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**NASA Technical Memorandum 104636**

# **Atomic Oxygen and Space Environment Effects on Aerospace Materials Flown with EOIM-III Experiment**

**John J. Scialdone, Carroll H. Clatterbuck, Mary Ayres-Treusdell,  
Gloria Park, and Diane Kolos**

**November 1996**





## Errata

Table 3, pages 9 and 10, under the *Thermo-Optical Properties* columns' identifications:

- The two *Absorption* titles should be changed to ***Absorptance***.
- The Absorptance column on the left reflects the absorptance values ***before flight***. The absorptance column on the right reflects the values ***after flight***.

References, page 33: The name of the co-author in reference 1 indicated as *Visentive*, should be ***Visentine***.



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**1996**

This publication is available from the NASA Center for Aerospace Information,  
800 Elkridge Landing Road, Linthicum Heights, MD 21090-2934, (301) 621-0390.

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# Atomic Oxygen and Space Environment Effects on Aerospace Materials Flown with EOIM-III Experiment

## Abstract

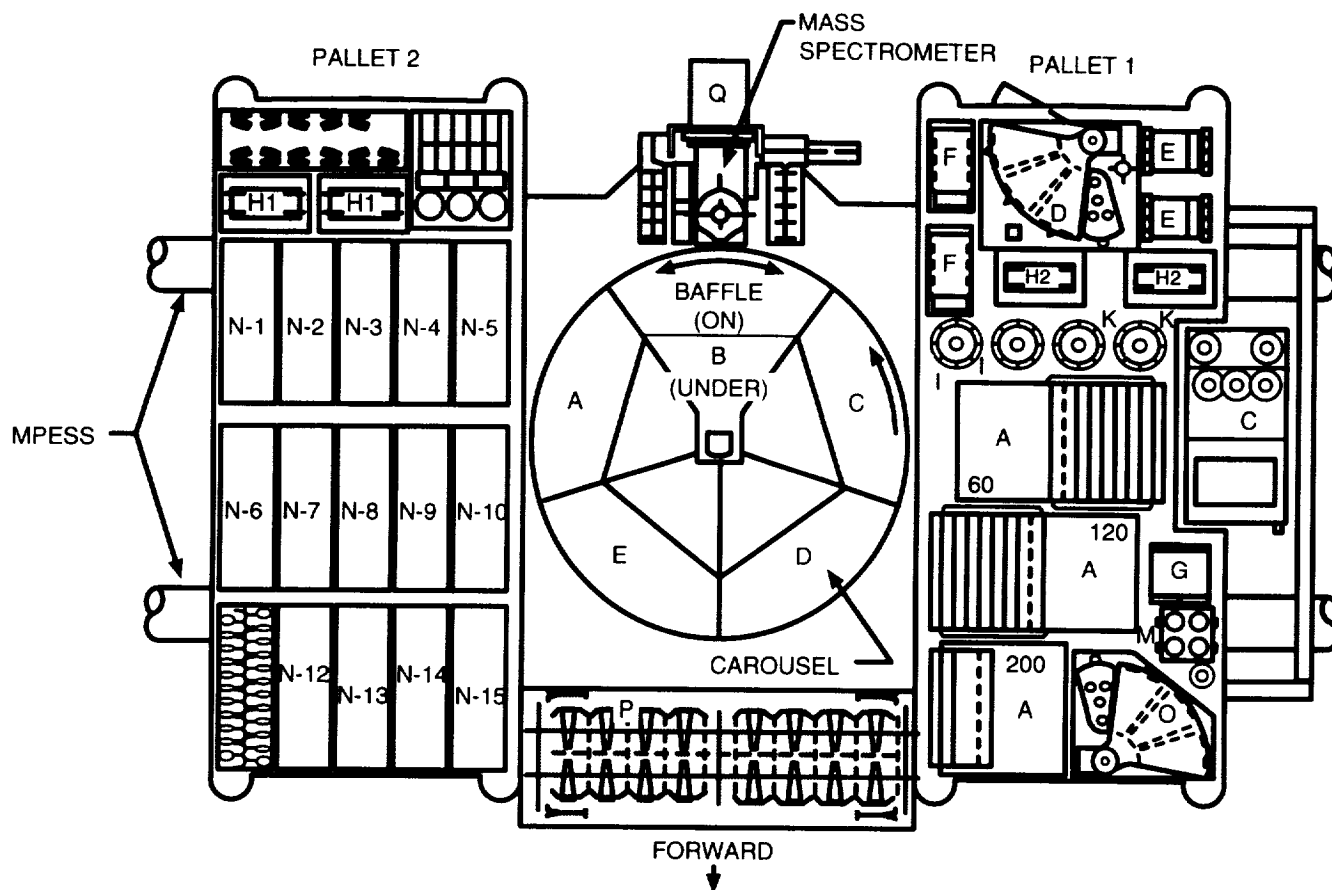
Polymer materials samples mounted on a passive carrier tray were flown aboard the STS-46 Atlantis shuttle as complement to the EOIM-III (Evaluation of Oxygen Interaction with Materials) experiment to evaluate the effects of atomic oxygen on the materials and to measure the gaseous shuttle bay environment.

The morphological changes of the samples produced by the atomic oxygen fluence of  $2.07\text{E}-20$  atoms/cm<sup>2</sup> are being reported. The changes have been verified using Electron Spectroscopy for Chemical Analysis (ESCA), gravimetric measurement, microscopic observations and thermo-optical measurements. The samples, including Kapton, Delrin, epoxies, Beta Cloth, Chemglaze Z306, silver Teflon, silicone coatings, 3M tape and Uralane and Ultem, PEEK, Victrex (PES), Polyethersulfone and Polymethylpentene thermoplastic, have been characterized by their oxygen reaction efficiency on the basis of their erosion losses and the oxygen fluence. (See Table 1 for source name.) Those efficiencies have been compared to results from other experiments, when available. The efficiencies of the samples are all in the range of E-24 g/atom. The results indicate that the reaction efficiencies of the reported materials can be grouped in about three ranges of values. The least affected materials which have efficiencies varying from 1 to 10 E-25 g/atom, include silicones, epoxies, Uralane and Teflon. A second group with efficiency from 10 to 45 E-25 g/atom includes additional silicone coatings, the Chemglaze Z306 paint and Kapton. The third range from 50 to 75 E-25 includes organic compound such as Pentene, Peek, Ultem, Sulfone and a 3M tape. A Delrin sample had the highest reaction efficiency of 179 E-25 g/atom. Two samples, the aluminum Beta cloth X389-7 and the epoxy fiberglass G-11 nonflame retardant, showed a slight mass increase.

## 1.0 Introduction

The Atlantis Shuttle STS Mission 46, of July/August 1992, carried in orbit a large number of experiments collectively grouped under the designation of Evaluation of Oxygen Interaction with Materials (EOIM-III)—third phase. The experiments had been designed: (1) to provide atomic oxygen reactivity measurements; (2) to understand its reaction mechanism and dynamics; and (3) to characterize the induced environment in the shuttle bay. The instruments to carry out these functions are depicted in Figure 1a.

The experiment instrumentation included a mass spectrometer for measurement of the gaseous atomic fluxes and other instrumentation to verify the environment, the direction and energies of the various fluxes. Among these test experiments were 15 passive tray carriers, identified in Figure 1a by the letter N, carrying samples provided by NASA centers, Aerospace Corporation, University of Alabama, European Space Agency, Canada Space Agency and Japan Space Agency. These trays, shown in Figure 1b, included nominal openings of 1/2" and 1" diameter which accommodated materials samples mounted on aluminum backing disks.



ATOMIC INTERACTION EXPERIMENTS:

- A - HEATED PLATE (JSC), 3EA
- B - ATOM SCATTERING EXPERIMENT (UAH), 1EA
- C - ENVIRONMENT MONITOR PACKAGE (GSFC), 1EA
- D - SOLAR UV EXPERIMENT (JSC), 1EA
- E - STATIC STRESS FIXTURE (MSFC), 2EA
- F - UNIFORM STRESS FIXTURE (MSFC), 2EA
- G - ATOMIC OXYGEN MONITOR (MSFC), 1EA
- H1 - COMPOSITE STRESS FIXTURE (LaRC), 2EA
- H2 - COMPOSITE STRESS FIXTURE (JSC), 2EA

- I - SCATTEROMETER (JPL), 2EA
- J - MECHANICAL STRESS FIXTURE (LeRC), 11EA
- K - REFLECTOMETER (LeRC), 2EA
- L - PINHOLE CAMERA (LeRC), 1EA
- M - SCATTEROMETER (AEROSPACE CORP.), 1EA
- N - PASSIVE SAMPLE CARRIERS, 15EA
- O - VARIABLE EXPOSURE TRAY, 1EA
- P - FREEDOM ARRAY MATERIALS EXPOSURE EXPERIMENT (LeRC), 1EA
- Q - QUADRUPE MASS SPECTROMETER, 1EA

Figure 1a. A line drawing of the EOIM-III payload identifying the various features. The forward edge of the payload is at the bottom of the line drawing.

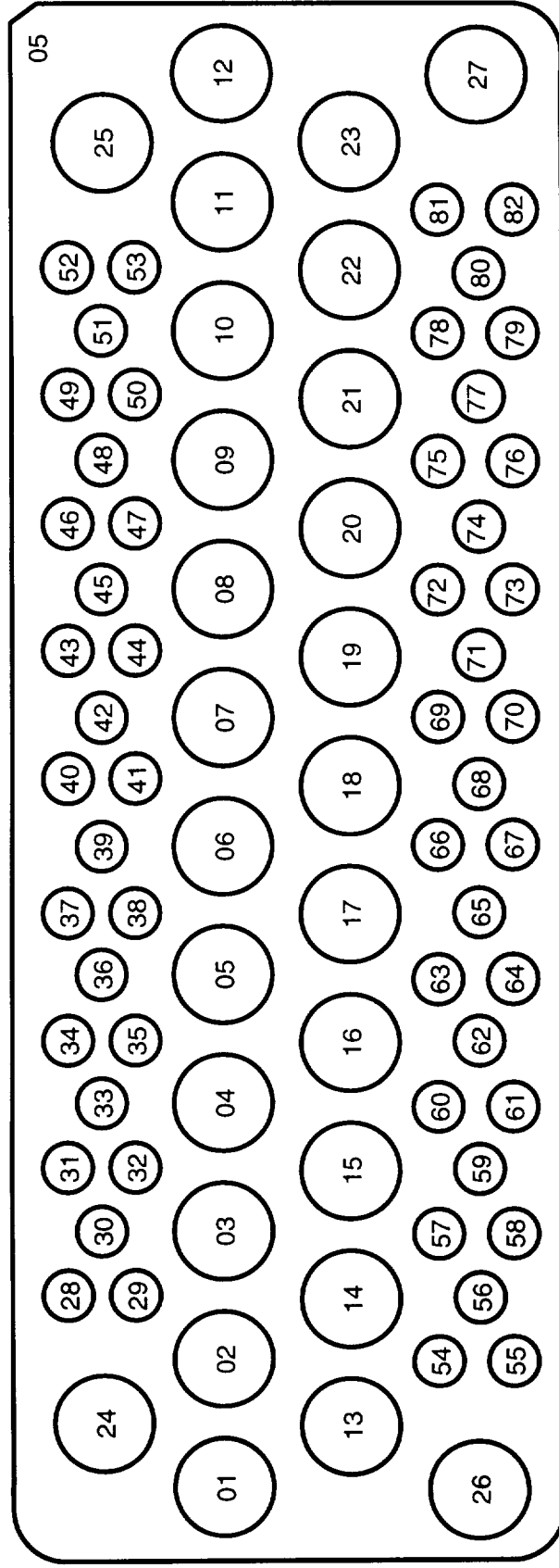


Figure 1b. EOIM-III Sample Carrier Viewed in the Inverted (Loading) Position

The passive trays were not temperature controlled, however, other trays were. Among these passive trays, the one indicated as N-5 was provided by the Materials Engineering Branch of GSFC. It included 49 samples prepared by GSFC, 27 by GE-Astro, 4 by IITRI and 2 by Martin Marietta. The samples consisted of thermal control paints, films, coatings and other assembly and construction materials. This report will cover only the samples prepared by GSFC (Table 1), since the guest samples were returned for analyses to their respective organizations. Of the GSFC samples, film samples are not reported in this paper, as they were reported in another document, NASA TM-104621. The analyses were carried out to evaluate the effects that the oxygen flux, in conjunction with UV radiation, ionizing radiation, thermal cycling, plasma interaction and micrometeoroid/debris, have on materials used for or proposed for space applications. These types of environments, especially Atomic Oxygen (ATOX) modified by orbit altitude, spacecraft inclination and by instruments' orientation, have been shown by many flight experiments to degrade materials and S/C performances. The characterization of those effects consists of the evaluation of the exposed material thermo-optical properties, its surface erosion and/or the rates of changes of those parameters.

## **2.0 Experimental**

The STS-46 Atlantis flew at an altitude of 228-230km (123-124 miles) with an orbital inclination of 28°. The trays and other experiments were exposed for 58 hours. The materials oriented for normal incidence were exposed to average fluxes of  $1.5 \times 10^{15} \text{ cm}^{-2} \text{ s}^{-1}$  consisting mainly of O, N<sub>2</sub>, O<sub>2</sub> and H. The temperature was passively controlled and with some exceptions, it ranged between 15°C and 40°C. The

atomic oxygen fluence was  $2.07 \times 10^{20} \text{ atoms/cm}^2$ . The fluence was reported to be in agreement with a fluence based on the Kapton erosion and its reaction efficiency (ref. 1).

Table 2 shows the solar UV spectral incidence (as reported in ref.2) experienced during flight.

**Table 2. Cumulative Solar Ultraviolet Spectral Incidence**

Wavelength, nm	Cumulative incidence, J/cm <sup>2</sup>
250-200	22.4
200-150	1.10
150-119	0.128
121.5	0.103
119-10	0.04

The samples listed in Table 1, were vacuum baked at 65°C for 48 hours previous to the flight. The mass of those samples were recorded at that time. An additional mass measurement was carried out near the flight date. On return from flight, the samples were reweighed. An additional mass measurement of the samples was carried out after exposure to a vacuum for 48 hours at 20°C. This last measurement was performed to eliminate any contaminants which may have been deposited on the samples from the time of landing. The mass loss in orbit was then assumed to be the difference from the mass measured nearest to the launch time and the mass measured after the last vacuum exposure at 20°C.

The results are shown in Table 3. Based on the mass loss and the fluence, a reaction efficiency has been calculated. It should be noted that the samples have been protected in a container against possible contamination.

Table 1. Materials List

ID NO.	MATERIALS	CHEMICAL TYPE	USES	PHOTO	REFLEC-TANCE	PAGE NO.
SP-1	CV-1144-0 Silicone on Delrin	Dimethyl Diphenyl Silicone Copolymer	Atomic Oxygen Protective Overcoat	Fig. 2	Fig. 3	Page 36
SP-2	CV-2500 Silicone on Delrin	Dimethyl Silicone	Encapsulant, Coating, Adhesive	Fig. 4	Fig. 5	Page 37
SP-3	Delrin II 900	Crystalline Thermoplastic homopolymer	Multicavity Molds	Fig. 6	Fig. 7	Page 38
SP-4	Epoxy Fiberglass G-11 (Flame Retardant)	Epoxy	Electrical Insulator, Structural	Fig. 8	Fig. 9	Page 39
SP-5	Epoxy Fiberglass G-11 (No Flame Retardant)	Epoxy	Electrical Insulator, Structural	Fig. 10	Fig. 11	Page 40
W-22	CV-1144-0 Silicone on Silver Coated Teflon	Dimethyl Diphenyl Silicone Copolymer	Atomic Oxygen Protective Overcoat	Fig. 12	Fig. 13	Page 41
W-23	CV-2500 Silicone on Ag Coated Teflon	Dimethyl Silicone	Encapsulant, Coating, Adhesive	Fig. 14	Fig. 15	Page 42
W-24	Teflon with Silver Coated Backing	Tetrafluoroethylene/hexafluoropropylene	Thermal Coating Material	Fig. 16	Fig. 17	Page 43
W-25	Silver Coated Teflon with Center Hole Cut-out	Tetrafluoroethylene/hexafluoropropylene	Thermal Coating Material	Fig. 18	Fig. 19	Page 44
W-26	CV-1144-0 Clear Silicone Coating on Kapton H Film	Dimethyl Diphenyl Silicone Copolymer	Atomic Oxygen Protective Overcoat	Fig. 20	Fig. 21	Page 45
W-27	CV-1142 Silicone Coating on Aluminum	Phenyl Silicone Polymer	Sealing, Caulking, Adhesive	Fig. 22	Fig. 23	Page 46
W-28	CV-1500 Black Silicone on Aluminum	Phenyl Silicone Polymer	R.F. And EMI Shielding, Adhesive	Fig. 24	Fig. 25	Page 47
W-29	CV-2566 Red Silicone on Aluminum	Diphenyl Dimethyl Silicone Copolymer	Sealing, Potting, Encapsulant, Adhesive	Fig. 26	Fig. 27	Page 48
X-11	X389-7 Beta Cloth on Aluminum Backing	Glass Fabric/Teflon (PTFE) Aluminum	Protective Sheet/Curtains	Fig. 28	Fig. 29	Page 49
X-12	CV-1144-0 Silicone on X389-7 Beta Cloth	Dimethyl Diphenyl Silicone Copolymer	Atomic Oxygen Protective Overcoat	Fig. 30	Fig. 31	Page 50

Table 1. Materials List (cont.)

ID NO.	MATERIALS	CHEMICAL TYPE	USES	PHOTO	REFLECTION	PAGE NO.
X-13	Chemglaze Z306 Black Paint	Polyurethane	Black Paint	Fig. 32	Fig. 33	Page 51
X-35	Uitem-1000	Polyetherimide	Flexible Circuits, Cable and Wire Wrap	Fig. 34	Fig. 35	Page 52
X-36	PEEK 450G	Polyetheretherketone	Advanced Composites in Aircraft	Fig. 36	Fig. 37	Page 53
X-38	CV-2500 Silicone on Kapton H Film	Dimethyl Silicone	Encapsulant, Coating, Adhesive	Fig. 38	Fig. 39	Page 54
X-40	Polyethersulfone 4800-G (PES)	Polyethersulfone	Medical Applications, Thermal Sensors	Fig. 40	Fig. 41	Page 55
X-42	TPX Film	Polymethylpentene	Barrier Film, High Temperature Packaging, Ultra Sound Equipment	Fig. 42	Fig. 43	Page 56
X-50	3M, Pressure Sensitive Tape No. 5	Polyester/Acrylic Adhesive	Electrical Insulation	Fig. 44	Fig. 45	Page 57
X-66	Uralane 5750 LV-A/B	Polyurethane	Conformal Coating	Fig. 46	Fig. 47	Page 58
X-67	Uralane 5753 LV-A/B	Polyurethane	Potting, Encapsulate, Adhesive	Fig. 48	Fig. 49	Page 59
X-68	Epon 828/Versamid 140/TiO <sub>2</sub>	Epoxy	Torque Stripping, Adhesive	Fig. 50	Fig. 51	Page 60
X-69	Aluminized Beta Cloth X389-7 (Aluminized Exposed)	Glass Fabric/Teflon (PTFE) Aluminum	Protective Sheet/Curtain	Fig. 52	Fig. 53	Page 61

### MATERIAL SOURCES

TPX is a registered trademark of MITSUBISHI

Petrochemical Indiana, Ltd.

ULTEM is a registered trademark of G.E. Co.

VICTREX PES and PEEK are of ICI, Ltd.

TEFLON, KAPTON, and DELRIN are products of DUPONT Co.

CV-SILICONES are products of NUSIL Technology

CHEMGLAZES are products of LORD Industrial Coatings

Beta Cloths are a product of OAK Material Group, Inc.

No. 5 Tape is a product of 3M Co.

URALANE a product of Ciba-Geigy Corp.

EPON 828 is a product of Shell Chemical Co.

VERSAMID 140 is a product of Henkel Corp.

Table 3. Summary of Polymers Reaction Efficiencies

MATERIAL	REACTION RATE BASED ON TOTAL SAMPLE AREA g/ATOM	REACTION RATE BASED ON EXPOSED AREA g/ATOM	THERMO-OPTICAL PROPERTIES					DENSITY g/cm <sup>3</sup> (APPROX.) (3)
			REFLECT-ANCE	ABSORP-TION	ABSORP-TION	% Δ (ABSORP) (4)	EMITTANCE (1)	
CV-2500 Silicone on Silver Coated Teflon	1.561 E-26	1.132 E-25	Fig. 15	0.692	0.714	3.18	885-NA	1.04
X389-7 Beta Cloth on Aluminum Backing	1.004 E-25	1.549 E-25	Fig. 29	0.277	0.281	1.44	0.873-0.906	—
Teflon with Ag Coated Backing	1.779 E-25	2.741 E-25	Fig. 17	0.065	0.112	—	0.793-0.808	—
Uralane 5753 LV-A/B	1.862 E-25	2.860 E-25	Fig. 49	0.612	0.651	6.37	0.880-0.912	1.0
CV-1144-0 Silicone on X389-7 Beta Cloth	2.033 E-25	3.158 E-25	Fig. 31	0.410	0.459	11.9	0.908-0.922	1.01
Epoxy Fiberglass, G-11, Flame Retardant	3.892 E-25	5.958 E-25	Fig. 9	0.643	0.657	2.17	0.906-0.903	—
Uralane 5750 LV-A/B	5.734 E-25	8.818 E-25	Fig. 47	0.558	0.648	16.12	0.843-0.878	0.96
CV-1144-0 Silicone on Silver Coated Teflon	6.427 E-25	9.831 E-25	Fig. 13	0.730	0.749	2.60	0.896-0.909	1.01
Epon 828/Versamide 140/TiO <sub>2</sub>	6.382 E-25	9.831 E-25	Fig. 51	0.212	0.289	36.3	0.905-0.898	—
CV-1142 Silicone Coating on Aluminum	8.432 E-25	1.299 E-24	Fig. 23	0.564	0.592	4.96	0.888-0.998	1.12
Chem Glaze Z-306 Black Paint	1.260 E-24	1.978 E-24	Fig. 33	0.959	0.981	2.29	0.912-0.914	0.95
CV-2500 Silicone on Kapton-H Film	1.162 E-24	1.805 E-24	Fig. 39	0.661	0.655	-0.90	0.921-0.914	1.04
CV-1500 Black Silicone on Aluminum	1.204 E-24	2.234 E-24	Fig. 25	0.931	0.927	-0.43	0.880-NA	1.24
CV-2566 Red Silicone on Aluminum	1.454 E-24	2.240 E-24	Fig. 27	0.679	0.695	2.35	0.899-0.904	1.50

Table 3. Summary of Polymers Reaction Efficiencies (cont.)

MATERIAL	REACTION RATE BASED ON TOTAL SAMPLE AREA g/ATOM	REACTION RATE BASED ON EXPOSED AREA g/ATOM	THERMO-OPTICAL PROPERTIES				DENSITY g/cm <sup>3</sup> (APPROX.) (3)
			REFLECT-ANCE	ABSORP-TION	ABSORP-TION	% Δ (ABSORP) (4)	EMITTANCE (1)
CV-2500 Silicone on Delrin II 900 NC	1.508 E-24	2.276 E-24	Fig. 5	0.394	0.466	18.27	0.929-0.920
CV-1144-0 Clear Silicone Coating on Kapton-H Film	1.727 E-24	2.657 E-24	Fig. 21	0.758	0.769	1.45	0.882-0.914
CV-1144 Silicone on Delrin II 900 NC (2)	+2.896 E-24	+4.355 E-24	Fig. 3	0.401	0.492	22.6	0.926-0.912
Polymethylpentene (TPX) Film	3.247 E-24	5.011 E-24	Fig. 43	0.489	0.540	10.42	0.856-0.873
Polyethersulfone 4800 G (PES)	3.622 E-24	5.607 E-24	Fig. 41	0.539	0.619	16.35	0.889-0.895
PEEK 450 G	3.732 E-24	5.785 E-24	Fig. 37	0.617	0.681	12.96	0.880-0.894
3M Pressure Sensitive Tape No. 5	4.108 E-24	6.328 E-24	Fig. 45	0.434	0.523	20.50	0.735-0.751
UItem-1000	4.454 E-24	6.894 E-24	Fig. 33	0.596	0.659	10.57	0.897-0.899
Delrin II 900	1.198 E-23	1.790 E-23	Fig. 7	0.384	0.403	4.94	0.910-0.895
Silver Coated Teflon with Center Hole Cut-out	7.761 E-24	1.189 E-23	Fig. 19	0.550	0.546	0.72	0.059-0.062
Aluminum Beta Cloth X389-7 (Aluminized Exposed) (2)	+4.605 E-26	+7.150 E-26	Fig. 53	0.263	0.266	1.14	0.125-0.125
Epoxy Fiberglass G11, No Flame Retardant (2)	+2.665 E-24	+4.023 E-24	Fig. 11	0.692	0.720	4.04	0.910-0.908



### NOTES FOR TABLE 3

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Fluence: 2.07 E20 atoms/cm<sup>2</sup>

FLIGHT: STS-46 Atlantis

ORBIT: 228–230 km, 28° Inclination

Sample Area: 1.2449 cm<sup>2</sup>

Sample Area: 0.8107 cm<sup>2</sup> (Exposed)

(1) Control Sample Emittance: The two indicated values of the control (not flight sample) were measured at different times as indicated on the reflectance plots. The samples were maintained in a clean closed container held at ambient conditions. The flight sample emittance could not be measured because of the measuring instrument's limitations for holding the small flight samples.

(2) These samples indicated a mass increase following the flight exposure. The nature of the mass increase has not been explored. It could be attributed to increases of oxygen or contamination.

(3) The densities' values are obtained from manufactures' data or from literature. The actual values for the tested coatings may be different due to their preparations, their coating layering and/or air inclusions. They are included so that they may be used, if desired, to obtain reaction efficiency in terms of eroded volume, cm<sup>3</sup>/atom.

(4) The percent change of the absorptance is affected by the thickness of the coating and the backing materials.

As a reference, the commonly agreed oxygen reaction rate for Kapton is  $4.26 \times 10^{-24}$  g/atom or  $3 \times 10^{-24}$  cm<sup>3</sup>/atom.

The characterization of each sample is indicated in the following pages, and it includes: the sample descriptions, the measurements taken, and the exposed sample analyses.

