

LOW EARTH ORBIT ATOMIC OXYGEN SIMULATION FOR
DURABILITY EVALUATION OF SOLAR REFLECTOR SURFACES

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ABSTRACT

To evaluate the performance and durability of solar reflector surfaces in the atomic oxygen environment typical of low Earth orbit (LEO) one must expose the reflector surface either directly to LEO or to ground-laboratory atomic oxygen environments. Although actual LEO exposures are most desired, such opportunities are typically scarce, expensive, and of limited duration. As a result, ground-laboratory exposures must be relied upon as the most practical long-term durability evaluation technique. Plasma ashers are widely used as LEO simulation facilities by producing atomic oxygen environments for durability evaluation of potential spacecraft materials. Atomic oxygen arrival differs between ground and space exposure in that plasma asher exposure produces isotropic arrival and space solar tracking produces sweeping arrival. Differences in initial impact reaction probability occur, dependent upon the energy and species existing in these environments. Due to the variations in ground-laboratory and space atomic oxygen, quantification of in-space performance based on plasma asher testing is not straightforward. This paper addresses the various atomic oxygen interactions that can occur with reflector surfaces, such as undercutting in organic substrates at protective coating defect sites, ground-laboratory techniques recommended for evaluating the atomic oxygen durability of reflectors based on asher exposures, and computational techniques which make use of ground-laboratory atomic oxygen exposure to predict in-space LEO durability.

INTRODUCTION

Long term space exposure on the Long Duration Exposure Facility (LDEF), which orbited in the low Earth orbit environment for 5.8 years, provided evidence of environmental degradation of many potential spacecraft materials. Organic materials are particularly susceptible to erosive degradation in LEO. A number of polymer films up to 0.076 mm (0.003") thick located on the leading edge of LDEF were completely eroded, and approximately 1 ply (0.127 mm) of graphite epoxy composite was eroded (ref. 1). The ram atomic oxygen fluence for the leading edge of LDEF (8° yaw off-set) was 8.72×10^{21} atoms/cm² (ref. 2). Figure 1 shows the erosion morphology of a fluoro-polymer (polychlorotrifluoroethylene) which was located on the leading edge of LDEF (row 9). This cone-like morphology is typical of direct ram impact erosion of organic materials.

Atomic oxygen, formed through photodissociation of molecular oxygen by ultraviolet (UV) radiation having wavelengths less than 240 nm, is the predominant species in LEO (ref. 3). Spacecraft orbiting at altitudes of ≈400 km ram into these oxygen atoms with velocities on the order of ≈7,000 m/sec. At ram velocities the oxygen atoms have an average impact energy of 4.5 eV (ref. 4). These oxygen atoms have sufficient energy to break chemical bonds and oxidize many materials. In the case of organic materials, the oxidation product is often a volatile species (ref. 5). The use of thin film inorganic protective coatings has been found to protect underlying organic materials from atomic oxygen erosion. In general, metal oxides (i.e. SiO₂) and metals which form inherent protective oxide layers (i.e. Al) provide protection from atomic oxygen interaction.

To evaluate the performance and durability of potential spacecraft materials in the LEO atomic oxygen environment one must expose the material either directly to LEO (such as on LDEF or on the shuttle) or to ground-laboratory atomic oxygen environments. Although actual LEO exposures are most desired, such opportunities are typically scarce, expensive, and of limited duration (i.e. typical shuttle exposure duration is 40-80 hours, with atomic oxygen fluences generally $\leq 4 \times 10^{20}$ atoms/cm²). As a result, ground-laboratory exposures must be relied upon as the most practical evaluation technique.

This paper discusses various atomic oxygen interactions that can occur with solar reflector materials, ground-laboratory techniques recommended for evaluating atomic oxygen durability of solar reflectors using plasma ashers, and computational techniques which make use of ground-laboratory atomic oxygen exposure to predict in-space LEO durability.

ATOMIC OXYGEN UNDERCUTTING ON LDEF

Materials shielded from atomic oxygen by means of protective coatings are still vulnerable to atomic oxygen degradation due to undercutting oxidation (oxidation below the defect site that can exceed the original defect area) at protective coating defect sites. Undercutting can occur from sweeping ram atomic oxygen exposure if a spacecraft rotates with respect to its direction of travel. Undercutting can also occur if the spacecraft is oriented with a fixed direction of travel. There are three contributions to direct ram atomic oxygen undercutting: scattering of unreacted atomic oxygen (both from scattered energetic as well as thermally accommodated), angular distribution of incoming atomic oxygen flux due to thermal velocity contributions, and spacecraft orbital inclination with respect to the Earth's velocity vector (ref. 6). Scanning electron micrographs in figures 2 and 3 show atomic oxygen undercutting of a protected (400 Å Al/800 Å Cr) graphite epoxy composite coupon which was located on the leading edge of LDEF. A crack in the protective coating next to a larger circular defect is shown before and after removal of the protective coating in figures 2a and 2b. Figure 2c shows the profile of the undercut cavity at the crack site. This profile was obtained by tilting the sample at 45° and viewing through the large defect cavity. Figure 3a is an image of what appears to be a micrometeoroid or debris impact site that resulted in damage to the protective coating. Figure 3b shows the amount of undercut damage below the protective coating at this impact area. The integrity of the protective coating is important for providing protection. Figure 4 provides a view of a protective coating which did not remain intact on the leading edge of LDEF. Energy dispersive x-ray analysis indicates that the coating is Al₂O₃. The original film thickness is not known but it appears that the film was < 1000 Å. Significant undercutting may have contributed to the failure of this coating. Although atomic oxygen undercutting is expected to occur in LEO, direct ram atomic oxygen undercutting has not been documented prior to LDEF retrieval.

SOLAR REFLECTOR DURABILITY ISSUES

Solar reflector concentrators have been designed for use on Solar Dynamic Power Modules (SDPM) for delivery of additional electrical power for Space Station Freedom (SSF). In a SDPM, the solar concentrator reflects and focuses solar energy into the receiver of a heat engine. Various types of reflector compositions have been considered for solar concentrators for SSF and for advanced solar dynamic concepts. The solar concentrator designed and LEO durability tested for SSF was composed of a sandwich type structure with graphite epoxy face and back sheets bonded to an Al honey-comb core. A multi-layer reflective/protective system was designed for LEO durability. Silver was chosen as the reflective material. Silver will oxidize in the presence of atomic oxygen, therefore two atomic oxygen protective layers were deposited on top of the Ag, Al₂O₃ (also an adhesion promoting layer), followed by an outer coating of SiO₂. Figure 5 shows a sketch of a SDPM with a section view of the concentrator. For efficient operation of the SDPM, the solar concentrator must have and maintain a high solar specular reflectance in LEO. Maintaining a high solar specular reflectance is the critical atomic oxygen durability issue.

