

AEDC-TR-93-7

AD-A267 202



Solar Absorptance of Optical Surfaces
Contaminated with Spacecraft
Material Outgassing Products

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June 1993

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Final Report for Period July 8 – July 27, 1992

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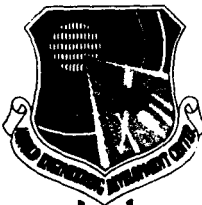
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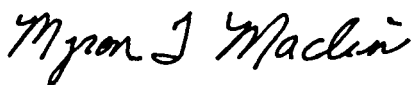
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APPROVAL STATEMENT

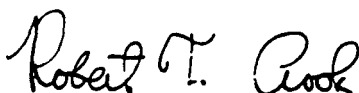
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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering 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 July 1993	3. REPORT TYPE AND DATES COVERED Final Report for July 8 - 27, 1992		
4. TITLE AND SUBTITLE Solar Absorptance of Optical Surfaces Contaminated with Spacecraft Material Outgassing Products		5. FUNDING NUMBERS PE 62102F DB72VW		
6. AUTHOR(S) Bertrand, W. T. and Wood, B. E. Calspan Corporation/AEDC Operations				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Arnold Engineering Development Center/DOT Air Force Materiel Command Arnold Air Force Base, TN 37389-5000		8. PERFORMING ORGANIZATION REPORT NUMBER AEDC-TR-93-7		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Wright Laboratory Materiel Directorate (AFWL/ML) Wright-Patterson AFB, OH 45433		10. SPONSORING/MONITORING AGENCY REPORT NUMBER		
11. SUPPLEMENTARY NOTES Available in Defense Technical Information Center (DTIC).				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.		12b. DISTRIBUTION CODE		
13. ABSTRACT (Maximum 200 words) As satellite applications become more sophisticated and satellite lifetimes are extended, the roles of contamination prediction and control become increasingly important. Contamination can alter the spectral characteristics of cryogenically cooled optical systems, increase the solar absorptance of thermal control surfaces causing the spacecraft to overheat, or degrade the power output of solar cells. The Solar Absorptance Measurements Chamber was developed to measure the change in integrated solar absorptance of aluminum coated mirrors by condensed outgassing contaminants irradiated by a solar simulator under vacuum. In previous tests, the location of the solar simulator did not allow irradiation of the sample mirror during the contamination phase. The test chamber was modified, and measurements were made to compare the solar absorptance change for samples irradiated during contamination to samples with no irradiation during contamination. Sources of the contaminants were two spacecraft materials, Furane Products Uralane® 5753-AB (LV) encapsulant and Dow Corning 93-500 encapsulant.				
14. SUBJECT TERMS solar absorptance quartz crystal microbalance		15. NUMBER OF PAGES 26		
		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 SAME AS REPORT	

PREFACE

The work reported herein was performed by the Arnold Engineering Development Center (AEDC), Air Force Materiel Command (AFMC), under Program Element 62102F. The results were obtained by Calspan Corporation, AEDC Operations, technical services contractor for Aerospace Flight Dynamics Testing at AEDC, AFMC, Arnold Air Force Base, TN, under AEDC Project No. DB72VW (V32K-CT). The project was sponsored by the Air Force Wright Laboratory Materiel Directorate (AFWL/ML), Wright Patterson AFB, OH. The AFWL/ML Project Manager was Lt. Michele Jones, and the AEDC Project Manager was Capt. Seth Shepherd.

The authors would like to thank Bill Hobbs, Winfred Johnson, and L. E. Phillips for their help with the Solar Absorptance Measurements (SAM) Chamber operation and instrumentation, and John Henry Jones for the spectrometer data acquisition program.

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1.0 INTRODUCTION

As satellite applications become more sophisticated and satellite lifetimes are extended, the roles of contamination prediction and control become increasingly important. Contamination can alter the spectral characteristics of cryogenically cooled optical systems, increase the solar absorptance of thermal control surfaces causing the spacecraft to overheat, or degrade the power output of solar cells.

The Air Force Wright Laboratory Materiel Directorate (AFWL/ML) is pursuing a plan to determine the outgassing properties of materials and the effects of condensed gases on critical surfaces. The Solar Absorptance Measurements (SAM) Chamber was built to investigate the effects of solar radiation on contaminant films. The primary goal of this work was to obtain the absorptance change on an aluminum mirror as a function of contaminant thickness and solar irradiation time. The spectral absorptance measurements were made over the wavelength range from 250 to 2,300 nm. Because the samples were non-transmitting, the spectral absorptance, $\alpha(\lambda)$, can be determined from $1 - r(\lambda)$, where $r(\lambda)$ is the spectral reflectance. The spectral reflectance was the quantity measured.

In previous tests (Ref. 1) a contaminant was condensed on an aluminum mirror in vacuum, and the change in reflectance was measured as a function of film thickness. Then, the contaminated mirror was irradiated with a xenon solar lamp, and the change in reflectance with solar irradiation time was measured.

To better simulate the process on a spacecraft, the test chamber was modified to provide solar irradiation of the sample mirror during deposition of the contaminant. A specified thickness of contaminant was deposited on the mirror. Exposure of the sample continued until no change in reflectance was measured. Solar absorptance data were obtained for outgassed products from two spacecraft materials to evaluate the effect of the new test procedure. The materials were Furane Products Uralane® 5753 – A/B (LV) urethane casting compound and Dow Corning 93-500 encapsulant.