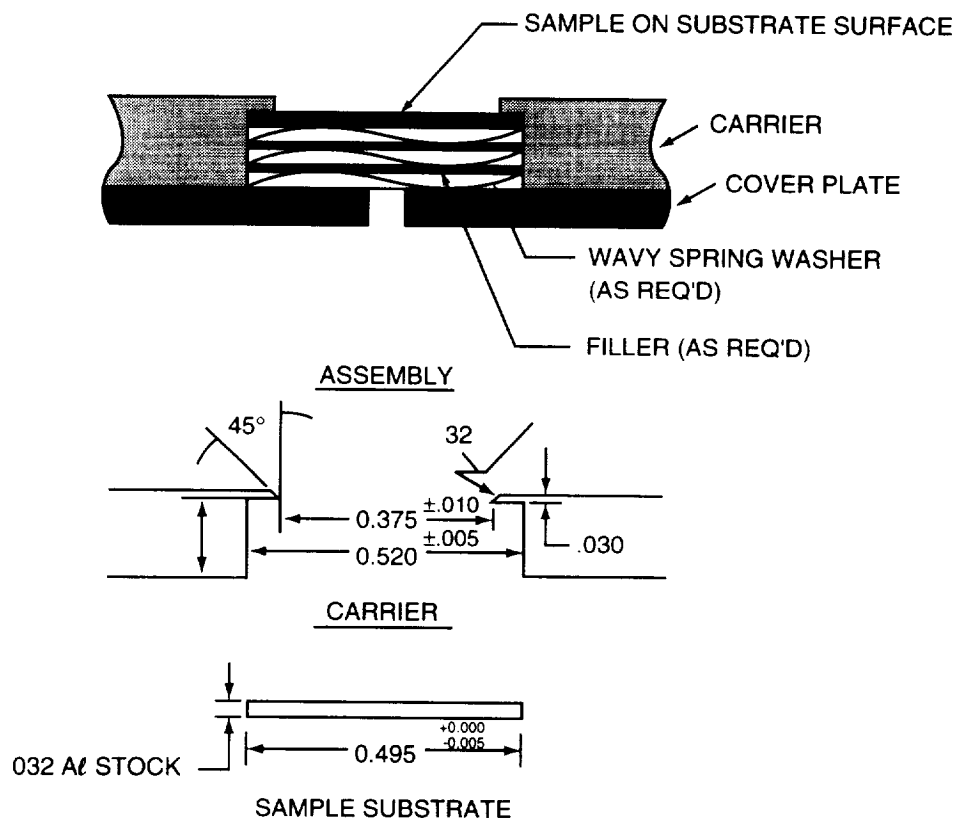
The samples were prepared and mounted in accordance with the sketch below. In general, the sample material was applied to an aluminum substrate either directly or with an adhesive, or the sample was simply supported in the receptacle. These samples were then assembled and held in place as shown in the aluminum tray, Figure 1b. The samples were partially shielded and held in place with the aluminum cover, as shown in Figure 1c below.

## 2.1 Data and Measurements Taken

The effect of the space environment on the samples is indicated by providing the following descriptive parameters.

The sample weight loss (g): this is the difference between the weight of the samples before and after the flight missions.

Comparisons of the spectral reflectance, the integrated absorption and emittance of the coatings, before and after space environment exposure were made. These were measured using the Perkin Elmer (P.E.)  $\lambda$ -9 spectrophotometer.



NOTE: THE DIMENSION ARE IN INCHES

Figure 1c. Sample Carrier Assembly

The Electron Spectroscopy of Chemical Analysis (ESCA/XPS) was used as part of the surface analysis to determine elemental and chemical composition of the samples within a depth of 100 Å (up to some 50 monolayers) employing x-rays to emit photoelectrons.

Photographic and microscopic documentation shows the reference and flight surface appearances and related evaluation of the changes that may have occurred following space exposure.

### **3.0 Sample Descriptions and Flight Results**

The figure number indicated with the sample title refers to the pictorial view of the flight control sample.

#### **3.1 CV-1144-0 Silicone Coating on Delrin II (Figure 2)**

##### *Sample Description*

This sample is made of a one part, diethyl silicone copolymer dispersion overcoat specifically designed for atomic oxygen surface protection. The silicone has low outgassing, and excellent adhesive properties. It contains a thinner and is ready for use as-received for brush, dipping, and spraying application.

##### *Sample Configuration*

The silicone sample thickness was 0.30988 cm and its mass was 0.04610 grams. The Delrin was self supporting and was not attached to a substrate. The silicone was applied directly to the Delrin surface by brush and properly cured.

##### *Visual Inspection*

The shielded area of this exposed sample is white and shiny and the outer edge is recessed. The exposed area is yellowed, raised, and pitted. There is an oval spot near the center that is not as shiny as the rest of the area.

##### *High Magnification Inspection*

The sample shows a faint yellowing when compared to the control. This point is too subtle to document. Cracks, especially near the edge of the material, are evident. Those cracks get finer towards the center of the sample. Possible particle impact areas exist. The control sample, on the other hand, is transparent and no yellowing or cracking is visible.

##### *ESCA Analysis*

The sample is a Delrin II 900 NC10 with a CV-1144-0 silicone over coating. The control specimen contains carbon, oxygen, and silicon. The chemical states of carbon and silicon correspond to the silicone. The flight specimen does not indicate any change in chemical composition. The same elemental composition, as well as the identical chemical states, were detected on the flight specimen as the control specimen.

##### *Radiative Properties*

The loss of reflectance is shown in Figure 3. The absorptivity changed from 0.401 to 0.492. The emissivity as measured on the control sample was 0.926 - 0.912. The emissivity for the pre- and post- flight sample are not reported since the sample could not be fitted in the available spectrophotometer.

##### *Physical Analysis*

The mass gained by the sample was  $7.3 \times 10^{-4}$  g. The percent of the mass change when attributed to the coating was estimated to be 0.1280.

##### *Oxygen Erosion*

The reaction rate based on the above mass gained, the fluence of  $2.07 \times 10^{+20}$  atom/cm<sup>2</sup> and the exposed area of 0.81073 cm<sup>2</sup> is 4.355 E-24 g/atom. This is a negative reaction rate, i.e., a gain of mass as a function of atoms impingement.

### **3.2 CV-2500 Silicone Coat On Delrin (Figure 4)**

#### *Sample Description*

This sample is a two component, clear, CV-2500 silicone overcoat for surface protection from extreme environmental conditions. It has excellent low outgassing, and is commonly used for protection of electronic assemblies and components. It is also usable as an adhesive in low strength applications.

#### *Sample Configuration*

The thickness of the silicone was 0.37084 cm and its mass was 0.29302 grams. The silicone was applied directly to the surface of the Delrin by brush and properly cured.

#### *Visual Inspection*

The CV-2500 silicone coating on Delrin on the shielded area of the flight sample was compressed and smooth. The exposed area, on the other hand, was discolored (yellow) and shiny. Low magnification of the sample showed evidence of cracking.

#### *High Magnification Inspection*

The high magnification showed more visible cracking.

#### *ESCA Analysis*

This sample is a CV-2500 silicone coating on a Delrin II NC900 substrate. There is no chemical change in the CV-2500 silicone coating as a result of the space exposure. Both samples, the flight and the control, indicate similar composition on the surface and contain C, O and Si. The binding energies of the Si and O peaks match the binding energy values of silicone. The control sample contained, in addition to silicone, some SiO<sub>2</sub>.

#### *Radiative Properties*

The absorptance of the coating changed from 0.394 to 0.466 and the emittance of the con-

trol sample was 0.929 with an eventual change with time to 0.920. The reflectance in Figure 5 shows changes in the range of 400 to 1000 nm and from 1700 to 2400 nm.

#### *Physical Analysis*

The mass loss of the sample was  $3.82 \times 10^{-4}$  g which attributed to the coating, corresponds to a coating percentage loss of 0.224.

#### *Oxygen Erosion*

The oxygen reaction rate based on the above mass loss, the oxygen fluence and the exposed sample area of 0.81073 cm<sup>2</sup> is  $2.276 \times 10^{-24}$  g/atom.

### **3.3 Delrin II 900 (Figure 6)**

#### *Sample Description*

Delrin II is an acetyl homopolymer crystalline injection molding resin having excellent stiffness, tensile strength, and creep resistance under a wide range of temperature and humidity conditions.

#### *Sample Configuration*

The thickness of the sample was 0.33553 cm and its mass was 0.55317 grams. The Delrin sample was attached directly to the surface of an aluminum carrier disk with a pressure sensitive transfer adhesive.

#### *Visual Inspection*

The shielded area of the Delrin 900 NC 10 was depressed and smooth. The exposed area was raised and soft.

#### *High Magnification Inspection*

The Delrin exposed area was smoother than the protected area.

#### *ESCA Analysis*

The control specimen of the structural polymer called Delrin II 900 NC10 has carbon, oxygen, and a small amount of fluorine. The 67% of

carbon is in C=O bond, and 33% is in C-(H,C) bonds. The flight specimen, on the other hand, has carbon, oxygen, silicon and a trace amount of chlorine. The silicon, fluorine and chlorine appear to be surface contaminants. The chemical state of carbon on the flight specimen consists of 59% of C=O, 19% C-O, 22% C-(H,C) bonds.

#### *Radiative Properties*

The reflectance of this sample is shown in Figure 7. Loss of reflectance occurred in the 400-700 nm wavelengths, with a few percentage losses in the range beyond 1000 nm. The absorptance changed from .384 to .403. The emittance of the control was .910 and with time became .895.

#### *Physical Analysis*

The mass loss was  $3.0 \times 10^{-3}$  g of the total.

#### *Oxygen Erosion*

The oxygen reaction rate based on the weight loss, the exposed area and the fluence of  $2.07 \times 10^{20}$  was  $1.7905 \times 10^{-23}$  g/atom.

### **3.4 Epoxy Fiberglass, G-11, with a Flame Retardant (Figure 8)**

#### *Sample Description*

The G-11 epoxy fiberglass was a reinforced laminate product of multi-layers of a continuous filament of glass fabric, impregnated with a ther-

mosetting epoxy resin binder. The G-11 is similar in all properties to the grade G-11 non-flame resistant, but is formulated to have at least a V-1 classification when tested to UL 94.

#### *Sample Configuration*

The thickness of the G-11 epoxy fiberglass was 0.15011 cm, and its mass was 0.33968 grams. The sample was self supporting and not attached to a substrate.

#### *Visual Inspection*

The shielded area of the sample is tan/yellow, uniformly textured (not smooth) and slightly reflective. The exposed area was darker, less reflective, white with a regular pattern which is clearly visible within the sample.

#### *High Magnification Inspection*

The exposed region is darker and appears smoother than the shielded part.

#### *ESCA Analysis*

The sample is a composite used for structural purposes. The flight specimen showed a few damaged areas where the surfaces had been scratched. The scratched area, and the unaffected area on the flight specimen, as well as the control specimen, were analyzed. The elemental compositions and the chemical state of carbon of these three areas are listed in the table below. The atomic percents listed in the table are approximate numbers.

Elemental Composition and the Chemical States of Carbon in the G-11 Epoxy Fiberglass			
Elements	Control	Scratched Area (Flight)	Unaffected Area (Flight)
C	82 atom %	61 atom %	67 atom %
O	12	31	26
N	-	2	2
Si	5	5	3
Br	0.3	-	1.6
Sb	-	1	-
Bonding States	Control	Scratched Area	Unaffected Area
O-C=O	-	35%	-
C=O	49%	31%	23%
C-O	-	19%	39%
C-(H,C)	51%	15%	38%

The presence of antimony on the scratched area suggests that the surface was damaged with a substance that contained antimony.

#### *Radiative Properties*

Figure 9 shows that there was some small improvement in the reflectance of the sample. The absorptance changed from 0.643 to 0.657. The emittance of the control was .906 and later was 0.903.

#### *Physical Analysis*

The epoxy fiberglass mass loss was  $1.0 \times 10^{-4}$  g.

#### *Oxygen Erosion*

The reaction rate computed for this sample was  $5.958\text{E-}25$  g/atom.

### **3.5 Epoxy Fiberglass, G-11, with No Flame Retardant (Figure 10)**

#### *Sample Description*

The G-11 epoxy fiberglass was a reinforced laminated product of multi-layers of a continuous filament glass cloth which has been impregnated with a thermosetting epoxy resin binder. This product was laminated under high pressure and temperature to form a dense solid product capable of having good mechanical and electrical properties. It has no flame retardant properties.

#### *Sample Configuration*

The thickness of the G-11 epoxy fiberglass was 0.18288 cm and the mass of the sample was 0.33570g. The sample was self supporting and was not attached to a substrate.

#### *Visual Inspection*

The shielded area of the epoxy fiberglass is dull and pale mustard in color. The exposed area was "velvety" with a mustard color.

#### *High Magnification Inspection*

The sample exposed surface is smoother and darker than the shielded area.

#### *ESCA Analysis*

This sample is a G11 epoxy fiberglass structural polymer. The control specimen has carbon, oxygen, nitrogen, silicon, fluorine, and trace amounts of chlorine and sulfur. The carbon on the control specimen is in C-(H,C), C-O, C-F bonds. The flight specimen has all the elements in the control specimen except chlorine. There was more oxygen and less carbon on the flight specimen than the control specimen. Furthermore, no C-F bonds were detected on the flight specimen. Only the C-(H-C) and C-O bonds were detected.

The increase in oxygen concentration and the absence of C-F bonds indicate the chemical change that occurred on the exposed surface.

#### *Radiative Properties*

Figure 11 of the sample reflectance shows that with the exception of a loss of reflectance in the 400-650 nm region, the sample developed a slightly improved reflectance. The absorptance changed from 0.692 to 0.720 and the control emittance was 0.910 and later 0.908.

#### *Physical Analysis*

This sample showed a mass increase of  $6.87 \times 10^{-4}$  g.

#### *Oxygen Erosion*

Based on the mass increase of the sample, a negative reaction rate of  $4.023 \times 10^{-24}$  g/atom can be calculated. The increase does not appear to be resulting from contamination.

### **3.6 CV-1144-0 Silicone on Silver Coated Teflon (Figure 12)**

#### *Sample Description*

This sample was a one part diethyl silicone copolymer dispersion applied over a Teflon (FEP) surface. This silicone was specially designed and processed for atomic oxygen resistance in space applications and has an extremely low outgassing property. The CV-1144-0 was prepared by the manufacturer as a RTV dispersion in a thinner for application by brush, dipping, or spray.

#### *Sample Configuration*

The thickness of the sample was 0.17754 cm and its mass, 0.10883 grams. The silver Teflon (FEP) was attached to an aluminum carrier disk with a pressure sensitive transfer adhesive. The silicone on Silver was exposed to the environment.

#### *Visual Inspection*

The exposed material is transparent and shiny. The shielded area is clear. At the intersection of the shielded and exposed area, the coating is less reflective (flat appearance). The exposed area is tinted a faint yellow and is raised and slightly convex.

#### *High Magnification Inspection*

Networks of cracks are visible at the edges of the exposed area. Some large individual cracks extend toward the center. Fine cracks in the center are visible at high magnification.

#### *ESCA Analysis*

This is a silverized Teflon (FEP) with CV-1144-0 overcoating. The silver side had been exposed to the oxygen erosion. Both the control and the flight specimens contain carbon, oxygen, and silicon. The concentrations of each element were approximately the same and the chemical states of carbon were the same on

both specimens. This indicated that the exposure to space has no effect on the silver side.

#### *Radiative Properties*

The reflectance versus wavelength are shown in Figure 13. The exposed material shows a slight loss of reflectance. The integrated absorbance changed from 0.730 to 0.749. The control sample emittance prior to flight was 0.896.

#### *Physical Analysis*

The mass loss of the sample was 0.00016 g. The percentage of change when attributed to the coating was 0.0089.

#### *Oxygen Erosion*

The reaction rate based on the above mass loss, the AO fluence of  $2.07 \times 10^{20}$  atom/cm<sup>2</sup> is  $9.8318 \times 10^{-25}$  g/atom.

### **3.7 CV-2500 Silicone on Silver Coated Teflon (Figure 14)**

#### *Sample Description*

This sample was a clear, two component CV-2500 silicone applied over a silver coated Teflon (FEP) surface by brush. This silicone has extreme low outgassing properties and is used as an embedding or potting compound where good environmental protection for electronic assemblies and components is essential.

#### *Sample Configuration*

The thickness of the sample coating was 0.13716 cm and its mass was 0.07331 grams. The Teflon (FEP) film was attached to an aluminum carrier disk with a pressure sensitive transfer adhesive. The silver side was exposed to the environment.

#### *Visual Inspection*

The coating over the silver was transparent, shiny and reflective. The shielded area was a recessed, impressed line at an interface between

the shielded and the exposed areas. Approximately 1/4 x 1/4 cm chip of coating was missing (half from exposed area and half from shielded area). The exposed area was raised and slightly convex.

#### *High Magnification Inspection*

A visible crack in the surface of the exposed area was more pronounced at the outer edges. A break in the surface coating was exposed on the subsurface layer; this exposure was in the shielded region.

#### *ESCA Analysis*

This sample consists of a silver Teflon (FEP) with CV-2500 silicone coating. The elemental compositions of the control and the flight specimens are carbon, oxygen, and silicon. The concentrations of each element were the same and the chemical states of carbon were the same on both specimens. This indicates that the exposure to space has no chemical effect on the surface of the silver Teflon.

#### *Radiative Properties*

The reflectance versus wavelength is shown in Figure (15). A slight loss of about 2-3% occurred throughout the scanned wavelengths. The absorptance increased from 0.692 to 0.714. The emittance of the control sample was 0.885.

#### *Physical Analysis*

The mass loss of the sample was  $1.9 \times 10^{-5}$  g. The percentage of mass change attributed to the coating was 0.0131.

#### *Oxygen Erosion*

The reaction rate based on the above mass loss, the fluence of  $2.07 \times 10^{20}$  and the sample's exposed area of  $0.81072 \text{ cm}^2$  is  $1.1325 \times 10^{-25}$  g/atom.

### **3.8 Teflon with Silver Coated Backing (Figure 16)**

#### *Sample Description*

This sample is a Teflon (FEP) film with a vapor deposited silver coating on one surface.

#### *Sample Configuration*

The thickness of the sample is 0.107188 cm and its mass is 0.04860 grams. The Teflon (FEP) sample was attached to an aluminum carrier disk with a pressure sensitive transfer adhesive. The Teflon (FEP) film was exposed to the environment.

#### *Visual Inspection*

The sample is reflective. The intersection of shielded and exposed areas is recessed and scratched.

#### *High Magnification Inspection*

There is no difference between the shielded area and the control sample.

#### *ESCA Analysis*

The sample is a silver Teflon (FEP) film with the Teflon side up. The control specimen has carbon and fluorine. The control specimen consists of mostly  $[-\text{CF}_2 - \text{CF}_2-]$  bonds that are typical of Teflon surfaces. The flight specimen which contains carbon, oxygen and fluorine, shows some conversion of the  $[-\text{CF}_2 - \text{CF}_2-]$  bonds to  $[-\text{CF}_2 - \text{CFH}-]$  bonds.

#### *Radiative Properties*

The reflectance versus wavelength is shown in Figure 17. The reflectance changed less than 6 percent from 600 to 2400 nm. The absorptance changed from 0.065 to 0.112. The emittance of the control sample was 0.793 originally and changed to 0.808.



### *Physical Analysis*

The mass loss is  $4.6 \times 10^{-5}$  g. The change of the coating mass was estimated at about 0.00288 percent.

### *Oxygen Erosion*

The oxygen reaction rate based on the given fluence, and the sample exposed area of  $0.81073 \text{ cm}^2$  is  $2.7410 \times 10^{-25}$  g/atom.

### **3.9 Silver Coated Teflon (with center hole cut-out) (Figure 18)**

#### *Sample Description*

The silver coated Teflon (FEP) is a copolymer film. This sample has a center hole cut out configuration for atomic oxygen effects on the surface edges.

#### *Sample Configuration*

The thickness of the sample was 0.10795 cm and its mass was 0.04252 grams. The sample was attached to an aluminum carrier disk with an acrylic transfer adhesive. The silver surface was exposed to the environment.

### *Visual Inspection*

The interface between shielded and exposed areas has a line, which is scratched and recessed. The exposed area is slightly yellowed. A 1/2 cm diameter "hole" is cut at the center of the sample.

### *High Magnification Inspection*

The sample shows cracks around the 1/2 cm diameter hole.

Spherical regions ringing the cracks are only in the exposed region. At high magnification the cracks appear superficial with possible deposits. Color of sample in these regions changes from black to blue and then to tan.

### *ESCA Analysis*

The sample is a silver Teflon with the silver side up. This specimen has a 1/2 cm hole in the center to study the edge effects near the opening. Three areas were analyzed: the control specimen, near the inner edge on the flight specimen, and away from the edge on the flight specimen. The elemental compositions of the three analyzed areas are as shown in Table 4 below.

**Table 4. Elemental Composition of the Three Areas Analyzed on the Control and Flight Samples**

Elements	Control Sample	Flown Sample Near Edge	Flown Sample Away from Edge
C	80 atomic %	51 atomic %	54 atomic %
O	17	20	18
N	2	—	12
Ag	0.4	10	6
Ni	1	3	3
Si	—	8	4
F	—	2	1
S	—	4	2
Cl	—	4	1

To determine whether the fluorine found on the flight specimen is a surface contaminant or from the Teflon layer that is below the exposed silver surface, the two areas on the flight specimen were sputter etched. After the surfaces were sputter etched, the fluorine concentration increased by five times. This proves that the Teflon layer which was underneath the silver is very near the surface due to the erosion of the silver layer. Thus, we can conclude that the atomic oxygen eroded the silver, and this erosion is accelerated near the edge.

#### *Radiative Properties*

The reflectance vs. wavelength is shown in Figure 19. The reflectance was changed to less than 1 % from about 700 to 2400 nm while an increase of the same amount is shown below 700nm. The absorptance changed from 0.550 to 0.546. The emittance of the control sample was 0.059 to 0.062.

#### *Physical Analysis*

The mass loss was 0.00199g. The percentage of mass change, based on the coating was about 0.435.

#### *Oxygen Erosion*

The reaction rate based on the known fluence, and the exposed area of  $1.2429 \text{ cm}^2$  is  $1.189 \times 10^{-23} \text{ g/atom}$ .

### **3.10 CV-1144-0 Clear Silicone on Kapton H Film (Figure 20)**

#### *Sample Description*

The Kapton H, is a polyimide film, overcoated with a one part silicone material which is specifically designed to provide atomic oxygen protection to the Kapton surface. The CV-1144-0 silicone is a low outgassing dimethyl diphenyl silicone copolymer used for high and low temperature applications.

#### *Sample Configuration*

The silicone thickness on the Kapton surface was 0.17297 cm and its mass was 0.09347 grams. The Kapton was attached to an aluminum carrier disk by use of a pressure sensitive acrylic transfer adhesive. The silicone was brush coated to the Kapton and properly cured.

#### *Visual Inspection*

The surface is shiny and transparent. The shielded area is recessed at the edge. The exposed area is raised above the retained area. Tracks of raised and recessed areas exist between the substrate and coating.

#### *High Magnification Inspection*

A network of cracking was visible at the outer edge of the exposed area. Finer cracks were visible near the center.

#### *ESCA Analysis*

This is a Kapton H film with a CV-1144-0 silicone coating. The control specimen had carbon, oxygen, and silicon. The 59% of carbon is a C-O bond, and the remainder is 41% C-(H,C) bonds. The 34% of silicon is in a form of silicone, 42% is a  $\text{SiO}_x$ , and 24% is  $\text{SiO}_2$ .

The flight specimen has carbon, oxygen, silicon, nitrogen, and a trace amount of tin. The 80% of carbon is a C=O bond, and the remainder is 20% C-(H,C) bonds. The 26% of silicon is silicone, 56% is  $\text{SiO}_x$ , and 18% is  $\text{SiO}_2$ . This shows that some silicone on the surface of the flight material has oxidized to form oxides. The emerging nitrogen peak on the flight specimen corresponds to Kapton which is under the silicone coating. Thus, we can conclude that the atomic oxygen had oxidized some of the silicone and that the coating had been eroded.

#### *Radiative Properties*

Figure 21 shows the reflectance of the sample, small changes on the order of 1-2% have occurred as a result of the exposure throughout the range of the wavelengths. The absorptance changed from 0.758 to 0.769. The emittance of the control sample was originally 0.882 which increased to 0.914.

#### *Physical Analysis*

The mass loss of the sample was  $4.46 \times 10^{-4}$  g. The percentage of mass loss attributed to the coating is 0.1196.

#### *Oxygen Erosion*

The reaction rate, based on the given fluence, mass loss and the exposed area of  $0.8107 \text{ cm}^2$  is  $2.6575 \times 10^{-24}$  g/atom.

### **3.11 CV-1142 Silicone Coating on Aluminum (Figure 22)**

#### *Sample Description*

This is a one part phenyl silicone sealant. It is a non-corrosive, translucent, non-slumping, one part moisture cured material specially designed and processed for applications requiring extreme low temperatures, low outgassing and minimal volatile condensable. This silicone is usable for sealing, caulking, and is usable as an adhesive.

#### *Sample Configuration*

The thickness of the silicone was 0.15113 cm and its mass was 0.08847 g. The silicone was applied directly to an aluminum carrier disk and properly cured.

#### *Visual Inspection*

The sample surface is translucent and flat. The shielded area is clear. The exposed area is tinted and yellow/gray in color.

#### *High Magnification Inspection*

The sample surface is slightly discolored within the exposed area, which is barely visible at low magnification. This variation may be mostly due to linear marking at the edge of the supported region. High magnification shows no change from the exposed to shielded regions.

#### *ESCA Analysis*

The control specimen of the CV-1142 silicone coating contains carbon, oxygen, and silicon. The carbon on the surface contains C-(H,C) bonds, and the silicon is 100% in the form of silicone. The flight specimen has carbon, oxygen, silicon, and a trace amount of tin. The flight specimen has a lower carbon concentration and higher oxygen and silicone concentration than the control. The chemical state of carbon is the same as the control specimen, but the silicon has 56% Si-O as in silicone and 44% is  $\text{SiO}_2$ . This indicates that some of the silicone on the surface had been treated in space to form  $\text{SiO}_2$ .

#### *Radiative Properties*

The reflectance of the sample shown in Figure 23 indicates a change of the absorptance from 0.564 to 0.592. A change of about 15% occurred at the lower wavelengths. The emittance of the control was 0.888, which increased with time to 0.998.

#### *Physical Analysis*

The mass loss of the sample is  $2.18 \times 10^{-4}$  g. The loss attributed to the coating was about  $2.6 \times 10^{-3}$  percent.

#### *Oxygen Erosion*

The reaction rate, based on the exposed surface, was  $1.299 \times 10^{-24}$  g/atom.

### **3.12 CV-1500 Black Silicone on Aluminum (Figure 24)**

#### *Sample Description*

CV-1500 is a one part electrically conductive phenyl silicone. It is non-corrosive, black in color, non-slumping, and specially processed for applications requiring low temperatures and minimal volatile condensable under extreme conditions.

#### *Sample Configuration*

The thickness of the silicone sample was 0.24409 cm and its mass was 0.21290 g. The silicone was applied to the surface of an aluminum carrier disk and properly cured.

#### *Visual Inspections*

There were no visible differences between the shielded and the exposed areas.

#### *High Magnification Inspection*

The exposed region is similar to the shielded region with voids where the silicone was depleted.

#### *ESCA Analysis*

The sample is a black, electrically conductive silicone coating called CV-1500. This specimen showed identical behavior as the CV-1142 coating. The control specimen has carbon, oxygen, and silicon on its surface. The flight specimen had carbon, oxygen, silicon, and a trace amount of tin. The carbon concentration is lower and the oxygen and silicon concentrations are higher in the flight specimen than in the control specimen. While the carbon bonding state remains the same, the flight specimen shows more oxidized silicone than the control specimen.

#### *Radiative Properties*

Figure 25 shows the reflectance versus wavelength for this silicone coating sample. The absorptance changed from 0.931 to about

0.927. The reflectance remained below 10% throughout the shown wavelength spectrum. The emittance of the control was 0.880.

#### *Physical Analysis*

The mass loss of the sample was  $3.75 \times 10^{-4}$  g. If attributed to the coating, the percentage loss is  $3.56 \times 10^{-3}$ .

#### *Oxygen Erosion*

The reaction rate for the exposed area, based on the above loss, and fluence is  $2.23452 \times 10^{-24}$  g/atom.

### **3.13 CV-2566 Red Silicone on Aluminum (Figure 26)**

#### *Sample Description*

The CV-2566 silicone is a two part, flowable, red silicone specially processed for applications requiring low temperatures, low outgassing and minimal volatile condensables under extreme operating conditions. This silicone is based on a diphenyl dimethyl silicone used for sealing, encapsulation, and as an adhesive.

