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TREND ANALYSIS OF IN-SITU SPECTRAL REFLECTANCE DATA FROM THE THERMAL CONTROL SURFACES EXPERIMENT (TCSE)

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SUMMARY

The Thermal Control Surfaces Experiment (TCSE) on the LDEF was a comprehensive experiment that combined in-space measurements with extensive pre- and post-flight analyses of thermal control surfaces to determine the effects of exposure to the low Earth orbit (LEO) space environment. The TCSE is the first space experiment to directly measure in-situ total hemispherical reflectance of thermal control surfaces in the same way they are routinely measured in the laboratory. In-space optical measurements performed by the TCSE provide the unique opportunity for trend analysis of the performance of materials in the space environment. Such trend analysis of flight data offers the potential to develop an empirical lifetime prediction model for several thermal control surfaces. For material research, trend analysis of the TCSE flight data, particularly the spectral data, can provide insight into the damage mechanisms of space exposure.

Trend analysis for the TCSE samples has been limited to those materials that were not significantly eroded by the atomic oxygen (AO) environment. The performance of several materials on the LDEF mission was dominated by AO effects. Trend analysis was performed on both the detailed spectral reflectance measurements (in-space, pre-flight, and post-flight) and on the integrated solar absorptance (α_s).

Results of this analysis for the five selected TCSE materials are presented along with the spectral flight data. Possible degradation and effects mechanisms will be discussed to better understand and predict the behavior of these materials in the LEO space environment.

INTRODUCTION

The long term effects of the natural and induced space environment on spacecraft surfaces are critically important to 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 behavior of materials and coatings in the space environment continues to be a limiting technology for spacecraft and experiments. 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 thermal control surfaces.

PRECEDING [illegible]

The TCSE was a comprehensive experiment that combined in-space measurements with extensive pre- and post-flight analyses of thermal control surfaces to determine the effects of exposure to the low Earth orbit (LEO) space environment.[1] The TCSE is the first space experiment to directly measure in-situ total hemispherical reflectance of thermal control surfaces in the same way they are routinely measured in the laboratory.

EXPERIMENT DESCRIPTION

The TCSE was 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 (see Figure 1). The primary TCSE in-space measurement was total hemispherical reflectance as a function of wavelength from 250 to 2500 nm using a scanning integrating sphere reflectometer. The measurements were repeated at preprogrammed intervals until battery power depletion.

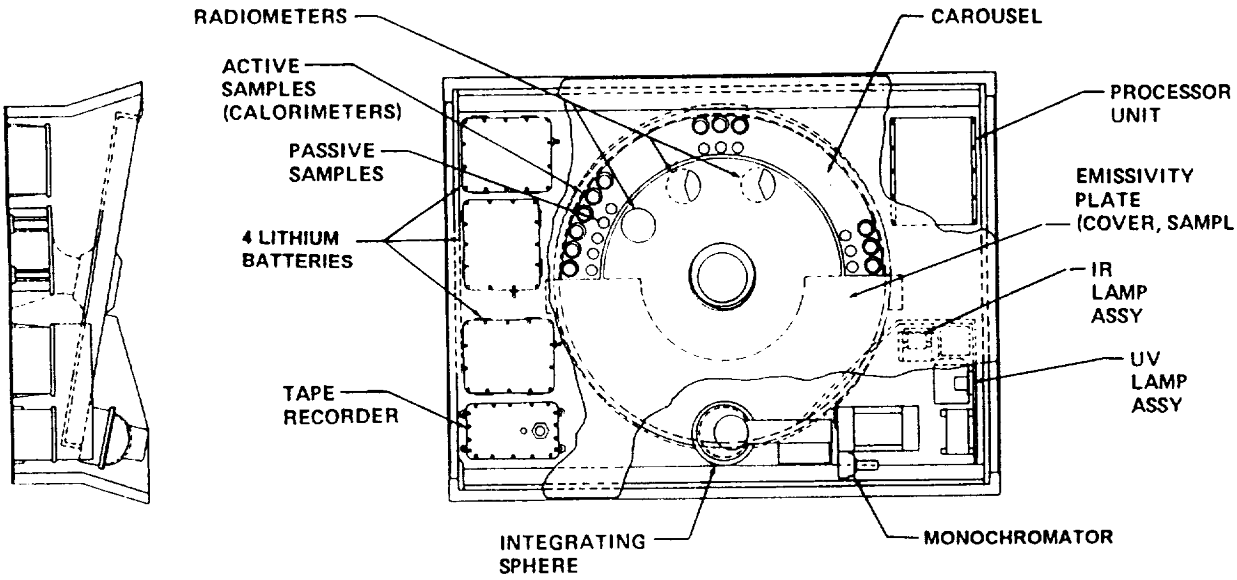

Figure 1. TCSE Assembly.

The LDEF, with the TCSE on board, 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 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 TCSE was located on the leading edge (row 9) of LDEF and at the Earth end of this row (position A9). The LDEF leading edge (and the TCSE) was offset from the RAM vector by 8.1°. This LDEF/TCSE orientation and mission duration provided the following exposure environment for the TCSE samples:

Total space exposure	5 years 10 months
Atomic oxygen fluence[2]	8.3 x 10^{21} atoms/cm^2
Solar UV exposure[2]	1.0 x 10^4 ESH
Thermal cycles	3.3 x 10^4 cycles
Radiation (at surface)[3]	3.0 x 10^5 rads

The TCSE operated for the first 584 days of the LDEF mission before its batteries were depleted. Although the flight recorder malfunctioned, data were recovered for the last 421 days of this operational period. The recovered data included eleven sets of reflectometry data. The battery power was fully expended while the sample carousel was being rotated, leaving the carousel in a partially open position. This carousel position permitted exposure of 35 of the samples for the complete LDEF mission (69.2 months), while 14 samples were exposed for only 19.5 months and were protected from the direct space environment for the subsequent four years.

DEGRADATION TREND ANALYSIS

Long duration of space missions requires significant extrapolation of flight and ground simulation data to provide predictions of end-of-life properties for thermal control surfaces. This is particularly true for NASA programs such as the Space Station, AXAF and the Hubble Space Telescope. The in-space optical measurements performed by the TCSE offer the unique opportunity to perform a trend analysis on the performance of materials in the space environment. Trend analysis of flight data provides the potential to develop an empirical prediction model for some of the thermal control surfaces. For material research, trend analysis of the TCSE flight data can provide insight into the damage mechanisms of space exposure.

The trend analysis for the TCSE samples has been limited to those materials that were not significantly eroded by the atomic oxygen (AO) environment. The performance of several materials on the LDEF mission was dominated by AO effects. This is particularly true for unprotected A276 and Tedlar where the AO eroded away the surface layers faster than they were degraded by Solar UV. This resulted in a fresh surface with unchanged or slightly improved optical properties.

Trend analyses have been performed on five materials:

- Z93 White Paint
- YB71 White Paint
- S13G/LO White Paint
- A276 White Paint and protective overcoats
- Silver Teflon

These analyses were performed on both detailed spectral reflectance data and derived integrated solar absorptance (α_s). This data includes both in-space and ground based pre-flight and post-flight measurements. The solar absorptance data was analyzed using regression analysis to develop an empirical lifetime model for these materials. Empirical prediction models must be used with caution, however, because they can be misleading and have no scientific basis. The TCSE data provides the only in-situ optical data providing time history of the optical changes to materials exposed to the space environment. The analysis of this data provides the first insight into these time dependent material changes and enables the development of a prediction model. Other in-situ optical measurement experiments should be performed to verify this data and to provide data on new and improved materials. Several standard regression analyses were evaluated including polynomial, exponential, logarithmic and power fit functions. For integrated α_s the power regression analysis provided a better fit of the experimental data. The power regression line takes the form:

$$\alpha_s = e^{(a+b\ \ln(t))}$$

While the analysis of solar absorptance data is of great benefit to spacecraft designers, it is the analysis of the spectral data that provides the best insight into the different damage mechanisms of the space environment on materials. For most materials, there are more than one, and potentially many, competing mechanisms of damage due to the combined space environment. In many cases different damage mechanisms exhibit effects in different spectral ranges. The trend analysis of reflectance changes at different wavelengths will aid in separating different mechanistic effects.

In the following discussions, the results of the trend analyses are presented for the five selected materials. Data is shown for both integrated solar absorptance and spectral reflectance. Some of this α_s data has been previously reported[4] but is repeated to relate the spectral data to the integrated α_s data. The format of the data presentation is described in the first section for Z93 White Paint.

Z93 White Paint

Figure 2 shows the performance of Z93 for the LDEF mission. Solar absorptance is plotted versus exposure time. There appear to be at least two mechanisms that affected the Z93 solar absorptance during the LDEF mission. The first is a short term improvement (decrease) in α_s typical of silicate coatings in thermal vacuum. This improvement is normally associated with loss of water from the ceramic matrix. In ground simulation tests this process takes a much shorter time than the TCSE flight data suggests. This slower loss of water may be due to the cold temperature of the TCSE Z93 sample mounted on a thermally isolated calorimeter. The temperature of the Z93 sample ranged from approximately -55°C to +6°C but remained well below 0°C most of the time.

The short term improvement is dominant for the first year of exposure after which a long term degradation mechanism becomes dominant. The results of the power regression analysis for the short and long term effects are also shown in Figure 2. Figure 3 plots the long term regression model for Z93 on a log scale allowing extrapolation out to 30 years. The regression analysis projects a 30 year end-of-life value for Z93 of $\alpha_s = 0.185$. This predicted value is statistically a most probable value and not a worse case value.

