

SMC-TR-93-25

AD-A266 284



AEROSPACE REPORT NO.
TR-93(3935)-9

Performance of Silvered Teflon Thermal Control Blankets on Spacecraft

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15 March 1993

Prepared for

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93-14892



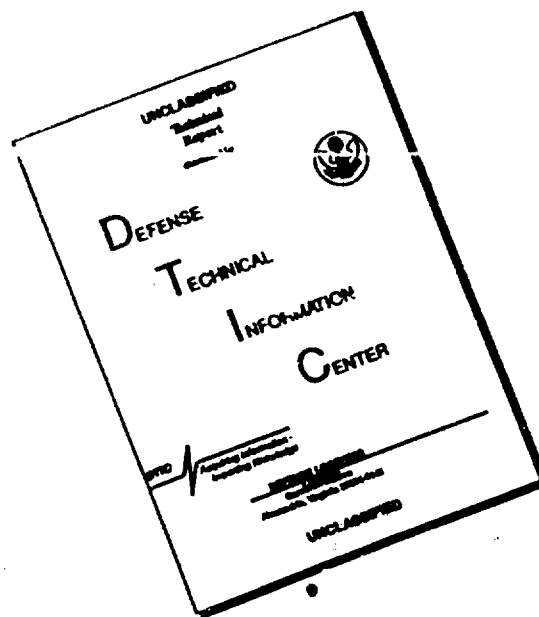
Engineering and Technology Group

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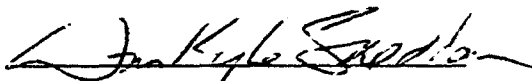
This report was submitted by The Aerospace Corporation, El Segundo, CA 90245-4691, under Contract No. F04701-88-C-0089 with the Space and Missile Systems Center, P. O. Box 92960, Los Angeles, CA 90009-2960. It was reviewed and approved for The Aerospace Corporation by R. W. Fillers, Principal Director, Mechanics and Materials Technology Center. Capt. Don Johnson was the Space Test Program project officer responsible for the retrieval of LDEF.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.



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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified			1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited		
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE					
4. PERFORMING ORGANIZATION REPORT NUMBER(S) TR-93(3935)-9			5. MONITORING ORGANIZATION REPORT NUMBER(S) SMC-TR-93-25		
6a. NAME OF PERFORMING ORGANIZATION The Aerospace Corporation Technology Operations		6b. OFFICE SYMBOL (if applicable)	7a. NAME OF MONITORING ORGANIZATION Space and Missile Systems Center		
6c. ADDRESS (City, State, and ZIP Code) El Segundo, CA 90245-4691			7b. ADDRESS (City, State, and ZIP Code) Los Angeles Air Force Base Los Angeles, CA 90009-2960		
8a. NAME OF FUNDING/SPONSORING ORGANIZATION		8b. OFFICE SYMBOL (if applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F04701-88-C-0089		
8c. ADDRESS (City, State, and ZIP Code)			10. SOURCE OF FUNDING NUMBERS		
			PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.
11. TITLE (Include Security Classification) Performance of Silvered Teflon Thermal Control Blankets on Spacecraft					
12. PERSONAL AUTHOR(S) Pippin, Gary; Stuckey, Wayne. K.; and Hemminger, Carol S.					
13a. TYPE OF REPORT		13b. TIME COVERED FROM _____ TO _____		14. DATE OF REPORT (Year, Month, Day) 15 March 1993	
15. PAGE COUNT 20					
16. SUPPLEMENTARY NOTATION					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) Ag/FEP, Teflon, Thermal Control, LDEF, Atomic Oxygen, Solar Ultraviolet Radiation, Contamination		
FIELD	GROUP	SUB-GROUP			
19. ABSTRACT (Continue on reverse if necessary and identify by block number) Silver-backed fluorinated ethylene propylene Teflon (Ag/FEP) thin film material was used for thermal control in many locations on the Long Duration Exposure Facility (LDEF). The Ag/FEP registered the effects of atomic oxygen, solar ultraviolet radiation, meteoroid and debris impacts, thermal cycling, and contamination. This report summarizes the post-flight condition of the Ag/FEP, compares the results with performance on other spacecraft, and presents lifetime estimates for use under a variety of environmental exposures. Measurements of optical property changes, thickness loss, and mechanical property and surface chemistry changes with exposure conditions, and their significance for design considerations and expected performance lifetimes are reported for material flown on LDEF. The LDEF based data provides detailed information on performance of Ag/FEP under relatively long term exposure in low Earth orbit. Comparison of this data with results from short term shuttle flights, Solar Max, SCATHA, other satellites and ground based measurements is made to present a comprehensive summary of the use of this material for spacecraft applications.					
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION Unclassified		
22a. NAME OF RESPONSIBLE INDIVIDUAL			22b. TELEPHONE (Include Area Code)		22c. OFFICE SYMBOL

