Analysis of Metallized Teflon™ Thin Film Materials Performance on Satellites

H. Gary Pippin*, Eugene Normand†, and Suzanne L. B. Woll‡
Boeing Phantom Works, Seattle, WA

Rachel Kamenetzky§
NASA Kennedy Space Center, FL

Abstract

Laboratory and on-orbit performance data for two common thermal control materials, silver- and aluminum-backed (metallized) fluorinated ethyl-propylene (FEP) was collected from a variety of sources and analyzed. This paper demonstrates that the change in solar absorptance, α, is a strong function of particulate radiation for these materials. Examination of additional data shows that the atomic oxygen recession rate is a strong function of solar exposure with an induction period of between 25 to 50 equivalent solar hours. The relationships determined in this analysis were incorporated into an electronic knowledge base, the "Spacecraft Materials Selector," under NASA contract NAS8-98213.

Dr. H. Gary Pippin
The Boeing Company
P.O. Box 3707, MC 73-09
Seattle, WA 98124-2207
harold.g.pippin@boeing.com
(425) 234-7959

Dr. Eugene Normand, Boeing (253) 773-7592
Dr. Suzanne L. B. Woll, Boeing (253) 657-4133
Rachel Kamenetzky, NASA KSC (321) 867-6018

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* Technical Fellow, The Boeing Company, Phantom Works, Non-metallic Materials Technology, PO Box 3707, MS 73-09, Seattle, WA 98124-2207, Member AIAA.
† Technical Fellow, The Boeing Company, Chief Scientist, Boeing Radiation Effects Laboratory, PO Box 3707, MS 3T-50, Seattle, WA 98124-2207.
‡ Senior Systems Engineer, The Boeing Company, Space and Communications, PO Box 3707, MS 82-72, Seattle, WA 98124-2207.
§ Materials and Processes Engineer, NASA Kennedy Space Center, ISS/Payload Processing Directorate, UB-G5, KSC, FL 32899.

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‡ Senior Systems Engineer, The Boeing Company, Space and Communications, PO Box 3999, MS 82-72, Seattle, WA 98124-2499.

§ Materials and Processes Engineer, has moved to NASA Kennedy Space Center, ISS/Payload Processing Directorate, UB-G5, KSC, FL 32899.

Nomenclature

AO Atomic oxygen fluence (atoms oxygen/cm^2)

ESH Equivalent solar hours

R_e Reaction efficiency ($1*10^{-24}$ cm^3/ atom oxygen)

α solar absorptance

ε thermal emittance

Introduction

Materials performance data from operational spacecraft and spacecraft experiments has been slowly accumulating over the past 30 years[1-7]. Much of this data has been obtained indirectly by analyzing temperature measurements that were telemetered from space to the ground. Changes in sample temperature represent a change in the thermal control properties of these materials. The Space Transportation System (STS) has made it possible to actually retrieve materials flown on free flyers or on the STS itself. Material properties from these specimens have been examined pre- and post-flight.

Available materials data found in the literature are for specific materials onboard specific missions at specific altitudes over varying periods of time. The objective of NASA contract NAS8-98213 was to collect the available spacecraft materials data on several well-known materials, analyze the date with respect to space environmental effects and capture the results in an electronic knowledge base. The NASA knowledge base is known as the "Spacecraft Materials Selector."

Performance data for silver- and aluminum-backed fluorinated ethylpropylene (FEP) materials is discussed and analyzed in this paper. These materials are also known as silverized and aluminized Teflon™. First, the change in solar absorptance, α, of these metallized materials as a function of particulate radiation is examined. Second, the variation of the atomic oxygen induced material recession rate of these materials is discussed.

The Effect of Particulate Radiation

Ground-Based Laboratory Data

Using the Combined Radiation Effects Test Chamber (CRETC) at the Boeing Radiation Effects Laboratory (BREL) in Seattle, WA in the 1970s, thermal control coatings were simultaneously exposed to solar ultraviolet (UV) light and particulate radiation. Coatings were irradiated with mono-energetic electrons along with solar UV, and in some cases, also with a beam of low energy protons. Solar absorptance values were determined for the various radiation test conditions by integrating the in-situ reflectance data over the solar spectrum. Data for Ag and Al-backed FEP are contained in three reports.[8-10]

In this work, an extensive set of the CRETC laboratory test data was re-examined and analyzed. The authors calculated the electron dose deposited for the three different test regimes (electron energies of 50, 80 and 115 keV) to obtain solar absorptance data as a function of the electron dose. The test conditions are shown in Table I and the calculated solar absorptance data for metallized FEP are plotted in Figure 1. Energy deposition by protons was

assumed to be insignificant because the low energy (50 keV) protons that were used in the test have such a short range in Teflon™ that their energy deposition occurs only within the first 1% of the Teflon™. Since greater than 99% of the Teflon™ receives no proton energy deposition, the proton energy deposition can be ignored in terms of effects on bulk, physical properties.

