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Environmental Durability Issues for Solar Power Systems in Low Earth Orbit

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Prepared for the
1995 International Solar Energy Conference
cosponsored by ASME, JSME, and JSES
Lahaina, Maui, Hawaii, March 19-24, 1995



National Aeronautics and
Space Administration

N95-15769

Unclas

G3/20 0031439

(NASA-TM-106775) ENVIRONMENTAL
DURABILITY ISSUES FOR SOLAR POWER
SYSTEMS IN LOW EARTH ORBIT (NASA.
Lewis Research Center) 14 p

ENVIRONMENTAL DURABILITY ISSUES FOR SOLAR POWER SYSTEMS IN LOW EARTH ORBIT

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ABSTRACT

Space solar power systems for use in the low Earth orbit (LEO) environment experience a variety of harsh environmental conditions. Materials used for solar power generation in LEO need to be durable to environmental threats such as atomic oxygen, ultraviolet (UV) radiation, thermal cycling, and micrometeoroid and debris impact. Another threat to LEO solar power performance is due to contamination from other spacecraft components. This paper gives an overview of these LEO environmental issues as they relate to space solar power system materials. Issues addressed include atomic oxygen erosion of organic materials, atomic oxygen undercutting of protective coatings, UV darkening of ceramics, UV embrittlement of Teflon, effects of thermal cycling on organic composites, and contamination due to silicone and organic materials. Specific examples of samples from the Long Duration Exposure Facility (LDEF) and materials returned from the first servicing mission of the Hubble Space Telescope (HST) are presented. Issues concerning ground laboratory facilities which simulate the LEO environment are discussed along with ground-to-space correlation issues.

INTRODUCTION

Solar power systems in LEO will encounter a variety of harsh environmental conditions including atomic oxygen, UV radiation, thermal cycling, micrometeoroid and debris impact, and self-contamination. Each of these can adversely affect space power system performance. Combined environmental interactions can be even more detrimental. It is therefore crucial to understand the effects of the space environment on materials when designing LEO solar power systems.

Materials retrieved from LDEF (5.8 years in LEO) and components from the recently serviced HST (3.6 years in LEO) provide a valuable source of long term in-space exposure information. LDEF

was unique in that it was a long-term materials experiment, and it orbited in a fixed orientation with respect to its velocity direction. The fixed orbital direction resulted in different atomic oxygen to UV fluence ratios on the leading and trailing edges. The leading edge received a high atomic oxygen fluence (9×10^{21} atoms/cm²) and the trailing edge a very low atomic oxygen fluence (3×10^3 atoms/cm²) (Stein, 1992). The leading and trailing edges received similar UV radiation exposures (11,156 equivalent sun hours (ESH) and 11,110 ESH, respectively) (Bourassa and Gillis, 1992). This unique situation allows the evaluation of different LEO environmental effects, particularly comparisons of UV versus combined UV/atomic oxygen effects. The HST returned materials received varying magnitudes of UV exposure. These surfaces also received relatively low atomic oxygen fluences (an estimated average of $\approx 2.4 \times 10^{20}$ atoms/cm² for the constantly rotating surfaces). This low fluence is due to HST's higher orbit (≈ 570 km) compared to LDEF (≈ 480 decayed to ≈ 330 km). For example, returned HST magnetometer multilayer insulation (MLI) surfaces had UV exposures varying from $\approx 4,480$ ESH to $\approx 11,340$ ESH (Hitch, 1994). Short in-space exposure experiments on the Shuttle have also been conducted. This paper gives an overview of LEO environmental issues as they relate to solar power system materials durability, and provides examples of environmental interactions with materials retrieved from LDEF and HST.

ATOMIC OXYGEN

Atomic oxygen is formed when UV radiation (< 243 nm) from the Sun photodissociates molecular oxygen in the upper atmosphere (Banks, Mirtich et al., 1990). In LEO these neutral oxygen atoms have mean free paths on the order of 10^4 m, resulting in extremely low probabilities of reassociation. Atomic oxygen is the predominant species in LEO (below $\approx 1,000$ km) (U.S. Standard Atmosphere, 1976). As a spacecraft travels in its orbit (with a velocity on the

order of 7.7 km/sec) it rams into the atomic oxygen (hence the term ram atomic oxygen). The flux of atomic oxygen at Space Station altitudes is approximately 3.6×10^{14} atoms/cm² sec for normal incident ram surfaces and 9.1×10^{13} atoms/cm² sec for solar facing (sweeping ram) surfaces. A number of processes can take place when an oxygen atom strikes a spacecraft surface at orbital velocities. These include: chemical reaction with surface atoms or adsorbed molecules; thermal accommodation; or recombination, or excitation of ram species (Gregory, 1987). Atomic oxygen impacting spacecraft materials at ram velocities has an average energy of 4.5 eV (Banks, Rutledge et al., 1990) and reacts with and degrades susceptible materials such as organic substances, certain metals and oxides. Chemical reactions are believed to be responsible for most ram atomic oxygen erosion (Coulter, 1986).

The high flux of atomic oxygen impacting spacecraft surfaces in LEO and the high probabilities of reaction (for example, ≈ 0.14 for polyimide Kapton) (Banks, Rutledge et al., 1990) result in oxidation rates which can be unacceptable for high fluence missions. Several thin polymer materials and several plies of composite materials located on the leading edge of LDEF were completely eroded away during the 5.8 years in LEO (Stein and Pippin, 1991). Figure 1 shows a fluoropolymer (polychlorotrifluoroethylene) which was exposed to near normal incidence ram atomic oxygen on LDEF. This sample developed a cone-like morphology which is characteristic of directed atomic oxygen erosion. All materials which produce exclusively volatile oxidation products appear to develop such cones. Similar surface morphologies develop in ground based atomic oxygen beam facilities if the arrival direction is fixed.

Atomic oxygen protective coatings can be effective in preventing atomic oxygen erosion. The coatings must be nonreactive to atomic oxygen and serve as a barrier with minimal pinhole and scratch defects (areas where there is no coating protecting the underlying material). Typically, films consisting of metal oxides, fluoropolymer-filled metal oxides, or elemental metals which develop nonvolatile protective oxides are used for atomic oxygen protective coatings. For example, SiO_x ($1.9 < x < 2.0$) sputter deposited films (1300 Å thick) have been selected for protection of Kapton solar array (SA) blankets for Space Station. Although such

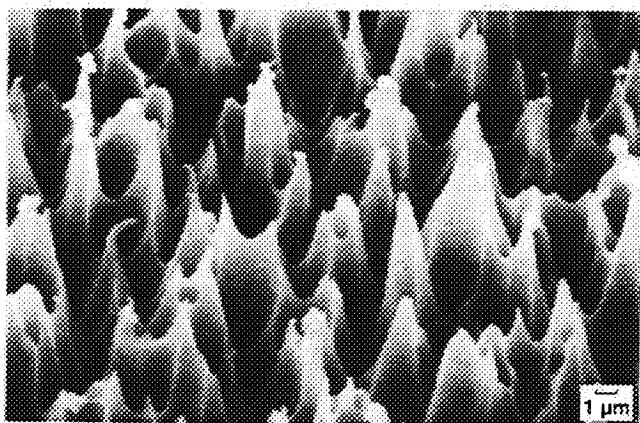


Figure 1.—This fluoropolymer which was located on the leading edge of LDEF shows the recession morphology which is typical of directed ram atomic oxygen erosion.