#### *Sample Configuration*

The thickness of the silicone was 0.25806 cm and its mass was 0.24561 g. The silicone was applied directly to the surface of an aluminum carrier disk and properly cured.

#### *Visual Inspection*

The color of CV-2566 was dark orange, shiny and opaque. The shielded area has a convex curvature. The exposed area is raised, sharply convex, and cloudy, but less cloudy at the interface between the exposed and the shielded areas.

#### *High Magnification Inspection*

The sample shows a crack network around the outside diameter of the exposed area. The central portion shows mud cracks across the exposed region.

#### *ESCA Analysis*

The control specimen of this CV-2566 coating had carbon, oxygen, silicon, and a small amount of fluorine. Since fluorine is not a constituent in the CV-2566 composition and it is present in a small amount, it is assumed to be a surface contaminant. The chemical states of carbon and silicon are typical of the silicone. The flight specimen had carbon, oxygen, and silicon. It also had the same chemical states of carbon and silicon. No chemical changes were detected on the flight specimen.

#### *Radiative Properties*

The absorptance of the coating changed from 0.679 to 0.695. The reflectance, as shown in Figure 27, changed throughout the wavelength by about one to two percent. The emittance of the control sample was 0.899 changing with time to 0.904.

#### *Physical Analysis*

The mass loss of the sample was  $3.76 \times 10^{-4}$  g and if attributed to the coating, the percentage loss of the coating was  $1.873 \times 10^{-3}$ .

#### *Oxygen Erosion*

The reaction rate of the coating, based on the fluence and exposed area, is calculated to be  $2.24048 \text{ E-}24 \text{ g/atom}$ .

### **3.14 X389-7 Beta Cloth on Aluminum Backing (Beta Cloth Exposed) (Figure 28)**

#### *Sample Description*

Beta cloth is tightly woven "beta" fiberglass fabric having a light sizing to provide flexibility. A Teflon (PTFE) coating is applied to one surface side of the fabric to provide abrasion resistance and to meet non-combustible properties for an oxygen atmosphere. The other side of the beta fabric has been coated with a layer of vapor deposited aluminum for thermal stability. The material is used in applications for ESD and for thermal control.

#### *Sample Configuration*

The thickness of the beta cloth was 0.10972 cm and its mass was 0.04583 g. The beta cloth PTFE surface was exposed to the environment. The aluminum surface was attached with an acrylic adhesive to the carrier aluminum disk.

#### *Visual Inspection*

The Beta cloth shows slight discoloration (yellowed) on its exposed surface.

#### *High Magnification Inspection*

Differences between the control and the exposed samples were evident.

#### *ESCA Analysis*

This is an aluminized beta cloth (X389-7), which has the beta cloth side facing up. The flight and the control specimens contain carbon, oxygen, fluorine, and a small amount of silicon. The concentration of each element on the specimens are similar and the chemical state of the carbon indicates that both surfaces are made of Teflon coated beta cloth that are identical in composition. No atomic oxygen effects were observed.

#### *Radiative Properties*

There is an improvement in reflectivity as shown in Figure 29. The absorptance changed from 0.277 to 0.281. The emittance of the control sample was 0.873 and then 0.906 at the time of the last measurement.

#### *Physical Analysis*

The mass loss of the sample was  $2.6 \times 10^{-5}$  g. The percentage change based on the Beta cloth was  $1.52 \times 10^{-3}$ .

#### *Oxygen Erosion*

The reaction rate, based on exposed area, was calculated to be  $1.549 \times 10^{-25} \text{ g/atom}$ .

### **3.15 CV-1144-0 Silicone on Beta Cloth (Figure 30)**

#### *Sample Description*

Beta cloth is a tightly woven "beta" fiberglass fabric having a light sizing to provide flexibility. A teflon coating (PTFE) is applied to the fabric surface to provide abrasion resistance and to meet combustion specifications in an oxygen atmosphere. The other side of the beta glass fabric has been coated with a layer of vapor deposited aluminum for thermal stability. A thin layer of translucent CV-1144-0 silicone coating has been applied to the Teflon surface of the beta cloth for atomic oxygen protection.

#### *Sample Configuration*

The thickness of the beta cloth/CV-1144-0 silicone coating was 0.16383 cm and its mass was 0.10212 g. The thickness of the CV-1144-0 was 0.0283 cm. The sample was attached to an aluminum carrier disk with an acrylic transfer adhesive.

#### *Visual Inspection*

The Beta cloth is coated with a clear silicone coating. The shielded area is visibly white with an exposed "yellowed" area.

#### *High Magnification Inspection*

The sample is yellowed with surface crazing.

#### *ESCA Analysis*

The sample is a fiberglass cloth that is coated with Teflon and then with CV-1144-0. The control specimen contains carbon, oxygen, and silicon. This composition reflects the CV-1144-0 layer. There was 62% of C-O bond and 38% of C-(H,C). The silicon had 58% in Si=O and 42% in Si-O bonds. The flight specimen, on the other hand, had carbon, oxygen, nitrogen, and silicone. The carbon concentration decreased from 53 atom percent in the control

specimen to 43 atom percent; the oxygen concentration increased from 23 atom percent to 32 atom percent. The silicon concentration remained the same. The chemical state of the flight specimen shows that more silicon on the flight specimen is oxidized to Si=O bonds than the control specimen.

#### *Radiative Properties*

The reflectance of the sample is shown in Figure 31. The absorptance of the exposed sample changed from 0.410 to 0.459 and the emittance of the control sample was 0.908 and later 0.922.

#### *Physical Analysis*

The mass change of the sample was  $5.3 \times 10^{-5}$  g. The percentage attributed to the coating was  $9.8 \times 10^{-5}$ .

#### *Oxygen Erosion*

The reaction rate based on the exposed area was  $3.158 \times 10^{-25}$  g/atom.

### **3.16 Chemglaze Z-306 Polyurethane Paint (Figure 32)**

#### *Sample Description*

Chemglaze Z-306 is one part flexible polyurethane paint. The paint was a flat black absorptive polyurethane which fully cures by reacting with moisture in about 10 days. The paint exhibits excellent abrasion resistance, low outgassing, and adhesive properties.

#### *Sample Configuration*

The thickness of the Z306 black paint was 0.09271 cm and its mass was 0.01790 g. The paint was applied directly to the aluminum carrier disk.

#### *Visual Inspection*

The shielded area of the paint is a flat black. The exposed area is a "velvet" black.

#### *High Magnification Inspection*

The exposed region is darker and appears smoother than the shielded, with striations.

#### *ESCA Analysis*

This is a polyurethane coating called Chemglaze Z-306. Both the control and the flight specimen contain carbon, oxygen, nitrogen, and silicon on the surface. The flight specimen, however, has 30% less carbon, 14% more oxygen, and 16% more silicon. The control specimen has 7% of carbon in O-C = O bonds, 20% in C-O bonds, and 73% in C-(H,C) bonds. The silicon on the flight specimen is highly oxidized.

The atomic oxygen has oxidized the silicon that is on the surface.

#### *Radiative Properties*

The reflectance versus wavelength is shown in Figure 33. The absorptance of the exposed sample changed from 0.959 to 0.981. The emittance of the control sample was 0.912 and later 0.914.

#### *Physical Analysis*

The sample lost  $3.32 \times 10^{-4}$  g. The percentage loss of the coating was  $3.28 \times 10^{-2}$ .

#### *Oxygen Erosion*

The oxygen reaction rate was  $1.978 \times 10^{-24}$  g/atom, based on the exposed area and the given fluence.

### **3.17. Ultem-1000 (Figure 34)**

#### *Sample Description*

Ultem-1000 is polyetherimide polymer material without glass fabric reinforcement. It is a high performance material noted for its high strength, long term high temperature heat resistance and electrical properties.

#### *Sample Configuration*

The thickness of the Ultem sample was 0.14859 cm and its mass was 0.09644 g. The sample was attached to an aluminum carrier disk with an acrylic transfer adhesive.

#### *Visual Inspection*

The shielded area of the sample was shiny, of amber color, with minute bubbles on the outer edge of disk. The exposed area was cloudy, opaque, dull, with small triangular smudge marks.

#### *High Magnification Inspection*

The exposed area of the Ultem was opaque. The shielded region was transparent. The region had no discernible features at low magnification. High magnification showed etched and a finely scratched surface.

#### *ESCA Analysis*

The sample was an amorphous thermoplastic polyetherimide called Ultem-1000, often used for molding structure. The control specimen contains carbon, oxygen, nitrogen, silicon, and trace amounts of chlorine, sulfur, and sodium. The flight specimen showed the same four basic elements as the control specimen, but did not show the trace elements. The carbon on the control specimen consisted of 5% O - C = O bond, 13% C-O bond, and 82% C - (H,C) bonds. The carbon on the flight specimen had 12% C = O, 22% C - O, and 66% C - (H,C) bonds. It appears that the exposure to atomic oxygen altered the bonding state of the polyetherimide to a more oxygenated state.

#### *Radiative Properties*

The change in reflectance was shown in Figure 35. The absorptance of the sample changed from 0.596 to 0.659. The control emittance was 0.897 and later 0.899.

#### *Physical Analysis*

The flight sample lost  $1.157 \times 10^{-3}$  g or  $6.1 \times 10^{-2}$  percent of the original weight.

#### *Oxygen Erosion*

The reaction rate was  $6.894 \times 10^{-24}$  g/atom.

### **3.18 PEEK 450G (Figure 36)**

#### *Sample Description*

PEEK 450G is a Polyetheretherketone polymer material. It is noted for its high temperature applications, good abrasion and excellent chemical resistance, and electrical properties.

#### *Sample Configuration*

The thickness of the sample was 0.12217 cm and its mass was 0.05782 g. The sample was attached to the carrier disk with a pressure sensitive acrylic transfer adhesive.

#### *Visual Inspection*

The shielded area of Peek 450G is shiny, clear and taupe in color. The exposed area is cloudy, dull and opaque.

#### *High Magnification Inspection*

The exposed surface is opaque and sand colored with little discernible morphology, even at high magnification. The surface has a spotted, etched look with faint scratches.

#### *ESCA Analysis*

The flight and the control specimens contained carbon, oxygen, nitrogen, and silicon. The concentration of each element was the same between the two specimens. The chemical states of carbon were also the same. No changes in the chemical composition were detected as the result of the exposure to space environment.

#### *Radiative Properties*

The reflectance of the Peek sample dropped about 5% throughout the explored wave-

lengths, as shown in Figure 37. The absorbance changed from 0.617 to 0.681. The emitance of the control sample was 0.880 and eventually 0.894.

#### *Physical Analysis*

The sample loss was  $9.71 \times 10^{-4}$  g, or as a percentage loss, it was 0.1366.

#### *Oxygen Erosion*

The reaction rate of the PEEK was calculated to be  $5.78 \times 10^{-24}$  g/atom based on the exposed area.

### **3.19 CV-2500 Silicone on Kapton H Film (Figure 38)**

#### *Sample Description*

A two part, clear silicone, specifically designed for applications requiring low outgassing and minimal volatile condensables, was applied on the Kapton surface.

#### *Sample Configuration*

The thickness of the silicone was 0.15189 cm and its mass was 0.07679 g. The silicone was applied to the Kapton surface after a proper primer application. The Kapton was applied to carrier substrate disk by a pressure sensitive acrylic transfer adhesive. The thickness of the Kapton is 0.0283 cm.

#### *Visual Inspections*

The shielded area of the silicone coated Kapton was depressed. The exposed area of the substrate was crazed. The entire surface had a uniform color and texture.

#### *High Magnification Inspection*

The sample included bubbles below the surface. The surface is crazed.

#### *ESCA Analysis*

The sample was a Kapton H film with a CV-2500 silicone overcoating. The control and



flight specimens had the same amounts of carbon, oxygen, and silicon on the surfaces. No chemical changes were observed between the control and the flight specimen.

#### *Radiative Properties*

The reflectance of the sample is shown in Figure 39. It showed small variations throughout the scanned wavelength.

#### *Physical Analysis*

The mass loss of the sample was  $3.03 \times 10^{-4}$  g. The percentage of coating loss was  $3.39 \times 10^{-2}$ .

#### *Oxygen Erosion*

The reaction rate, based on the above mass loss and the exposed area, was  $1.805 \times 10^{-24}$  g/atom.

### **3.20 Polyethersulfone 4800-G (PES)** **(Figure 40)**

#### *Sample Description*

Victrex PES is a transparent Polyethersulfone polymer material having exceptional mechanical properties, high temperature, and excellent electrical properties over a varying temperatures range. The PES is commonly used in medical applications because of its excellent resistance to sterilization methods.

#### *Sample Configuration*

The thickness of the sample was 0.14935 cm and its mass was 0.09954 g. The sample was attached to an aluminum carrier disk with an acrylic pressure sensitive transfer adhesive.

#### *Visual Inspections*

The shielded area of the sample was clear, with a light brown tint. The exposed area was opaque, cloudy and tan.

#### *High Magnification Inspection*

The exposed area was opaque and yellowed.

#### *ESCA Analysis*

The sample was a Polyethersulfone called Victrex PES 4800G. The flight and control specimens contained carbon, oxygen, nitrogen, silicon, and sulfur. There was a slight decrease in carbon concentration and increase in oxygen concentration. While the control specimen consisted of 96% C - (H,C) bonds and 4% C - O bonds, the flight specimen had 28% of C - (H,C), 18% C = O, 53% O - C = O. Since the Polyethersulfone primarily consists of C - C and C - O bonds, the C = O and O - C = O bonds detected on the flight specimen reflect the transformed composition from the atomic oxygen exposure.

#### *Radiative Properties*

The changes in reflectance produced by the flight are shown in Figure 41. The absorptance increased from 0.539 to 0.619. The emittance of the control sample was 0.889 and eventually 0.895.

#### *Physical Analysis*

The exposed sample lost  $9.41 \times 10^{-4}$  g and, in terms of coating of percentage loss, about  $2.10 \times 10^{-3}$ .

#### *Oxygen Erosion*

The oxygen erosion rate of the exposed area was  $5.607 \times 10^{-24}$  g/atom.

### **3.21 Polymethylpentene (TPX) Film** **(Figure 42)**

#### *Sample Description*

Polymethylpentene (TPX) is a transparent film having excellent electrical, chemical and high temperature properties. It is said to possess the lowest specific gravity of any known thermoplastic. It is commonly used for cable and wire wrap.

#### *Sample Configuration*

The thickness of the sample was 0.14605 cm and its mass was 0.06735 g. The TPX film was attached to an aluminum carrier disk with a pressure sensitive acrylic transfer adhesive.

#### *Visual Inspections*

The sample shielded area was clear and shiny. The exposed area was cloudy and opaque.

#### *High Magnification Inspection*

The exposed film was clouded.

#### *ESCA Analysis*

The sample material was a molding structure made of polymethylpentene. The control specimen was carbon, oxygen, and a trace amount of sulfur. The 66% of carbon was in C - O bond and the other 34% was the C - (H,C) bonds. The flight specimen, however, had carbon, oxygen, and small amounts of nitrogen and silicon. As with other specimens, the carbon concentration decreased and the oxygen concentration increased on the flight specimen from the control specimen. However, these changes in elemental composition are small and not reflected in the carbon bonding state. The chemical state of carbon on the flight specimen was similar to the control specimen.

#### *Radiative Properties*

The changes in reflectance of the exposed sample are shown in Figure 43. Its absorptance changed from 0.489 to 0.540. The emittance of the control sample was 0.856 and later 0.873.

#### *Physical Analysis*

The sample lost  $8.41 \times 10^{-4}$  g. In terms of percentage loss in thickness, it was 0.1189.

#### *Oxygen Erosion*

The oxygen reaction rate, based on the sample exposed area, was  $5.01 \times 10^{-24}$  g/atom.

### **3.22 3M Pressure Sensitive Tape No. 5 (Figure 44)**

#### *Sample Description*

3M Scotch Brand Electrical Tape 5 is a one mil, transparent polyester film with a thermosetting, pressure-sensitive acrylic adhesive. It was a single coated tape featuring an acrylic adhesive system that offers excellent resistant to most common solvents and hydraulics fluids. It has excellent electrical properties, and good adhesive strength to most surfaces.

#### *Sample Configuration*

The thickness of the sample was 0.0889 cm and its mass was 0.00829 g. The tape was attached directly to an aluminum carrier disk with its own adhesive.

#### *Visual Inspections*

The shielded area of the tape was flat and transparent. The exposed area was gray, opaque and slightly darker with a gray spot off the center. No discernible morphology was apparent at low magnification.

#### *High Magnification Inspection*

The tape had a translucent surface with a gray layer in the exposed region. High magnification showed an etched surface.

#### *ESCA Analysis*

The sample was a polyester tape and was identified as 3M tape #5. The flight and the control specimen both have carbon, oxygen, nitrogen, and a small amount of silicon. There was less carbon and more oxygen on the flight specimen than the control specimen. The chemical states of carbon of both specimens also reflect the difference in carbon and oxygen concentration. The carbon in the control specimen is O - C = O, C - O, and C - (H,C) bonds. The carbon in the flight specimen was in C = O, C - O, and C - (H,C) bonds.

#### *Radiative Properties*

Figure 45 shows the sample changes in reflectance from 300 to 2400 nm. The loss was close to 10% in most of the region. The absorptance changed from 0.434 to 0.523. The control emittance was 0.735 and eventually changed to 0.751.

#### *Physical Analysis*

The tape mass loss was  $1.062 \times 10^{-3}$  g and the thickness change was about 1.114 percent.

#### *Oxygen Erosion*

The reaction rate was calculated to be  $6.328 \times 10^{-24}$  g/atom.

### **3.23 Uralane 5750LV-A/B (Figure 46)**

#### *Sample Description*

Uralane 5750 (Diphenylmethane diisocyanate/Polyols in Solvent) is a translucent, soft, two part, polyurethane conformal coating designed specifically for insulating printed circuit boards and electronic components. The material exhibits excellent resistance to heat as well as humid conditions. As a cured coating, it has very low outgassing and condensable properties for use in outer space and high vacuum environments.

#### *Sample Configuration*

The thickness of the sample was 0.11201 cm and its mass was 0.19765 g. The coating was applied directly to the surface of an aluminum carrier disk.

#### *Visual Inspections*

The shielded area of the Uralane Coating was transparent and shiny. The exposed area was cloudy, dull and opaque.

#### *High Magnification Inspection*

The sample exposed region was opaque and grayish in color.

#### *ESCA Analysis*

The sample was a Uralane 5750 LV A/B coating. Both the control and flight specimens had carbon, oxygen, nitrogen, and silicon. However, the concentrations of these elements on the flight specimen differ from the control specimen. The flight specimen had slightly less carbon and nitrogen, while having more oxygen and silicone. The chemical state of carbon on the control specimen was 67% C-(H,C), 26% C-O, and 7% O-C=O. The carbon on the flight specimen was bonded 58% C-(H,C), 34% C-O, and 8% C=O.

#### *Radiative Properties*

Figure 47 shows the reflectance changes of the Uralane sample. Losses in reflectance of the order of 7-8% have occurred over the entire analyzed wavelengths. The absorptance changed from .558 to .648. The emittance of the control sample changed from .843 to .878 during the interval of the measurement.

#### *Physical Analysis*

The mass loss was  $1.48 \times 10^{-4}$  g with a change in coating thickness of about 0.1046 percent.

#### *Oxygen Erosion*

The reaction rate for the sample, based on the exposed area, was  $8.8188 \times 10^{-25}$  g/atom.

### **3.24 Uralane 5753 LV-A/B (Figure 48)**

#### *Sample Description*

Uralane 5753 (Aromatic Diisocyanate/Hydroxy Terminated Polyols) is a translucent amber, 100% solid, two part polyurethane encapsulant and coating material, which, when cured, provides excellent electrical insulation and hydrolytic stability to electrical and electronic components.

#### *Sample Configuration*

The thickness of the sample was 0.12877 cm and its mass was 0.033879 g. The Uralane

material was applied directly to the surface of the aluminum carrier disk.

#### *Visual Inspections*

The shielded area of the Uralane 5753 was shiny. The exposed area was cloudy, dull and opaque.

#### *High Magnification Inspection*

The exposed region of the sample was grayish and opaque with no visible features. The shielded region had a clear appearance.

#### *ESCA Analysis*

This is a Uralane 5753LV-A/B over coating on an aluminum substrate. Both specimens, flight and control, consisted of carbon, oxygen, nitrogen and silicon. The reference specimen also contained a small amount of fluorine. When the surfaces are sputter etched, the silicon and fluorine concentrations decreased, indicating that they reflect only surface compositions. The chemical state of carbon on both specimens showed similar bonding states that correspond to polyurethane. There is no chemical change in the Uralane coating as a result of the space exposure.

#### *Radiative Properties*

Figure 49 shows that the sample reflectance loss occurred mainly between 300 and 1400 nm. The absorption increased from 0.612 to 0.651. The emittance of the control sample changed from 0.880 to 0.912 during the measurement period.

#### *Physical Analysis*

The sample mass loss was  $4.8 \times 10^{-5}$  g and the percentage of change was about  $3.67 \times 10^{-2}$ .

#### *Oxygen Erosion*

The reaction rate was calculated to be  $2.8601 \times 10^{-25}$  g/atom.

### **3.25 Epon 828/Versamid 140/Titanium Dioxide (Figure 50)**

#### *Sample Description*

Epon 828 is an undiluted clear difunctional Bisphenol A/epichlorohydrin derived liquid epoxy resin. The Versamid 140 is a medium viscosity, reactive polyamide resin, based on dimerized fatty acid and polyamines. The Epon, when cross linked, or hardened with an appropriate liquid curing agent will provide excellent mechanical and adhesive properties. A white titanium dioxide pigment has been added for application identification.

#### *Sample Configuration*

The thickness of the sample was 0.10261 cm and its mass was 0.02650 grams. The epoxy sample was adhesively bonded directly to the surface of an aluminum carrier disk.

#### *Visual Inspection*

The shielded area of the Epon 828 with Versamid 140 and  $\text{TiO}_2$  was pale yellow and shiny. The exposed area was white, dull, with dirt specks with metallic flakes.

#### *High Magnification Inspection*

The exposed area of the sample was white while the shielded region was slightly yellowish. High magnification showed the exposed area was less smooth and had a "frosted" appearance.

#### *ESCA Analysis*

The sample was an epoxy 828 with Versamid 140 curing agent and with  $\text{TiO}_2$  pigment. The control specimen contained carbon, nitrogen, silicon, and oxygen. The 44% of carbon is C = O, 27% is C - O and 29% is C - (H, C). The flight specimen had carbon, oxygen, aluminum and silicon. The flight specimen had substantially less carbon, 37 atomic % as opposed to

77 atomic %. It showed an increase in oxygen, 47 atom % from 11 atom %, and in silicon concentration. There was some aluminum on the flight specimen that was transferred from the aluminum sample tray. The  $\text{TiO}_2$  coating was not detected. The chemical state of carbon on the flight specimen was 62% O-C=O and 38% C-(H,C). The atomic oxygen has altered the chemical state of this material.

#### *Radiative Properties*

The reflectance of the sample decreased about 10% between 400 and 1600 nm, as shown in Figure 51. The absorbance changed from 0.212 to 0.289 and the emittance of the control changed from 0.905 to 0.898 during the measurement period.

#### *Physical Analysis*

The sample mass loss was  $1.65 \times 10^{-4}$  g with a mass loss of  $2.685 \times 10^{-2}$  percent.

#### *Oxygen Erosion*

The oxygen reaction rate was  $9.831 \times 10^{-25}$  x g/atom.

### **3.26 Aluminized Beta Cloth X389-7 (Aluminized Exposed (Figure 52))**

#### *Sample Description*

Beta Cloth is a tightly woven "beta" fiberglass fabric having a light silene sizing to provide flexibility. A Teflon (PTFE) coating was applied to one surface to provide abrasion resistance and to meet combustion properties in an oxygen atmosphere. The other side of the beta glass fabric had been coated with a layer of vapor deposited aluminum for thermal stability. The material is used in applications for ESD and thermal control.

#### *Sample Configuration*

The thickness of the beta cloth was 0.11125 cm and its mass was 0.46756 g. The aluminized surface of the beta cloth faced the ex-

posed environment. The cloth was attached to the aluminum carrier disk by use of a pressure sensitive acrylic transfer adhesive. The aluminum surface faced the environment.

#### *Visual Inspections*

The sample was an aluminized textured, glass fabric cloth that was uniformly woven.

#### *High Magnification Inspection*

The metallization on the cloth was missing from the uppermost surface of several fiber bundles.

#### *ESCA Analysis*

The sample was an aluminized beta cloth X389-7 with the aluminum side exposed to space. The control specimen consisted of carbon, oxygen, nitrogen, silicon, fluorine, aluminum, and a trace amount of sodium. The 95% of carbon was hydrocarbon, while 5% was fluorocarbon. The flight specimen contained carbon, oxygen, silicon, calcium, fluorine, aluminum and sodium. The carbon and fluorine concentration decreased, and the oxygen, aluminum, and silicon concentration increased on the flight specimen. Only hydrocarbon was detected on the flight specimen. The sources for calcium, sodium, and nitrogen are not known at this time.

#### *Radiative properties*

As shown in Figure 53, the reflectance of the flight sample changed about one percent throughout the measured wavelengths. The absorbance changed from 0.263 to 0.266 and the emittance of the control sample remained at 0.125.

#### *Physical Analysis*

The sample gained  $0.2 \times 10^{-5}$  g or  $1.2 \times 10^{-2}$  percent of the original mass.

#### *Oxygen Erosion*

The reaction rate, based on exposed area, the mass gained and the oxygen fluence, was calculated to be  $7.15 \times 10^{-26}$  g/atom.

## **4.0 Analysis of Results**

The morphological changes resulting from the exposure of the 25 samples to atomic oxygen and other space effects are shown in Table 3. The table shows for each sample described in the preceding pages the following:

- Oxygen reaction efficiencies in terms of mass loss/atomic oxygen, based on the total area or the exposed area of the sample.
- The reflectance of the sample before and after environment exposure.
- The absorptance before and after with the respective percentage change.
- The emittance for the control sample (the non-exposed) was measured at a distance of several months apart.
- The approximate density of the exposed materials was taken from literature or the manufacturer's catalogs.

The reaction rate efficiencies of test materials can be grouped as follows: the least affected in terms of the erosion have efficiencies from  $1 \times 10^{-25}$  to  $10 \times 10^{-25}$  (g/atoms). This group includes 9 samples, of which 3 are silicones, 2 are epoxies, 2 are Uralane and one of each, a beta cloth and a Teflon.

A second group has efficiencies varying from  $10 \times 10^{-25}$  to about  $43 \times 10^{-25}$ , and it includes 9 materials consisting of 8 silicones and the polyurethane Z-306 Chemglaze black paint. This group includes the commonly referenced reaction efficiency of Kapton ( $3 \times 10^{-24}$  cm<sup>3</sup>/atom or  $4.26 \times 10^{-24}$  g/atom when the Kapton density is taken to be 1.42 g/cm<sup>3</sup>).

A third group, with efficiencies from 50 to  $69 \times 10^{-25}$  includes 5 organic samples: Pentene, one sulfone, one PEEK, 3M tape and one Ultem.

A single material, Delrin II, had the largest erosion efficiency,  $179 \times 10^{-25}$  g/atom.

Three materials, Aluminum beta cloth X389-7, Epoxy fiberglass G11, and CV-1144 Siclicone on Delrin, had an increase in mass which could be translated in a positive reaction rate of about  $7 \times 10^{-26}$ ,  $4 \times 10^{-24}$ , and  $4.35 \times 10^{-24}$ , respectively. The fiberglass sample showing this behavior is to be compared to a similar fiberglass sample (SP-4) which included a fire retardant component and has an erosion efficiency of  $5.9 \times 10^{-25}$  g/atom.