Table I. CRETC Ground-Based Test Conditions

Material	Thickness (mil)	Particles	Voltage (keV)	Reference
Ag/FEP	5	e+p	50	8
Ag/FEP	5	e only	50	8
Al/FEP	5	e+p	115*	9
Ag-Inconel/FEP	5	e+p	115*	9
Ag embossed/FEP	2	e+p	115*	9
Ag/FEP	2	e+p	115*	9
Al/FEP	5	e+p	115*	9
Ag-Inconel/FEP	5	e+p	115*	9
Ag embossed/FEP	5	e+p	115*	9
Al/FEP	2	e only	80*	10

*For this case, the dose deposited by the electrons was adjusted because the thickness of the Teflon™ was less than the electron's full range, thus only a fraction of the electron's energy was deposited.

All of the solar absorptance versus electron dose curves obtained using the CRETC data have the same overall shape. Some variations may be

attributable to small differences in the metallic backing material. For example, one sample had an embossed, silver backing while another FEP sample had a combined, silver and Inconel backing. In other cases, some variations may arise as a result of different UV sun rates being used in similar sets of tests.

On-Orbit Data

Published data providing the change in solar absorptance as a function of time on-orbit was gathered for 5-mil thick Ag/FEP and Al/FEP materials on the NTS-2 satellite[2], several NavStar Global Positioning Satellites[3] (GPSs), the P78-2 (SCATHA) experiment[4], and the STP P72-1 (ML-101) satellite[5]. The NTS-2 satellite orbited at 20,000 km and the Navstar satellites orbited at 20,180 km, all with a 63° inclination. The SCATHA experiment flew in a geosynchronous, 36,000 km orbit at a 9° inclination. The ML-101 satellite orbited at 745 km at a 98° inclination. Reports on materials flown on each of these satellites provide data for solar absorptance change with time. In this work, the authors calculated the radiation dose absorbed within the metallized FEP based on the various satellite orbits and time periods using a two-step process and examined the change in solar absorptance as a function of that radiation dose.

First, the NASA trapped belt environmental codes, AE8 for electrons and AP8 for protons, were used to calculate the daily particle fluxes for each satellite orbit. The Navstar and NTS-2 satellites were in very similar orbits and the same radiation environment was used for both.

Next, the total radiation dose absorbed by a particular material over the length of its mission was determined. The daily particle fluxes were divided into

energy bins. The flux in each bin was multiplied by the corresponding stopping power, and then by the energy range of the bin. The products were summed over the full energy range to yield the daily absorbed dose. The daily dose was then multiplied by the number of days to obtain the mission dose. The dose calculation can be expressed by the following equation:

$$D = t * \sum_{E} \left(\frac{dN}{dE} \right) * S(E) * \Delta E$$

where t = number of days in mission, dN/dE is the daily particle flux (particles/cm^2 day MeV), S(E) is the stopping power (rad cm^2), ΔE is the width of the energy bin and D=total ionizing dose in rads.

The range of the particle needs to be less than or equal to the thickness of the material in order to have all of the particle's energy deposited. For thin films like the 2 to 5 mil, metallized Teflon™ thermal control films studied here, most of the energy is deposited within the film by low energy particles, but there are differences between the contribution of the electrons and protons. The particle range (the distance a particle will travel before giving up all of its energy in a particular material) plays an important role. For 500 keV electrons in Teflon™, the range is 43 mils, hence only a small fraction of the energy will be deposited within the thin film. For 100 keV electrons, the range is 3.65 mil so that all or almost all of the energy is deposited in the film. For protons, the situation is different. Because the proton ranges are so short, all of the energy is deposited, but within a very thin outer layer of the film; for 1000 keV protons, the particle range is 0.6 mil and, for 100 keV protons, it is 0.04 mils [12].

