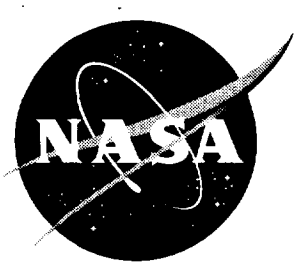

NASA Technical Paper 3595

Evaluation of Thermal Control Coatings and Polymeric Materials Exposed to Ground Simulated Atomic Oxygen and Vacuum Ultraviolet Radiation

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December 1995

ACKNOWLEDGMENTS

The authors gratefully acknowledge the contributions of John Schwarzmann of the Princeton Plasma Physics Laboratory and Perry Gray of Microcraft Inc. to this effort. The authors also wish to thank Don Burch and Whitney Hubbs of the Physical Sciences Branch and Mary Hayden of the Environmental Effects Branch, Engineering Physics Division, Materials and Processes Laboratory at MSFC for their support.

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ACRONYMS AND ABBREVIATIONS

A	amps
AO	atomic oxygen
AODTS	Atomic Oxygen Drift Tube System
°C	degrees Centigrade
CAA	chromic acid anodize
cm	centimeter
ESH	equivalent Sun hours
EUV	enhanced ultraviolet radiation
eV	electron volt
°F	degrees Fahrenheit
FEP	fluorinated ethylene propylene
GHz	gigahertz
in	inch
km/s	kilometer per second
kW	kilowatt
LDEF	Long Duration Exposure Facility
LEO	low-Earth orbit
LPSR	laboratory portable spectroreflectometer
mi	mile
mi/h	miles per hour
MSFC	Marshall Space Flight Center
nm	nanometer
PEEK	polyetheretherketone
PPPL	Princeton Plasma Physics Laboratory

RF	radio frequency
SAA	sulfuric acid anodize
UV	ultraviolet
VUV	vacuum ultraviolet
W	watts
μm	micrometer

TECHNICAL PAPER

EVALUATION OF THERMAL CONTROL COATINGS AND POLYMERIC MATERIALS EXPOSED TO GROUND SIMULATED ATOMIC OXYGEN AND VACUUM ULTRAVIOLET RADIATION

INTRODUCTION

Over the past decade, aerospace designers, scientists, and engineers have worked to achieve a better understanding of the space environment and its effect on potential engineering materials and material processes. Material durability data generated from retrieved long-term space satellite experiments and from short-term space shuttle flight experiments have proven to be invaluable to the material scientist community. However, the cost in terms of time and dollars for this type of testing is often prohibitive. As a result, aerospace designers must increasingly rely on data generated from ground test simulations.

The low-Earth orbit (LEO) environment is defined as that region of space between 200 and 1,000 km (124 to 621 mi) above the Earth and is characterized by the presence of atomic nitrogen, hydrogen, helium, and, most predominately, atomic oxygen (AO). Produced by the interaction of molecular oxygen and ultraviolet (UV) radiation, AO has been shown to produce considerable damage to orbiting spacecraft that typically travel in this region at a velocity on the order of 8 km/s (18,000 mi/h). At this velocity, AO impacts the surface of the space vehicle with an energy of approximately 5 to 7 eV, causing significant erosion and oxidation damage to exposed materials.

NASA's plans for the development of a space station involve placement of the spacecraft within the LEO environment. In order to evaluate environmental effects on potential space station materials, various thermal control coatings and polymeric materials were exposed to AO and vacuum ultraviolet (VUV) radiation, singly and combined, in a series of tests conducted in the Princeton Plasma Physics Laboratory (PPPL) 5 eV Neutral Atomic Oxygen Facility and in the MSFC EH15 Atomic Oxygen Drift Tube System (AODTS). Thermal control samples evaluated in this study included black duranodic anodized, chromic acid anodized, and sulfuric acid anodized aluminum, an inorganic black paint (currently under development by AZ Technology), Z93 white paint samples with the original PS7 binder and the new K2130 binder, Chemfab 250 beta cloth, with and without aluminization. Polymeric samples evaluated in this test series included bulk Halar™, bulk polyetheretherketone (PEEK), and silverized FEP Teflon™. Samples were evaluated for changes in mass, thickness, solar absorptance, and infrared emittance.

Oftentimes, controversies arise among investigators concerning the accuracy of measured optical/thermal properties made using different spectroreflectometers and techniques. Thus, in addition to investigating material durability, a secondary goal of this test series was to evaluate and compare measurements from two different spectroreflectometers typically used by MSFC EH15 investigators and by the private sector to measure total hemispherical reflectance/thermal solar absorptance. The EH15 Beckman DK2 spectroreflectometer was used for both the PPPL and AODTS test specimens to measure diffuse reflectance from 200 to 2,500 nm. This instrument uses a 20.3-cm (8-in) diameter integrating sphere coated with magnesium oxide in which the sample is centrally located. In addition, reflectance measurements were also made using the AZ Technology laboratory portable spectroreflectometer (LPSR). This instrument measures diffuse reflectance from 250 to 2,500 nm using a 10-cm (4-in) diameter integrating sphere. In this reflectometer, measurements are made with the sample located at the rear of the integrating sphere.

TEST DESCRIPTION

The Neutral Atomic Oxygen Beam Facility (fig. 1) located at the PPPL was developed under contract with MSFC. The system produces a 5-eV neutral AO beam by placing a metal plate in contact with magnetically (3 to 4 kgauss) confined AO plasma. The AO plasma is produced by a radio frequency (RF) driven lower hybrid plasma source. A magnetron supplies 1 kW of power at a frequency of 2.45 GHz to the center pin to produce the plasma. Because of the facility geometry, the AO plasma is magnetically confined such that a 1-cm (0.39-in) diameter plasma column is produced on centerline of the test chamber. The plasma column interacts with an electrically biased metallic plate. The bias applied to the plate accelerates ions from the plasma to the plate. During the acceleration process, the ions gain energy equal to the difference in the plasma potential and the neutralizer plate bias. Once the ions hit the plate, they collect an electron from the metal lattice and become neutral. Following collision with the neutralizer plate, the atoms are reflected toward the test specimen at a fraction of their precollision energy. The fraction of energy lost by the reflected atoms is a function of the type of material used to make the neutralizer plate. Because the energy of the reflected atom depends on the plasma potential, which is inherently subject to slight variations, not all atoms will be accelerated by the same potential difference. Thus, the reflected atoms will have a slight energy distribution.[1]

To best simulate orbital AO, the beam facility supplies 5-eV AO atoms, but the source is tunable from 3 to 20 eV. The limiting factor in the length of test runs in the system is the heating of the RF electrode. During operation of the system, the neutralizer plate collects nearly 4 A of ion current from the plasma. In order to maintain space charge conditions, the same amount of electron current must be lost from the plasma. Most of the electrons are collected by the electrode. Heating in the system has been limited by operating in a pulsed fashion with a duty cycle between 5 and 15 percent on-time.

The AO flux produced by the PPPL system ranges from 5×10^{15} to 1×10^{16} atoms/cm^2. During production of the AO plasma, the system produces electromagnetic radiation. This radiation is produced primarily during the dissociation and ionization process. Attempts to identify and quantify the radiation

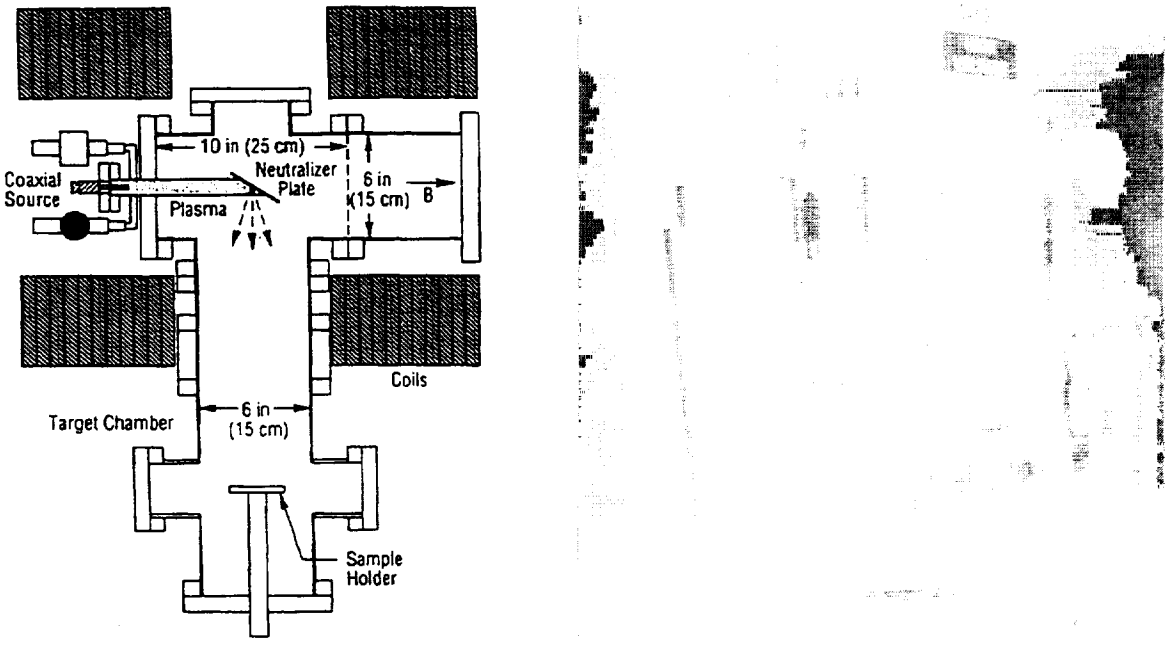

Figure 1. PPPL 5-eV AO test system.

using a photodiode with appropriate narrow band filters indicated that the primary radiation line was 130 nm, the AO resonant peak in the VUV region. The VUV intensity was determined to be nearly 200 times the Sun's intensity averaged over the duty cycle. In order to eliminate possible magnetic interactions, appropriate shielding is placed around the diode.

The PPPL facility was used to expose various 2.54-cm (1-in) diameter samples over a series of two separate runs in the facility. Test samples were placed in specially designed sample fixtures capable of holding 14 individual specimens. These specimens were placed in the test chamber 5.5 cm (2.17 in) from the neutralizer plate. Thermocouples attached to the sample holder indicated a slight rise in temperature from 22 °C (72 °F) to approximately 50 °C (122 °F) where it remained over the test period. The increase in temperature was primarily due to heat radiating from the neutralizer plate and from the magnets. Kapton™ and Lexan™, materials of known AO reactivity, indicated the AO fluence of test run No. 1 was 1.2×10^{21} atoms/cm^2 for the four samples located in the center of the holder and 6.3×10^{20} atoms/cm^2 for the samples located on the outer edge of the sample holder. The samples in this test were exposed to approximately 8,000 equivalent Sun hours (ESH) of VUV radiation. Control samples for test run No. 2 indicated an AO fluence of 1.1×10^{21} atoms/cm^2 for the center samples and an AO fluence of 5.6×10^{20} atoms/cm^2 for the remaining samples. These samples also received approximately 8,000 ESH of VUV radiation.

Unlike the PPPL facility that is capable of producing neutral 5-eV AO, the AODTS facility (fig. 2) produces a thermal AO plasma. Generated by a 14.7-MHz RF field, the AODTS plasma contains both AO atoms and ions, molecular oxygen atoms and ions, and excited state atoms and electrons. However, the AODTS facility is designed such that samples are exposed outside the RF field. This eliminates sample exposure to any plasma charged particles and unwanted sample heating.

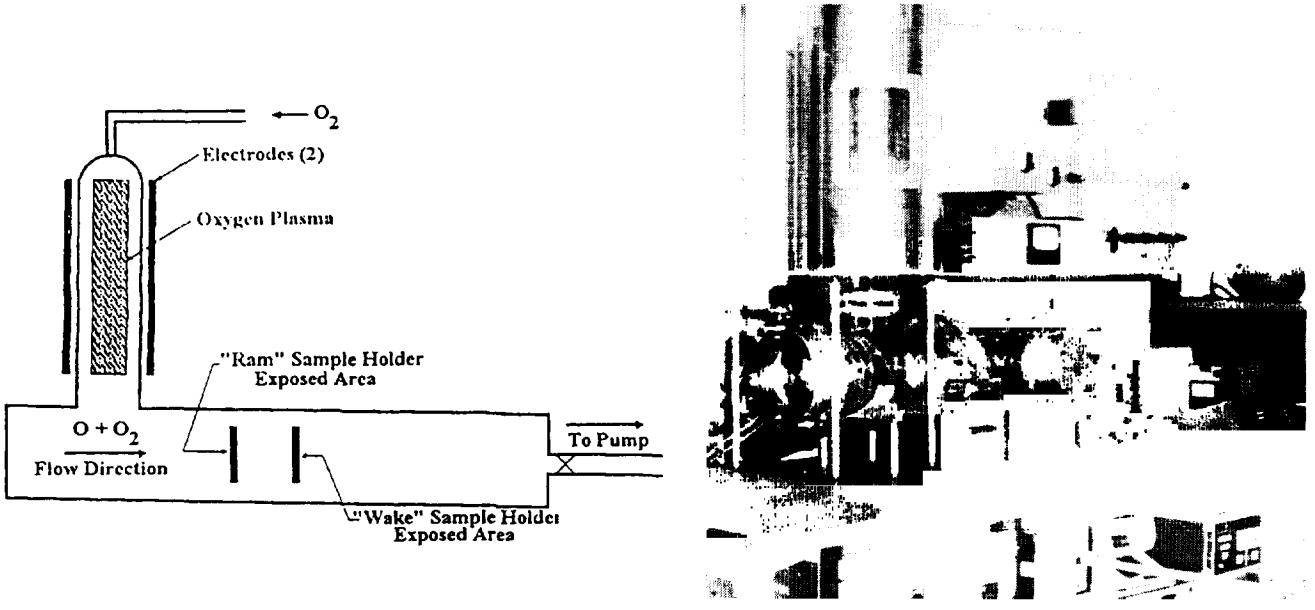

Figure 2. AODTS thermal AO test system.

A total of twenty-eight 2.54-cm (1-in) diameter samples were exposed in the AODTS system using the same two sample fixtures used in the PPPL test series. Fourteen samples were tested such that the exposed surface faced in the general drift direction ("ram"), while a second set of 14 samples faced 180° from the drift direction ("wake"). The AO plasma was generated using an RF power of 150 W. Samples were exposed at a test pressure of 90 mtorr and an average test temperature, as monitored by thermocouples attached to the sample holders, of 25 °C (77 °F). Polyethylene samples were used to monitor the total AO flux for both the ram and wake positions. Over the testing period, the AODTS

chamber was brought up to atmospheric pressure a total of four times in order to remove and replace the polyethylene monitoring samples. Total sample exposure time was just over 64 days (1,538.11 hours), producing a ram AO fluence of 7.1×10^{22} atoms/cm^2 and a wake fluence of 2.1×10^{22} atoms/cm^2.

Black Duranodic Anodized Aluminum

A total of six duranodic samples* were tested, of which two were used as lab controls, two were exposed in the AODTS test, while the remaining two were exposed in the PPPL test. In the PPPL test, one sample was fully exposed to the environment, while the other was protected from AO by a UV-transmitting window. Sample coating thickness of 47.2 μm (1.86 mils) was measured before exposure.

No visible change in appearance was noted following exposure in either the PPPL or AODTS facility. Mass, coating thickness, reflectance/solar absorptance, and infrared emittance measurements were made on all the samples both pre- and posttest. LPSR and DK2 reflectance curves for both the AODTS- and PPPL-exposed specimens are shown in figures 3 and 4, while mass, coating thickness, solar absorptance, and infrared emittance raw data are included in appendices A and B.Table 1 summarizes the optical data for both the PPPL- and AODTS-exposed duranodic samples. Infrared emittance for these and all other samples was measured with a Gier-Dunkle DB100 infrared reflectometer. The average preexposure values were derived from data taken on the two control and the two test samples for each respective test prior to exposure. By way of comparison, McDonnell Douglas Aerospace reported pretest values for the Duranodic samples at 0.87 for solar absorptance, using a Perkin-Elmer Lambda 9 reflectometer, and 0.87 for infrared emittance (corrected). Although the LPSR and the DK2 differ in the absolute value of solar absorptance, both do indicate that the solar absorptance was not greatly affected by exposure. The greatest change in solar absorptance was indicated by the LPSR, with an approximately 2.4-percent decrease as a result of the PPPL UV exposure. Emittance values were unchanged as a result of exposure in the PPPL test and AODTS test.

Table 1. Black duranodic anodized aluminum test results.

