IN-
p. 45

THERMAL CONTROL SURFACES EXPERIMENT FLIGHT SYSTEM PERFORMANCE

Donald R. Wilkes
Leigh L. Hummer
AZ Technology, Inc.
3322 Memorial Parkway SW, Suite 93
Huntsville, AL 35801
Phone: 205/880-7481; Fax: 205/880-7483

James M. Zwiener
NASA Marshall Space Flight Center
Marshall Space Flight Center, AL 35812
Phone: 205/544-2528; Fax: 205/544-0212

INTRODUCTION

The Thermal Control Surfaces Experiment (TCSE) is the most complex system (other than the LDEF with its experiments) retrieved after long term space exposure. The TCSE is a microcosm of complex electro-optical payloads being developed and flown by NASA and the DoD including SDI.

The objective of the TCSE on the LDEF was to determine the effects of the near-Earth orbital environment and the LDEF induced environment on spacecraft thermal control surfaces.

The TCSE was a comprehensive experiment that combined in-space measurements with extensive post-flight analyses of thermal control surfaces to determine the effects of exposure to the low earth orbit space environment. The TCSE was the first space experiment to measure the optical properties of thermal control surfaces the way they are routinely measured in the laboratory.

TCSE FLIGHT HARDWARE

The TCSE is a completely self-contained experiment package; providing its own power, data system, integrating sphere reflectometer, and pre-programmed controller for automatically exposing, monitoring, and measuring the sample materials. The TCSE was developed as a protoflight instrument where one instrument was built, made to work within required specifications, tested, and flown. Environmental qualification testing was performed at MSFC that included vibration, thermal vacuum, and electromagnetic interference (EMI) tests.

The TCSE was built in a 305 mm (12 in.) deep LDEF tray (see Figure 1). The 25 active and 24 passive samples were mounted in a semicircular pattern on a circular carousel. The active and passive test samples differed in that the space effects on the passive test samples were determined only by pre- and post-flight evaluation. The optical properties of the 25 "active" samples were measured in-space as well as in pre- and post-flight analysis. The carousel is tilted at 11

(NASA-TM-1) THERMAL CONTROL SURFACES EXPERIMENT FLIGHT SYSTEM PERFORMANCE (NASA) 45 p CSCL
N91-
Unclas

degrees from the outer tray surface to allow a 115 mm (4.5 inch) diameter integrating sphere to fit between the deep end of the carousel and the outer shroud. This design satisfied the LDEF requirement to remain within the outer edges of the tray and also provide a field of view of space greater than 150 degrees for the samples. This design maintained mechanical simplicity and inherent reliability. Figure 2 shows the basic specifications for the TCSE flight hardware.

Sample Carousel

The TCSE sample carousel design enabled the test samples to be either protected from or exposed to the space environment as well as to be positioned for optical measurement. In the exposed condition, the samples experienced space exposure for approximately 23 1/2 hours each earth day. During the protected period of time (approximately 1/2 hour), calorimetric measurements of emittance were made. The protected environment also prevented exposure of the experiment test samples to ground processing and launch contamination.

The carousel subsystem was comprised of the carousel assembly, a stepper motor controlled by the DACS to effect movement of the carousel assembly, a geneva drive assembly, and an emissivity plate. The geneva drive enabled precise repeatable angular rotation such that the same spot on each flight sample was measured. Pre-flight testing proved the inherent reliability of the geneva drive assembly and the positioning accuracy of each sample. The emissivity plate, combined with calorimeters, was used for the emittance measurements.

Radiometers

Three radiometers were used to monitor the irradiance from the sun (direct solar), earth albedo (reflected), and earth IR (emitted) incident on the TCSE. The radiometer data enabled calculation of solar absorptance and total emittance when combined with calorimeter temperature data. The radiometers were mounted on the carousel and were rotated with the flight samples. The three radiometers used thermopile detectors painted flat black and domed collection optics to measure the energy flux on the TCSE. The direct solar radiometer was installed with a field-of-view equal to the flight samples. A quartz lens was used for the spectral region of 200 to 3000 nm. This region contains over 98 percent of the sun's electromagnetic energy. Like the direct solar radiometer, the earth albedo radiometer used a quartz lens. However, the earth IR radiometer used a germanium lens for the infrared spectrum from 2000 to 20000 nm. The earth albedo and earth IR radiometers were installed with covers such that they had a clear view of only the earth. Data from the radiometers were recorded at minute intervals over a two hour period each day of the active mission.

Calorimeters

Calorimeter sample holders provided a simple method to determine the solar absorptance (α_S) and total emittance (ε_T) of the active flight samples. This calorimetric technique measured the inputs to the heat balance equation and calculated solar absorptance and total emittance for the flight samples. The in-space measurements required for this calculation were the temperature of the test sample and the external heat inputs as measured by the irradiance monitors. The calorimeters were designed to isolate the flight sample material thermally from the TCSE to minimize errors caused by radiative and conductive losses. The TCSE calorimeter design was developed originally by the Goddard Space Flight Center (GSFC) and flown on the ATS-1, ATS-2, and OAO-C satellites.[1]

The calorimetric measurement procedure used on the TCSE is an improvement over past experiments for determining total emittance. Previous experiments determined total emittance when the calorimeter viewed deep space only (i.e., no view of the sun or earth). This orientation was difficult to insure, and the time spent in this orientation was, at times, too short to provide accurate measurements. The TCSE procedure, however, rotated the samples inside the instrument, where they viewed only a heavy, black "emissivity" plate. This geometry greatly simplifies the heat balance equation and removes any sun or earth effects.

Reflectometer Subsystem

The TCSE reflectometer optical design, illustrated in Figure 3, is one that is used routinely in the laboratory to measure spectral reflectance. Two light sources, tungsten and deuterium lamps, are used with a scanning prism monochromator with selectable slit widths to provide the monochromatic energy for the spectral measurement. A 115 mm (4.5 inch) diameter integrating sphere collects both the specularly - and diffusely - reflected light from a wall mounted sample to provide the angularly integrated measurement capability. Figure 4 illustrates the integrating sphere geometry. Kodak Barium Sulfate ($BaSO_4$) was used for the sphere coating because it was easy to apply, durable enough to withstand the launch environment, and had good optical properties. A UV enhanced silicon photodiode detector and a lead sulfide detector were used with the integrating sphere for the required 250 to 2500 nm spectral range.

Data Acquisition and Control System

The TCSE Data Acquisition and Control System (DACS) is shown in Figure 5 and controls all aspects of the TCSE operation. The heart of the DACS is an RCA 1802 CMOS microprocessor with associated memory and input/control ports. A 12-bit analog-to-digital (A-D) converter and analog multiplexer are used to read to measurement data.

A low-power, 25-bit real-time clock was used to keep mission elapsed time. The real-time clock was the only TCSE subsystem that ran continuously from the LDEF "start" signal through battery depletion. The clock subsystem turned on the DACS once each 24 hour day of the active TCSE mission. The DACS, in turn, looked at its internal schedule to determine what functions were to be done that day. At the completion of the day's measurements, the DACS turned itself off, leaving only the real-time clock operating.

There were two measurement cycles that the data system controlled, the "daily" measurements and the "reflectance" measurements. The daily measurements were performed once each day after the initial turn-on delay period. The reflectance measurements were performed at intervals varying from once a week at the beginning of the mission to once a month after three months as defined by the stored program in the data system.

In the daily measurement sequence (with the carousel in the exposed position), each of 64 analog channels were sampled once each 64 seconds for 90 minutes. The daily data included calorimeters, radiometers, and housekeeping data. The carousel was then rotated to the protected position and the measurements continued for another 30 minutes. At the end of this cycle, the carousel rotated the samples to the exposed position.

In the reflectance measurement sequence, each sample was positioned in-turn under the integrating sphere twice for reflectance measurements. Each sample, beginning with sample one and continuing through sample 25, was positioned under the integrating sphere and the ultraviolet (UV) portion of the measurements taken. This sequence was then repeated, only in reverse order (sample 25 through sample one) for the visible and infrared (IR) measurements. At the completion of this sequence, the carousel rotated the samples to the exposed position.

The reflectometer electronic subsystem is shown in Figure 6. The DACS controls the monochromator wavelength and slit width, selects the appropriate detector and lamp, and measures the reflectance values. Phase Sensitive Detection (PSD) techniques are utilized with analog and digital Multiple Time Averaging (MTA) to minimize the effects of stray light, drift, offset, $^1/_f$ noise and white noise.[2]

TCSE MISSION SUMMARY

The LDEF was placed in low earth orbit by the Shuttle Challenger on April 7, 1984 (see Figure 16). LDEF was retrieved by the Shuttle on January 12, 1990 after 5 years 10 months in space. The orbit had a 28.5° inclination and an initial altitude of 463 km (250 N mi). The orbit degraded over the 5 year 10 month mission to an altitude of 330 km (178 N mi). This LDEF/TCSE orientation and mission duration provided the following exposure environment for the TCSE:

Total space exposure	5 years 10 months
Atomic oxygen fluence[3]	8.0×10^{21} atoms/cm^2
Solar UV exposure[4]	1.0×10^{4} ESH
Thermal cycles	3.3×10^{4} cycles
Radiation (at surface)[5]	3.0×10^{5} rads

When the LDEF was placed in orbit by the Shuttle, a "start" signal was sent by LDEF to the TCSE to engage a relay and turn on the TCSE power. The TCSE was preprogrammed to wait for ten days before exposing the samples to allow the initial outgassing load to diminish. The TCSE was launched aboard the LDEF with the carousel rotated to the "closed" position to protect the samples from ground processing and the launch environment.

On mission day 10, the initial daily and reflectance measurements were performed. The carousel was rotated to the open position to expose all test samples. The daily measurements were repeated every day until mission day 582 (19.5 months) when the TCSE batteries were depleted. The reflectance measurements on the test samples were repeated once a week for four weeks, then once every two weeks for eight weeks, and finally once a month until battery power was expended. The TCSE batteries were sized to provide a 50% margin of additional energy for the nominal 9-12 month LDEF mission.

The TCSE operated for 582 days before battery depletion. The battery power was finally expended while the sample carousel was being rotated. This left the carousel in a partially closed position. Figure 7 is a photograph taken during the LDEF retrieval operations showing where the carousel rotation stopped. This carousel position caused 35 of the samples to be exposed for the complete LDEF mission (69.2 months), and 14 exposed for only 582 days (19.5 months) and therefore protected from the space environment for the subsequent four years.

TCSE SYSTEM PERFORMANCE

The TCSE flight hardware system performed very well during the LDEF mission.[6] A post flight functional test was performed and the TCSE remains functional. A few anomalies have been detected in post-flight data analysis, inspection, and functional tests. The systems analyses performed is only the initial effort required to fully characterize the effects of the long term space exposure. Performance of the TCSE system and operational anomalies discovered to date are described in this section.

Recorder

The TCSE data system utilized a Lockheed Electronics Company (LEC) model MIM four-track tape recorder to store the flight data. The flight recorder was removed and handcarried to the Lockheed Electronics Company for transcription of the flight data and an analysis of the condition of the recorder.

Upon opening the recorder it was determined that a relay in the track switching circuit had failed with the wiper on one set of contacts stuck in an in-between state. This condition prevented the relay from receiving additional track switching commands and resulted in the overwriting of one of the three tracks of data collected by the TCSE. The LEC engineers manually energized the relay coil and the relay contact latched properly. This relay and the complete recorder system performed within specification for the check-out tests and flight data playback.

The MIM tape recorder is a four-track unit that records tracks 1 and 3 in the forward direction and tracks 2 and 4 in the reverse direction. At the completion of the TCSE mission, the recorder stopped with the tape positioned near the end of track 1. However, it was determined that track 3 data was written over track 1 data. Because the MIM recorder uses a saturation recording method, track 3 data was recovered. Track 2 data was recovered with no problems. Some track 1 data was apparent in gaps between track 3 data blocks and may be recoverable. This failure and its cause will be investigated further in later studies. The LEC and NASA/LaRC personnel provided a very valuable service in this analysis and in the recovery of the TCSE flight data.

The recovered TCSE flight data was decoded and separated into data sets. By analyzing the clock data in each data set, it was determined that the TCSE operated for 582 days (19.5 months) after LDEF deployment. Data were recovered for the last 421 days of this operational period. The overwriting of track 1 data by the recorder resulted in the loss of data for the first 161 days of the TCSE mission. The recovered data included eleven reflectometry data sets and 421 daily data sets.

Reflectometer

The analyzed flight data shows the reflectometer performed very well. The measurement repeatability over several months is demonstrated in Figure 8 and is generally within 1 to 2 percent. This excellent performance indicates that sample property changes measured by the TCSE reflectometer were accurate and did occur. Late in the active TCSE mission the reflectometer UV data became noisy. The reflectometer remains functional and operated normally during post-flight testing. The optical data from the functional tests were acceptable from 2500 nm through 500 nm but were suspect below 500 nm.[6] Further tests are performed to better characterize the condition of the reflectometer.

Batteries

Four standard lithium range safety batteries were used to power the TCSE. These batteries were developed for the Shuttle Solid Rocket Booster (SRB) range safety system. The batteries were selected based on their high energy density and ready availability at MSFC. These batteries had a predicted life of greater than 15 months from calculated power requirements. The actual battery life extended through 582 mission days (19.5 months). Each battery was rated at 28 Volts Direct Current (VDC) and self-contained in a two-part Nylafil case. An ethylene propylene o-ring was used to seal the case. Due to the characteristics of the lithium electrolyte, each cell was designed to vent into the cavity when overpressurization occurred. During an overpressurization condition, a small diaphragm on each cell balloons out and is pricked by a metal pin to relieve pressure. The escaping gas is then contained within the Nylafil case by the ethylene propylene o-ring.

During the initial post-flight deintegration, a noticeable odor was evident inside the TCSE. The source of odor from inside the TCSE was identified as the electrolyte from the lithium batteries. The batteries were removed from the TCSE and bagged. Each of the four batteries in the TCSE had this odor. One battery was cut open to check the cell diaphragms and the battery o-ring. All cells had vented, noted by punctured diaphragms. In addition, the battery o-ring had a complete compression set allowing the electrolyte gas to escape from the batteries.

Flight data revealed the battery temperatures ranged from 13 to 27^{o}C and the voltage ranged from a nominal 36 Volts at the start of the mission to 25 Volts at battery depletion.

Sample Carousel

Post-flight analyses of the recorded TCSE data show that the carousel subsystem operated as designed most of the time, but indicate an intermittent rotational problem. From the recorded flight data, the carousel drive mechanism experienced some difficulty in rotating reliably from sample position 25 to sample 24 during the reflectance measurements. This difficulty appeared to be more prominent towards the end of the useful battery life. This problem was investigated briefly during a post-flight function check-out test. Attempts were made to simulate the problem by adjusting the battery supply voltage (and energy levels) from 28 to 21 volts as well as energizing the lamps and other components of the reflectometer subsystem to simulate increased energy requirements on the power system. Unfortunately, the carousel rotation anomaly could not be reproduced in these initial ground tests. All other post-flight carousel functional tests were nominal.

Data Acquisition and Control System

The initial analysis of the TCSE flight data shows that the DACS performed very well during the active TCSE mission. Post-flight functional tests show that the DACS remains functional after the extended dormant period in space. The clock data on each recorded data buffer showed that the DACS started a measurement sequence precisely on 24 hour increments as measured by the TCSE clock. The daily sequence was repeated for 582 days until the batteries were depleted. Because of the recorder malfunction, only 421 days of data were recovered.

The data from the post-flight functional tests were analyzed to check the condition of the analog measurement system. There were five reference channels among the 64 analog channels. These provided a calibration for thermistors and platinum thermometers. The values of these readings depend on current sources in the measurement circuits, precision reference resistors, scaling amplifiers, and the A-D converter. For four of these reference channels, the range of values measured over the two hour test exactly matched the pre-flight and in-flight values. The fifth measurement was off one count in 900 or just over 0.1%. This test verified that the analog measurement system remains within design specifications.

Only one anomaly has been observed in the DACS operation. The 25th clock bit appeared to be set to a logical "1" too early and remained in that condition throughout the mission. This bit was also set to "1" during the post-flight testing -- indicating a failure. This condition was not a problem in the data analysis because the sequential nature of the data allowed recovery of the full clock data.

Thermal

The TCSE thermal design and analysis considered worse case conditions for the LDEF and TCSE mission. Some yaw (x-axis) instability was expected for the gravity-gradient stabilized LDEF and was considered in the thermal analysis. This resulted in wide variations in the predicted temperatures of the TCSE. However, little yaw occurred, and the satellite proved to be very stable--resulting in moderate temperatures.

The TCSE used 2 mil silver Teflon as the outside (exposed) surface coating and black painted aluminum for inside and back surfaces. The top cover (shroud) was thermally isolated from the TCSE structure. The TCSE was thermally coupled to the LDEF structure for passive thermal control, and was dependent upon this environment for thermal stability.

The temperatures of selective components on the TCSE were monitored throughout the active TCSE mission. Figure 9 compares predicted data to measured data for selected components. The measured data temperature ranges represent the lowest and highest temperatures recorded by any of the applicable sensors. Figures 10-12 represent typical daily thermal excursions experienced by selected TCSE components.

SUMMARY

The performance of the TCSE flight system on the LDEF was excellent. The few anomalies that were experienced did not prevent the TCSE from meeting its design and experimental goals. The performance of the TCSE confirms that low cost, complex experiment packages can be developed that perform well in space. There remains much to learn from the TCSE hardware about the effects of long term space exposure on systems. This initial analysis only begins the process to derive these benefits from the TCSE.