As particle range and stopping power values for Teflon™ were not available, the authors used the corresponding data for Freon™ (density of $1.25 \cdot 10^{-3}$ g/cm^3), a compound of similar atomic composition, and adjusted the results by the density of Teflon™ (2.2 g/cm^3).[11] The validity of the methodology was verified by comparing the stopping power and the range for protons in the two materials using the SRIM code[12]., which agreed within <2%.

Lastly, the electron dose was plotted against the change in solar absorptance as shown in Figure 2. The data follows a logarithmic degradation trend similar to that predicted by the ground-based laboratory data; however, the on-orbit data degradation is greater for an equivalent electron dose. A curve fit of on-orbit satellite data shows that the solar absorptance of uncoated Ag/FEP or Al/FEP, at altitudes ranging from low Earth orbits to geosynchronous orbits, can be estimated for a given time period as

$$\alpha = \alpha_o + 0.27\ (1 - e^{(-\text{ electron deposited dose})/2.0E8}),$$

where the electron deposited dose is in rads. This engineering design curve has been incorporated into the Spacecraft Materials Selector knowledge base.

Discussion

Metallized Teflon™ materials exposed on-orbit showed greater degradation rates than identical materials that experienced ground-based electron exposure in the CRETC. At $1 \bullet 10^8$ rad, the CRETC data shows a change in solar absorptance ranging from 0.03-0.06, while, at $3 \bullet 10^8$ rad, the change ranges from 0.07-0.11 for the satellite data shown in Figure 2.

The differences in magnitude of the changes can not be attributed to contamination. ML-101, SCATHA, NTS-2 and several of the GPS satellites had optical solar reflectors (OSR) that served as contamination witness plates. Data from ML-101, SCATHA and NTS-2 were already adjusted for contamination by subtracting the change in solar absorptance observed on the OSRs from the change in absorptance observed on the metallized Teflon™ material. No adjustment for contamination was made to the NavStar data because the essentially linear changes in solar absorptance observed for the OSRs on the GPS satellites as a function of time are not characteristic of contamination induced changes.[3]

There is one more data point in the published literature on silverized FEP that is of interest.[7] The Long Duration Exposure Facility (LDEF) had many silverized FEP surfaces exposed only to the sun, and to particulate radiation, primarily during its passes through the South Atlantic Anomaly. Despite that fact that the surface radiation dose is uncertain because the altitude at which LDEF flew varied over the mission, the surface dose is estimated to be in the range of 0.3 to 1 Mrads. Changes in α were essentially zero for each of the surfaces that did not experience mechanical failure, indicating that the change in solar absorptance at an absorbed dose of less than 1 Mrads is essentially insignificant. This dose is very small compared with results from the other satellites discussed in this work and provides a lower bound for the relationship determined.

Atomic Oxygen Recession Rate of FEP Teflon

Thin films of metallized Teflon™ have been used on numerous spacecraft as a thermal control coating because of their excellent α/ε ratios and relative stability in a wide variety of orbits. Under atomic oxygen exposure, these materials are susceptible to erosion, although metallized Teflon™ materials generally hold up well relative to many other coating materials. The authors of this work gathered available data in order to examine the material recession rate of metallized Teflon™. As the erosion occurs on the space-facing FEP side of metallized Teflon™, the actual metal used as the second surface mirror is inconsequential to this discussion.

For Teflon™ materials to erode under low Earth orbit conditions of atomic oxygen alone, oxygen atoms need to abstract fluorine atoms from carbon atoms. Thermodynamics are generally not favorable. The approximately 5 eV FEP carbon-fluorine bond strength is more than twice the approximately 2 eV strength of an oxygen-fluorine bond, making it unlikely that a fluorine atom would give up a carbon atom in exchange for an oxygen atom.[13]

It has been proposed that an "induction" period of direct solar exposure is required for FEP prior to attack by atomic oxygen.[1] During the induction period, carbon-fluorine and/or carbon-carbon bonds are ruptured after absorbing short wavelength, vacuum ultraviolet (VUV) radiation. The radiation process gradually produces a population of energetic, free radical sites where oxygen atoms may react.

If the mechanism for FEP erosion is a function of the number of available free radical sites and if the number of sites increases with increasing solar exposure, one would expect the erosion rate to also increase with increasing solar exposure. Data from several Space Transportation System flights[6], a Lockheed experiment[1], and the Long Duration Exposure Facility[7] were examined to test this hypothesis.