Figures 4 and 5 show the spectral reflectance data for Z93. All spectral reflectance data presented in this paper are plotted as normalized change in reflectance.

$$\text{Delta } R/R = (\rho-\rho_o)/\rho_o$$

where ρ_o = initial reflectance (time = 0)
ρ= reflectance at time t

Figure 4 plots normalized reflectance change versus exposure time for five selected wavelengths while Figure 5 plots normalized reflectance change versus wavelength at four different exposure times. These data show that the short term improvement in reflectance of Z93 (attributed to loss of water) is broad banded with the major changes occurring in the infrared as expected. It is somewhat surprising to also see this improvement at the shorter wavelengths. The longer term degradation mechanism occurs mainly below 1000 nm. Even though the changes are small, they are significant because the solar energy curve peaks in this spectral range.

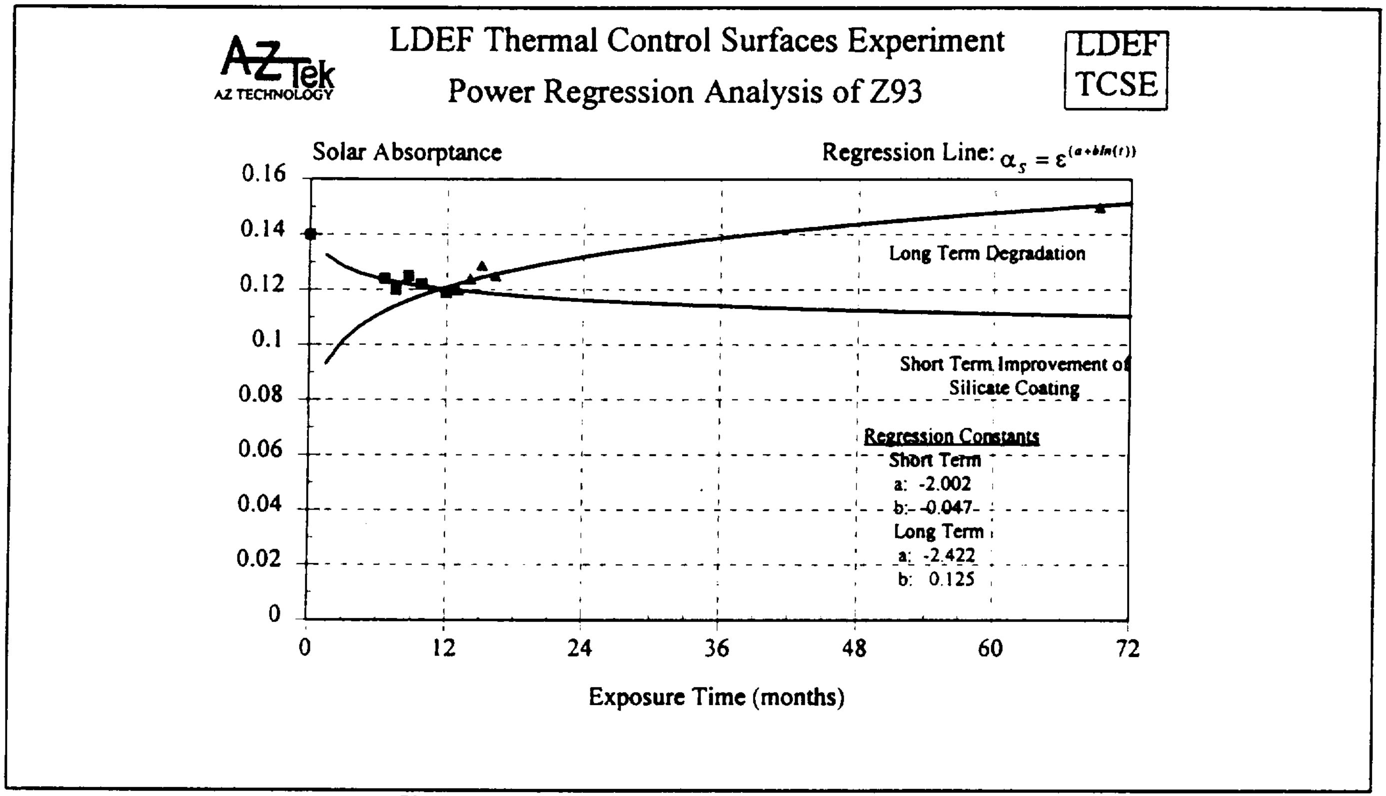

Figure 2. Power Regression Analysis of Z93.

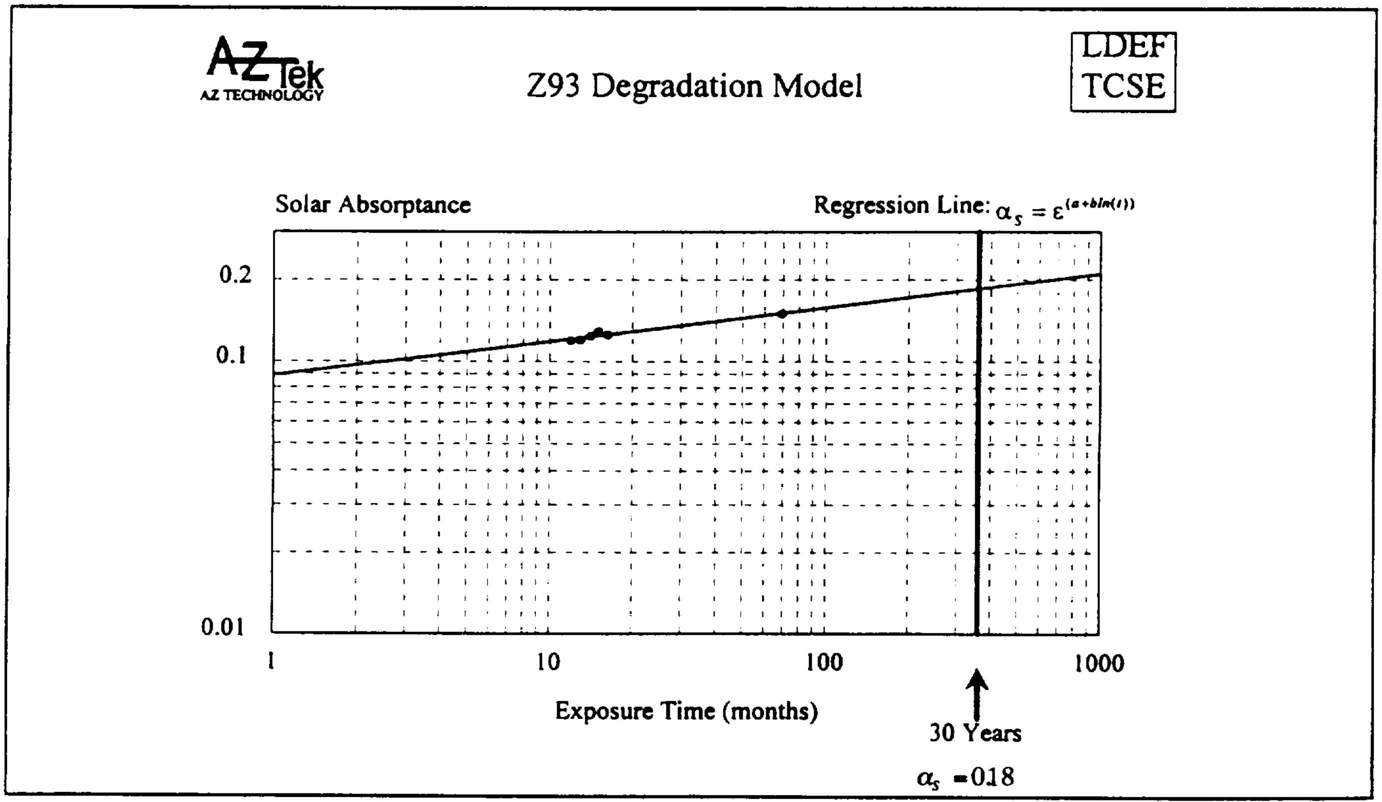

Figure 3. Z93 Degradation Model.