REFERENCES

1. Reichard, Penelope J. and Triolo, J.J.; "Pre-flight Testing of the ATS-1 Thermal Coating Experiment." Proc. of the AIAA Thermophysics Specialist Conference, AIAA Paper 67-333, April 17-20, 1967.

2. Wilmhurst, T.H.; "Signal Recovery from Noise in Electronic Instrumentation." Adam Hilger Ltd, 1981.

3. Bourassa, R.J. and Gillis, J.R.; "Atomic Oxygen Flux and Fluence Calculation for Long Duration Exposure Facility (LDEF) LDEF Supporting Data," Contract NAS1-18224, January 1991.

4. Berrios, W.M.; "Long Duration Exposure Facility Post-Flight Thermal Analysis, Orbital/Thermal Environment Data Package," NASA LaRC, Hampton, VA, October 3, 1990.

5. Benton, E.V. and Heinrich, W.; "Ionizing Radiation Exposure of LDEF", University of San Francisco Report USF-TR-77, August 1990.

6. Wilkes, D.R. and Hummer, L.L.; "Thermal Control Surfaces Experiment Initial Flight Data Analysis," Final Report for Contract NAS8-36288; AZ Technology Report No.: 90-1-100-2, June 1991.

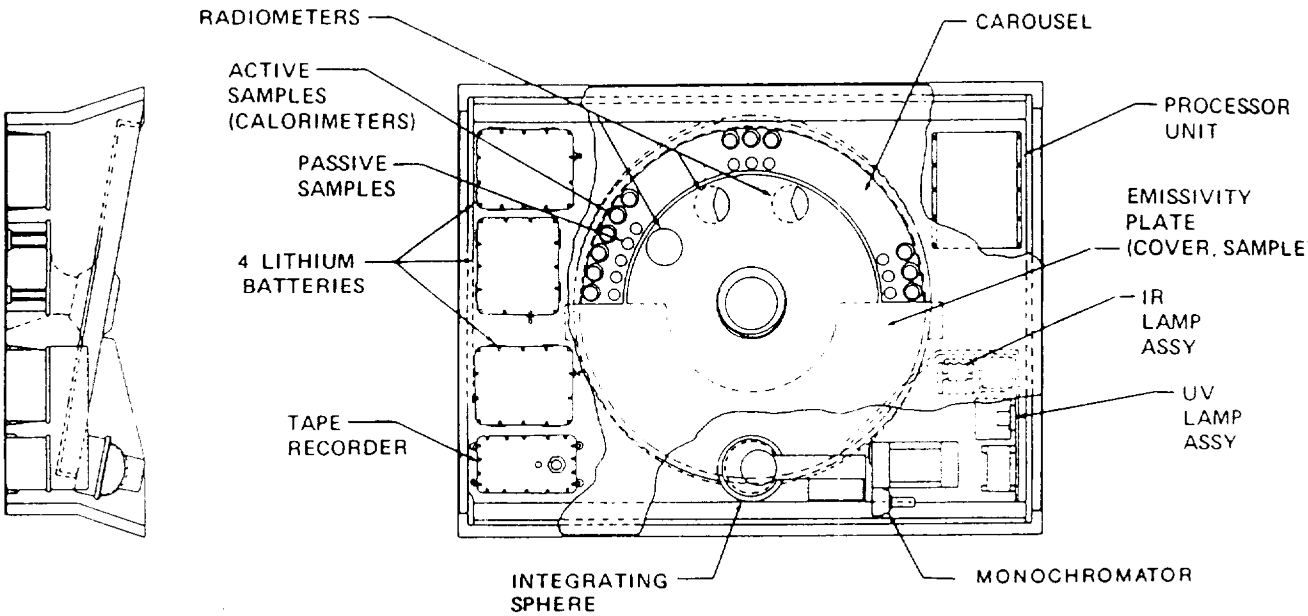


Figure 1 - TCSE Assembly

Size	1.24m x .84m x .30m (48.75 x 33 x 12 in.)
Weight	80.5kg (177 Pounds)
System Controller	1802 MicroProcessor
Battery Capacity	72 Amp Hours at 28 VDC
Data Recorder	Lockheed 4200
-Capacity	54×10^6 Bits
Reflectometer	
-Wavelength Range	250 to 2500 nm
-Wavelength Resolution ($\Delta\lambda/\lambda$)	$\leq$ 5%
-Reflectance Accuracy	2%
-Reflectance Repeatability	1%
Calorimetric Measurements	
-Solar Absorptance	Accuracy - 5%
-Total Emittance	Accuracy - 5%