For all three data sets, the atomic oxygen fluences were estimated using computer codes. In the case of the Lockheed data, the atomic oxygen fluence estimate was confirmed by the lifetime of a Kapton sample of known initial thickness flown adjacent to the Ag/FEP specimen. Despite the fact that LDEF was in orbit for 5.8 years compared to the 105 days for the Lockheed experiment, the total fluence of atomic oxygen to the material surfaces on the Lockheed flight experiment was approximately 20 times the fluence for the material on LDEF.

The short term (<1 week) STS data is calculated assuming mass loss of the entire specimen. The atomic oxygen induced recession rate estimates from STS flights are less than 0.05 cm^3/atom of oxygen. Solar exposure levels on material specimens during a space shuttle flight are only a few equivalent solar hours (ESH). Such a low solar exposure level is not sufficient to damage the FEP to any significant degree. Impinging oxygen atoms will find few free radical sites available for reaction. The atomic oxygen-induced FEP recession rates reported from STS flights are thus considered essentially upper bounds, estimated by assuming complete recession of thin FEP films by the atomic oxygen fluence received during specific Space Shuttle flights.

The intermediate term (105 day) Lockheed data was reported as thermal emittance values at specific times, with the thermal emittance having been calculated from telemetered temperature measurements. Thermal emittance of silverized or aluminized Teflon™ is a function of thickness of the FEP layer. In this work, the thickness of the flight specimens was estimated using the Sheldahl emissivity correlation shown plotted in Figure 3.[14] The total solar exposure on the Lockheed experiment was approximately 300 ESH, distributed relatively evenly over the 105 day experiment. The average recession rate for each interval of ESH was then calculated by dividing the change in thickness over the interval by the atomic oxygen fluence for that interval. The data and the calculated recession rates are shown in Table II.

Table II. Summary of Lockheed FEP Data[1,14]

Time (days)	ESH	α	ε	Estimated Thickness (mm)	AO fluence (10^{21}atom/cm^2)	Reaction Efficiency, R_e (10^{24}atom/cm^2)	Cumulative AO fluence (10^{21}atom/cm^2)
0	17	0.16	0.56	0.027	0	0	0
6.1	25	0.20	0.56	0.027	1.18	0	1.18
34	97	0.23	0.55	0.0255	4.4	0.023	5.6
60	170	0.22	0.50	0.019	4.3	0.14	9.9
88	251	0.21	0.45	0.014	5.1	0.10	15.0
105	300	0.21	0.37	0.008	3.5	0.17	18.5

Based on the data and the fact that the uncertainty in the emissivity measurement is +/-0.01, the induction period for the Lockheed Teflon™ materials

is estimated to be 100 ESH or less. If the first 0.01 reduction in emissivity is real, the corresponding reduction in thickness would be approximately 0.04 mil for a specimen nominally 1-2 mils thick. Using an estimated fluence of $4.4 \cdot 10^{21}$ atoms/cm^2 between day 6 and 34, the estimated recession rate at 97 ESH is $0.023 \cdot 10^{-24}$ cm^3/atom oxygen. Based on emissivity changes of -0.06, -0.11 and -0.19, recession rates for the remaining time intervals are estimated to be 0.14, 0.10, and $0.17 \cdot 10^{-24}$ cm^3/atom, respectively. No contamination effects were evident on this experiment that would invalidate this approach. An optical witness plate flown on the Lockheed experiment showed essentially no change in α/ε ratio over the duration of the exposure.

The long-term (5.8 years) exposure data from LDEF are based on both mass difference and thickness change measurements. Results from the Long Duration Exposure Facility experiment indicate that, for the entire range of exposure conditions encountered in LEO, the solar absorptance of the silverized Teflon™ was essentially unchanged.[15] The total solar exposure on LDEF was approximately 11,000 ESH. The actual exposure received was dependent upon the location of the specimen and the angle on incidence. Even still, for these exposure conditions, the induction period is relatively insignificant for determining the recession rate. The on-orbit atomic oxygen fluence ranged from virtually zero up to $9 \cdot 10^{21}$ atoms atomic oxygen/cm^2. The average recession rate for a specimen from LDEF with a given solar exposure was calculated in a previous work by dividing the change in mass or thickness of that specimen by the atomic oxygen fluence observed at that specimen's location.[16]

The calculated atomic oxygen reaction rates, also known as reaction efficiencies, are plotted in Figure 4. A curve fit of Lockheed satellite and LDEF data shows that the atomic oxygen recession rate of metallized FEP in low Earth orbits can be approximated as a semilog function of solar exposure

$$R_e = 0.0555 \ln (ESH) - 0.184$$

The STS data point is included in Figure 4 but was not used in the curve fit of the data because it is considered a worst-case estimate. Thus, the recession rate has been shown to be a strong function of solar exposure and the induction period has been estimated at approximately 25-50 ESH. This engineering design curve has been incorporated into the Spacecraft Materials Selector knowledge base.