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INTRODUCTION

Silverized Teflon (Ag/FEP) is a widely used passive thermal control material for space applications. The material has a very low α/ϵ ratio (<0.1) for low operating temperatures and is fabricated with various FEP thicknesses (as the Teflon thickness increases, the emittance increases). It is low outgassing and, because of its flexibility, can be applied around complex, curved shapes. Ag/FEP has achieved multiyear lifetimes under a variety of exposure conditions, as demonstrated by the Long Duration Exposure Facility (LDEF) (ref. 1), Solar Max (ref. 2), Spacecraft Charging at High Altitudes (SCATHA) (ref. 3), and other flight experiments (refs. 4, 5). Ag/FEP material has been held in place on spacecraft by a variety of methods: mechanical clamping, direct adhesive bonding of tapes and sheets, and by Velcro tape adhesively bonded to back surfaces. On LDEF, for example, 5-mil blankets held by Velcro and clamping were used for thermal control over 3 x 4 ft areas on each of 17 trays. Adhesively bonded 2-mil and 5-mil sheets were used on other LDEF experiments both for thermal control and as tape to hold other thermal control blankets in place.

Performance data over extended time periods is available from a number of flights. The observed effects on optical properties, mechanical properties, and surface chemistry will be summarized in this report. This leads to a discussion of performance life estimates and other design lessons for Ag/FEP thermal control material.

LDEF RESULTS SUMMARY

The LDEF flight has provided the opportunity to substantially increase our knowledge of the performance of Ag/FEP in low earth orbit (LEO), improving our understanding of both the expected performance and the limitations of this material. Specimens on the leading edge (rows 7-11) of LDEF were exposed to both atomic oxygen and solar UV. Those specimens located toward the trailing edge (rows 1-5 and 12) received only the solar exposure. Row 6 was a transition region, with some exposure to atomic oxygen, but at reduced levels relative to the leading edge rows.

OPTICAL PROPERTIES

A variety of visible changes were observed in the Ag/FEP surfaces on both leading- and trailing-edge samples. The exposed leading-edge blanket surfaces appeared uniformly foggy or clouded. The exposed trailing-edge blanket FEP surfaces were "patterned" in some areas with alternating transparent and clouded bands. Clouded areas were observed on many blanket edges, particularly near the bends between exposed and masked material ("transition zone"). Areas of orange/brown discoloration were notable near some of the keyhole-shaped vent slots along the edges of the Ag/FEP blankets.

A large number of optical property measurements were made on LDEF blankets (ref. 6). For the baseline measurement, areas not visibly contaminated and with no visible impacts and/or delaminations were chosen. Figures 1 and 2 show the distribution of end-of-mission absorption and emittance values around the LDEF. Solar absorptance remained constant to within experimental

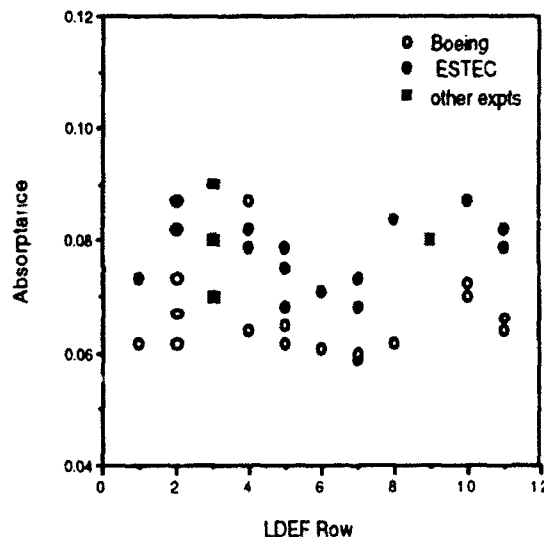


Figure 1. Absorptance of Ag/FEP vs location on LDEF.

