Analysis of Ag/FEP Thermal Control Blanket Performance from Multiple Satellites

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Introduction

Materials performance data from operational spacecraft and spacecraft experiments has slowly accumulated over the years. Much of this data is obtained indirectly by analyzing temperature measurements telemetered to ground. Due to the Space Transportation System (STS) program, materials performance data has also been obtained by flying materials on satellites, or on the Space Shuttle itself, for limited periods of time, and then returning the materials to ground for post-flight examination.

During the course of NASA contract NAS8-98213, the authors have extended the analysis of data reported for selected materials flown on a variety of spacecraft over the past 30 years[1-7].

In this paper we discuss changes in two properties of silver- or aluminum-backed (metallized) FEP Teflon due to exposure to specific environmental factors on-orbit.

First, the change in solar absorptance (α_s) of metallized FEP Teflon as a function of particulate radiation will be discussed. Data providing the change in solar absorptance of metallized FEP as a function of days on orbit has been published for NTS-2 satellite[2], several NavStar Global Positioning Satellites[3] (GPS), the SCATHA[4] experiment, and the ML-101[5] satellite. The unique approach that we have taken is to calculate the absorbed

radiation dose within the Ag/FEP for the various satellite orbits, and to plot the change in solar absorptance, α_s, as a function of the dose; the behavior agrees with the same data from laboratory tests.

Second, the variation of the atomic oxygen induced material recession rate of metallized FEP will be discussed. Data from certain Space Shuttle flights[6], a Lockheed experiment[1] [~105 days in low Earth orbit (LEO)], and the Long Duration Exposure Facility[7] allows the variation of the material recession rate of Ag/FEP to be estimated under conditions that include atomic oxygen exposure.

Solar Absorptance Changes Correlated with Ionizing Radiation Dose

Published data for changes in solar absorptance of either Ag/FEP or Al/FEP as a function of time on orbit exists for a number of different satellites. Data for both Al/FEP and Ag/FEP are used in the following analysis. We also utilize an extensive set of laboratory test data[8-10] that is available on the change in solar absorptance of metallized FEP as a function of electron fluence. This testing was carried out during the 1970s in the Combined Radiation Effects Test Chamber (CRETC) at the Boeing Radiation Effects Laboratory (BREL).
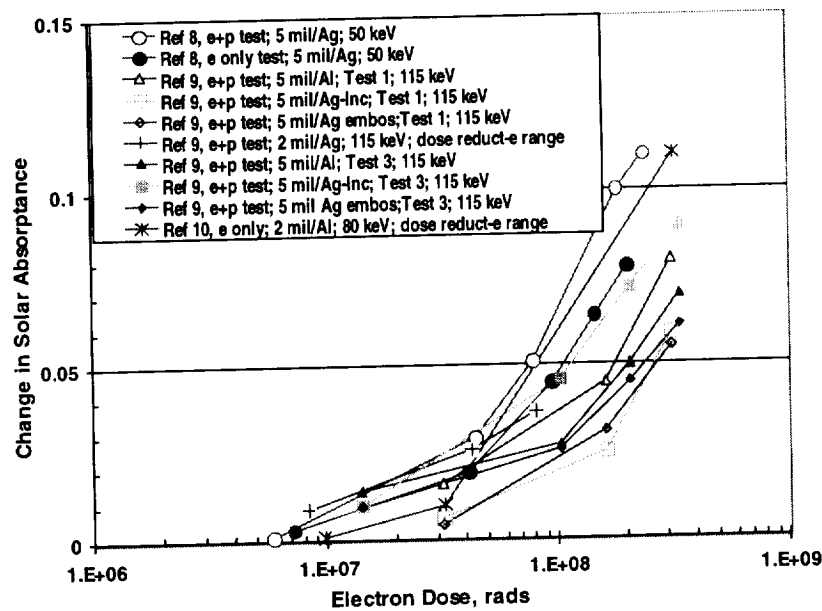
Figure 1 Plot of change in solar absorptance in Al/FEP and Ag/FEP test samples as measured in the CRETC laboratory chamber as a function of the absorbed electron dose.