Other concentrator concepts have been considered either for SSF SDPM or for advanced solar dynamic systems with a variety of substrates including stainless steel, aluminum and glass. If an inorganic substrate such as Al or SiO₂ is used with a Ag reflective coating, Ag-oxide can expand out of the protective coating defect sites and a Ag-oxide "fluff" can develop (see figure 6)(ref. 7). Although undercutting is prevented in this case, the Ag-oxide can cause a decrease in the solar specular reflectance (ref. 7). If an organic material is used, such as graphite epoxy as the substrate for SDPM concentrators, then atomic oxygen undercutting can occur at protective coating defect sites. Decreases in solar specular reflectance due to atomic oxygen interactions with oxidizable reflectors result from oxidation of the reflecting material at defect sites, and undercutting and subsequent reflective material oxidation at defect sites. If the protective film tears when undercut, curling of the protective/reflective film will allow more atomic oxygen to enter the defect area and a catastrophic undercutting-tearing propagation process can occur. Figure 7 shows atomic oxygen undercutting, and tearing of the reflective and protective films in a graphite epoxy concentrator coupon after a Kapton based effective fluence of 3×10^{21} atoms/cm². The extent of the undercutting is visible as a

bright area around the defect sites. In this case the undercut regions of several defects have propagated into each other. Figure 8 is a micrograph of the adjoining undercut cavities of several defect sites where the reflective and protective films have flaked off due to lack of support from the volatilized substrate.

The use of a leveling layer on rough graphite epoxy substrates has been found to significantly reduce the number of protective coating defect sites. In the case of line of site deposition, if a rough substrate is being coated, areas in the shadow will not be coated. These sites are then vulnerable to atomic oxygen erosion. If a surface tension leveling layer is first applied to the graphite epoxy followed by reflective and protective coatings, the number of atomic oxygen defect sites has been found to be reduced by up to 2 orders of magnitude (ref. 8). In addition to decreased defect density, the specular reflectance may also be improved through the use of a leveling coating.

GROUND-LABORATORY ATOMIC OXYGEN

Radio frequency generated plasma ashers are widely used for LEO durability evaluation by producing an inexpensive, high flux atomic oxygen environment. The environment that plasma ashers produce when operated on air contains oxygen and nitrogen ions, atoms and molecules (ref. 10). Studies on Kapton have found that the nitrogen species have a negligible effect on the erosion processes (ref. 11). Ashers typically provide accelerated exposures with atomic oxygen effective fluxes (based on Kapton erosion) on the order of 10^{15} atoms/cm² sec as opposed to 10^{14} atoms/cm² sec at 400 km in LEO (ref. 9). The arrival of oxygen atoms on a surface differs between asher and space exposure in that plasma asher exposure produces isotropic arrival and space produces either direct ram arrival or sweeping arrival on solar tracking surfaces. In addition, differences in the initial impact reaction probability occur which are dependent upon the energy and species existing in these environments. The erosion yield of organic materials has been found to be dependent on the impact energy of the incident atomic oxygen. The erosion yield of Kapton was found to be proportional to the 0.68 power of the impact energy by Ferguson (ref. 12), and proportional to $e^{-0.38}/\text{Energy}$ by Koontz (ref. 13).

The average reaction probability upon first impact (at normal incidence) for direct space ram or sweeping space ram with Kapton is approximately 0.138 (ref. 4). The majority of unreacted atomic oxygen is believed to thermally accommodate and leave the surface with a cosine distribution. For plasma ashers, the reaction probability on first impact is thought not to be greater than 0.0054 (ref. 13). In both space and plasma environments the reaction probability for the second and subsequent impacts is approximately 0.00134 because the atoms have thermal energies (0.04 eV for 300 K) (ref. 13). Because of the higher initial impact reaction probability, direct ram exposure will produce a deeper undercut cavity than would be produced by the same actual fluence in an asher. In the asher, the cavity beneath a pin window defect will be shallower but wider. This is due to the high absolute fluences needed to produce effective fluences simulating space because of the low thermal energies. For solar facing systems which are exposed to sweeping ram arrival, the undercut cavity will be shallower and wider than direct ram impact, but not as shallow and wide as asher exposures. Because the atomic oxygen impact energies, reaction probabilities, and direction of arrival are different between plasma asher atomic oxygen exposure and space atomic oxygen exposure, one cannot directly extrapolate space predictions based on asher exposures. A Monte Carlo model is currently being developed at Lewis for predicting undercut profiles for ground-based and LEO atomic oxygen exposures (ref. 13). The model will be used to predict long term LEO atomic oxygen durability of Space Station Freedom (SSF) power system materials.

GROUND-LABORATORY TECHNIQUES FOR ATOMIC OXYGEN DURABILITY EVALUATION

The following techniques are recommended for atomic oxygen durability evaluation of solar reflectors using a plasma asher. First, it is important to carefully document pristine samples. Detailed characterization prior to and after atomic oxygen exposure is critical for understanding any failure mechanisms involved and for projecting durability trends. For solar reflector surfaces, it is advised to document the pristine solar specular reflectance, solar absorptance, and the surface morphology. Optical microscopy is a technique which can provide non-destructive surface morphology characterization. Some surface features are only noticeable using polarized light, so both polarized and non-polarized images should be obtained when possible. Due to variations in surface morphology and reflectance of test coupons, care should be taken when obtaining reflectance values to measure exactly the same location(s) prior to and after atomic oxygen exposure. For large aperture specular reflectance measurements, (such as

with integrating spheres) it is advised to obtain at least two measurements (preferably at 90° rotation) and average the values. For small aperture reflectance measurements (such as D&S 15 R reflectometer), an average of 5 or more values should be made.

One should expose a witness coupon during plasma ashing simultaneously with the sample coupon in order to calculate the effective atomic oxygen fluence. It is recommended to use a coupon of the same material being evaluated if in-space erosion data exist. For example, if a solar reflector with a graphite epoxy substrate is being evaluated, an uncoated graphite epoxy witness coupon should be simultaneously ashed with the concentrator sample. For a material whose in-space erosion is not known, Kapton polyimide is frequently used as a witness coupon because the erosion yield of Kapton in LEO has been well characterized ($3.0 \times 10^{-24} \text{cm}^3/\text{atom}$) (ref. 14). A piece of 0.0127 cm Kapton can be used for continuous exposure for approximately 4 days, or an approximate effective fluence of $1 \times 10^{21} \text{atoms/cm}^2$. Pyrolytic graphite can be used for long term exposures because samples are generally thicker and the erosion yield is less than half that of Kapton. Due to the hygroscopic nature of polymer materials it is best to dehydrate the witness coupons prior to measuring the mass. Kapton 0.0127 cm thick is completely dehydrated in 48 hours under vacuum. Thicker material may take longer to dehydrate. Because the flux can vary in the asher chamber, the witness coupon should be placed in close proximity to the sample being evaluated. It is recommended that the sample being evaluated should be placed in the center of the asher. Glass racks can be custom made with a variety of spacings (for exposure on all sides) to position samples. After atomic oxygen asher exposure, the effective fluence (F) can be calculated as shown in equation 1.