2.0 EXPERIMENTAL TEST APPARATUS

2.1 SOLAR ABSORPTANCE MEASUREMENTS CHAMBER

The Solar Absorptance Measurements (SAM) Chamber provides a technique for measuring changes in the absorption of solar radiation by thermal control or optical surfaces contaminated by outgassing products at vacuum conditions. The equipment also allows generation of the outgassing products within the chamber and the determination of the amount of material deposited on the sample surface using a Quartz Crystal Microbalance (QCM). The condensed

outgassing products can be irradiated by simulated solar radiation during and after deposition. The chamber and associated contamination equipment are shown in Fig. 1. The details of each of these systems are discussed separately in the following sections.

The SAM Chamber vacuum is maintained by a 360-ℓ/sec turbomolecular pump. The chamber is also outfitted with a liquid nitrogen cooled liner that can be used when test conditions dictate; however, this liner was not cooled for the measurements reported herein. Pressure in the chamber is measured with a Bayard-Alpert-type ion gauge and can be maintained below 4×10^{-6} torr when the contaminant load is small.

2.2 EFFUSION CELL

The outgassing products for contaminating the sample surface are generated using an effusion cell, shown schematically in Fig. 2. The effusion cell has a cylindrical aluminum body 8.9 cm (3.5 in.) long with an internal bore of 4.45 cm (1.75 in.) in diameter. One end is closed, and the other end has a replaceable orifice plate and a shutter to interrupt the contamination flux, if required. The material used to produce the outgassing flux is loaded into the open end of the effusion cell. Three band heating elements clamped around the outside of the cylinder are used to heat the effusion cell to the desired temperature, usually 125°C. A platinum resistance temperature detector (RTD) mounted in the effusion cell housing senses the effusion cell temperature. Output of the RTD feeds a proportional temperature controller which varies the power applied to the heaters, keeping the effusion cell temperature within 1°C of the set point. The controller has an analog output from which the effusion cell temperature is recorded. The effusion cell is capable of maintaining temperatures from ambient to 200°C.

The effusion cell is lined with disposable aluminum foil liners. The liners and aluminum foil sample boat are baked at 125°C for 24 hr prior to each material test. This ensures that the deposited contaminants come from the material being tested and not the peripheral components. New aluminum foil liners and boats are installed after each material test. To terminate the effusion cell output, the effusion cell is equipped with a shutter that can be closed.

2.3 QUARTZ CRYSTAL MICROBALANCE (QCM)

For measuring the mass deposition on the sample surface, a water-cooled QCM is used. The QCM and the sample-collecting surface are located equidistant from the effusion cell exit and symmetrically about the effusion cell axis. Prior to testing, a second QCM was placed at the position of the sample mirror to determine the uniformity of the contaminant flux from the effusion cell.

A QCM is based on the principle that the oscillation frequency of a quartz crystal varies proportionally to its mass or any mass adhering to the crystal surface. The oscillation frequency is also dependent upon other things such as temperature. To compensate for temperature effects, the QCMs selected are made up of two quartz crystal oscillators in a single housing (Fig. 3). The oscillator outputs are mixed, and their difference frequency is monitored. One crystal oscillator (the reference oscillator) is enclosed and shielded from contaminants, sensing temperature effects but not contaminants. One surface of the other quartz crystal oscillator is polished to an optical finish and overcoated with aluminum. It is exposed to the contaminant flow and is used as the mass-sensing oscillator. The change between the two oscillator frequencies, (i.e., the change in the difference frequency) is attributed to the accumulated mass from the contaminant.

The relation between the difference frequency change (Δf) and the deposited mass (Δm) can be expressed as (Ref. 2)

$$\Delta m = 1.4 \times 10^{(-9)} \Delta f \text{ gm/Hz} \quad (1)$$

or

$$\Delta m/S = 4.43 \times 10^{-9} \Delta f \text{ gm/cm}^2 * \text{Hz} \quad (2)$$

where S = surface area of the sensing crystal electrode, 0.316 cm^2 . If a density of 1.0 gm/cm^3 is assumed for the film, then the change in film thickness (t) can be calculated from the frequency change (Δf) using the equation

$$\Delta t = 4.43 \times 10^{-9} \times \Delta f \quad (3)$$

where t is given in cm and Δf is given in Hz. For the results presented, a specific gravity of 1.0 was assumed.

Both quartz crystals have crystal cuts selected to minimize temperature effects at the selected operating temperature. In this case, the crystal cut is optimized for 25°C operation by using crystals with a cut of 35.2 deg . Temperatures of the QCM and sample are stabilized by flowing water through passages in the QCM housing and the sample arm.

The QCM has a platinum resistance device placed between the sensing and reference crystals that functions as both a temperature sensor and a low-power (2-W) heater through a time-sharing electronic circuit. In this way, the temperature of the crystals may be monitored and small temperature changes made.

The QCM electronic controller has three analog outputs. They are mass, temperature, and mass rate. In addition, the frequency can be sent to a counter or a frequency-to-voltage

converter. The mass deposited on the sensing crystal is determined by recording the change in mass directly or by monitoring the difference frequency between the sensing crystal and the reference crystal.

2.4 CONTAMINATION DEPOSITION SURFACES

The sample mirrors consisted of 2.5-cm-diam nickel mirrors with a bare aluminum coating. The mirror assembly was mounted to the positioning arm of the SAM Chamber. The positioning arm was maintained near 25°C by flowing water from a temperature-controlled bath through it.