The BREL carried out many tests on thermal coatings during the 1970s using the CRETC in which the reflectance of the coatings was measured as they were simultaneously exposed to UV and particulate radiation. The reflectance data was integrated over wavelength to obtain the solar absorptance values. Three reports, summarizing this kind of testing on silver and aluminum backed FEP teflon, have been used to collect solar absorptance data as a function of the deposited radiation dose.

The coatings were irradiated with monoenergetic electrons along with UV, and in some cases, also with a beam of low energy protons. The electron dose deposited was calculated for the three different test regimes (electron energies of 50, 80 and 115 keV), and Figure 1 contains the results in which the change in solar absorptance is plotted as a function of the deposited electron dose.

All of the CRETC curves, α_s vs. dose, have the same overall shape. In some cases there were small differences in the metallic backing material, e.g., embossed silvered FEP compared to FEP with a combined silver and Inconel backing. In other cases the sun rate (UV) was different between two sets of tests (test 2, 1.5 sun rate vs. test 3, 1 sun rate). The protons, usually with an energy of 50 keV, have a very short range in teflon (0.02 mil), compared to the thickness of the teflon, 2 or 5 mils. Thus the proton energy deposition was considered to be too localized to have an appreciable effect on α_s of the entire coating sample, and wasn't included. The manner in which the electron dose within the teflon is calculated is described later.

Our approach is to calculate the absorbed radiation dose in the Ag/FEP for the various satellite orbits, and then to plot the change in solar absorptance, α_s, as a function of this dose. The absorptance data portrayed in this way is in good agreement with laboratory test results (controlled irradiation using mono-energetic electron beams) in the same kind of coatings, as shown in Figure 1. The corresponding particulate radiation dose rate has been determined for each orbit, so for a given satellite and a given period of time, the accumulated dose in the FEP was determined.

The FEP-coated materials (5 mils) were used on the STP P72-1 (ML-101) satellite launched by Air Force in Oct 1972 [745 km, 98° orbit], the P78-2 (SCATHA experiment) Satellite (9° inclination, geosynchronous i.e, 36,000 km), Navstar satellites (MEO, 20,180 km and 63° inclination), and NTS-2, (20,000 km, 63°).

Reports on materials flown on each of these satellites provide data for solar absorptance change with time. The "effective" dose rate of radiation (electrons and protons) from all sources, for the orbit of each of these satellites was determined, and the cumulative