The spectral reflectances of these samples, measured before and after the flight using a (P.E.)  $\lambda$ -9 spectrophotometer, are shown on the respective figures. The figures list the integrated absorptances of the samples before and after flight exposure and two values of the emittance for the non-exposed control sample. These values for the non-exposed samples were taken at a time interval of several months from each other. The emittances of the flown samples could not be measured because of their physical sizes.

Table 3 shows the percentage of change of the absorptances. The percentage of change for the sample EPON 828 Versamide 140 amounted to a value as large as 36%. Two samples CV-2500 silicone on Kapton H film and CV-1500 black silicone show a small absorptance change (less than one percent). These thermo-optical changes reflect the sample coating thickness (on the order of 2 to  $10 \times 10^{-3}$  in, as indicated in the sample description) and the nature of the substrates.

Table 3 also lists a coating material density value. This value was taken from manufacturers' catalogs or from literature. It may be used to obtain approximate values of the volume reaction efficiency (cm<sup>3</sup>/atom). The actual density may be somewhat different because of the sample preparation, the layering of the coating, voids

and other factors employed on the application of the coating.

## **5.0 Conclusions**

Twenty-five material samples, mostly polymeric coatings, varying in the thicknesses between 2 and  $10 \times 10^{-3}$  in., were attached to aluminum disc substrates and mounted in a tray and carried aboard the STS-46 Atlantis shuttle. They were exposed to the shuttle bay environment at an orbit of 228-230 km and at a  $28^\circ$  inclination. The exposure of these coating samples in space complemented several other tests on the effect of the atomic oxygen and space environment on materials and the measurement of the environment in the shuttle bay in space.

The exposure of those coatings to the induced gaseous plasmas, radiation, and to a ram oxygen fluence of  $2.07 \times 10^{20}$  atom/cm<sup>2</sup> resulted in their erosion and morphological changes. Those changes have been verified using XPS analysis, microscopic observations, and thermo-optical measurements. The results have been tabulated. The measured reaction efficiencies, based on the mass loss expressed in grams of materials removed per oxygen atom, have been reported. The results show that the reaction efficiencies of the materials reported here can be grouped in about three ranges of values. The least affected materials with efficiencies varying from  $1 \text{ E-}25$  to  $10 \text{ E-}25$  (g/atom) include silicone, epoxies, Uralane and Teflon. A second group from about  $10 \text{ E-}25$  to  $45 \text{ E-}25$  includes additional silicones coatings and includes the Z-306 Chemglaze paint. This range of values includes the Kapton which is commonly reported to have an efficiency of  $42.6 \times 10^{-25}$  (g/atom). The third range from  $50$  to  $75 \text{ E-}25$  includes organic compounds such as Pentene, PEEK, Ultem, Sulfone and 3M tape. A Delrin

sample indicated the highest reaction ( $179 \times 10^{-25}$ ) and three samples showed a slight increase in mass rather than loss. The thermo-optical changes in absorptance and reflectances resulting from the exposure have been reported. A few samples suffered considerable changes in absorptance.

## **6.0 Acknowledgments**

We wish to thank J. Townsend, W. Peters, F. Gross, J. Colony, and J. Benavides who have contributed either in the submission of samples to be exposed or to the analysis of the experimental results. Special thanks to L. Leger of the Johnson Space Center (JSC) for providing us space in the EOIM-III experiment.

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# FIGURES

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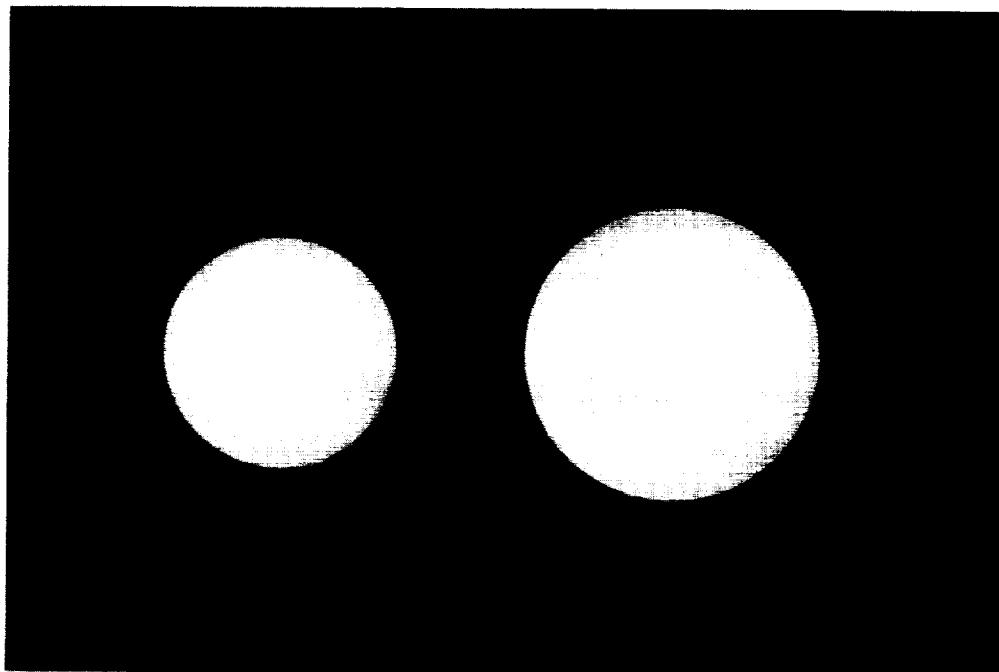


Figure 2. CV-1144-0 Silicone on Delrin—Left, flight sample; right, control sample

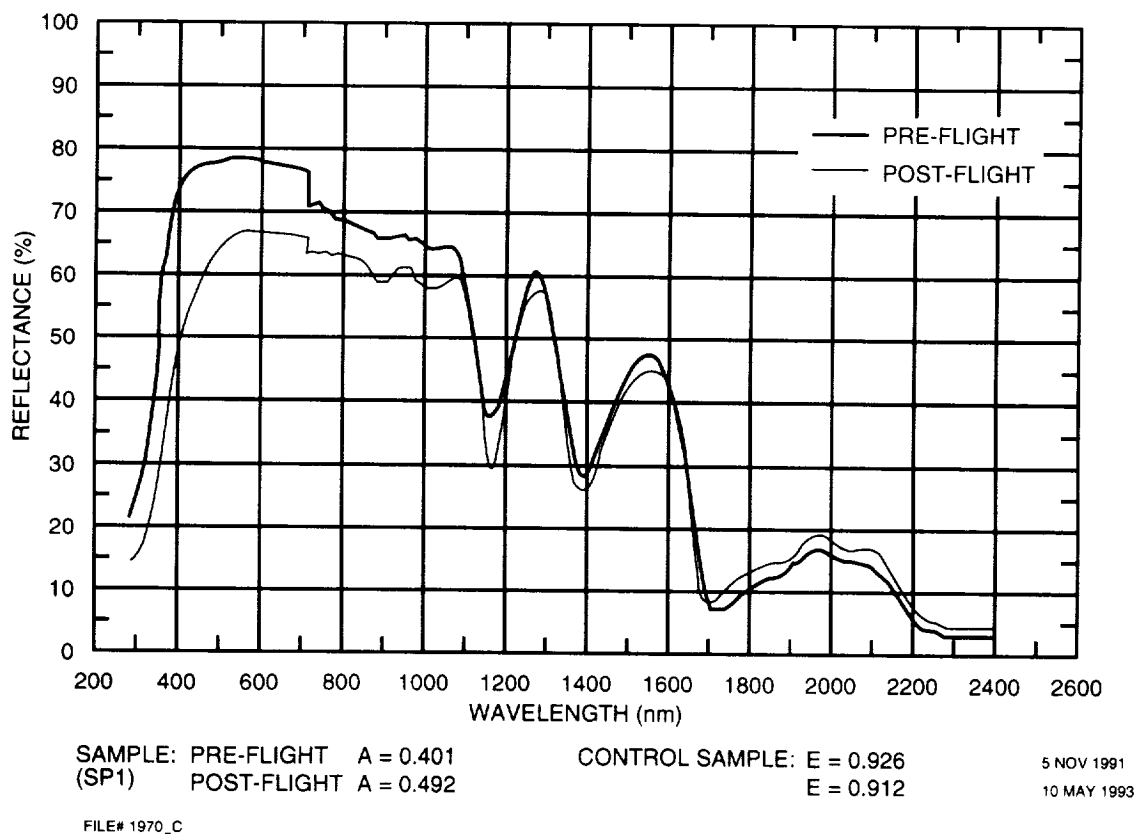


Figure 3. CV-1144-0 Silicone Coating on Delrin —Reflectance vs. Wavelength

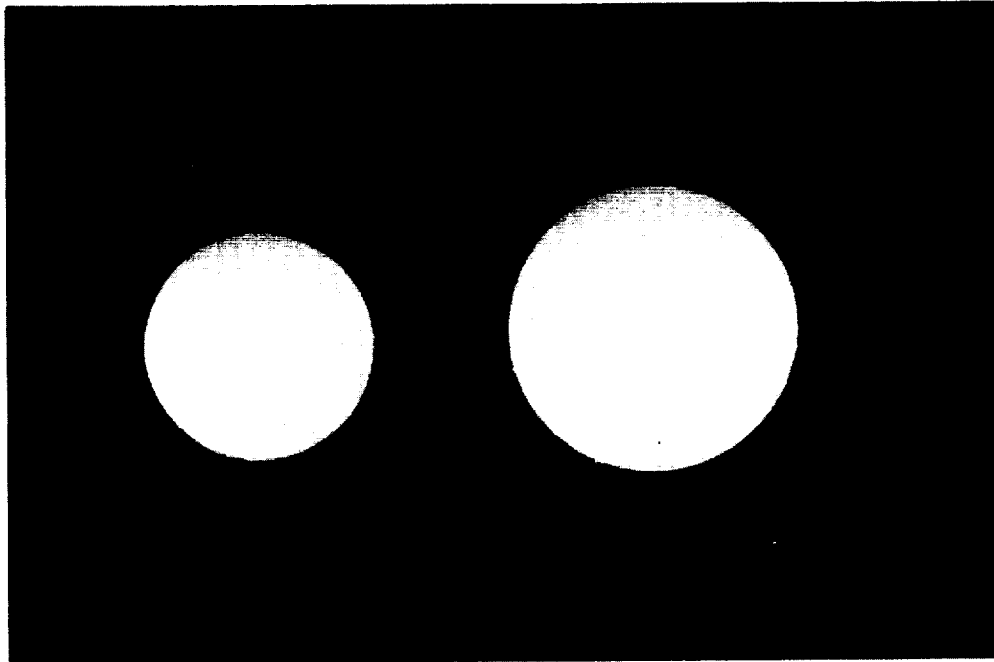


Figure 4. CV-2500 Silicone on Delrin—Left, flight sample; right, control sample

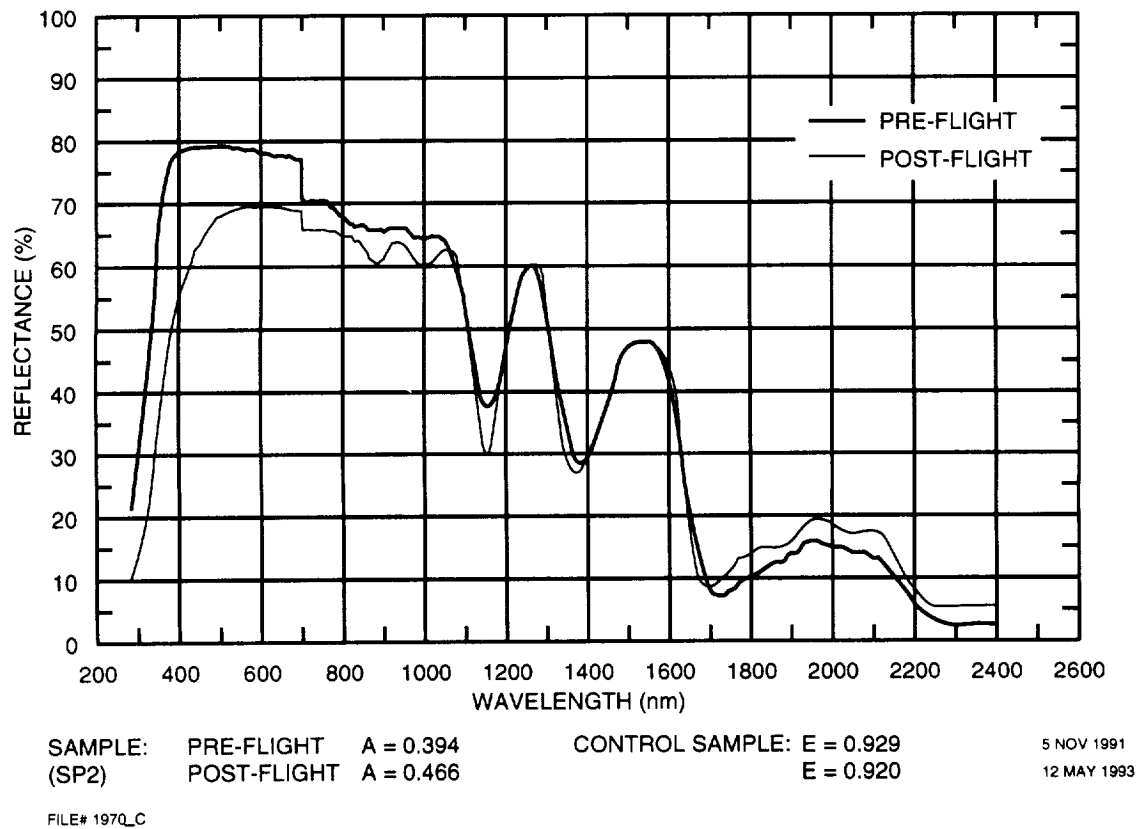


Figure 5. CV-2500 Silicone Coating on Delrin

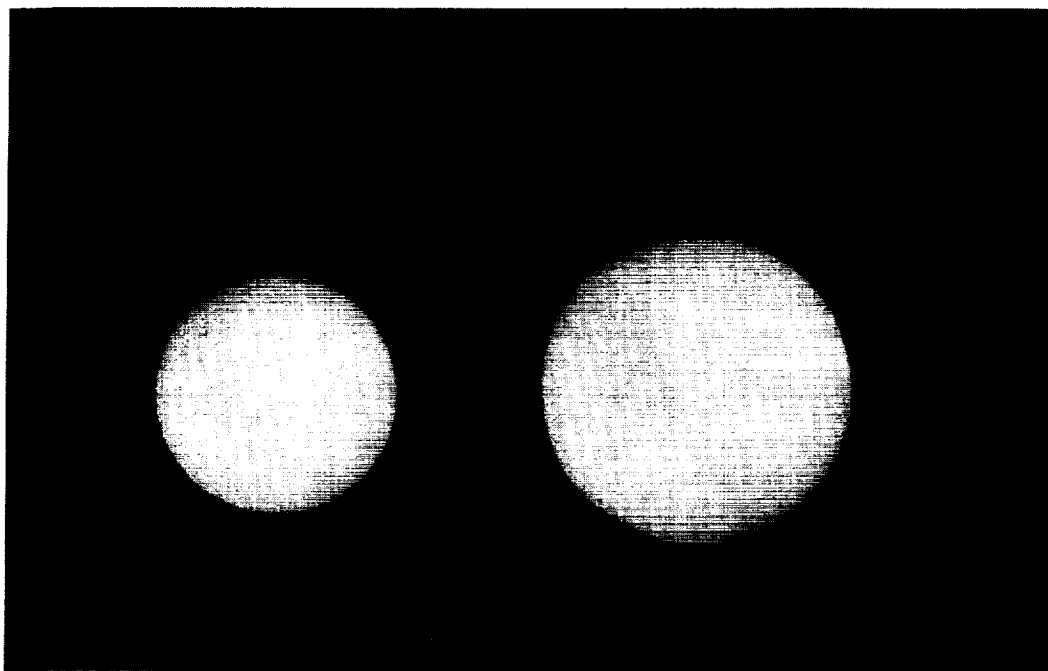


Figure 6. Delrin II 900—Left, flight sample; right, control sample

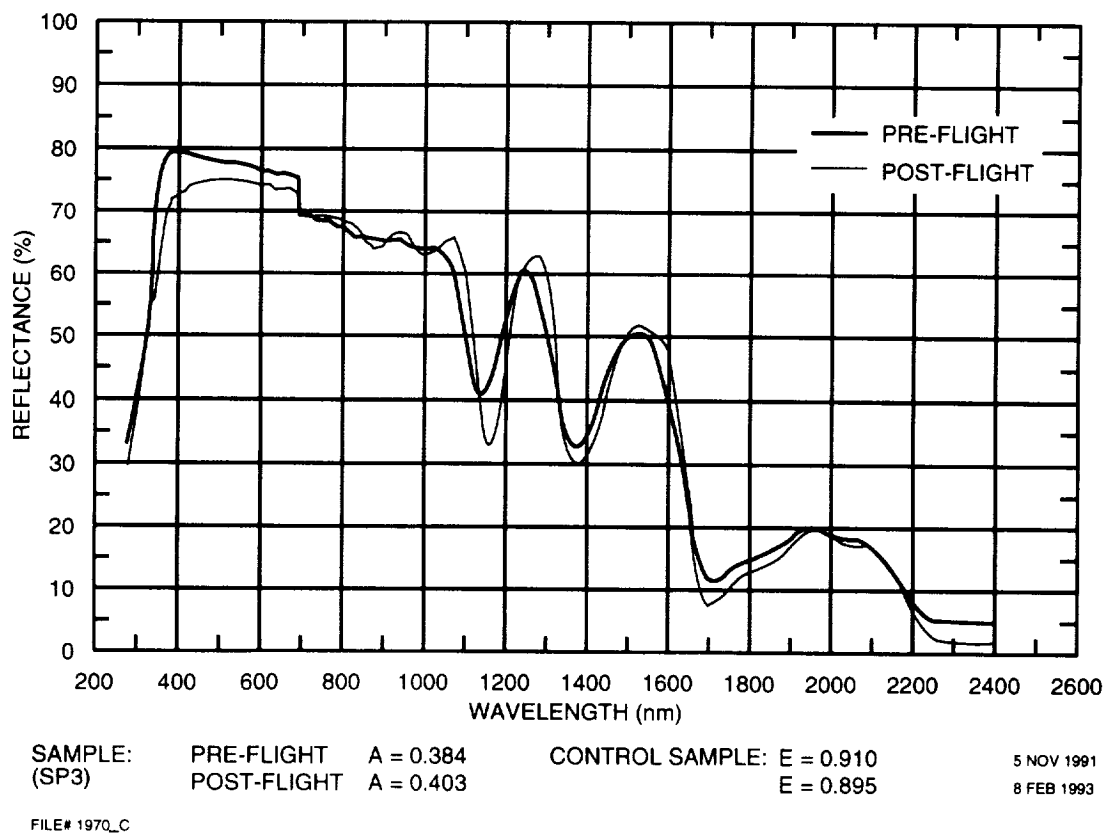


Figure 7. Delrin II 900—Reflectance vs. Wavelength

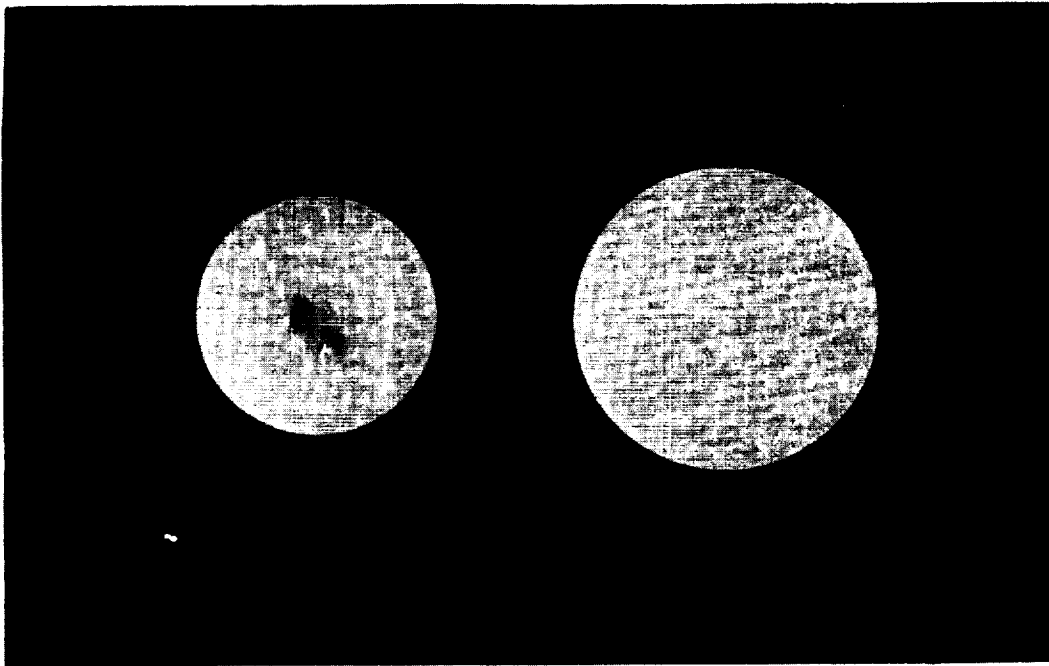
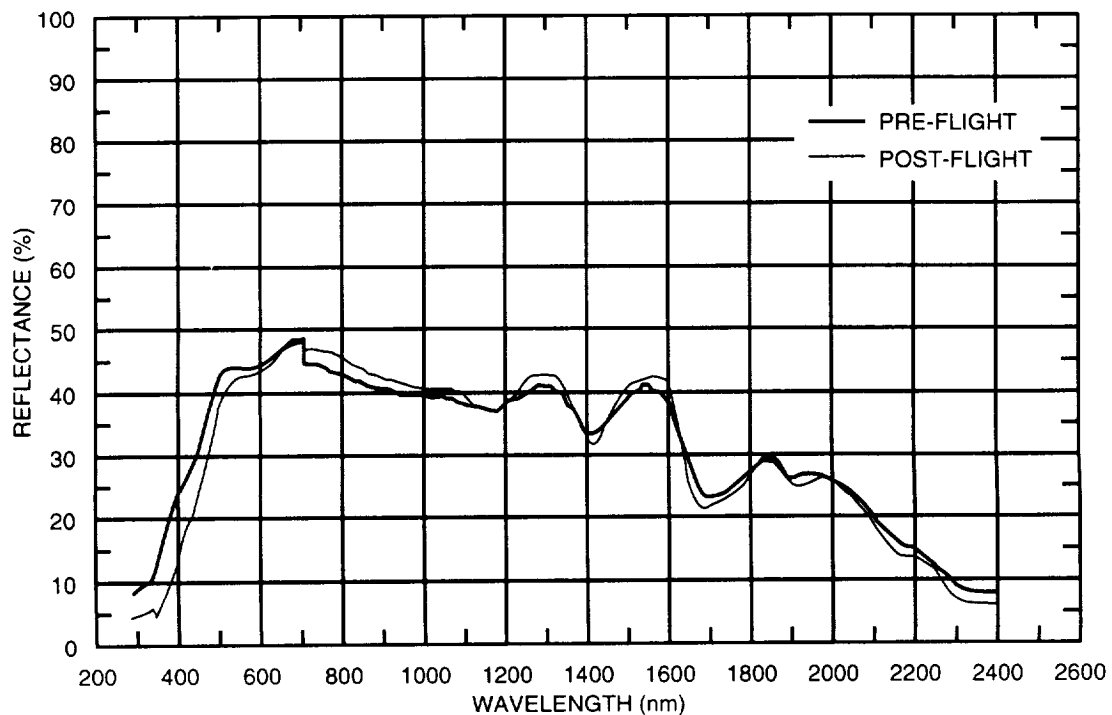


Figure 8. Epoxy Fiberglass G-11 (Flame Retardant)—Left, flight sample; right, control sample



SAMPLE: PRE-FLIGHT A = 0.643  
(SP4) POST-FLIGHT A = 0.657

CONTROL SAMPLE: E = 0.906  
E = 0.903

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Figure 9. Epoxy Fiberglass G-11 (Flame Retardant)—Reflectance vs. Wavelength

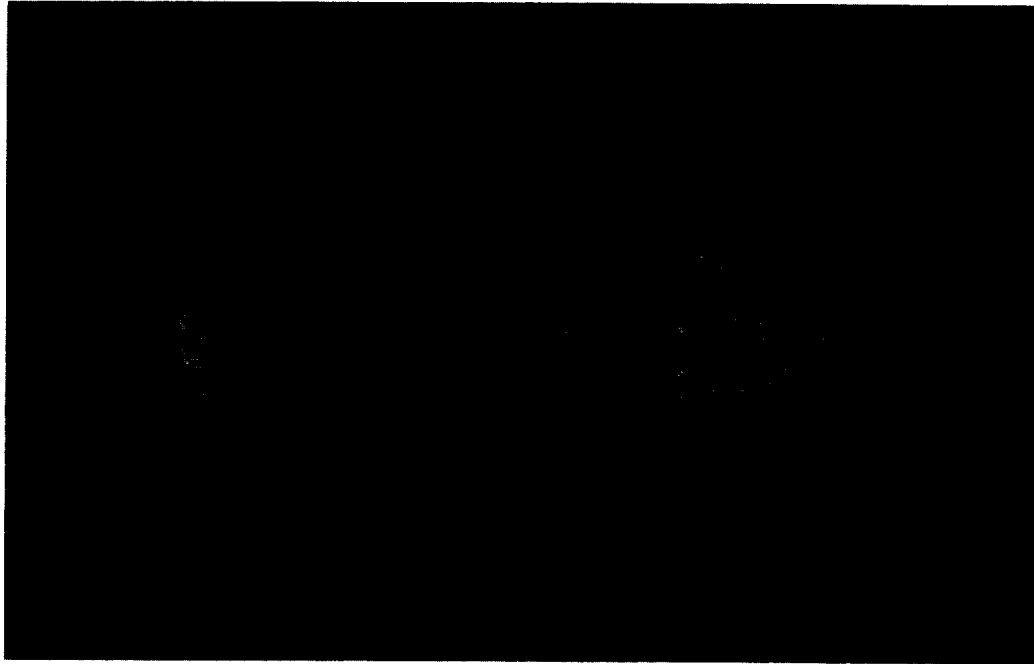
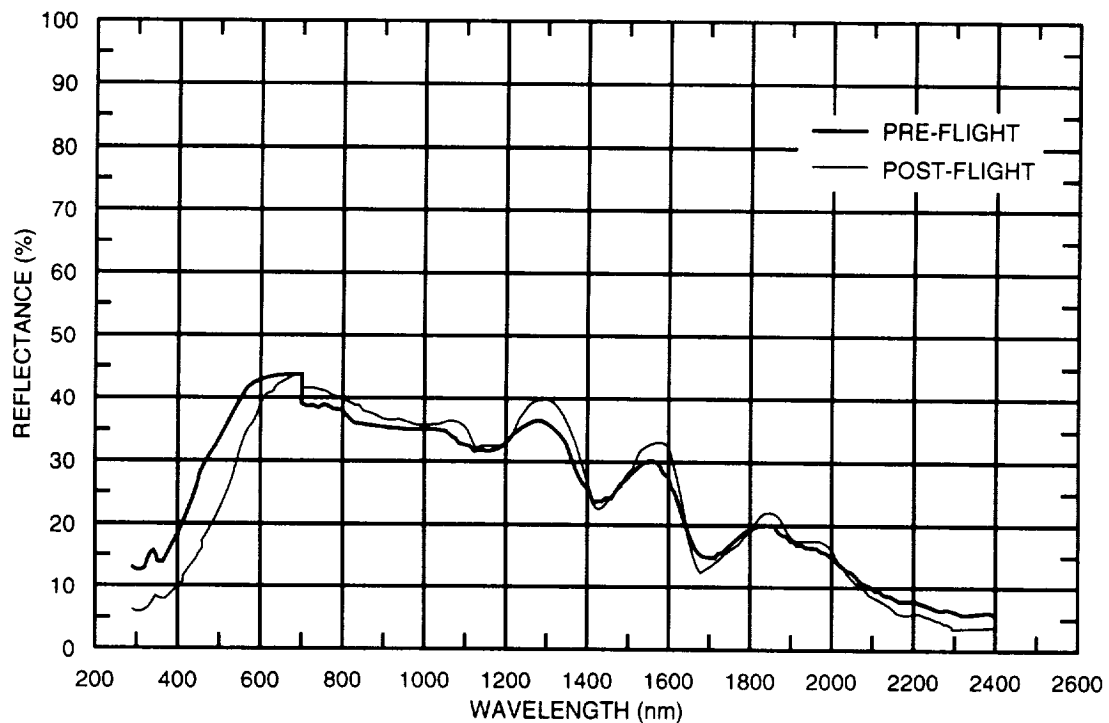