$$F = \frac{(M_o - M_a)}{A \rho E} \quad (1)$$

where:

- M_o = original dehydrated witness coupon mass, g
- M_a = ashed dehydrated witness coupon mass, g
- A = surface area of witness coupon, cm^2
- ρ = density of witness coupon, g/cm^2
- E = in-space erosion yield of witness coupon, cm^3/atom

One of the common problems with atomic oxygen exposure in ground-laboratory facilities and in space, is the interaction with silicones and the resulting contamination. Silicone contamination was found on many samples on LDEF (ref. 15) and in some cases resided as a brown film (ref. 16). Silicone contamination as deposited in the asher (on samples, witness coupons, support racks and chamber walls) can range from a thin rainbow film, to a thick waffled deposit as shown in figure 9. Silicone contamination, once obtained inside an asher, will linger and be re-deposited on inside walls and on samples well after the original source of silicone is removed. To decrease the threat of silicone contamination on samples in plasma ashers one should not use the gaskets which contain silicone, such as those typically provided by the manufacture. Second, do not use any silicone-containing vacuum grease. Even brands which are quoted not to contain silicones, can show Si peaks with Energy Dispersive X-ray analysis. It is recommended to use a petroleum jelly as a vacuum grease. It is also important to keep the pressure above 60 mtorr to prevent back streaming of the pump oil which can contain silicone. Ashers can be partially cleaned of silicone contamination by running the ashers empty with cleaned microscope slides in them. It is believed that some of the silicone fragments will be deposited onto the slides, and so frequent replacement will reduce the contamination. If silicone contamination is severe, it is recommended to replace all removable parts (including the inner and outer chambers). If possible, it is advised to have two ashers, one for evaluating silicone-containing materials, and one for "clean" non-silicone containing samples.

Often during atomic oxygen exposure it is desirable to mask a section of the sample. For example, to determine the effect of atomic oxygen on the transmittance of a transparent sample generally only one side of the sample should be exposed to the plasma environment. In many cases samples have protective coatings deposited on one side only. For thin samples coated on one side it is necessary to mask the back-side of the sample so that only the protected side is exposed to the plasma for evaluation. Aluminum foil is a flexible, atomic oxygen durable material which can be considered, but it should be kept in mind that metals heat up in RF plasmas and may also cause local flux increases. The recommended material for masking samples is glass. The backside of a thin sample can be adequately protected

by sandwiching the sample between two glass slides, with the top slide containing holes for exposure. It is critical that there be intimate contact between the masking material and the sample, because a plasma can form inside an air pocket, and atomic oxygen scattering allows the oxygen atoms to travel along thin pathways.

When evaluating results from plasma asher exposures, it needs to be kept in mind that there is a high level of vacuum ultraviolet radiation (VUV) produced in the plasma environment. The exact level of VUV is not known, but is reported to have a flux of $10^{12} - 10^{14}$ photons $\text{cm}^{-2}\text{s}^{-1}$ at 130 nm, as compared to $\approx 4 \times 10^{11}$ photons $\text{cm}^{-2}\text{s}^{-1}$ at 121.6 nm in LEO (ref. 17). It is therefore difficult to determine if certain appearance changes, such as discoloration, are due to UV darkening, or atomic oxygen interactions, or both. Atomic oxygen durability evaluation of solar concentrator coupons for SSF indicated spectral changes and a corresponding surface yellowing with plasma asher exposure (ref. 18). Analytical analysis (secondary ion mass spectroscopy & Auger electron analysis) indicated the deposition of an oxide film which may have occurred during plasma ashing. Therefore the possibility of discoloration due to a variation in the oxide thickness or color center formation through stoichiometric changes due to interaction with atomic oxygen appears to be as likely a contributor to darkening as UV solarization (ref. 18). In an attempt to further understand the potential for film deposition during plasma ashing, a SDPM concentrator coupon, such as those described under Solar Reflector Durability Issues, was 1/3 covered with a fused silica slide and then exposed to atomic oxygen in a "clean" plasma asher. After an effective fluence of 2.1×10^{21} atoms/ cm^2 the exposed side of the coupon, particularly near the fused silica cover, was discolored (whitish) as seen in figure 10. This indicated that either a film had been deposited on the exposed side or color centers had developed. X-ray photoelectron spectroscopy analysis of the exposed and unexposed sides indicate the top oxide layer (SiO_x) is 100 Å thicker on the atomic oxygen exposed side than the on masked side. A complication with this technique is that a very large area is scanned (1 mm) and probably contains undercut defect sites. The oxide film may appear thicker if the undercut film has curled down into the undercut cavity.

Another durability evaluation issue that one should recognize when using plasma ashers is the potential acceleration in atomic oxygen damage which can occur during iterative ashing. Often it is desirable to observe trends such as solar specular reflectance change versus effective fluence. Concentrator coupons durability tested for use on SSF have been found to undergo accelerated erosion damage when iteratively ashed, as opposed to continuously ashed to the same effective fluence (ref. 18). It is advised when ashing samples iteratively, to ash at least one similar sample continuously to the same effective fluence to check for accelerated damage due to repeated atmospheric exposures and pressure changes.

EXTRAPOLATION OF IN-SPACE REFLECTANCE DEGRADATION BASED ON GROUND-LABORATORY TESTING

Although ground-laboratory plasma asher testing is highly valuable to discriminate relative solar specular reflectance performance of reflector surfaces in an atomic oxygen environment, quantification of in-space reflectance durability based on plasma asher testing is not obvious. A series of conversion factors does allow reasonable arguments to be made to perform this extrapolation. Based on the results of Banks, et.al. (ref. 19), if one assumes that the concentrator surface consists of an atomic oxygen protective coating over an oxidizable substrate with pin window defects, then the rate of change of solar specular reflectance $\rho_{p,s}$ with atomic oxygen fluence in sweeping space ram, f_s , can be expressed as an identity of conversion terms shown in Equation 2:

$$\frac{d\rho_s}{dF_s} = \frac{d\rho_s}{dN_s} \frac{dN_s}{dV_s} \frac{dV_s}{dV_a} \frac{dV_a}{dN_a} \frac{dN_a}{d\rho_a} \frac{d\rho_a}{dF_e} \quad (2)$$

where:

- ρ_s = solar specular reflectance for pin window defects in space
- ρ_a = solar specular reflectance for pin window defects in plasma ashers
- F_s = atomic oxygen fluence in sweeping space ram, atoms/ cm^2
- F_e = Kapton effective atomic oxygen fluence in plasma ashers, effective atoms/ cm^2
- N_s = non-reflecting undercut area below pin window defects in space, cm^2