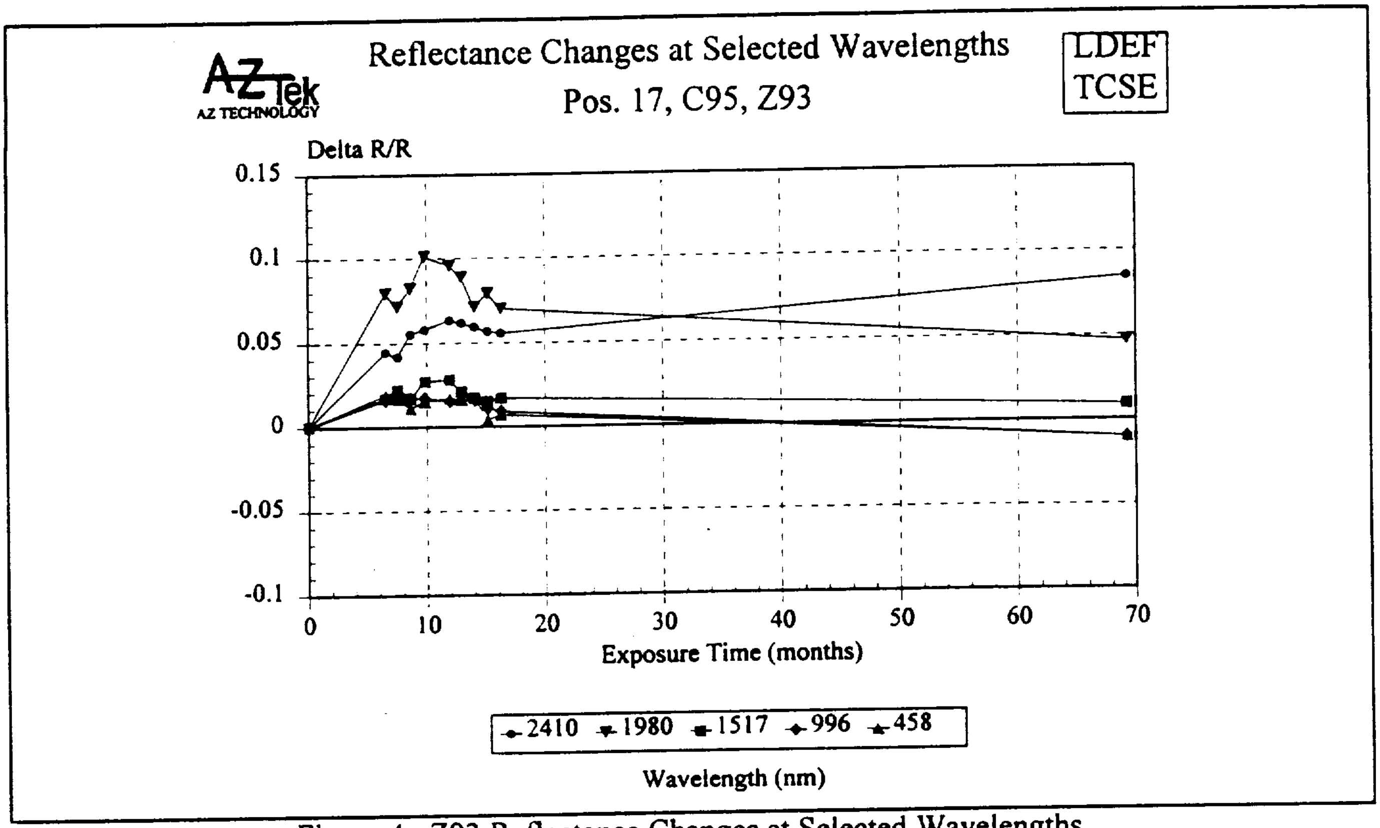

Figure 4. Z93 Reflectance Changes at Selected Wavelengths.

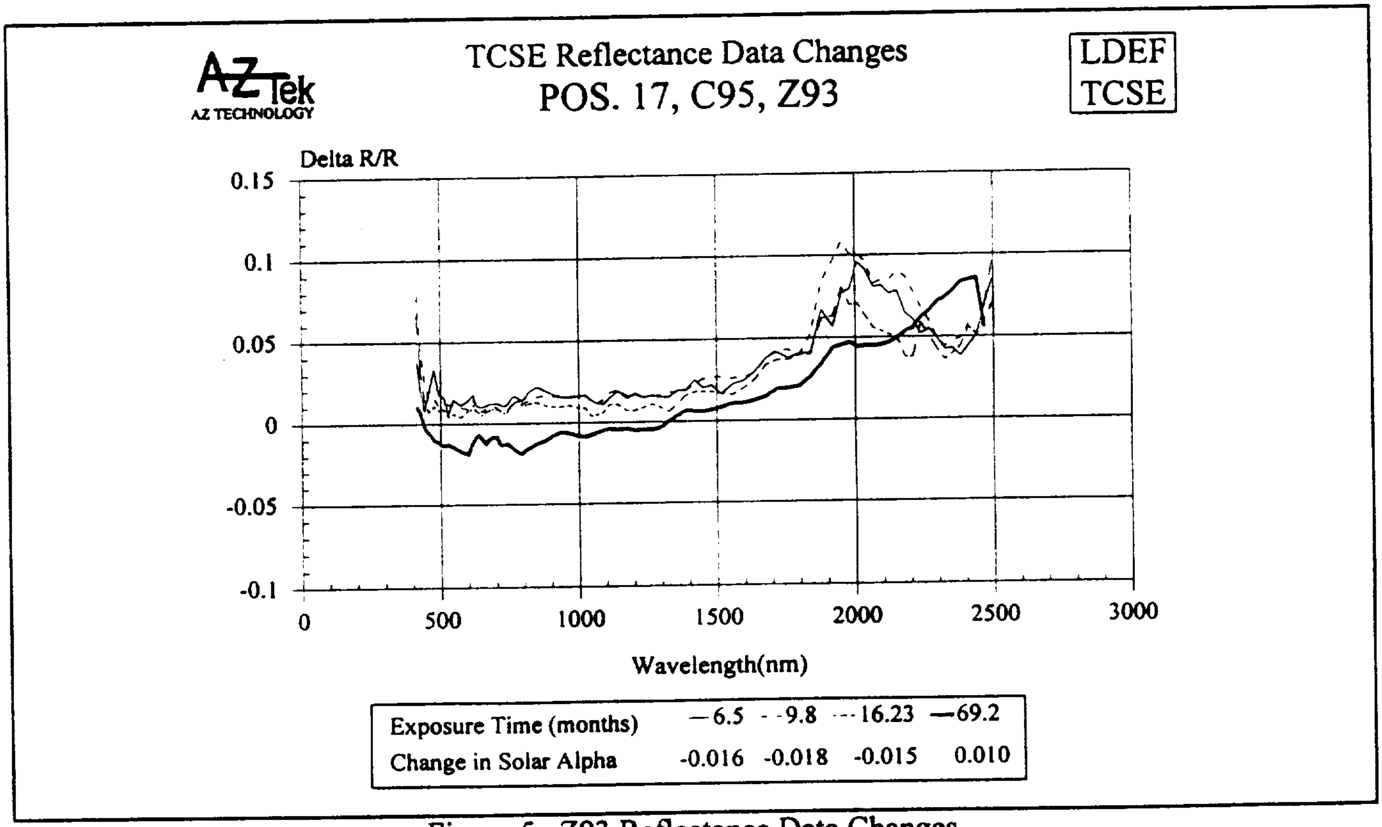

Figure 5. Z93 Reflectance Data Changes.

YB71 White Paint

YB71 exhibited very similar changes to Z93 during the LDEF mission as shown in Figure 6. The reflectance changes for the first fifteen months are nearly identical for both materials (see Figures 5 and 6). This is not surprising as both white coatings use the same potassium silicate binder. What is surprising, however, is the greater degradation of spectral reflectance (and solar absorptance) of the YB71 over Z93. In ground simulation testing before the LDEF mission, YB71 was more stable than Z93.

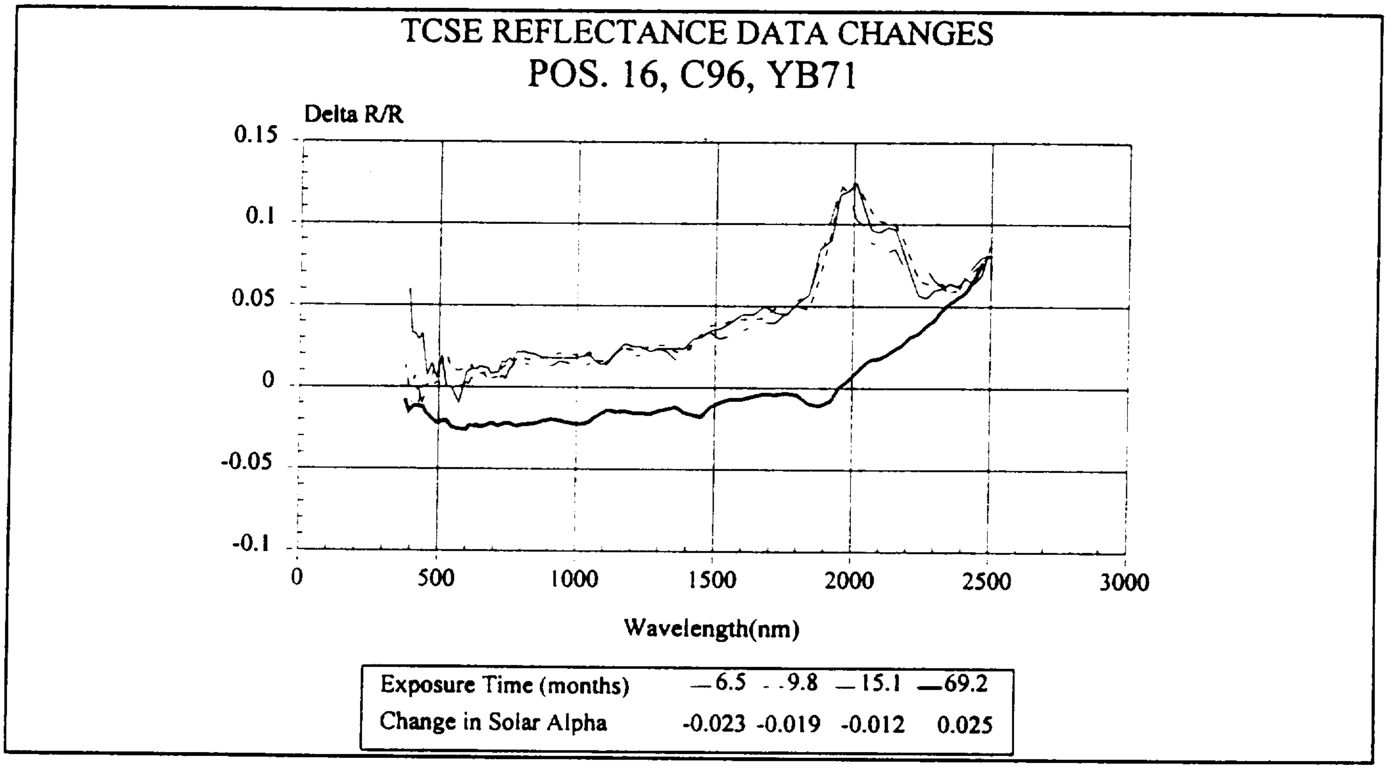

Figure 6. YB71 Reflectance Data Changes.

S13G/LO White Paint

Figure 7 shows the solar absorptance changes for S13G/LO over the LDEF mission. As with most of the TCSE active samples, there is an initial period in which the rate of change is different than the subsequent changes. This indicates a different dominant damage mechanism than later in the mission. The regression analysis provides a good fit if the initial data point is ignored. The degradation model for S13G/LO is shown in Figure 8. Significant changes in S13G/LO were expected but actual changes were somewhat larger than expected.