Discussion

Operational satellite data concerning the degradation of silverized Teflon™ due to two different space environments has been reviewed and analyzed. In one case, the increase in solar absorptance of Ag/FEP on several satellites scales has been shown to be a function of the deposited ionizing radiation dose. The satellite data is also consistent with similar laboratory data taken at Boeing's CRETC facility using monoenergetic electron beams. Metallized Teflon™ materials exposed on-orbit have greater degradation rates than identical materials that experienced ground-based electron exposure in the CRETC. However, the trends in the solar absorptance change with dose for ground and on-orbit measurements are qualitatively similar.

In the second case, the atomic oxygen recession rate of Ag/FEP was found to be a strong function of solar UV exposure. Analysis of the Lockheed satellite data supports the existence of an "induction period" prior to significant attack of Ag/FEP by atomic oxygen. The induction period of approximately 25-50 ESH of exposure is required before material property changes are noticeable.

The largest atomic oxygen recession rate observed thus far for Ag/FEP, $0.34 \cdot 10^{-24}$ cm^3/atom, came from the LDEF data and is consistent with the previous findings. In comparison, this value for Ag/FEP is an order of magnitude less than the widely accepted atomic oxygen induced recession rate of $3.0 \cdot 10^{-24}$ cm^3/atom for Kapton™, another thermal control material with no fluorine.

Acknowledgements

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Fig. 1 Change in solar absorptance of Al/FEP and Ag/FEP materials as a function of electron dose as measured in the CRETC laboratory chamber.[8-10]

Fig. 2 Change in solar absorptance of Al/FEP and Ag/FEP materials as a function of absorbed electron dose as derived from satellite measurements.

Fig. 3 Emissivity of Ag/FEP as a function of thickness[14]