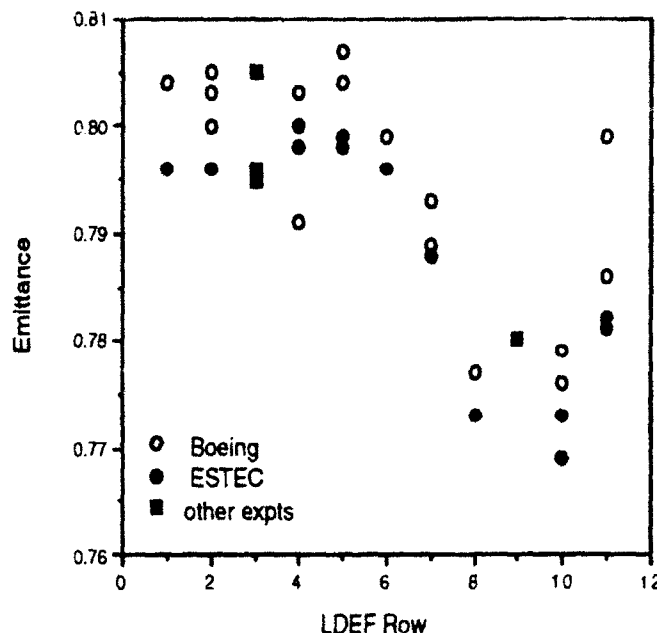


Figure 2. Emittance of Ag/FEP vs location on LDEF.

uncertainty, except for small areas where contaminant films were deposited or impacts had occurred. Locations that were adhesively bonded to an aluminum substrate were darkened in areas where cracking of the silver and inconel layers allowed the underlying adhesive to bleed through over time and be exposed to solar radiation (ref. 7). This process led to increases in absorptance up to 0.25 in small areas. Data from both Boeing Defense & Space Group and the European Space Research and Technology Centre (ESTEC) show the expected decrease in emissivity as the thickness is decreased. The thickness change observed from leading-edge blankets was a consequence of atomic oxygen reaction with the FEP surface after the polymer structure was altered by vacuum ultraviolet (VUV) photons. Most blanket areas from the trailing edge side, exposed only to solar UV, remained specular. The diffuse reflectance increased for those areas toward the leading edge roughened by exposure to both atomic oxygen and solar UV, giving rise to the uniformly clouded appearance.

MECHANICAL PROPERTIES

Mechanical property changes that occurred in 5-mil Ag/FEP on LDEF (ref. 8) are indicated by the property data in Table 1. FEP from the trailing edge that was embrittled due to solar exposure had ultimate tensile values decreased by about one-third relative to controls. The %-elongation to failure of the solar UV embrittled material also decreased by about 20%, while the recessed FEP from the leading edge was still flexible with %-elongation to failure values only slightly decreased relative to controls. The leading-edge mechanical properties are not signifi-

Table 1. Mechanical Properties Changes of FEP with Exposure on LDEF

FEP from Ag/FEP Blankets	% Elongation to Failure ($\pm 40\%$)	Ultimate Tensile Strength, N/mm ² (± 3 N/mm ²)
Trailing Edge, Rows 1-6		
Exposed	230	14
Masked	300	21
Leading Edge, Rows 7-11		
Exposed	290	19
Masked	310	20

cantly different, although thinning of the Teflon would ultimately lead to reduced mechanical properties.

Comparisons between specimens from the leading edge and trailing edge, which had each been flexed over a 90° corner, showed that the FEP from the leading edge was still intact, and no cracking was visible under a 100x microscope. FEP from the trailing edge, which showed no cracking prior to flexure, showed a large number of parallel cracks in the area of the specimen flexed around the radius. These cracks did not extend completely through the FEP layer, leading to the conclusion that only the UV damaged portion of the FEP was cracking. This observation, together with the tensile measurements and the observation from the leading-edge specimens that up to about 20% of the thickness was recessed, suggests that significant UV damage extended about one-quarter of the way through the material.