2.5 REFLECTANCE MEASURING APPARATUS

The reflectance measurement apparatus consists of a Beckman DK2A, double beam, quartz prism spectrometer with the Beckman integrating sphere reflectance attachment. The reflectance attachment was modified by removing the internal sphere and redirecting the two optical beams into an external integrating sphere attached to the SAM Chamber and maintained at the same pressure as the SAM Chamber. The reflectance sample mirror is mounted to a positioning arm that can be translated and rotated (see Fig. 1). For reflectance measurements, the sample mirror is inserted into the integrating sphere. To contaminate the mirror, the arm is retracted until the mirror is in front of the effusion cell.

The Beckman DK2A consists of a light source housing that directs light into the entrance slit of a quartz prism monochromator. The monochromatic light leaving the monochromator exit slit passes through a 480-Hz chopper to a cam-driven oscillating mirror. The oscillating mirror alternately directs the light into two different optical paths. The light in the first optical path, the sample beam, is directed toward a mirror that focuses an image of the exit slit upon the reflectance sample inside the integrating sphere. The light traversing the second optical path, the reference beam, is directed to a second mirror that projects an image of the slit upon the inside sphere wall. The optical signal is converted to an electrical analog by a light detector viewing the inside of the sphere through a fused silica window. The original Beckman vacuum tube electronics were upgraded by purchasing solid-state electronics (Ref. 3). The solid-state electronics demodulate the sample and reference signals, then output the ratio of sample to reference signal in both analog and digital form. The analog of the ratio of the output is recorded on the Beckman X-Y plotter, and the digital version of the sample to reference signal ratio is recorded by a computer. The Beckman mechanically scans the wavelength range of 250 to 2,300 nm. A 13-bit absolute encoder was added to the prism drive gear to provide a digital output of the wavelength for the computer to record.

Two light sources are used. A deuterium lamp is used for wavelengths less than 350 nm, and a tungsten halogen lamp is switched in place for wavelengths greater than 350 nm.

The reference beam signal is kept at a constant value by adjusting the slit width for the lead sulfide detector and adjusting the detector high voltage for the photomultiplier tube. The external integrating sphere is 20 cm (8 in.) in diameter with three ports. One port, with a 5-cm diam, was used to attach the integrating sphere to the SAM Chamber for reflectance sample insertion. The second port, with a 3-cm diam and a fused silica window, was used to pass the light into the sphere. The third port, with a 3-cm diam and a fused silica window, was located on top of the sphere out of the plane of the first two ports. The third port was used by the light detectors.

As much as practical, the sphere was configured to meet the requirements set forth by Edwards (Ref. 4) for absolute reflectance measurements as follows:

1. A baffle was placed such that the detector could not see the light impinging on the reflectance sample.
2. No baffle was used between the detector and where the reference beam impinged on the sphere wall.
3. The ratio of the sphere port area to sphere wall area was minimized.
4. A diffuse sphere wall was used.
5. All of the sphere wall was seen by the detector.

The first two requirements were met by locating a baffle between the detector and the reflectance sample. The third, minimizing the port-to-sphere surface area, was the reason for increasing the sphere diameter from 15 cm, as originally supplied with the reflectance attachment, to 20 cm. The area of the ports on the 20-cm sphere amounted to eight percent of the sphere wall area. The fourth, a diffuse sphere wall was obtained by coating the inside of the sphere with a barium sulfate paint available from Eastman Kodak (Ref. 5). The last requirement was not met since the detectors were mounted outside the vacuum window limiting their field of view. The detector configuration was modified to increase the field of view.

Prior to this test a window with its mounting flange was attached to the top of the integrating sphere. The window flange was welded to the sphere by means of a short 1-in.-diam, 1-in.-long neck. A side window photomultiplier tube in its housing was mounted above the window. The photomultiplier tube was used as the detector for the 250- to 650-nm range.

The photomultiplier could view an estimated 25 percent of the integrating sphere inner surface. The detector for the 650- to 2,200-nm wavelength region was a 5-mm² lead sulfide detector. The lead sulfide detector, being smaller than the photomultiplier tube, was mounted in front of the photomultiplier sensitive surface. This mounting gave similar fields of view for the detectors and maximized the lead sulfide detector signal in an attempt to increase the long wavelength range.

A new detector mounting system was designed and installed to improve the signal-to-noise ratio at both ends of the wavelength range and to increase the portion of the sphere inside surface viewed by the detectors. First, an electrical feedthrough was installed in the sphere wall, and the lead sulfide detector was mounted inside the sphere near the top sphere wall. The new mounting position improved the lead sulfide detector field of view to approximately 80 percent of the sphere inner wall. This improved view provided a much improved detector signal.

The photomultiplier detector changes were more extensive. A 13-mm-diam end window photomultiplier tube with good sensitivity in the 250- to 650-nm range was purchased. The integrating sphere window modification consisted of fabricating a small recessed window assembly that would slide inside the existing neck of the integrating sphere. The end window photomultiplier tube was then mounted against the recessed window. This new photomultiplier mount assembly increased the view of the sphere interior to an estimated 60 percent. In addition, by removing the lead sulfide detector from the front of the photomultiplier tube, the light reaching the photomultiplier was increased an additional factor of two.

2.6 SOLAR LAMP

A 1-kW xenon lamp with a fused silica condenser lens was used for the solar irradiance simulator. The solar lamp was controlled by a constant current power supply. The controlled current maintained the total irradiance at a constant value. The irradiance was determined using a calibrated thermopile. The total irradiance measured by the thermopile is reported as total solar equivalent (total suns) irradiance using the air mass zero solar equivalent value of 135 mW-cm². Lamp output was monitored for relative intensity changes by a photomultiplier with a Corning CS7-54 bandpass filter (250 to 400 nm) and a silicon cell mounted outside the chamber.