N_a = non-reflecting undercut area below pin window defects in plasma ashers, cm^2
 V_s = undercut cavity volume below pin window defects for in space, cm^3
 V_a = undercut cavity volume below pin windows in plasma ashers, cm^3

One can show that:

$$\frac{d\rho_s}{dN_s} = \left(\frac{dN_a}{d\rho_a} \right)^{-1} = -\rho_s n \quad (3)$$

where:

ρ_0 = unexposed solar specular reflectance
 n = number of pin window defects per cm^2

Thus, the first and fifth factors in Equation 2 cancel. One can also show that:

$$\frac{dN_s}{dV_s} = \frac{1}{cV_s^{\frac{1}{3}}} \quad (4)$$

where:

c = constant

and:

$$\frac{dV_a}{dN_a} = cV_a^{\frac{1}{3}} \quad (5)$$

Note that for Equations 4 and 5 the constant is the same in each equation because the geometry of the undercut cavities are assumed to be approximately the same for plasma ashers and sweeping space ram, that of a one-half prolate spheroid. One can also argue, based on reference (ref. 19), that:

$$\frac{dV_s}{dV_a} = \frac{P_i + \frac{(1-P_r) k P_t A_s}{k P_t A_s + \pi r_d^2}}{4P_t + \frac{(1-4P_r) k A_a}{k P_t A_a + \pi r_d^2}} \quad (6)$$

where:

P_i = atomic oxygen initial impact reaction probability in space = 0.138
 A_a = surface area of undercut cavity in plasma asher, cm^2
 P_t = reaction probability of thermally accommodated atomic oxygen
 A_s = surface area of undercut cavity in space, cm^2
 r_d = pin window defect radius, cm
 k = 2/3

For the purposes of further quantification of Equation 6, the erosion yield of the undercut polymer material is assumed to be $3 \times 10^{-24} \text{ cm}^3/\text{atom}$ for normal incident atoms. The value, k , is used to correct the reaction probabilities for averaging overall angle of incidence in a defect cavity, knowing that the erosion yields depend on $(\cos$

$\Theta)^{1/2}$ where Θ is the angle from normal incidence (see reference 19). Based on reference 13, the presence of more reaction-excited species in an asher causes the asher atomic oxygen initial reaction probability to be four times that of subsequent interactions. Although the erosion modeling is based on Kapton, the equation is valid for different erosion yield reflector substrates provided Kapton effective fluence F_e measurements are made. The reaction probability of normal incident thermally accommodated atomic oxygen, P_t , is 0.00134. Thus, equations 4, 5, and 6 are fluence-dependent, which implies that the conversion of plasma asher to in-space performance will be fluence-dependent. The term $d\rho_a/df_e$ is the input change in solar specular reflectance with respect to effective atomic oxygen fluence. The last term can be quantified through Monte Carlo modeling measurements as shown in reference (ref. 19), and is given by:

$$\frac{dF_e}{dF_s} = \frac{dy_a}{dy_s} = 0.0483 \quad (\text{ref. 13}) \quad (7)$$

where:

y_a = Monte Carlo predicted Kapton thickness loss for uncoated Kapton in a plasma asher, Monte Carlo cell length units

y_s = Monte Carlo predicted Kapton thickness loss for uncoated Kapton in a sweeping space ram environment, Monte Carlo cell length units

The ratio dy_a/dy_s is not simply equal to $4P_t/P_i$ because in an asher the reaction probability for scattered thermally accommodated atoms can contribute measurably to erosion of an unprotected rough material, whereas in space the higher reaction probability of energetic atoms dominates.

Thus, combining equations 2-7 results in a range of ground-laboratory to in-space projection coefficients depending on whether large undercut cavities exist ($A_s > \pi r_d^2$, high fluence) or undercut cavities on the same order of magnitude as the defect area ($A_s \approx \pi r_d^2$, low fluence) exist. Substituting quantities in the equations results in the following fluence-dependent relationships.

For small undercut cavities ($A_s \approx \pi r_d^2$):

$$\frac{d\rho_s}{dF_s} = \frac{d\rho_a}{dF_e} \quad (8)$$

For large undercut cavities ($A_s > \pi r_d^2$):

$$\frac{d\rho_s}{dF_s} = 0.05 \frac{d\rho_a}{dF_e} \quad (9)$$

Thus, as can be seen in Equation 8 and Equation 9, for low fluence exposure, the degradation of solar specular reflectance in space occurs at the same rate measured in plasma ashers, whereas for high fluence the rate of degradation of in-space reflectance is only 5% that which is observed in a plasma asher, with a range of degradation rates in between. The reason the plasma asher degradation rate is much higher than that which occurs in space for high fluences is related to the high degree of trapping (in the undercut cavity) of thermally accommodated atomic oxygen. Samples are exposed to very high quantities of thermally accommodated atomic oxygen in the asher, because a larger quantity of lower energy thermally accommodated oxygen atoms are needed to achieve an equivalent effective fluence based on high energy LEO ram atomic oxygen.

Two concentrator coupons continuously ashed to a Kapton based effective fluence of 3.1×10^{21} atom/cm² (1.08 years on SSF) were found to decrease in solar specular reflectance by 0.055 and 0.085, with resulting values of 0.806 and 0.775 (ref. 18). If this data were directly extrapolated to 15 years on SSF, it would be predicted that the remaining solar specular reflectance would be only 0.096 and 0.000. Based on the above calculated ground-laboratory

to in-space projection coefficient for large undercut cavities, and the plasma asher results, the predicted solar specular reflectance for 1.08 year in LEO would be 0.858 to 0.856. Figure 11 shows solar specular reflectance decrease versus atomic oxygen fluence for asher results and for the LEO predictions based on the asher results. The lines represent the average of two values (two LEO predicted solar specular reflectance values appear as one). The calculated prediction for in-space solar specular reflectance for 15 years, based on the asher results for 1.08 years, would be 0.819 to 0.804. This is the best case scenario because the smallest projection coefficient was used. For more accurate lifetime predictions, higher effective fluence exposures should be conducted.

CONCLUSIONS

Materials shielded with an atomic oxygen protective coating are still vulnerable to LEO atomic oxygen degradation due to undercutting at defect sites. Protected organic materials located on the leading edge of LDEF provided evidence of atomic oxygen undercutting in direct ram exposure. To evaluate performance and durability of potential spacecraft materials, ground-laboratory exposures are relied upon as the most practical technique. Techniques have been recommended for durability testing of solar reflector coupons using a plasma asher. Although plasma ashers provide atomic oxygen environments which are quite different from LEO, these facilities provide an easy, inexpensive method to evaluate the atomic oxygen durability of potential spacecraft materials. Because of the variations in the arrival direction of oxygen atoms, reaction probability (based on impact energy), and species in plasma ashers as compared to space, direct extrapolation cannot be made from asher exposures. Correction calculations must be made in order to extrapolate in-space reflectance degradation based on plasma asher exposure. Based on calculation conversion, for low fluences, the solar specular reflectance degradation would be at the same rate in LEO as in ashers. For high fluences, the rate of solar specular reflectance degradation in space would be only 5% of that observed in an asher. This is a result of the high absolute atomic oxygen fluence in plasma ashers needed to produce reasonable effective fluences. The high absolute fluence of oxygen trapped in undercut cavities results in higher rates of undercutting in the asher as compared to space.