The Ag/FEP tapes holding the thermal control blankets for the Naval Research Laboratory cosmic ray detection experiment (M0001) failed along at least two sides of every blanket. The most likely cause was shrinking and stretching due to thermal cycling. Some aluminum-backed FEP specimens from The Aerospace Corporation Space Environmental Effects on Materials Experiment (M0003) also failed mechanically during flight. This failure has been attributed to stress induced by thermal cycling and not to any significant material property change. The Ag/FEP blankets mounted with Velcro from the back, with large areas free to stretch during solar exposure, did not fail. Ag/FEP material adhesively bonded to aluminum substrates also remained intact mechanically. Cracking of the silver and inconel layers of adhesively-bonded Ag/FEP films have been attributed to flexing/stretching during pre-flight application to hardware (refs. 7, 9), and not to on-orbit stresses.

SURFACE AND CHEMICAL ANALYSES

The leading-edge samples of Ag/FEP from rows 7 to 11 all had roughened surfaces typical of high-velocity atomic oxygen erosion of polymers. The highly textured surfaces gave rise to diffuse light scattering and the consequent cloudy appearance. The FEP reaction efficiency on the leading edge was measured at 0.34×10^{-24} cm³/O atom (ref. 10). Analysis by X-ray photoelectron spectroscopy (XPS) of the exposed surfaces showed that the surface composition and chemistry of the FEP remaining after erosion was indistinguishable from the control FEP, except for trace amounts of some contaminants, including oxygen (refs. 11, 12). Most deposited contaminants and damaged polymer were removed during atomic oxygen erosion.

The FEP surfaces exposed on the trailing edge of LDEF underwent changes that were observed both by scanning electron microscopy (SEM) and XPS. Within short distances on some trailing-

edge samples, both the surface morphology and surface contamination levels were observed to change dramatically (refs. 11,12). The FEP surfaces nearest to row 3 were moderately to heavily contaminated, and the blanket surface areas that appear fogged or cloudy had become sufficiently diffuse to be observed visibly. Further from row 3, FEP surfaces showed little texture development and no significant contamination except oxygen, possibly from post-flight exposure to moisture.

XPS data for the trailing-edge surfaces fell into two categories. The first was characterized by low contamination levels ($\text{Si} < 1\%$) and a carbon 1s spectrum that arises from degradation of the FEP surface. The spectral changes were consistent with damage to the carbon backbone of the Teflon polymer, resulting in molecular weight degradation, new chain terminations, branching, and crosslinking through free-radical reactions. The solar UV radiation exposure of the LDEF surfaces caused this FEP surface degradation. The FEP surfaces were also exposed to the stress of about 34,000 thermal cycles with calculated minimum temperatures of about -54°C , but the maximum temperatures calculated for Ag/FEP blankets on LDEF were less than 0°C and not sufficient to break chemical bonds. The second category of trailing-edge surfaces was characterized by moderate to high levels of surface contamination (Si, O, C, N, and S, and sometimes Cl). Contaminant carbon, thought to build up on the trailing-edge surfaces from decomposition products of outgassed silicones and hydrocarbons, was distinguished from FEP and degraded FEP carbon by binding energy, and was measured at $\leq 20\%$ of the total surface composition. The predominant chemical state of Si identified on the trailing-edge FEP surfaces was SiO_2 . The contaminant film was probably patchy on a submicron scale, with significant areas covered by $<100 \text{ \AA}$ of deposited contamination.

COMPARISON WITH OTHER FLIGHT EXPERIENCE WITH AG/FEP

Prior to shuttle operations, a number of spacecraft flew with either Ag/FEP or Al/FEP material as test specimens on thermal control coating experiments (refs. 3-5,13,14). Thermal data from each of these experiments was telemetered to the ground, and the optical properties data were deduced indirectly from the calorimetry, as shown in Table 2. Spacecraft at altitudes ranging from tens to hundreds of thousands of kilometers showed rather large changes in absorptance over time. Among spacecraft flown at altitudes less than 1000 km, specimens on both OSO-H (ref. 13) and ML-101 (ref. 14) experiments showed rapid changes of about 0.02 in absorptance during the first month in orbit, followed by very slow, small changes over the following months and years. A likely cause of the early changes was contamination due to rapid outgassing and initial venting of the spacecraft.