coatings themselves are durable to atomic oxygen, pinhole and scratch defects allow atomic oxygen to oxidize the underlying polymer near the defect site resulting in atomic oxygen undercutting. Such defects occur as a result of microscopic irregularities in the surface, contaminant particles on the surface, and handling or processing scratches. Defect densities ranging from 200 to 1,000 defects per cm² are typical for 1300 Å thick SiO_x coated Kapton-H (Rutledge and Olle, 1993). Even with these defect densities, thermal energy plasma asher ground laboratory tests have indicated that the use of such protective coatings reduces the oxidation rate of the underlying material by 2 orders of magnitude and the SiO_x coated Kapton is predicted to be durable for 15 years on Space Station (Rutledge and Olle, 1993). Thermal energy plasma ashers are used as a low cost source of high flux atomic oxygen. The asher generates an oxygen atom containing plasma by exciting ambient air with 100 W of continuous RF power at 13.56 MHz.

Figure 2(a) is an electron micrograph of microscopic cracks in an aluminized-Kapton sample which was exposed to near normal incident ram atomic oxygen on the leading edge of LDEF. The same sample area is imaged in figure 2(b) with the Al chemically removed. The exposure to $\approx 6 \times 10^{21}$ atoms/cm² resulted in undercutting oxidation of the Kapton which is far wider than the width of the initial crack defects. Atomic oxygen undercutting with normal incidence ram attack can occur because there are atomic oxygen velocity components which are transverse to the ram direction. These transverse components are due to thermal velocity, orbital inclination, and scattering contributions (de Groh and Banks, 1991). Severe undercutting can threaten the structural stability of thin materials such as Kapton SA blankets. This is why extensive research efforts and fabrication improvements have been made which have resulted in the decrease of SA blanket protective coating defect densities to levels which make the blankets durable for 15 years in space (Rutledge and Olle, 1993). Atomic oxygen undercutting can also cause changes in optical properties. This has been observed in ground test durability evaluations of solar concentrators (de Groh and Banks, 1991). Use of a leveling coating on graphite epoxy solar concentrator surfaces under reflective and protective coatings can decrease the number of protective coating defects and greatly improve atomic oxygen durability (Jaworske et al., 1994).

Atomic oxygen interaction with silicones differs greatly from that with organic polymers. The reaction of atomic oxygen with most silicones results in the oxidation of methyl groups with an associated weight loss and shrinkage of the exposed surface. At the same time, there is a gradual conversion of SiO radicals to SiO₂ on these silicone surfaces which adds to the mass of the surface. The net result is that relatively little change in weight occurs for atomic oxygen exposed silicones, and silicone surfaces typically convert to silica and craze as a result of shrinkage due to the removal of the methyl groups. Because of the small weight change, silicones were considered to be atomic oxygen durable compared to other polymers which can be oxidatively eroded away. Figure 3 is an optical micrograph of a silicone (DC 93-500) prior to, and after, exposure to LEO atomic oxygen on the Environmental Oxygen Interaction with Materials III (EOIM-III) shuttle experiment. This sample was exposed to a ram atomic oxygen fluence of $\approx 2.3 \times 10^{20}$ atoms/cm², and shows surface crazing as it converts to silica with atomic oxygen

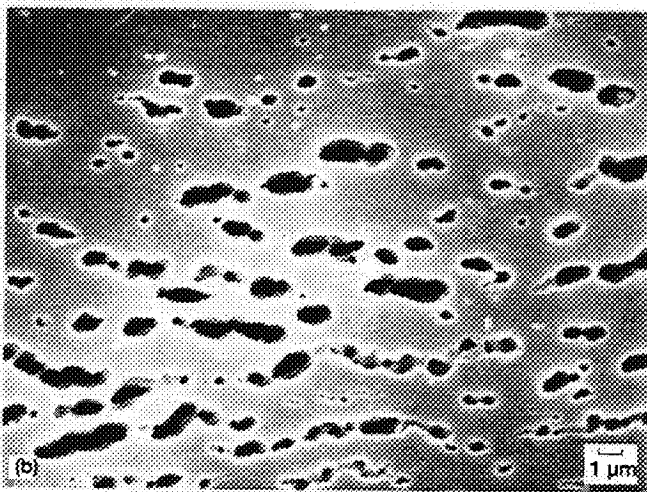
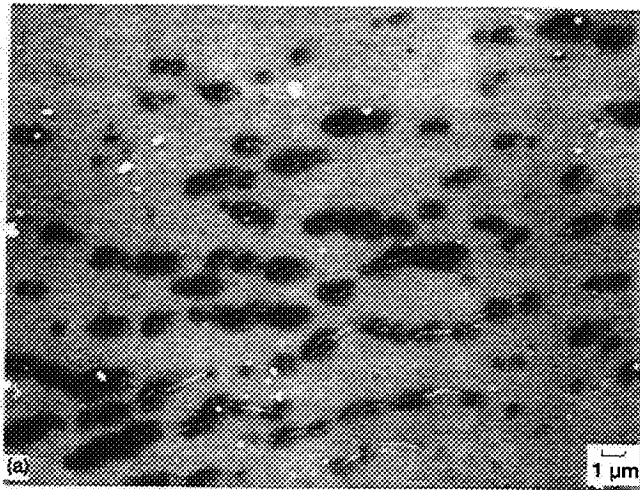


Figure 2.—Aluminized-Kapton from the leading edge of LDEF showing atomic oxygen undercutting at microscopic cracks in the Al. (a) Cracks in the Al coating. (b) Undercut voids in Kapton visible after chemical removal of the Al.

exposure. Silicones have been used as protective coatings. For example, silicone was used to protect organic bicycle reflectors on LDEF. This silicone, along with other silicones on the leading edge of LDEF, were found to craze and allow erosion of organic material at crack sites (Banks, Dever et al., 1991). Crazing of silicones and conversion to silica can be simulated in atomic oxygen ground facilities with both thermal energy plasma asher and beam facilities.

In-space atomic oxygen durability predictions based on ground tests are crucial to allow low cost materials selection decisions to be made in a timely manner. But, accurate predictions of in-space durability based on ground testing is complicated due to differences between ground laboratory and LEO atomic oxygen environments. These differences include oxygen species, energy, arrival direction, temperature and flux. Facility calibration requires the establishment of a correlation between the ground and in-space environments. High fluence atomic oxygen durabilities of unprotected

materials can be assessed in ground facilities by calibrating with witness samples of similar chemistry having known in-space erosion yields. Because the erosion yield of polyimide Kapton-H in space is well documented (3×10^{-24} cm³/atom) (Knotz et al., 1991), Kapton is often used as a calibration witness with unknown materials.