radiation dose as a function of time for the coatings on each satellite was obtained. . In reality, almost all the dose was contributed by the trapped electrons, although small contributions were also made by protons in some orbits. The change in solar absorptance of metallized FEP as a function of the cumulative dose has been plotted in Figure 2 for each of these satellites.
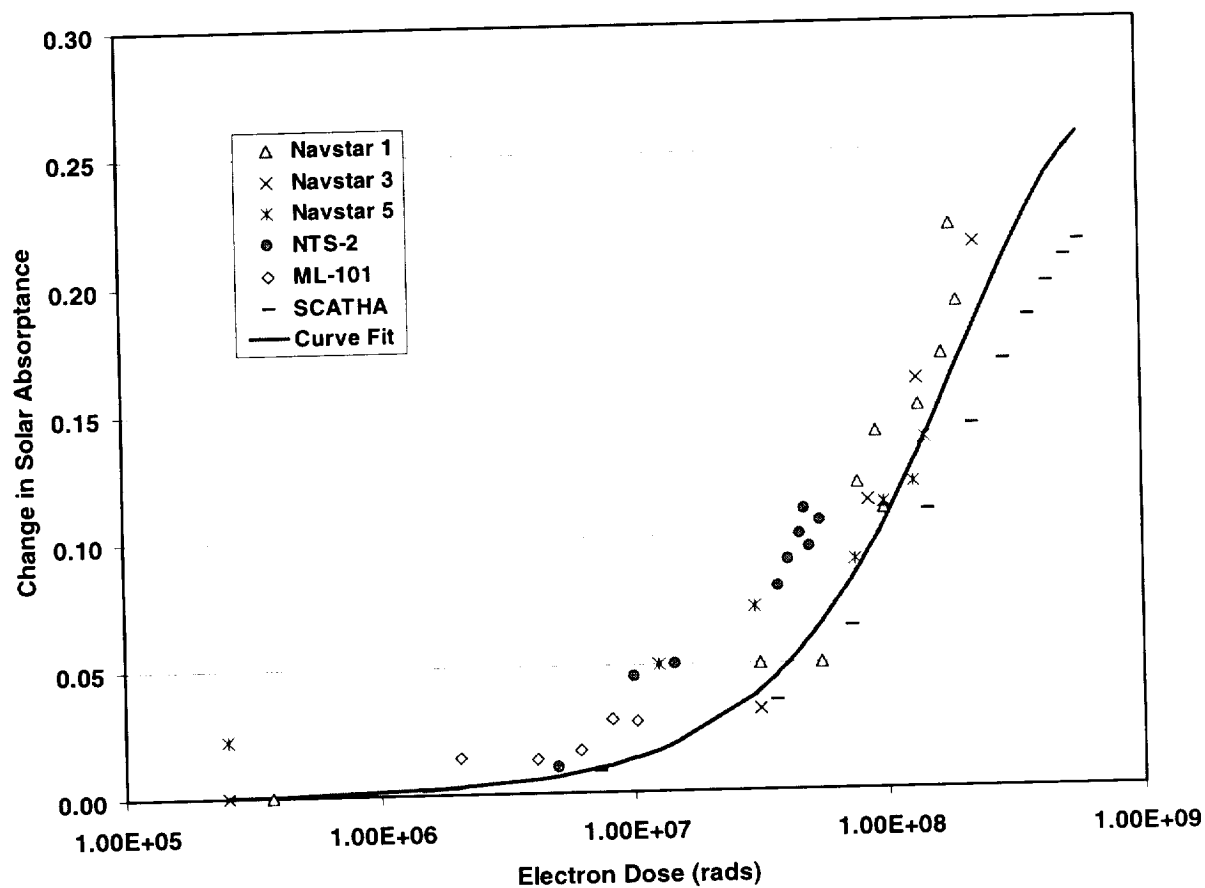

Figure 2. Plot of change in solar absorptance of Al/FEP and Ag/FEP material as measured on-orbit as a function of the absorbed electron dose

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. Changes in α_s were essentially zero for each of these surfaces (some non-zero changes were observed for adhesive-backed metallized FEP films due to mechanical failure of the metal layer). The surface radiation dose is uncertain because the altitude at which LDEF flew varied over the mission, especially during the final few months of the mission. Nevertheless, the surface dose is estimated to be in the range of 0.3-1 E6 rads. Even the upper end of this range is insignificant compared to the dose levels experienced by the other satellites. Essentially, LDEF serves as an "engineering zero" with no change in the α_s and an absorbed dose of less than E6 rads.

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 adjusted by subtracting the change in solar absorptance observed on the OSRs from the change in absorptance observed on the metallized Teflon material. The essentially linear changes in solar absorptance observed for the OSRs on the GPS satellites as a function of time is not characteristic of contamination induced changes. No adjustment for contamination was made to the NavStar data.

Determination of Total Particulate Radiation Dose

The radiation analysis entailed two different aspects, determining the particle fluxes for each orbit, and calculating the absorbed dose within the teflon from those fluxes. 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, so the same radiation environment was used for both.

Because the coating materials are so thin, most of the energy deposited will be by low energy particles. For example, 500 keV electrons have a particle range (distance particle will travel before giving up all of its energy) of 43 mils in teflon, but 100 keV electrons have a range of 3.65 mil. The range of the particle needs to be similar to the thickness of the coatings, 2 and 5 mils, in order to have most of the particle's energy deposited. Furthermore, the particle flux increases sharply with decreasing energy. With protons, the range of 1000 keV protons is 0.6 mil, and for 100 keV protons it is .04 mils. Thus, most of the energy deposition is from electrons with energies < 100 keV.