Exposure	PPPL Exposure Fluence ~ 6.8×10^{20} atoms/cm^2 VUV Irradiance ~ 8,000 ESH (130 nm)			AODTS Exposure Fluence ~ 2.1×10^{22} atoms/cm^2		
	LPSR α_s	DK2 α_s	ε_{IR}	LPSR α_s	DK2 α_s	ε_{IR}
Average preexposure	0.84	0.88	0.88	0.84	0.89	0.88
Posttest controls	0.84	0.88	0.88	0.84	0.88	0.88
VUV-exposed	0.82	0.89	0.88			
5 eV AO+VUV	0.83	0.89	0.88			
Thermal AO				0.83	0.88	0.88

* Duranodic and sulfuric acid anodized aluminum samples provided by Cherie Jones, McDonnell Douglas Aerospace, Huntington Beach, CA.

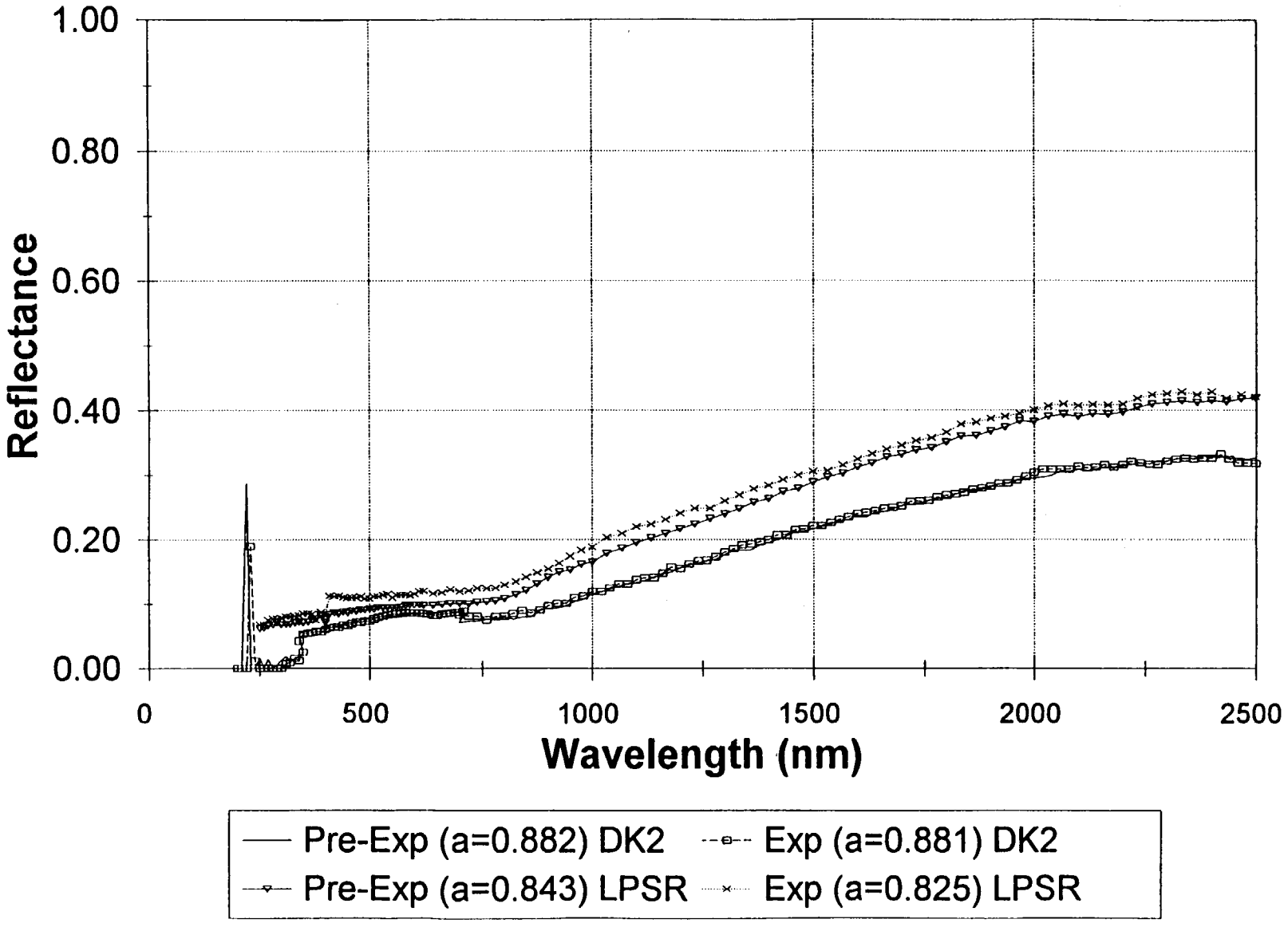

Figure 3. DK2 and LPSR reflectance of AODTS-exposed black duranodic anodized aluminum.

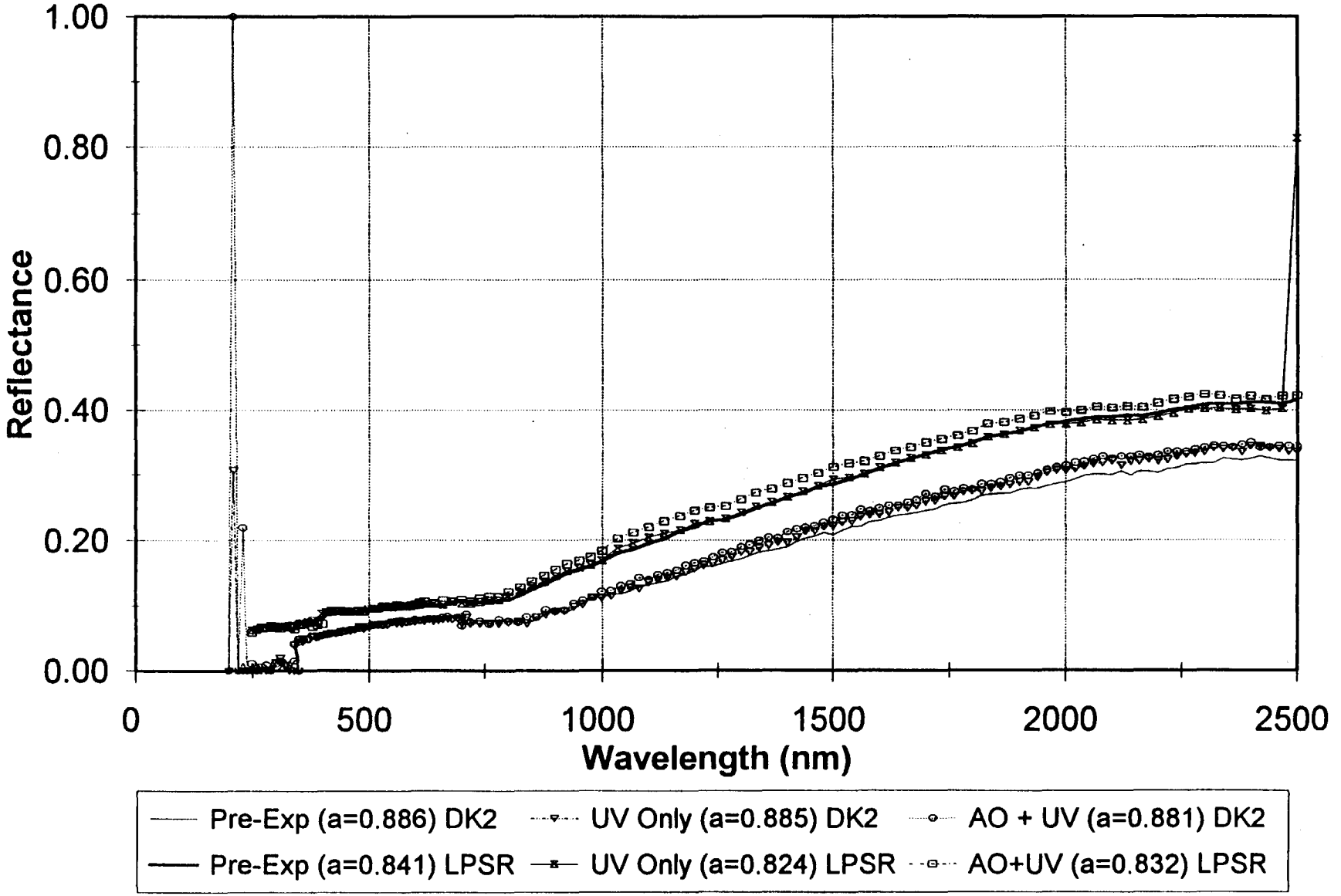

Figure 4. DK2 and LPSR reflectance of PPPL-exposed black duranodic anodized aluminum.

Chromic Acid Anodized Aluminum

A total of 15 chromic acid anodized (CAA) aluminum samples† were tested for susceptibility to AO and VUV degradation. Five samples each of three different anodized coating thickness, noted here in order of decreasing thickness as 75TK, 45MM, and 30TN, were evaluated. Two samples of each set were exposed in the AODTS test, two were exposed in the PPPL test, and the remaining sample used as a lab control. In the PPPL test, one sample was fully exposed to the environment while the other was protected from AO by a UV-transmitting window.

No visible change in appearance was noted following exposure in either the PPPL or AODTS facility. Mass, coating thickness, reflectance/solar absorptance, and infrared emittance measurements were made on all the CAA samples before and after exposure. LPSR and DK2 reflectance curves of the various anodize thicknesses are shown in figures 5 through 10, while mass, coating thickness, solar absorptance, and infrared emittance raw data are shown in appendices A and B.

Table 2 summarizes the optical data for both the PPPL- and AODTS-exposed CAA samples. The average preexposure values were derived from data taken on the control and the two test samples for the AODTS test prior to exposure. Although the LPSR and the DK2 differ in the absolute value of solar absorptance, both do indicate that the solar absorptance was not greatly affected by exposure. Variations in the 30TN sample reflectance indicate an extremely thin oxide layer with some scatter from the substrate. Emittance values for the thicker 75TK samples were stable following exposure in the PPPL test and AODTS test. Emittance values for the thinner 45MM and 30TN samples showed a decrease ranging from 4 to 13 percent.

Table 2. CAA aluminum test results.

Type CAA	Exposure	PPPL Exposure Fluence ~ 6.8×10^{20} atoms/cm^2 VUV Irradiance ~ 8,000 ESH (130 nm)			AODTS Exposure Fluence ~ 2.1×10^{22} atoms/cm^2		
		LPSR α_s	DK2 α_s	ε_{IR}	LPSR α_s	DK2 α_s	ε_{IR}
75TK	Average preexposure	0.36	0.40	0.73	0.37	0.40	0.73
75TK	Posttest controls				0.37	0.40	0.73
75TK	VUV exposed	0.37	0.40	0.73			
75TK	5 eV AO+VUV	0.37	0.41	0.73			
75TK	Thermal AO				0.37	0.40	0.72
45MM	Average preexposure	0.34	0.37	0.50	0.34	0.36	0.50
45MM	Posttest controls				0.33	0.36	0.50
45MM	VUV exposed	0.33	0.37	0.48			
45MM	5 eV AO+VUV	0.33	0.37	0.48			
45MM	Thermal AO				0.33	0.36	0.49
30TN	Average preexposure	0.29	0.32	0.30	0.29	0.32	0.30
30TN	Posttest controls				0.29	0.33	0.30
30TN	VUV exposed	0.29	0.32	0.28			
30TN	5 eV AO+VUV	0.28	0.32	0.26			
30TN	Thermal AO				0.29	0.32	0.29

† Samples provided by Johnny Golden, Boeing Aerospace, Seattle, WA.

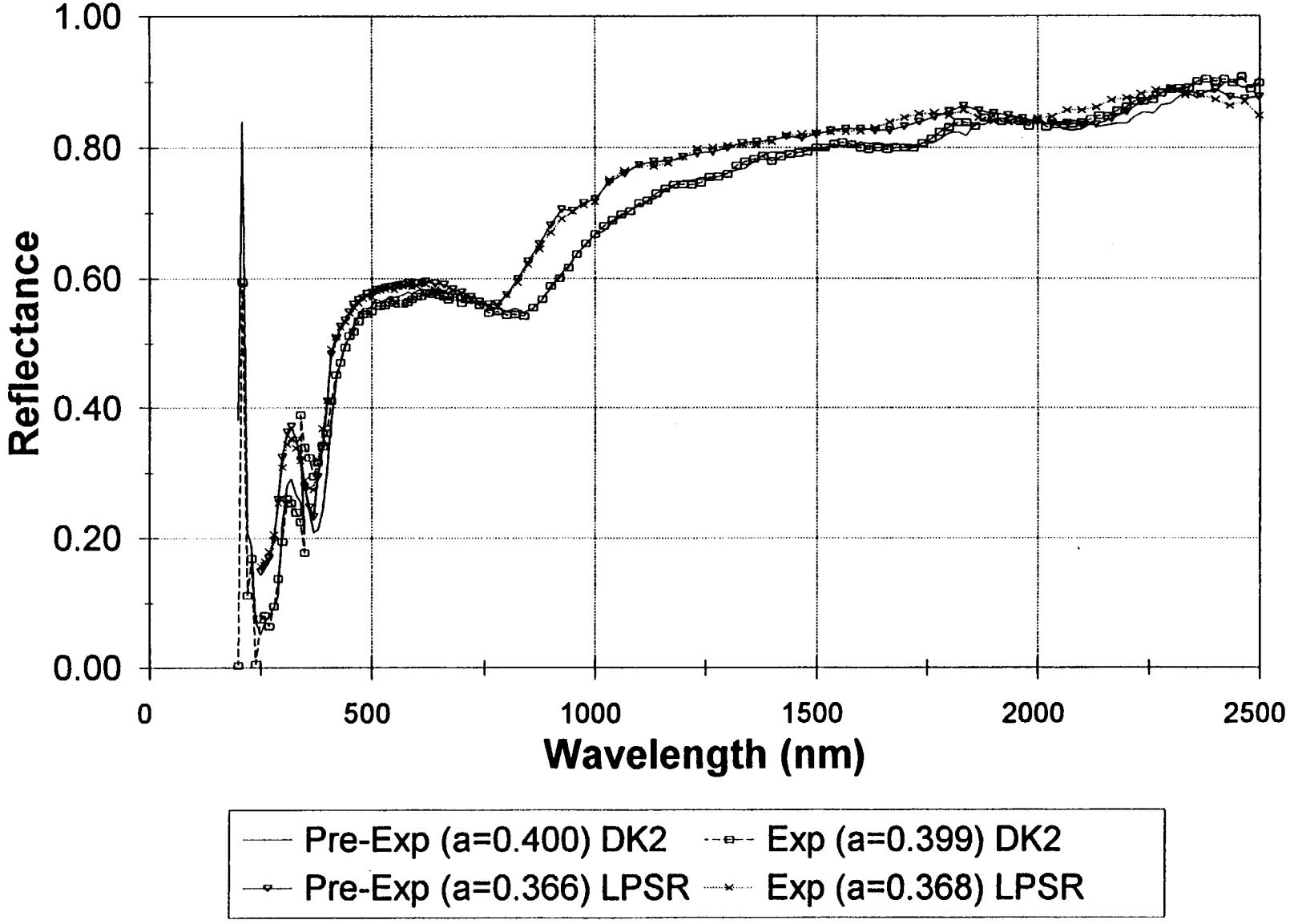

Figure 5. DK2 and LPSR reflectance of AODTS-exposed 75TK chromic acid anodized aluminum.