The prediction of in-space durability of protected organic materials has proven to be difficult due to the lack of information concerning the rate of in-space undercutting oxidation at defect sites in protective coatings. Although undercutting oxidation is well-characterized in thermal energy plasma asher systems, the rate of undercutting oxidation is greatly reduced in LEO where 4.5 eV atomic oxygen impinges upon protected materials. This is due to differences in the quantities of atoms necessary to produce equivalent surface erosion of unprotected materials in space and in thermal energy plasma ashers. The ratio of durability in-space to that

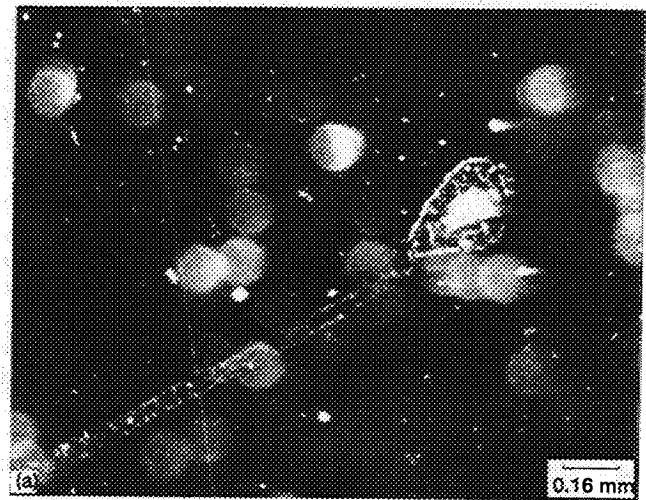


Figure 3.—DC 93-500 silicone exposed to atomic oxygen on the EOIM-III shuttle experiment. (a) Preflight. (b) Postflight showing silicone to silica conversion crazing.

in thermal energy plasma systems can be predicted using Monte Carlo computational modeling of atomic oxygen undercutting oxidation. Such computational modeling allows prediction of the shape and rate of undercutting oxidation. Current predictions indicate that in-space durability of protected materials may be 20 times that predicted by thermal energy plasma asher results (Banks et al., 1992). Accurate correlation between thermal energy plasma exposure and in-space durability will be achievable through improved modeling of currently known in-space results such as from LDEF, and additional high fluence in-space durability evaluation coupled with ground laboratory evaluation of identical protected materials. Such space experiments to improve the accuracy of the modeling are currently under study as part of the NASA In-Space Technology Experiments program.

ULTRAVIOLET RADIATION

Ultraviolet radiation is typically defined as electromagnetic radiation of wavelengths between approximately 10 and 400 nm. UV radiation is further divided into regions called near, far and extreme UV, consisting of wavelengths between 400 and 300 nm, 300 and 200 nm, and 200 and 10 nm, respectively (Koller, 1965). Because the extreme UV is strongly absorbed by air, it propagates only in vacuum and therefore this region is also called vacuum ultraviolet (VUV). In the LEO environment approximately 10% of the solar constant (139.6 mW/cm^2) is in the UV region, and only about 0.1 percent is in the UV which is shorter than 200 nm (Koller, 1965).

Absorption of ultraviolet radiation by an organic molecule raises the molecule to an excited state. If the energy of the absorbed photon is equal to or greater than the binding energy of the molecule, bond breaking can occur. For absorbed photons with energies lower than the binding energy of the molecule, the energy of the photon will be re-emitted in the form of fluorescence, dissipated in the form of heat, or transferred as electronic energy from one functional group on a molecule to another (Slomp, 1988; Dever, 1991). Initiation of a chemical reaction by UV radiation can lead to degradation of polymer properties such as adhesion, color, flexibility, hardness, and toughness (Koller, 1965).

In the case of polymers, UV radiation can induce crosslinking as a result of bond dissociation. Crosslinking will change the properties of polymers and can result in embrittlement and surface crazing. For example, the tensile strength of Mylar has been shown to degrade with UV exposure (Slomp, 1988). The mechanical properties of other polymers such as Fluorinated Ethylene Propylene (FEP) Teflon and polyethylene located on LDEF were also found to be negatively affected by solar UV (Stein, 1992). Some polymer materials however, such as polyimide Kapton, are UV durable due in part to the strengths of both the imide and aromatic ring bonding structures.

During the first HST servicing mission the astronauts returned to Earth with one of the solar arrays and a few other materials. Some of these materials are being evaluated for environmental durability by Goddard with the help of the Electro-Physics Branch at Lewis. These materials include aluminized-Teflon MLI from the magne-

tometers and aluminized-Teflon MLI from the solar array drive arm. Aluminized or silvered FEP Teflon second surface mirrors are commonly used to insulate spacecraft. The aluminized-Teflon outer layer from both the magnetometers and solar array drive arm were found to be embrittled on solar facing surfaces. Figure 4(a) for example, shows a section of MLI surface which is severely cracked after 3.5 years in LEO. This section of magnetometer MLI received the highest UV exposure (11,340 ESH). Cracking may have been induced when the UV embrittled pieces were peeled off the magnetometer boxes by the astronauts (the MLI was attached by Velcro). Figure 4(b) shows a crack extending from a vent hole in the Teflon MLI from the solar array drive arm. The crack extends all the way through the Teflon layer indicating embrittlement through the depth of the film (believed to be 0.13 mm thick). Both the magnetometer and solar array drive arm MLI had surfaces which received lower levels of UV radiation. Surface cracking has not been observed on the low UV exposure sides of the magnetometer MLI (4,480 ESH)

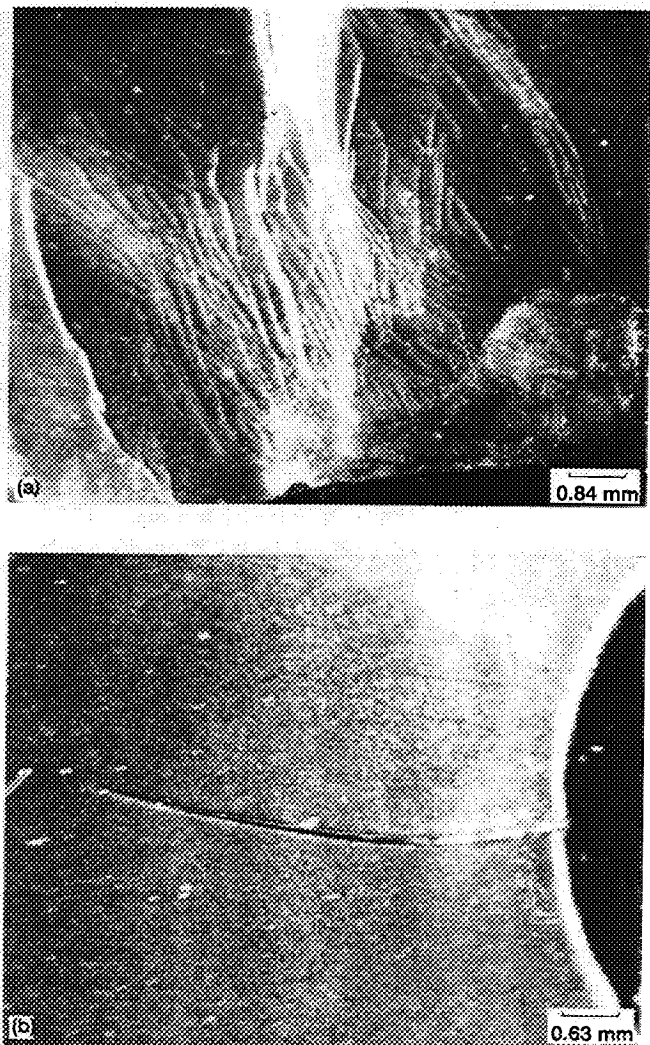


Figure 4.—Embrittled FEP Teflon after 3.6 years in LEO on HST. (a) Magnetometer MLI. (b) Solar array drive arm MLI.

or solar array drive arm MLI. Ground tests performed by Lewis on the VUV/atomic oxygen durability of aluminized-Teflon for use as thermal shield material on HST (to shield the solar array bi-stem booms) did not predict the extent of embrittlement witnessed in the HST environment. The analysis of the returned materials will be used to modify ground-to-space correlations to improve the reliability of long term durability predictions based on ground tests.