The calculation of the energy deposition was carried out in an approximate manner by carefully using the differential particle flux, dividing the energy range of each particle type into finely subdivided groups, multiplying the differential flux by the stopping power within each group and integrating over the full energy range. Since electron range and stopping power for teflon weren't available[11], we used the corresponding data for freon, which has similar atomic composition, and adjusted by the density of teflon (2.2 gm/cc). This was further verified by comparing the proton range for the two materials from the SRIM[12] code.

Discussion of Results

An engineering design curve has been constructed as a curve fit to data for solar absorptance change as a function of total electron dose. The curve is based on the

similarity of results from data examined from the 7 satellites. This engineering design curve has been incorporated into an electronic knowledge base. The engineering curve provides estimates of solar absorptance of uncoated Ag/FEP or al/FEP, at altitudes ranging from LEO to well above GEO. The end of mission solar absorptance estimated from curve fits of data.from the group of spacecraft is

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

where the electron deposited dose is in rads.

The approach to constructing the design curve was to calculate the deposited dose rate within the teflon from the trapped belt radiation (electrons and protons) for each of these orbits, and thus obtain the cumulative deposited radiation dose for the FEP coatings on each satellite.

In addition, LDEF serves as an "engineering zero" data point. The solar absorptance changes observed on LDEF are very slight compared with results from the other satellites, essentially no change in α_s. The upper bound estimate of the deposited dose for LDEF is 1E6 rads, which is insignificant compared to the dose levels experienced by the other satellites.

Estimate of the atomic oxygen recession rate of silverized Teflon

Thin films of metallized teflon have been used on numerous spacecraft as thermal control coating because of their excellent α/ε ratios and relative stability in a wide variety of orbits. The differences in performance relative to many other coating materials are due to the strength of the C-F bond relative to the C-C and C-H bonds, and that the interaction

of FEP with high energy particles is different than for inorganic paints that may have oxygen atoms ejected by collsion.

Under low Earth orbit conditions an O-atom can easily abstract a hydrogen atom from a carbon atom. However, an O atom will not abstract a fluorine atom from a carbon atom under low Earth orbit conditions, because the thermodynamics are not favorable. The O-F bond strength is about 2.2 ev. It has been proposed[1] that an "induction" period of direct solar exposure is required for FEP prior to attack by atomic oxygen. In 1985, Lockheed conducted a materials flight experiment that demonstrated the existence of an induction period. During the induction period C-F and/or C-C bonds are ruptured after absorbing short wavelength vacuum ultraviolet radiation. This process gradually produces a population of free radical sites where oxygen atoms may react.

One consequence of an induction period is that the effective atomic oxygen recession rate on FEP varies with time. A comparison of three data sets demonstrate this fact, the short term (<1 week) Space Shuttle data, the long term (5.8 years), relatively high atomic oxygen fluence, data from LDEF, and the intermediate term (105 days), very high atomic oxygen fluence, data from the Lockheed flight experiment. The short term Space Shuttle measurements are based on mass difference limits and atomic oxygen fluence was estimated from computer codes. The long-term exposure results from LDEF are based on mass differences and thickness decrease to estimate the material loss and atomic oxygen was predicted from computer codes. The Lockheed data was reported as thermal emittance changes with time calculated from temperature data.

The solar exposure level on the Lockheed experiment was ~300 ESH, distributed relatively evenly over the 105 day experiment. The atomic oxygen fluence was estimated

from computer models and partially confirmed by the lifetime of a Kapton sample flown adjacent to the Ag/FEP specimen. The flux of atomic oxygen to the material surfaces on the Lockheed flight experiment was approximately 20 times the average flux for the material on LDEF. An optical witness plate flown on the Lockheed experiment showed essentially no change in α/ε ratio over the duration of the exposure indicating that contamination effects on these measurements were insignificant.

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. Conditions ranged up to ~9×10^{21} atoms/cm^2 of atomic oxygen and solar exposure up to 11,000 ESH on certain samples, to about 11,000 ESH solar exposure, with essentially no atomic oxygen exposure, on other samples. The exposure envelope of the Lockheed experiment is well within this range. This supports the conclusion that the changes in temperatures measured for the metallized Teflon on the Lockheed flight experiment were driven by changes in thermal emittance.