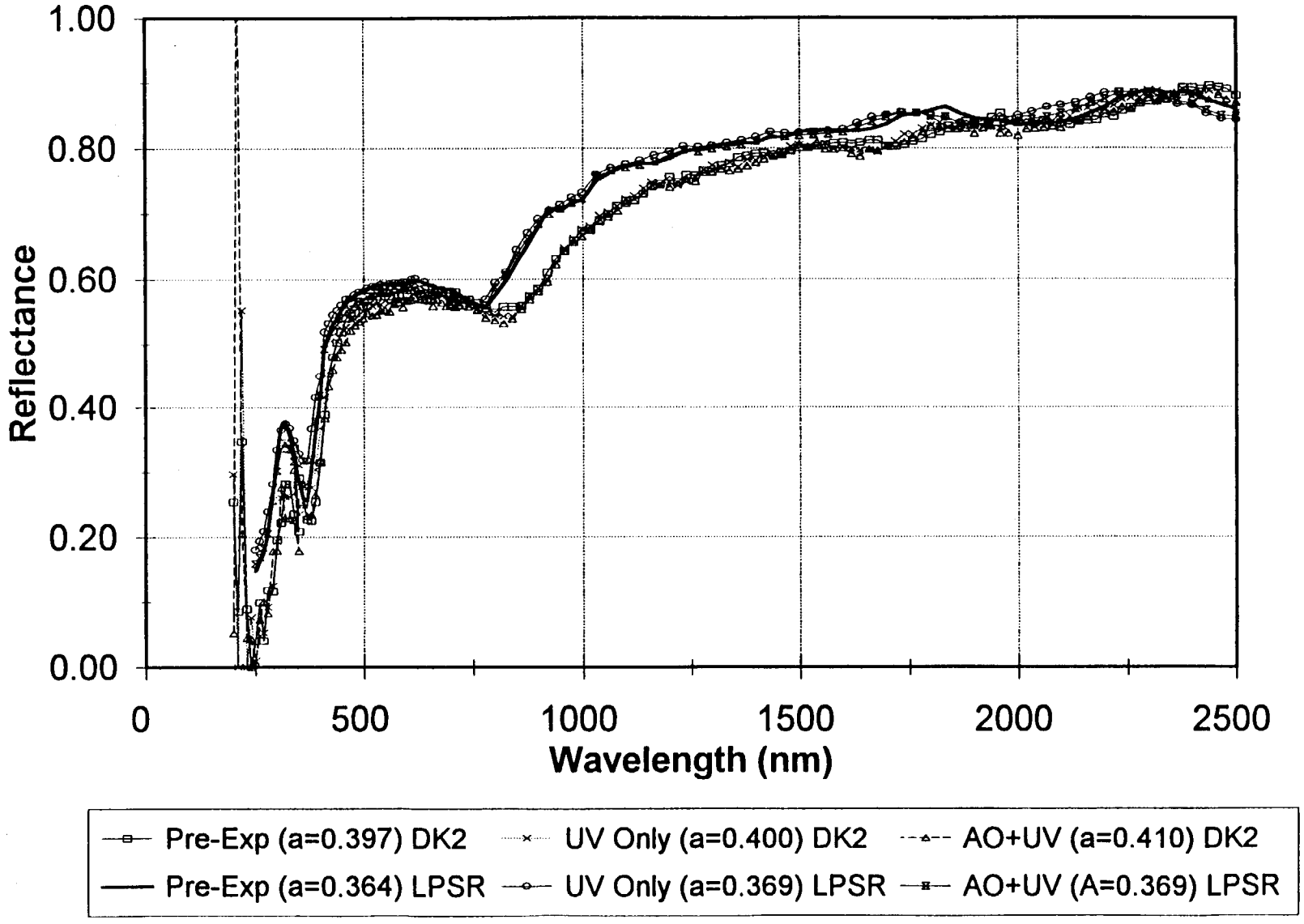

Figure 6. DK2 and LPSR reflectance of PPPL-exposed 75TK chromic acid anodized aluminum.

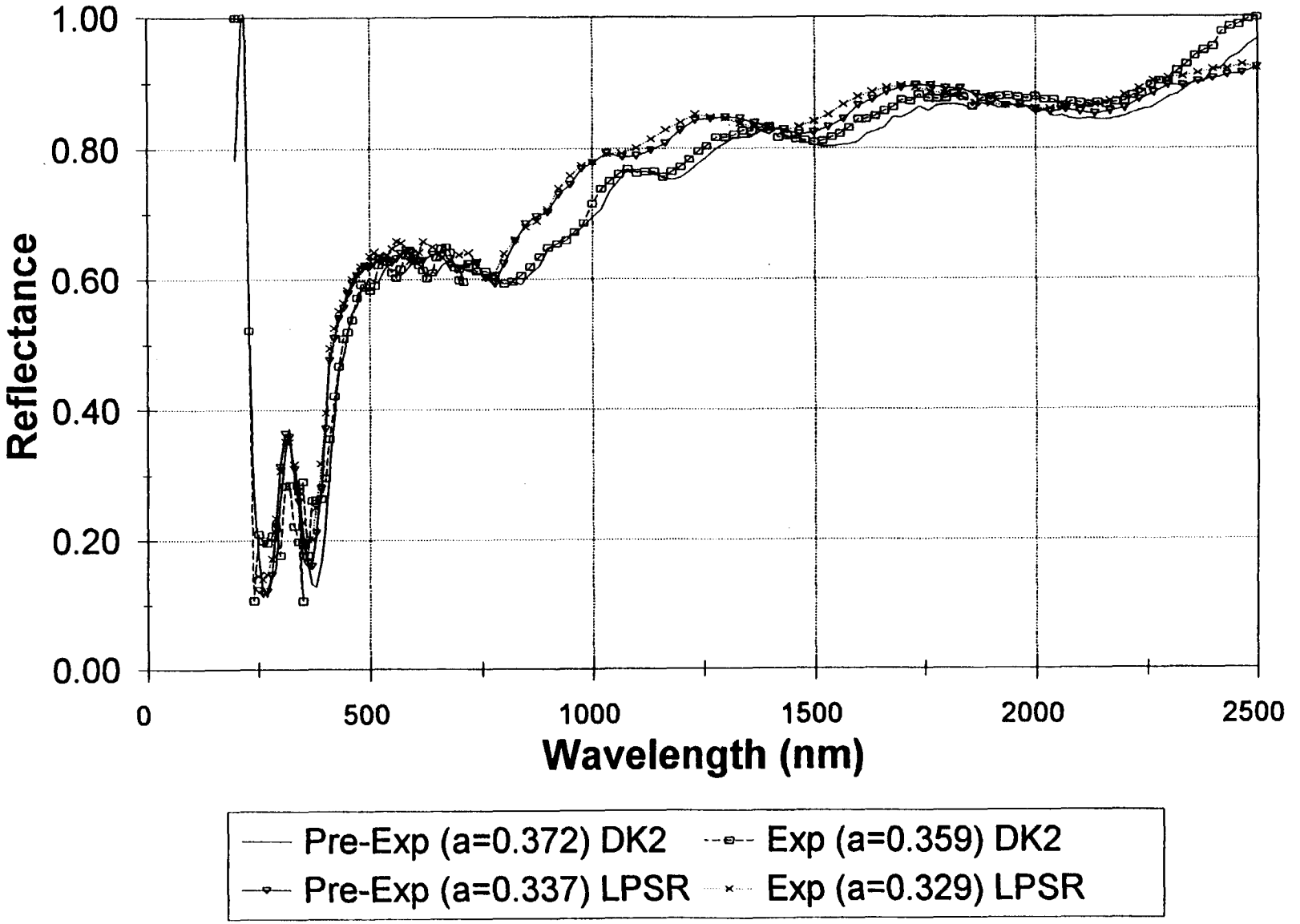

Figure 7. DK2 and LPSR reflectance of AODTS-exposed 45MM chromic acid anodized aluminum.

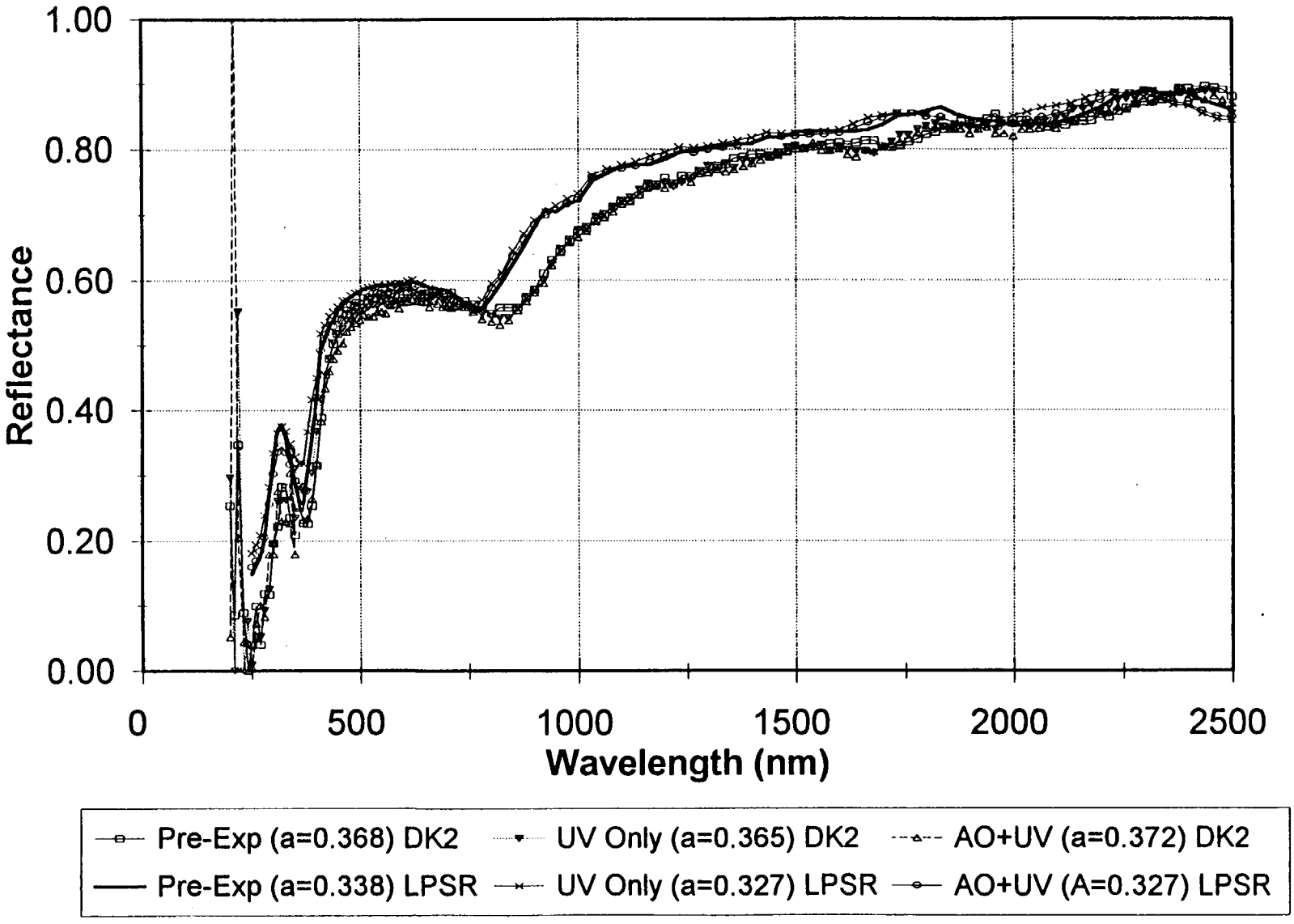

Figure 8. DK2 and LPSR reflectance of PPPL-exposed 45MM chromic acid anodized aluminum.

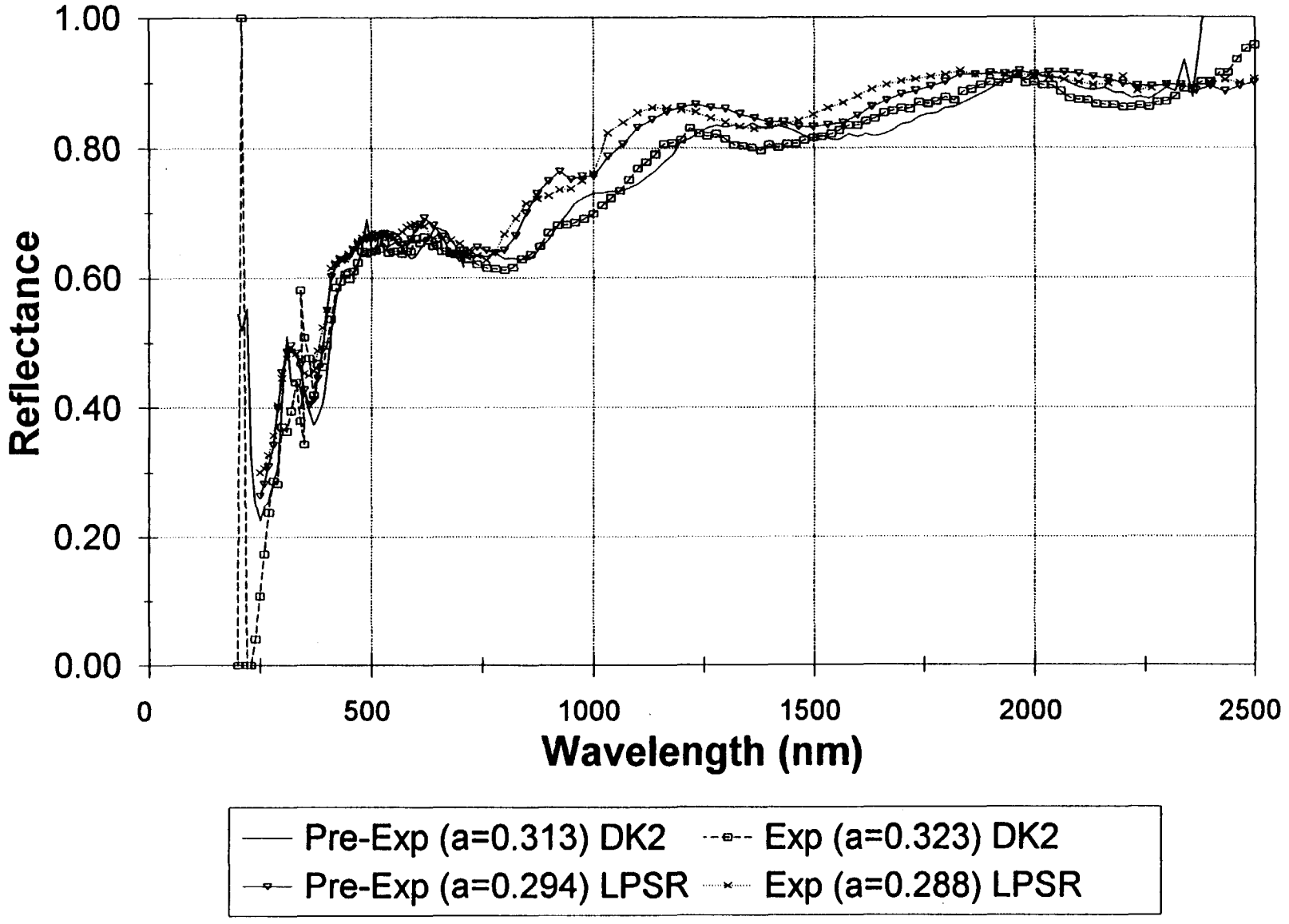

Figure 9. DK2 and LPSR reflectance of AODTS-exposed 30TN chromic acid anodized aluminum.

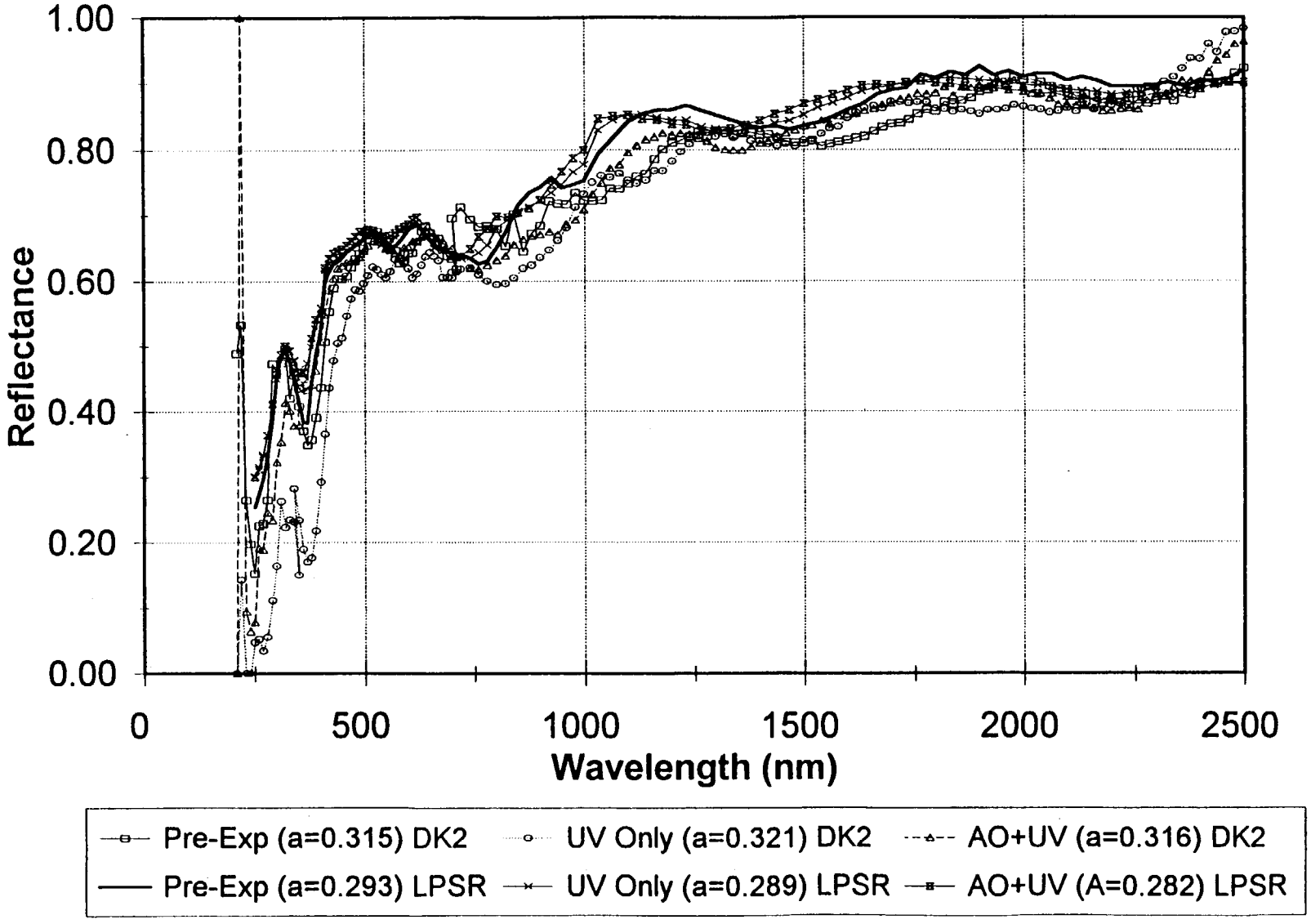

Figure 10. DK2 and LPSR reflectance of PPPL-exposed 30TN chromic acid anodized aluminum.