Figure 10. Epoxy Fiberglass G-11, No Flame Retardant—Left, flight sample; right, control sample



SAMPLE: PRE-FLIGHT A = 0.692  
(SP5) POST-FLIGHT A = 0.720

CONTROL SAMPLE: E = 0.910  
E = 0.908

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25 MAR 1993

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Figure 11. Epoxy Fiberglass G-11, No Flame Retardant—Reflectance vs. Wavelength



Figure 12. CV-1144-0 Silicone on Silver Coated Teflon—Left, flight sample; right, control sample

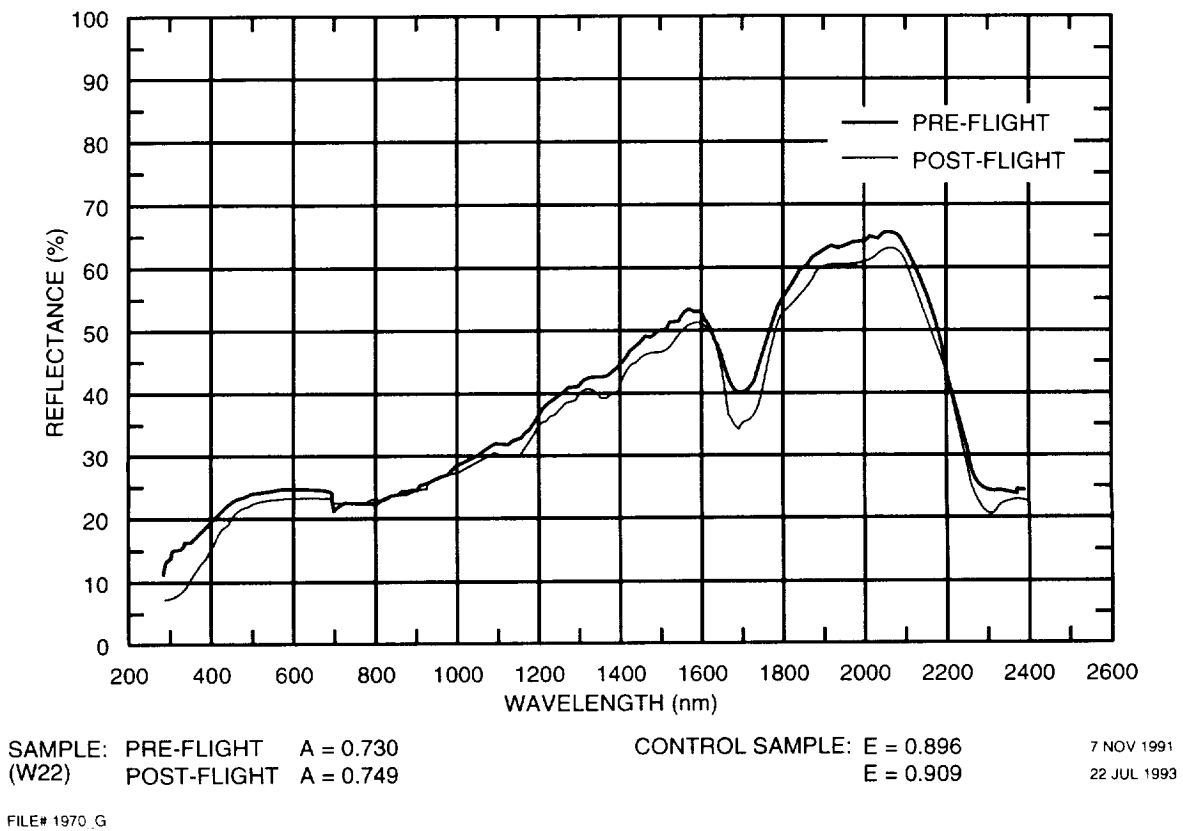


Figure 13. CV-1144-0 Silicone on Silver Coated Teflon—Reflectance vs. Wavelength



Figure 14. CV-2500 Silicone on Silver Coated Teflon—Left, flight sample; right, control sample

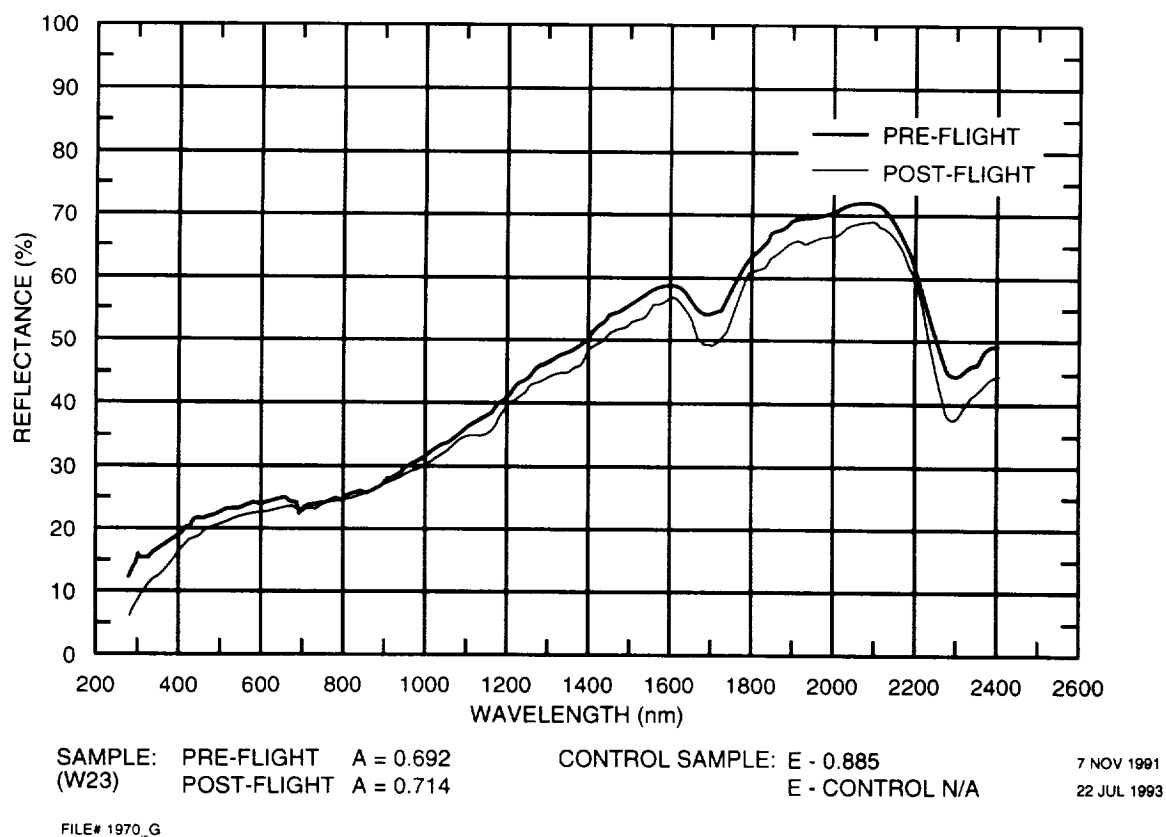


Figure 15. CV-2500 Silicone on Silver Coated Teflon—Reflectance vs. Wavelength



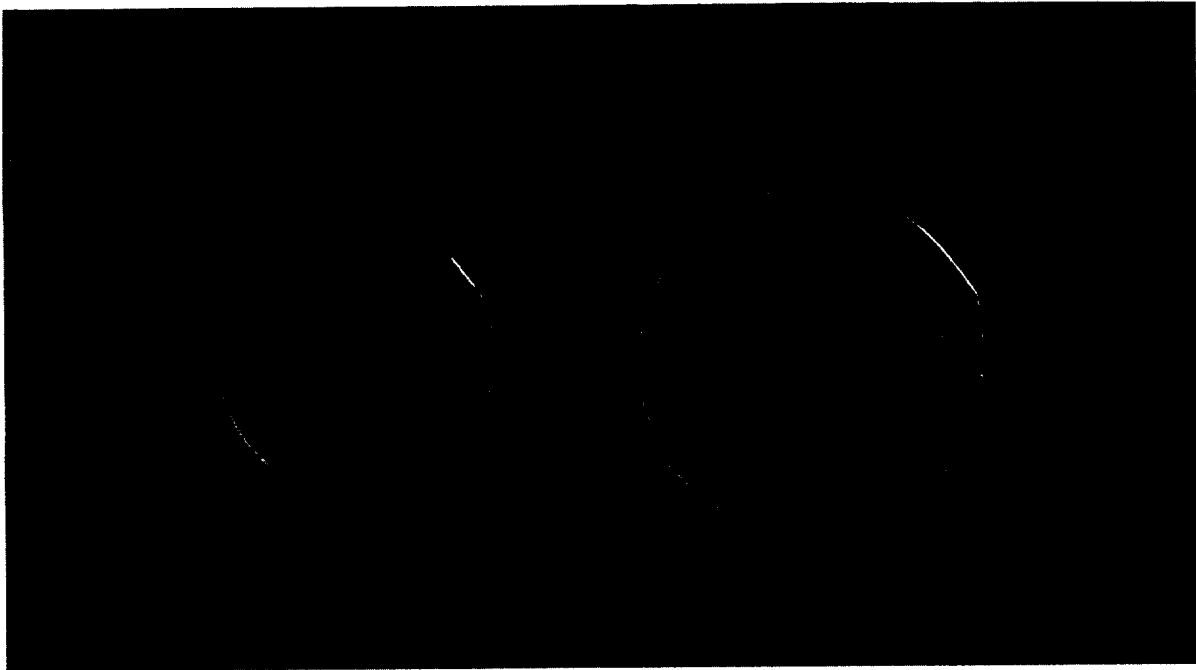
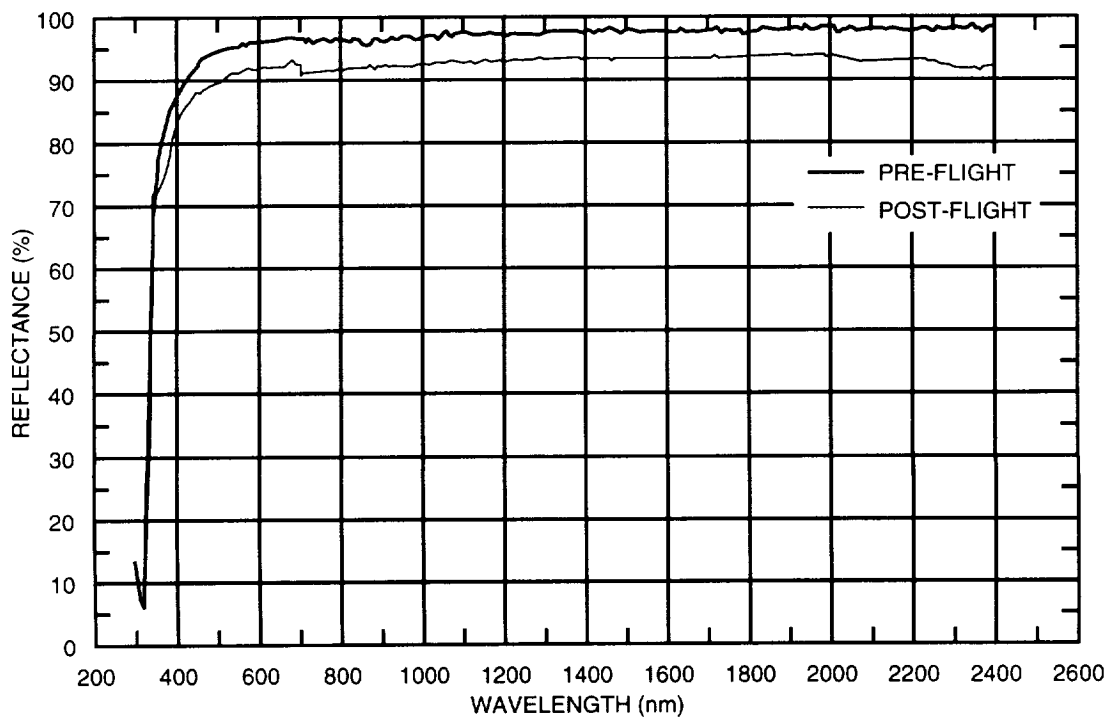


Figure 16. Teflon with Silver Coated Backing—Left, flight sample; right, control sample



SAMPLE: PRE-FLIGHT A = 0.065  
(W24) POST-FLIGHT A = 0.112

CONTROL SAMPLE: E = 0.793  
E = 0.808

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Figure 17. Teflon with Silver Coated Backing—Reflectance vs. Wavelength

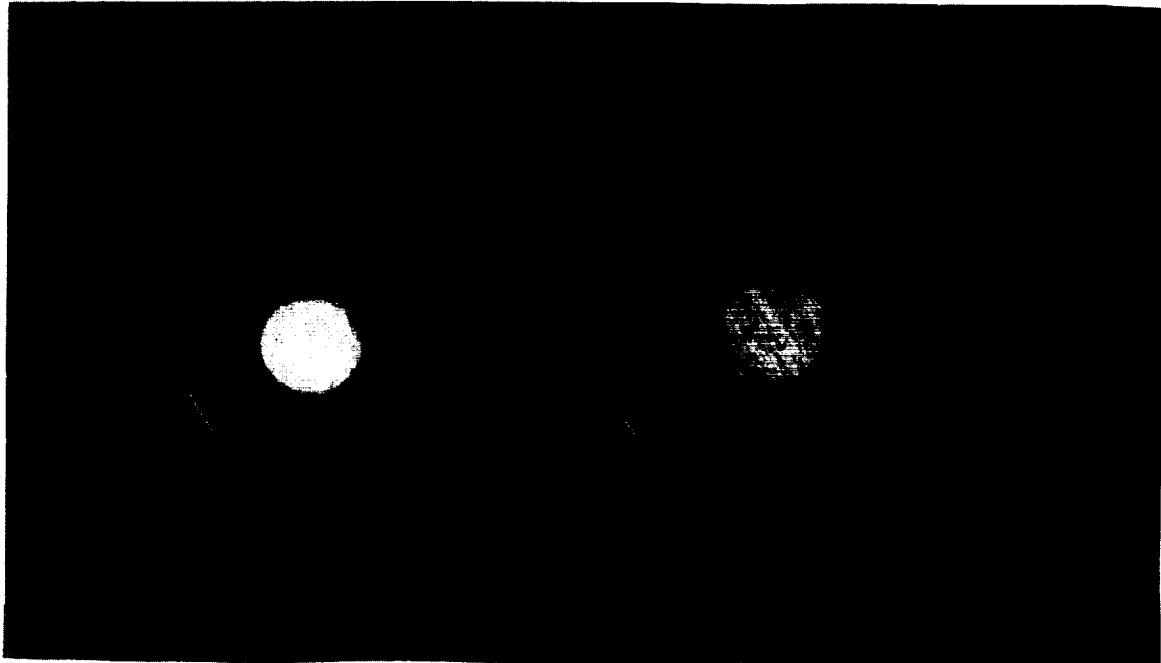
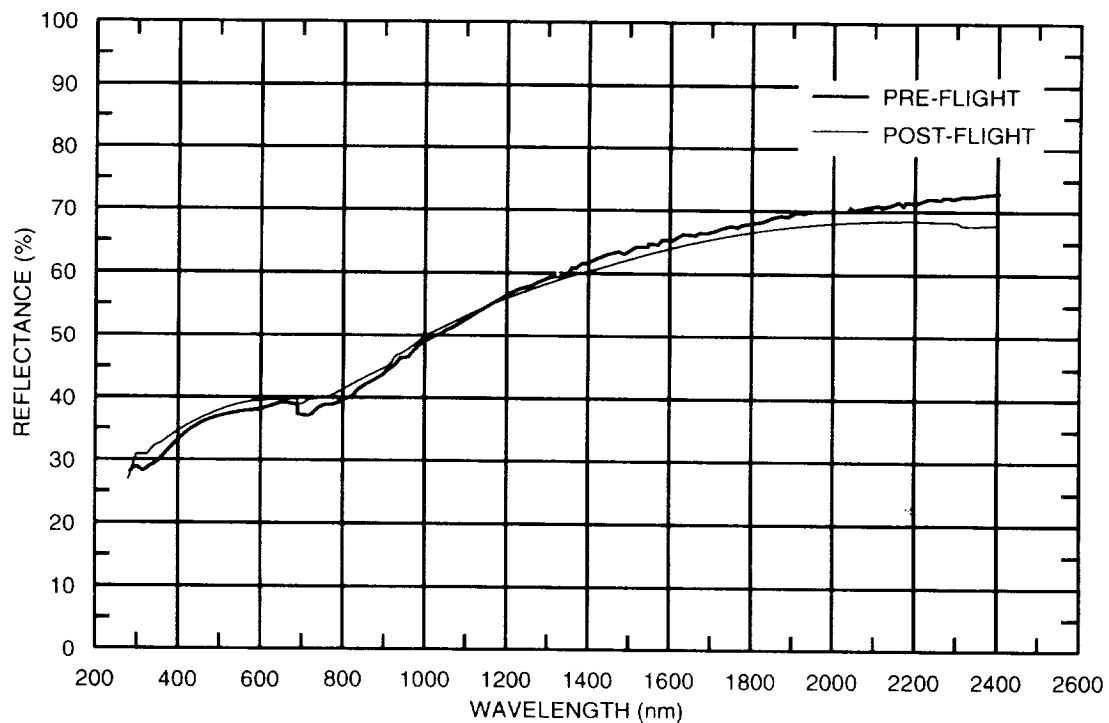


Figure 18. Silver Coated Teflon with Center Hole Cut-out—Left, flight sample; right, control sample



SAMPLE: PRE-FLIGHT A = 0.550  
(W25) POST-FLIGHT A = 0.546

CONTROL SAMPLE: E = 0.059  
E = 0.062

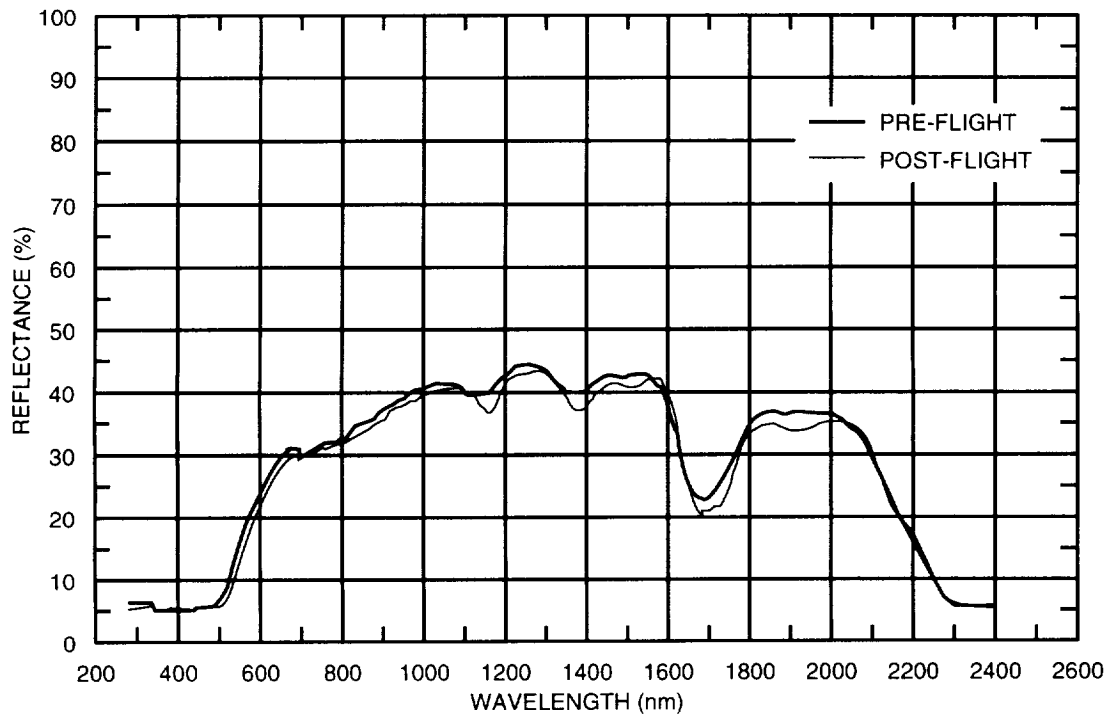
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Figure 19. Silver Coated Teflon with Center Hole Cut-out—Reflectance vs. Wavelength



Figure 20. CV-1144-0 Clear Silicone Coating on Kapton H Film—Left, flight sample; right control sample



SAMPLE: PRE-FLIGHT A = 0.758  
(W26) POST-FLIGHT A = 0.769

CONTROL SAMPLE: E = 0.882  
E = 0.914

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Figure 21. CV-1144-0 Clear Silicone Coating on Kapton H Film—Reflectance vs. Wavelength

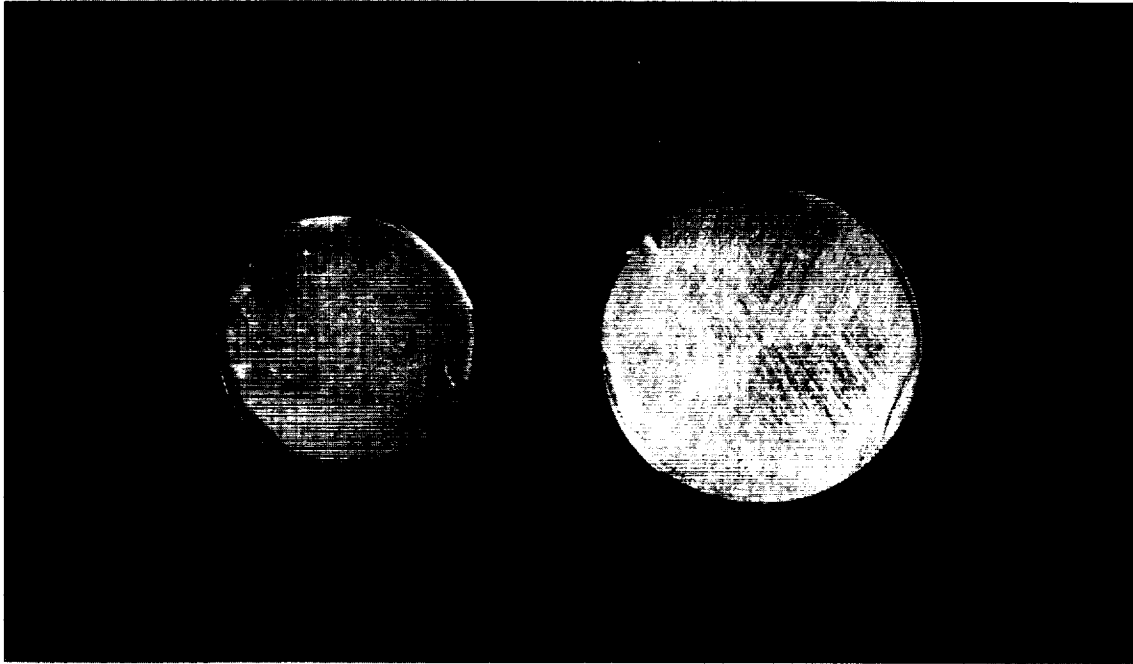
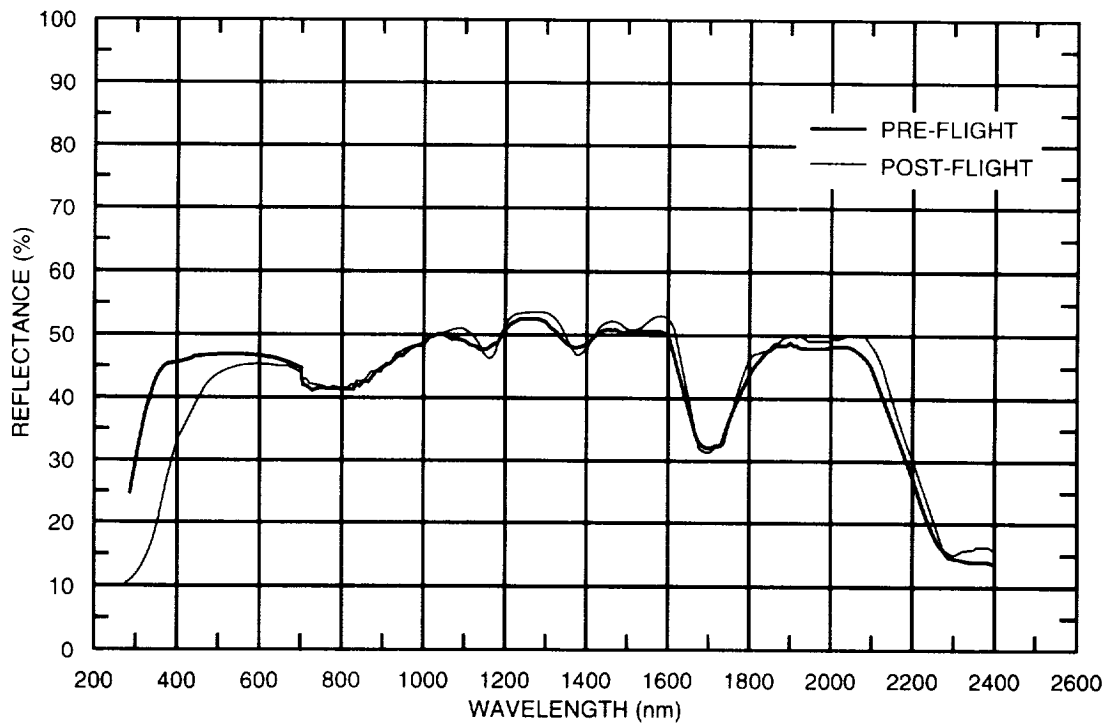


Figure 22. CV-1142-0 Silicone Coating on Aluminum —Left, flight sample; right control sample



SAMPLE: PRE-FLIGHT A = 0.564  
(W27) POST-FLIGHT A = 0.592

CONTROL SAMPLE: E = 0.888  
E = 0.998

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Figure 23. CV-1142 Silicone Coating on Aluminum—Reflectance vs. Wavelength



Figure 24. CV-1500 Black Silicone on Aluminum—Left, flight sample; right, control sample