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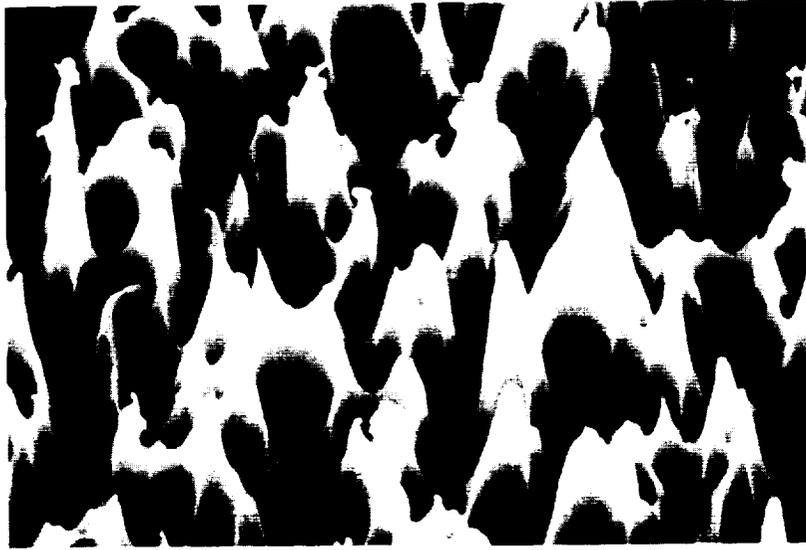


Figure 1. Polychlorotrifluoroethylene exposed to LEO atomic oxygen on the leading edge of LDEF. Typical erosion morphology of LEO direct ram atomic oxygen erosion of polymers.

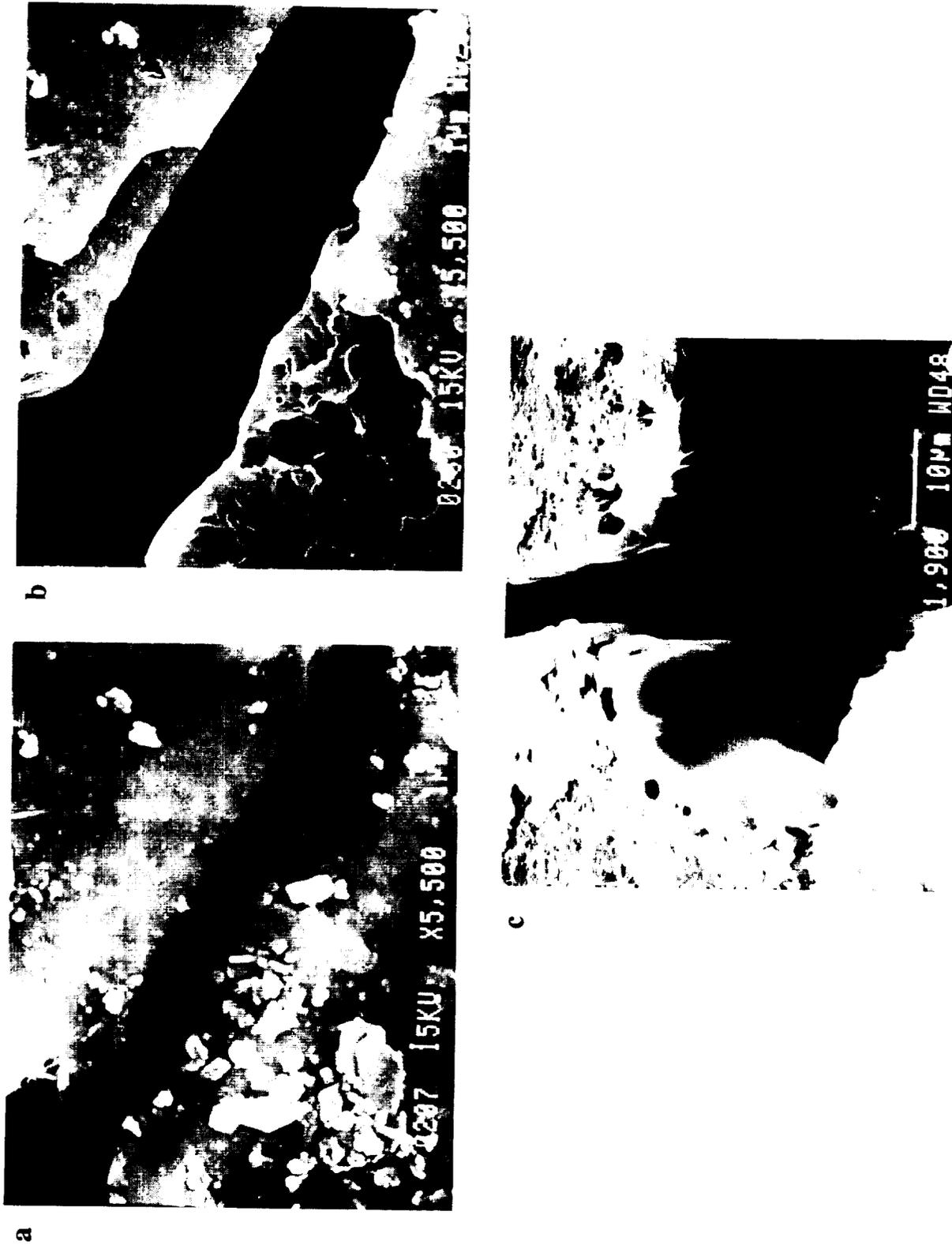
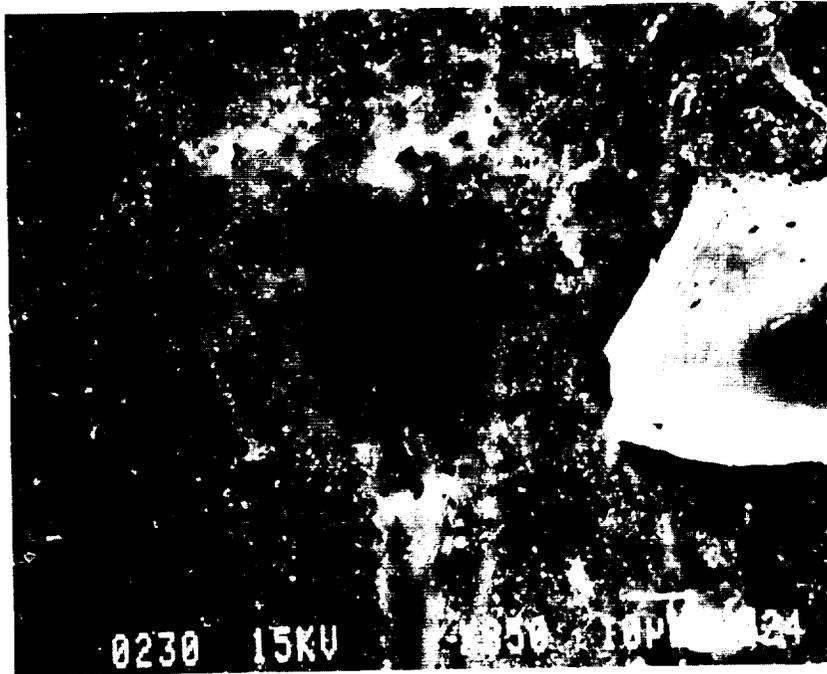