Sulfuric Acid Anodized Aluminum

A total of six sulfuric acid anodized (SAA) aluminum samples were tested, of which two were used as lab controls. Two of the six were exposed in the AODTS test while the remaining two were exposed in the PPPL test. In the PPPL test, one sample was fully exposed to the environment, while the other was protected from AO by a UV-transmitting window. Pretest coating thickness was reported to be 15.2 μm (0.6 mils).

No visible change in appearance was noted following exposure in either the PPPL or AODTS facility. Mass, coating thickness, reflectance/solar absorptance, and infrared emittance measurements were made on all the SAA samples before and after exposure. LPSR and DK2 reflectance curves are shown in figures 11 and 12, while mass, coating thickness, solar absorptance, and infrared emittance raw data are shown in appendices A and B.

Table 3 summarizes the optical data for both the PPPL- and AODTS-exposed SAA samples. The average preexposure values were derived from data taken on the two control and the two test samples for each respective test prior to exposure. By way of comparison, McDonnell Douglas reported pretest values of 0.45 for solar absorptance using a Perkin Elmer Lambda 9 spectroreflectometer and 0.86 for infrared emittance. Although the LPSR and the DK2 differ in the absolute value of solar absorptance, both do indicate that the solar absorptance was not greatly affected by exposure. Emittance values were also unchanged as a result of exposure in the PPPL test and AODTS test.

Table 3. SAA aluminum test results.

Exposure	PPPL Exposure Fluence ~ 1.2×10^{20} atoms/cm^2 VUV Irradiance ~ 8,000 ESH (130 nm)			AODTS Exposure Fluence ~ 7.1×10^{22} atoms/cm^2		
	LPSR α_s	DK2 α_s	ε_{IR}	LPSR α_s	DK2 α_s	ε_{IR}
Average preexposure	0.40	0.45	0.86	0.40	0.45	0.86
Posttest controls				0.41	0.45	0.86
VUV exposed	0.40	0.45	0.86			
5 eV AO+VUV	0.41	0.46	0.86			
Thermal AO				0.39	0.44	0.86

Black Inorganic Paint

A newly developed black inorganic paint‡ composed of a copper oxide-iron oxide mixture with a potassium silicate Kasil 2130 binder was evaluated for AO sensitivity. A total of five paint samples were tested and evaluated, of which one was used as a lab control. Two of the five were exposed to thermal AO in the AODTS test, while the remaining two were exposed to 5-eV oxygen in the PPPL test.

No visible change in appearance was noted following exposure in either the PPPL or AODTS facility. Reflectance/solar absorptance and infrared emittance measurements were made on all the paint samples prior to and following exposure. LPSR and DK2 reflectance curves are shown in figures 13 and 14 while mass, coating thickness, solar absorptance and infrared emittance raw data are shown in appendices A and B.

‡ Samples provided by Richard Mell, AZ Technology, Huntsville, AL.

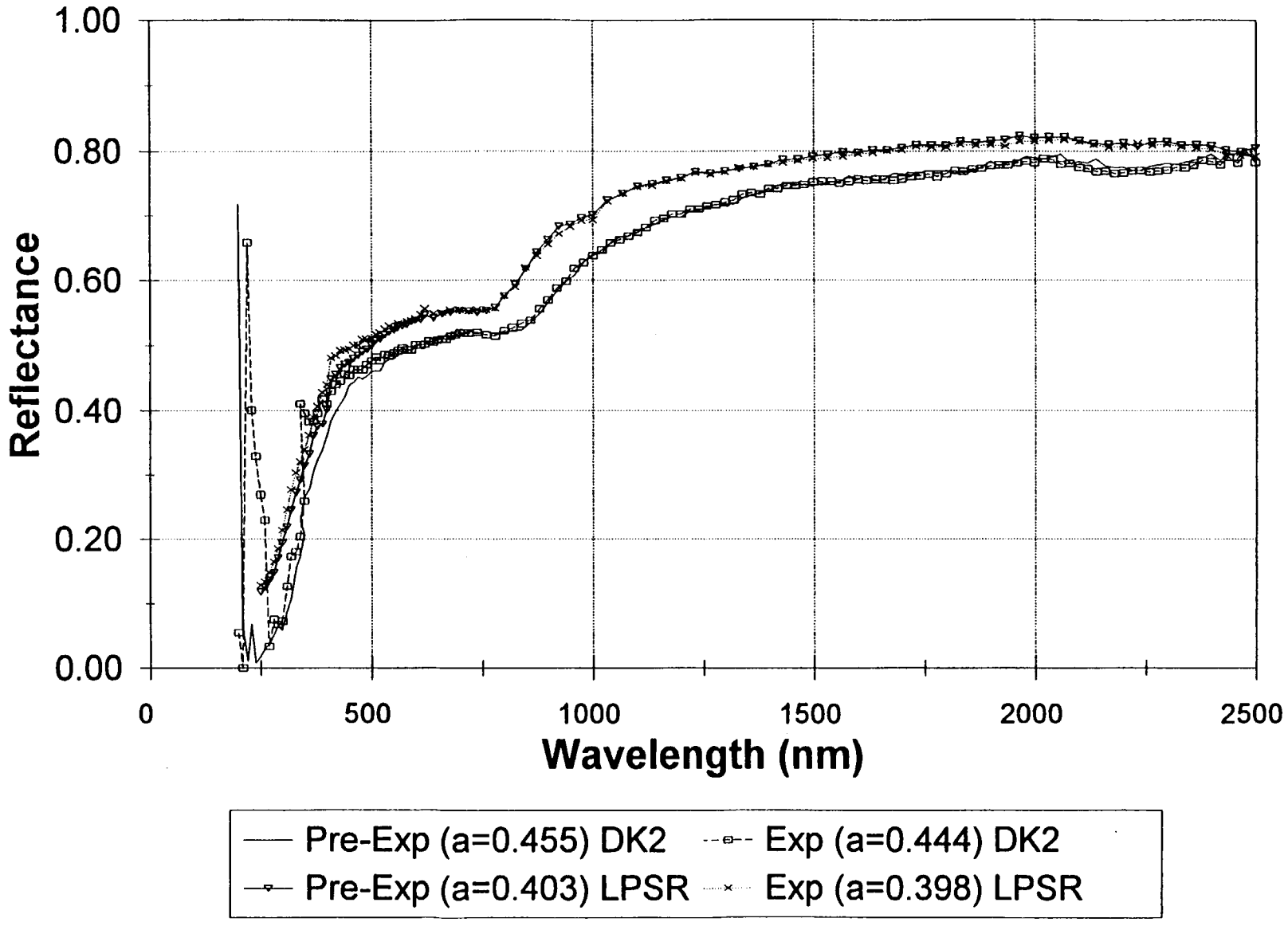

Figure 11. DK2 and LPSR reflectance of AODTS-exposed sulfuric acid anodized aluminum.

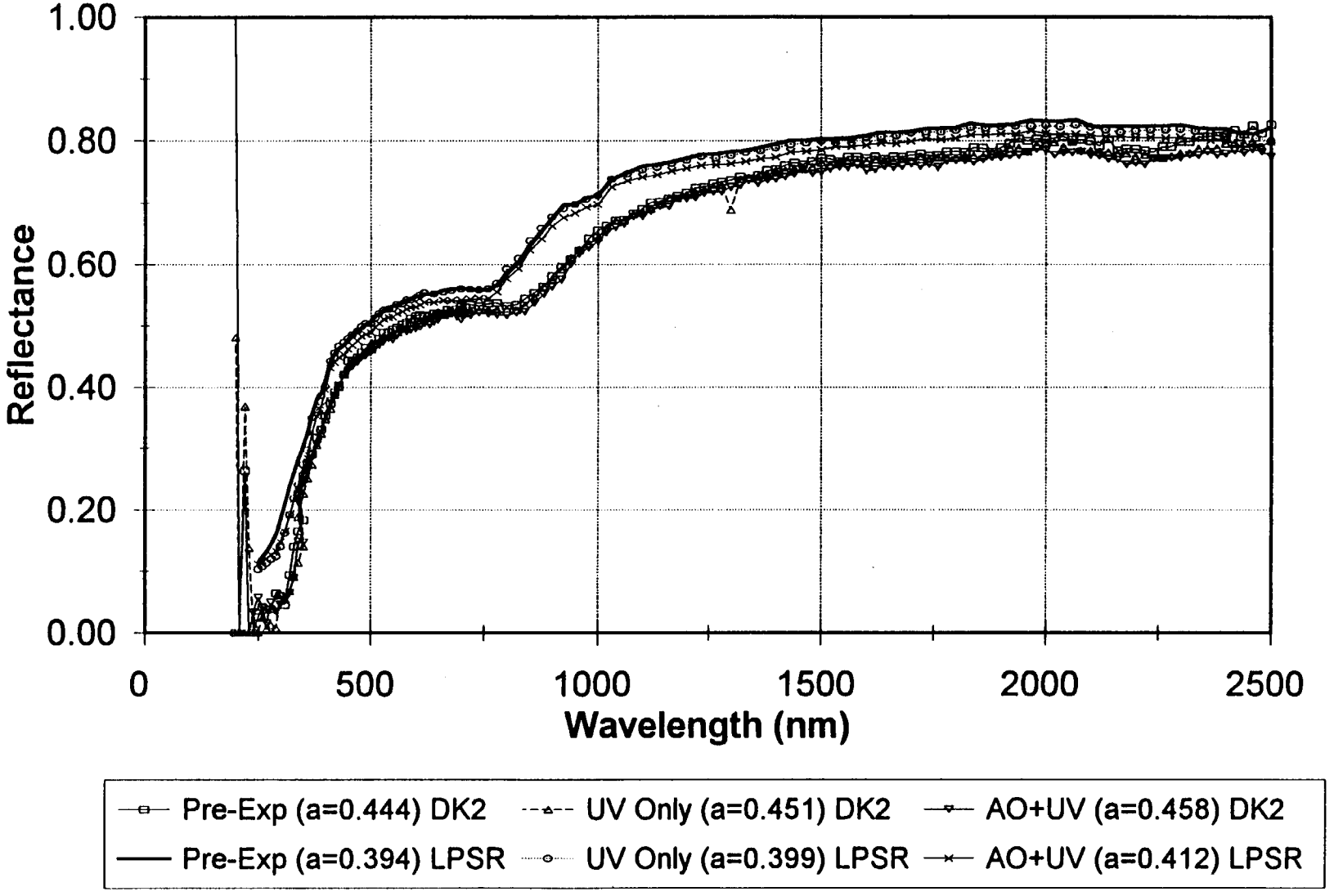

Figure 12. DK2 and LPSR reflectance of PPPL-exposed sulfuric acid anodized aluminum.

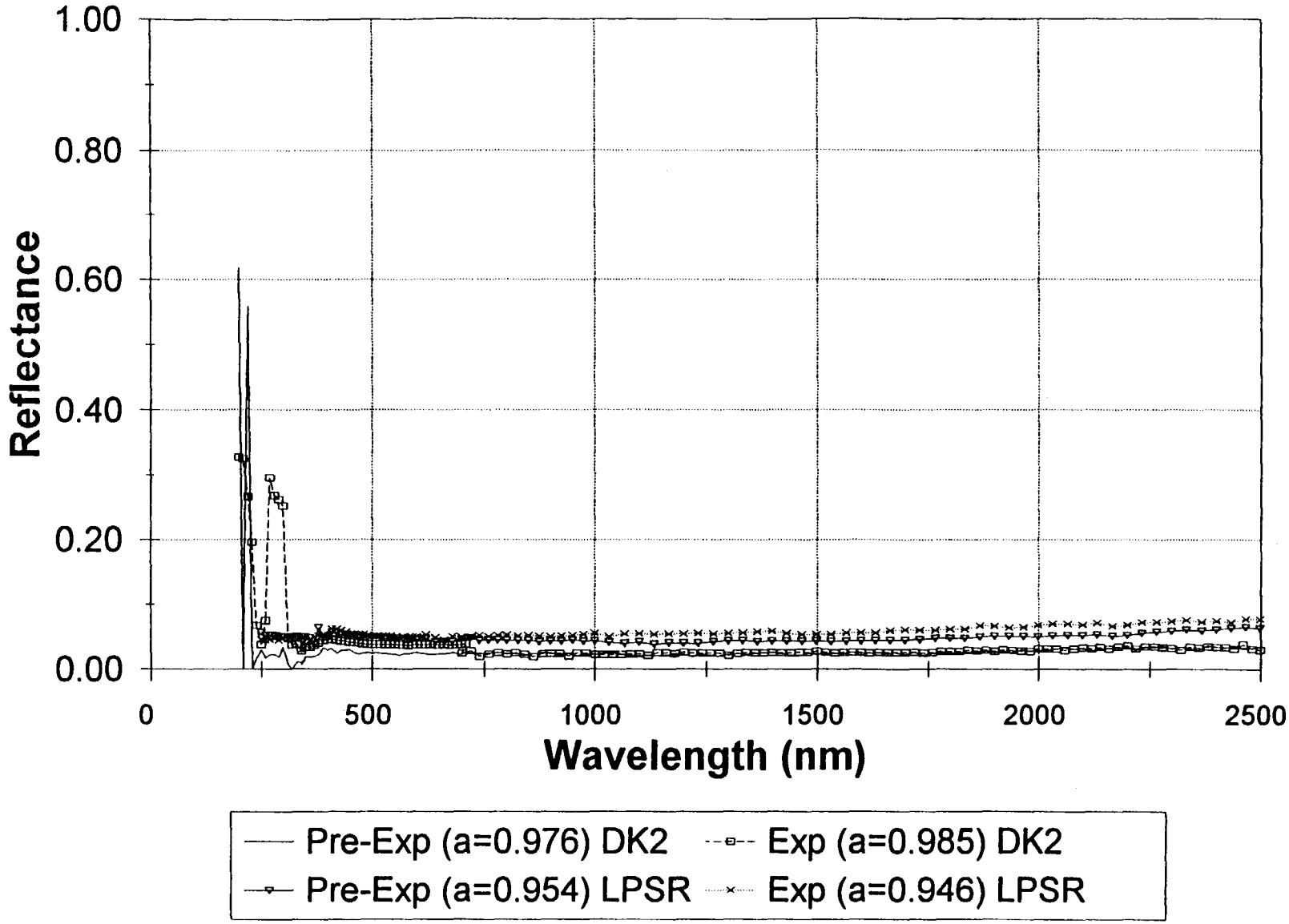

Figure 13. DK2 and LPSR reflectance of AODTS-exposed black inorganic paint.