To irradiate the sample during contamination, the lamp was positioned at a chamber window port aligned 45 deg to the sample surface. Lamp power was set to provide one sun as measured by the thermopile aligned perpendicular to the lamp optic axis.

2.7 DATA ACQUISITION SYSTEM

A microcomputer with a hard disk and a floppy disk storage media was used to acquire and store the data from the measurements. The reflectance data were obtained directly from the spectrometer in digital form. The LUSI® electronics transmitted digital intensity data at the rate of 10 readings/sec. For each intensity reading received, the computer would record the spectrometer wavelength from a 13-bit digital encoder mounted to the spectrometer prism drive gear. Approximately 5,000 points were obtained for each spectrometer scan. These data were recorded on a floppy disk and transferred to another computer for off-line reduction.

A 64-channel data logger was used to read the analog voltages from the chamber transducers such as pressures, temperatures, QCM controller output, solar cell output, and the solar lamp intensity monitors. When not being used to read the spectrometer, the microcomputer recorded selected channels from the data logger at selected intervals varying between 1 min and 4 hr.

3.0 EXPERIMENTAL TEST PROCEDURE

3.1 INTRODUCTION

Measurements of absorptance change with contaminant thickness and solar irradiation time were obtained for two spacecraft materials. The contaminating samples were prepared, installed in the SAM Chamber, heated to 125°C, and contaminants condensed upon the aluminized mirror irradiated by a solar simulator. The degradation was periodically measured and recorded.

3.2 SAMPLE PREPARATION

The two component samples were prepared as specified by the manufacturer and weighed to the specified mixing ratios. One component was added to a disposable aluminum mixing container and weighed, then the other component was added until the correct mixing ratio by weight was obtained. Measurements were made on an analytical balance capable of 0.1-mg precision. After preparation, the sample material was transferred to a previously outgassed and weighed aluminum foil boat. The boat had nominal dimensions, 4 by 2.5 by 2.0 cm deep, weighed 1 gm, and was filled with 10 gm of sample material. The material sample was cured and put in a 50-percent relative humidity container for at least 24 hr.

The Uralane manufacturer's cure schedule of 8 hr at 95°C, plus 24 hr at 25°C, was used. The DC 93-500 sample was cured at room temperature for 24 hr.

3.3 EFFUSION CELL PREPARATION

Prior to the first test of each type of material, the effusion cell interior was cleaned with Freon®, and a new foil liner was installed. The effusion cell was then outgassed under vacuum at 125°C for 24 hr.

3.4 QCM PREPARATION

The QCM was cleaned with ethyl alcohol or Freon and dried under vacuum. The QCM was mounted at a symmetric location with the same distance horizontally from the effusion cell aperture and vertically from the effusion cell centerline as the test surface.

3.5 MIRROR PREPARATION

The aluminum overcoated nickel mirrors were provided by AFWL. Prior to installation in the chamber, a cylindrical aluminum (1-cm long by 1-cm diam) mounting adapter was bonded to the rear surface of the mirror. A low outgassing epoxy bonding adhesive was used. The assembly was cured at 60°C for more than 12 hr prior to installation in the SAM Chamber.

The pretest reflectance scans of the mirror were taken under vacuum to minimize changes in the optical path by shifting of the integrating sphere windows with sphere pressure change.

3.6 RELATIVE REFLECTANCE MEASUREMENT

The reflectance degradation test proceeded as follows:

1. Cooling water to the QCM and the mirror sample arm was turned on. Water from the temperature-controlled bath to the sample arm and the QCM was series-connected to provide similar cooling water conditions.
2. The material sample was installed in the effusion cell, and the effusion cell shutter was closed.
3. The SAM Chamber was closed and pumped down.
4. Under vacuum, the sample mirror was inserted into the integrating sphere for a reflectance measurement. Because the mirror was a specular reflector, care was taken to rotate the mirror to a precise index point after it was inserted.

This minimized the potential effects of the integrating sphere angular distribution sensitivity.

5. The sample mirror was retracted to face the effusion cell and solar simulator.
6. The effusion cell shutter was opened, and the effusion cell temperature was increased to 125°C.
7. The contaminant buildup was monitored by observing the QCM frequency change. At the desired thickness, the mirror was reinserted into the integrating sphere, a reflectance measurement was made, the mirror was retracted, and the contamination of the mirror was resumed.
8. Repeat spectral measurements were made as desired.
9. When the desired contaminant level was obtained, the effusion cell was closed and the heaters turned off.
10. At desired times, the mirror sample was inserted into the integrating sphere to measure the degraded reflectance, then retracted for continued solar irradiation.

3.7 ABSORPTANCE CALCULATION

The absorptance (α) obtained is the integral of the spectral absorptance weighted by the standard solar irradiance spectrum at one astronomical unit distance, air mass zero (Ref. 6). The results reported are the differences between the baseline, the integrated absorptance of the uncontaminated mirror, and the contaminated mirror integrated absorptance ($\Delta\alpha$).

The relative spectral absorptance is taken to be one minus the spectral reflectance. The integrated solar absorptance can be represented as follows:

$$\alpha = 1 - \left(\int R E d\lambda / \int E d\lambda \right) \quad (4)$$

where

α = the integrated, solar weighted, relative absorptance; unitless

R = the relative spectral reflectance of the mirror; unitless

E = the standard solar spectral irradiance outside the earth's atmosphere;
 $\text{W}/\text{cm}^{-2}\text{-}\mu\text{m}^{-1}$

λ = spectral wavelength; μm

The limits of integration are defined to be over the entire solar spectrum; however, the range 0.25 to 2.3 μm contains 95 percent of the solar irradiance. This spectral range was used for the absorptance determination.