Figure 2. Protected (400Å Al/800Å Cr) graphite epoxy composite exposed to LEO atomic oxygen on the leading edge of LDEF: a. Crack site prior to removal of the protective coating, b. Undercut area at crack site after removal of protective coating, c. Undercut cavity profile at crack defect site (45° tilt).

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a



b

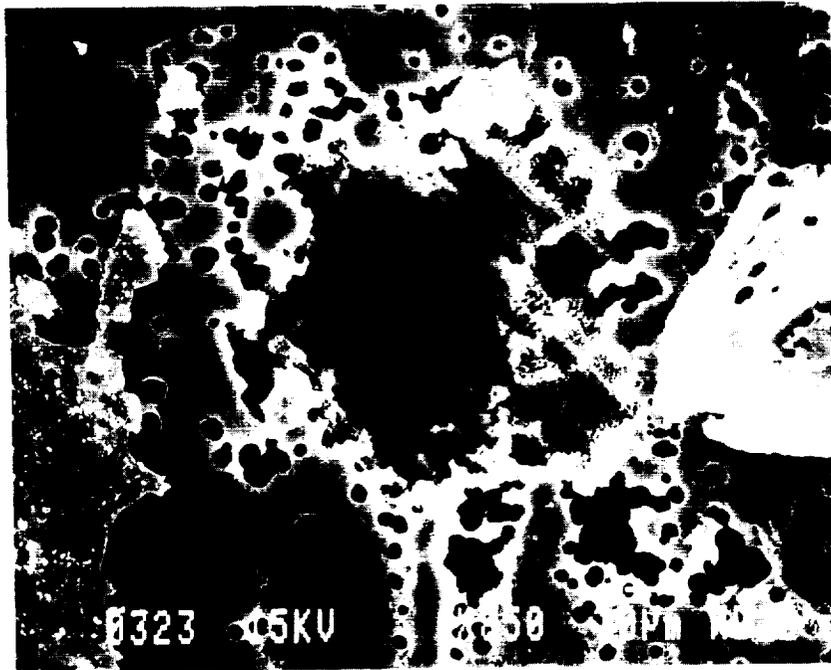


Figure 3. Protected (400Å Al/800Å Cr) graphite epoxy composite exposed to LEO atomic oxygen on the leading edge of LDEF: a. Damage in protective coating at possible impact site, b. Extent of undercut damage visible after removal of protective coating.

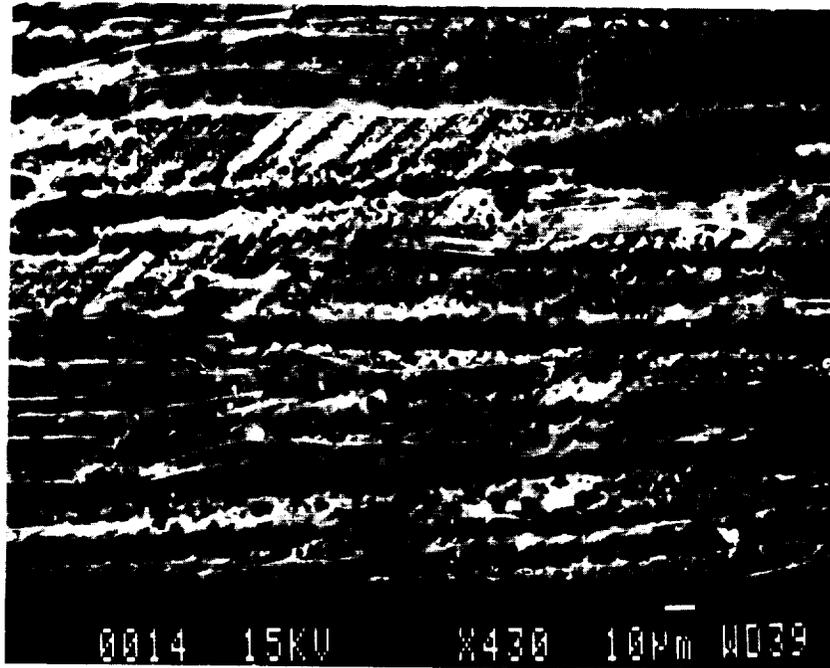


Figure 4. Failure of a protective coating exposed to LEO atomic oxygen on the leading edge of LDEF.