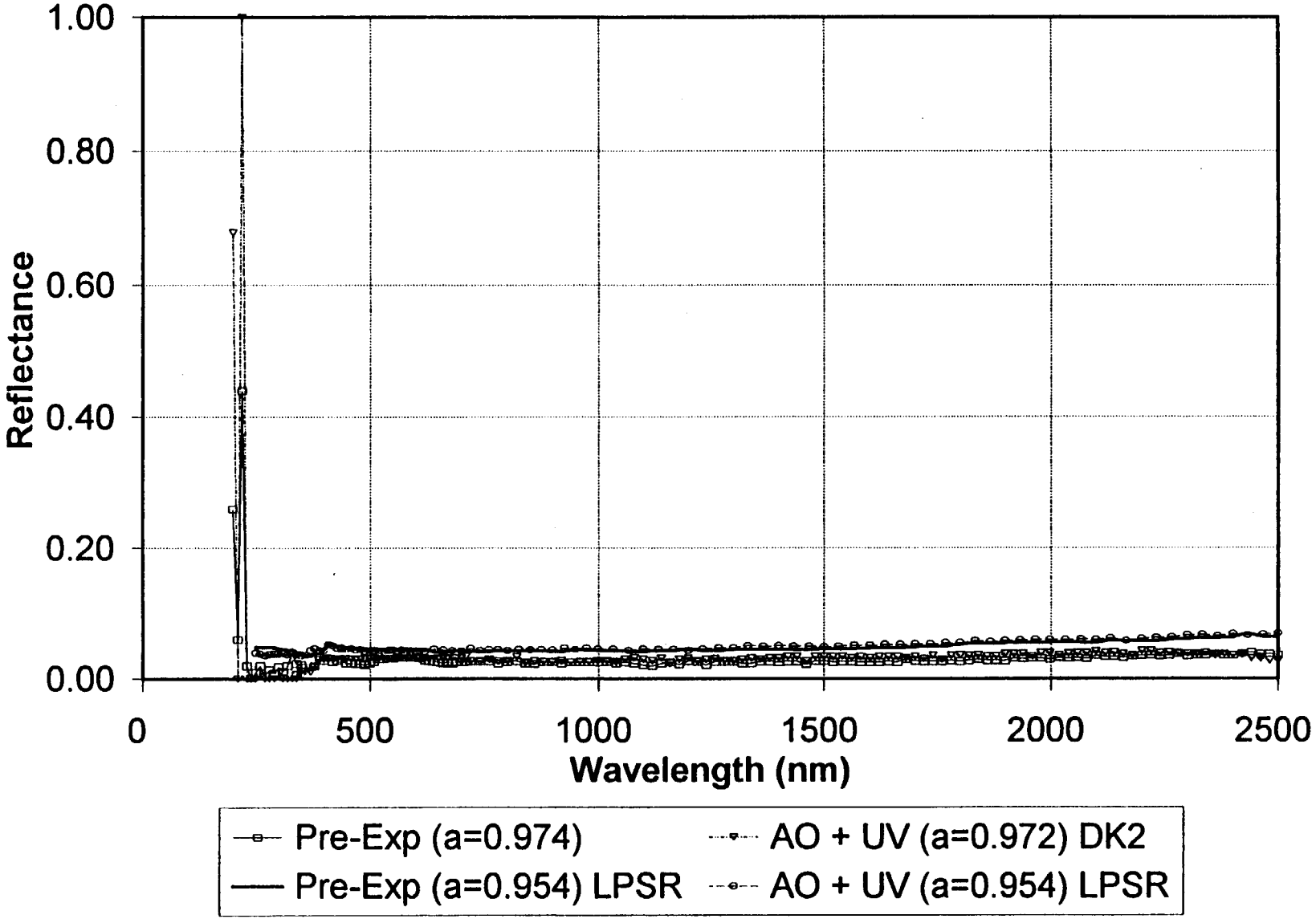

Figure 14. DK2 and LPSR reflectance of PPPL-exposed black inorganic paint.

Table 4 summarizes the optical data for both the PPPL- and AODTS-exposed paint samples. The average preexposure values were derived from data taken using the control and the two test samples for the AODTS test prior to exposure. Although the LPSR and the DK2 differ in the absolute value of solar absorptance, both do indicate that the solar absorptance was not greatly affected by exposure. Emittance values were also unaffected by exposure in the PPPL test and AODTS test.

Table 4. Black inorganic paint test results.

Exposure	PPPL Exposure Fluence ~ 7.2×10^{20} atoms/cm^2 VUV Irradiance ~ 8,000 ESH (130 nm)			AODTS Exposure Fluence ~ 2.1×10^{22} atoms/cm^2		
	LPSR α_s	DK2 α_s	ε_{IR}	LPSR α_s	DK2 α_s	ε_{IR}
Average preexposure	0.95	0.97	0.89	0.95	0.98	0.90
Posttest controls				0.95	0.97	0.90
VUV exposed	0.95	0.97	0.89			
Thermal AO				0.95	0.98	0.90

Z93 White Paint

A series of tests were conducted on the AO/AO+UV stability of the "new" Z93 coating made using K2130 binder as compared to the "original" Z93 made using the PS7 binder. Both PS7 and K2130 binder coatings were tested for AO stability in the AODTS system. The Illinois Institute of Technology Research Institute (IITRI) supplied a batch of PS7 and K2130 binder Z93 samples[§] for testing. In addition, McDonnell Douglas Aerospace supplied a batch of PS7 and K2130 binder Z93 samples[**] for AODTS testing. No visible change in appearance was noted following exposure in the AODTS facility. Table 5 summarizes the thermal properties measured both pre- and posttest for the PS7 and K2130 binder samples exposed in the AODTS. The average preexposure values were derived from data taken on the controls and the two test samples for each respective test prior to exposure. DK2 reflectance for exposed IITRI samples with PS7 and K2130 is shown in figure 15 (no LPSR data available). DK2 reflectance for some

Table 5. Z93 AODTS test results.

AO Fluence ~ 2.1×10^{22} atoms/cm^2	Original PS7 Binder			New Kasil 2130 Binder		
	LPSR α_s	DK2 α_s	ε_{IR}	LPSR α_s	DK2 α_s	ε_{IR}
IITRI Z93						
Average preexposure		0.16	0.92		0.16	0.92
Posttest controls		0.15	0.92		0.16	0.92
Thermal AO exposed	0.15	0.16	0.92	0.15	0.16	0.92
McDonnell Douglas Z93						
Average preexposure	0.14	0.17	0.92	0.15	0.17	0.93
Posttest controls	0.15	0.16	0.92	0.16	0.17	0.92
Thermal AO exposed	0.15	0.16	0.91	0.16	0.17	0.92

[§] Samples provided by Dr. Yosh Harada, IITRI, Chicago, IL.

[**] Samples provided by Hank Babel, McDonnell Douglas, Huntington Beach, CA.

of the IITRI-supplied PS7- and K2130-exposed samples is shown in figure 15 (no LPSR data available). LPSR and DK2 reflectance curves for the McDonnell Douglas PS7 and K2130 samples can be found in figures 16 and 17. Solar absorptance and infrared emittance raw data for all the samples can be found in appendices A and B. As evident from the data, both solar absorptance and infrared emittance were not significantly affected by the test exposures. Water desorption was noted, as shown in the slight increase in infrared reflectance.

Two samples of each binder formulation supplied by IITRI were also tested at the PPPL facility, configured such that one of each binder type was protected from AO by a UV-transmitting window. The K2130 binder samples initially appeared dry and cracked; exposure in the PPPL test caused the paint to flake away from the aluminum substrate and thus no posttest data could be taken. Table 6 summarizes the optical properties measured pre- and posttest for the PS7 binder samples exposed in the PPPL test. LPSR and DK2 reflectance curves for the Z93 PS7 samples can be found in figure 18. As in the AODTS test, both solar absorptance and infrared emittance were not significantly affected by the AO exposure.

Table 6. Z93 PPPL test results.

IITRI Z93/PS7 Binder	PPPL Exposure Fluence ~ 7.2×10^{20} atoms/cm^2 VUV Irradiance ~ 8,000 ESH (130 nm)		
Exposure	LPSR α_s	DK2 α_s	ε_{IR}
Average preexposure	0.15	0.17	0.92
VUV exposed	0.15	0.16	0.92
5 eV AO+VUV	0.15	0.16	0.92

Polymers

Bulk samples of Halar™, a copolymer of chlorotrifluoroethylene and ethylene, PEEK, and 1-in button samples of 127-μm (0.005-in) silverized FEP Teflon™ tape were exposed in the PPPL and AODTS test systems. In the PPPL test a UV-transmitting window was used to protect one of the two silver Teflon™ test samples from AO, thus exposing the sample to VUV radiation only. Both the Halar™ and PEEK samples appeared lighter in the exposed region as a result of exposure in the PPPL and AODTS test systems. The silverized Teflon™ specimen exposed to both AO and VUV radiation in the PPPL test appeared more diffuse and white in color in the exposed region, but the specimen that was exposed to only VUV showed no visible change in appearance. The AODTS-exposed silverized Teflon™ appeared to have a slight milky white film over the exposed region. Mass, thickness change, and some optical data can be found in appendices A and B. Reflectance curves for the AgFEP samples can be found in figures 19 and 20. Solar absorptance and infrared emittance values for the AgFEP samples are summarized in table 7. AO reaction efficiencies for all three polymers were calculated based on mass and thickness change. These values can be found in table 8 along with previous shuttle flight data for comparison.

Beta Cloth

One sample each of Chemfab 250 beta cloth and aluminized beta cloth was exposed to VUV radiation only in the PPPL test. Samples were protected from AO by a UV-transmitting window. Posttest visual observations indicated that both beta cloth samples appeared slightly yellow in the exposed region. In addition, one sample of aluminized beta cloth, previously exposed to approximately 700 ESH of enhanced ultraviolet (EUV) radiation from 250 to 400 nm in the EH15 EUV solar simulator, was exposed

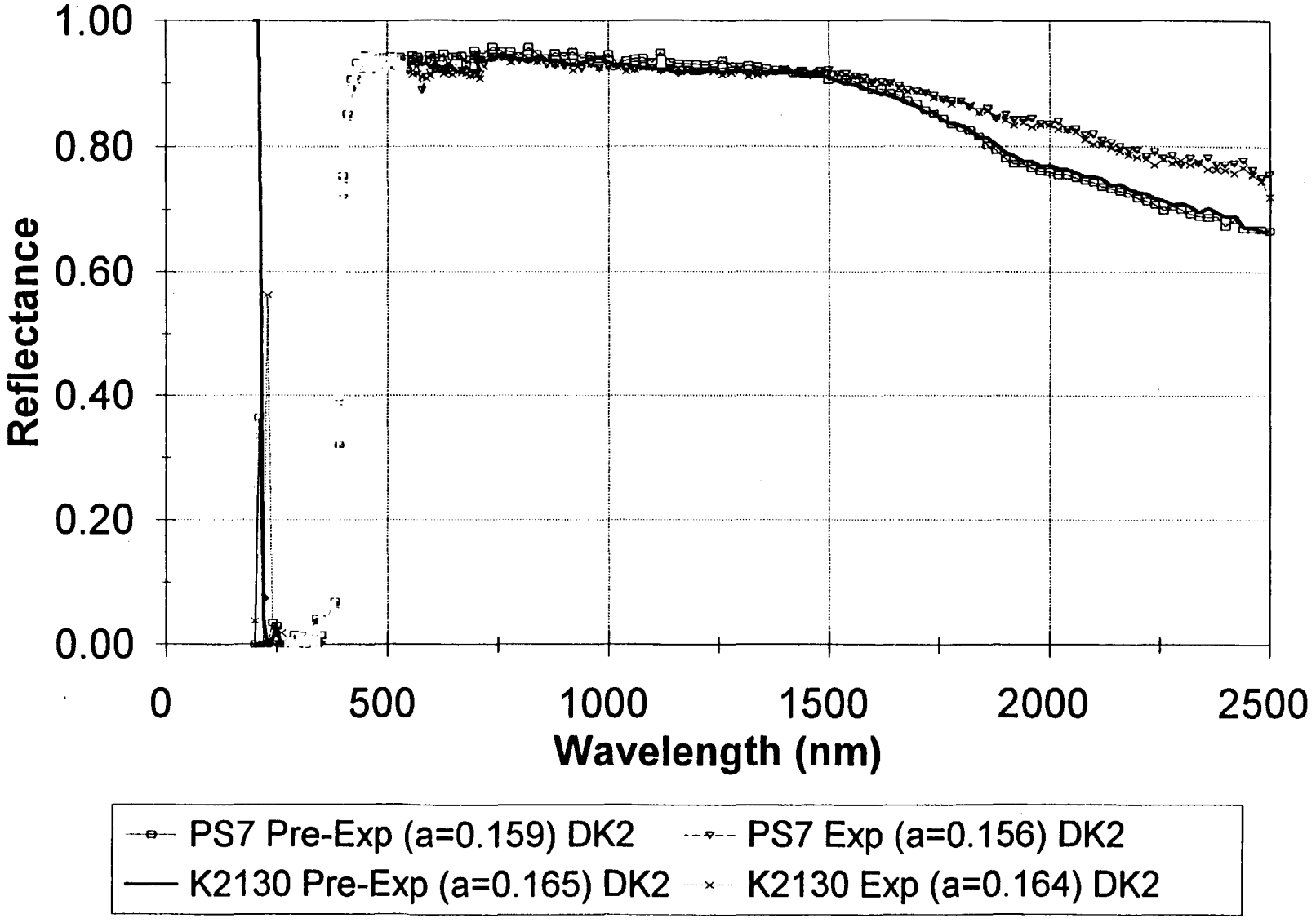

Figure 15. DK2 reflectance of AODTS-exposed Z93 (IITRI) as a function of binder type.

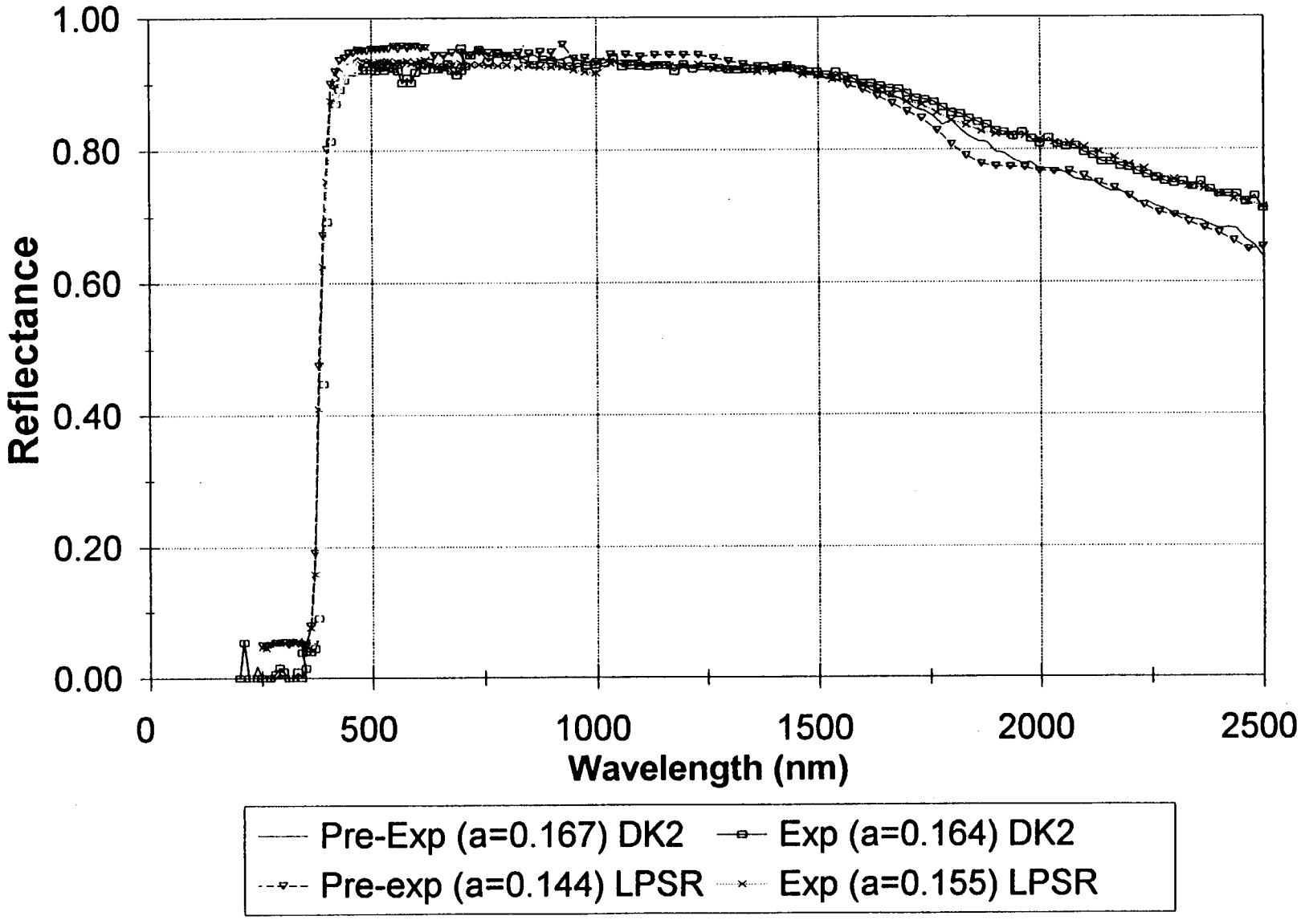

Figure 16. DK2 and LPSR reflectance of AODTS-exposed Z93/PS7 binder (McDonnell Douglas).