The computer program that calculated the absorptance proceeded as follows:

1. The standard spectral irradiance values, E , for air mass zero were stored in a table.
2. The spectral reflectance measurements, R , for the 0.25- to 2.3- μm region, were read into a table.
3. The R and E data were interpolated to obtain 500 values from 0.25 to 2.3 μm .
4. The absorptance was calculated using:

$$\alpha = 1 - \text{Sum } (R_i E_i) / \text{Sum } (E_i) \quad (5)$$

where the sums are over all 500 points.

5. The change in absorptance was taken as the difference between the clean mirror absorptance and the contaminated mirror absorptance.

4.0 RESULTS AND DISCUSSION

4.1 MIRROR CONTAMINATION RESULTS

4.1.1 Furane Products Uralane 5753-A/B(LV)

The change in integrated solar absorptance ($\Delta\alpha$) as a function of solar irradiation time for Uralane is shown in Fig. 4. Data obtained with irradiation during contamination, film A (square symbols), are compared to data obtained with no irradiation during contamination, film B (circle symbols). Film thickness reached 250 Å after 110 hr of material outgassing at 125°C. The $\Delta\alpha$ value after outgassing for film A was 3.7 times larger than the value obtained for film B. After an additional 66 hr of irradiation, the $\Delta\alpha$

of film A was 13.6 percent, and the value for film B was 5.5 percent. Film B was irradiated for 177 total hr, and the final delta alpha was 7.1 percent.

4.1.2 Dow Corning 93-500 Space-Grade Encapsulant

The change in integrated solar absorptance (delta alpha) as a function of solar irradiation time for DC 93-500 is shown in Fig. 5. Data obtained with irradiation during contamination, film A (square symbols), are compared to data obtained with no irradiation during contamination, film B (circle symbols). Film thickness reached 734 Å after 31 hr of material outgassing at 125°C. The delta alpha values after outgassing were 5.7 and 4.8 percent for film A and B, respectively. After 148 hr of irradiation delta alpha values were 10.8 and 7.9 percent for film A and B, respectively.

4.2 ERRORS

The reflectance measured was not absolute reflectance; however, changes in the measured reflectance from the clean mirror values effectively removes the repeatable instrument factors and gives the degradation of the mirror from the contaminants.

The precision of the reflectance measurement was evaluated by making 10 reflectance measurement cycles over a period of 240 hr. The reflectance measurement cycle consisted of inserting the mirror in the integrating sphere, making a reflectance scan, then retracting the mirror arm into the solar irradiation position. For a given wavelength, these reflectance measurements had a standard deviation of 0.005 (roughly 0.5 percent of the clean mirror reflectance). However, on other occasions, the instrument was observed to have a 0.01 to 0.03 shift in the reflectance over a portion of the spectrum, usually on the infrared end. In most cases the cause was obvious and was corrected; but, in a few cases no immediate reason could be found that would lead to this higher error. The estimated upper limit on the precision of the reflectance is 0.03 (roughly 3 percent of the clean mirror reflectance).

Alpha is derived from the reflectance measurements [Eq. (4)]. Because the reflectance is weighted by the solar energy spectrum and is integrated over the solar band, errors at the extremes of the spectrum have little effect, and the random noise in a reflectance scan tends to cancel itself. Looking at the scatter in alpha for repeated reflectance scans, the precision for alpha is estimated to be 0.01. From measurements of the tare mirrors, it is estimated that the maximum bias error in alpha from background contamination is 0.01 for the measurements presented.

5.0 CONCLUDING REMARKS

The Solar Absorptance Measurements Chamber was developed to measure the change in integrated solar absorptance ($\Delta\alpha$) of aluminum coated mirrors by condensed outgassing contaminants irradiated by a solar simulator under vacuum. In previous tests (Ref. 1), the location of the solar simulator did not allow irradiation of the sample mirror during the contamination phase. The test chamber was modified, and measurements were made to compare the solar absorptance change for samples irradiated during contamination to samples with no irradiation during contamination. Sources of the contaminants were two spacecraft materials, Furane Products Uralane 5753-AB (LV) encapsulant, and Dow Corning 93-500 encapsulant. $\Delta\alpha$ as a function of solar irradiation time is presented for each material.

$\Delta\alpha$ values were higher for the samples irradiated during contamination. The test results confirm that irradiation during contamination is necessary to simulate the contamination process of a spacecraft.

Recommendations for additional studies include:

1. Previous measurements of $\Delta\alpha$ for samples contaminated without solar irradiance should be repeated.
2. The rate of outgassing from the effusion cell varies with time. Measurements should be made to determine the effect of deposition rate on $\Delta\alpha$.