Figures 9 and 10 show the spectral reflectance changes for S13G/LO. The only significant changes occurred below 1000 nm which resulted in the large changes in integrated solar absorptance.

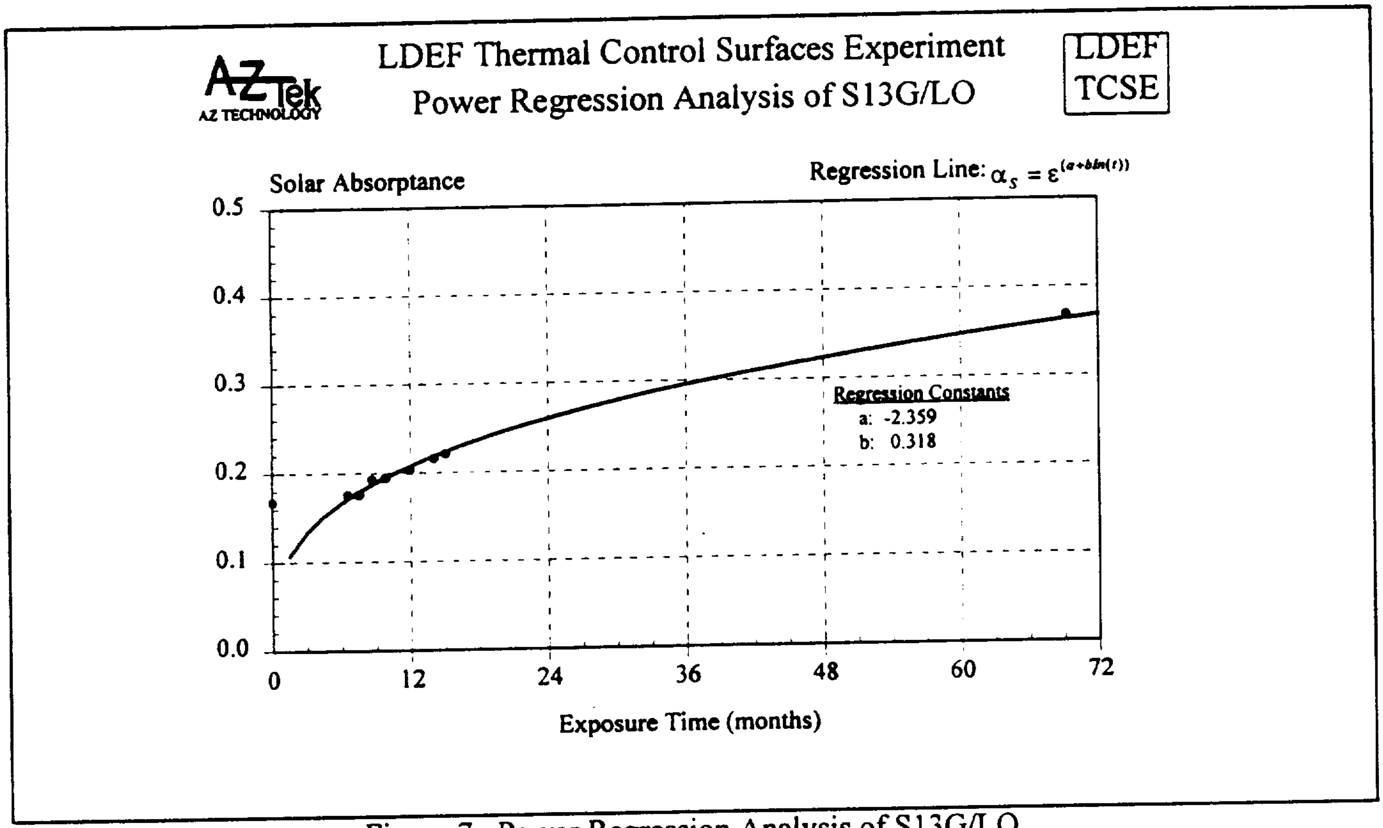

Figure 7. Power Regression Analysis of S13G/LO.

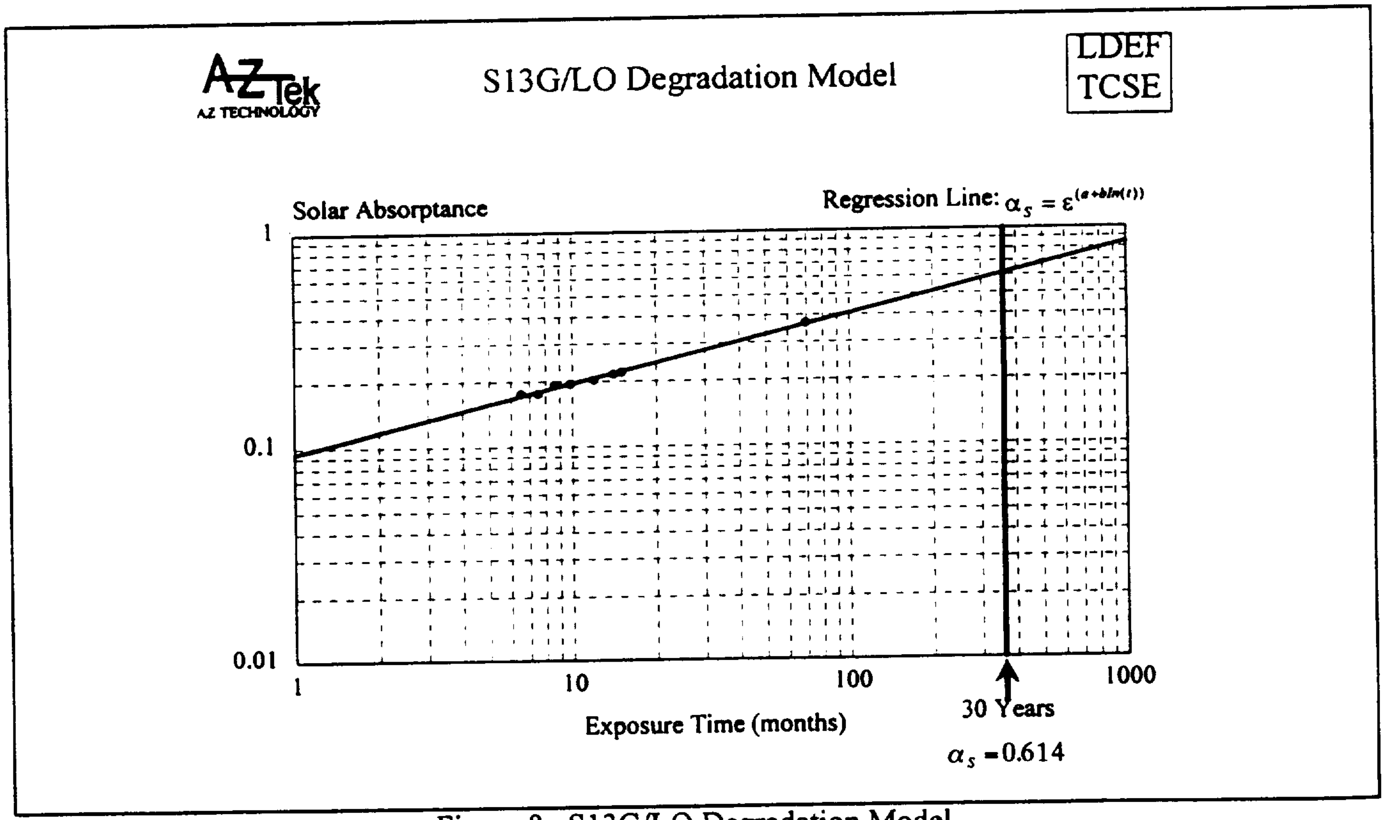

Figure 8. S13G/LO Degradation Model.