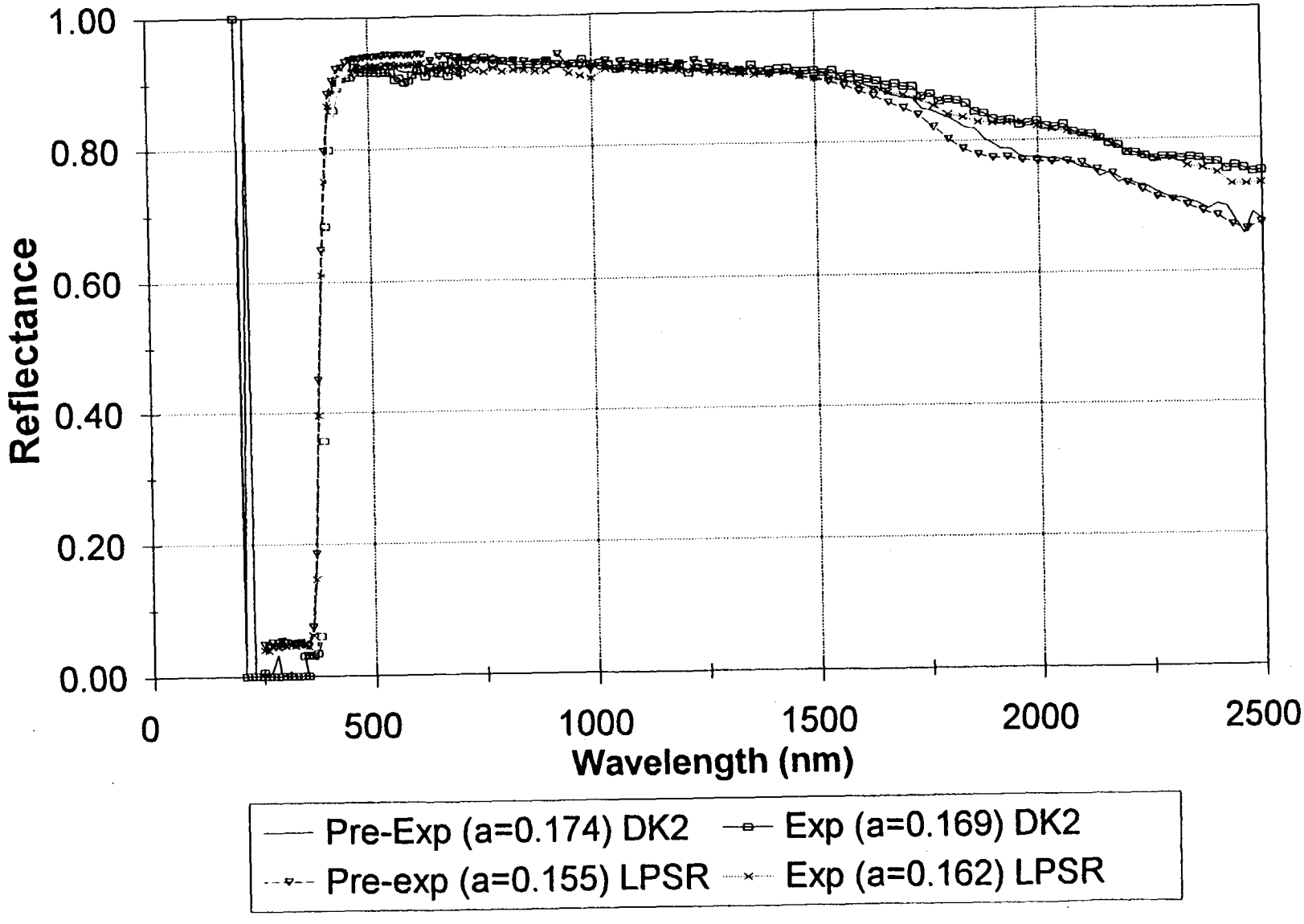

Figure 17. DK2 and LPSR reflectance of AODTS-exposed Z93/K2130 binder (McDonnell Douglas).

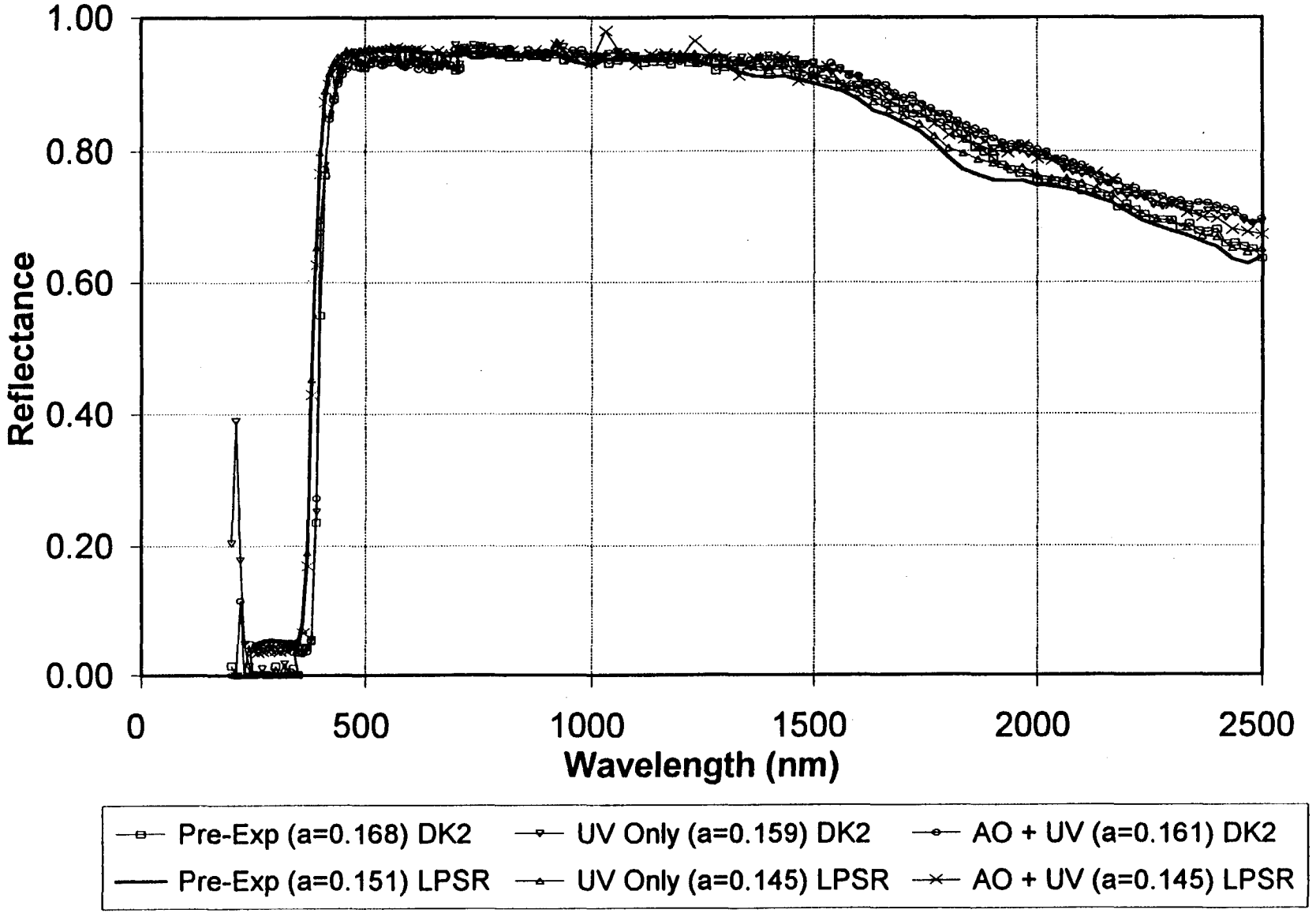

Figure 18. DK2 and LPSR reflectance of PPPL-exposed Z93/PS7 binder (IITRI).

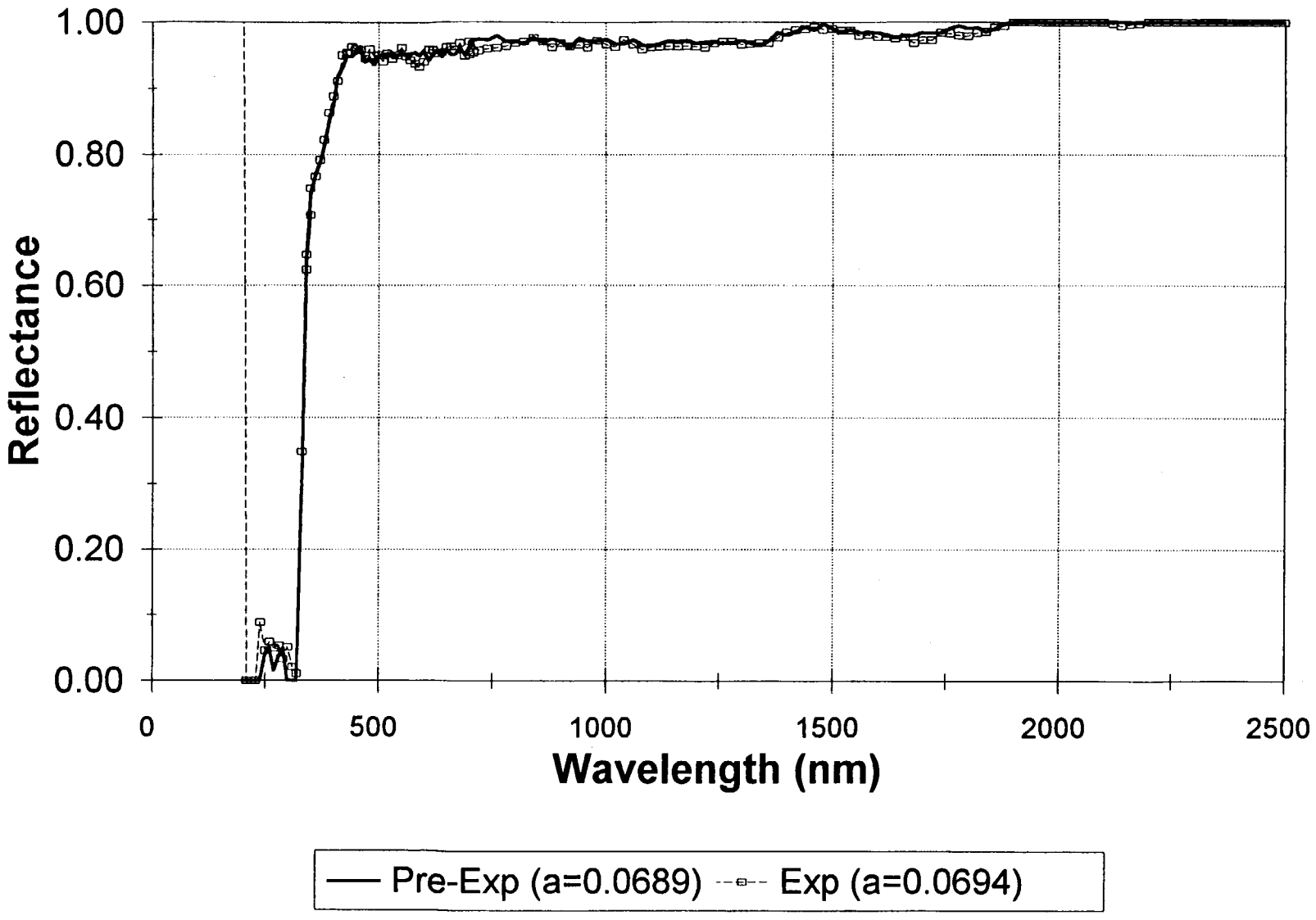

Figure 19. DK2 reflectance of AODTS-exposed silvered FEP Teflon™ tape.

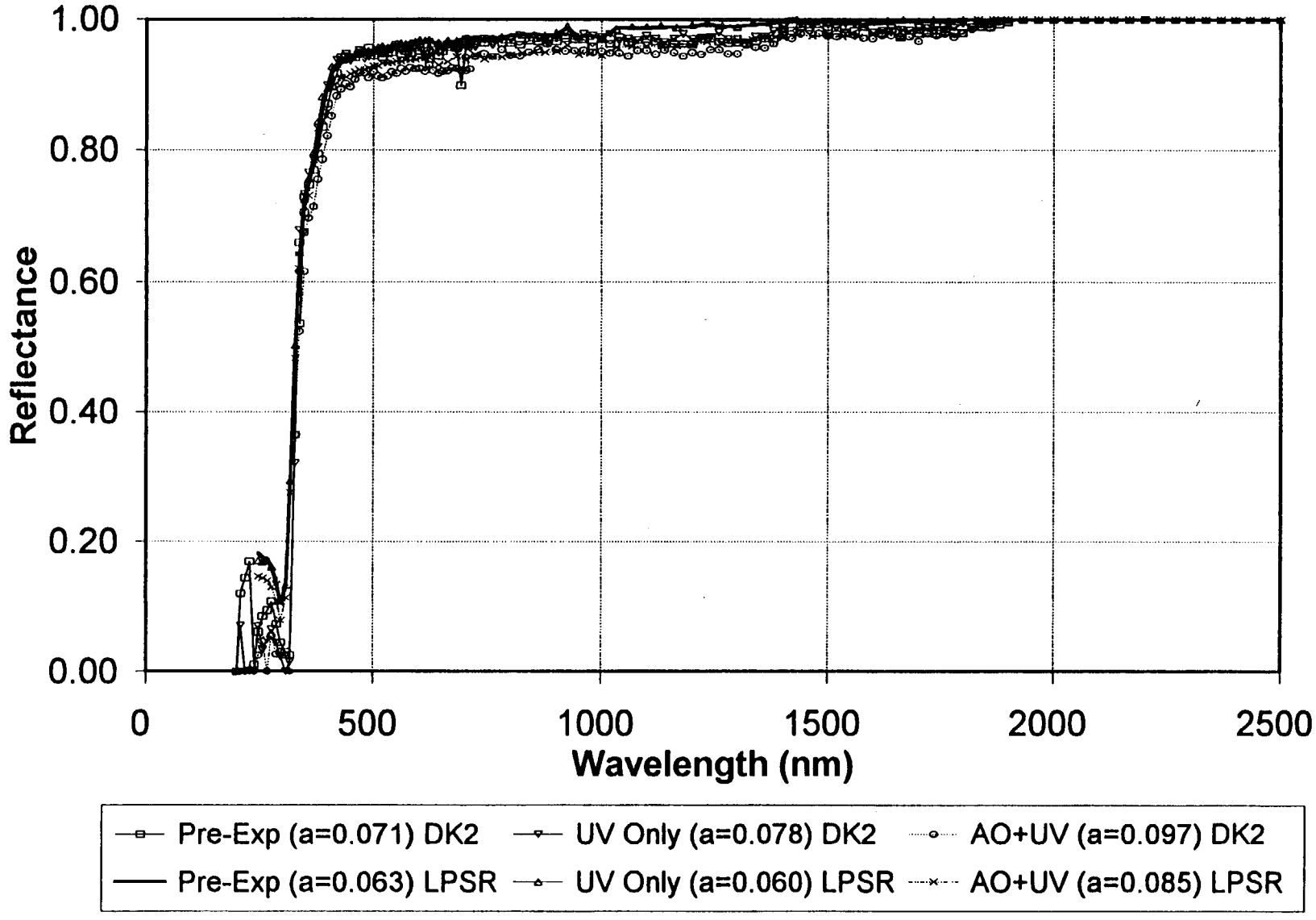

Figure 20. DK2 and LPSR reflectance of PPPL-exposed silverized FEP Teflon™ tape.

Table 7. Silverized Teflon™ test results.

Exposure	PPPL Exposure Fluence ~ 1.1×10^{20} atoms/cm^2 VUV Irradiance ~ 8,000 ESH (130 nm)			AODTS Exposure Fluence ~ 7.1×10^{22} atoms/cm^2		
	LPSR α_s	DK2 α_s	ε_{IR}	LPSR α_s	DK2 α_s	ε_{IR}
Average preexposure	0.062	0.072	0.80		0.069	0.81
VUV exposed	0.060	0.068	0.80			
5 eV AO+VUV	0.085	0.094	0.70			
Thermal AO				0.068	0.068	0.78

Table 8. Reaction efficiencies ($\times10^{-24}$ cm^3/atom) for space- and lab-exposed polymers.

AO Reaction Efficiency x 10^{-24} cm^3/atom							
Sample	STS-5 and STS-8	MSFC STS-41	LDEF A0171	MSFC EOIM-3	JSC EOIM-3	PPPL	AODTS
Fluence atoms/cm^2	1.0×10^{20}	1.0×10^{20}	6.93×10^{21}	2.2×10^{20}	2.2×10^{20}	7.2×10^{20} + 8,000 ESH VUV	7.10×10^{22}
Halar (bulk)		1.6†† 1.0†† 2.0§§	2.1§§	2.0§§ 2.5††	2.1§§	3.2§§ 3.4§§ 3.2†† 3.0††	0.034§§ 0.023§§ 0.014††
PEEK (bulk)		4.8§§	2.3§§	2.0§§ 2.0§§ 3.7†† 4.0††	3.9§§ Mfg. by Victrix	2.8§§ 3.0††	0.11§§ 0.12§§
FEP Teflon™ (film)	<0.05		0.34†† <A0178>	0.082† @ 60 °C 0.094† @ 120 °C 0.082† @ 120 °C	0.046	6.6§§ 5.9†† <AgFEP>	0.023§§ 0.023†† <AgFEP>

Atomic Reaction Efficiency
††Based on change in thickness
§§Based on change in mass

to thermal AO in the AODTS test. Examination of this sample prior to exposure in the AODTS test indicated that it had been clearly yellowed by the 700 ESH of EUV. Following AODTS exposure, the sample appeared in almost pristine condition, having been "cleaned" or bleached by the AO exposure. The decrease in solar absorptance following exposure in the AODTS system clearly verifies this cleaning effect. Mass, solar absorptance, and infrared emittance raw data for the samples are shown in appendices A and B. LPSR and DK2 reflectance curves are shown in figures 21, 22, and 23. Tables 9 and 10 summarize the optical data for the PPPL and AODTS tests.