Figure 2 - TCSE Flight Hardware Specifications

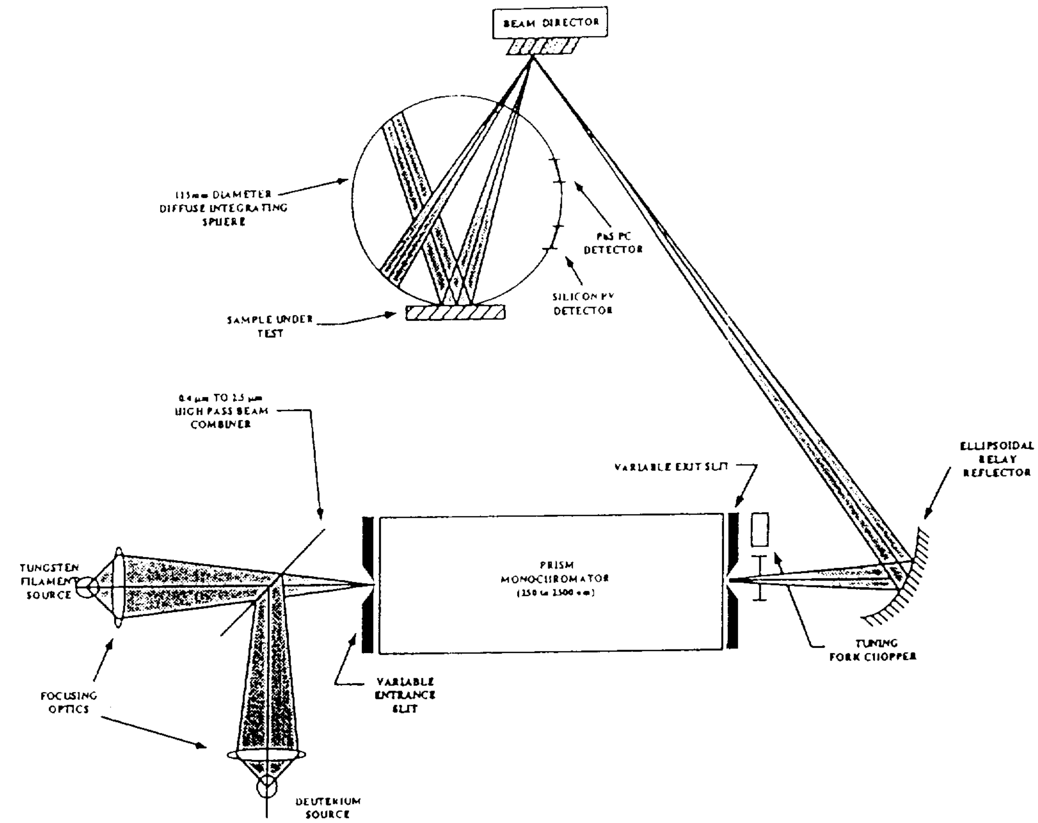


Figure 3 - Reflectometer Optical Schematic

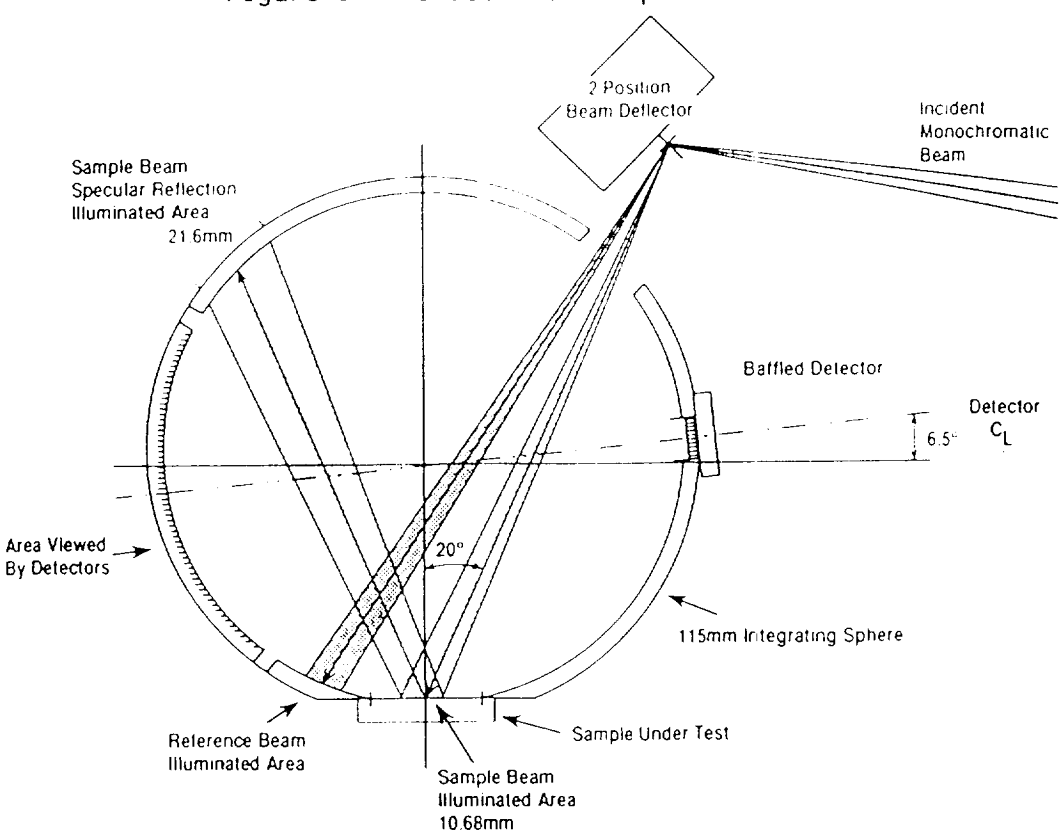


Figure 4 - Integrating Sphere Geometry

ORIGINAL PAGE IS
OF POOR QUALITY

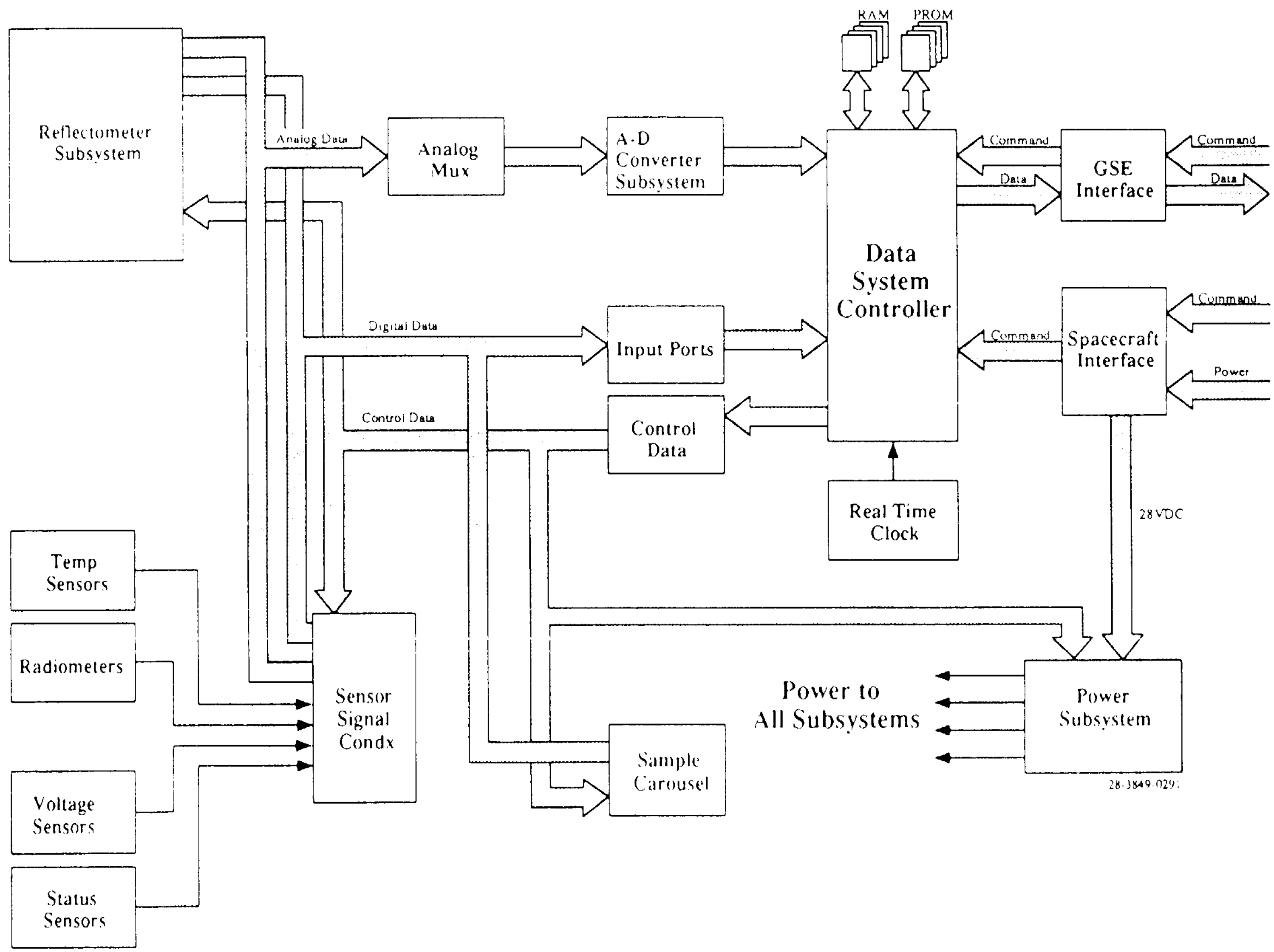


Figure 5 - TCSE Data and Control System

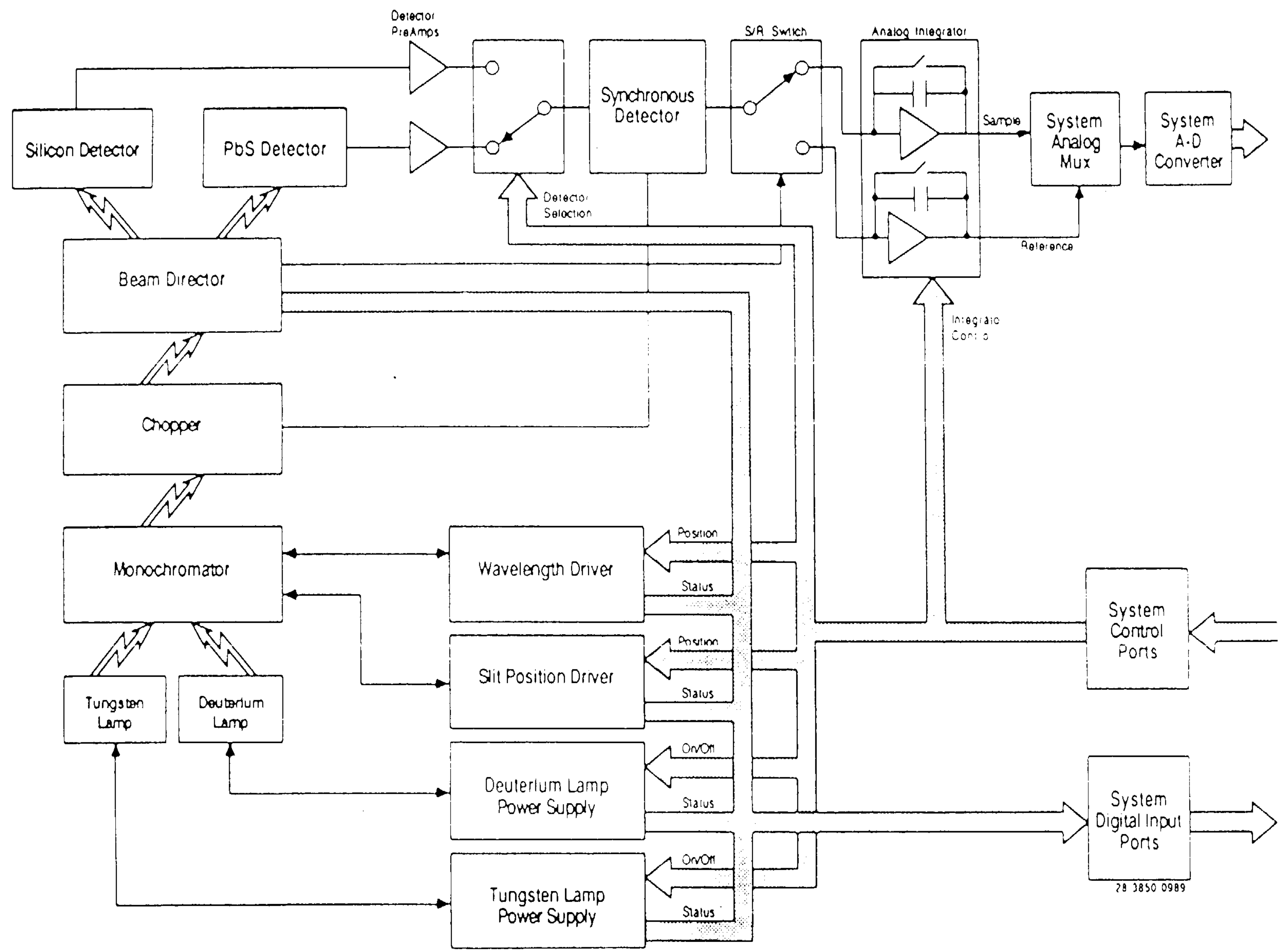


Figure 6 - TCSE Reflectometer Subsystem

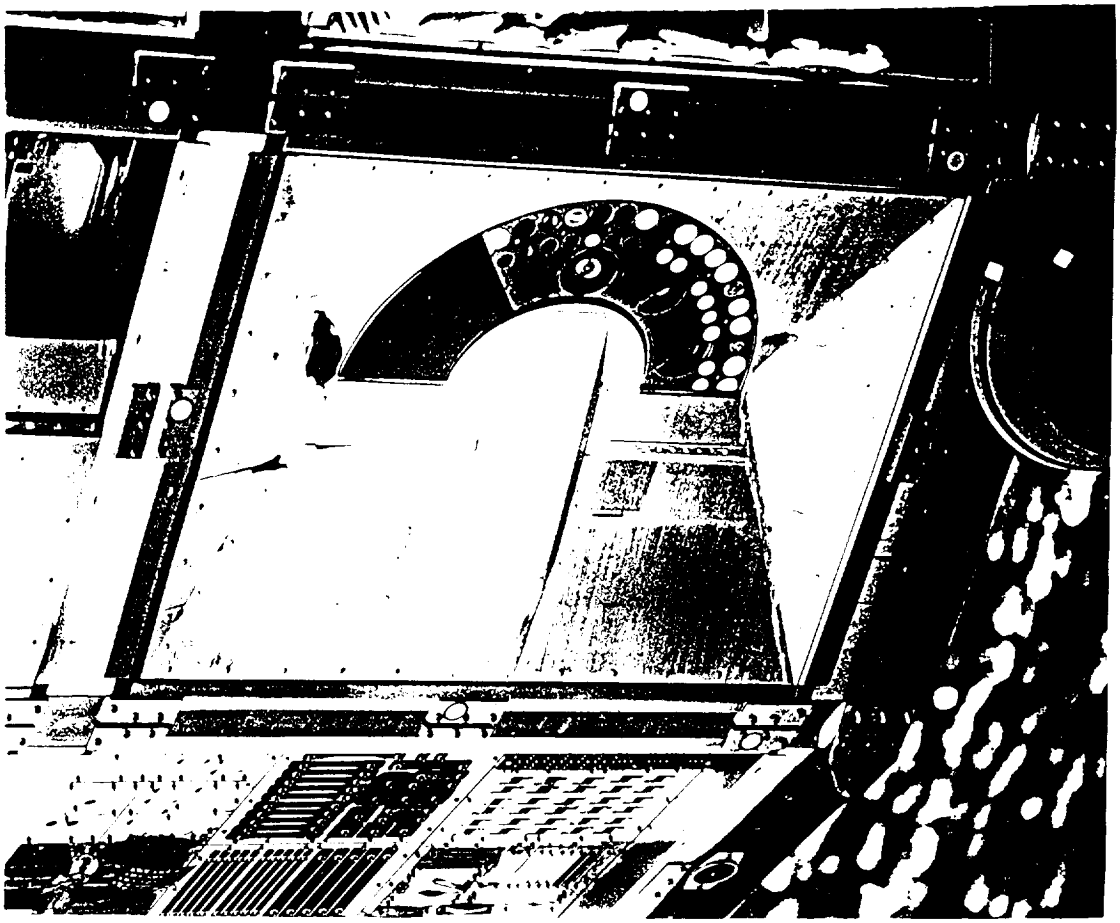


Figure 7 - TCSE Condition during LDEF Retrieval

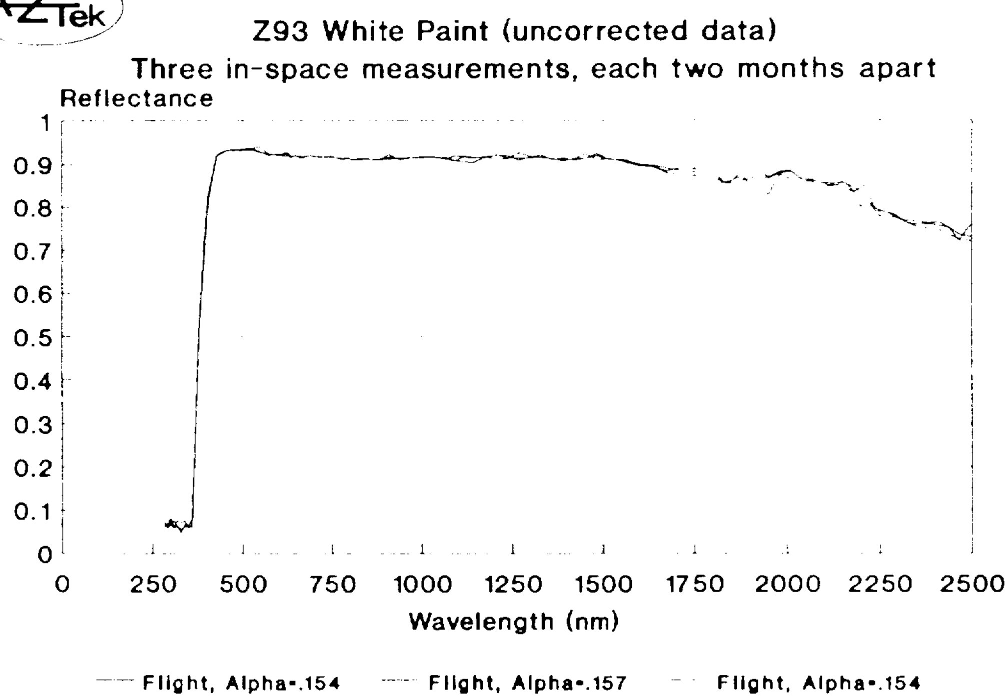


Figure 8 - Flight Reflectometer Performance

ORIGINAL PAGE
COLOR PHOTOGRAPH

Component	Predicted Temp. Limit Min (°C)	Predicted Temp. Limit Max (°C)	Measured Temp. Limit * Min (°C)	Measured Temp. Limit * Max (°C)
Integrating Sphere	-25	41	6	19
Batteries	-23	43	13	27
Electronics (DACS)	-27	41	17	29
Emissivity Plate	-25	40	-2	17
Radiometers			14	39
Passive Sample Hldrs.			15	43
Shroud (Front Cover)			-43	5

* Preliminary Data

Figure 9 - TCSE Predicted vs. Measured Thermal Data

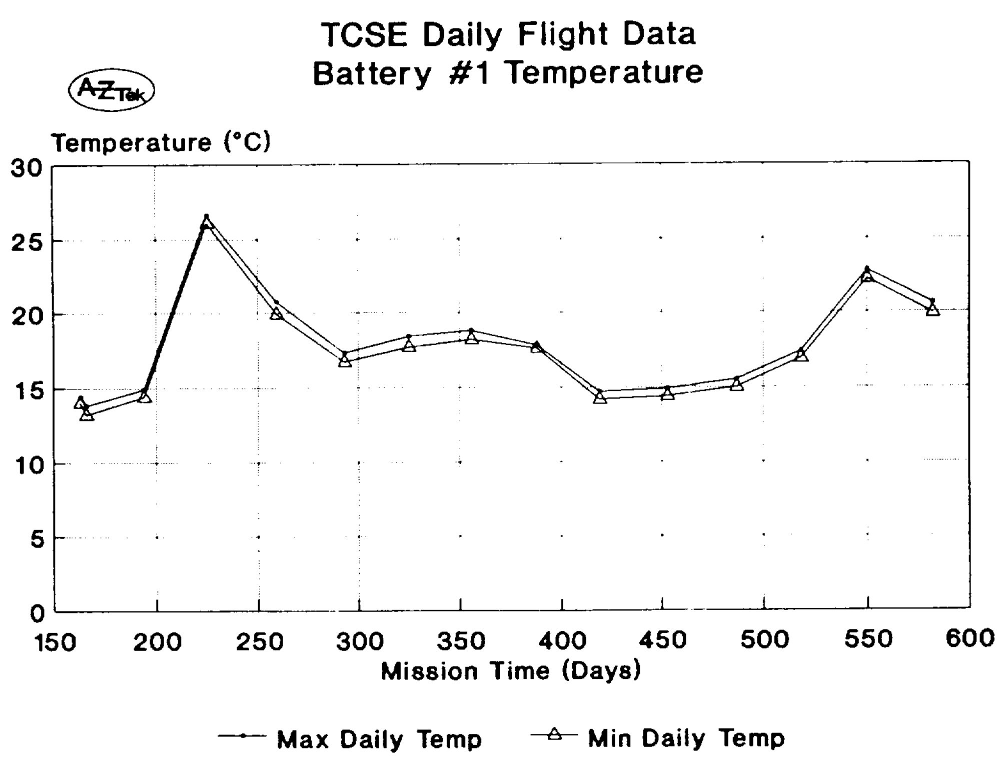


Figure 10 - Battery Temperature

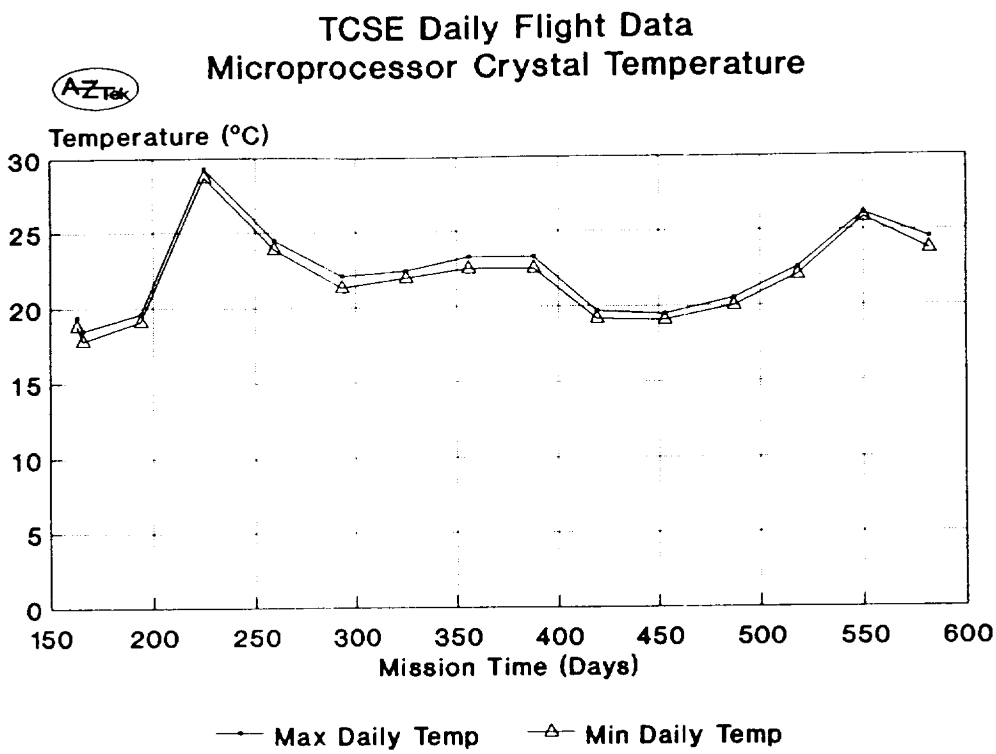


Figure 11 - DACS Internal Temperature

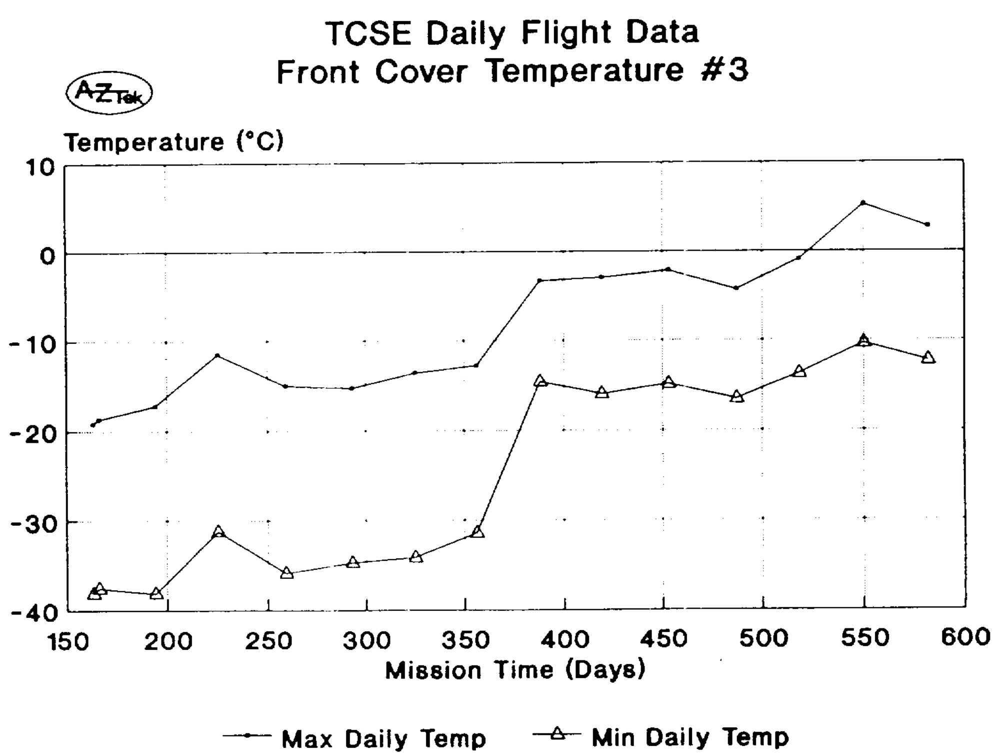


Figure 12 - Front Cover Temperature

INITIAL MATERIALS EVALUATION OF THE THERMAL CONTROL SURFACES EXPERIMENT (S0069)

Donald R. Wilkes
M. John Brown
Leigh L. Hummer

AZ Technology, Inc.
3322 Memorial Parkway SW, Suite 93
Huntsville, AL 35801
Phone: 205/880-7481, Fax: 205/880-7483

James M. Zwiener
NASA Marshall Space Flight Center
Marshall Space Flight Center, AL 35812
Phone: (205)544-2528, Fax: (205)544-0212

INTRODUCTION

The natural and induced long term effects of the space environment on spacecraft surfaces are critically important to many of NASA's future spacecraft--including the Space Station. The damaging constituents of this environment include thermal vacuum, solar ultraviolet radiation, atomic oxygen, particulate radiation, and the spacecraft induced environment. The inability to exactly simulate this complex combination of constituents results in a major difference in the stability of materials between laboratory testing and flight testing. The Thermal Control Surfaces Experiment (TCSE) was flown on the National Aeronautics and Space Administration (NASA) Long Duration Exposure Facility (LDEF) to study these environmental effects on surfaces--particularly on thermal control surfaces.

The TCSE was a comprehensive experiment that combined in-space measurements with extensive post-flight analyses of thermal control surfaces to determine the effects of exposure to the low earth orbit space environment. The TCSE is the first space experiment to measure the optical properties of thermal control surfaces the way they are routinely measured in the laboratory.

EXPERIMENT DESCRIPTION

The basic objective of the TCSE on the LDEF was to determine the effects of the near-Earth orbital environment and the LDEF induced environment on spacecraft thermal control surfaces. In summary, the specific mission objectives of TCSE were to:

- o Determine the effects of the natural and induced space environment on thermal control surfaces
- o Provide in-space performance data on thermal control surfaces

- o Provide in-space comparison to ground-based environmental testing of materials

- o Develop and prove instrumentation to perform in-space optical testing of materials.

To accomplish these objectives, the TCSE exposed selected material samples to the space environment and used in-flight and post-flight measurements of their thermo-optical properties to determine the effects of this exposure.[1] The TCSE hardware was designed to expose 25 "active" and 24 "passive" test samples to the LDEF orbital environment. The active and passive test samples differed in that the space effects on the passive test samples were determined only by pre- and post-flight evaluation. The optical properties of the 25 "active" samples were measured in-space as well as in pre- and post-flight analysis.

In-Space Measurements

The primary TCSE in-space measurement was hemispherical reflectance as a function of wavelength (100 wavelength steps from 250 to 2500 nm) using a scanning integrating sphere reflectometer. The measurements were repeated at preprogrammed intervals over the mission duration.

The secondary measurement used calorimetric methods to calculate solar absorptance and thermal emittance from temperature-versus-time measurements. The "active" sample surfaces were applied to thermally isolated (calorimeter) sample holders. To aid in the calorimetric calculations, three radiometers were used to measure the radiant energy (solar and Earth albedo, Earth albedo, and Earth infrared (IR) emitted) incident upon the samples. The radiometers also determined the total exposure of the samples to direct solar irradiance.

Flight Samples

The materials chosen for the TCSE mission comprised the thermal control surfaces of the greatest current interest (in 1983) to NASA, MSFC and the thermophysical community. The samples flown on the TCSE mission were:

- o A276 White Paint
- o A276/OI650 Clear Overcoat
- o A276/RTV670 Clear Overcoat
- o S13G/LO White Paint
- o Z93 White Paint
- o YB71 White Paint
- o YB71 over Z93
- o Chromic Acid Anodize
- o Silver/FEP Teflon (2 mil)
- o Silver/FEP Teflon (5 mil)
- o Silver/FEP Teflon (5 mil Diffuse)
- o White Tedlar
- o D111 Black Paint
- o Z302 Black Paint

- Z302/OI650 Clear Overcoat
- Z302/RTV670 Clear Overcoat
- KRS-5 IR Crystal
- Silver

Many of these materials were selected because they are good reflectors of solar energy while also being good emitters of thermal energy to the cold sink of space, i.e. they have a low solar absorptance (α_S) and a high room temperature emittance (ε_T). The range of low α_S/ε_T thermal control surfaces include materials that were expected to be very stable for the planned 9-12 month LDEF mission while others chosen because they were expected to degrade significantly.