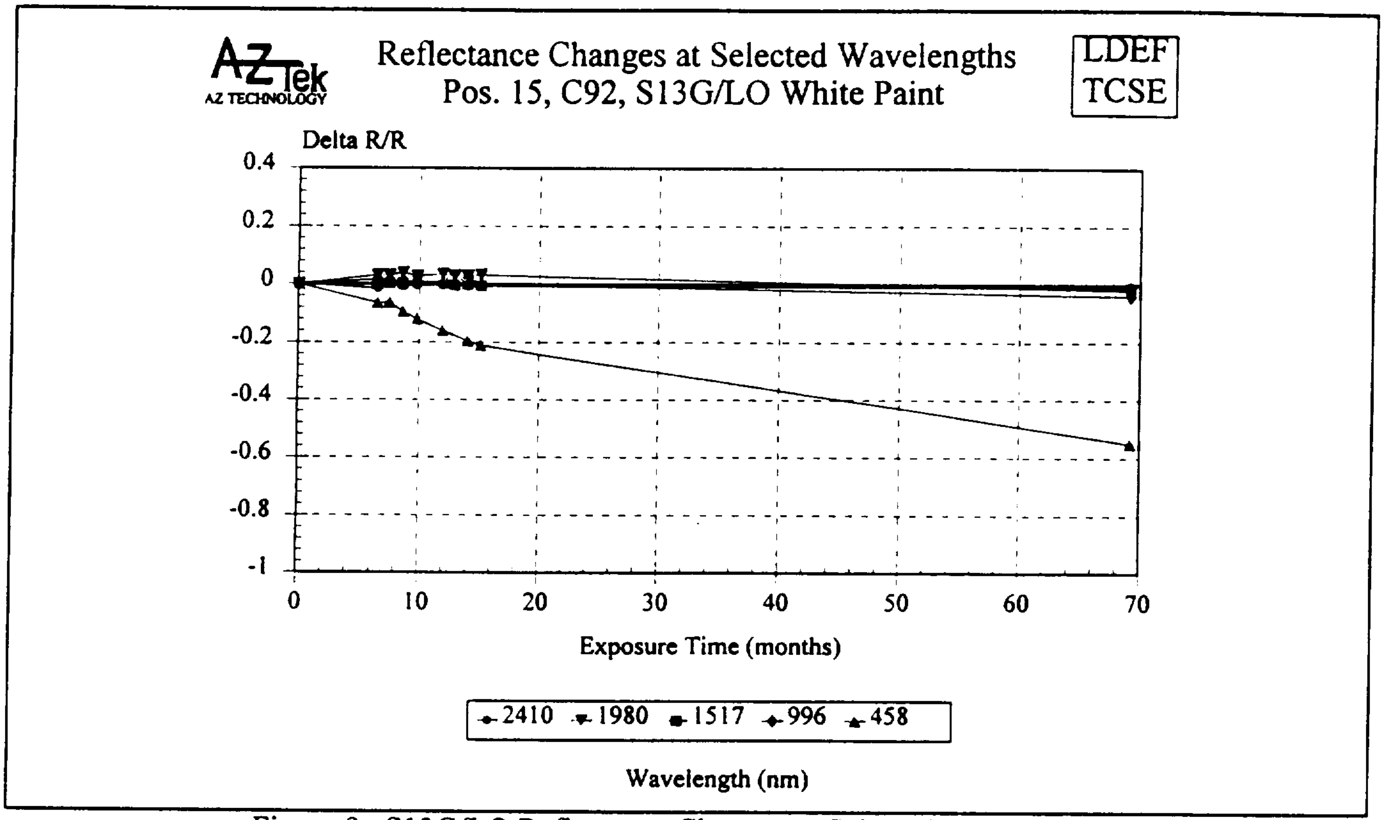

Figure 9. S13G/LO Reflectance Changes at Selected Wavelengths.

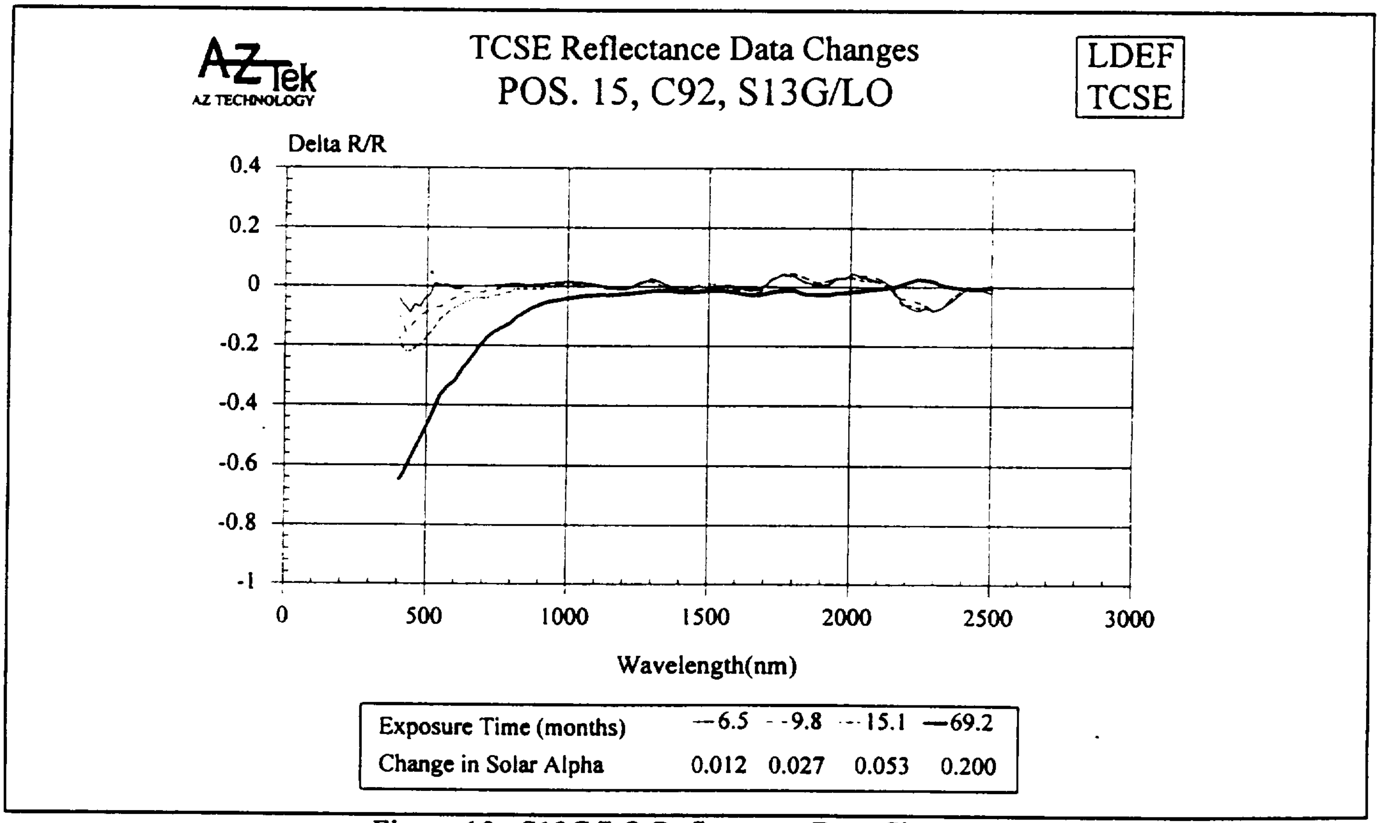

Figure 10. S13G/LO Reflectance Data Changes.

A276 White Paint and Protective Overcoats

Chemglaze A276 is a widely used white coating that was known to erode in atomic oxygen (AO) even before the LDEF mission. To evaluate their effectiveness, RTV670 and OI650 clear silicone protective overcoats were applied to A276. Figures 11-13 show the performance of the three coating systems during the LDEF exposure. Figure 13 shows that without a protective overcoating, A276 had relatively small changes for the first sixteen months. Exposure to the very large AO fluence during the subsequent four years eroded the damaged surface layer exposing a pigment dominated surface with even better reflectance than the pre-flight surface. The A276 with the protective overcoatings degraded significantly. Figure 14 compares post-flight reflectance changes for the three A276 surfaces and an LDEF trailing edge A276 sample from Dr. Palmer Peters and Dr. John Gregory's AO114 experiment. The AO114 trailing edge sample saw only a small amount of AO and was significantly damaged by solar UV exposure. Some of the damage to the TCSE overcoated samples may be in the overcoat itself. However, as shown in Figure 14, the damage spectra of the UV degraded AO114 A276 samples are very similar to the TCSE overcoated samples in both magnitude and spectral range.

Silver Teflon

Samples of both 5 mil and 2 mil thick silver Teflon were flown on the TCSE active sample array. The 5 mil material was optically very stable for the LDEF mission. AO exposure resulted in the loss of approximately 1 mil of Teflon and a textured diffuse surface. Figure 15 shows the variation of solar absorptance versus exposure time for 5 mil silver Teflon. As with several other materials, an improvement (decrease) in solar absorptance was measured early in the mission. This was followed by a small degradation for the remainder of the mission. Power regression analysis provides a fair fit to this long term degradation. Figure 16 extends this degradation model and predicts an excellent 30 year solar absorptance of 0.1.

Figure 17 shows the spectral reflectance changes over the mission duration. A slight increase in the 1700 to 2500 nm infrared range early in the mission is offset by the long term degradation below 1400 nm.

The 2 mil silver Teflon active sample was the same material that was applied to the TCSE front cover. This material suffered from an internal contamination and optical degradation that has been previously documented.[5] The silver and inconnel backing layer was cracked during the application process allowing the acrylic adhesive to migrate into the layer between the silver and the Teflon. Solar UV then darkened the adhesive resulting in an overall optical degradation. Figure 18 shows the spectral reflectance changes of the 2 mil silver Teflon. The data up to 15 months is nearly identical to the 5 mil material. The degradation during the subsequent four years indicates that the internal contamination required several years to become significant.

