\epsilon$ from pristine sample
SST-5	0	0	0	0	0.810	
SST-1	853	4.43×10^{21}	2.48	4.03	0.811	0.001
SST-2	1095	4.43×10^{21}	3.18	4.03	0.809	-0.001
SST-4	1004	4.43×10^{21}	2.92	4.03	0.808	-0.002
UST-1	0	0	0	0	0.859	
UST-2	1103	4.17×10^{21}	3.21	3.79	0.853	-0.006
UST-3	878	4.17×10^{21}	2.55	3.79	0.857	-0.002
UST-4	978	4.17×10^{21}	2.84	3.79	0.857	-0.002
ZPLM-2	0	0	0	0	0.911	
ZPLM-1	1337	4.43×10^{21}	3.89	4.03	0.911	0
ZPLM-5	1304	4.17×10^{21}	3.79	3.79	0.909	-0.002

All changes in emittance were within experimental error, indicating no significant changes in emittance due to AO-VUV exposure. A reduction in emittance for silvered Teflon® would be expected if enough of the Teflon® material was eroded by atomic oxygen. For the exposure fluences provided in AO-VUV Tests 1 and 2, erosion was not significant enough to cause emittance degradation.

4. Conclusions

VUV-induced solar absorptance degradation of the of Z-93P white paint ISS radiator coating occurred at a faster rate for samples coated with outgassed products from radiation crosslinked Tefzel® than for samples not coated with Tefzel® products when both were exposed to VUV equivalent sun hours representative of 4.5 to 7 years on ISS. Tefzel® power cable insulation is a possible source of contamination for ISS radiators. Solar absorptance increases of approximately 0.04 for the Tefzel®-contaminated Z-93P coatings were indicative of worst-case testing where AO, which could reverse solar absorptance degradation, was not present.

SiOₓ-coated and uncoated silvered Teflon® samples, along with Z-93P witness samples, were exposed to the combined environments of AO and VUV for ISS radiator equivalent exposures of 2.5 to 4 years. These samples were not previously exposed to outgassed products from Tefzel®. Samples exposed in these tests showed changes in solar absorptance and thermal emittance that were within instrument error indicating durability of these materials to the ISS environment for this level of exposure where contaminants were not present.

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