Another class of materials flown on the TCSE was black paints. These are important as solar energy absorbers and light absorbers for science instruments.

Some of the materials were expected to react with the residual atomic oxygen at the LDEF orbital altitude. Transparent coatings were applied over a few of these samples to protect the samples from AO.

TCSE Flight Hardware

The TCSE is a completely self-contained experiment package; providing its own power, data system, reflectometer, and pre-programmed controller for automatically exposing, monitoring, and measuring the sample materials. The TCSE was developed as a protoflight instrument where one instrument was built, made to work within required specifications, qualification tested, and flown.

The TCSE was built in a 305 mm (12 in.) deep LDEF tray (see Figure 1). The active and passive samples were mounted in a semicircular pattern on a circular carousel. The carousel is tilted at 11 degrees from the outer tray surface to allow a 115 mm (4.5 inch) diameter integrating sphere to fit between the deep end of the carousel and the outer shroud. This design satisfied the LDEF requirement to remain within the outer edges of the tray and also provide a field of view of space greater than 150 degrees for the samples. This design maintained mechanical simplicity and inherent reliability. Figure 2 shows the basic specifications for the TCSE flight hardware.

TCSE MISSION SUMMARY

The LDEF was placed in low earth orbit by the Shuttle Challenger on April 7, 1984. LDEF was retrieved by the Shuttle on January 12, 1990 after 5 years 10 months in space. The orbit had a 28.5° inclination and an initial altitude of 463 km (250 N mi). The orbit degraded over the 5 year 10 month mission to an altitude of 330 km (178 N mi).

The LDEF was gravity-gradient stabilized and mass loaded so that one end of LDEF always pointed at the earth and one side pointed into the velocity vector or RAM direction. The LDEF was deployed with the TCSE located on the leading edge (row 9) of LDEF and at the earth end of this row (position A9). In this configuration, the TCSE was facing the RAM direction. The actual LDEF orientation was slightly offset from this planned orientation. The LDEF was rotated about the long axis where row 9 was offset from the RAM direction by about 8^{o}.[2] This LDEF/TCSE orientation and mission duration provided the following exposure environment for the TCSE:

Total space exposure	5 years 10 months
Atomic oxygen fluence[3]	8.0×10^{21} atoms/cm^2
Solar UV exposure[4]	1.0×10^{4} ESH
Thermal cycles	3.3×10^{4} cycles
Radiation (at surface)[5]	3.0×10^{5} rads

The TCSE operated for 582 days before battery depletion.[6] The battery power was finally expended while the sample carousel was being rotated. This left the carousel in a partially closed position. Figure 3 is a photograph taken during the LDEF retrieval operations showing where the carousel rotation stopped. This carousel position caused 35 of the samples to be exposed for the complete LDEF mission (69.2 months), and 14 exposed for only 582 days (19.5 months) and therefore protected from the space environment for the subsequent four years.

FLIGHT MATERIALS ANALYSIS

Many different changes were observed in the TCSE samples due to their prolonged space exposure. These changes ranged from the obvious cracking and peeling of the overcoated samples to the subtle changes of UV fluorescence in some samples.[7] Some samples changed more than expected while others changed less than expected.

The primary measurements used for this analysis were total hemispherical reflectance from 250 to 2500 nm. Both in-space and laboratory reflectance measurements were performed on the test samples. Laboratory measurements of spectral reflectance were obtained using a computer controlled Beckman model DK-2A Spectrophotometer equipped with a Gier-Dunkle 203 mm (8 inch) integrating sphere. The flight reflectometer provides similar data to the laboratory instrument.[1]

Figures 4 and 5 are pre-flight and post-flight photographs of the TCSE sample carousel showing changes to many of the samples. Figure 6 summarizes the optical measurements on the TCSE flight samples.[1]

A276 White Paint

Chemglaze A276 polyurethane white paint has been used on many short term space missions including Spacelab. It was known to degrade moderately under long term UV exposure and to be susceptible to AO erosion.[8] To evaluate the effectiveness of AO protective coatings, A276 samples were flown with and without overcoatings. Two materials were used as protective coatings over A276--RTV670 and Owens Illinois OI650.

The post-flight condition of the A276 samples were somewhat surprising in that the unprotected TCSE A276 samples are very white. Previous flight and laboratory tests indicate that almost six years of solar UV exposure should have rendered the

A276 a medium brown color. The overcoated TCSE samples, however, do exhibit the characteristic UV darkening. Initial visual inspection at KSC of unprotected A276 samples on the trailing edge of LDEF (almost no AO exposure) showed that they also degraded as expected.

Apparently, as the unprotected A276 samples on the RAM side of LDEF degraded, their surfaces were eroded away leaving a fresh, undamaged surface. Pippin[9] reported that the A276 binder eroded away leaving the white pigment exposed. Some degradation of this TiO_2 pigment should have also been observed due to UV exposure (in the absence of AO). It is possible that there was sufficient oxygen on leading edge surfaces to inhibit oxygen based pigment damage.[10]

Figure 7 shows pre-flight, in-space, and post-flight measurement of solar absorptance (α_S) for the unprotected A276 and overcoated A276 samples along with the detailed reflectance curves. These data show that both protective coatings protected the A276 from AO erosion but allowed the A276 coating to degrade from solar UV exposure. The data for the unprotected A276 shows only a small amount of degradation early in the almost 6 year exposure. While most of the AO fluence occurred late in the LDEF mission, the TCSE in-space measurements show there was sufficient AO present early in the mission to inhibit UV degradation.

Figures 8 and 9 show physical damage on the overcoated A276 calorimeter samples. The unprotected A276 samples did not crack or peel. The passive samples with these same protective coatings also crazed and cracked but did not peel. Calorimeter samples were thermally isolated from the TCSE structure and therefore saw wider temperature excursions, possibly causing the peeling of the overcoated samples.

The extended space exposure also changed the UV fluorescence of both the A276 and overcoated A276 coatings. This fluorescence is easily seen using a short wavelength inspection black light. The RTV670 and OI650 coatings glow a bright yellow under this UV illumination. Preliminary measurements show both a change in the peak wavelength and an increase in the magnitude of the fluorescence.[7]

Z93 White Paint

The Z93 white thermal control coatings flown on the TCSE were almost impervious to the 69 month LDEF mission (see Figure 10). The Z93 samples showed an initial improvement in the solar absorptance, which is typical of silicate coatings in a thermal vacuum environment. The initial improvement is due to an increased reflectance above 1300 nm. This is offset by a very slow degradation below 1000 nm and results in only a 0.01 overall degradation in solar absorptance for the extended space exposure. Because of the excellent performance of the Z93, it is the leading candidate for the radiator coating on Space Station Freedom.

As with the A276 samples, the LDEF space exposure also changed the UV fluorescence in the Z93 samples.[7] The unexposed Z93 coatings fluoresce naturally but much of this fluorescence was reduced by the LDEF exposure. Fluorescence of the ZnO pigment in Z93 and its decrease under UV exposure has been previously reported.[11] This reduced fluorescence in Z93 samples is not confined to the leading edge samples, but is also found on LDEF trailing edge samples as was observed on LDEF experiment AO114 samples.[1]

YB71 White Paint

The YB71 coatings on the TCSE behaved similarly to the Z93 samples. A small increase in the infrared reflectance early in the mission caused a decrease in solar absorptance (see Figure 11). This was offset by a slow long term degradation resulting in a small overall increase in solar absorptance. The TCSE YB71 samples were made before the preparation and application parameters for this new coating were finalized. This resulted in a wide spread in the initial solar absorptance for the different samples. The samples with YB71 applied over a primer coat of Z93 had a somewhat lower α_s than the other YB71 samples. Current YB71 samples are consistently below 0.10 solar absorptance.

S13G/LO White Paint

The S13G/LO samples on the TCSE degraded significantly on the LDEF mission. Figure 12 shows the change in solar absorptance for the LDEF mission of the TCSE S13G/LO calorimeter sample along with the spectral reflectance. As with Z93, the UV fluorescence of the S13G/LO coatings decreased markedly due to the LDEF exposure.[7]

White Tedlar Film

White Tedlar is another material that was expected to degrade over the 5.8 year LDEF mission due to solar UV exposure. Instead, the optical properties of this material improved slightly, as shown in Figure 13. The surface remained diffuse and white, similar to pre-flight observations. As with A276, Tedlar has been shown to be susceptible to AO erosion. The erosion effect of AO is the apparent reason for the lack of surface degradation of these flight samples.

The TCSE in-flight data shows that only a small degradation in solar absorptance was seen early in the LDEF mission. This indicates that, as with the A276 samples, there was sufficient AO early in the mission to erode away damaged material or otherwise inhibit significant degradation. The subsequent high AO fluence then eroded away all the damaged surface materials and even provided a slight improvement in solar absorptance. Similarly with the other samples, additional analyses are planned to better define these effects.

Chromic Acid Anodize

There were two chromic acid anodize samples on the TCSE sample carousel. These two samples degraded significantly during the first 18 months of the LDEF/TCSE mission as shown by the TCSE in-space measurements (see Figure 14). When the TCSE batteries were depleted (19.5 months mission time), the carousel stopped where one of the two anodize samples was exposed for the remainder of the LDEF mission while the other was protected. The two samples show significantly different appearance. The sample with 19.5 months exposure has an evenly colored appearance except for several small surface imperfections. The sample that was exposed for the entire 69.2 month mission has a mottled, washed out appearance. The detailed pre- and post-flight reflectance curves for the two anodize samples are shown in Figure 14. Further study will be required to determine why the solar absorptance of the anodize sample exposed for the complete mission improved in the latter stages of the mission.

Silver Teflon Solar Reflector

There were three different silver Teflon materials on the TCSE. The front cover of the TCSE and one calorimeter sample were two mil thick silver FEP Teflon bonded to the substrate with Y966 acrylic adhesive. The other samples were five mil thick silver FEP Teflon (specular and diffuse) and were bonded to the substrate with P223 adhesive.

The silver Teflon surfaces on the TCSE underwent significant appearance changes where the surface color was changed to a diffuse, whitish appearance. This change is caused by the eroding effect of atomic oxygen and results in a rough, light scattering surface. Preliminary measurements indicate a loss of about one mil of Teflon for the TCSE mission in addition to the roughened surface. A one mil loss of Teflon from the two mil samples would cause a significant loss of emittance, as was measured.[7]

While the AO roughened silver Teflon surfaces underwent striking appearance changes, the reflectance and solar absorptance did not degrade significantly due to this effect. For the 5 mil coatings with P223 adhesive, only small changes in reflectance (see Figure 15) and solar absorptance were measured. In addition, there was very little change in emittance.

The two mil silver Teflon coatings, however, did degrade significantly as shown in Figure 15. These coatings had a brown discoloration. Laboratory evaluation of these coatings with Nomarski microscopes revealed the discoloration was under the Teflon surface. Further investigation determined that the brown discoloration is associated with cracks in the silver/inconel metalized layer. Laboratory tests show that the application of the pre-adhesive type silver Teflon can crack the metalized layers. Removal of the paper backing on the adhesive and removal of air bubbles from beneath the silver Teflon can over-stress the metal layers causing significant cracking. It appears that a component of the adhesive migrated through the cracks into the interface with the Teflon over the long exposure to thermal vacuum. Subsequently, this internal contaminant was degraded by solar UV exposure causing the brown appearance. As a result, the reflectance decreased (see Figure 15) and more than doubled the solar absorptance.

The reflectance of the 2 mil silver Teflon, and its resulting solar absorptance, did not change significantly early in the TCSE mission. Only a small increase in solar absorptance was measured through the first 16 months of exposure. This indicates that this internal contamination and subsequent optical degradation occurs slowly over long space exposure.

Black Paints

Two different black paints were flown on the TCSE - IITRI D111 and Chemglaze Z302. D111 is a diffuse black paint that performed very well with little change in either optical properties or appearance as a result of the TCSE mission.

Z302 gloss black was the other black coating flown on the TCSE. Z302 has been shown to be susceptible to AO exposure.[8] In anticipation of these erosion effects, protective OI650 and RTV670 coatings were applied over some of the Z302 samples to evaluate their effectiveness. As expected, unprotected Z302 was heavily eroded by the AO exposure. Two of the TCSE Z302 coatings were exposed to the environment for the total 5.8 year LDEF mission. These unprotected Z302 sample surfaces eroded down to the primer coat. Two other samples were exposed for only 19.5 months and, while they did erode, still had good reflectance properties.

The overcoatings for the Z302 behaved similarly to the overcoatings on the A276 samples. The Z302 appears to have been protected by the overcoatings but the overcoats cracked and crazed. The coatings that were applied to the calorimeter sample holders peeled away from the substrate because of the wider temperature excursions of these thermally isolated samples.

In addition, the fluorescence of the Z302 samples changed due to the LDEF exposure. Using a short wavelength UV black light, the unprotected Z302 exhibited a pale green fluorescence while the overcoated samples fluoresced bright yellow. Initial spectral analysis of the Z302 samples show that the control samples naturally fluoresce; however, the LDEF exposure caused a wavelength shift and an increase in the magnitude of the fluorescence.[7] Additional studies will be performed to fully characterize these effects.

SUMMARY

The TCSE has provided excellent data on the behavior of materials and systems in the space environment. Expected effects did happen, but in some cases the magnitude of these effects was more or less than expected or was offset by competing processes. A number of unexpected changes were also observed, such as the changes in the UV fluorescence of many materials.

The performance of the materials tested on the TCSE ranges from very small changes to very large changes in optical and mechanical properties. The stability of some of the materials such as Z93, YB71 and silver Teflon (with P223 adhesive) shows there are some thermal control surfaces that are candidates for long term space missions. The materials that significantly degraded offer the opportunity to study space environment/material interactions.

The TCSE is the most comprehensive thermal control surfaces experiment ever flown. The TCSE is also the most complex system, other than the LDEF with experiments, recovered from space after extended exposure. The serendipitous extended exposure of the prolonged LDEF mission only added to the significance of the data gathered by the TCSE. In all, the TCSE was an unqualified success. This analysis effort has only begun the process of deriving the greatest benefit from the TCSE.

REFERENCES

1. Wilkes, D.R. and Hummer, L.L.; "Thermal Control Surfaces Experiment Initial Flight Data Analysis", Final Report for Contract NAS8-36288; AZ Technology Report No.: 90-1-100-2, June 1991.

2. Banks, B.A.; "LDEF Yaw Estimated at Eight Degrees", LDEF Spaceflight Environmental Effects Newsletter, Vol. II, Number 1, March 15, 1991.

3. Bourassa, R.J. and Gillis, J.R.; "Atomic Oxygen Flux and Fluence Calculation for Long Duration Exposure Facility (LDEF) LDEF Supporting Data", Contract NAS1-18224, January 1991.

4. Berrios, W.M.; "Long Duration Exposure Facility Post-Flight Thermal Analysis, Orbital/Thermal Environment Data Package," NASA LaRC, Hampton, VA, October 3, 1990.

5. Benton, E.V. and Heinrich, W.; "Ionizing Radiation Exposure of LDEF", University of San Francisco Report USF-TR-77, August 1990.

6. Wilkes, D.R., Hummer, L.L., and Zwiener, J.M.; "Thermal Control Surfaces Experiment Flight System Performance"; 1st LDEF Data Conference, NASA CP-19 . (Paper of this compilation.)

7. Zwiener, J.M., Wilkes, D.R., Hummer, L.L.; "Unusual Materials Effects Observed on the Thermal Control Surfaces Experiment (S0069)"; 1st LDEF Data Conference; NASA CP- , 19 . (Paper of this compilation).

8. Whitaker, A.F., Little, S.A., Harwell, R.J., Griner, D.B., DeHaye, R.F.; "Orbital Oxygen Effects on Thermal Control and Optical Materials, STS-8 Results", AIAA-85-0416, January 14, 1985.

9. Pippin, G.; "Materials SIG Summary Document Released", LDEF Spaceflight Environmental Effects Newsletter, Vol. I, Number 8, January 23, 1991.

10. Zerlaut, G.A., Gilligan, J.E.; "Study of In-situ Degradation of Thermal Control Surfaces", NASA Contract NAS8-21074 Final Report. IITRI Report U6061-29, Feb. 20, 1970.

11. Zerlaut, G.A. and Harada, Y., "Stable White Coatings", ITT Research Institute Report IITRI-C207-27, NASA Contract NAS7-100, January, 1964.