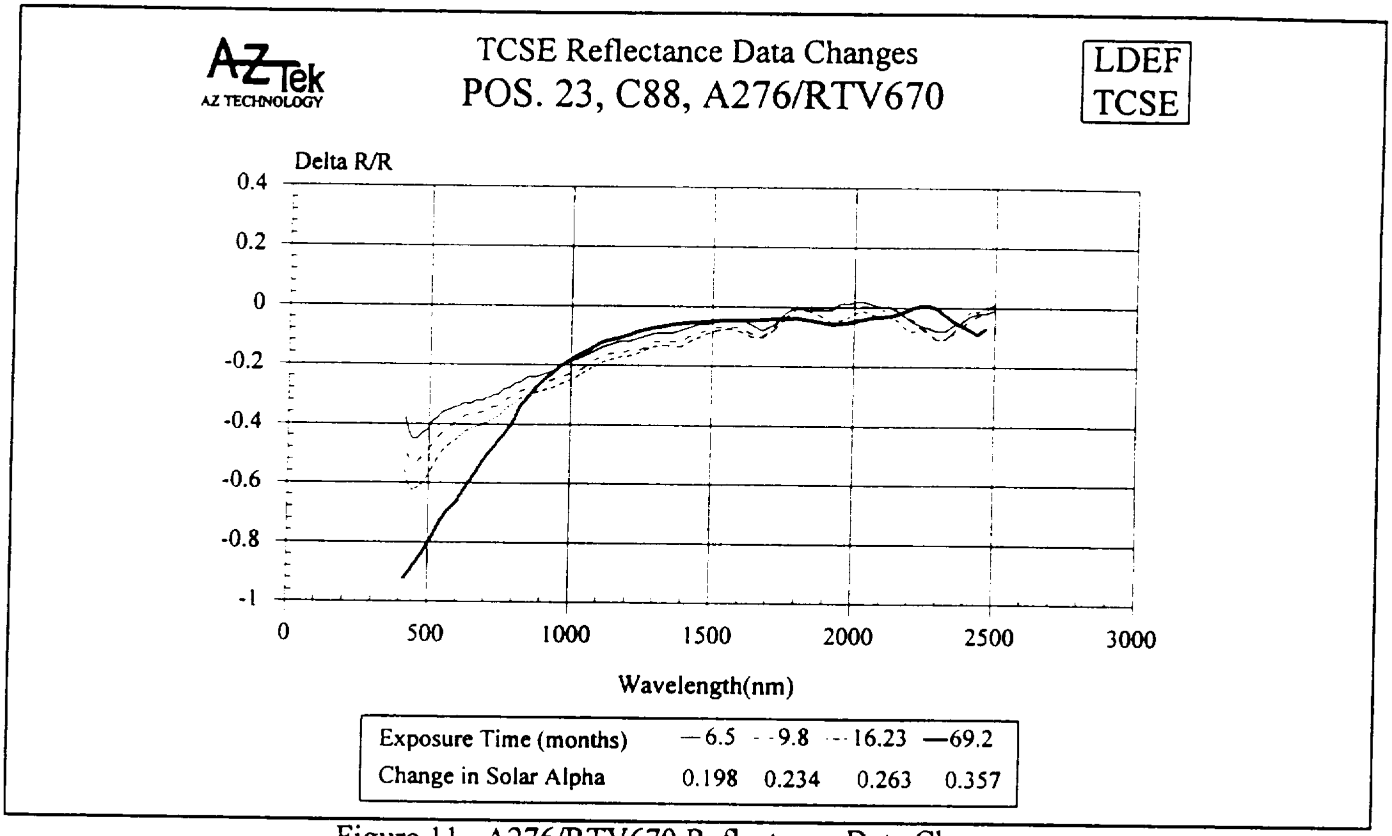

Figure 11. A276/RTV670 Reflectance Data Changes.

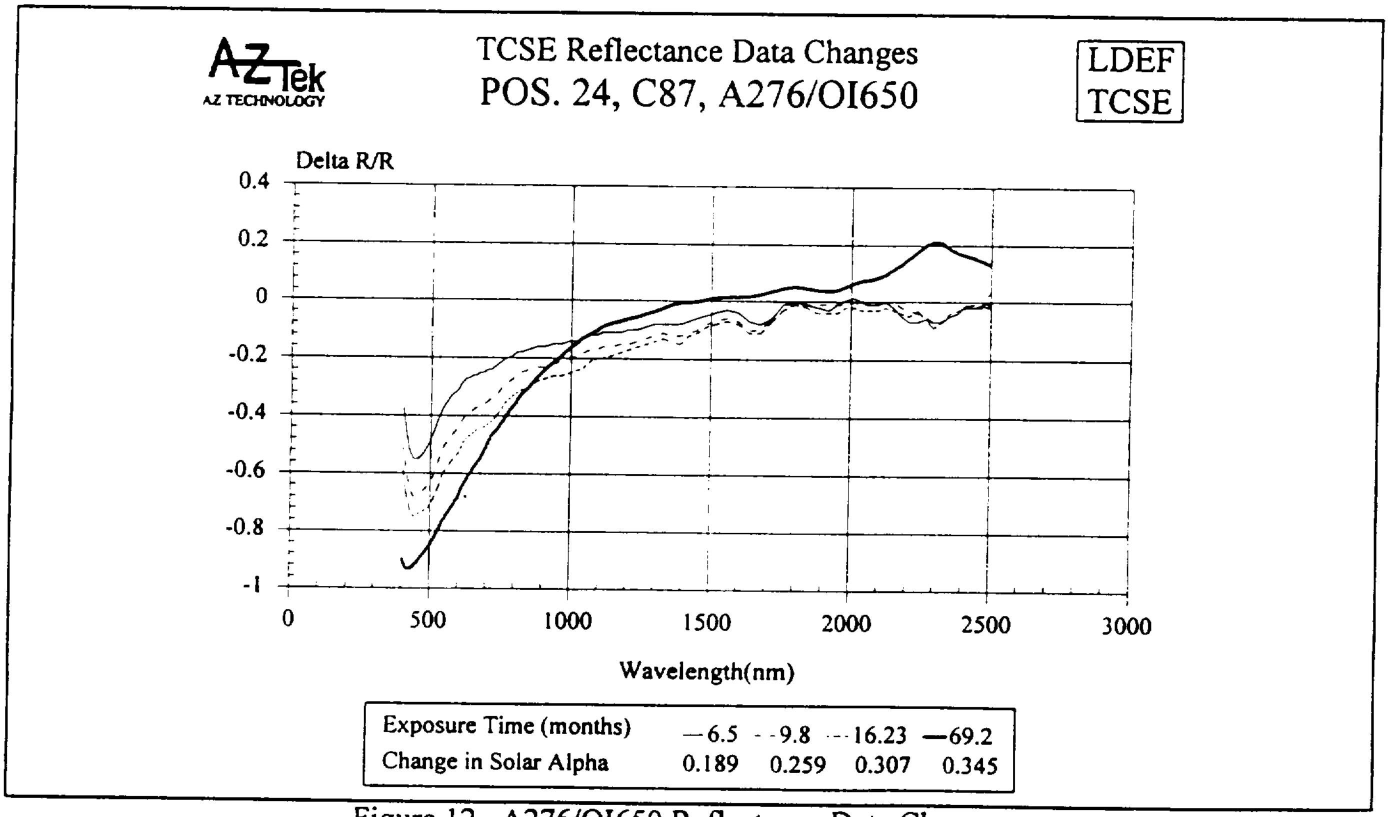

Figure 12. A276/OI650 Reflectance Data Changes.

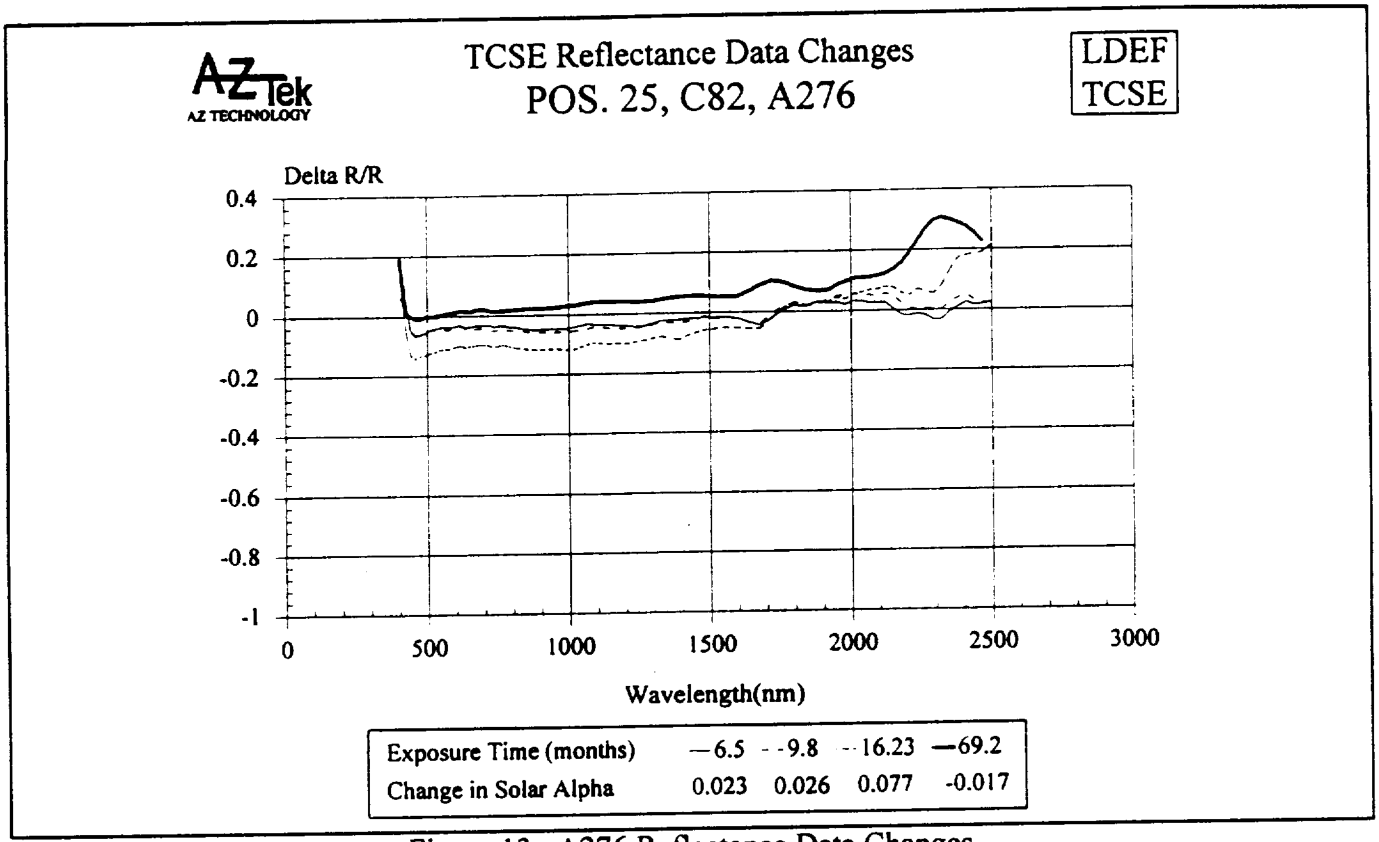

Figure 13. A276 Reflectance Data Changes.