Thermal emittance of silverized or aluminized teflon is a function of thickness of the FEP layer. By comparing the emittance determined for the flight specimen as a function of time with a curve fit of emittance of silverized teflon as a function of thickness, the thickness of the flight specimens can be estimated at specific times. This allows a determination of the average recession rate for each interval of time.

The atomic oxygen induced recession rate estimates from Space Shuttles flight are less than ~0.05 cm^3/atom. Solar exposure levels on material specimens during a space shuttle

flight are only a few ESH. This 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 Space Shuttle flights are essentially upper bounds, estimated by assuming complete recession of thin FEP films by the atomic oxygen fluence received during specific Space Shuttle flights. The actual recession rates are lower.

For the Lockheed flight experiment, no mass loss was detected for the first 6 days. The determination of the recession rate is limited by the uncertainty in the measurement of emissivity changes, +-0.01, as well as the estimate of atomic oxygen fluence. This emissivity change requires an average thickness change of ~0.04 mil for a specimen nominally about 1-2 mils thick.

The estimated fluence of 4.4×10^{21} atoms/cm^2 between day 6 and 34 of the flight, together with the estimate of ~0.04-0.08 mil recession for a 0.01-0.02 change in emittance gives an estimate of 0.023-0.046 x 10^{-24} cm^3/atom recession rate. This recession rate range estimated is similar to the maximum value estimated from Space Shuttle flights. This also suggests an induction period of around 100 ESH, maximum. Based on the emissivity changes, recession rates for the remaining time intervals are estimated to be 0.14, 0.10, and 0.17 x10^{-24} cm^3/atom, respectively.

The average recession rate determined for FEP on the LDEF was 0.34x10^{-24} cm^3/atom for exposures that included 1-9 x 10^{21} atoms/cm^2 and several thousand ESH solar UV. For these exposure conditions, the induction period is relatively insignificant for determining the recession rate. The 100 hour level of solar exposure was reached within a few weeks

for each FEP surface of interest on LDEF, and large majority of the atomic oxygen fluence was received during the later stages of the flight.

Time days	α	ε	Inferred thickness* mm	AO fluence 10^{21} atom/cm^2	Cumulative AO fluence 10^{21} atom/cm^2	Reaction Efficiency R_e 10^{-24} cm^3/atom
0	0.16	0.56	0.027	0	0	0
6.1	0.20	0.56	0.027	1.18	1.18	0
34	0.23	0.55	0.0255	4.4	5.6	0.046
60	0.22	0.50	0.019	4.3	9.9	0.14
88	0.21	0.45	0.014	5.1	15.0	0.10
105	0.21	0.37	0.008	3.5	18.5	0.17

Table 1. FEP results summarized from table 2 of AIAA paper 85-1066, together with thickness and recession rate estimates.

* Based on figure 19 in reference 1 and data published by Sheldahl, Inc. in their Thermal Control Materials and Films handbook

CONCLUSIONS

Operational satellite data concerning the degradation of silverized Teflon due to two different space environments has been reviewed and analyzed. In one case we note the increase in solar absorptance of Ag/FEP on several satellites scales with the deposited ionizing radiation dose, which is mainly due to low energy electrons. The satellite data is also consistent with similar laboratory data taken at Boeing's CRETC facility using monoenergetic electron beams. Further, the solar absorptance data on LDEF serves as an

"engineering zero" data point. Hardly any change in solar absorptance was noted, and the deposited electron dose was very low compared to that on the other satellites. The conclusion is that metallized teflon materials exposed on-orbit have greater degradation rates than identical materials that experienced ground-based electron exposure. However, the trends in the solar absorptance change with dose are qualitatively similar.

In the second case, it is the interaction of the Ag/FEP with atomic oxygen that is addressed. Lockheed demonstrated the existance of an "induction period" prior to significant attack of Ag/FEP by atomic oxygen. Our analysis of the data indicates about 100 ESH of exposure are required before material property changes begin to be noticed. The LDEF data is consistent with the previous findings and provides a measurement of the long-term atomic oxygen recession rate for Ag/FEP.

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