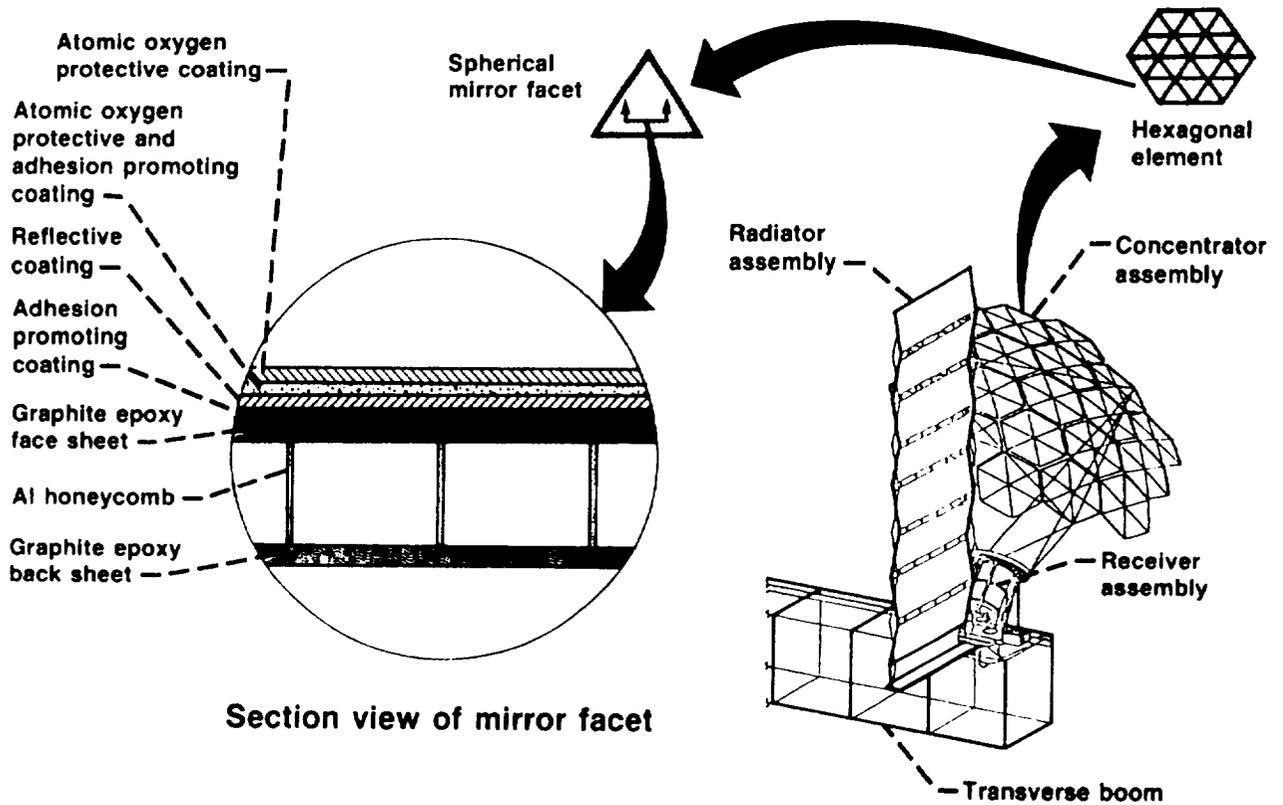


Figure 5. Solar concentrator for Space Station Freedom Solar Dynamic Power Module.

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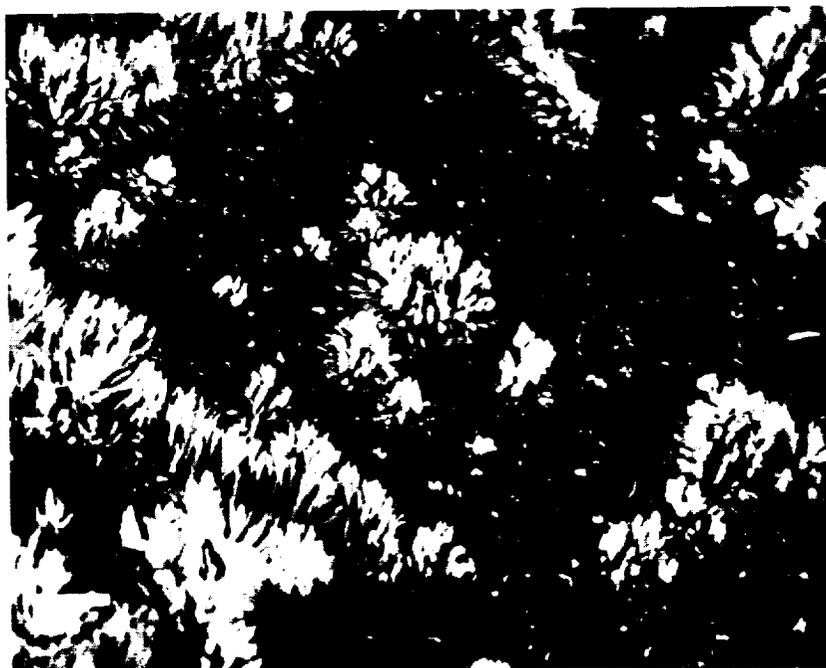


Figure 6. Silver-oxide "fluff" extending out of protective coating defect sites after atomic oxygen plasma exposure.



Figure 7. Atomic oxygen undercutting in a concentrator coupon. Protective coating film failure through an undercutting-tearing propagation process.

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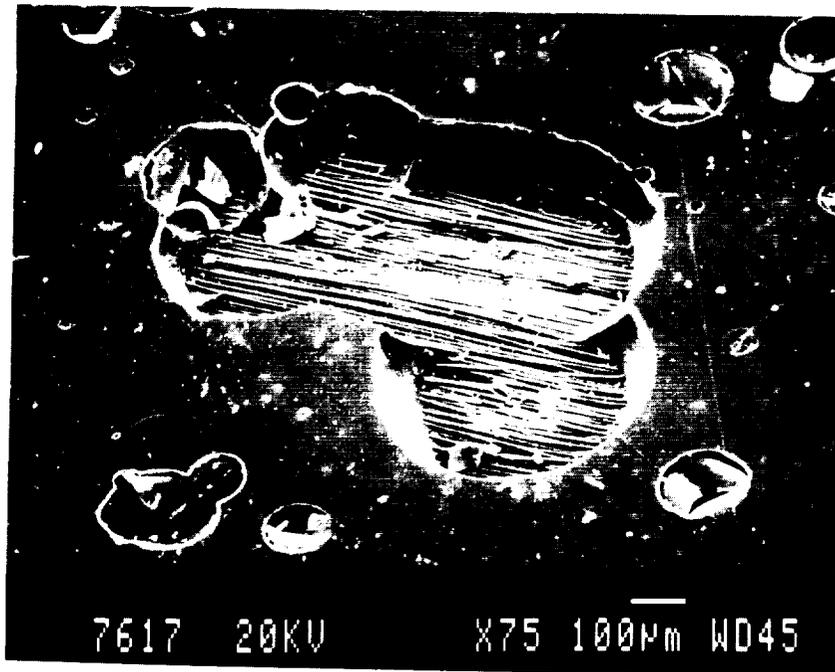


Figure 8. Atomic oxygen undercut cavities in a concentrator coupon exposed to a Kapton effective fluence of 3×10^{21} atoms/cm².



Figure 9. Silicone contamination on a Kapton witness coupon deposited during plasma ashing.