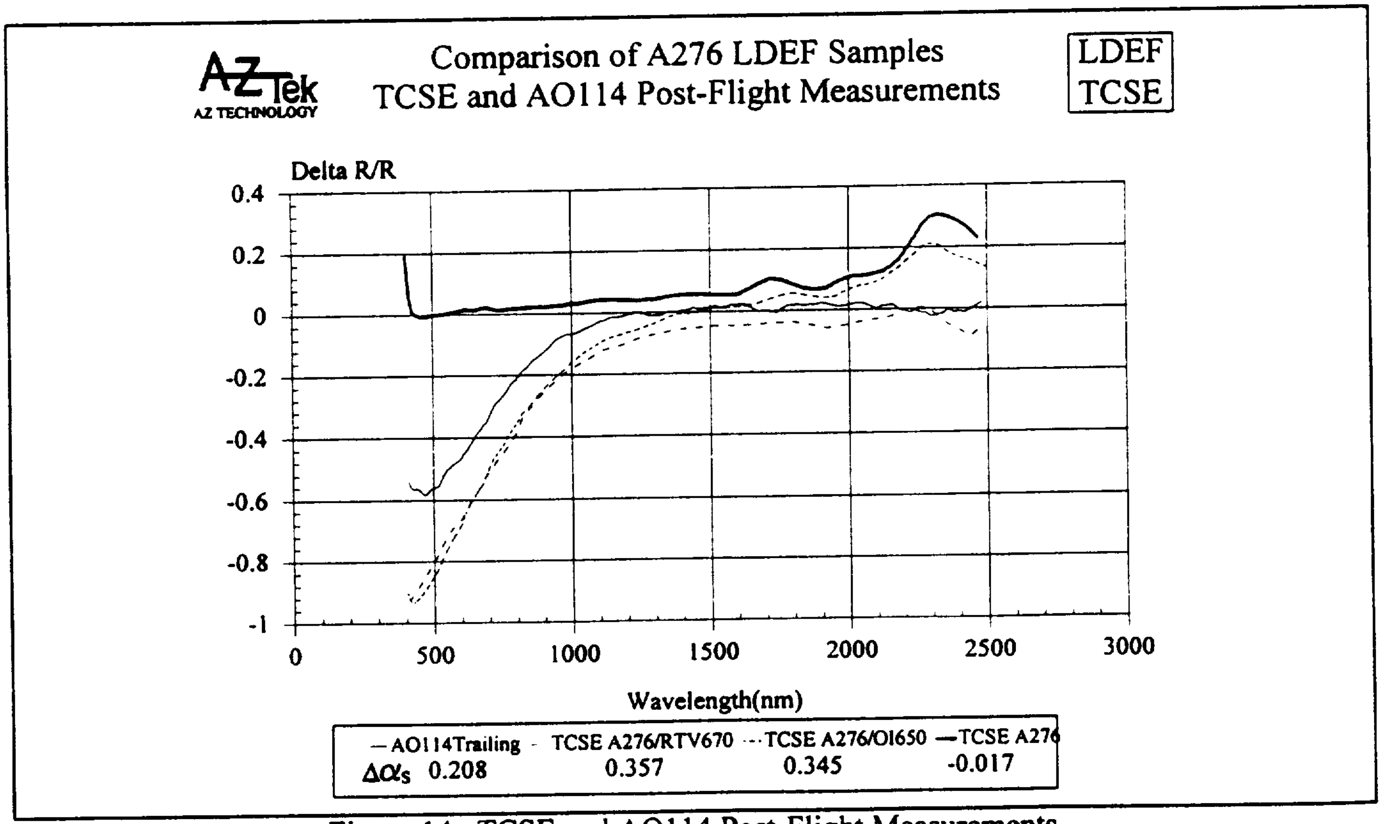

Figure 14. TCSE and AO114 Post-Flight Measurements.

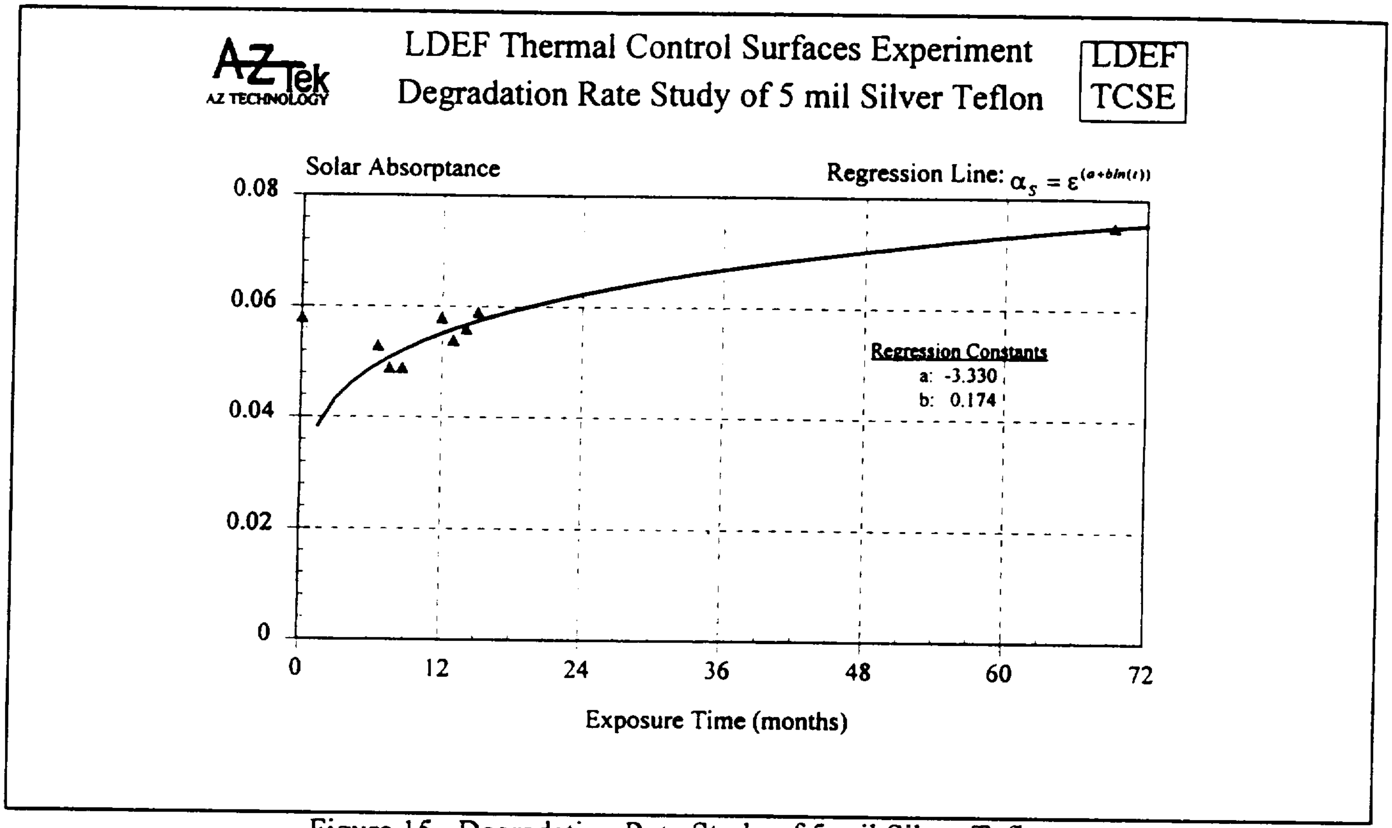

Figure 15. Degradation Rate Study of 5 mil Silver Teflon.

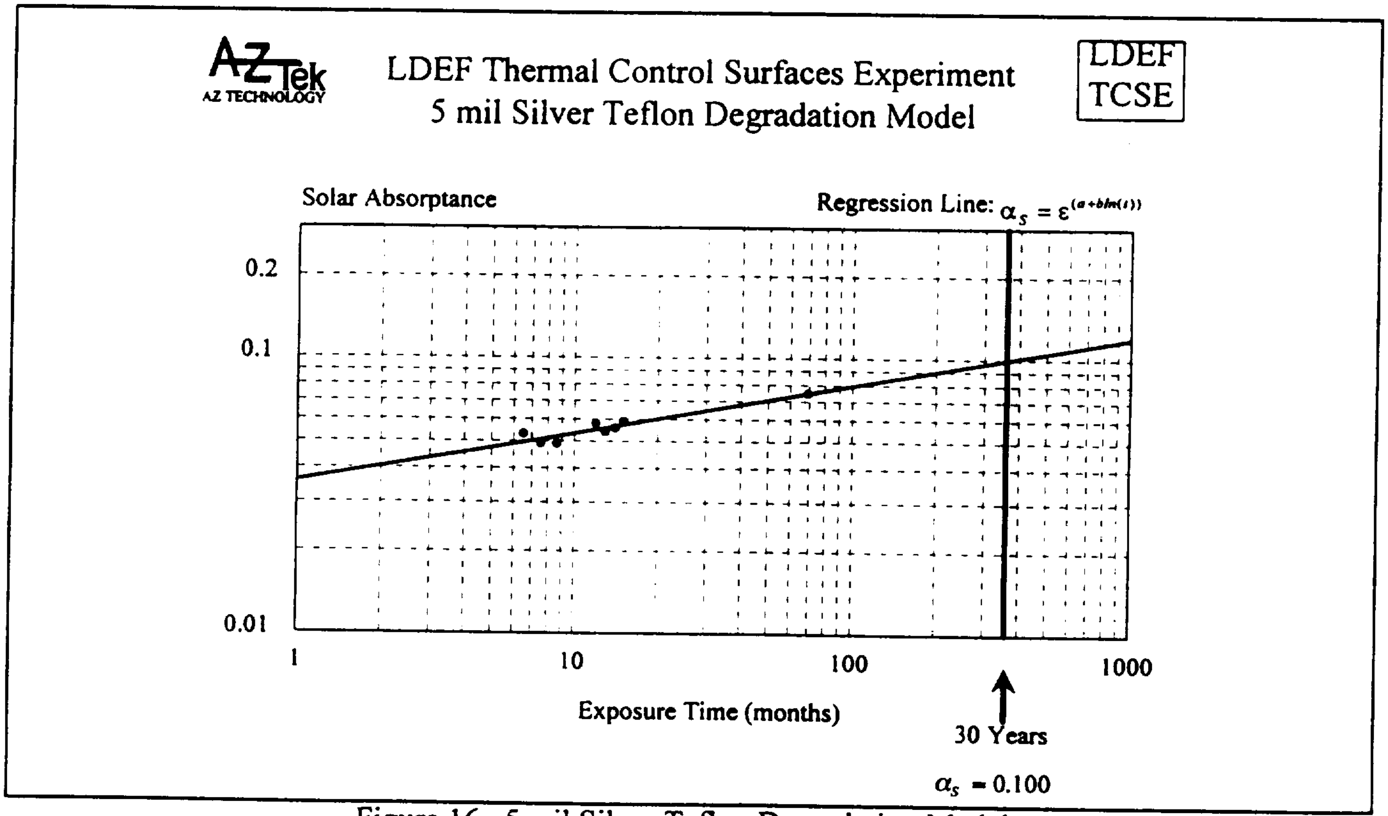

Figure 16. 5 mil Silver Teflon Degradation Model.