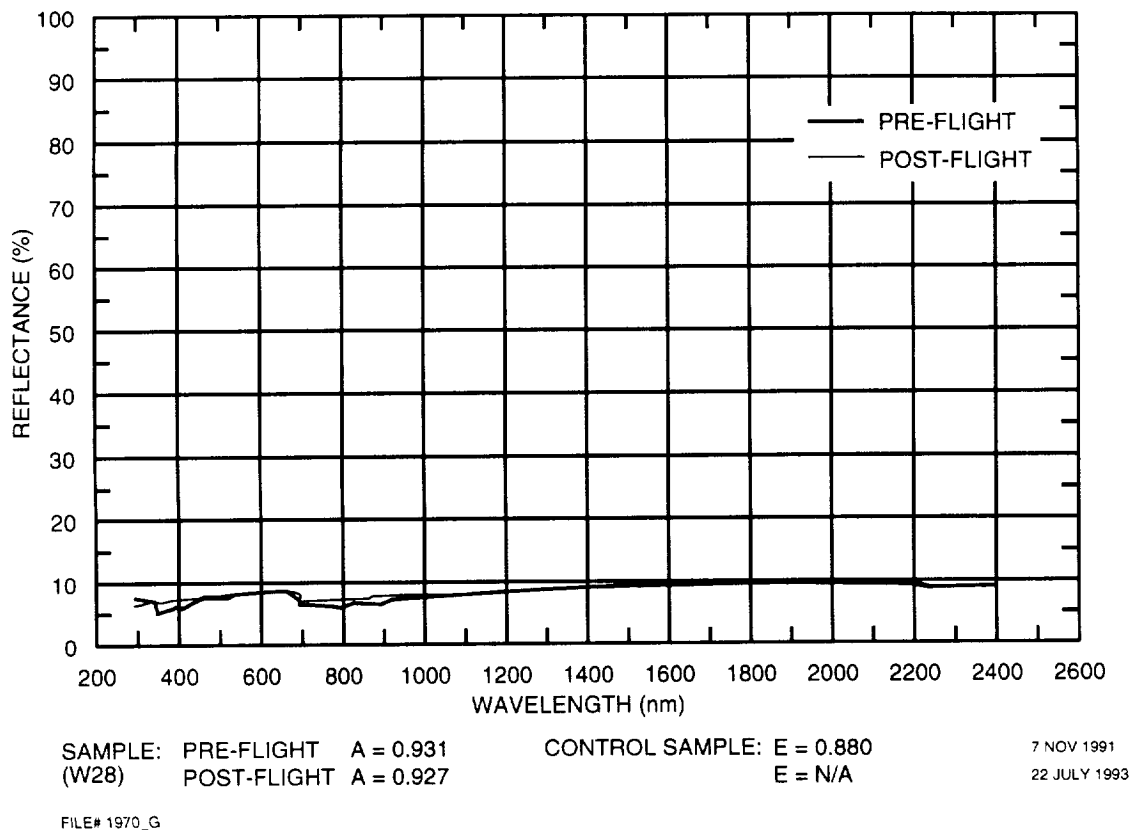


Figure 25. CV-1500 Black Silicone on Aluminum—Reflectance vs. Wavelength

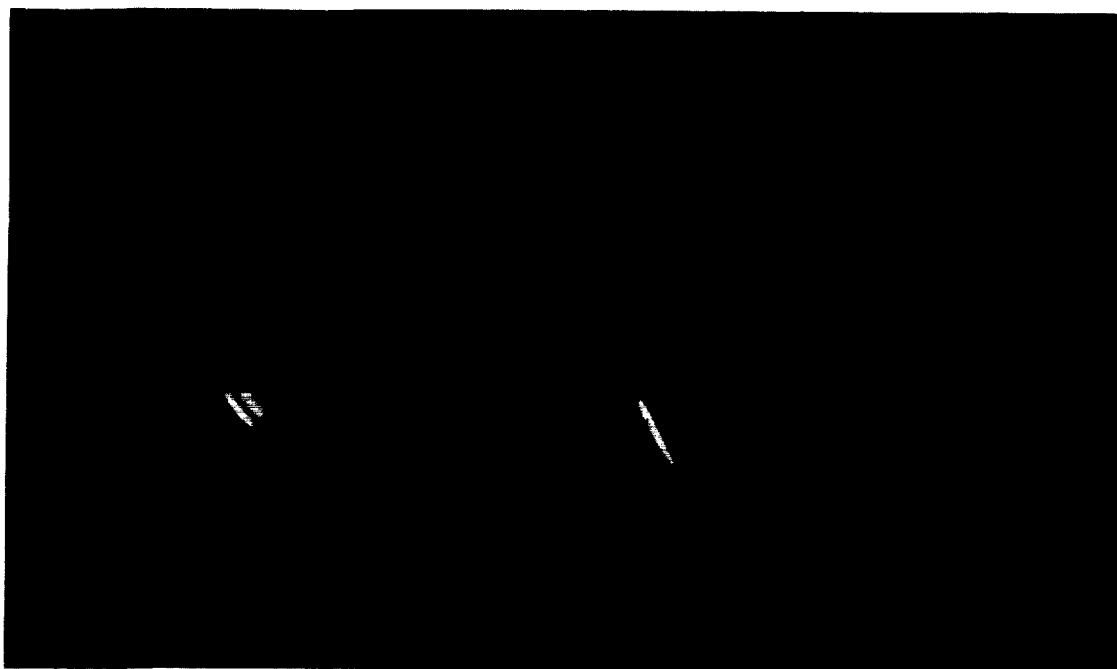


Figure 26. CV-2566 Red Silicone on Aluminum—Left, flight sample; right, control sample

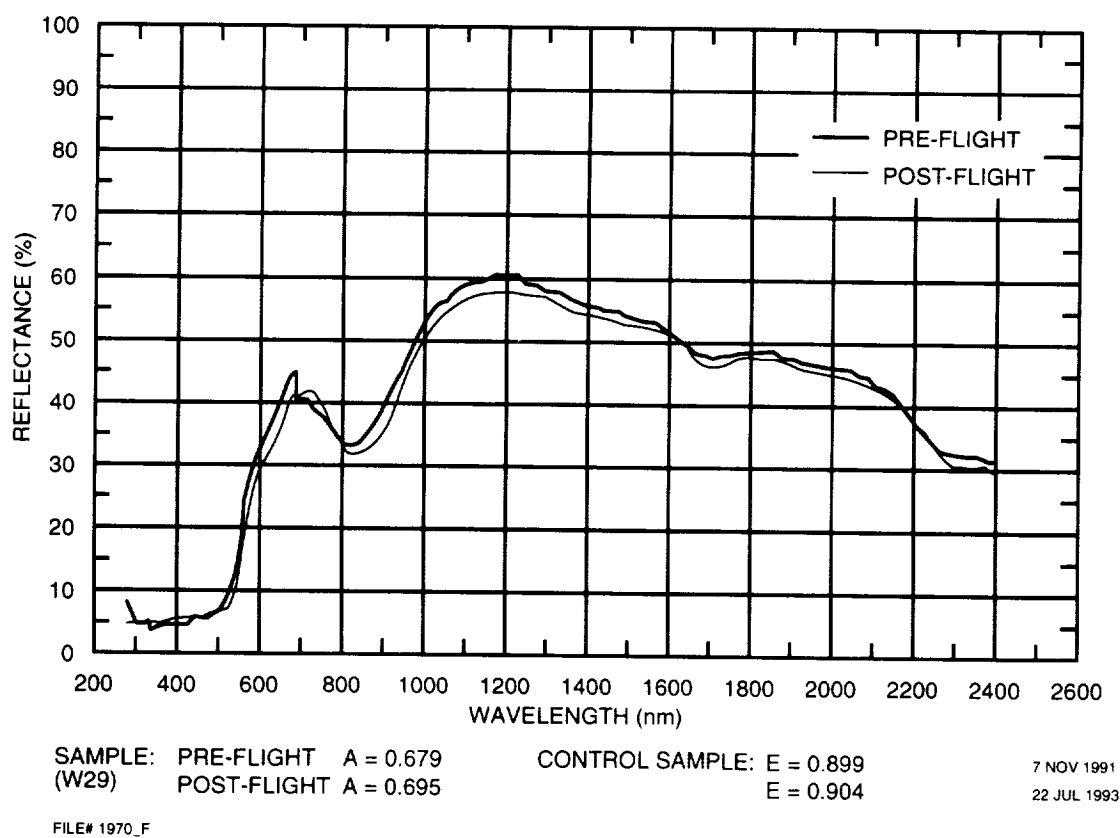


Figure 27. CV-2566 Red Silicone on Aluminum—Reflectance vs. Wavelength

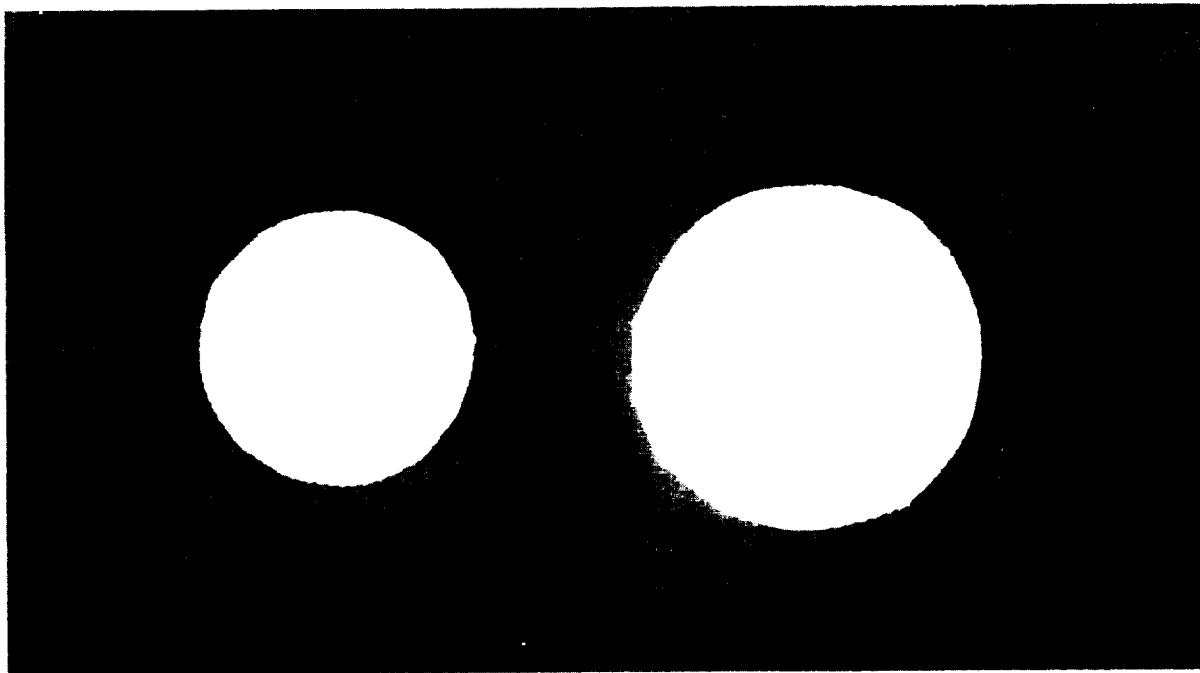
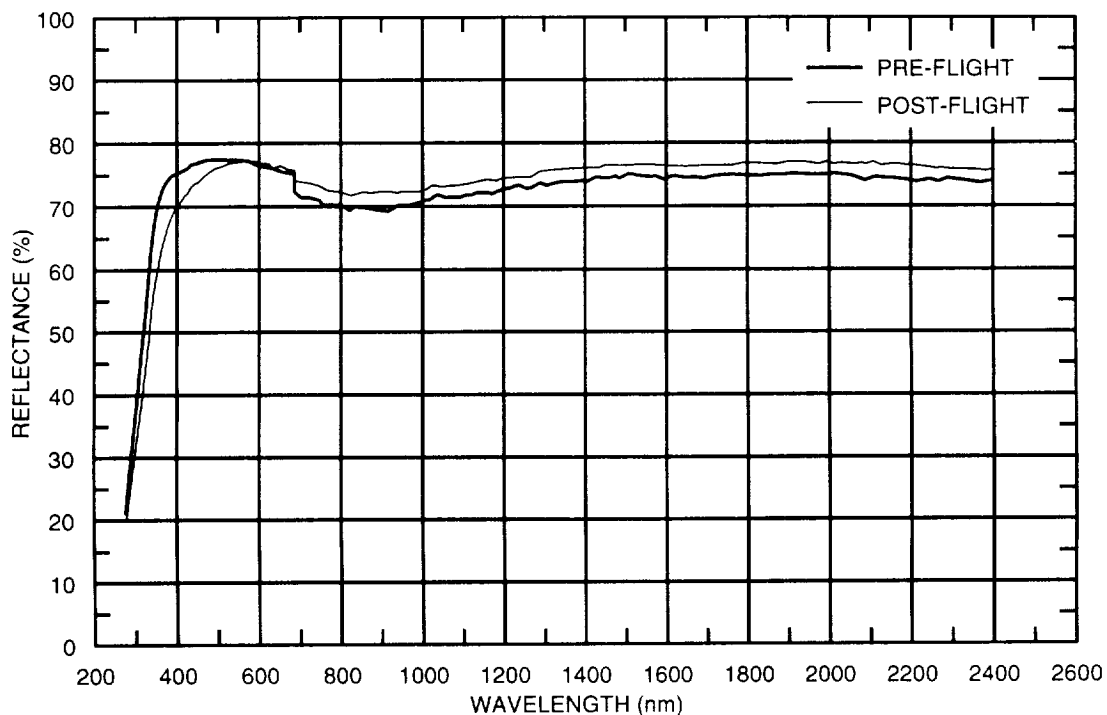


Figure 28. X389-7 Beta Cloth on Aluminum Backing (Beta Cloth Exposed)—Left, flight sample; right, control sample



SAMPLE: PRE-FLIGHT A = 0.277  
(X11) POST-FLIGHT A = 0.281

CONTROL SAMPLE: E = 0.873  
E = 0.906

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Figure 29. X389-7 Beta Cloth on Aluminum Backing (Beta Cloth Exposed)—Reflectance vs. Wavelength

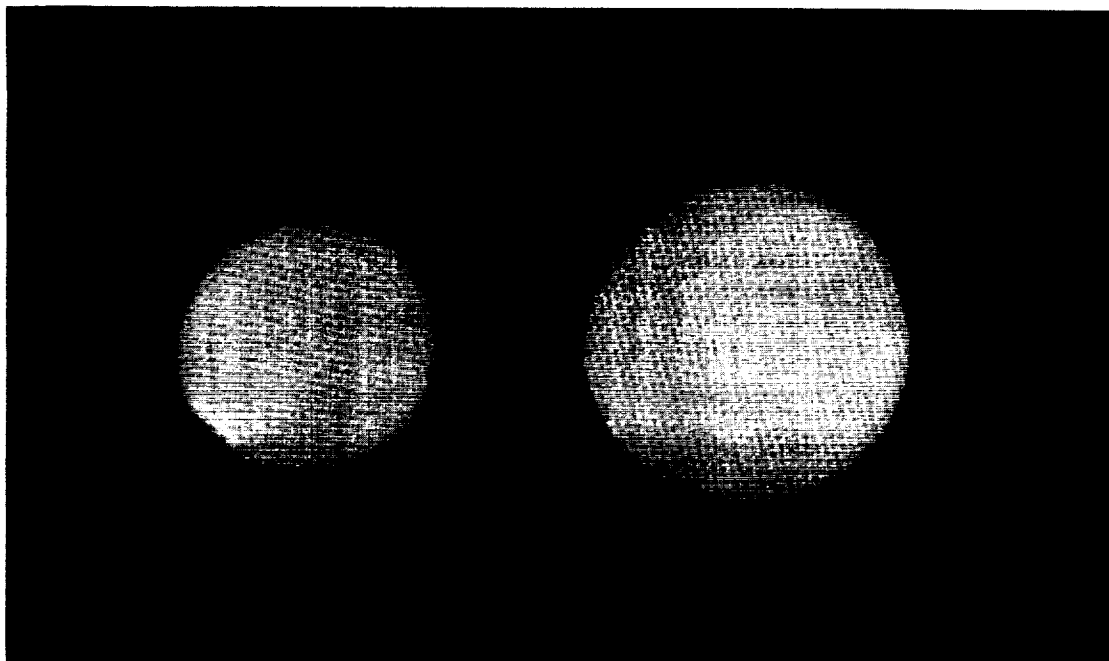


Figure 30. CV-1144-0 Silicone X389-7 on Beta Cloth—Left, flight sample; right, control sample

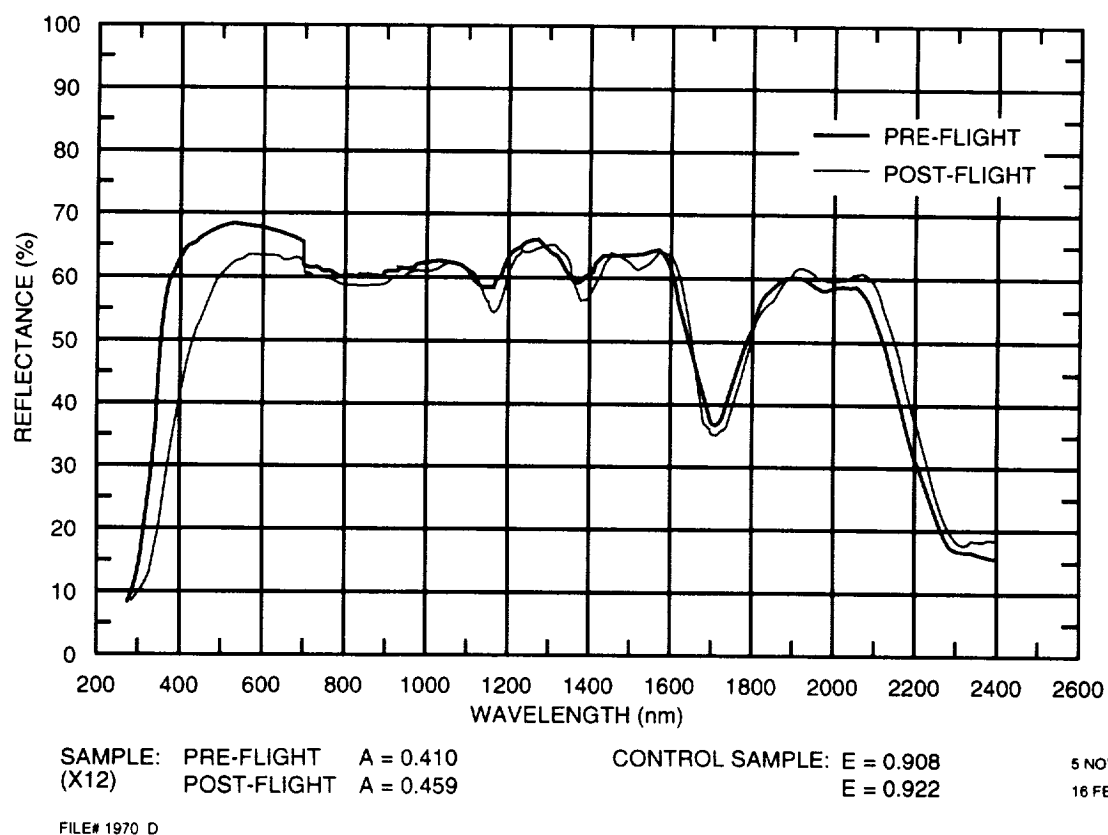


Figure 31. CV-1144-0 Silicone X389-7 on Beta Cloth—Reflectance vs. Wavelength



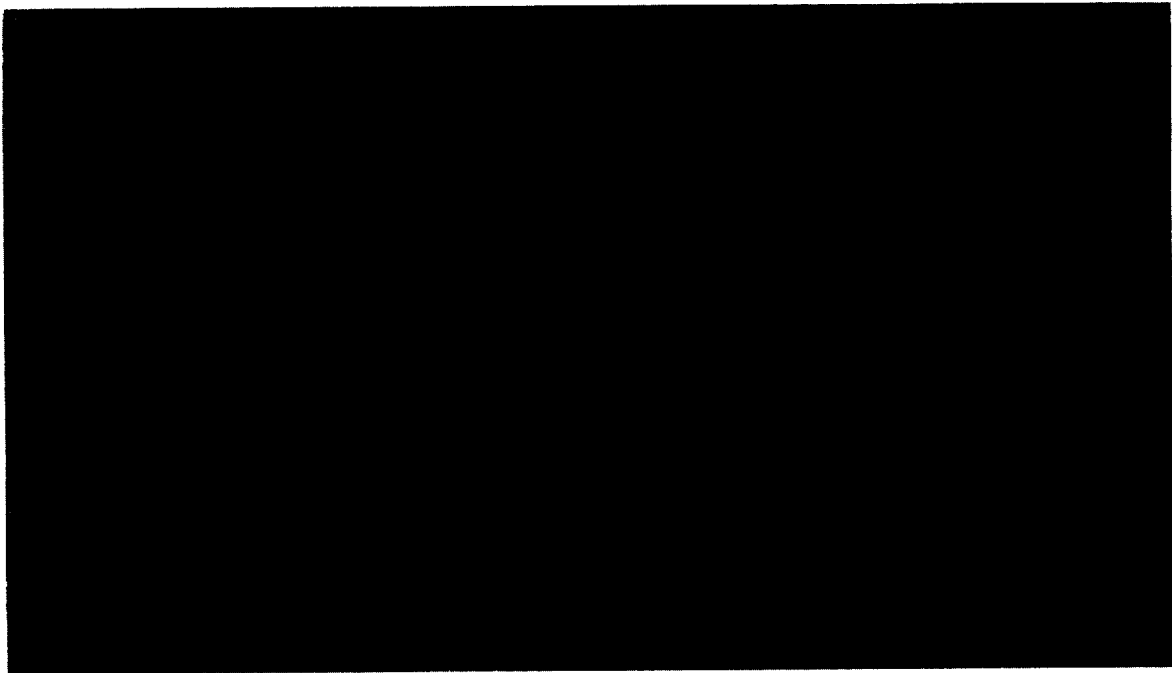


Figure 32. Chemglaze Z-306 Polyurethane Black Paint—Left, flight sample; right, control sample