The Solar Max repair mission, conducted on STS-41-C after the deployment of LDEF in 1984, returned 5-mil Ag/FEP surfaces that had been in orbit from February 1980 until April 1984 at altitudes that decreased from 574 to 491 km. Post-flight measurements of solar absorptance (α_s) were made in many areas with values of 0.06 to 0.11 representing 80% to 90% of the Ag/FEP area (ref. 2). As was observed on LDEF, these areas show minimal degradation compared to typical values of 0.05 to 0.07 for unflown Ag/FEP. In the remaining area, the solar absorptance had increased to values ranging from 0.28 to 0.4, but in these regions, the silver Teflon either had been visibly contaminated or had environmental exposure on both sides of the film, resulting in severe degradation of the inconel and silver metallization layers. The tensile strength and elongation were also measured on the returned Solar Max samples with results similar to the changes observed on the LDEF samples. The thermal control performance of Ag/FEP in the LEO environment has generally been stable unless erosion of the Teflon on the leading edge by atomic oxygen erosion occurs, which can obviously result in emissivity changes. The more recent shuttle flights were too short in duration to cause large changes in the Ag/FEP (ref. 15).

Table 2. Flight Experience with Metallized Teflon

Altitude (Inclination)	Spacecraft	Thermal Property Changes
235,639 x 201,599 km (17°)	IMP-H	$\Delta\alpha_s \geq 0.07$ over 12,000 ESH
237,056 x 370 - 1600 km (29°)	IMP-1	Large $\Delta\alpha_s$ over time
43,288 x 27,578 km (7.9°)	P78-2 (SCATHA)	$\Delta\alpha_s > 0.2$ over 10 years (~27,800 ESH)
778 x 737 km (98°)	ML-101	$\Delta\alpha_s < 0.02$ initial; then low $\Delta\alpha_s$ over time
574 - 491 km (28.5°)	Solar Max	$\Delta\alpha_s \leq 0.04$ typical; some areas 0.28 to 0.4 (~4 yrs)
560 x 327 km (33°)	OSO-H	Rapid $\Delta\alpha_s$ / ϵ ~0.02, then constant (~8000 ESH)
480 - 330 km (28.5°)	LDEF	$\Delta\alpha_s \leq 0.01$ typical; some areas >0.24 (~5.8 yrs)
270 km (28.5°)	STS-41G Shuttle Flight (EOIM-II)	Slight Changes (<100 ESH)
220 km (28.5°)	STS-8 Shuttle Flight (EOIM-I)	Slight Changes (<100 ESH)

Results from SCATHA are now available that cover ten years of on-orbit performance of thermal control materials at geosynchronous altitudes (ref. 3). In five years, both 5-mil and 2-mil Ag/FEP had degraded to α_s values of greater than 0.24 due to electron and proton radiation. Contamination on SCATHA was probably not significant in these measurements, and these data should represent the material performance at geosynchronous altitudes. The Interplanetary Explorer missions IMP-H and IMP-1 (ref. 13) were flown at even higher altitudes, which have a similar UV and solar wind environment as geosynchronous altitudes, but are beyond the trapped-radiation, charged-particle belt. The Ag/FEP samples showed less degradation than observed on SCATHA.

The flight recession rate data for Ag/FEP shown in Table 3 comes from essentially three sources: shuttle flights (ref. 15), results from a Lockheed Missiles & Space Company, Inc. experiment published in 1985 (ref. 16), and the LDEF exposures (ref. 10). The Effects of Oxygen Interaction with Materials (EOIM) experiments were based on a well-documented exposure on orbit and measurements of the returned flight samples. Due to the short mission, which limited oxygen atom fluence and also the UV exposure, the erosion of the Teflon was too low on EOIM I and II to make an accurate measurement. A limit for the erosion rate was determined to be $\leq 0.05 \text{ cm}^3/\text{O atom}$. FEP exposed to atomic oxygen for the first 2 months on the Lockheed flight experiment showed little recession. After 2 months and $\sim 100 \text{ ESH UV}$, the optical properties of the Ag/FEP on the Lockheed flight began to change in a manner suggesting material recession. For the last few days of exposure on the Lockheed experiment, the calculated recession rate was only about $0.13 \times 10^{-24} \text{ cm}^3/\text{O atom}$, barely 1/3 of the average LDEF rate. The Teflon surfaces returned from the Solar Max Repair Mission did show evidence of the characteristic texture of an oxygen atom-eroded surface, but measurements of material loss were not reported.