Fig. 4 Recession rate of Ag/FEP as a function of solar exposure

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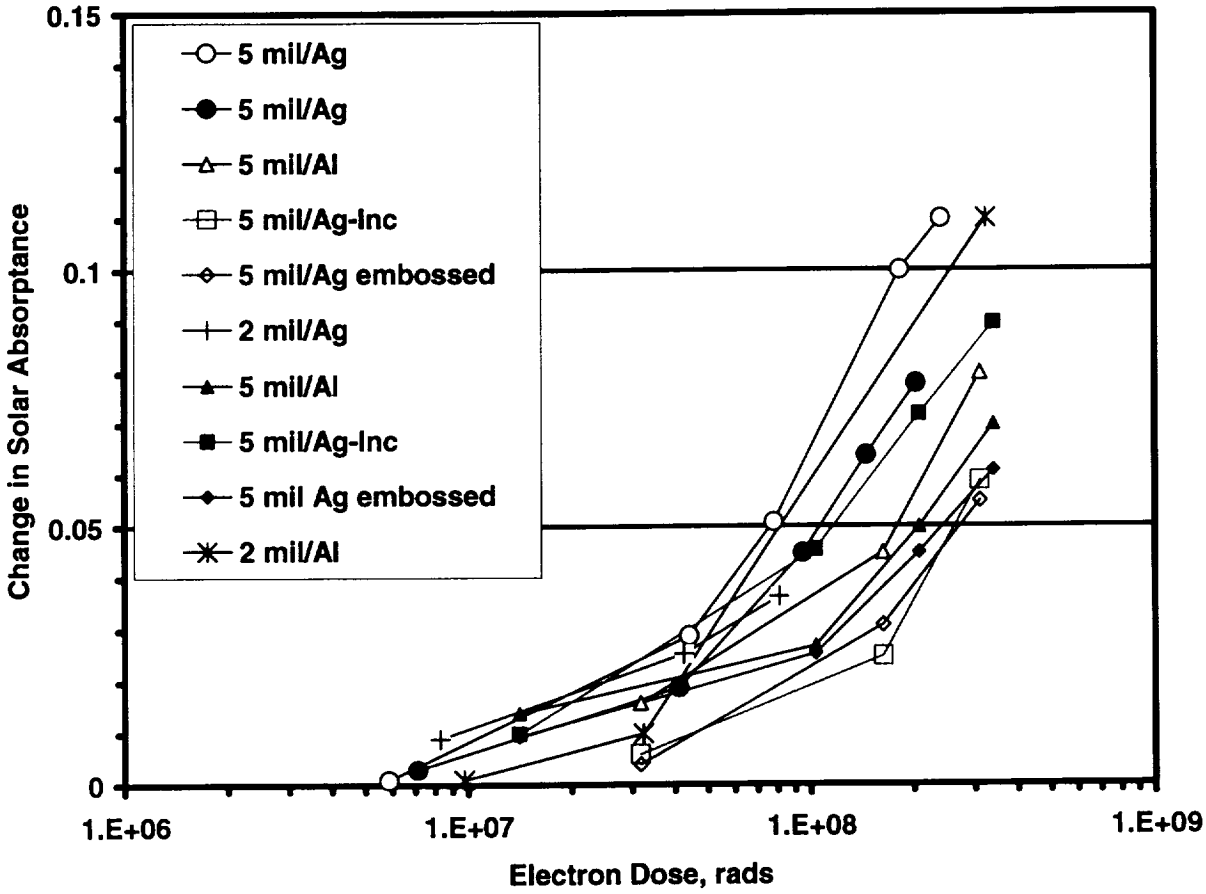
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Change in Solar Absorptance
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5 mil/Ag
5 mil/Al
5 mil/Ag-Inc
5 mil/Ag embossed
2 mil/Ag
5 mil/Al
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5 mil Ag embossed