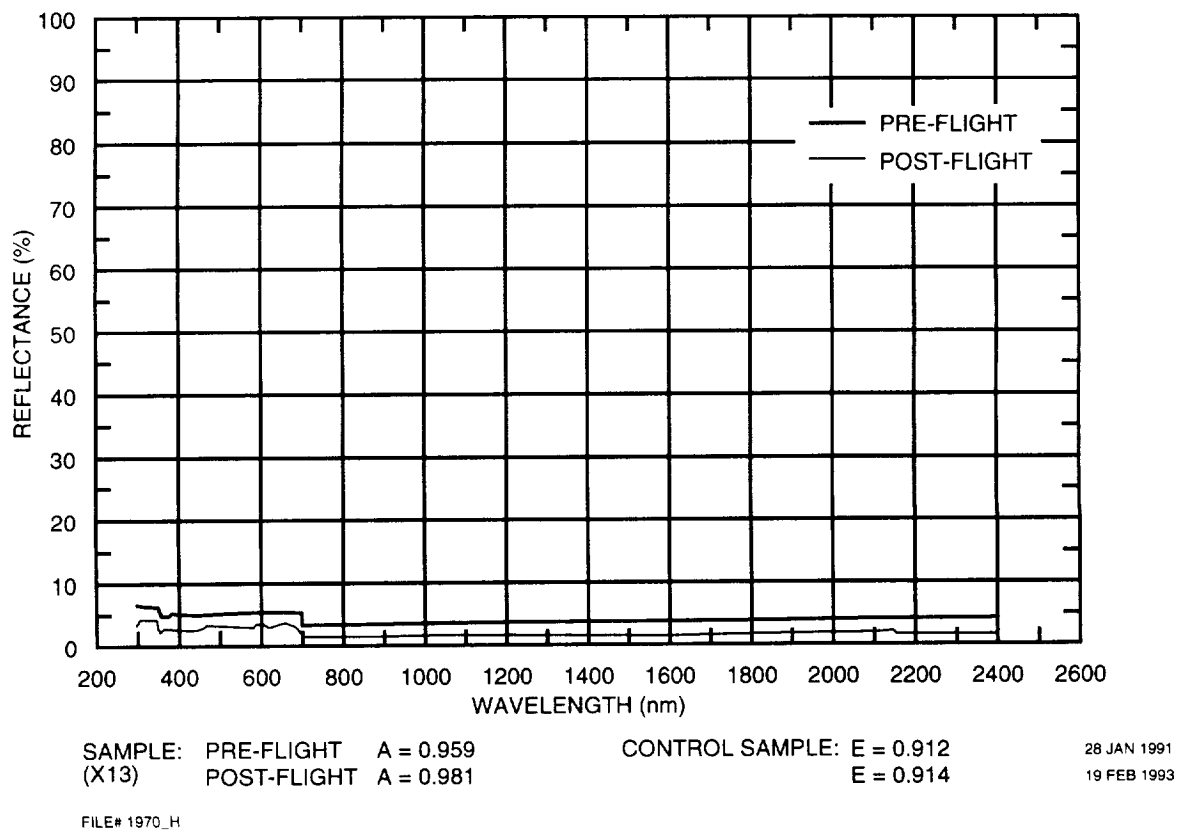


Figure 33. Chemglaze Z-306 Polyurethane Black Paint—Reflectance vs. Wavelength

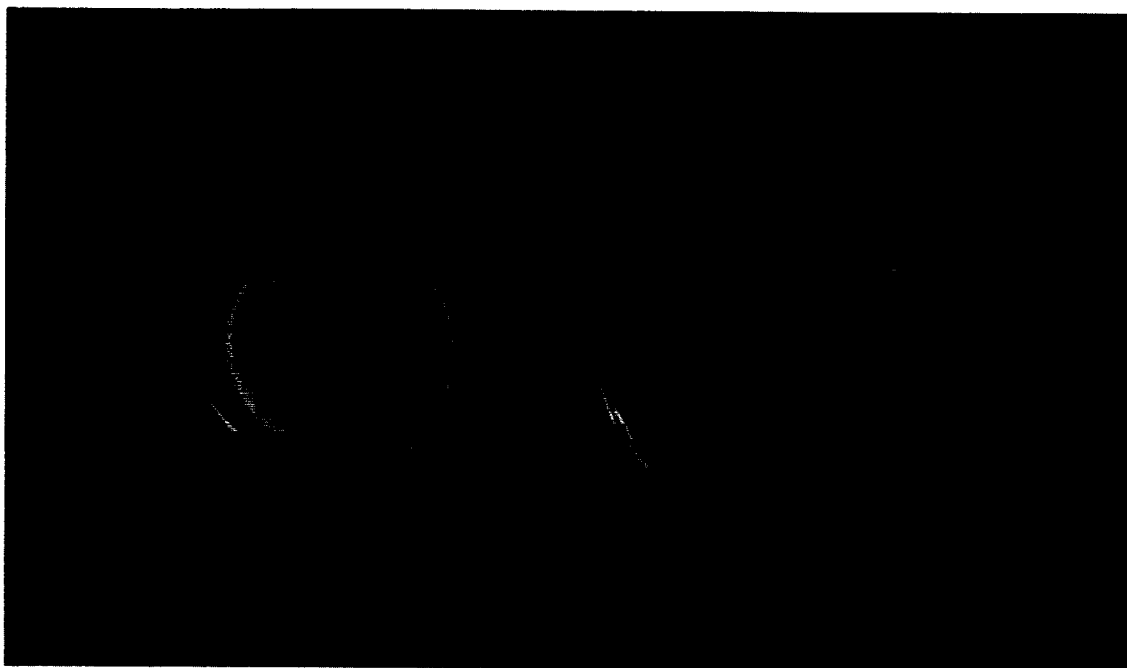


Figure 34. Ultem-1000—Left, flight sample; right, control sample

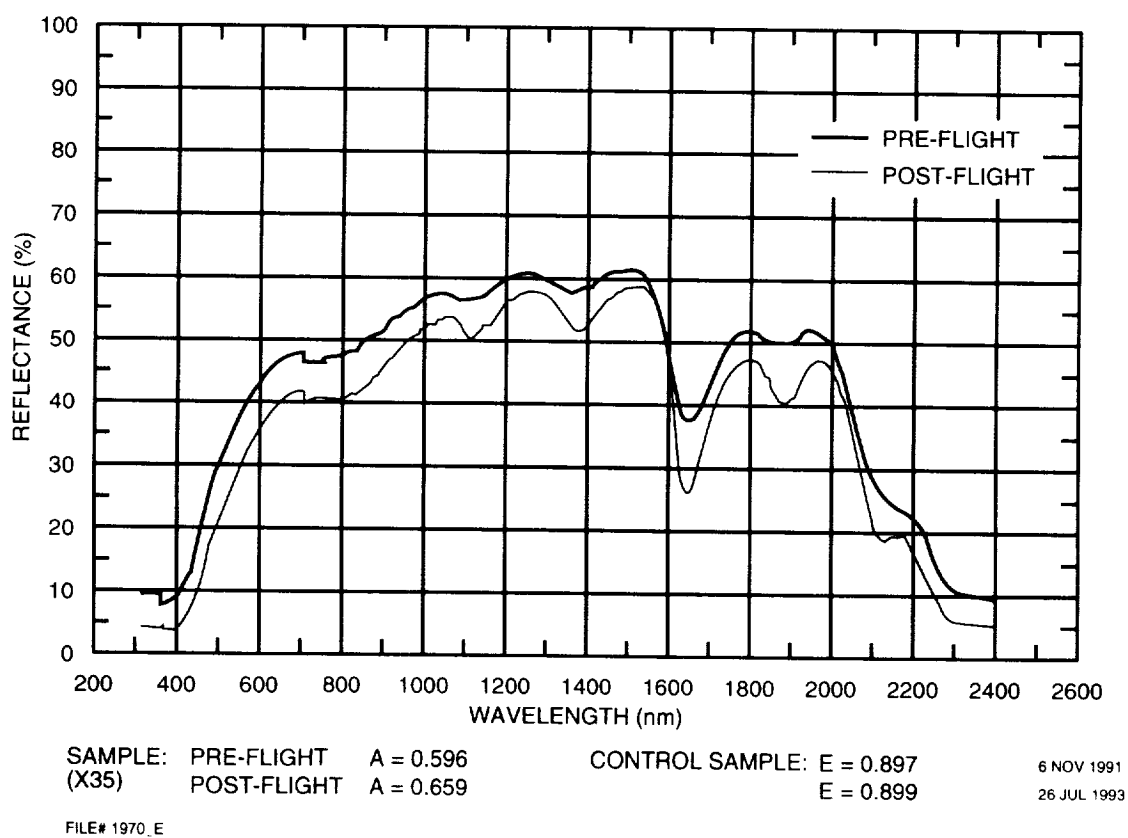


Figure 35. Ultem-1000—Reflectance vs. Wavelength

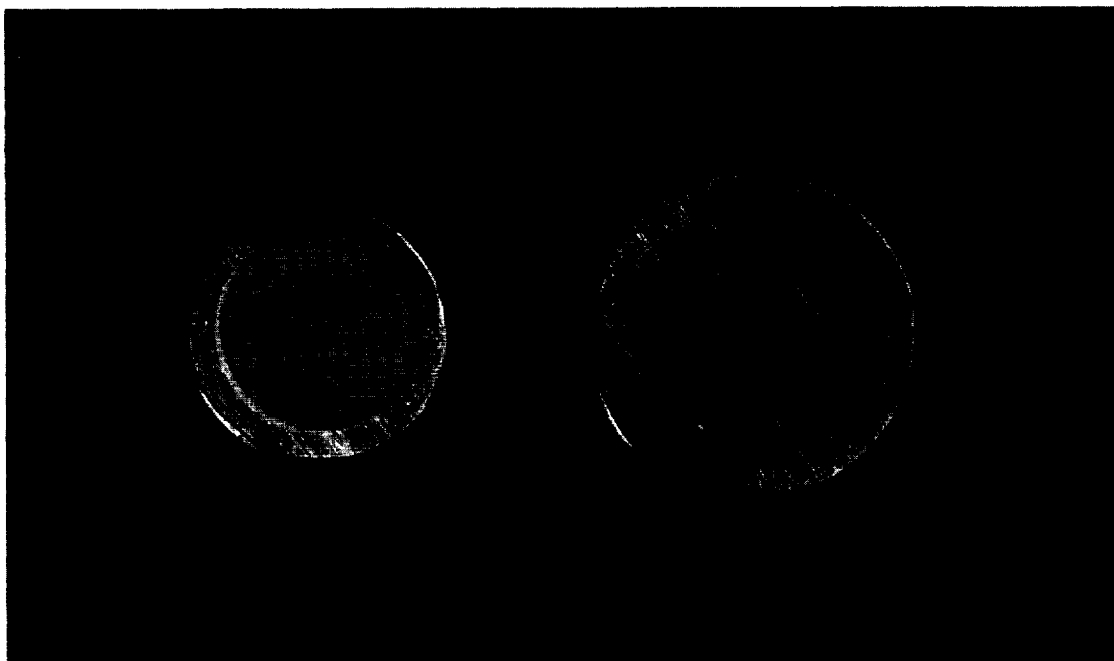


Figure 36. PEEK 450G—Left, flight sample; right, control sample

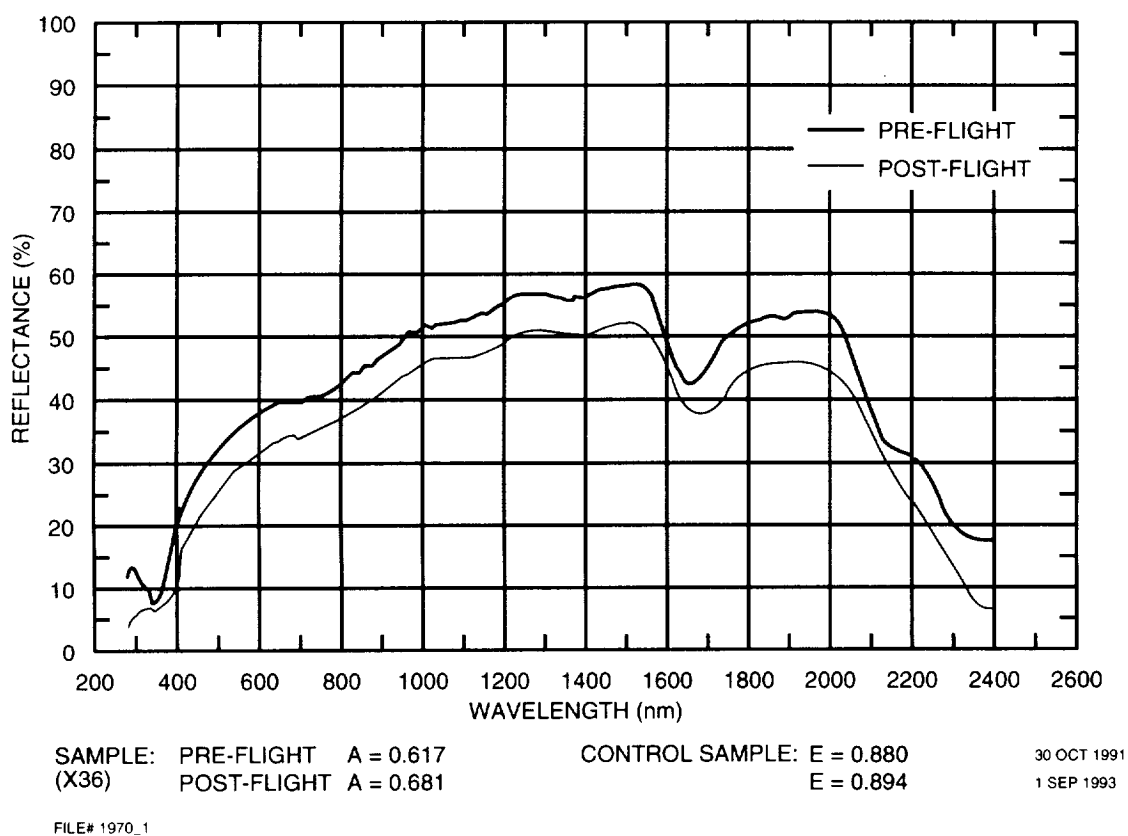


Figure 37. PEEK 450G—Reflectance vs. Wavelength

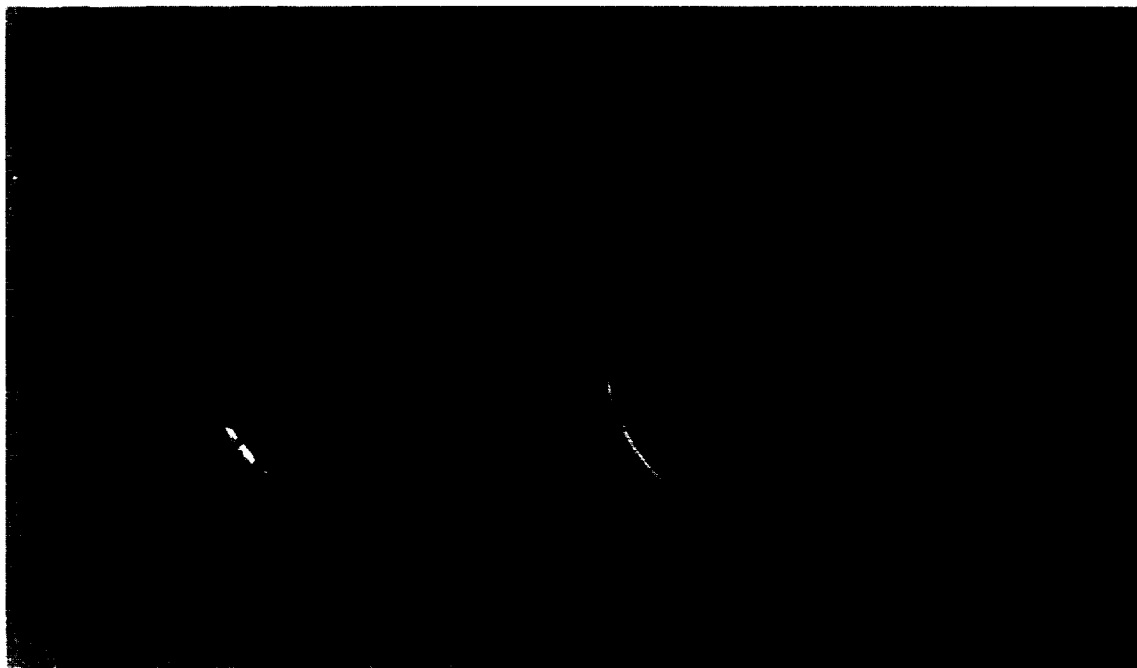


Figure 38. CV-2500 Silicone on Kapton H Film—Left, flight sample; right, control sample

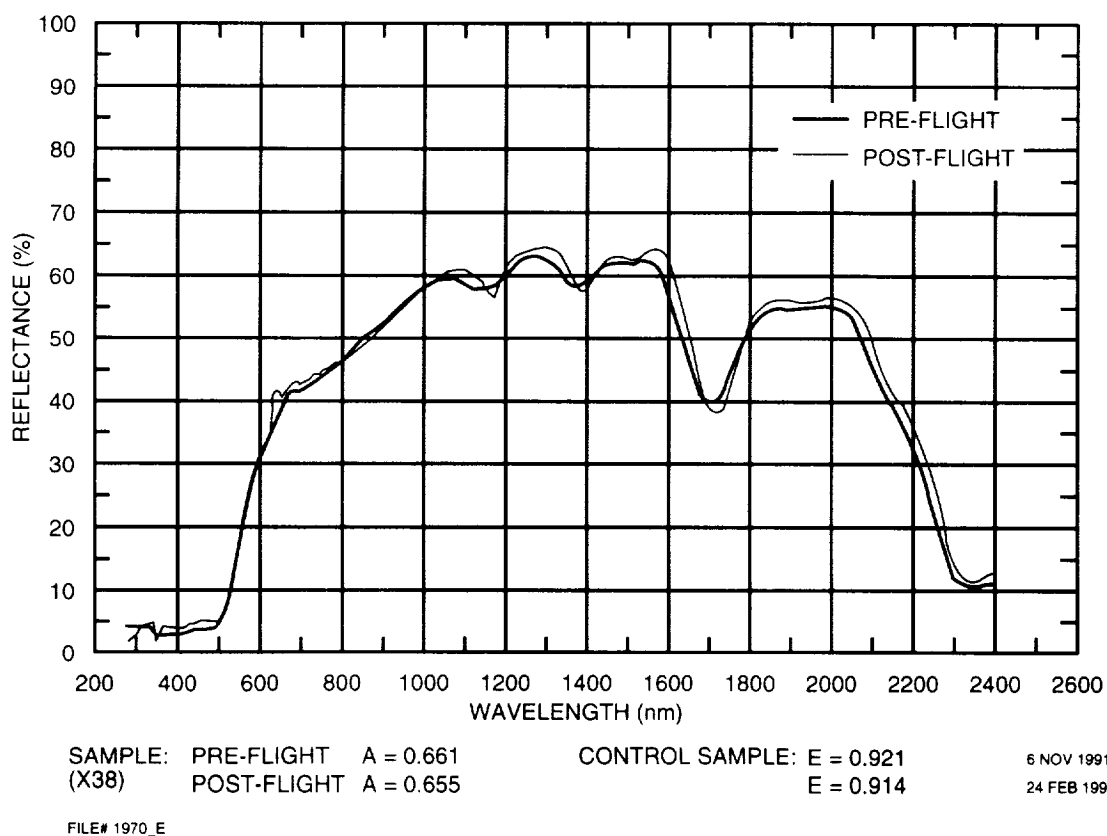


Figure 39. CV-2500 Silicone on Kapton H Film—Reflectance vs. Wavelength

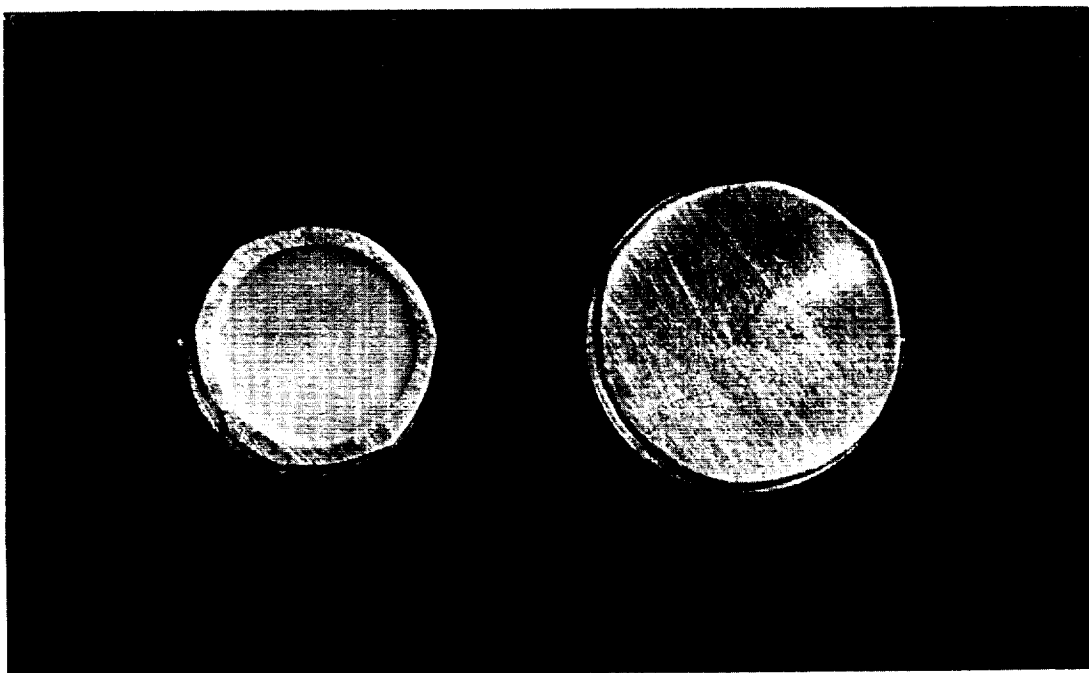
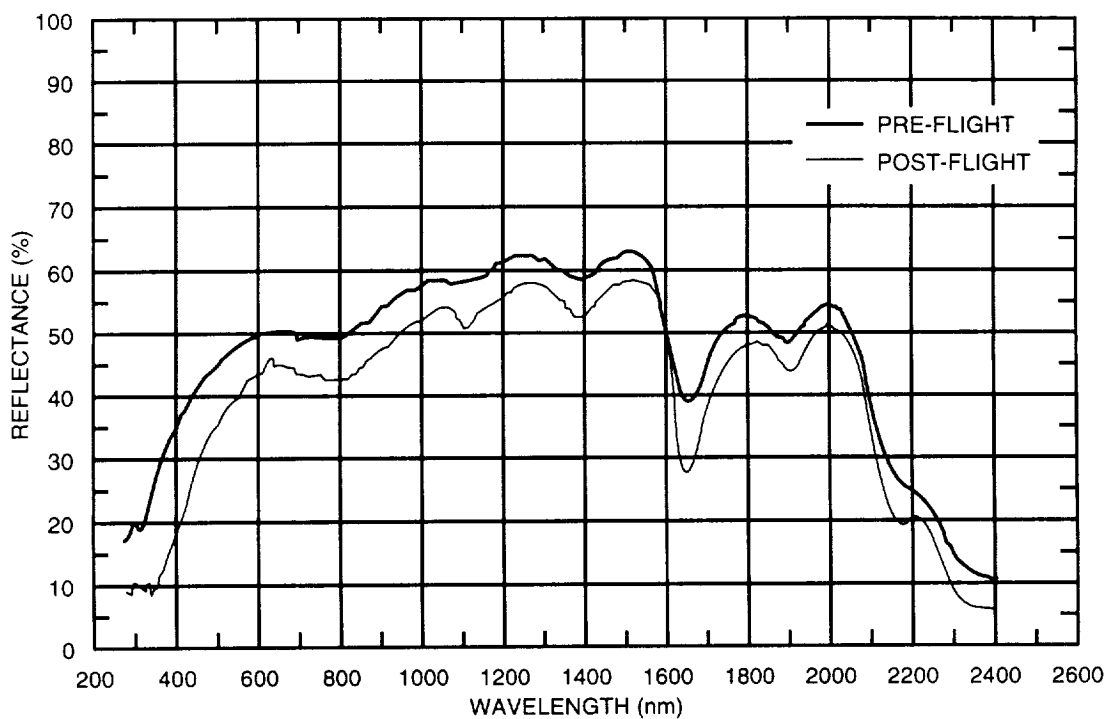


Figure 40. Polyethersulfone 4800-G (PES)—Left, flight sample; right, control sample



SAMPLE: PRE-FLIGHT A = 0.539  
(X40) POST-FLIGHT A = 0.619

CONTROL SAMPLE: E = 0.889  
E = 0.895

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Figure 41. Polyethersulfone 4800-G (PES)—Reflectance vs. Wavelength

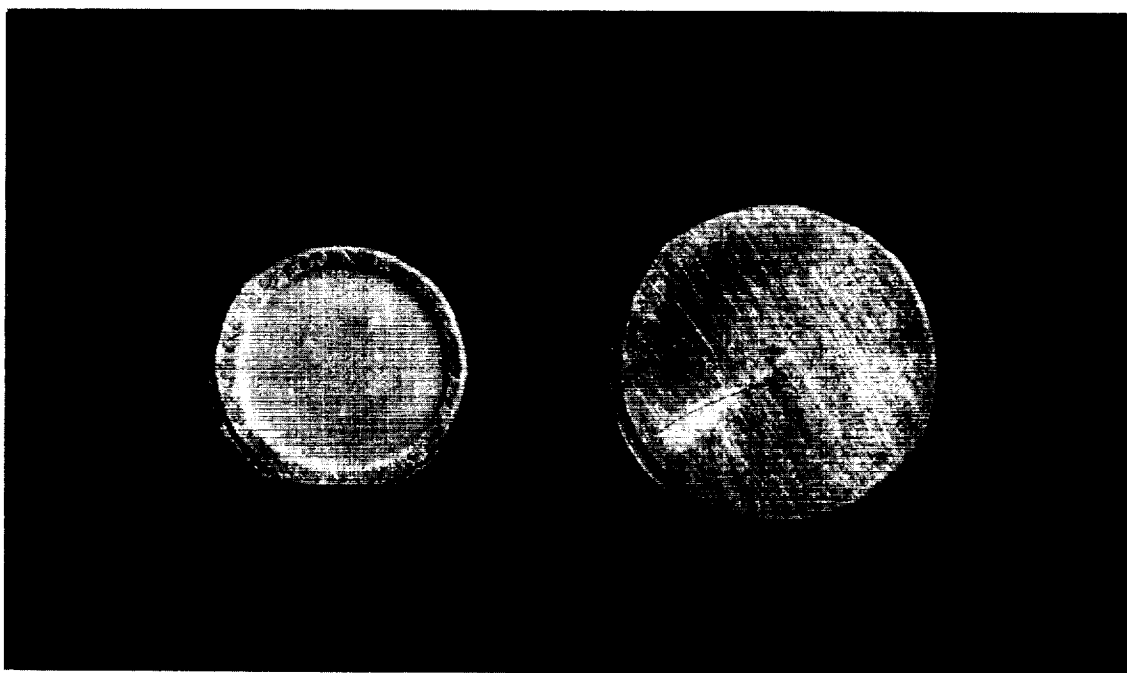


Figure 42. TPX Film—Left, flight sample; right, control sample

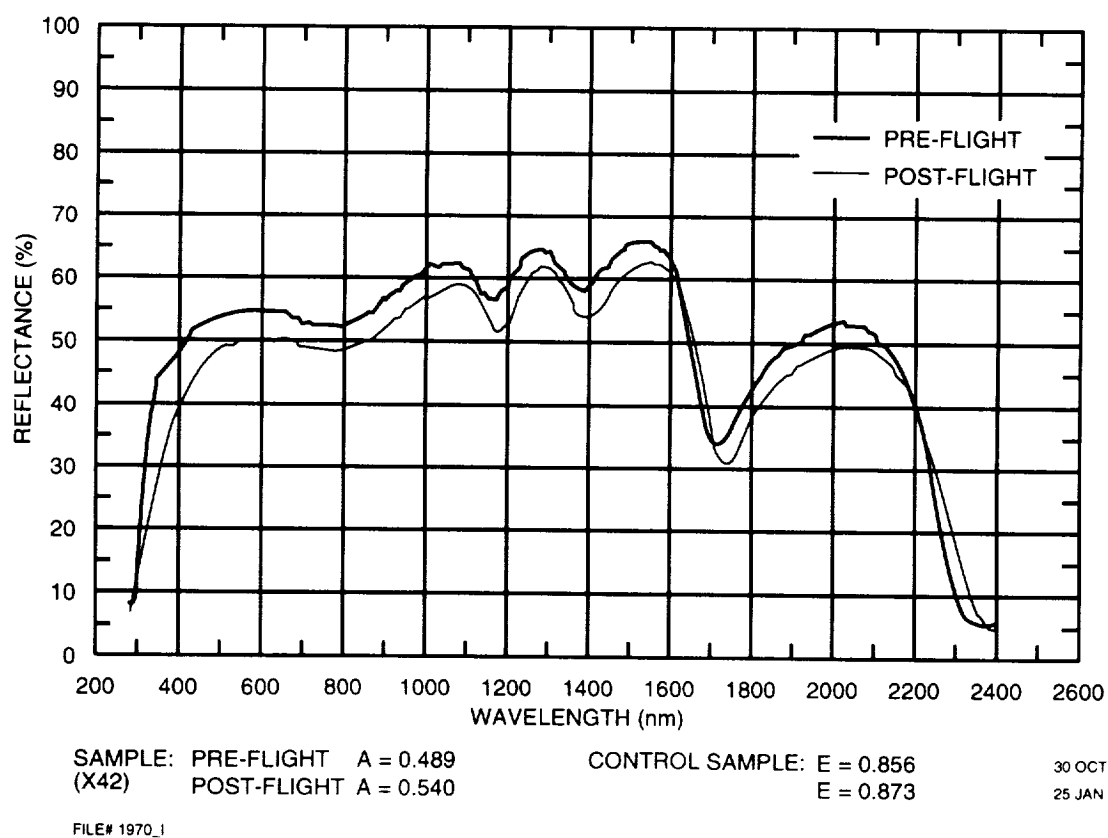


Figure 43. TPX Film—Reflectance vs. Wavelength

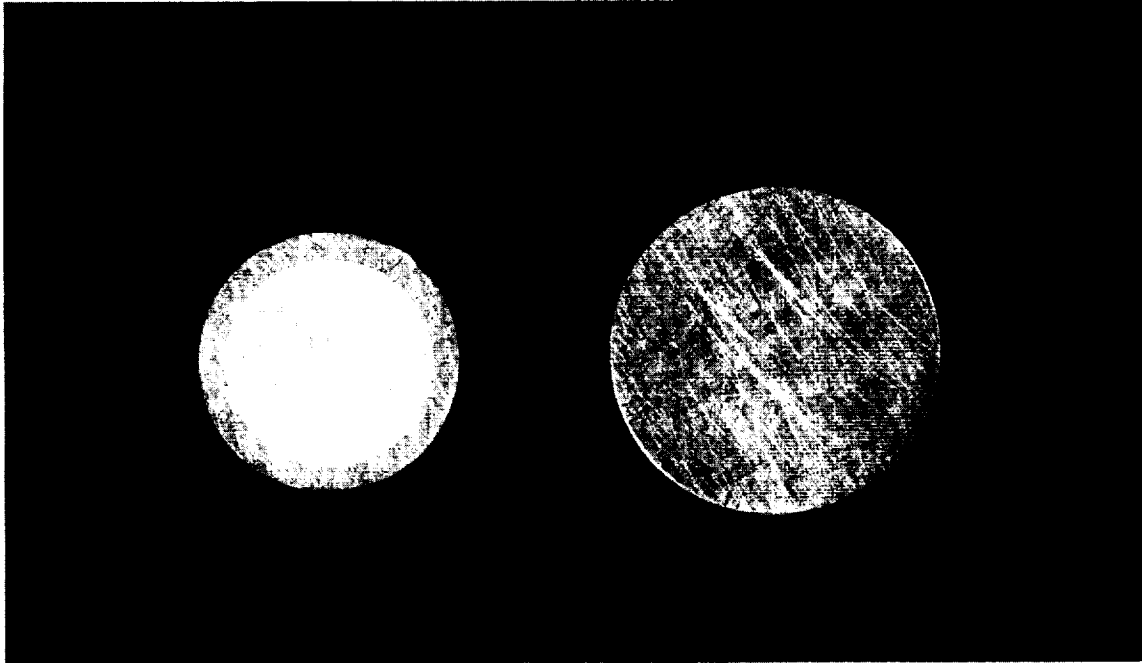


Figure 44. 3M-Pressure Sensitive Tape No. 5—Left, flight sample; right, control sample