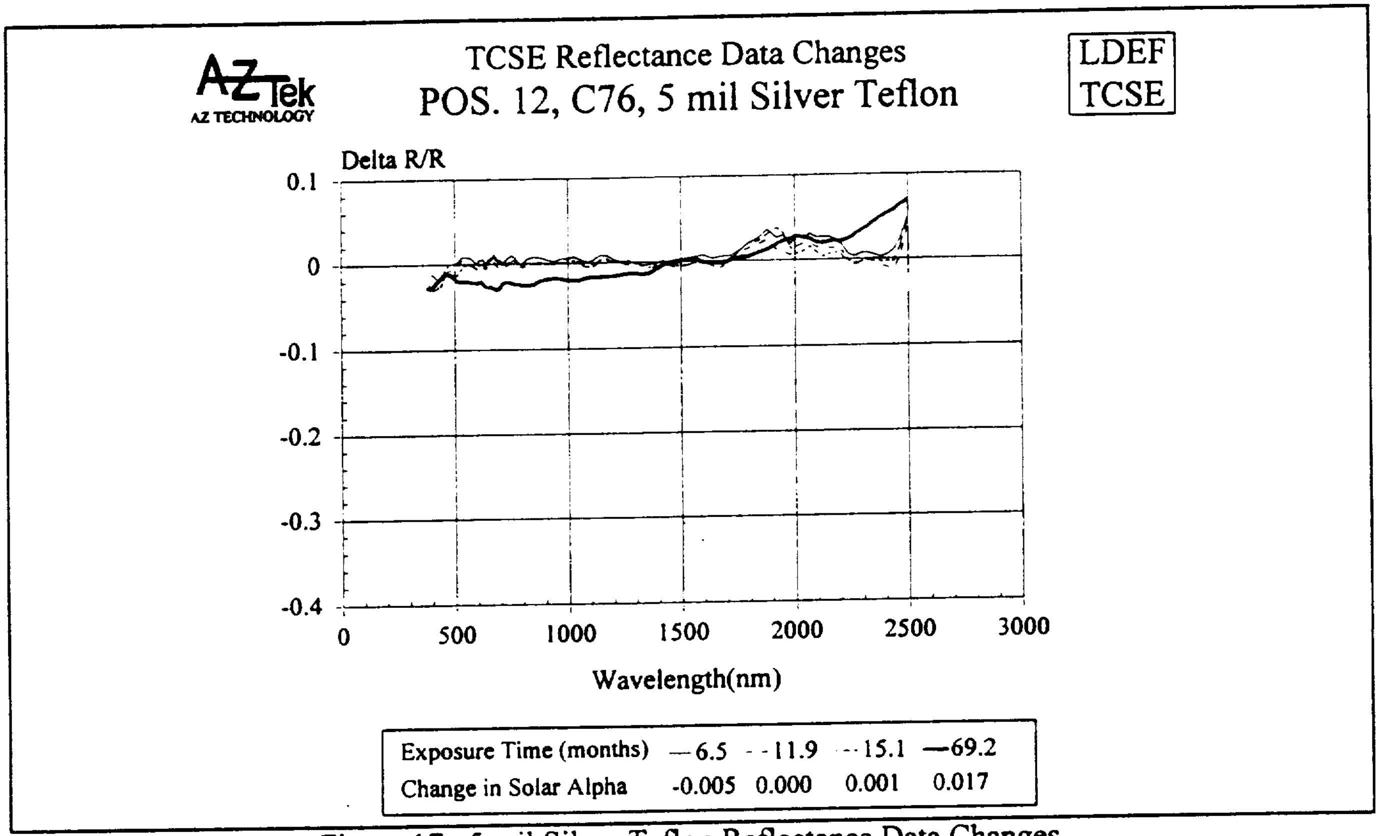

Figure 17. 5 mil Silver Teflon Reflectance Data Changes.

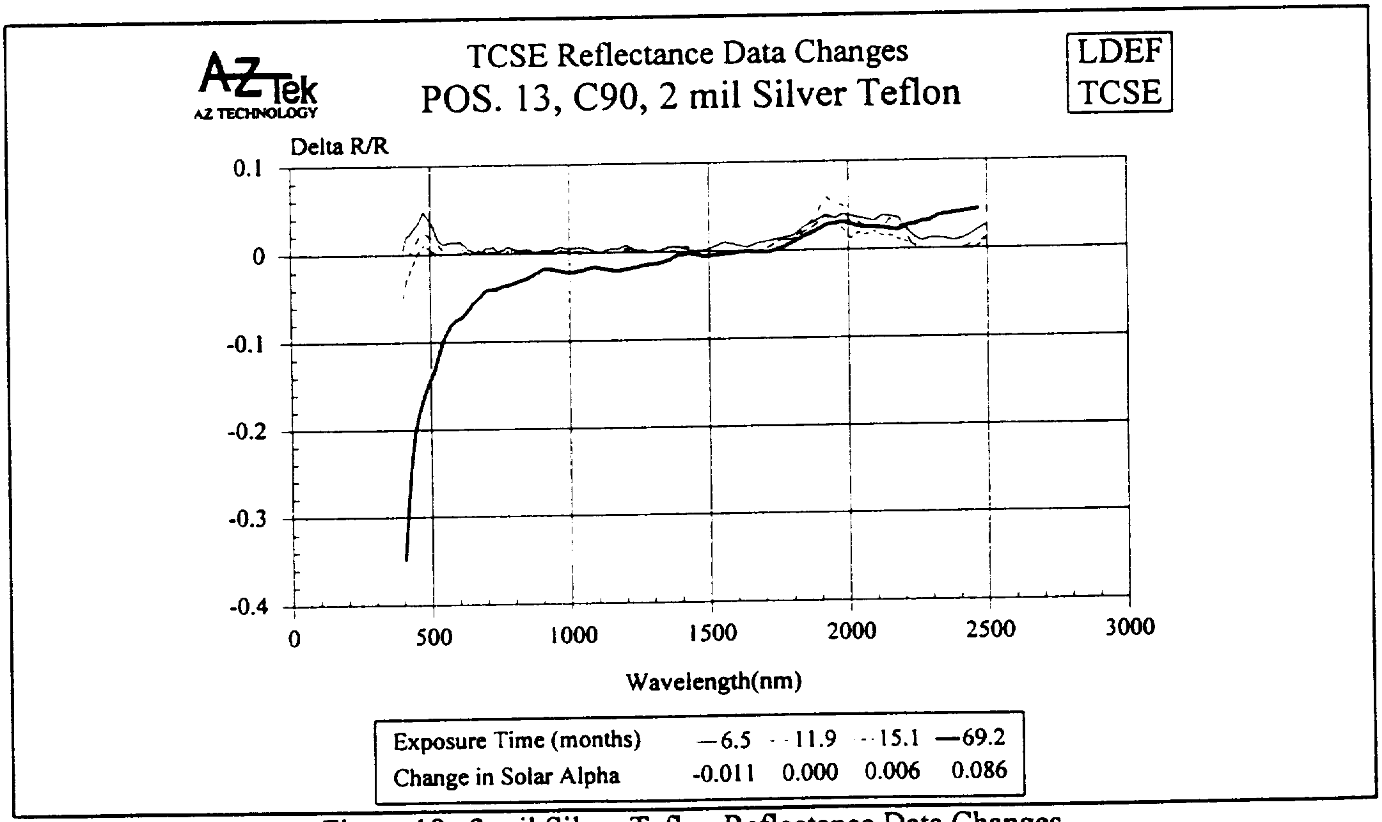

Figure 18. 2 mil Silver Teflon Reflectance Data Changes.

CONCLUSION

The TCSE in-space spectral reflectance measurements and analysis of this data demonstrate the benefit of active type materials space experiments. This time dependent data provides insight into how thermal control surfaces behave in the space environment and enables the development of lifetime prediction models.

The results of this effort are based on one space mission and in most cases only one sample of a material. While the quality of the data is excellent, the lifetime prediction models should be used with caution. The extrapolated data is statistically a most likely value and not a worst case value.

The study of the trends in the TCSE spectral reflectance data provides a unique view of how materials degrade in the space environment. This data and the post-flight surface analysis demonstrate the very complex nature of the behavior of materials operating in this environment. Many issues remain in understanding the effects of the space environment on materials. Additional flight opportunities are needed for active optical experiments measuring these effects. To address this need, the In-Space Technical Experiments Program (IN-STEP) Optical Properties Monitor (OPM) is being developed for a 1997 mission. The OPM is an in-space optical laboratory for the in-situ study of materials.[6]

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6 Wilkes, D.R.; "Next Generation Optical Instruments and Space Experiment Based on the Thermal Control Surfaces Experiment (S0069)," *Second LDEF Post-Retrieval Symposium*, NASA CP-3194, 1993, pp. 1521-1533.