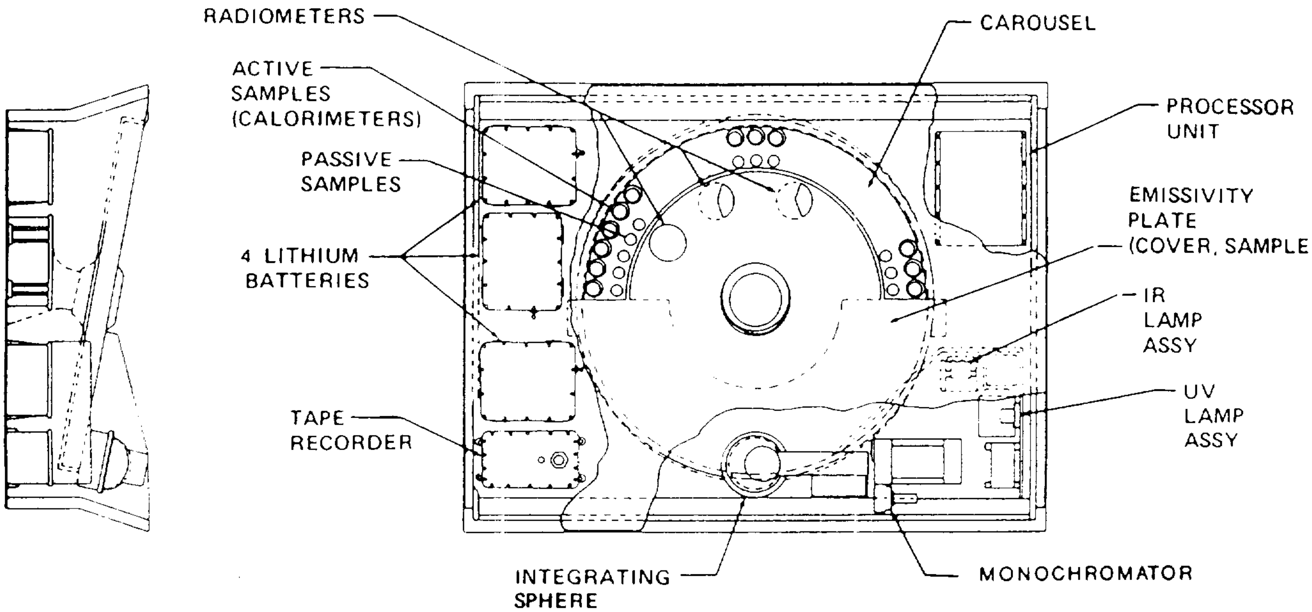


Figure 1 - TCSE Assembly

Size	1.24m x .84m x .30m (48.75 x 33 x 12 in.)
Weight	80.5kg (177 Pounds)
System Controller	1802 MicroProcessor
Battery Capacity	72 Amp Hours at 28 VDC
Data Recorder -Capacity	Lockheed 4200 54×10^6 Bits
Reflectometer	
-Wavelength Range	250 to 2500 nm
-Wavelength Resolution ($\Delta\lambda/\lambda$)	$\leq$ 5%
-Reflectance Accuracy	2%
-Reflectance Repeatability	1%
Calorimetric Measurements	
-Solar Absorptance	Accuracy - 5%
-Total Emittance	Accuracy - 5%

Figure 2 - TCSE Flight Hardware Specifications

Figure 3 - TCSE Condition during LDEF Retrieval

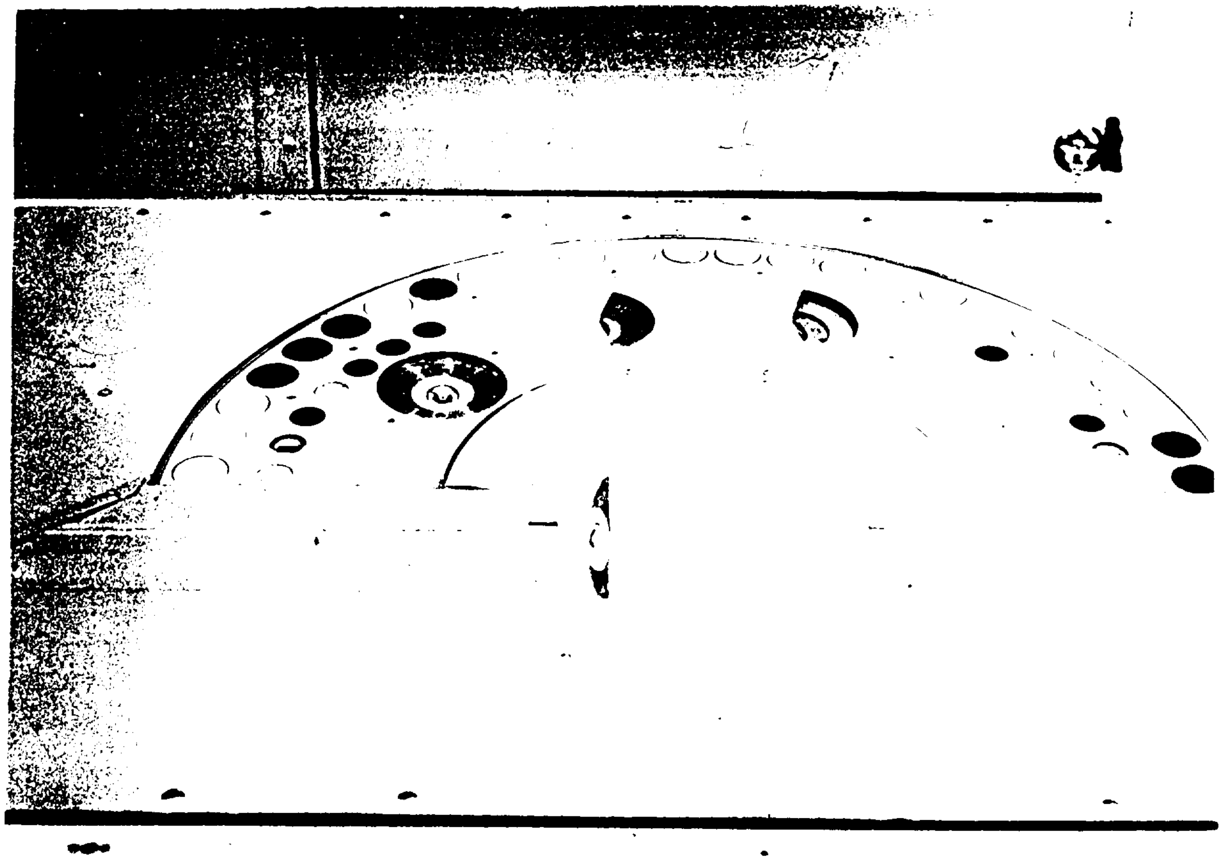


Figure 4 - Pre-flight Photograph of the TCSE Flight Samples

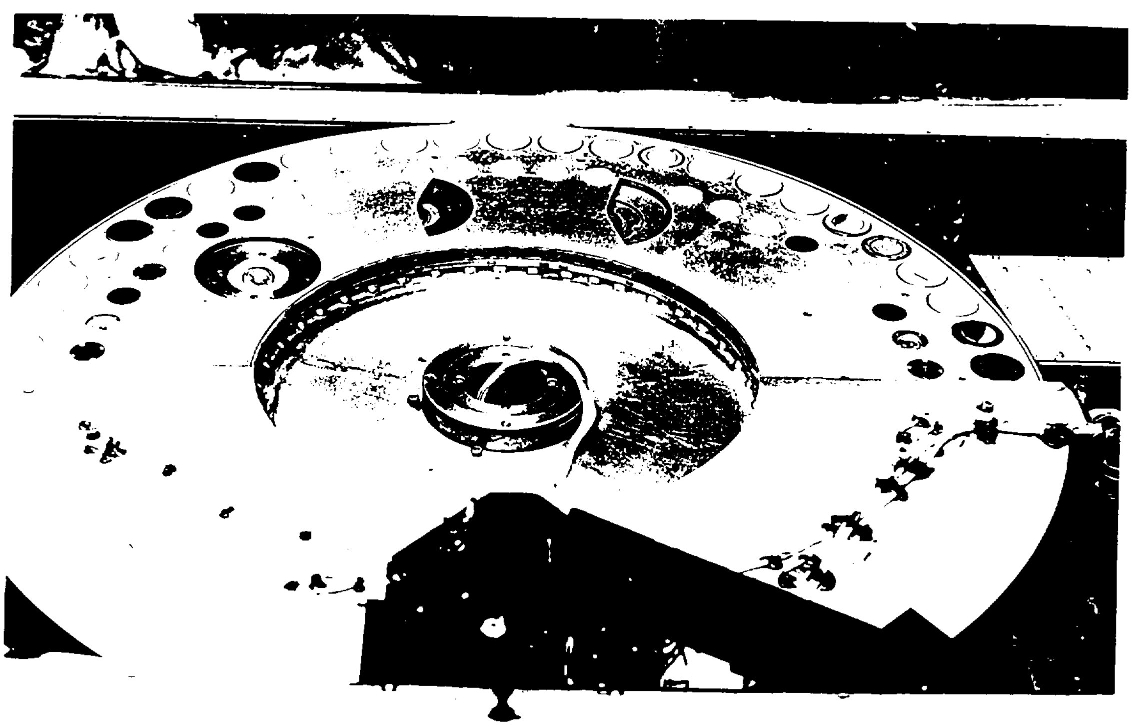


Figure 5 - Post-flight Photograph of the TCSE Flight Samples

Material	Source	Pre-flt	Solar Absorbtance (α_S) In-flt (15 Months)	Post-flt	$\Delta\alpha_S$	Emittance (ε_T) Pre-flt	Post-flt	$\Delta\varepsilon_T$
Tedlar	MSFC	.25	.26	.22	-.03			
A276	MSFC	.25	.30	.24	-.01	.90	.93	.03
A276 w/RTV670	MSFC	.27	.53	.62	.35	.91	.88	-.03
A276 w/OI650	MSFC	.25	.54	.59	.34	.90	.89	-.01
Z93	IITRI	.14	.13	.15	.01	.91	.92	.01
S13G-LO	IITRI	.18	.22	.37	.19	.90	.89	-.01
YB71	IITRI	.13	.12	.15	.02	.90	.89	-.01
YB71 over Z93	IITRI	.10	.11	.11	.01	.85	.87	.02
Silver Teflon (2 mil)	Sheldahl	.07	.08	.16	.09	.66	.46	20
Silver Teflon (5 mil)	LaRC	.06	.06	.08	.02	.81	.78	-.03
Silver Teflon (5 mil textured)	LaRC	.07	.08	.10	.03	.82	.79	-.03
Chromic Acid Anodize	LaRC	.40	.50	.47(.54*)	.07(.14*)	.84	.84	0
D111 Black	IITRI	.98	.99	.99	.01	.93	.90	-.03
Z302 Black	MSFC	.97	.98	.98*	.01	.91	.92	.01*
Z302/OI650	MSFC	.98	.99	.99	.01	.90	.90	0
Z302/RTV670	MSFC	.98	.99	.99	.01	.91	.90	-.01