The well-documented erosion observed for silver Teflon on the leading edge of LDEF results in a higher reaction efficiency for FEP Teflon than observed previously. This indicates that a synergistic effect exists with the atomic oxygen and UV. In contrast, linear relationships were observed for polymers such as Kapton, and there is good agreement on reaction efficiency between these same missions. The UV degradation, clearly indicated in the studies of the trailing-edge Teflon surface from LDEF, is undoubtedly responsible for the higher erosion observed on LDEF (ref. 11). The LDEF mission had a high UV exposure followed by an increasing atomic oxygen fluence during the flight, which resulted in nearly an order of magnitude higher reaction efficiency than observed on earlier flights. These data confirm that atomic oxygen-induced recession of FEP in LEO is also a function of UV exposure level.

Table 3. Flight Measurements of FEP Teflon Reaction Efficiency

Flight	Atomic Oxygen Fluence (Atoms/cm ²)	Ultraviolet (Hr)	Reaction Efficiency (cm ³ /O atom)
STS-8 Shuttle Flight (EOIM-I)	8.58×10^{19}	≤ 50	Not measured
STS-41G Shuttle Flight (EOIM-II)	3.5×10^{20}	≤ 50	$< 0.05 \times 10^{-24}$
Solar Max	$\sim 7 \times 10^{20}$	Unknown	Not measured
Lockheed Experiment	1.85×10^{22}	300	$0.075 - 0.13 \times 10^{-24}$
LDEF	$3.3 - 9.0 \times 10^{21}$	6000 - 11000	0.34×10^{-24}

PERFORMANCE LIFE ESTIMATES

Materials performance lifetime limits can be determined by several factors: increases in the α/ϵ ratio, causing increases in temperature above the allowed performance values; mechanical failure of the material; tearing due to thermal-cycling-induced stresses; embrittlement by solar VUV radiation, causing subsequent cracking; impact damage, creating punctures and associated damage and/or darkening of a portion of the blanket; and redeposition of outgassed contaminant materials that darken and change the absorptance characteristics of the material. Combined information from shuttle flights (ref. 15), LDEF (refs. 8, 10), Solar Max (ref. 2), and other flights (ref. 16) demonstrates that the recession rate of the Ag/FEP increases under combined UV and AO exposure. LDEF results provide the highest measured recession rates for this material seen to date.

An estimate of the expected environmental degradation for a specified mission can be made from the mission profile, which establishes the orbit and required lifetime. End-of-life requirements for the optical properties must be established. At geosynchronous altitude, the SCATHA degradation curves could be used to estimate the performance life with exposure to the trapped radiation charged particle belt. In LEO orbits, the atomic oxygen flux is strongly dependent upon altitude and solar activity. The atomic oxygen and solar UV fluences are determined based on the mission profile, and the total recession over the life of the mission is predicted. The minimum required thickness of the Ag/FEP material at end-of-life is based on the well established values for emittance of FEP as a function of thickness. The actual recession rate used will depend on the expected duration of the mission. For short periods of time in LEO, recession rates of $0.15 \times 10^{-24} \text{ cm}^3/\text{O atom}$ will be sufficient to establish recession. For missions of greater length, the LDEF value $0.34 \times 10^{-24} \text{ cm}^3/\text{O atom}$ is clearly more appropriate. In practice, the known reaction efficiency and expected oxygen fluence are used to predict the expected life of a film with a given initial thickness.

Lifetime predictions should also include consideration of the fraction of the blanket surface that will likely be darkened or destroyed by impacts and potential absorptance increases due to contaminant films over a fraction of the surface. These considerations were minor for LDEF. Impacts darkened 2% or less of the surface area of each LDEF blanket and delaminated <5% of the area on each blanket. Contaminant films caused absorptance values as high as about 0.25, but only for relatively small surface areas. The minimum area required for a given radiator would need to be scaled up by only 5% to 10% to compensate for these effects.