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1.E+07
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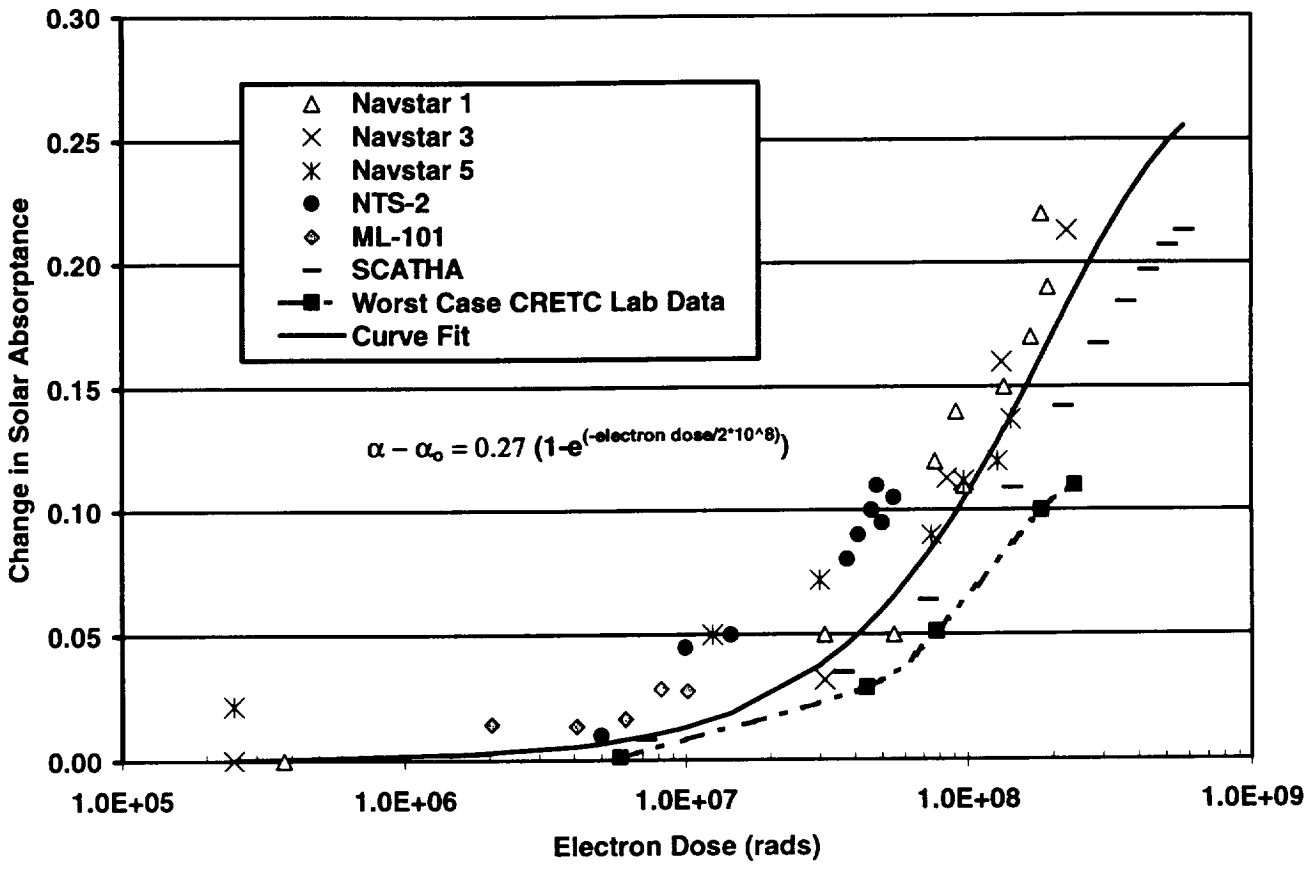
Electron Dose, rads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0.20
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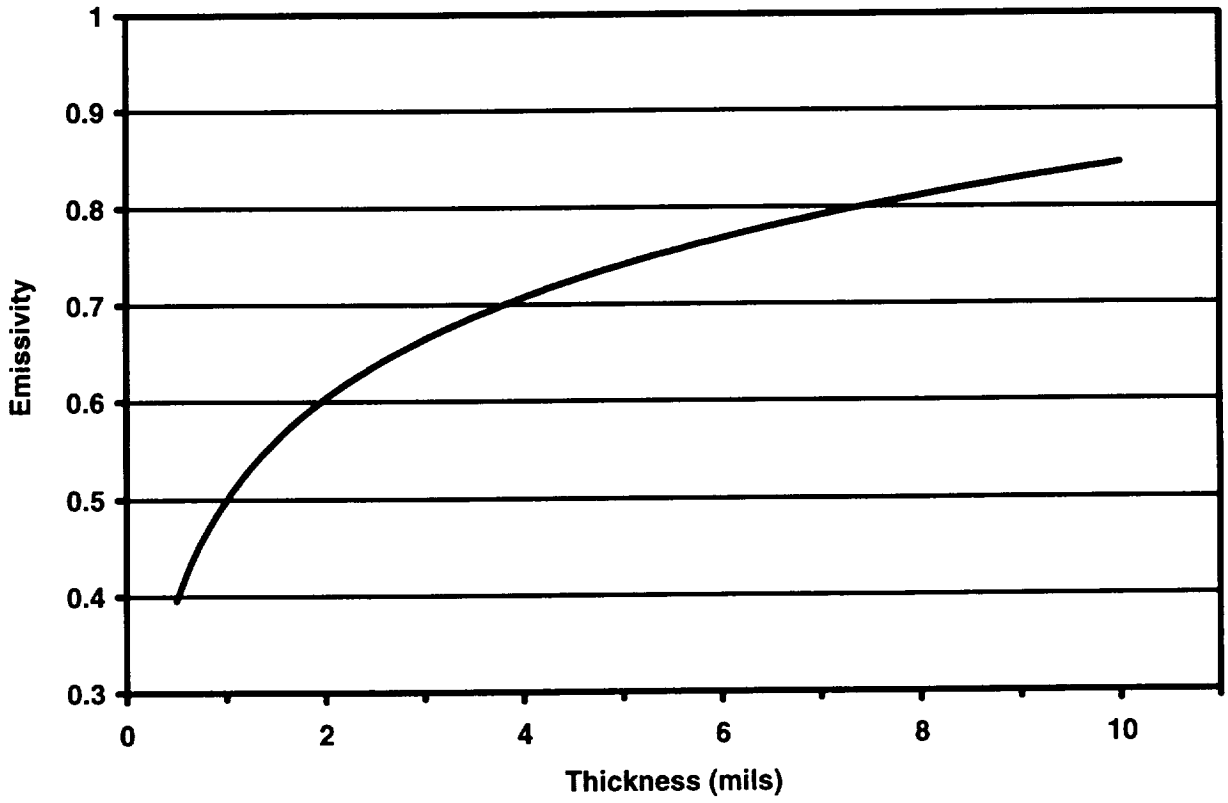
0.05
0.00
Change in Solar Absorptance
Navstar 1
Navstar 3
Navstar 5
NTS-2
ML-101
SCATHA
Worst Case CRETC Lab Data
Curve Fit