*19.5 Months Exposure

Figure 6 - TCSE Optical Measurement Summary

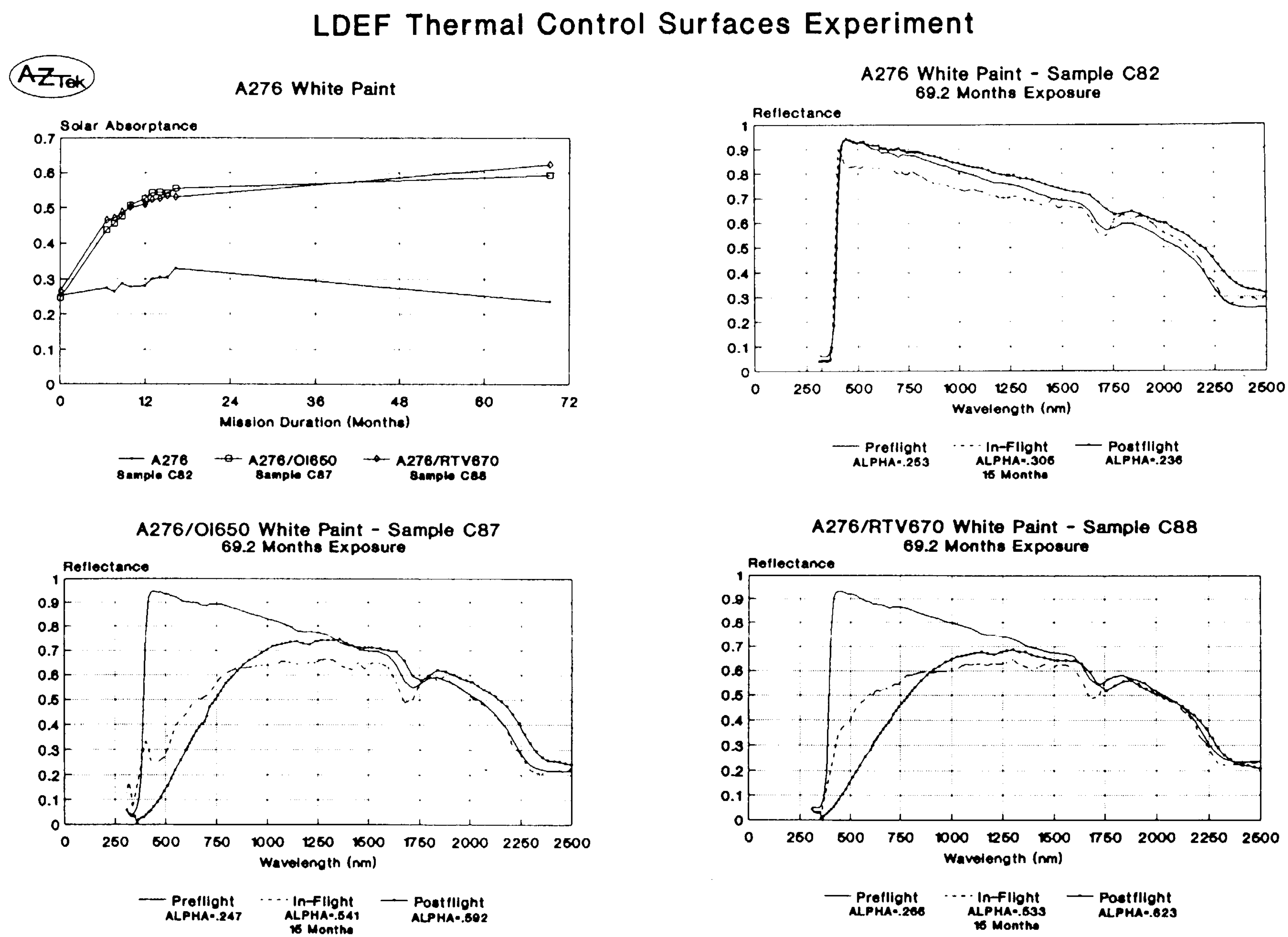


Figure 7 - Optical Properties of A276 White Paints

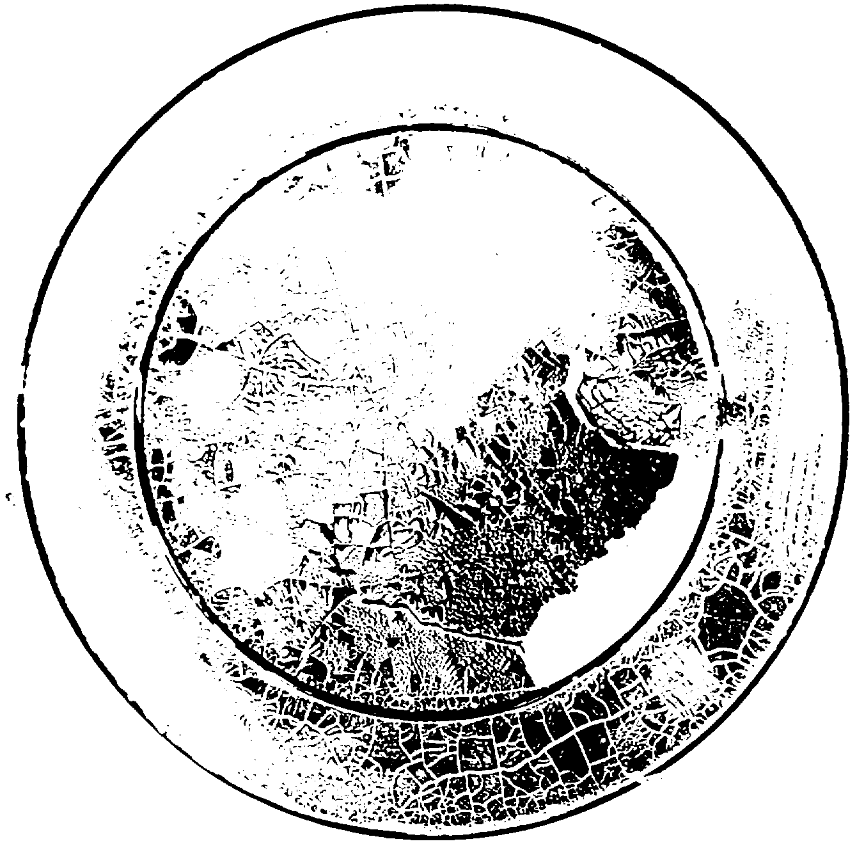


Figure 8 - Post-flight Condition of OI650 over A276

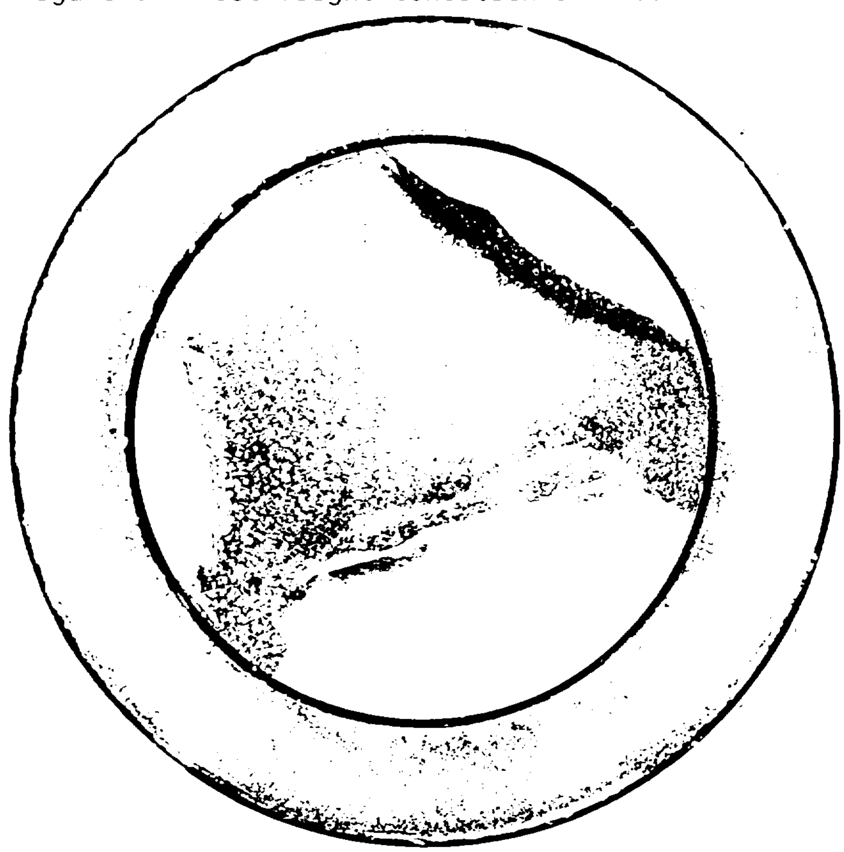


Figure 9 - Post-flight Condition of RTV670 over A276

LDEF Thermal Control Surfaces Experiment

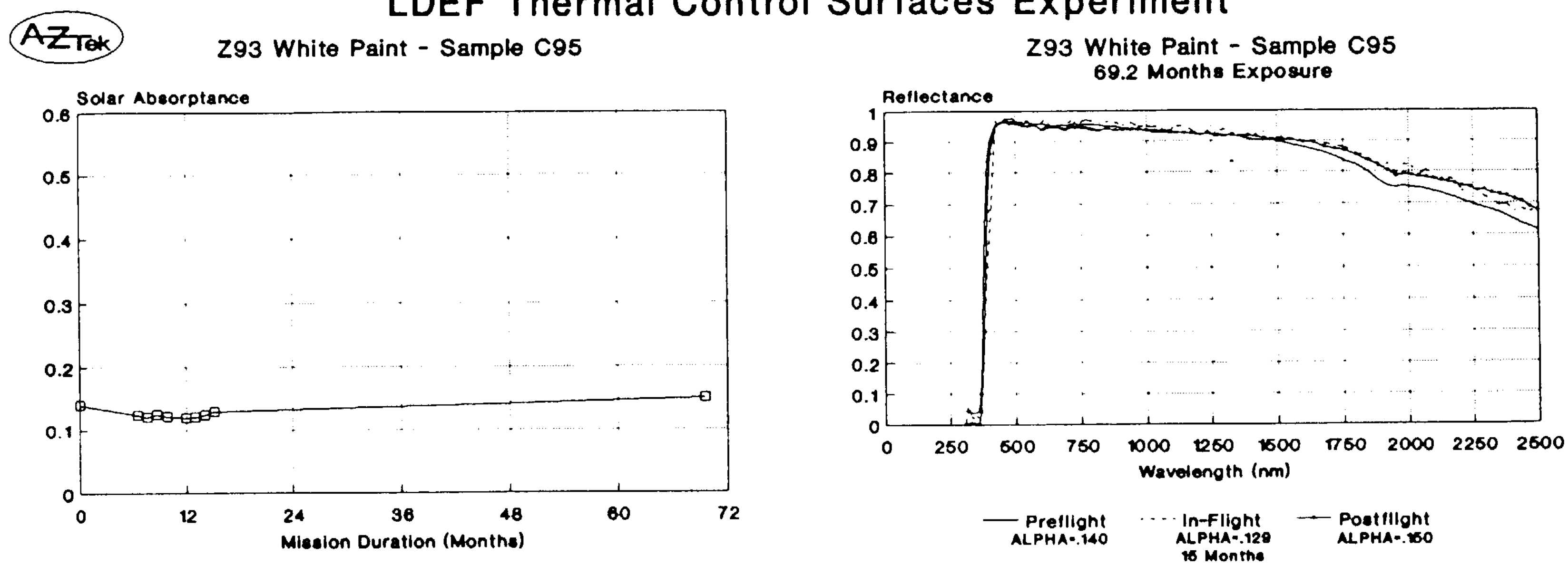


Figure 10 - Optical Properties of Z93 White Paint

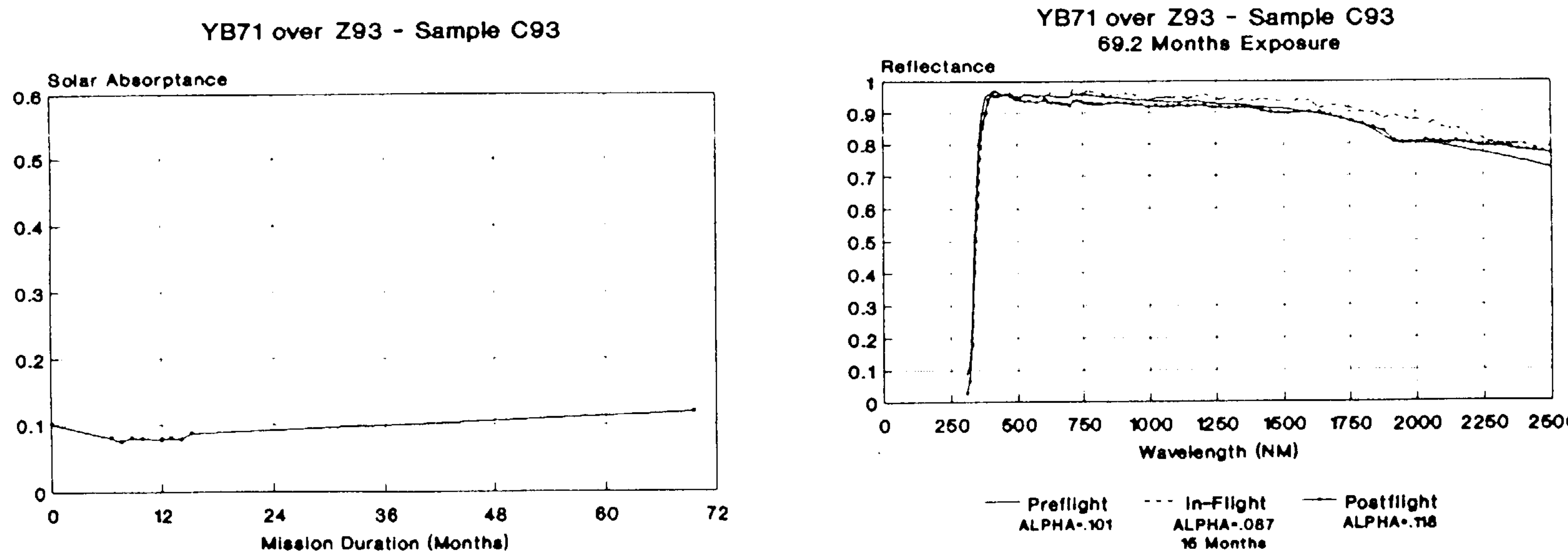


Figure 11 - Optical Properties of YB71 White Paint

LDEF Thermal Control Surfaces Experiment

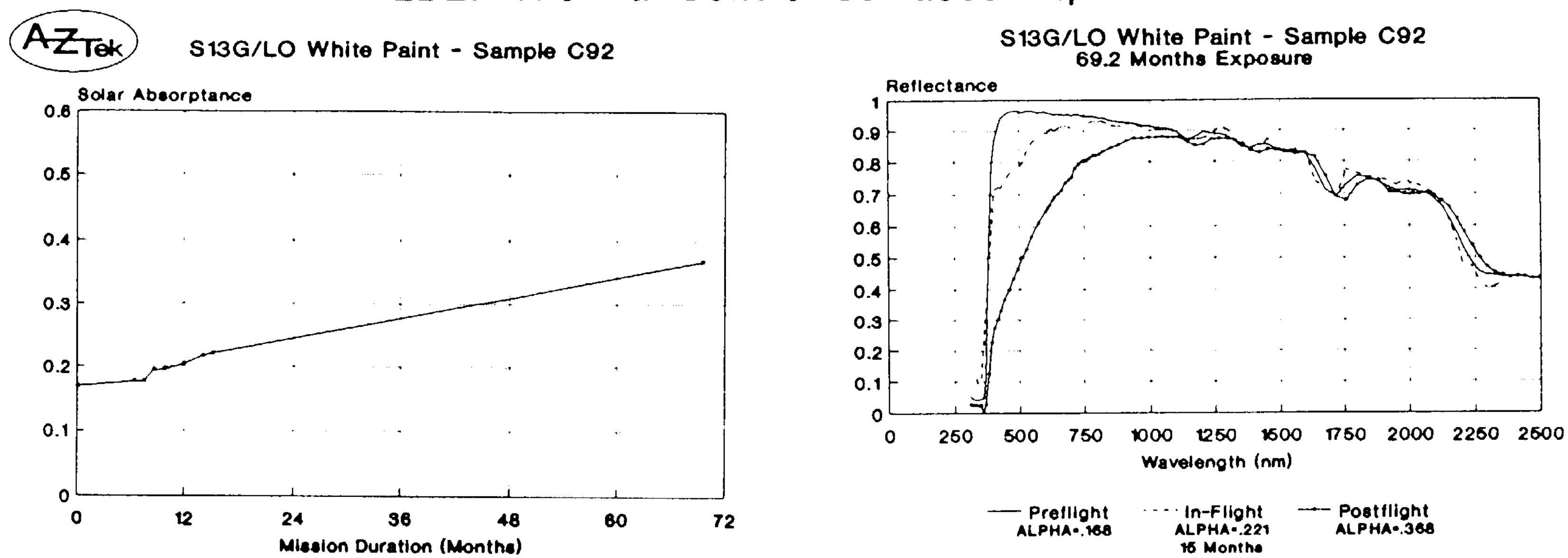


Figure 12 - Optical Properties of S13G/LO White Paint

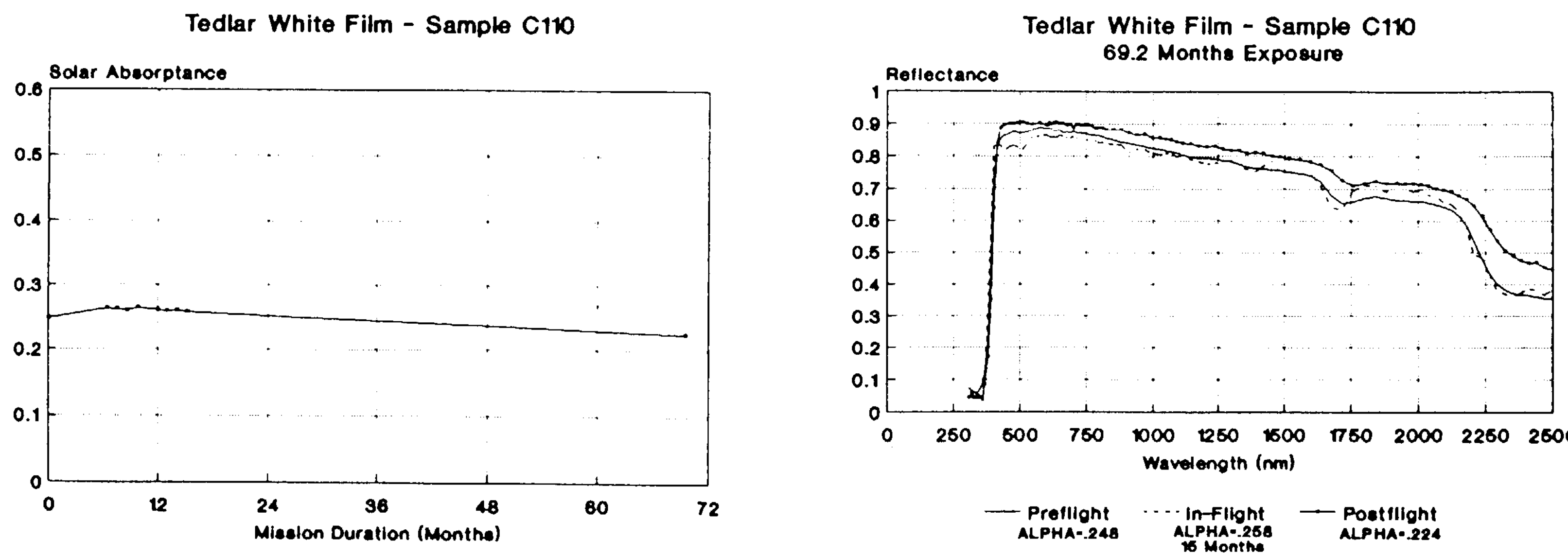


Figure 13 - Optical Properties of White Tedlar

LDEF Thermal Control Surfaces Experiment

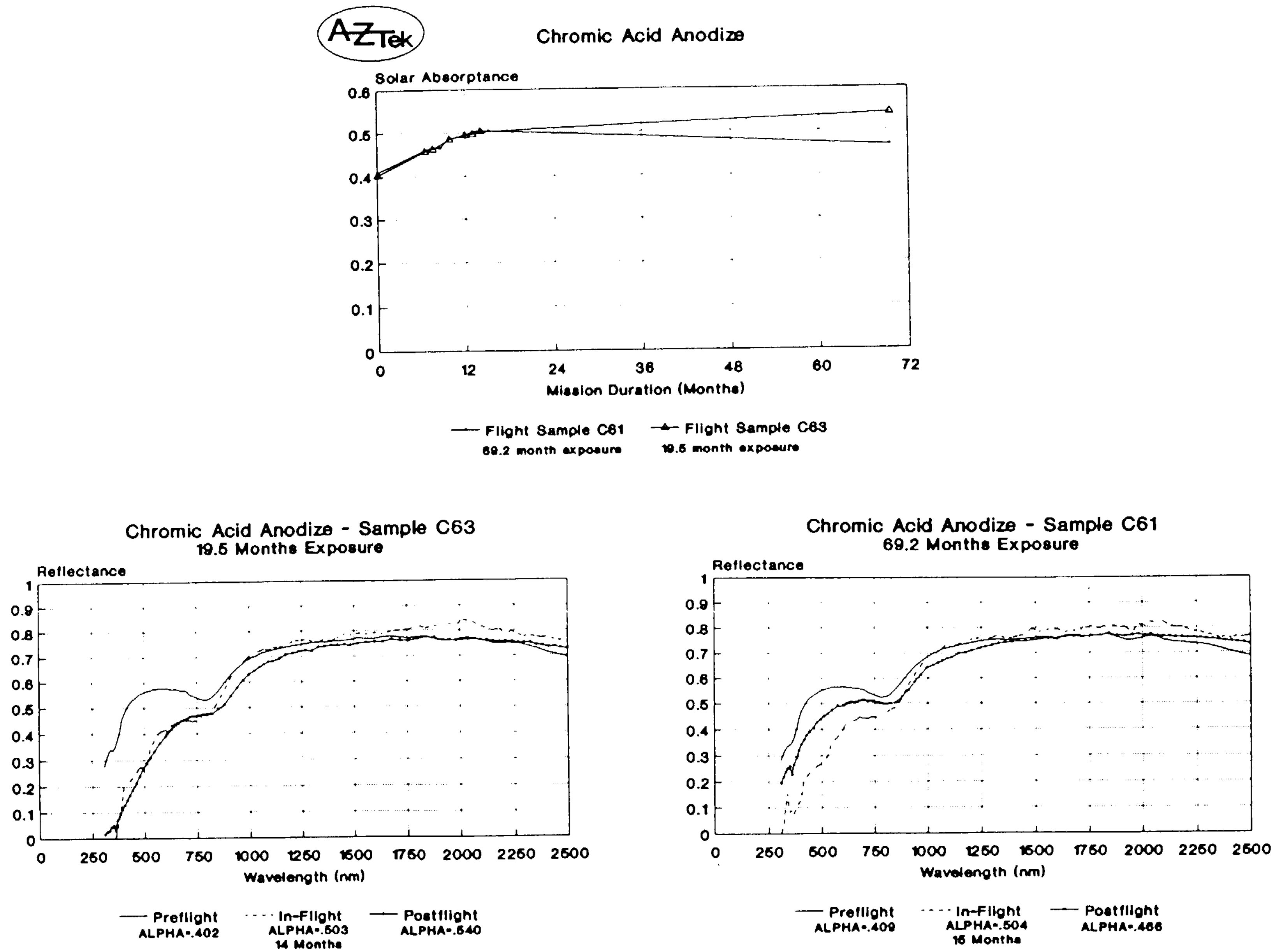


Figure 14 - Optical Properties of Chromic Acid Anodize

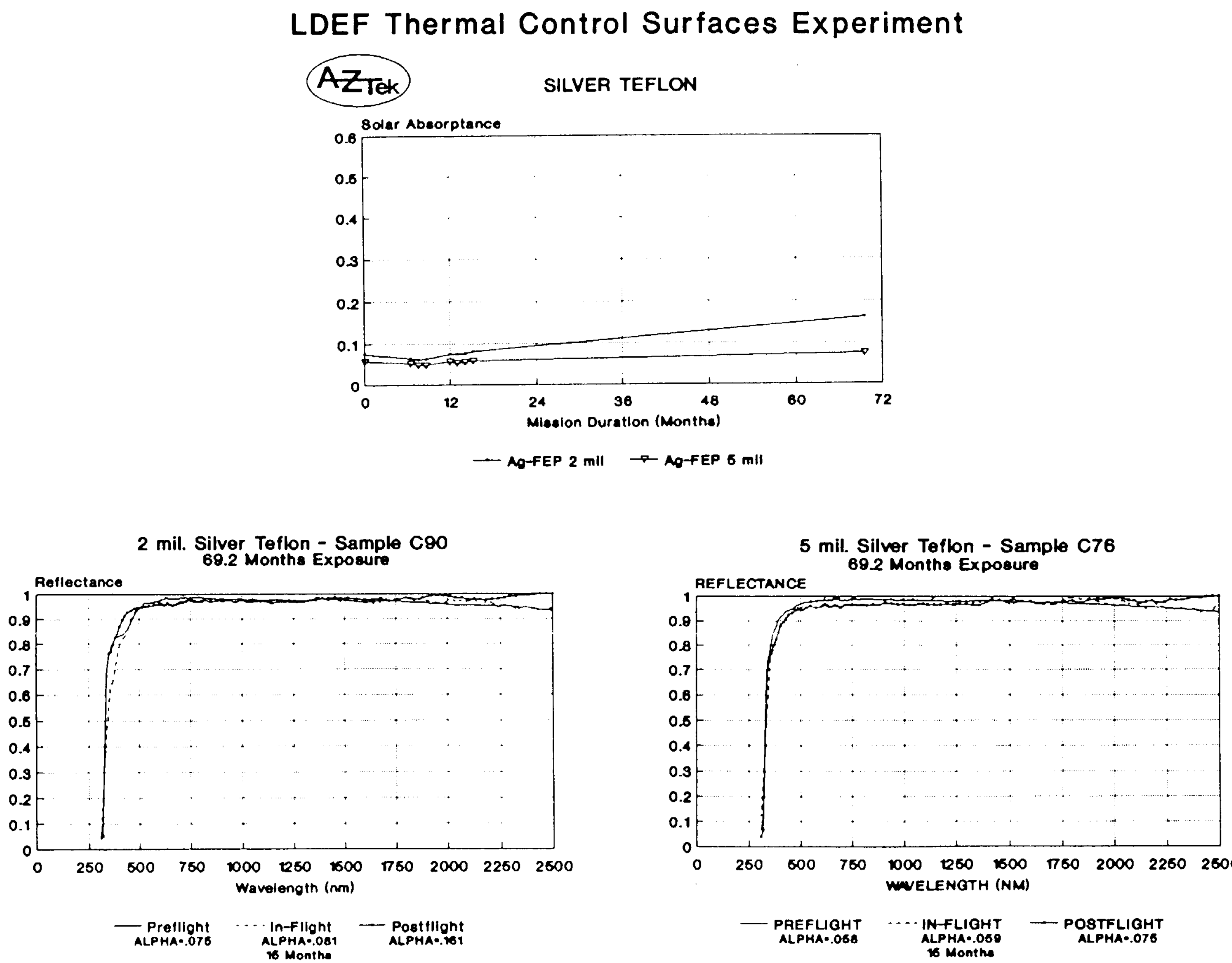


Figure 15 - Optical Properties of Silver Teflon

UNUSUAL MATERIALS EFFECTS OBSERVED ON THE THERMAL CONTROL SURFACES EXPERIMENT (S0069)

James M. Zwiener
Kenneth A. Herren
NASA Marshall Space Flight Center
Huntsville, Ala. 35812
Phone: 205/544-2528, Fax: 205/544-0212

Donald R. Wilkes
Leigh Hummer
Edgar R. Miller
AZ Technology
Huntsville, Ala. 35801
Phone: 205/880-7481, Fax: 205/880-7483

SUMMARY

A number of unusual effects were observed on the Thermal Control Surfaces Experiment (TCSE) test samples, front cover, and structural components. These effects include Atomic Oxygen (AO) texturing of the exposed surface of the silver Teflon (Ag/FEP) thermal control material, "brownish" discoloration of the Ag/FEP material, changes in fluorescence of thermal control paint samples, and meteoroid/debris impact effects on silver Teflon.

INTRODUCTION

The following paper provides an early assessment of the Thermal Control Surfaces Experiment (TCSE) in terms of what could be called "unusual" material effects that were caused by the 5.8 years exposure to the space environment. Unusual in the context of this discussion means effects on material or hardware that were either not expected or whose magnitude was more significant than anticipated. These effects are, in most cases, significant in that they may cause reconsideration of the utilization of some materials previously considered reasonably stable for long-term spacecraft applications. In addition, some of the detrimental effects can be avoided when the causes are understood, as in the case of the brownish discoloration of the silver Teflon (Ag/FEP) thermal control material. Information will be presented that details three of the many unusual effects found and investigated during the postflight analysis. These three effects are the changes to Ag/FEP, impact damage to TCSE front cover, and fluorescence changes of thermal control coatings.

SILVER TEFLON THERMAL CONTROL COATING

Overall Surface Observations

The inflight photograph in Figure 1 shows the TCSE location on row 9 and its orientation within approximately 8 degrees of the AO RAM vector. AO fluence in the RAM direction was 9.75×10^{21} atoms/cm^2.

An overall view of the front thermal cover is shown in Figure 2 after removal from the TCSE main structure during post flight disassembly. The front thermal cover has a Sheldahl 0.05 mm (2 mil) thick Ag/FEP thermal control material applied with Y966 acrylic adhesive. Covered areas have no apparent damage and are still highly specular. Areas exposed to the space environment are clearly delineated and have a diffuse, whitish appearance with brown discoloration. This brownish discoloration varies from light brown to dark brown. Changes in Ag/FEP visual appearance are the result of two damage mechanisms--AO erosion and internal damage associated with cracking of the silver/inconel layer.

Optical Property Measurements

Samples were cut from the TCSE front cover for optical property measurements. Total hemispherical reflectance measurements were made on samples from different locations on the front cover having varying degrees of damage. Figure 3A is a plot of this data showing the magnitude of reflectance loss in the brownish discolored regions. For those regions having a low degree of the brownish discoloration, it can be seen that the total reflectance values are basically unchanged with an solar absorptance (α_S) of 0.10 as compared to the ground reference sample (unexposed) with an α_S of ~0.08. The worse case brownish area had an solar absorptance as high as 0.49.

The emittance (ε_T) was also measured at several locations on the front panel and is plotted in Figure 3B. The protected areas were unchanged but exposed regions degraded from an emittance of 0.68 to 0.48. Comparison with measurements of ground control samples shows that approximately 25 microns (0.001 inch) to 33 microns (0.0013 inch) of Teflon was removed by AO. Eddy current thickness measurements confirm these numbers.

Atomic Oxygen Damage to the Surface of the Silver Teflon

AO erosion of the exposed Ag/FEP surface is typical of that observed on previous flight experiments. Erosion of the exposed Teflon surface creates a nonuniform etching pattern as shown in the Scanning Electron Microscope (SEM) photo in Figure 4. This results in a roughened surface with peaks ~1.5 microns apart which scatters incident light in a manner similar to a sand-blasted piece of glass.

Figure 5 shows a schematic cross section of the Ag/FEP as applied to the aluminum surface. The Ag/FEP is composed of an outer Teflon layer, a silver layer deposited on the Teflon, an inconel protective layer deposited on the silver, and

Y966 acrylic pressure sensitive adhesive. The silver layer provides the high reflectance (low absorptance) and the Teflon provides the high emittance for thermal control. As seen in the schematic for undamaged Teflon, the incident light (solar flux) transmits through the smooth clear Teflon and specularly reflects off the silver layer. AO damage to the Teflon creates a roughened surface which causes scattering of the incident light.

Optical measurements taken at position "1" in Figure 3, show that AO roughening alone produces less than a 0.03 increase is solar absorptance. Larger increases in solar absorptance were measured at positions "2" and "3" where the brownish discoloration occurs. Details of the brownish discoloration will be described in the following sections.

Silver Inconel Layer Cracking

A close up of the silver Teflon covered area is shown in Figure 6, showing that the silver/inconel layer is cracked. Location "1" is typical of most of the covered region having a regular, straight cracking pattern. Location "2" is where the two Ag/FEP layers meet and slightly overlap and is typical of areas that received excessive stress during application. When the Ag/FEP material is stressed, the silver/inconel layer cracks, even to the point of shattering as it is bent around protrusions.