Teflon embrittlement was also observed on the trailing edge, or wake side, of LDEF. Although the Teflon was not found to be crazed like the HST Teflon, surface cracks were induced when the Teflon was cut (Brinza, et al. 1991). Teflon on the leading edge of LDEF did not appear embrittled (Brinza et al., 1991). This is because the atomic oxygen fluence was high enough to remove the embrittled layer. The ratio of atomic oxygen fluence to UV ESH for the leading edge of LDEF was 8×10^{17} atoms/(cm²-ESH). The estimated HST thermal shield five year ratio of atomic oxygen fluence to UV ESH ratio is $\approx 4 \times 10^{15}$ atoms/(cm²-ESH). Teflon from the Solar Maximum Mission's retrieved attitude control system which received a high exposure of UV was found to be brittle also (Liang, et al. 1985). Other factors which affect the degree of embrittlement besides the UV ESH and atomic oxygen fluence, are temperature differences in the materials, the number of thermal cycles, and high energy electron or proton radiation.

Another type of UV radiation damage is solarization of glasses (Koller, 1965). Ultraviolet radiation induces a photochemical reaction that causes a decrease in ultraviolet transmittance and color changes. Radiation induced loss of transmittance has been attributed to color center formation, discoloration due to valence changes in chemical constituents, or opacification from devitrification (to cause crystallization) (Firestone and Harada, 1979). The darkening of glass materials due to UV radiation exposure is well documented (Firestone and Harada, 1979; Marsik et al., 1978; Weaver, 1965). An example of a solarization reaction which causes clear glass to discolor is the UV induced oxidation of manganese ion from Mn²⁺ (weakly colored) to Mn³⁺ (pink) (Koller, 1965). Some glass types, however, prove very resistant to UV radiation. Ceria doped glass is often used as a cover slide for photovoltaic solar cells because of its resistance to UV darkening (Rauschenbach, 1980). The following ranking of resistance to radiation damage has been determined: excellent resistance - sapphire (alumina), good resistance - fused silica, fair resistance - optical glass, and poor resistance ultra low expansion glass (Firestone and Harada, 1979).

Figure 5 shows spectral changes which were induced in a solar concentrator sample when exposed to 1000 SH of VUV radiation (de Groh et al., 1992). This sample was durability tested for solar dynamic power applications for Space Station. The concentrator sample was composed of graphite epoxy face and back sheets bonded to an aluminum honeycomb core. The reflective surface had 200 Å of Cu for adhesion to the graphite epoxy and for UV blockage, 1000 Å of Ag for reflectance, and the outer surface had two transparent atomic oxygen durable coatings, SiO₂ (700 Å) on top of Al₂O₃ (200 Å). The VUV induced spectral changes were attributed to UV darkening of the SiO₂ and/or Al₂O₃ layers due to color center formation, or due to the formation of AgO_x at the Al₂O₃/Ag interface upon Al-O bond breaking (de Groh et al., 1992). When the same type of concentrator sample was exposed to in-situ thermal cycling

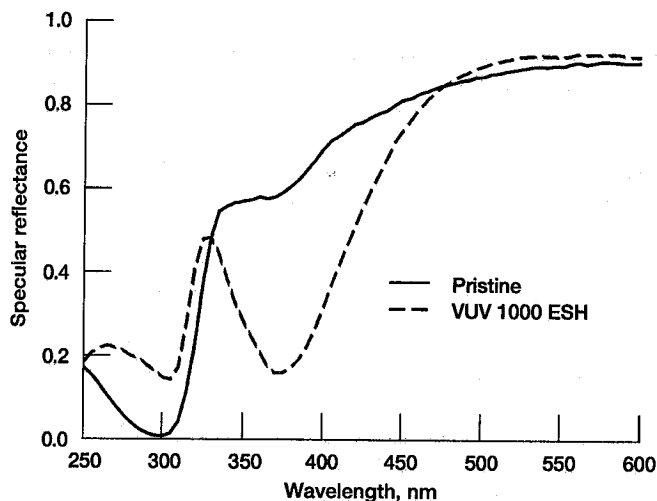


Figure 5.—Spectral changes in a solar concentrator sample due to 1000 ESH VUV radiation exposure.

with VUV exposure, the amount of spectral damage was found to be less. Koller states that the process of solarization can be reversed by heat treatment (Koller, 1965). White paint thermal control materials are also very vulnerable to UV degradation. These materials need to maintain their optical properties such as a low solar absorptance. Darkening due to UV radiation exposure can dramatically affect the temperature of the spacecraft system being thermally controlled. Exposure of certain white paints to UV radiation in vacuum can degrade the reflectance and cause UV darkening which increases the solar absorptance (Slemp, 1988). When some of these materials are then exposed to an oxygen environment, the oxygen “bleaches” the UV darkened surface and the UV degradation is reversed. This complicates the evaluation of optical property degradation of UV exposed samples when optical property measurements are taken in air. This is why NASA Lewis has incorporated an in-situ reflectance measurement system in their atomic oxygen beam/VUV radiation vacuum facility (Stidham et al., 1993). The solar radiation durability of white paints varies with chemistry. For example, various formulations of S13G/LO, comprised of potassium silicate encapsulated zinc oxide pigment in a methyl silicone binder, showed significant degradation upon exposure to 1000 ESH VUV which did not bleach when exposed to air. In contrast, Z-93 and YB-71, comprised of zinc oxide and zinc orthotitanate pigment, respectively, in a potassium silicate binder, exposed to the same VUV environment and measured in air showed minimal changes in solar absorptance (Dever et al., 1991). Z-93-P (very similar to Z-93) has been atomic oxygen and UV durability evaluated and has been chosen for radiator thermal control material for Space Station.

Ultraviolet radiation testing of sensitive spacecraft materials needs to be conducted to evaluate the long term UV durability in space. As previously mentioned, UV testing can be complicated due to bleaching effects in air. Another complication is that it is not easy to obtain a good correlation between the UV lamp spectra and the AM0 solar spectrum. A xenon short-arc lamp with a quartz envelope has a reasonable UV solar match from approximately 200

to 700 nm, but the intensity is much stronger in the infrared (IR) region (Slemp, 1988). Therefore, xenon lamps are often used in UV simulation facilities. Unfortunately, the intense IR can overheat the sample when accelerated tests are conducted. Therefore, acceleration factors of up to only 3X are recommended to avoid substantial overheating of the test samples (Slemp, 1988). Accelerated exposures can also potentially affect the damage mechanisms. Deuterium lamps can be used in vacuum to produce VUV radiation, but the spectra is not an exact match to the solar spectrum. This can make estimating ESH exposure very dependent upon the defined wavelength range of interest.