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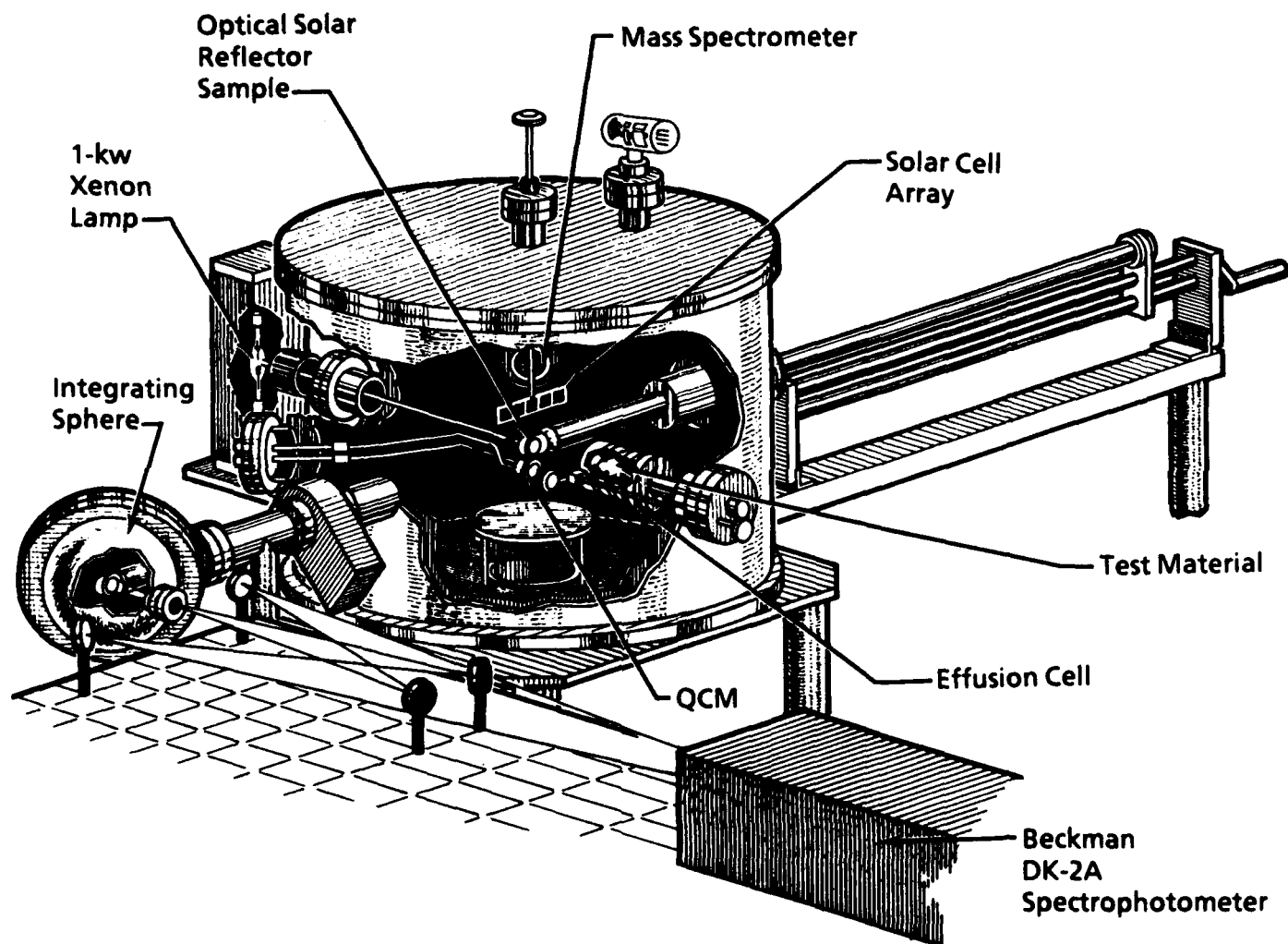


Figure 1. Solar Absorption Measurements Chamber.