Figure 7 shows a cross section of Ag/FEP during application. The silver/inconel layer undergoes severe stress during application as the Teflon layer is bent. The silver/inconel layer is on the outside of the bending radius and is stretched beyond its elastic limit and cracks. Ground tests were performed where new Ag/FEP was applied to aluminum plates identical to the TCSE front thermal cover. Results show that when Ag/FEP is applied to an aluminum substrate by the method shown in Figure 7, the silver/inconel layer cracks. Photomicrographs of Ag/FEP before and after application to the aluminum plates is presented in Figure 8. The induced cracking pattern is in the silver/inconel layer. Note that SEM inspection of new Ag/FEP applied to aluminum failed to find any cracks in the Teflon surface. Results for Ag/FEP with thicknesses from 0.25 mil to 5.0 mil show that cracking density decreases for increasing thickness of Teflon.

Silver Teflon Material Internal Damage

Silver Teflon on the TCSE that was exposed to AO and solar ultraviolet radiation has an overall whitish diffuse color. At specific locations (Figure 2 "C") a brownish streaking appearance is observed. Covered areas of Ag/FEP had neither the whitish diffuse color nor the brownish discoloration.

Figure 9A provides a close-up view of a sample (S-1) cut from the TCSE front thermal cover showing the typical brownish discoloration. The SEM image of this sample (Figure 4) shows that the Ag/FEP surface is not cracked nor is there any indication of a significant contaminant layer on the Ag/FEP that could cause the brownish appearance. The TCSE Ag/FEP was bonded to an aluminum substrate which prevented flexing of the material that might have caused cracks to show up in the top Teflon layer as has been observed on other experiments.

Visible microscopic examination also failed to find surface contamination in the brownish discolored areas. Internal damage to the Ag/FEP material in the form of a brownish streaking effect was observed along the silver/inconel cracks. This brownish color appears to have spread from silver/inconel cracks to the interface region between the Teflon and silver/inconel layer.

Referring to the view of sample S-1 in Figure 9A, area "1" has the typical AO damage but lacks the brownish discoloration, whereas area "2" has the typical brownish color. At area "3", in comparison, the surface diffuse layer of the Teflon was removed during the cutting operation returning the Ag/FEP to its original specular appearance. In general any contact including touching or wiping of the Teflon surface which has the whitish diffuse color returns it to its original specular appearance.

An enlargement of location "B" in Figure 9A is shown in Figure 9B. Note the brownish streaks/cracks going from area "1" to "2" were not disturbed by the removal of the surface diffuse layer on the Teflon.

Figure 9C, is an enlargement of area "C" of Figure 9B. The intensity of the brownish darkening can be seen to be a function of the closeness and degree of silver/inconel layer cracking. Areas "1" and "2" of Figure 9C have the diffuse Teflon surface which blurs the image of the cracks. When the diffuse layer is removed as in areas "3" and "4", a clearer image is seen of the silver/inconel cracks. These images demonstrate that the brownish streaking is not on the Teflon surface, and since the silver/inconel layer is opaque, the streaking must be located at the Teflon/silver interface. In addition it appears that the discoloration, which is probably a component of the adhesive, spreads outward from the cracks between the Teflon/silver interface.

Based on the postflight analysis the brownish streaking was the result a series of events, starting with the initial cracking of the silver/inconel layer during application to the TCSE front thermal cover. Subsequent long-term exposure to thermal cycling and solar ultraviolet caused the brownish discoloration. The intensity of the brownish discoloration is a direct function of the crack density which appears to be caused by excessive handling or stretching.

METEOROID/DEBRIS IMPACT PENETRATION ON THE FRONT COVER

The front cover of the TCSE experiment had one penetration from a meteoroid/debris impact. Figure 10A provides a close-up view of the impact showing the crater and Ag/FEP layer "blown" back from the crater rim. At location "1" of figure 10A, the Teflon layer has radial cracks emanating from the crater impact center. Some of the silver/inconel layer is still attached to the Teflon. For the Ag/FEP closest to the impact area, the silver/inconel and adhesive layers are missing. The exit of the impact event is shown in Figure 10B, with the small region indicated at area "1".

FLUORESCENCE CHANGES OF THERMAL CONTROL COATINGS

Most of the thermal control paint coatings underwent changes in their ultraviolet fluorescence characteristics. This was discovered during post-flight inspection with a UV black light. As an example, Z302 black paint with the OI650 overcoat had a bright yellow fluorescence when exposed to UV black light.

Ambient temperature fluorescence spectra for the TCSE flight samples of Z93, YB71, and Z302 are presented in Figures 11 and 12. The spectral peak at ~280 nm is the reflection of the irradiance source consisting of a 1 kilowatt HgXe source filtered through an attached monochromator. A Bechman DK2A spectrometer operating in the energy mode, was utilized for measuring the fluorescence emission.

As seen in Figure 11A the fluorescence for Z93 white paint is reduced after exposure to the space environment and decreases with increasing exposure. In addition, samples of Z93 from the LDEF leading and trailing edge of experiments (A0114/Gregory/Peters) exhibited identical fluorescence spectra. These spectra were also identical to the TCSE Z93 samples. The changes in fluorescence for Z93 is therefore independent of AO but is a function of the solar irradiation exposure.

Previous work at IITRI showed that the ZnO pigment in Z93 fluoresced. In comparison, YB71 white paint which has the same silicate binder as Z93 doesn't fluoresce (see Figure 11B). Therefore the source of the Z93 fluorescence is the ZnO pigment and not the silicate binder.

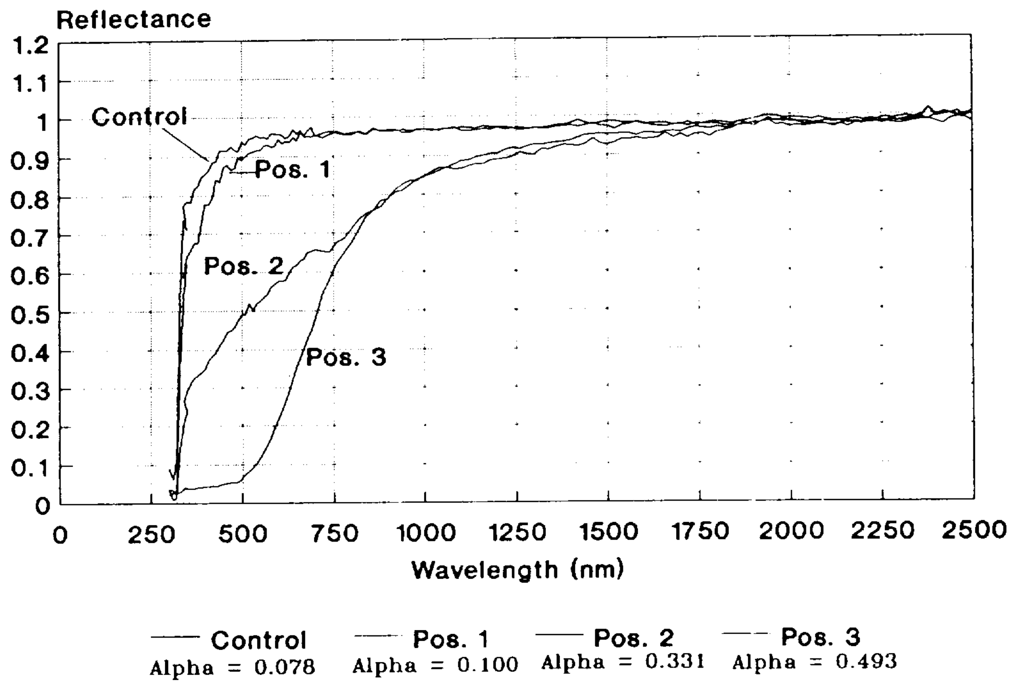
Fluorescence spectra for Z302 black paint exhibited a different effect than Z93 as shown in Figure 12. The fluorescence shifted from the ultraviolet region into the visible. A276 white paint samples had the same shift in fluorescence spectra as the Z302 material. In addition, the silicone overcoat on Z302 enhances its fluorescence spectra as seen by comparing the Z302/OI650 spectral data in Figure 12B to the uncoated Z302 data in Figure 12A.

CONCLUDING REMARKS

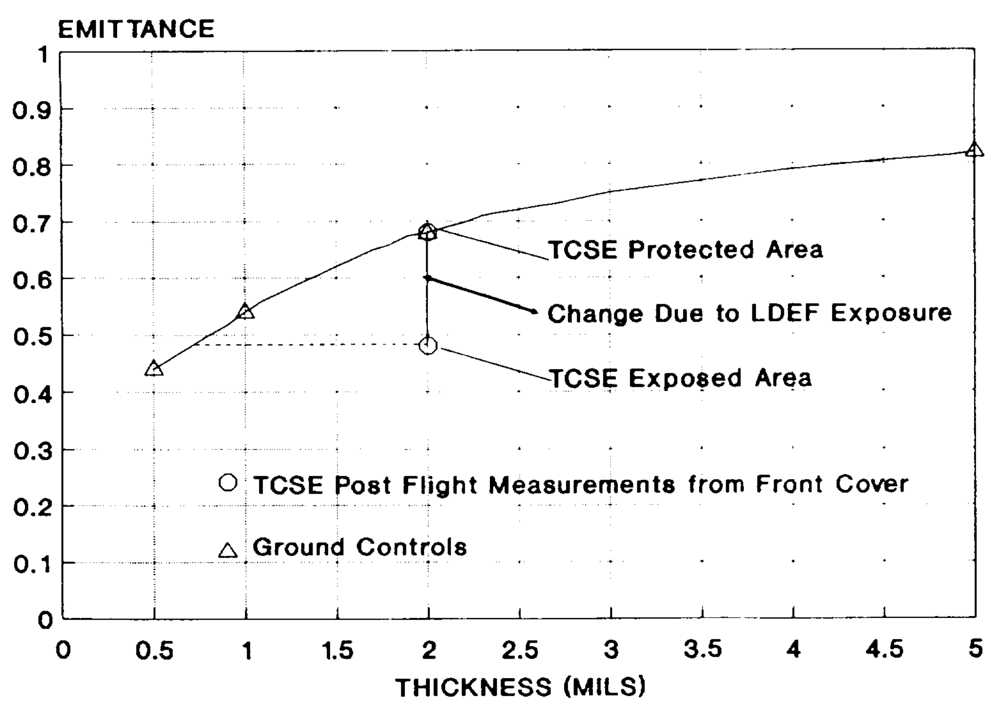
Besides the unusual material effects briefly described here, many other intriguing effects were found. Some of these unusual effects include changes to coatings internal to the TCSE experiment related to indirect exposure to AO, plume shaped shadow images found on the side of the TCSE LDEF tray along with image reversals, and light diffraction by exposed Ag/FEP. Other unusual effects included fiberglass panels covered with Ag/FEP which degraded differently than Ag/FEP on aluminum, and contamination internal to TCSE that appears affected by indirect AO and solar ultraviolet exposure. Studies are continuing to understand and fully characterize these "unusual effects" and determine their mechanisms.