Synergistic effects of atomic oxygen and UV have been identified. One example is that the solar UV radiation was found to accelerate the atomic oxygen erosion of Teflon and possibly polystyrene and polymethacrylate (PMMA) on LDEF (Stein, 1992). Atomic oxygen in LEO can also interact with the reaction intermediates caused by UV induced bond dissociation. The resulting photo-oxidation processes can cause discoloration of some polymers (Dever, 1991). Another combined atomic oxygen/UV effect is atomic oxygen removal of UV darkened surfaces, such as was seen on LDEF (Golden, 1991). Figure 6 is a plot of the solar absorptance of a white thermal control paint (A276) as a function of row position on LDEF (Golden, 1991). The white paint samples on the trailing edge (row 3) and neighboring rows (1, 2, 4 and 5) which received low atomic oxygen fluences ($\leq 10^{17}$ atoms/cm²) have increased solar absorptance values due to UV darkening. The samples on the leading edge (row 9) and neighboring rows (7, 8, 10 and 11) received high atomic oxygen fluences ($\geq 10^{21}$ atoms/cm²) and have solar absorptance values near that of the control sample due to atomic oxygen erosion of the UV darkened surface (Golden, 1991).

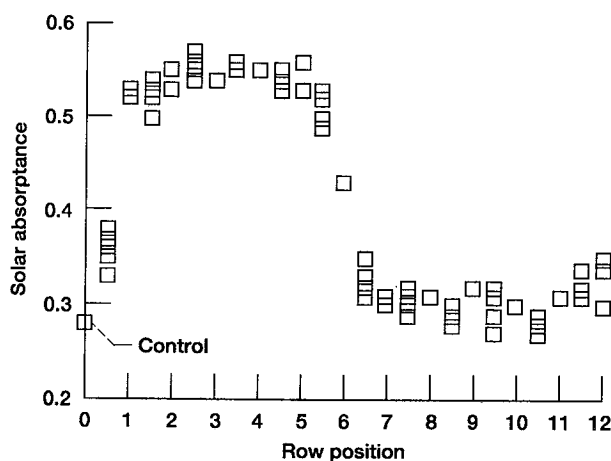


Figure 6.—Solar absorptance versus LDEF row, and their atomic oxygen fluence, for A276 white thermal control paint.(Golden, 1991)

THERMAL CYCLING

A vehicle in LEO orbits the Earth approximately every 90 min. During each orbit it undergoes a heating phase in the sunlight which is followed by a cooling period in the Earth's shadow. This cycle

creates a considerable temperature fluctuation that induces thermal stresses on the system components. Direct solar flux is the primary source for thermal radiation. Although some incident sunlight is reflected off the Earth's atmosphere (albedo), this occurrence does not significantly affect the thermal environment of a spacecraft in LEO. The amplitude of the temperature cycle depends on material properties such as emittance, absorptance, thermal conductivity, and specific heat.

The most recurrent defects that are induced by thermal cycling are microcracking of substrates or coatings, and delamination of coatings. Microcracking in an atomic oxygen protective coating exposes the underlying material to atomic oxygen, which could be damaging to the particular system. Figure 7 is a backscattered electron micrograph image of coated graphite epoxy which was located on the leading edge of LDEF. This backscattered electron image shows thermal cycle induced microcracks. These cracks became pathways for atomic oxygen attack of the underlying graphite epoxy. Relatively large undercut areas were observed at the crack sites.

The temperature variations induced during thermal cycling pose a particular threat to coated surfaces if the coating and substrate have substantially different coefficients of thermal expansion (CTE) and delamination occurs (Brady and Banks, 1990). Delamination of coatings can pose a host of problems depending on the coating purpose, but examples include particulate production, environmental degradation of the underlying material, and excessive system heating. Figure 8 shows an example of coating failure due to thermal cycling. This is a SiO₂ coated (14,000 Å) FEP Teflon sample which was tested as a potential material for the HST thermal shields. This material, as well as a multilayer metal oxide coated Teflon material, was found to fail by delamination and spalling of the glass coating with rapid thermal cycling exposure. The production of thousands of small pieces of glass in the HST environment would have been disastrous. These coated materials were eliminated as potential thermal shield materials due to their poor performance under thermal cycling exposure.

Rapid thermal cycling testing of solar array blanket coupons for potential use on the Space Station was conducted by the Photovoltaic Branch at Lewis (Scheiman and Smith, 1991). The tests

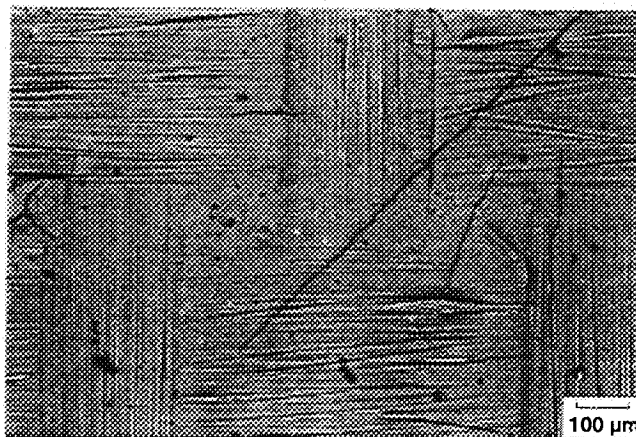


Figure 7.—Backscattered electron micrograph showing thermal cycle induced microcracks in an Al/Cr coated graphite epoxy sample which was located on the leading edge of LDEF.

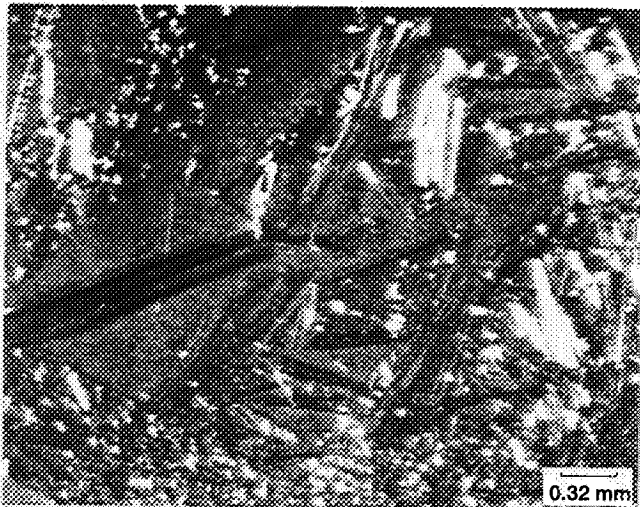


Figure 8.—Severe coating delamination and spalling failure attributed to thermal cycling. This SiO₂ coated Teflon sample was eliminated as a potential HST thermal shield material due to the thermal cycling induced failure.

were conducted to evaluate structural fatigue of welded interconnects and panel components with prolonged exposure to thermal cycling. After completion of up to 172 000 cycles in a ground test facility (−180 °C to +120 °C) the samples showed only a slight decrease in performance (a decrease of maximum 6 percent). The performance degradation was primarily due to a thermal stress induced rippling effect which caused fatigue cracks in the copper circuitry as well as an increase in series resistance of the solar cells and interconnects (Scheidt and Smith, 1991).