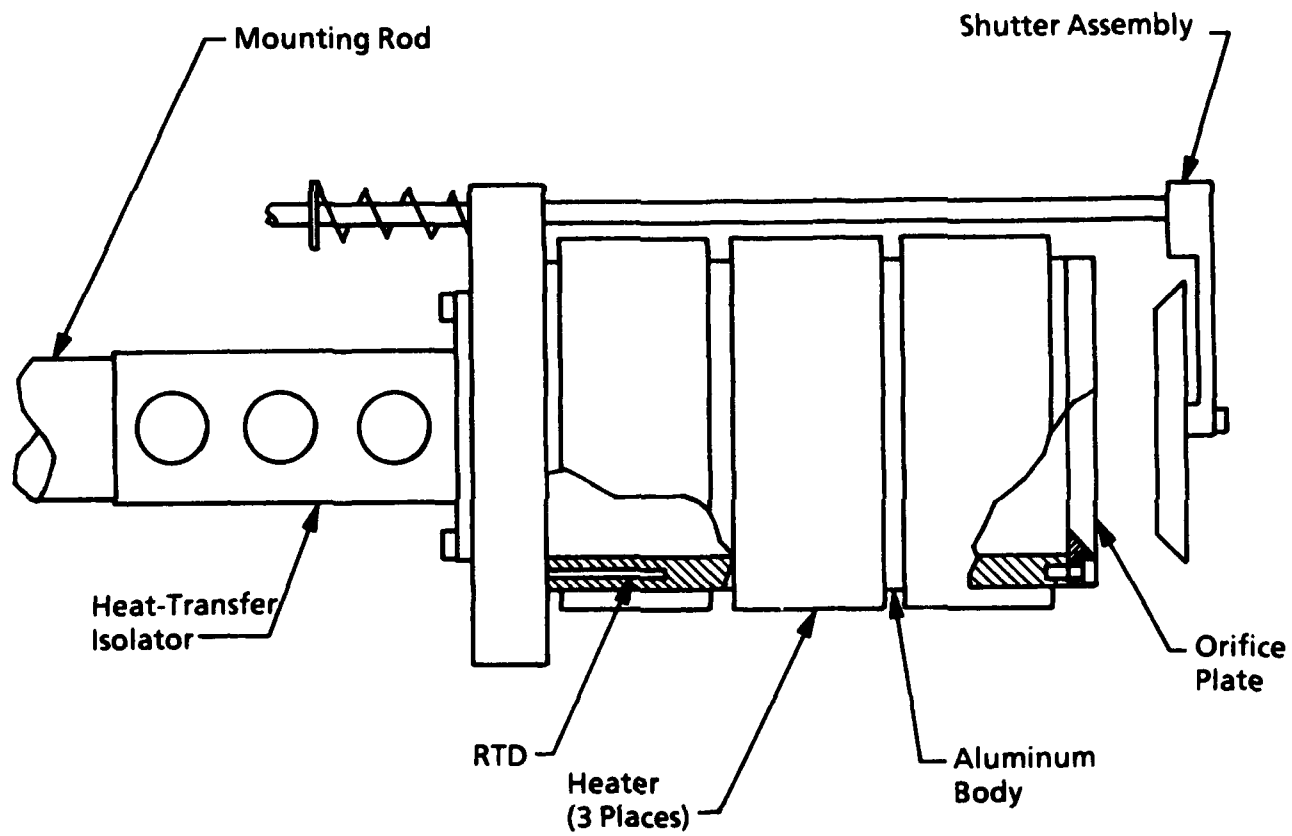


Figure 2. Effusion cell.

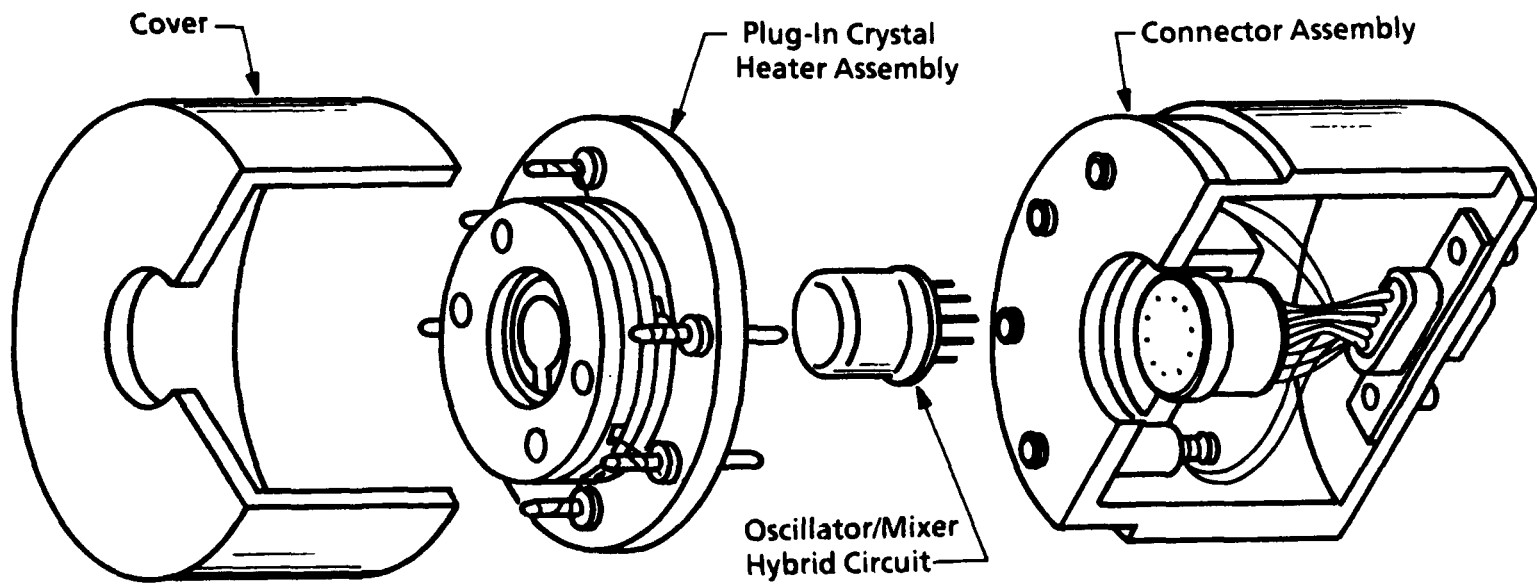


Figure 3. Quartz crystal microbalance, exploded view.