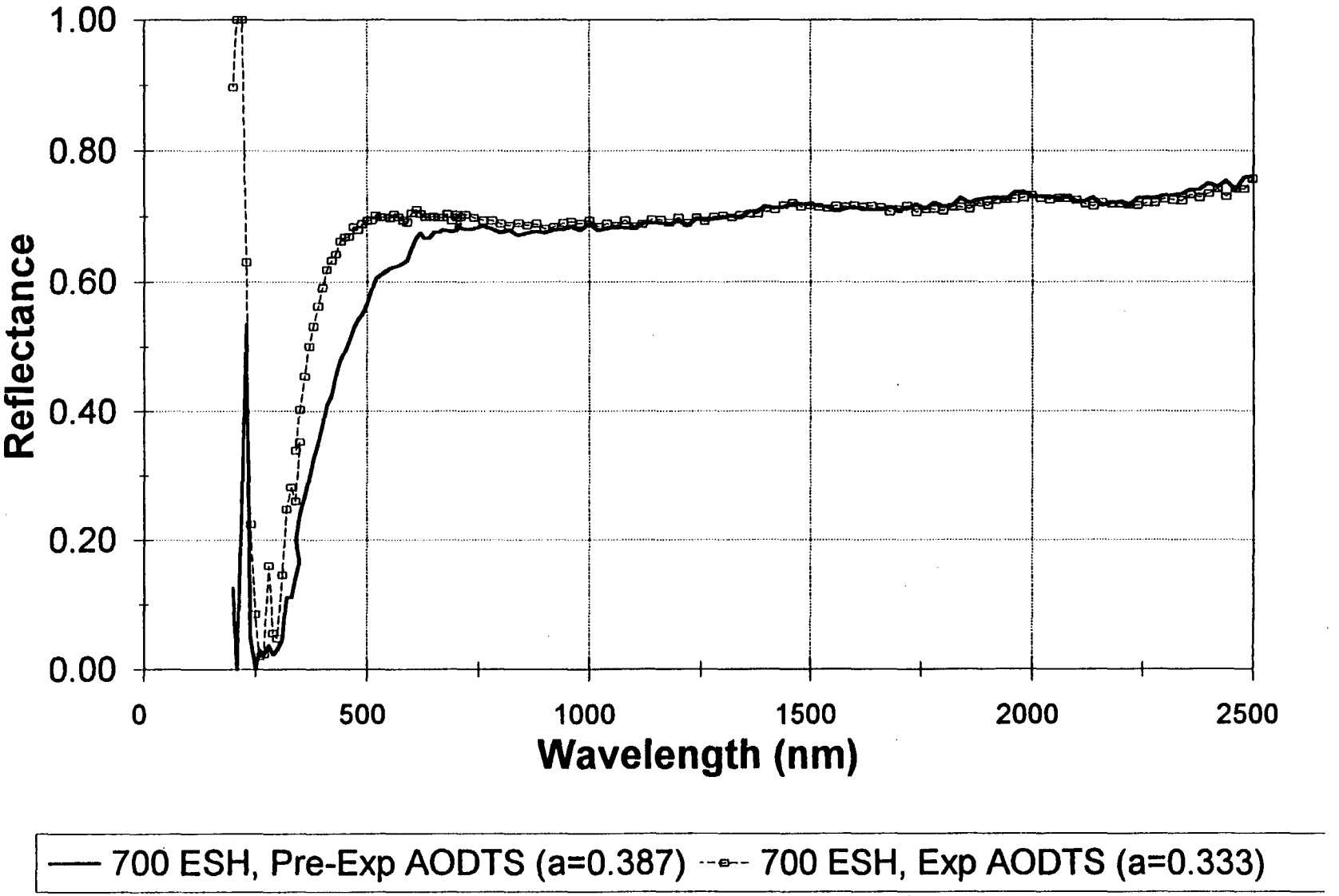

Figure 21. DK2 reflectance of EUV irradiated aluminized beta cloth bleached by AODTS AO.

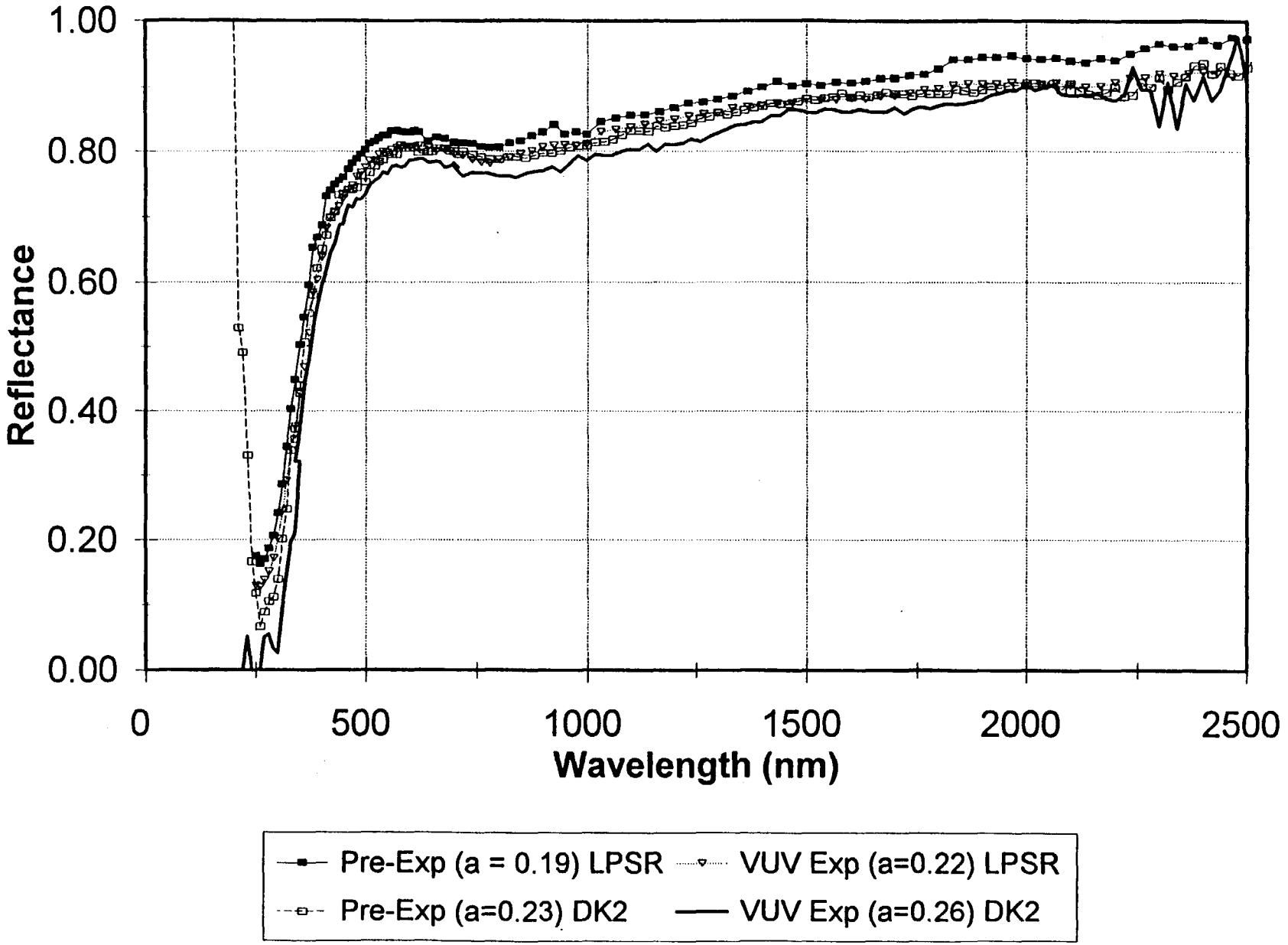

Figure 22. DK2 and LPSR reflectance of PPPL VUV-irradiated beta cloth.

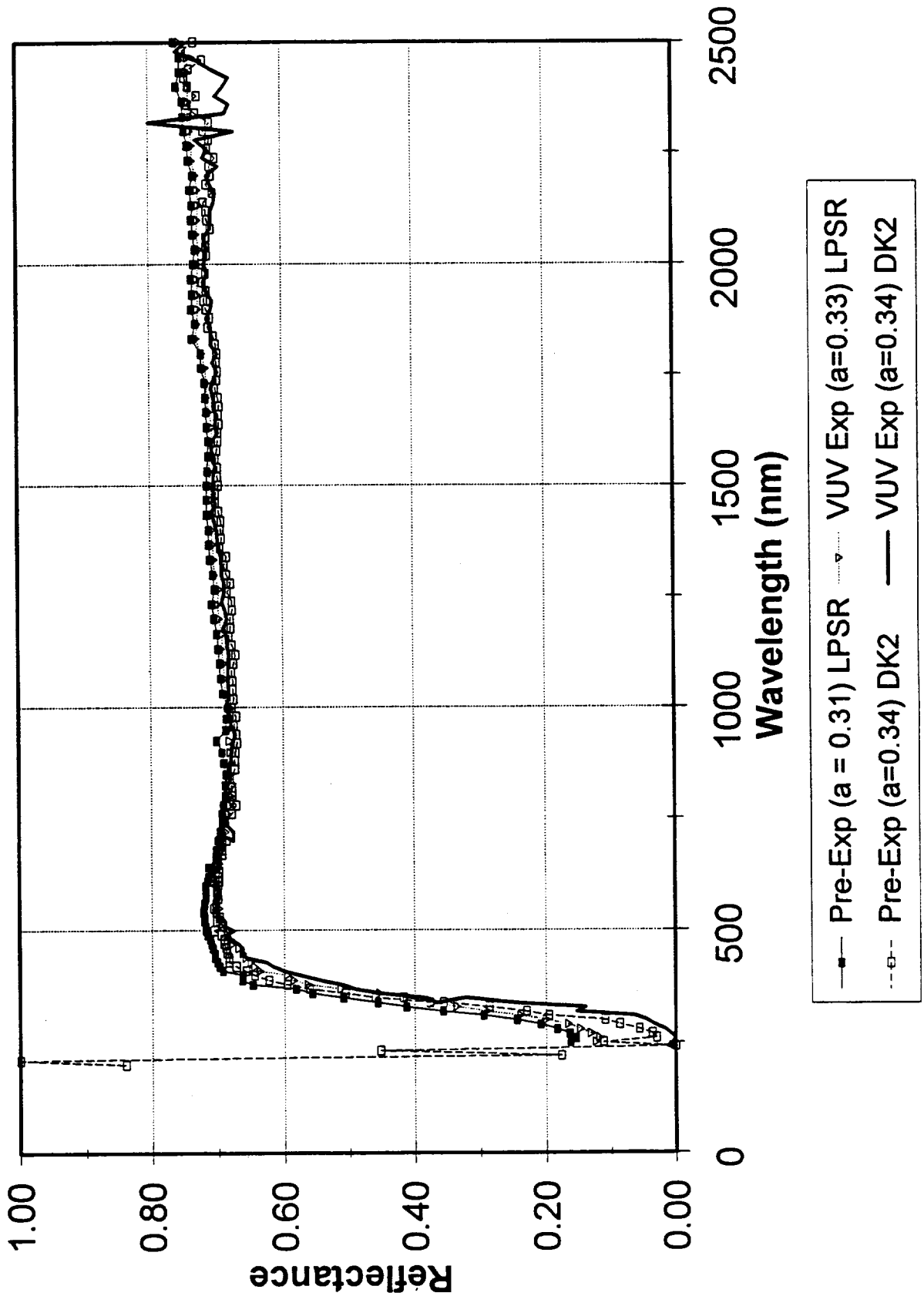

Figure 23. DK2 and LPSR reflectance of PPPL VUV-irradiated aluminized beta cloth.

Table 9. Test results of beta cloth exposed to PPPL VUV.

Exposure	PPPL Exposure VUV Irradiance ~ 8,000 ESH (130 nm)		
	LPSR α_s	DK2 α_s	ε_{IR}
Control – unaluminized	0.19	0.23	0.90
VUV exposed unaluminized	0.22	0.26	0.90
Control – aluminized	0.31	0.34	0.91
VUV exposed aluminized	0.33	0.34	0.90

Table 10. Test results of aluminized beta cloth exposed to AODTS and EUV.

Exposure	PPPL Exposure 2.1×10^{20} atoms/cm^2, EUV Irradiance ~ 700 ESH (250 to 400 nm)		
	LPSR α_s	DK2 α_s	ε_{IR}
Average preexposure	0.37	0.39	0.90
Thermal AO exposed	0.31	0.33	0.90

CONCLUSIONS

In general, thermal properties of the black anodized, sulfuric anodized, and chromic anodized samples remained fairly stable following exposure in the PPPL and AODTS tests. In addition, both the black inorganic and the Z93 thermal control paints showed little to no variation in thermal properties following exposure in either test. Reaction efficiencies for the bulk Halar™ and PEEK polymers exposed to AO and VUV in the PPPL test differ slightly from values generated from shuttle flight data. This slight difference is probably due to the VUV exposure in the PPPL test and slight differences in the chemical makeup of the different polymer sample lots. Bulk Halar™ samples exposed to thermal AO in the AODTS system appeared to have reaction efficiencies on the order of 100 times less than those samples exposed to neutral 5-eV AO. Bulk PEEK samples exposed to thermal AO in the AODTS system appeared to have reaction efficiencies on the order of only 20 times less than those samples exposed to neutral 5-eV AO. Thermal properties of the silverized FEP samples remained fairly stable following exposure to VUV radiation only in the PPPL test and to thermal AO only in the AODTS test. However, silverized FEP samples showed a large variation in both reaction efficiency and thermal properties when exposed to synergistic 5-eV AO and VUV in the PPPL test. Beta cloth specimens showed a slight increase in solar absorptance due to VUV exposure in the PPPL system. Beta cloth samples previously darkened by EUV radiation experienced a "cleaning" effect when exposed to thermal AO in the AODTS system as indicated by both visual observations and solar absorptance measurements.

Both the LPSR spectroreflectometer and the DK2 spectroreflectometer were fairly consistent in reporting changes in solar absorptance due to test exposures. However, variation in solar absorptance was evident for most all specimens when comparing absolute values measured using the LPSR spectroreflectometer and those values measured using the DK2 spectroreflectometer. Beta cloth and chromic acid anodized samples appeared to show the greatest difference between LPSR and DK2 values, while the duranodic, black inorganic, and Z93 specimens appeared to be more consistent. As a result, care should be taken when quoting and requiring specific absolute values of solar absorptance.

REFERENCE

1. Cuthbertson, J.W., Langer, W.D., Motley, R.W, and Vaughn, J.A.: "Atomic Oxygen Beam Source for Erosion Simulation." Fourth Annual Workshop on Space Operations Applications and Research, Albuquerque, NM, June 1990, NASA publication CP-3103, vol. II, pp. 734–741.