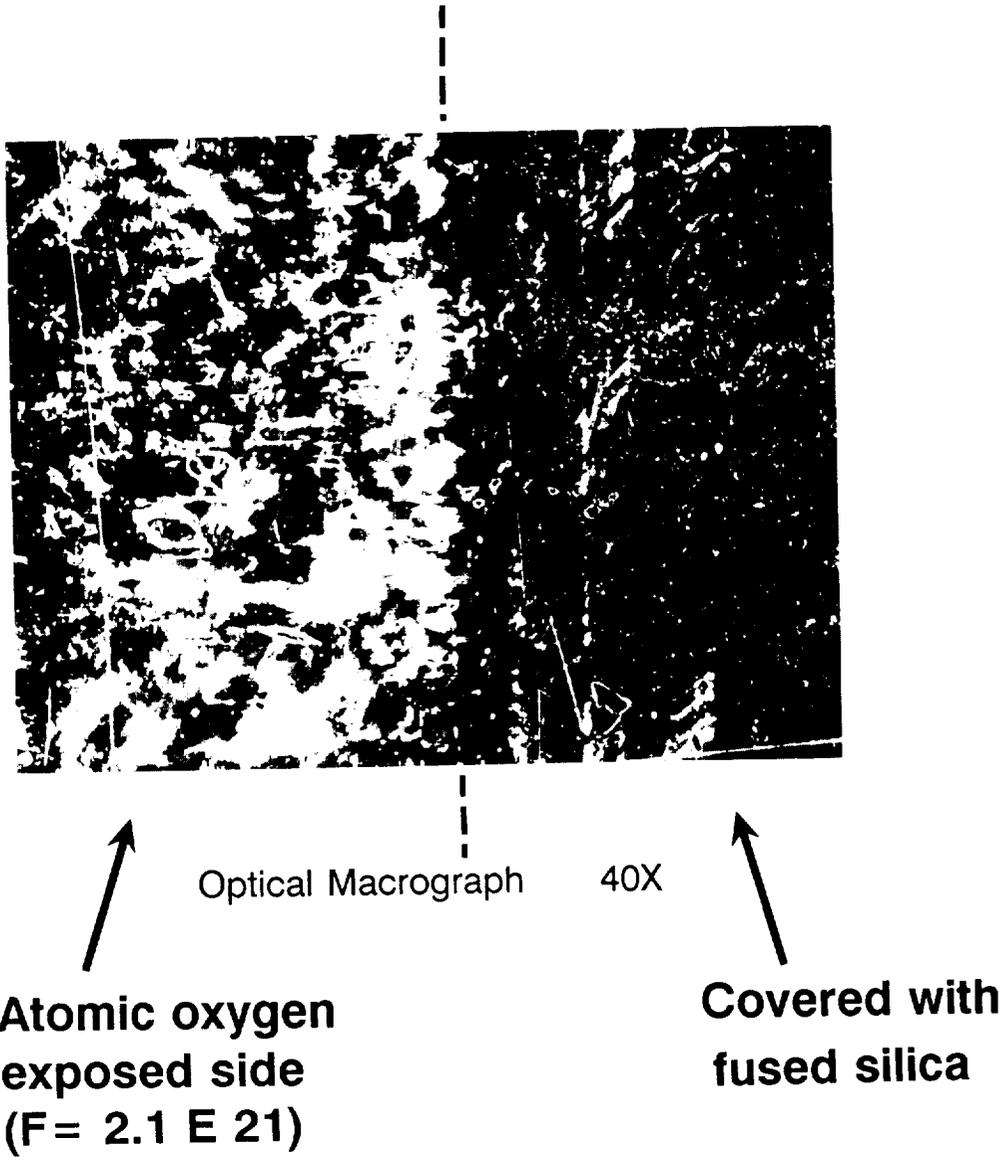


Figure 10. Concentrator coupon partially masked during atomic oxygen plasma exposure. The exposed side appears discolored.

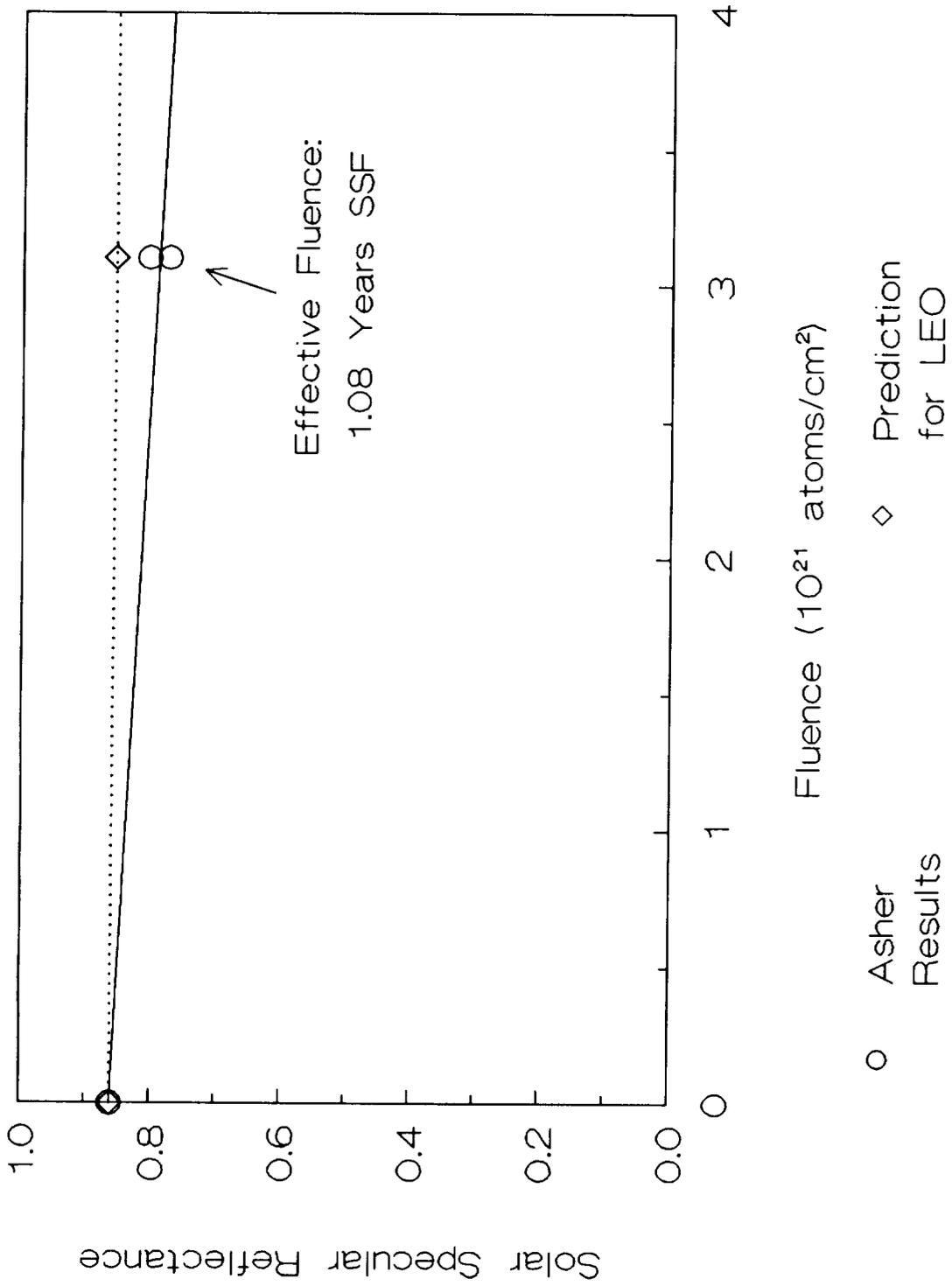


Figure 11. Ground-laboratory and in-space predictions of solar specular reflectance decrease with atomic oxygen exposure.