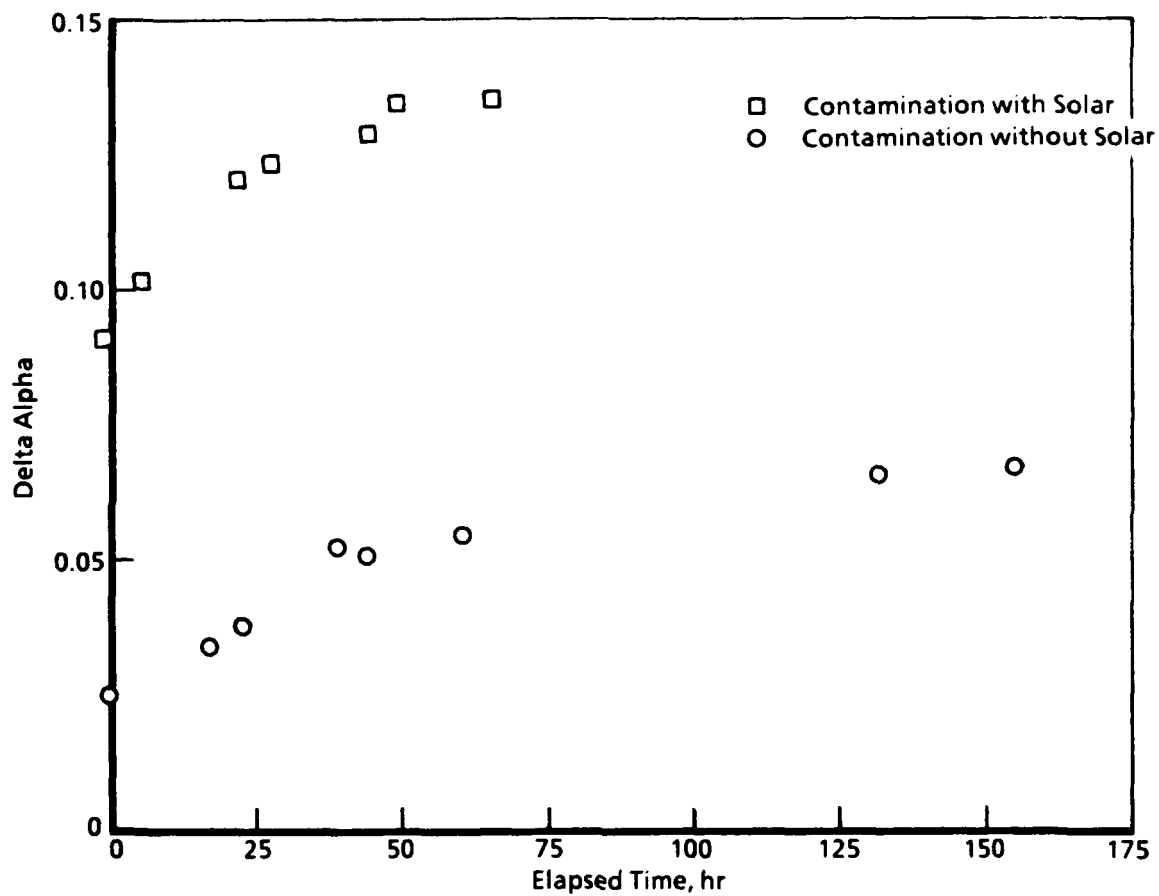


Figure 4. Mirror absorptance change as function of irradiation time, Uralane®.

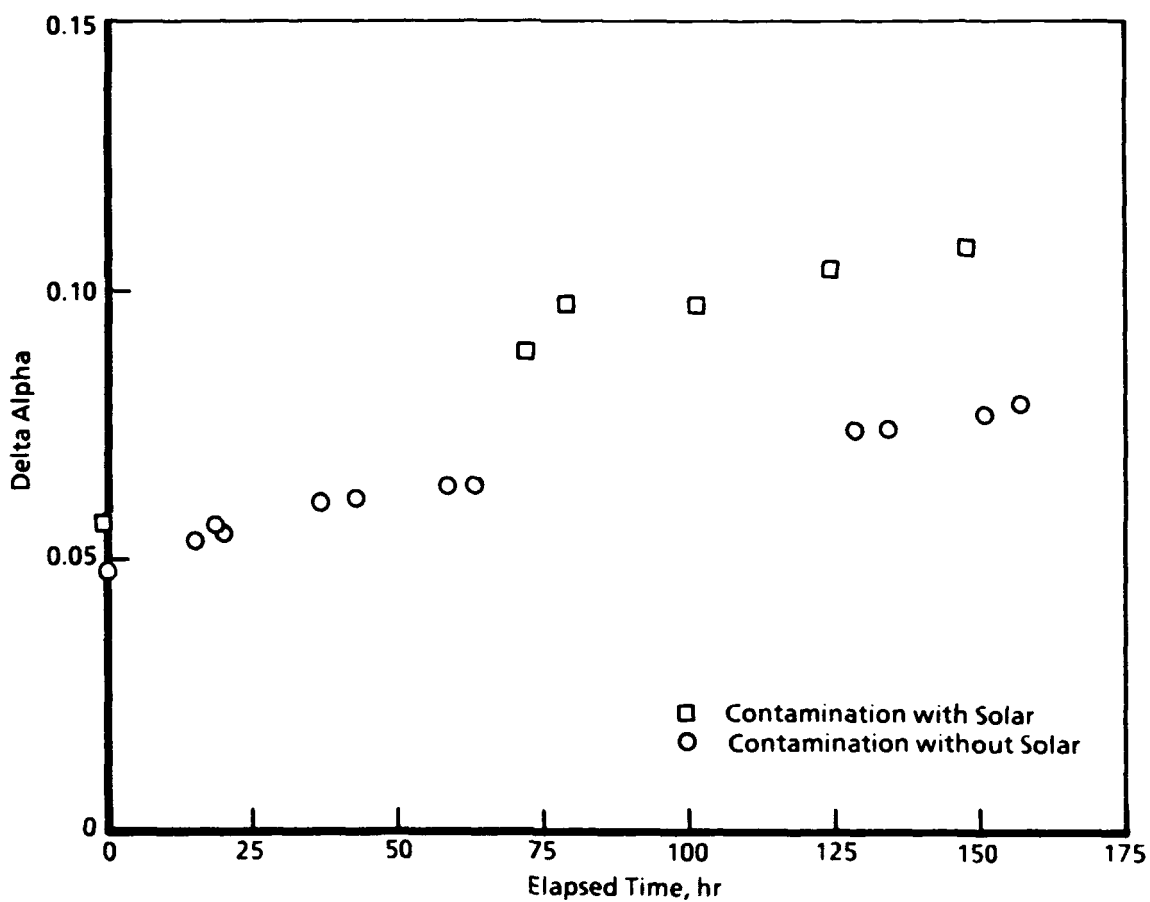


Figure 5. Mirror absorptance change as function of irradiation time, DC 93-500.