DESIGN AND PERFORMANCE LESSONS

In summary, the cumulative space environmental effects on Ag/FEP were a function of location and exposure orientation. The LDEF results for silver Teflon indicate that the thermal performance shows minimal degradation from the solar UV exposures of up to 11,000 ESH. The charged-particle environment at these LEO altitudes is too low to cause degradation, but at higher altitudes, up to geosynchronous altitudes, the Teflon is susceptible to degradation. Above geosynchronous altitudes, Teflon may have longer lifetimes due to the lower charged-particle environment. At the lower LEO altitudes, atomic oxygen erosion may result in degraded properties, depending on total fluence levels. The leading edge of LDEF was dominated by the effect of the atomic oxygen, resulting in erosion of the Teflon. The resulting surfaces were highly textured and not significantly contaminated. Contaminants and UV-degraded FEP were removed by the AO-induced surface erosion. The trailing-edge samples had a wide variety of surface morphologies, and extensive contamination was present. The chemical structure of the FEP that remained on leading-edge blankets was essentially identical to ground control specimens. On trailing-edge surface areas where contamination was relatively low (particularly at larger angles to the trailing edge), degraded FEP, caused by UV exposure, was detected using XPS measurements. This degradation appears to result from damage to the carbon backbone of the Teflon polymer, resulting in molecular weight degradation, new chain terminations, branching, and crosslinking through free-radical reactions. The UV degradation could have occurred at a relatively constant rate during the entire mission. Any increases in the rate would have occurred toward the end of the mission as the increased solar activity produced more energy in the VUV. Teflon erosion occurred more rapidly near the end of the mission as the altitude dropped and the atomic oxygen flux rapidly increased.

The problem of delamination of Ag/FEP thermal control material at the metal/polymer interface must still be addressed. This interface strength may degrade during Earth storage of Ag/FEP, and deterioration was accelerated in the space environment. Delamination of the Ag/FEP has the potential for catastrophic failure of the material's thermal control properties when unsupported; this was deterred on the LDEF blankets by the presence of the paint on the back surfaces. There is also interest in the effects of adhesive bonding on Ag/FEP performance. Discoloration and streaking was observed at the metal/polymer interface of adhesively bonded Ag/FEP on LDEF, with some degradation of thermal control properties. This was due to diffusion of adhesive components through cracks in the metallization layer, which were caused by improper application and/or handling.

Ag/FEP has demonstrated good performance over long-term exposures in selected environments. For a given design, the acceptability of metallized Teflon, either silver or aluminum, will depend on assessing degradation due to the charged-particle or atomic-oxygen environment expected for the planned orbit and lifetime.

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TECHNOLOGY OPERATIONS

The Aerospace Corporation functions as an "architect-engineer" for national security programs, specializing in advanced military space systems. The Corporation's Technology Operations supports the effective and timely development and operation of national security systems through scientific research and the application of advanced technology. Vital to the success of the Corporation is the technical staff's wide-ranging expertise and its ability to stay abreast of new technological developments and program support issues associated with rapidly evolving space systems. Contributing capabilities are provided by these individual Technology Centers:

Electronics Technology Center: Microelectronics, solid-state device physics, VLSI reliability, compound semiconductors, radiation hardening, data storage technologies, infrared detector devices and testing; electro-optics, quantum electronics, solid-state lasers, optical propagation and communications; cw and pulsed chemical laser development, optical resonators, beam control, atmospheric propagation, and laser effects and countermeasures; atomic frequency standards, applied laser spectroscopy, laser chemistry, laser optoelectronics, phase conjugation and coherent imaging, solar cell physics, battery electrochemistry, battery testing and evaluation.

Mechanics and Materials Technology Center: Evaluation and characterization of new materials: metals, alloys, ceramics, polymers and their composites, and new forms of carbon; development and analysis of thin films and deposition techniques; nondestructive evaluation, component failure analysis and reliability; fracture mechanics and stress corrosion; development and evaluation of hardened components; analysis and evaluation of materials at cryogenic and elevated temperatures; launch vehicle and reentry fluid mechanics, heat transfer and flight dynamics; chemical and electric propulsion; spacecraft structural mechanics, spacecraft survivability and vulnerability assessment; contamination, thermal and structural control; high temperature thermomechanics, gas kinetics and radiation; lubrication and surface phenomena.

Space and Environment Technology Center: Magnetospheric, auroral and cosmic ray physics, wave-particle interactions, magnetospheric plasma waves; atmospheric and ionospheric physics, density and composition of the upper atmosphere, remote sensing using atmospheric radiation; solar physics, infrared astronomy, infrared signature analysis; effects of solar activity, magnetic storms and nuclear explosions on the earth's atmosphere, ionosphere and magnetosphere; effects of electromagnetic and particulate radiations on space systems; space instrumentation; propellant chemistry, chemical dynamics, environmental chemistry, trace detection; atmospheric chemical reactions, atmospheric optics, light scattering, state-specific chemical reactions and radiative signatures of missile plumes, and sensor out-of-field-of-view rejection.