Metal matrix composites (MMC) such as graphite/Mg or graphite/Al exhibit thermal strain hysteresis and residual strain during thermal cycling (Potter, 1988; Le and Steckel, 1992). Both of these effects could compromise structural stability in the space environment. Analysis of LDEF post-flight samples, however, indicate that extensive thermal cycling causes strain hardening in the matrix which actually stabilizes the behavior of MMC's and decreases the magnitude of hysteresis. Graphite/Al composites have proven to be remarkably stable (Le and Steckel, 1992).

A synergistic effect is believed to be caused by the interaction of thermal cycling (and the corresponding temperature limits) with UV radiation such as an increased embrittlement of polymers. This is attributed to the decreased residence time of free radicals on the damaged surface with increasing temperature. Temperature is also known to affect the atomic oxygen reaction rate of materials (Gregory, 1986), and also plays a role in contamination residence.

MICROMETEORIODS AND DEBRIS

The presence of micrometeoroids and debris (M&D) particles in the LEO environment is a potential hazard to solar power systems. While micrometeoroids are of natural origin, space debris is man-made. Debris particles include remnants of collided or exploded spacecrafts, wastes, and refuse from abandoned operations such as

nonfunctional satellites. Micrometeoroids and debris fragments impact spacecrafts with high velocity and energy, causing surface cratering or penetrations. The particles themselves actually vaporize upon impact which makes it difficult to determine their origin through chemical analysis. Often, however, there is enough residual material in the impact craters to obtain an elemental breakdown. Elements such as Fe, Mg, Si, S and Ca are characteristic of natural impacters; Al, Ti, Zn, and Cu are typical for man-made artifacts (Mandeville, 1992; Simon et al., 1992). The average velocity for debris particles ranges from 10 to 13 km/sec and is about 19 km/sec for micrometeoroids (Meshishnek et al., 1992). Although various materials naturally respond somewhat differently to high-velocity impacts, the damage at a typical collision site is highly localized and does not extend beyond the immediate area of the impact.

Impacts on uncoated metals result in localized surface cratering (Meshishnek et al., 1992; Mirtich et al., 1992; Stella, 1991). A crater is usually circular in shape with a raised rim extending above the surface and a central melt region. Typically impacts on coated metal surfaces (nickel-coated copper, or rhodium on aluminum for example) produce a similar cratering as impacts on uncoated metal surfaces. Occasional cracking and/or delamination of the coating is observed in the vicinity of the crater (Meshishnek et al., 1992; Mirtich et al., 1992). Glass and ceramics behave somewhat differently. The damage area on fused silica is mostly confined to the actual impact site. Some radial cracking may occur, the propagation, however, is limited (Meshishnek et al., 1992). An interesting feature of impacts on glass is the protrusion of glass fibers from the melt crater (Wiedlocher, 1992). The examination of six glass types (BK-7, Fused Silica, Soda-lime-silica, Pyrex, Vycor and Zerodur), which were flown on LDEF, revealed that a 69 month exposure to the M&D environment did not change the overall physical strength of the samples (Wiedlocher, 1992).

Impacts on organic composite materials, which are primarily composed of graphite epoxy, may cause breakage of the outer layers of the matrix, internal ply delamination and local fiber fractures (Meshishnek et al., 1992; Tennyson and Manuelpillai, 1992). Metallized and unmetallized polymeric films show typical crater characteristics or circular perforations upon impact. Perforations in protective coatings on organic substrates, such as aluminized-Kapton or protected graphite epoxy, increase the susceptibility of the substrate to atomic oxygen erosion (Meshishnek et al., 1992). Some more unusual responses to M&D impacts are blistering of surface coatings, splattering of ejected material into neighboring areas and extensive cracking in ceramics (Meshishnek et al., 1992).

Durability evaluations of polished metal reflector surfaces for potential use in solar dynamic systems show that typical M&D damage was sufficiently small so as to have virtually no overall effect on the specular reflectance of the samples and therefore would not have a significant effect on the performance of the system (a loss of less than 1 percent of specular reflectance) (Mirtich et al., 1988; Mirtich and Kerslake 1990). Data was obtained from three satellites that had been exposed to a M&D environment for up to 20 years (SERT II, OSO III and LDEF). The evaluated material was Al on stainless steel (Mirtich et al., 1988; Mirtich and Kerslake, 1990). However, this particular material is not very susceptible to deterioration caused by other environmental threats such as atomic oxygen or UV radiation. As previously mentioned, the formation

of cracks and openings in atomic oxygen or UV protective coatings increases the vulnerability of materials like graphite epoxy or polymeric materials to atomic oxygen erosion and UV radiation. Other potential synergistic interactions with impacts include facilitation of spacecraft charging effects and contamination due to vaporization (Potter, 1988). It is also observed that pre-impact exposure of a material to one of these environmental agents can trigger an amplified destructive response to a M&D impact.

Figures 9 and 10 demonstrate various responses to M&D impacts which have been intensified through further (or previous) exposure to other environmental agents. Figure 9 shows an impact on a silvered Teflon thermal control blanket (0.12 to 0.14 mm FEP Teflon on top of 1000 to 1500 Å Silver, 200 to 400 Å Inconel and, 0.05 to 0.076 mm Chemglaze Z 306, a polyurethane based paint) flown on LDEF. The impact created a microscopic explosion that caused delamination of the Teflon which allowed further degradation of the silver through oxidation. Optical micrographs in figure 10 depict the effect of pre-impact UV exposure on a MLI blanket. The MLI overlay was located on the HST solar array drive arm that had been exposed to the space environment for 3.6 years. Figure 10(a) shows an impact on the UV shaded side of the arm. The damage is localized and delamination is confined to an area of about 4X the size of the impact crater. Figure 10(b) shows an impact of the same magnitude on the UV exposed side. Extensive delamination (about 16X the size of the impact) has occurred. Variations in the velocities or size of these particles may have contributed to these differences also.

These findings indicate that typically the M&D climate is not detrimental to a system, but that it is the synergistic interactions with other deterioration factors which are potentially harmful. However, the number of M&D impacts which are large enough to promote interaction is exceptionally small. Pinhole defects or scratches

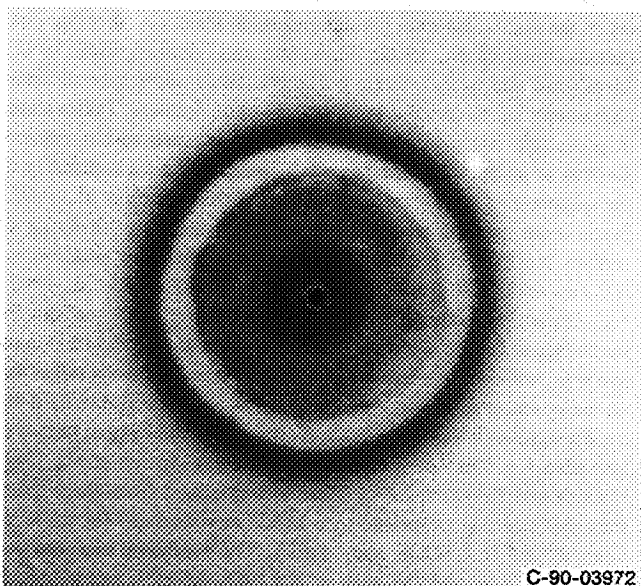


Figure 9.—Impact site from a LDEF silvered-Teflon sample. The impact caused delamination and subsequent oxidation of the Ag layer.