$\alpha - \alpha_o = 0.27\ (1\text{-}e^{(\text{-electron dose}/2*10^{\wedge}8)})$
1.0E+05
1.0E+06
1.0E+07
1.0E+08
1.0E+09
Electron Dose (rads)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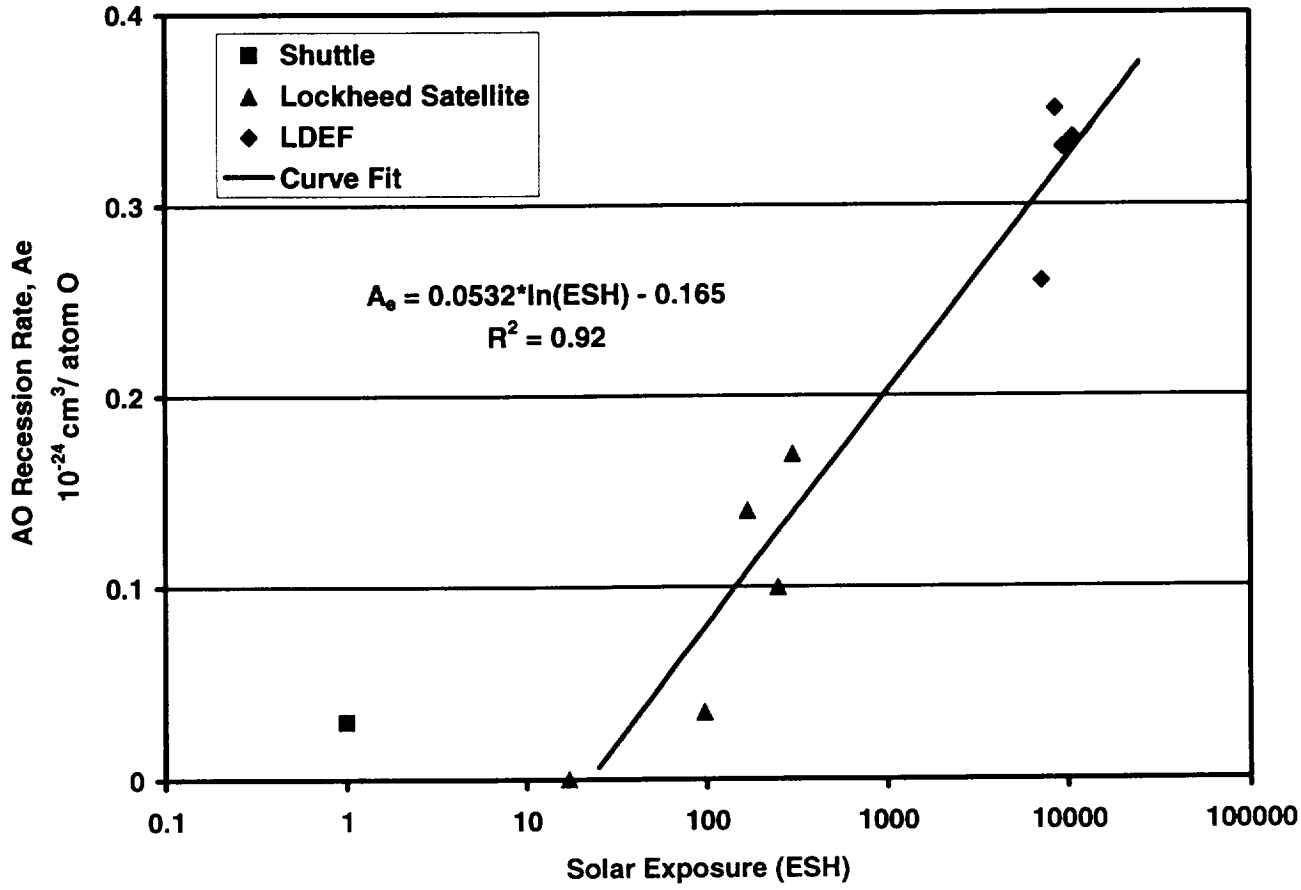
Thickness (mils)


Shuttle
Lockheed Satellite
LDEF
Curve Fit
$A_e = 0.0532*\ln(ESH) - 0.165$
$R^2 = 0.92$
AO Recession Rate, Ae
10^{-24} cm^3/ atom O
0.4
0.3
0.2
0.1
0
0.1
1
10
100
1000
10000
100000
Solar Exposure (ESH)