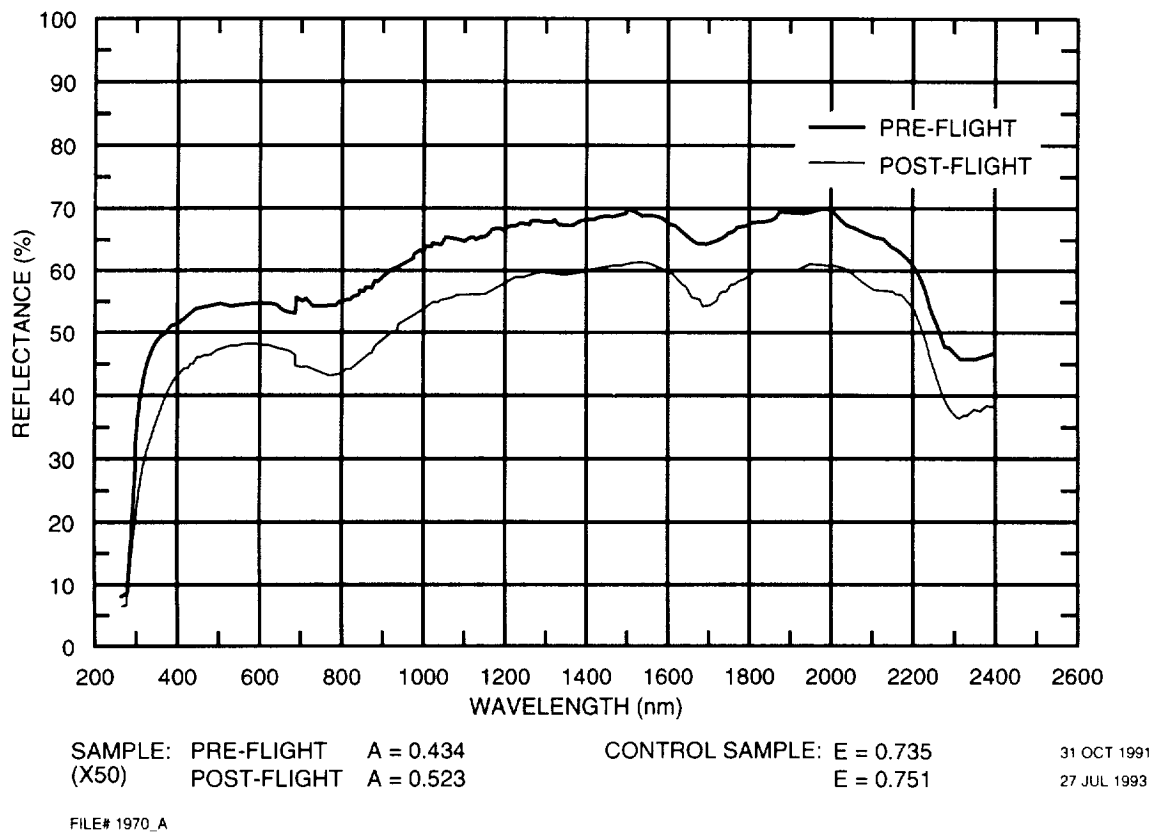


Figure 45. 3M-Pressure Sensitive Tape No. 5—Reflectance vs. Wavelength

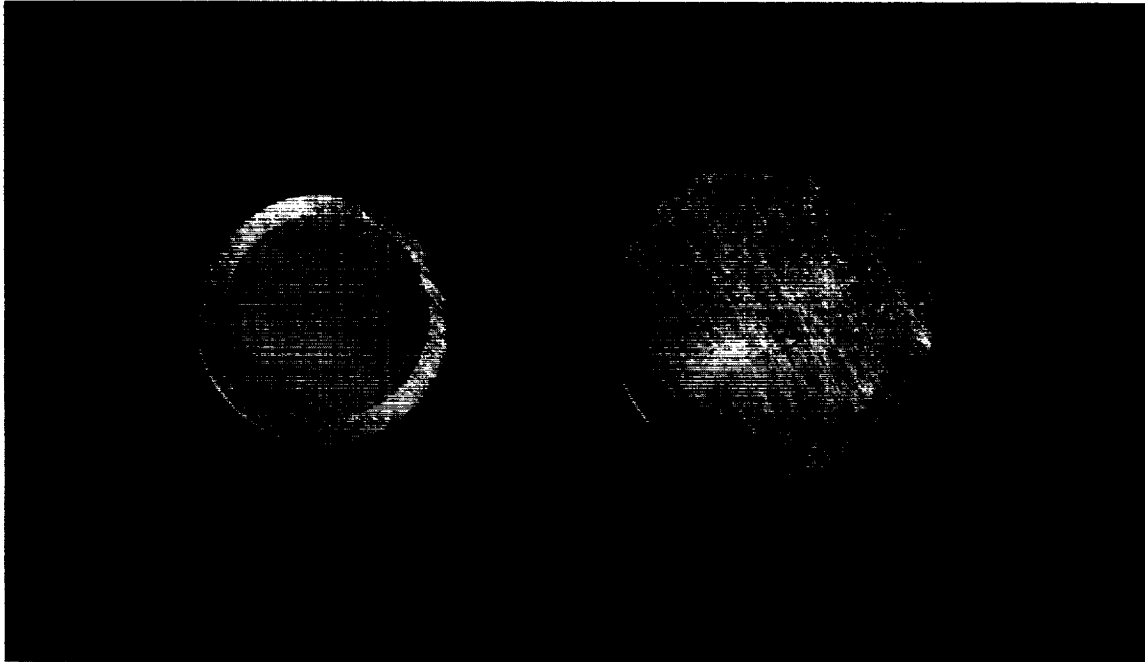
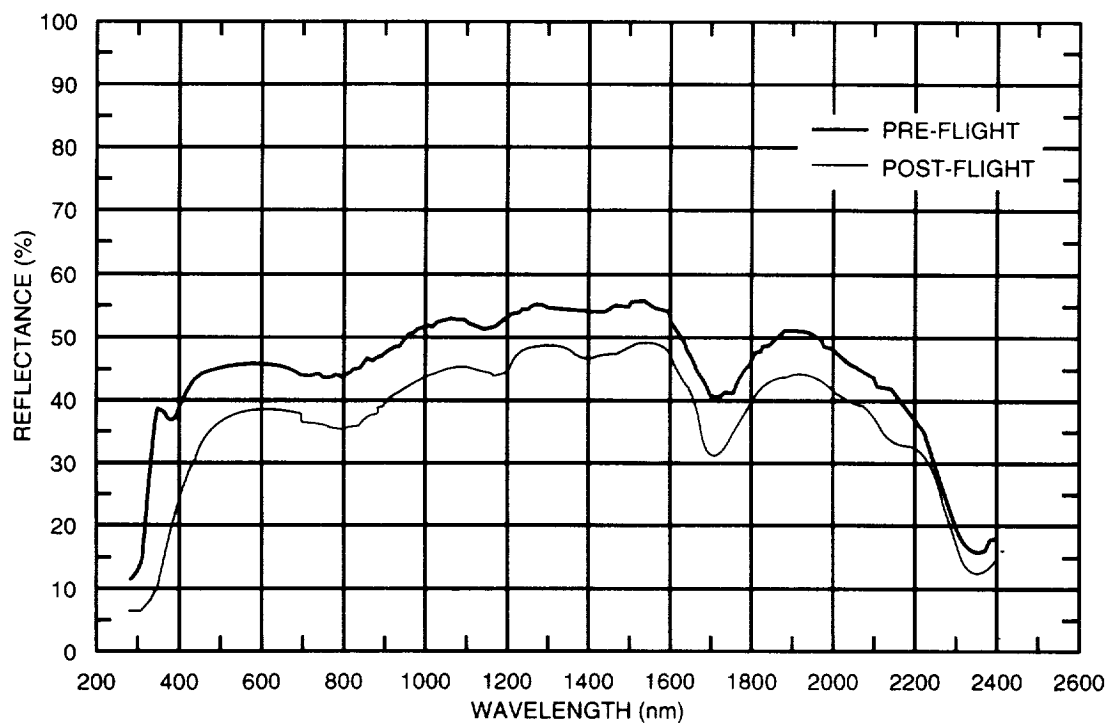


Figure 46. Uralane 5750LV-A/B—Left, flight sample; right, control sample



SAMPLE: PRE-FLIGHT A = 0.558  
(X66) POST-FLIGHT A = 0.648

CONTROL SAMPLE: E = 0.843  
E = 0.878

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Figure 47. Uralane 5750LV-A/B—Reflectance vs. Wavelength



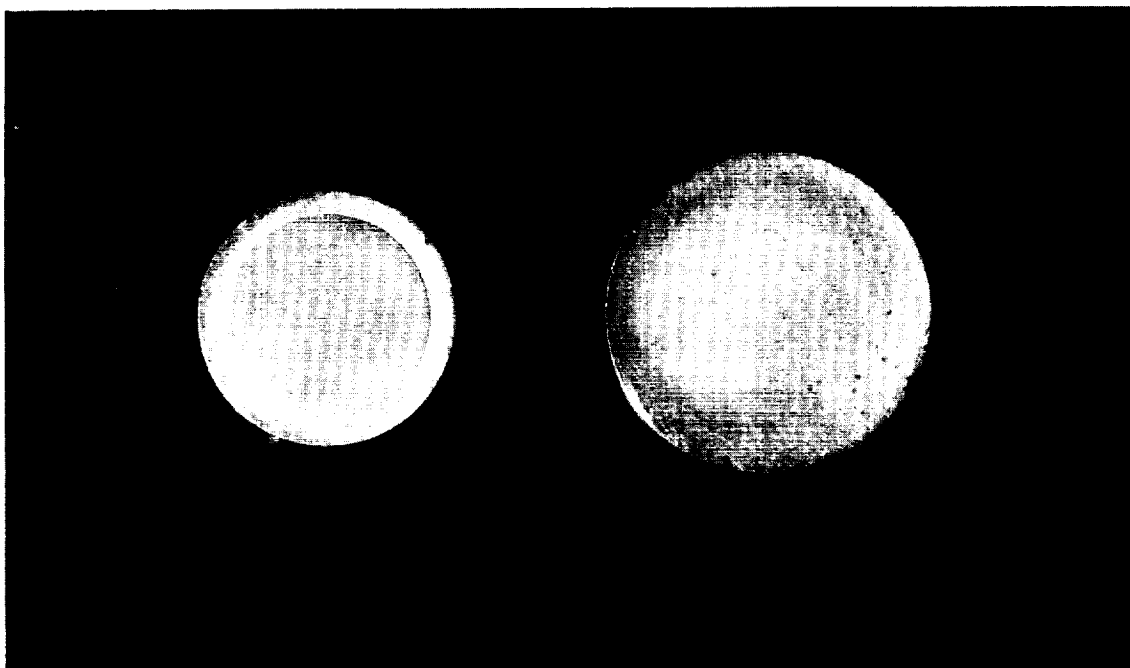


Figure 48. Uralane 5753LV-A/B—Left, flight sample; right, control sample

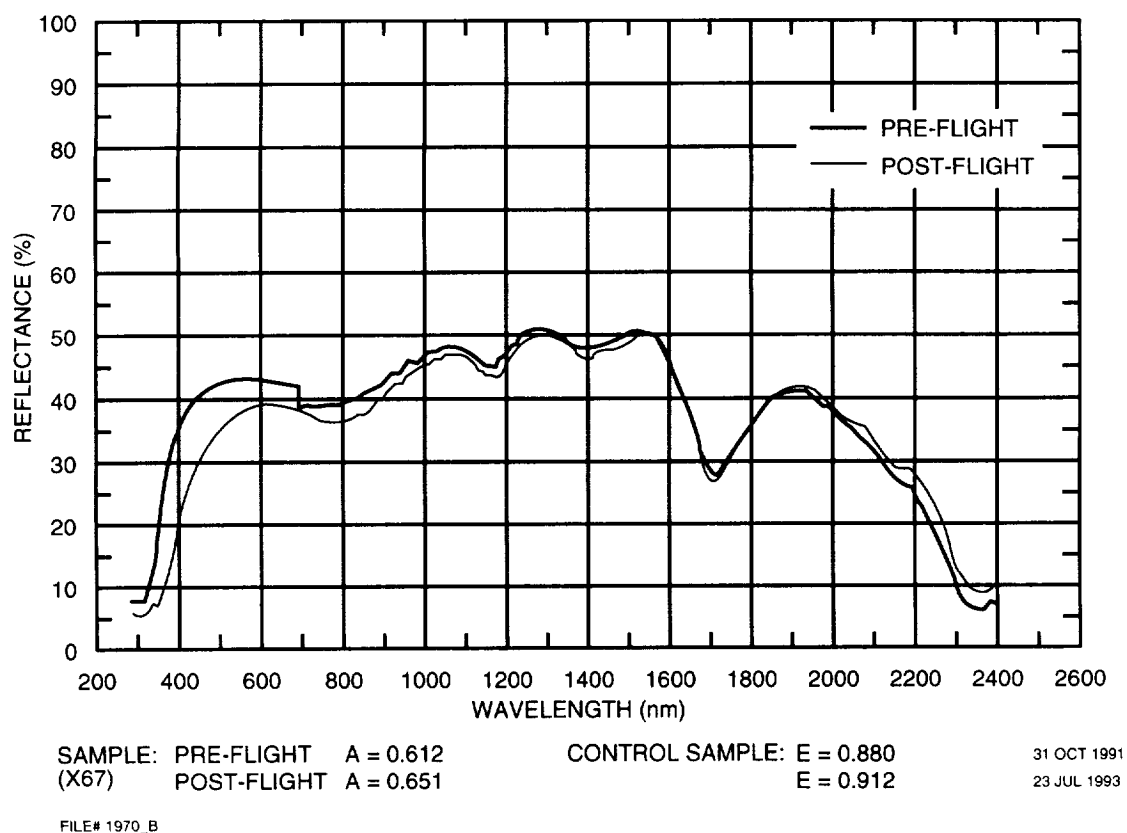


Figure 49. Uralane 5753LV-A/B—Reflectance vs. Wavelength

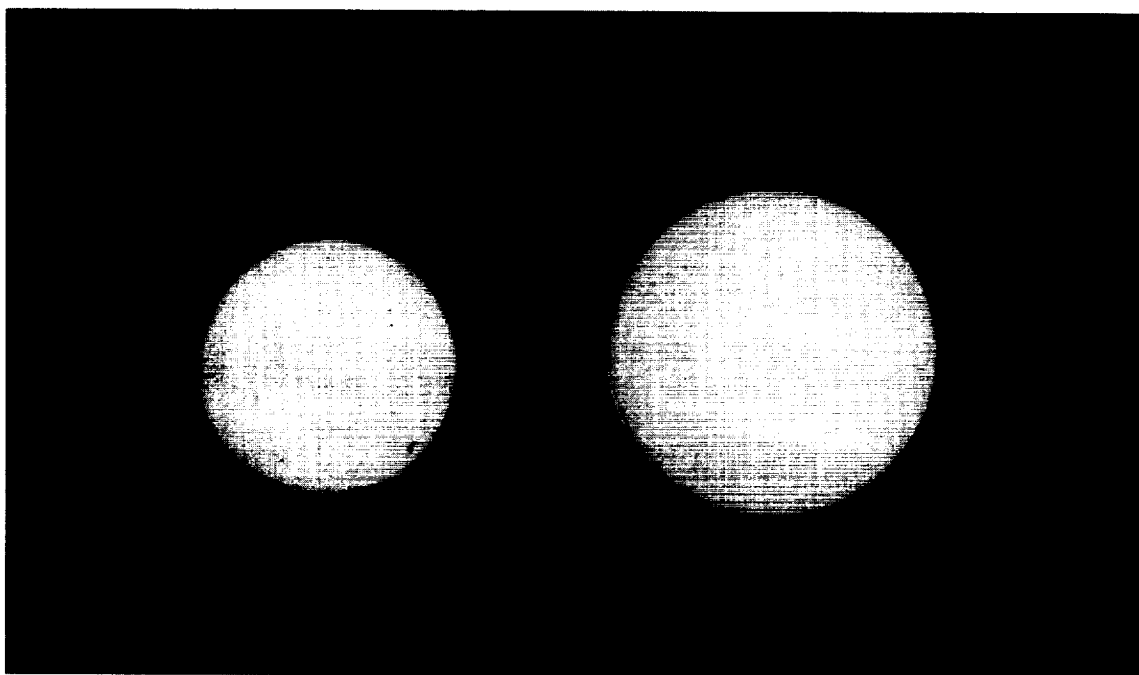


Figure 50. Epon 828/Versamid 140/TiO<sub>2</sub>—Left, flight sample; right, control sample

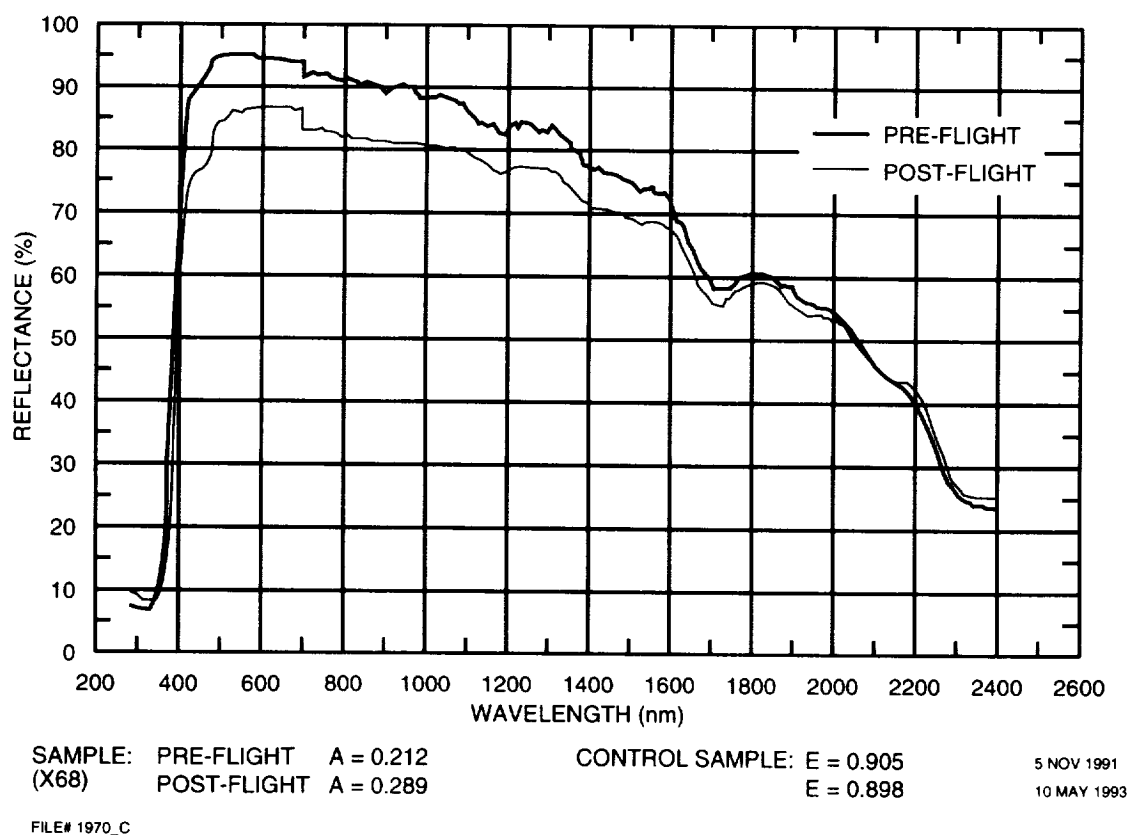


Figure 51. Epon 828/Versamid 140/TiO<sub>2</sub>—Reflectance vs. Wavelength

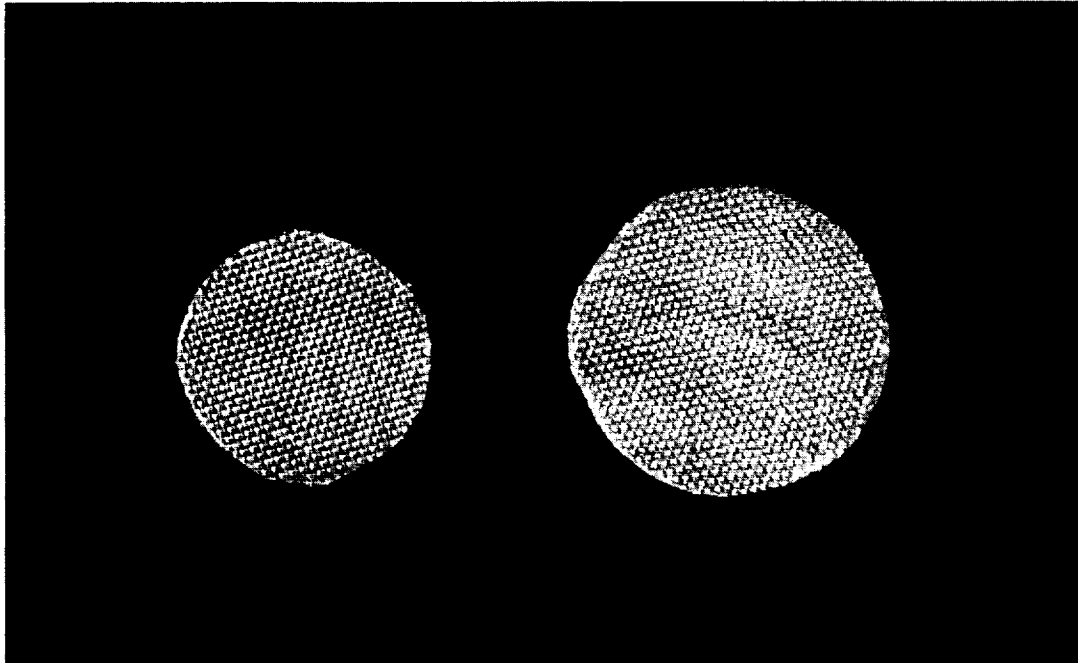


Figure 52. Aluminized Beta Cloth X389-7(Aluminized Exposed)—Left, flight sample; right, control sample

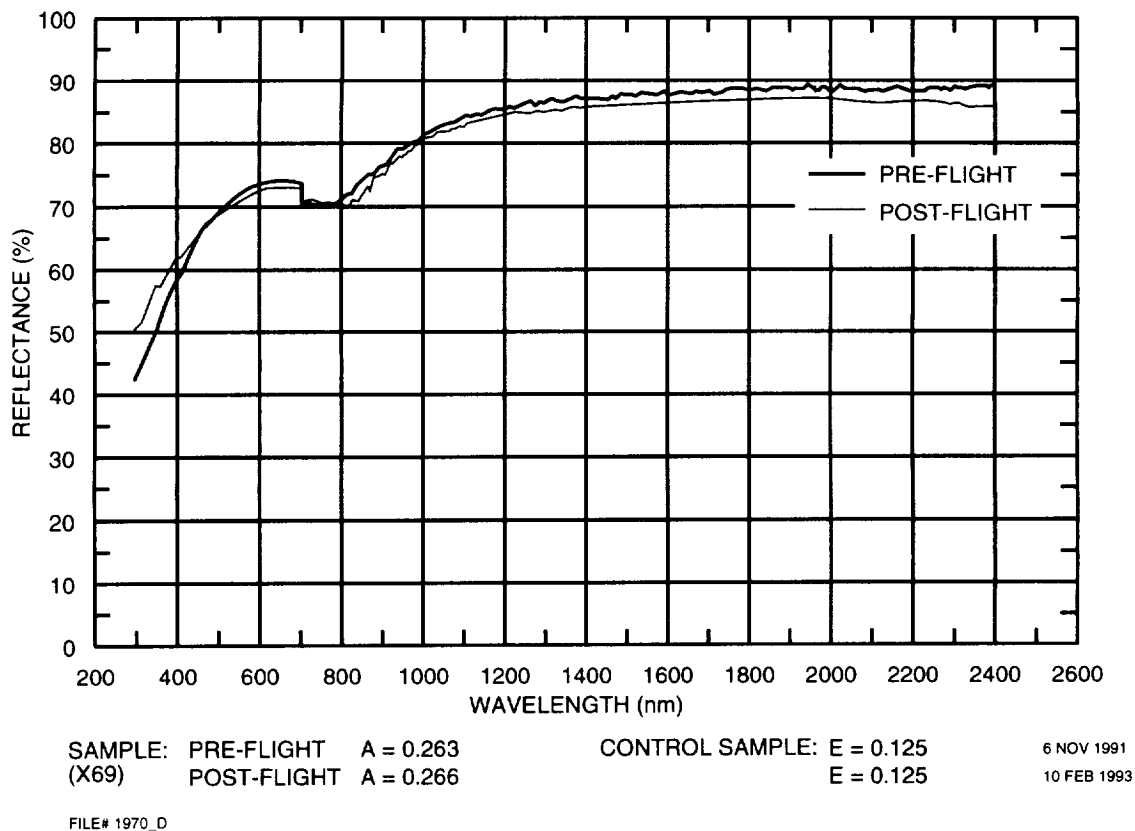


Figure 53. Aluminized Beta Cloth X389-7(Aluminized Exposed)—Reflectance vs. Wavelength



REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE November 1996		3. REPORT TYPE AND DATES COVERED Technical Memorandum
4. TITLE AND SUBTITLE  Atomic Oxygen and Space Environment Effects on Aerospace Materials Flown with EOIM-III Experiment			5. FUNDING NUMBERS  Code 313	
6. AUTHOR(S)  John J. Scialdone, Carroll H. Clatterbuck, Mary Ayres-Treusdell, Gloria Park, and Diane Kolos				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)  Goddard Space Flight Center Greenbelt, Maryland 20771			8. PERFORMING ORGANIZATION REPORT NUMBER  96B00084	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)  NASA Aeronautics and Space Administration Washington, D.C. 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER  TM-104636	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT  Unclassified-Unlimited Subject Category: 24 Report available from the NASA Center for AeroSpace Information, 800 Elkridge Landing Road, Linthicum Heights, MD 21090; (301) 621-0390.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) <p>Polymer materials samples mounted on a passive carrier tray were flown aboard the STS-46 Atlantis shuttle as complement to the EOIM-III (Evaluation of Oxygen Interaction with Materials) experiment to evaluate the effects of atomic oxygen on the materials and to measure the gaseous shuttle bay environment.</p> <p>The morphological changes of the samples produced by the atomic oxygen fluence of <math>2.07\text{E-}20</math> atoms/cm<sup>2</sup> are being reported. The changes have been verified using Electron Spectroscopy for Chemical Analysis (ESCA), gravimetric measurement, microscopic observations and thermo-optical measurements. The samples, including Kapton, Delrin, epoxies, Beta Cloth, Chemglaze Z306, silver Teflon, silicone coatings, 3M tape and Uralane and Ultem, PEEK, Victrex (PES), Polyethersulfone and Polymethylpentene thermoplastic, have been characterized by their oxygen reaction efficiency on the basis of their erosion losses and the oxygen fluence. (See Table 1 for source name.) Those efficiencies have been compared to results from other experiments, when available. The efficiencies of the samples are all in the range of E-24 g/atom. The results indicate that the reaction efficiencies of the reported materials can be grouped in about three ranges of values. The least affected materials which have efficiencies varying from 1 to 10 E-25 g/atom, include silicones, epoxies, Uralane and Teflon. A second group with efficiency from 10 to 45 E-25 g/atom includes additional silicone coatings, the Chemglaze Z306 paint and Kapton. The third range from 50 to 75 E-25 includes organic compound such as Pentene, Peek, Ultem, Sulfone and a 3M tape. A Delrin sample had the highest reaction efficiency of 179 E-25 g/atom. Two samples, the aluminum Beta cloth X389-7 and the epoxy fiberglass G-11 nonflame retardant, showed a slight mass increase.</p>				
14. SUBJECT TERMS Polymer materials, STS-46 Atlantis, ESCA, EOIM-III			15. NUMBER OF PAGES 61	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited	