Figure 3 - Optical Properties of TCSE Front Cover

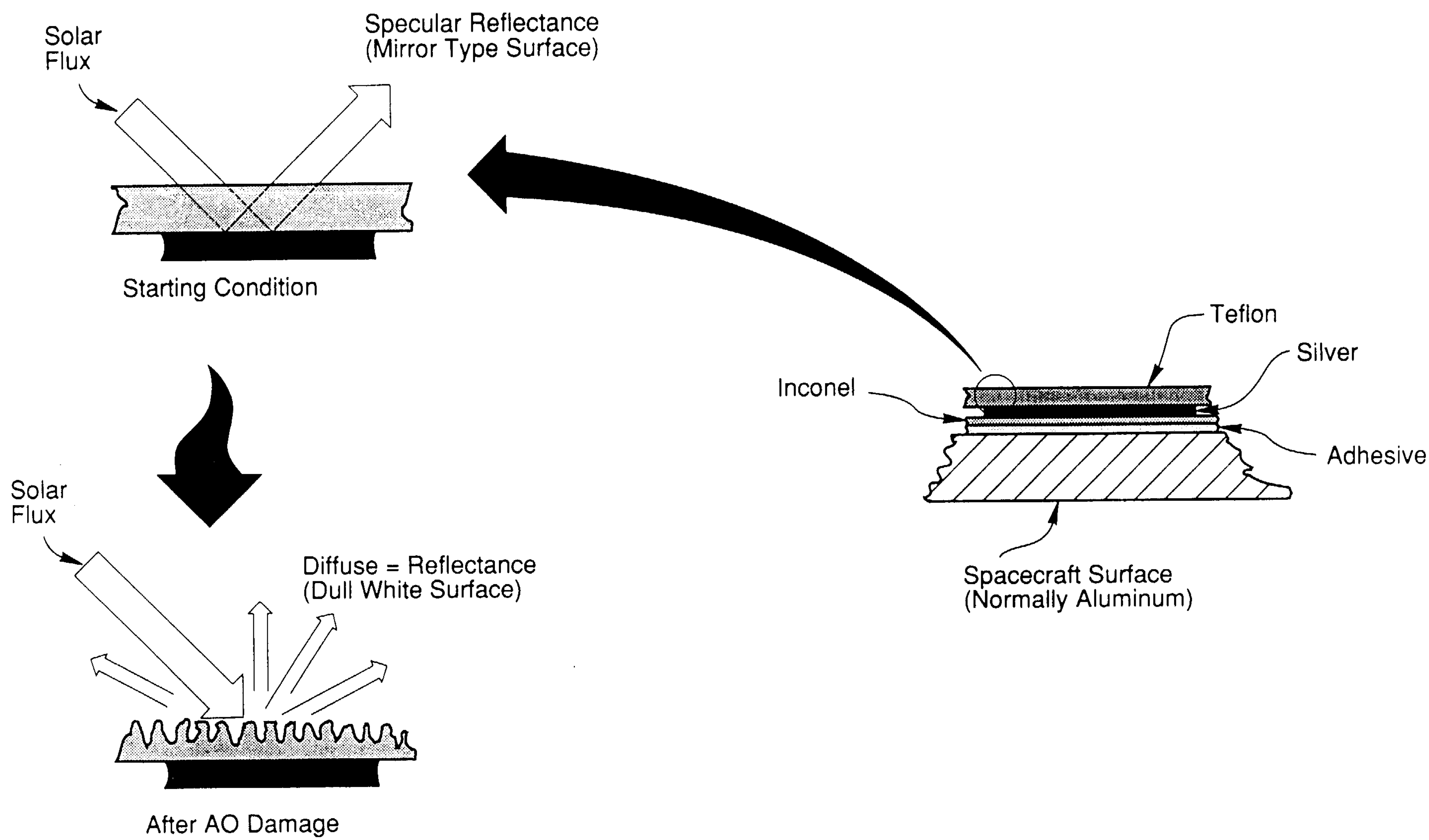
A. VARIATION IN REFLECTANCE PROPERTIES OF SILVER TEFLON



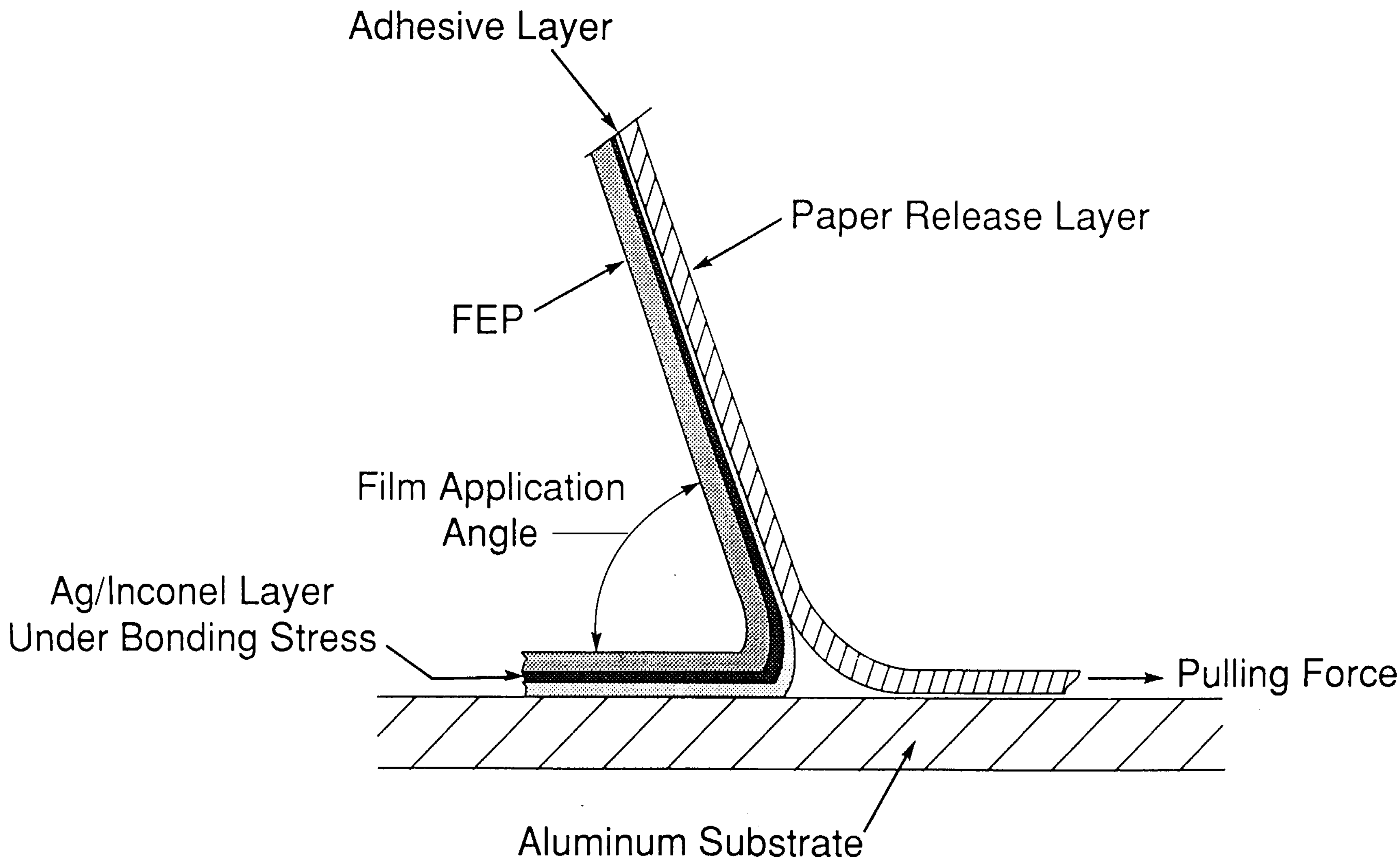
B. EMITTANCE OF SILVER TEFLON



Silver Teflon Thermal Control Coating
Atomic Oxygen Effect

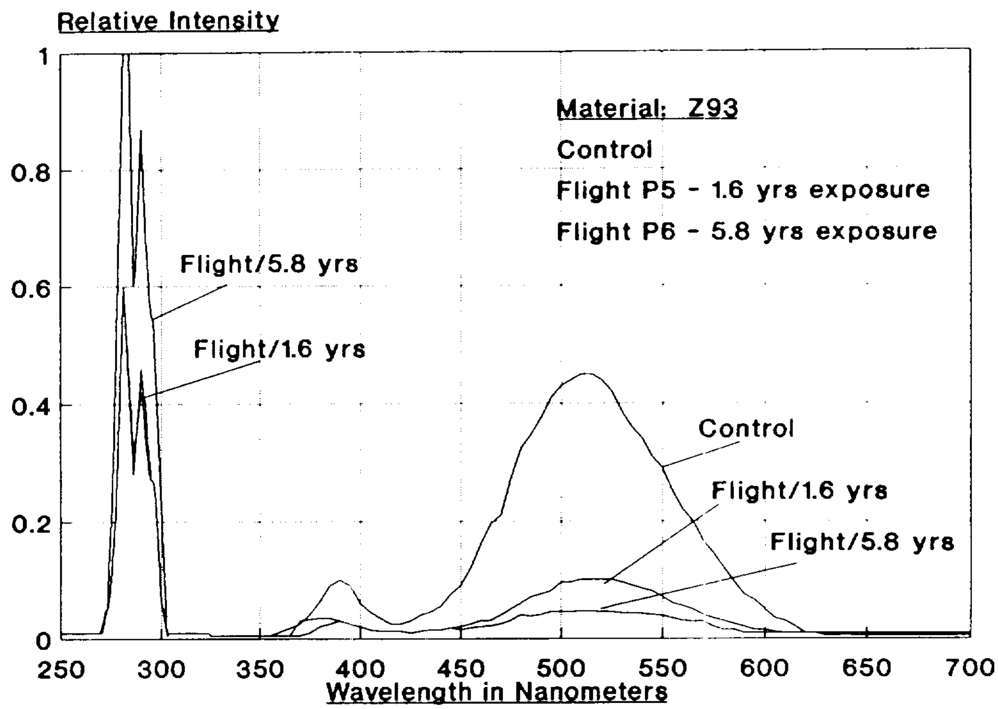


5-11818-0-322



Schematic of Silver Teflon Application

THERMAL CONTROL SURFACES EXPERIMENT S0069



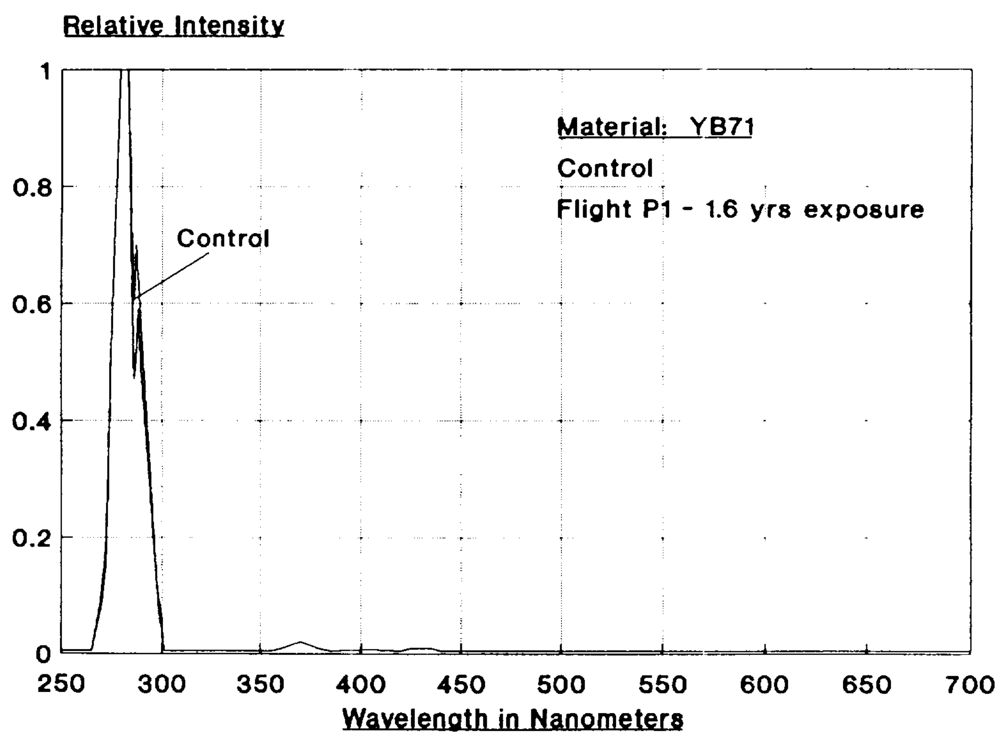


Figure 11 - Fluorescence Spectra of Z93 and YB71

THERMAL CONTROL SURFACES EXPERIMENT S0069

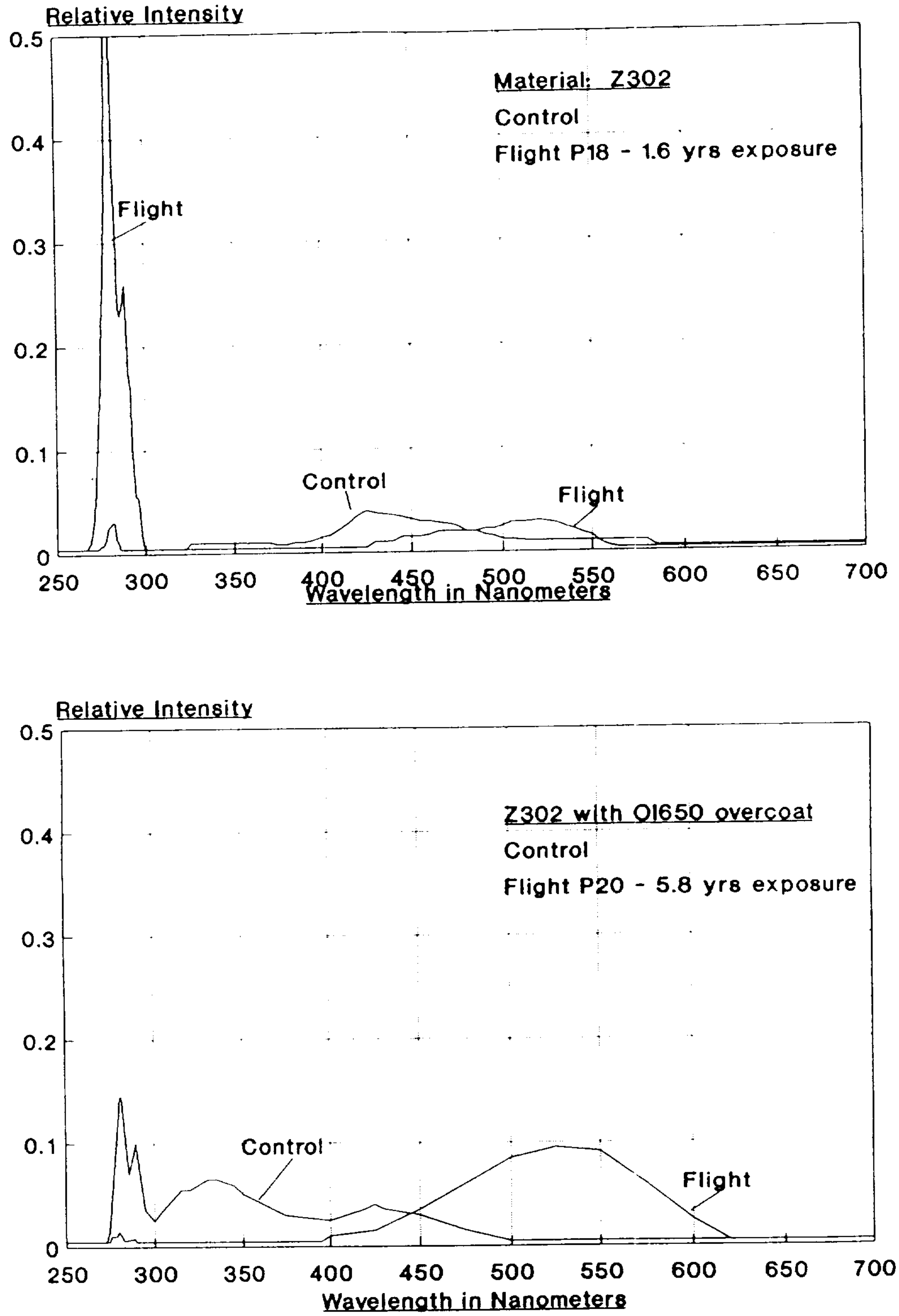


Figure 12 - Fluorescence Spectra of Z302 and Z302 with OI650 Overcoat