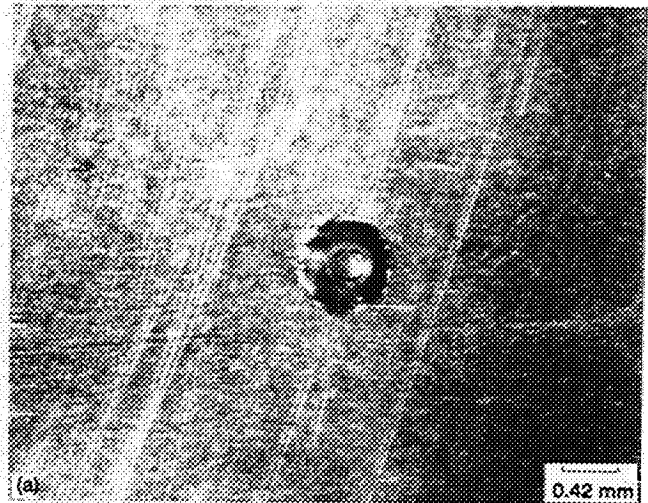


Figure 10.—Impact sites from HST solar array drive arm MLI. (a) Solar shaded side with very localized damage (4X impact crater). (b) Solar facing side with large delaminated damage site (16X impact crater).

in atomic oxygen protective coatings, that have been formed during fabrication and handling, are far more numerous and are a greater threat to the durability of solar power systems (Banks, Rutledge et al., 1991).

CONTAMINATION

LEO environment interaction induced contamination has become a serious threat to the performance of sensitive spacecraft systems. The major threat is degradation of optical surfaces. Thermal control materials can experience an increase in solar absorptance which can result in system over heating. Other sensitive power system optical surfaces include solar cell cover glass, and reflective or refractive solar concentrators.

The sources of contamination typically are outgas products of materials exposed to a vacuum environment, and fragment prod-

ucts from atomic oxygen and/or UV radiation interaction with materials. Contamination from non-outgassed sources such as thruster fires and water dumps is not discussed here. To reduce the threat of contamination from volatile outgas products, materials for use on spacecraft systems need to meet standard outgassing requirements. Materials are considered to be space flight qualified if they meet ASTM E 595 Standard Test Method for Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment. This test standard determines the volatile content of materials when exposed to a vacuum environment. The volatile condensable outgas products themselves can degrade spacecraft components as they deposit on sensitive components. Ultra-violet radiation and atomic oxygen fixing of these products further worsens the problem as the product often UV darkens as it is fixed to the surface. Although the ASTM E 595 standard test method identifies materials with unacceptable quantities of outgas products, it does not evaluate fragmented outgas products from additional LEO environmental interactions with atomic oxygen and UV radiation.

Because synergistic environmental interactions have not been considered when qualifying spacecraft materials, some materials have been deemed space flight worthy which pose serious LEO contamination threats. One of the primary sources of this type of contamination are silicones (used as lubricants, adhesives, coatings, etc. on spacecraft systems). Many silicones which meet the outgas requirements under ASTM E 595 have been found to cause serious contamination on spacecraft components and in ground-test facilities. As previously mentioned, silicone materials interact with atomic oxygen and eventually form a SiO_2 surface layer. This is why silicones were believed to be durable to atomic oxygen. During the process of silicone to silica conversion volatile outgas products can be formed which arrive on neighboring surfaces. If atomic oxygen is arriving at the surface which is also receiving a silicone contamination flux, then conversion of the silicones to silica can occur resulting in a nonvolatile contaminate which can gradually darken with UV exposure. LDEF was found to have this type of silicone contamination over most of its surfaces (Stein, 1992; Stein and Pipin, 1991). Figure 11 shows a close-up of a tray of materials which was 38° from the ram direction on LDEF on the Solar-Array Materials Passive experiment (Banks, Dever et al., 1991). The light colored samples (rectangular, square and tensile shaped) are silicones which were not properly outgassed and produced large quantities of contaminants on neighboring surfaces and samples. A shadowing effect can be seen to the right of each sample where the angled atomic oxygen attack turned the contaminant brown (there was very low fluence of atomic oxygen in the shadowed area) (Banks, Dever et al., 1991). Silicone contamination was also observed on materials returned from the Solar Maximum Mission spacecraft (Brinza et al., 1991).

Contaminating silicones are believed to be able to produce contamination products even after a surface SiO_2 has formed. ESCA depth profiling analysis of atomic oxygen plasma exposed silicone indicates that the SiO_2 conversion layer continues to thicken with atomic oxygen fluence (de Groh et al., 1992). In addition, surface crazing, which occurs during conversion to SiO_2 , appears to progress with increased atomic oxygen fluence, exposing fresh silicone (Whitaker et al., 1992). Both of these findings provide evidence

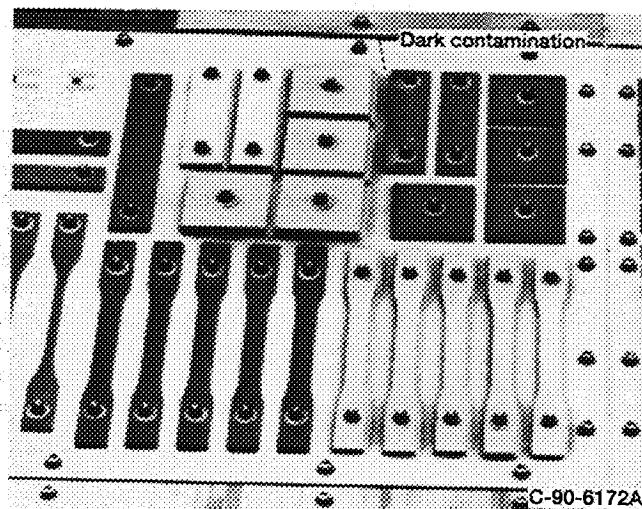


Figure 11.—Section of the LDEF Solar Array Materials Passive Experiment showing dark contamination to the right of light colored silicone samples.(Banks, Rutledge, et al. 1991)

that silicones can continue to be a source of contamination even after a surface SiO_2 layer has developed during atomic oxygen exposure.