APPENDIX A

AODTS Test Raw Data

Ram Fluence = 7.1 x 10^{22} atoms/cm^2 Wake Fluence = 2.1 x 10^{22} atoms/cm^2

April - June 1993

✡Dek-Tak

* Dek-Tak measurements did not yield any information

		Mass			Coating Thickness (Mils)					α_s LPSR			α_s DK2			Gier-Dunkle ε_{lr}		
Sample	Exposure	Pre-test (g)	Post-test (g)	Δ M (mg)	Pre-test	Post-test	Δ T (%)	Pre-test σ / n	Post-test σ / n	Pre-test	Post-test	Δ α_s (%)	Pre-test	Post-test	Δ α_s (%)	Pre-test	Post-test	Δ ε_{lr} (%)
Halar																		
#1b	RAM	2.26776	2.26168	0.608			0.38*											
#2b	Wake	2.27243	2.27124	0.119			*											
PEEK																		
1b	RAM	1.61593	1.60087	15.06			*				0.702						0.886	
2b	Wake	2.15300	2.14790	5.10			*				0.764						0.889	
AgFEP																		
1b	RAM	1.85592	1.84225	13.67	6.43 Mil	5.79 Mil	0.640 Mil		0.126/10		0.068		0.06890	0.0694	0.73	0.808	0.784	-3.0
2b	Control	1.7650			6.48 Mil								0.06829			0.807		
2*	Control		2.4343			6.59 Mil			0.076/11		0.060			0.068				
Duranodic																		
D3	Ram	1.43023	1.43069	0.460	1.4	1.4	0.0	0.015/10	0.006/10	0.843	0.825	-2.1	0.882	0.881	-0.11	0.882	0.880	-0.23
D4	Ram	1.42908	1.42963	0.550	1.4	1.4	0.0	0.008/10	0.013/10	0.846	0.829	-2.0	0.888	0.887	-0.11	0.882	0.880	-0.23
D5	Control	1.43000	1.43056	0.560	1.4	1.4	0.0	0.016/10	0.009/10	0.837	0.835	-0.24	0.879	0.874	-0.57	0.883	0.880	-0.34
D6	Control	1.43161	1.43206	0.450	1.4	1.4	0.0	0.017/10	0.013/10	0.844	0.839	-0.59	0.893	0.881	-1.3	0.882	0.879	-0.34
Sulfuric																		
S3	Ram	4.50837	4.50879	0.420	0.56	0.56	0.000	0.034/20	0.036/15	0.403	0.398	-1.2	0.455	0.444	-2.4	0.858	0.861	0.35
S4	Ram	4.50379	4.50408	0.290	0.58	0.53	-0.050	0.028/20	0.038/10	0.395	0.390	-1.3	0.453	0.439	-3.1	0.856	0.859	0.35
S5	Control	4.4776	4.47789	0.290	0.56	0.52	-0.040	0.026/20	0.020/10	0.394	0.396	0.51	0.449	0.440	-2.0	0.855	0.862	0.82
S6	Control	4.49390	4.49429	0.390	0.57	0.53	-0.040	0.022/20	0.022/10	0.406	0.414	2.0	0.455	0.459	0.88	0.858	0.864	0.70
CAA																		
75tk3	RAM	2.14292	2.14276	-0.160	0.100	0.123	0.023 (23)	0.013/25	0.019/20	0.366	0.368	0.55	0.400	0.399	-0.25	0.731	0.724	-0.96
75tk4	RAM	2.14433	2.14405	-0.280	0.095	0.134	0.039 (41)	0.011/25	0.012/20	0.370	0.363	-1.9	0.397	0.398	0.25	0.731	0.725	-0.82
75tk5	Control	2.14735	2.14734	-0.0100	0.97	0.139	.83 (86)	0.010/25	0.011/20	0.364	0.366	0.55	0.399	0.396	-0.75	0.729	0.732	0.41
45mm3	RAM	2.13376	2.13364	-0.120	0.080	0.073	0.007 (8.8)	0.011/25	0.014/20	0.337	0.329	-2.4	0.372	0.359	-3.5	0.506	0.490	-3.2
45mm4	RAM	2.13484	2.13475	-0.0900	0.080	0.091	0.011(13.8)	0.016/25	0.013/20	0.340	0.327	-3.8	0.366	0.366	0.0	0.501	0.488	-2.6
45mm5	Control	2.13376	2.13319	-0.570	0.080	0.090	0.010(12.5)	0.011/25	0.008/20	0.337	0.325	-3.6	0.372	0.364	-2.2	0.506	0.496	-2.0
30tn3	RAM	2.14357	2.14351	-0.0600	0.027	0.063	0.036 (133)	0.015/25	0.012/20	0.294	0.288	-2.0	0.313	0.323	3.2	0.306	0.295	-3.6
30tn4	RAM	2.14235	2.14231	-0.0400	0.021	0.066	0.045(214)	0.013/25	0.018/20	0.295	0.290	-1.7	0.323	0.321	-0.62	0.302	0.289	-4.3
30tn5	Control	2.14127	2.14123	-0.0400	0.026	0.073	0.047 (181)	0.018/25	0.014/20	0.294	0.290	-1.4	0.331	0.328	-0.91	0.302	0.298	-1.3
30tn6	Control	2.13653	2.13644	-0.0900	0.029	0.063	0.034 (117)	0.016/25	0.009/20	0.289	0.281	-2.8	0.319			0.294	0.287	-2.4
Al Beta Cloth		UV5+6	Beta 2															
ABC1b*	Wake	0.12933	0.12920	-0.13						0.366	0.309	-15.6	0.387	0.333	-14.0	0.904	0.899	-0.55

April - June 1993

Ram Fluence = 7.1 x 10^{22} atoms/cm^2 Wake Fluence = 2.1 x 10^{22} atoms/cm^2

		Mass			Coating Thickness (Mils)					α_s LPSR			α_s DK2			Gier-Dunkle ε_{ir}		
Sample	Exposure	Pre-test (g)	Post-test (g)	Δ M (mg)	Pre-test	Post-test	Δ T (%)	Pre-test σ / n	Post-test σ / n	Pre-test	Post-test	Δ α_s (%)	Pre-test	Post-test	Δ α_s (%)	Pre-test	Post-test	Δ ε_{ir} (%)
Ilti Z93																		
X31	Wake	1.83684									0.148		0.15885	0.156	-1.8	0.921	0.915	-0.65
X33	Control	1.85523									0.150		0.15284	0.154	0.76	0.921	0.918	-0.33
X40	Wake	1.82007	Stuck								0.152		0.15847			0.923	0.925	-.022
X27	Wake	1.77525									0.156		0.16523	0.164	-0.74	0.921	0.915	-0.65
X28	Control	1.80166									0.153		0.15705	0.162	3.2	0.921	0.919	-0.22
X30	Wake	1.77579									0.152		0.16289	0.163	0.0	0.922	0.916	-0.65
Black Inorganic																		
3	Wake	2.01403								0.954	0.951	-0.31	0.977	0.974	-0.31	0.895	0.896	0.11
4	Wake	2.01612								0.954	0.946	-0.84	0.976	0.985	0.92	0.895	0.896	0.11
7	Control	2.00927								0.954	0.953	-0.10	0.980	0.966	-1.4	0.896	0.901	0.56
MacDac Z93																		
KS1(new)	Wake	4.24926								0.155	.162	4.5	0.17361	0.169	-2.7	0.925	0.920	-0.54
KS2	Wake	4.21682								0.151	0.160	6.0	0.17226	0.168	-2.5	0.925	0.919	-0.65
KS3	Control	4.24743								0.153	0.159	3.9	0.17052	0.167	-2.1	0.925	0.923	-0.22
KS4	Control	4.35614								0.150	0.153	2.0	0.15950	0.164	3.1	0.926	0.924	-0.22
KS5	Mole Flux	4.22752								0.151			0.16594			0.926		
PS1(Orig)	Wake	4.27462								0.144	0.155	7.6	0.16654	0.164	-1.5	0.917	0.912	-0.55
PS2	Wake	4.25676								0.140	0.154	10.0	0.16458	0.163	-0.96	0.917	0.913	-0.44
PS3	Control	4.29406								0.141	0.154	0.92	0.16593	0.160	-3.6	0.918	0.914	-0.44
PS4	Control	4.25968								0.147	0.148	0.68	0.16547	0.166	0.32	0.919	0.917	-0.22
PS5	Control	4.28809								0.145	0.153	5.5	0.16793	0.159	-5.3	0.919	0.915	-0.44

APPENDIX B

PPPL Test Raw Data

February - March 1993

Test Series 1

		Mass			Coating Thickness (Mils)					α_s LPSR			α_s DK2			Gier-Dunkle ε_{Ir}		
Sample	Exposure	Pre-test (g)	Post-test (g)	Δ M (mg)	Pre-test	Post-test	Δ T	Pre-test σ / n	Post-test σ / n	Pre-test	Post-test	Δ α_s (%)	Pre-test	Post-test	Δ α_s (%)	Pre Test	Post Test	Δ ε_{Ir} (%)
Duranodic	None				1.86					0.87***						0.87		
D1	PPPL-Win PR10	1.43197	1.43205	0.08	1.4	1.4	0.00	0.014/13	0.013/20	0.841	0.824	-0.017 (-2.0)	0.886	0.885	-0.001 (-0.11)	0.882	0.883	0.001 (0.11)
D2	PPPL	1.43170	1.43177	0.07	1.4	1.4	0.00	0.008/10	0.012/20	0.832	0.832	0.0 (0.0)	0.879	0.881	-0.002(-0.23)	0.882	0.884	0.002 (0.23)
D3		1.43023			1.4			0.015/10		0.843			0.882			0.882		
D4		1.42908			1.4			0.008/10		0.846			0.888			0.882		
D5		1.43000			1.4			0.016/10		0.837			0.879			0.883		
D6		1.43161			1.4			0.017/10		0.844			0.893			0.882		
Sulphuric	None				0.60					0.43* :: 0.45*						0.86		
S1	PPPL-Win PR12	4.56170	4.56177	0.07	0.56	0.56	0.000	0.027/20	0.035/20	0.394	0.399	0.005 (1.3)	0.444	0.451	0.0070 (1.6)	0.858	0.861	0.003 (0.35)
S2	PPPL	4.52896	4.52907	0.11	0.58	0.58	0.000	0.034/20	0.030/20	0.400	0.412	0.012 (3.0)	0.449	0.458	0.009 (2.0)	0.857	0.860	0.004 (0.47)
S3		4.50837			0.56			0.034/20		0.403			0.455			0.858		
S4		4.50379			0.58			0.028/20		0.395			0.453			0.856		
S5		4.47746			0.56			0.026/20		0.394			0.449			0.855		
S6		4.49390			0.57			0.022/20		0.406			0.455			0.858		
Al Beta Cloth*	None															***0.905***		
ABC 1*	PPPL-Win PR13		0.12921							0.313	0.333	0.020 (6.4)	0.335	0.344	0.009 (2.7)		0.903	0.001 (0.11)
ABC 2*										0.309			0.331					
Beta Cloth*	None															***0.902***		
BC 1*	PPPL-Win PR14		0.1343							0.193	0.222	0.029 (15.0)	0.226	0.256	0.03 (13.3)		0.904	0.002 (0.22)
BC 2*										0.191			0.242					
CAA																		
75TK1	PPPL-Win PR15	2.14982	2.14941	-0.41	0.10	0.14	0.040	0.009/25	0.012/25	0.364	0.369	0.005 (1.4)	0.397	0.400	0.003 (0.76)	0.731	0.725	-0.006 (-0.82)
75TK2	PPPL	2.14509	2.14482	-0.27	0.10	0.14	0.040	0.011/25	0.012/25	0.365	0.369	0.004 (1.1)	0.405	0.410	0.005 (1.2)	0.733	0.726	-0.007 (-0.95)
45MM1	PPPL-Win PR11	2.13329	2.13317	-0.12	0.080	0.080	0.000	0.008/25	0.009/25	0.338	0.327	-0.011 (-3.3)	0.368	0.365	-0.003 (-0.82)	0.499	0.480	-0.019 (-3.81)
45MM2	PPPL	2.13456	2.13442	-0.14	0.080	0.070	0.100	0.011/25	0.013/25	0.338	0.327	-0.011 (-3.3)	0.374	0.372	-0.002 (-0.53)	0.503	0.478	-0.025 (-5.0)
30TN1	PPPL-Win PR9	2.14198	2.14183	-0.15	0.020	0.050	0.030	0.011/27	0.012/25	0.293	0.289	-0.004 (-1.4)	0.315	0.321	0.006 (1.9)	0.303	0.282	-0.021 (-7.0)
30TN2	PPPL	2.13527	2.13516	-6.7	0.030	0.050	0.020	0.017/15	0.013/25	0.296	0.282	-0.014 (-4.7)	0.319	0.316	-0.003 (-0.94)	0.293	0.263	-0.030 (-10.2)

AO fluence ≈ 6.84 x 10^{20} atoms/cm^2 ***Except***

for S1 and S2 which had a fluence ≈ 1.22 x 10^{21} atoms/cm^2

σ = Standard Deviation n = Number of measurements

* Light Section Microscope

** Dek-Tak

*** Eddy current

February - March 1993
Test Series 2

		Mass			Thickness					α_s LPSR			α_s DK2			Gier-Dunkle ε_{1r}		
Sample	Exposure	Pre-test (g)	Post-test (g)	Δ M (mg)	Pre-test	Pre-test σ / n	Post-test	Post-test σ / n	Δ T	Pre-test	Post-test	Δ α_s (%)	Pre-test	Post-test	Δ α_s (%)	Pre Test	Post Test	Δ ε_{1r}
Z93																		
A-060		1.30888								0.148			0.164			0.919		
A-041	PPPL - Win	1.31157	1.31101	-0.56						0.151	0.145	-0.006 (-4.0)	0.169	0.159	-0.010 (5.9)	0.920	0.919	-0.001 (-0.11)
A-044	PPPL	1.30494	1.30464	-0.30						0.144	0.145	-0.001 (-0.69)	0.162	0.161	0.001 (0.62)	0.921	0.919	-0.002 (-0.22)
A-086		1.28998								0.137			0.160			0.919		
A-087	PPPL - Win	1.30659	Cracked							0.136			0.160			0.919		
A-083	PPPL	1.28412	Cracked							0.143			0.167			0.919		
BL Inorganic																		
3		2.01403								0.954			0.977			0.895		
4		2.01612								0.954			0.976			0.896		
5	PPPL	2.01489	2.01493	0.04						0.954	0.954	0.0 (0.0)	0.974	0.972	-0.002 (-0.21)	0.889	0.889	0.0 (0.0)
6	PPPL	2.01329	2.01330	0.01						0.951	0.955	0.004 (0.42)	0.970	0.973	0.003 (0.31)	0.895	0.892	-0.003 (-0.34)
7		2.00927								0.953			0.980			0.896		
8																		
Ag Teflon																		
1	PPPL	0.83396	0.77333	-60.63	5.88*** (Mils)	0.095/20	3.36*** (Mils)	0.056/20	2.52 (Mils)	0.0619	0.085	0.0231 (37.3)	0.0727	0.0942	0.0215 (30)	0.801	0.697	-0.104 (-13.0)
2	PPPL - Win	0.57914	0.57807	-1.07	5.13* (Mils)					0.0627	0.060	-0.0027 (-4.3)	0.0705	0.0675	-0.0030 (-4.2)	0.803	0.802	-0.001 (-0.12)
Halar																		
5	PPPL	2.22342	2.21734	-6.08					22 µm**	0.763	0.776	0.013 (1.70)	0.516	0.525	0.009 (1.7)	0.921	0.934	0.013 (1.4)
6	PPPL	2.22941	2.22286	-6.55					22 µm**	0.766	0.773	-0.007(-0.91)	0.483	0.554	0.071 (14.7)	0.921	0.941	0.020 (2.2)
PEEK																		
3	PPPL	1.60177	1.59721	-4.56					20 µm**	0.722	0.728		0.752	0.743	-0.009 (-1.2)	0.889	0.919	0.030 (3.4)
4		1.61559								0.72			0.753			0.889		
A276																0.884		
3	PPPL - Win	1.14782	1.11543	-32.39						0.235	0.265	0.030 (12.8)		0.287			0.884	

AO Fluence ≈ 7.2 x 10^{20} atoms/cm^2 except for Ag Teflon #1 and #2 which had a

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	December 1995	Technical Paper

4. TITLE AND SUBTITLE
Evaluation of Thermal Control Coatings and Polymeric Materials Exposed to Ground Simulated Atomic Oxygen and Vacuum Ultraviolet Radiation

5. FUNDING NUMBERS

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

8. PERFORMING ORGANIZATON REPORT NUMBERS

M-798

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TP-3595

11. SUPPLEMENTARY NOTES

Prepared by Materials and Processes Laboratory, Science and Engineering Directorate.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified-Unlimited
Subject Category 18

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Numerous thermal control and polymeric samples with potential International Space Station applications were evaluated for atomic oxygen and vacuum ultraviolet radiation effects in the Princeton Plasma Physics Laboratory 5 eV Neutral Atomic Oxygen Facility and in the MSFC Atomic Oxygen Drift Tube System. Included in this study were samples of various anodized aluminum samples, ceramic paints, polymeric materials, and beta cloth, a Teflon®-impregnated fiberglass cloth. Aluminum anodizations tested were black duranodic, chromic acid anodize, and sulfuric acid anodize. Paint samples consisted of an inorganic glossy black paint and Z-93 white paint made with the original PS7 binder and the new K2130 binder. Polymeric samples evaluated included bulk Halar®, bulk PEEK, and silverized FEP Teflon®. Aluminized and nonaluminized Chemfab 250® beta cloth were also exposed. Samples were evaluated for changes in mass, thickness, solar absorptance, and infrared emittance. In addition to material effects, an investigation was made comparing diffuse reflectance/solar absorptance measurements made using a Beckman DK2 spectroreflectometer and like measurements made using an AZ Technology-developed laboratory portable spectroreflectometer.

14. SUBJECT TERMS
space environment, atomic oxygen, vacuum ultraviolet radiation, thermal control, anodized aluminum

15. NUMBER OF PAGES
49

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

National Aeronautics and
Space Administration
Code JTT
Washington, DC
20546–0001

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