Contamination, particularly silicone contamination, is observed in ground test facilities (carbon based contaminants would be oxidized by the atomic oxygen). If the rate of contaminant arrival is sufficiently high the Kapton fluence calibration witness samples can become partially or fully coated with a contaminant film, effecting calibration measurements. Figure 12 shows a Kapton calibration sample that has been completely coated with a thick oxidized silicone based contaminant layer during thermal energy plasma asher exposure. Care must be taken to eliminate unwanted sources of silicone during testing. The plasma ashers at Lewis are modified to remove silicone components (such as the silicone

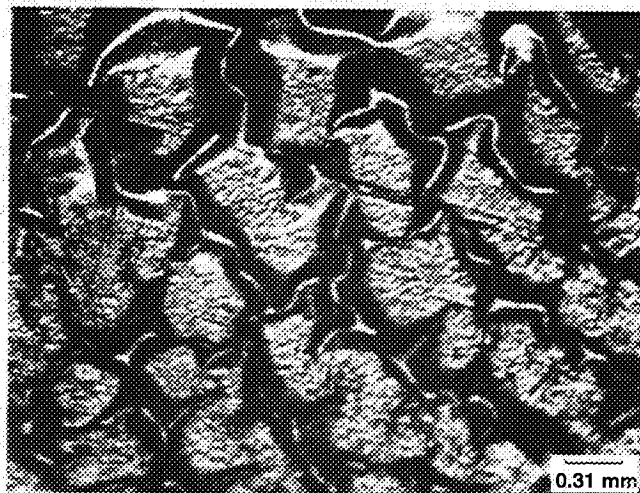


Figure 12.—Kapton calibration coupon covered with a thick silicone contamination film after thermal energy atomic oxygen plasma asher exposure.

containing rubber gasket which comes with the asher), and vaseline is used instead of silicone containing vacuum greases. Once an atomic oxygen facility gets contaminated, particularly plasma ashers, it is very difficult to clean it.

Molecular contamination was found all over LDEF, yet LDEF was still considered to be a clean spacecraft (Stein, 1992). Multiple internal and external sources of contamination were identified on LDEF (Stein and Pippen, 1992). Three general contaminant categories have been defined for the LDEF spacecraft. These are: carbon based films (from paint solvents, polymeric films and composite materials), silica or silicone based film (from adhesives, coatings, and paints) and particulates (from fibers, pollen, dust and degraded materials) (Stein, 1991). Heavy molecular contamination was found to have been line-of-site deposited (Stein and Pippen, 1991). The heaviest deposits were found on Solar UV sides. Carbon contaminating contaminants were found to be more prominent on the trailing edge of LDEF, while Si containing contaminants were more prominent on the leading edge of LDEF (Stein, 1992). This is partially due to atomic oxygen erosion of C contaminants from the leading edge. Results from LDEF contamination studies indicate that non-silicone materials and non-contaminating lubricants and polymers should be used on future spacecrafts (Stein, 1992).

CONCLUSIONS

Atomic oxygen can be very damaging to susceptible spacecraft materials. Organic materials which have volatile oxide products can be completely removed by high fluence atomic oxygen. Typically, thin film metal oxide coatings provide protection against atomic oxygen attack if the density of protective coating defects is sufficiently small. In-space atomic oxygen durability predictions based on ground tests are crucial for allowing low cost materials selection decisions to be made in a timely manner. However, accurate materials durability predictions are difficult to achieve due to differences in atomic oxygen environments (energy, species, temperature, arrival direction) between LEO and ground facilities. High fluence atomic oxygen in-space exposure tests are needed to determine reliable ground-to-space durability correlations.

Ultraviolet radiation can degrade materials through processes such as polymer embrittlement or UV darkening. A particular threat to space power materials is UV darkening of thermal control materials. Increased solar absorptance can dramatically affect the temperature of the spacecraft system being thermally controlled. Ground-based UV exposure testing is complicated by differences between UV lamp spectral intensity and the AM0 solar spectrum, by potential acceleration artifacts, and the bleaching phenomena some materials experience when brought to atmosphere.

Thermal cycling of space power materials can result in microcracking and delamination of coatings. Typically microcracking is not a serious structural threat, but cracking or delamination of coatings can cause a host of problems. Thermal cycling and the corresponding temperatures extremes can have significant synergistic effects with UV radiation, atomic oxygen and contamination.

Although various materials respond differently to M&D impacts, the damage at an impact site is usually highly localized, not extending significantly beyond the immediate area of the impact.

Therefore, the M&D climate is typically not functionally detrimental to a system, but synergistic interactions with other environmental threats (such as atomic oxygen attack at impact sites) can be potentially harmful.

Self-induced contamination is a threat to solar power optical and thermal control surfaces. Carbon and silicon based films are the main two contaminant film types. Based on LDEF results, carbon based films are typically more prominent on high UV/low atomic oxygen fluence surfaces, while silicon based films are more prominent on high UV/high atomic oxygen fluence surfaces. Self-induced contamination is a serious spacecraft materials durability problem. Unfortunately, current outgas contamination test methods do not account for crucial interactions of UV radiation and atomic oxygen during thermal vacuum testing.

Although there are many materials durability issues and concerns with respect to the LEO environment, numerous durable materials have been identified and used for solar power applications. The LEO environment is difficult to simulate, yet valid information on durability can be obtained with accurate ground to in-space calibration. Solar power materials need to be evaluated for environmental durability to ensure sustained system performance.

ACKNOWLEDGEMENT

The authors would like to thank Tom Zuby, of Unisys Government Systems Group, and the HST Program Office at Goddard Space Flight Center, for the unique opportunity to jointly evaluate the environmental durability of returned HST materials.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (<i>Leave blank</i>)	2. REPORT DATE November 1994	3. REPORT TYPE AND DATES COVERED Technical Memorandum	
4. TITLE AND SUBTITLE Environmental Durability Issues for Solar Power Systems in Low Earth Orbit		5. FUNDING NUMBERS WU-233-01-OE	
6. AUTHOR(S) Kim K. de Groh, Bruce A. Banks, and Daniela C. Smith		7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, D.C. 20546-0001		8. PERFORMING ORGANIZATION REPORT NUMBER E-9226	
11. SUPPLEMENTARY NOTES Prepared for the 1995 International Solar Energy Conference cosponsored by ASME, JSME, and JSES, Lahaina, Maui, Hawaii, March 19-24, 1995. Kim K. de Groh and Bruce A. Banks, NASA Lewis Research Center; Daniela C. Smith, Departments of Biology and Anthropology, Cleveland State University, Cleveland, Ohio 44115. Responsible person, Kim K. de Groh, organization code 5480, (216) 433-2297.		10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA TM-1067745	
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Categories 20 and 23		12b. DISTRIBUTION CODE	
13. ABSTRACT (<i>Maximum 200 words</i>) Space solar power systems for use in the low Earth orbit (LEO) environment experience a variety of harsh environmental conditions. Materials used for solar power generation in LEO need to be durable to environmental threats such as atomic oxygen, ultraviolet (UV) radiation, thermal cycling, and micrometeoroid and debris impact. Another threat to LEO solar power performance is due to contamination from other spacecraft components. This paper gives an overview of these LEO environmental issues as they relate to space solar power system materials. Issues addressed include atomic oxygen erosion of organic materials, atomic oxygen undercutting of protective coatings, UV darkening of ceramics, UV embrittlement of Teflon, effects of thermal cycling on organic composites, and contamination due to silicone and organic materials. Specific examples of samples from the Long Duration Exposure Facility (LDEF) and materials returned from the first servicing mission of the Hubble Space Telescope (HST) are presented. Issues concerning ground laboratory facilities which simulate the LEO environment are discussed along with ground-to-space correlation issues.			
14. SUBJECT TERMS Atomic oxygen; Ultraviolet radiation; Thermal cycling; Micrometeoroid and debris impacts; Contamination		15. NUMBER OF PAGES 15	
		16. PRICE CODE A03	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT