NASA Technical Memorandum 106146

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Prepared for the
38th International SAMPE Symposium and Exhibition
sponsored by the Society for the Advancement of Materials and Process Engineering
Anaheim, California, May 10–13, 1993

NASA

THE EFFECTS OF SIMULATED LOW EARTH ORBIT ENVIRONMENTS ON SPACECRAFT THERMAL CONTROL COATINGS

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ABSTRACT

Candidate Space Station Freedom radiator coatings including Z-93, YB-71, anodized aluminum and SiO_x-coated silvered Teflon® have been characterized for optical properties degradation upon exposure to environments containing atomic oxygen, vacuum ultraviolet (VUV) radiation and/or silicone contamination. YB-71 coatings showed a blue-gray discoloration, which has not been observed in space, upon exposure in atomic oxygen facilities which also provide exaggerated VUV radiation. This is evidence that damage mechanisms occur in these ground laboratory facilities which are different from those which occur in space. Radiator coatings exposed to an electron cyclotron resonance (ECR) atomic oxygen source in the presence of silicone-containing samples showed severe darkening from the intense VUV radiation provided by the ECR and from silicone contamination. Samples exposed to atomic oxygen from the ECR source and to VUV lamps, simultaneously, with in situ reflectance measurement, showed that significantly greater degradation occurred when samples received line-of-site ECR beam exposure than when samples were exposed to atomic oxygen scattered off of quartz surfaces without line-of-site view of the ECR beam. For white paints, exposure to air following atomic oxygen/VUV exposure reversed the darkening due to VUV damage. This illustrates the importance of in situ reflectance measurement.

INTRODUCTION

The Space Station Freedom (SSF) power system will contain radiator panels which reject waste heat to the space environment by thermal radiation. A liquid coolant will transfer heat to the radiator panels by passing through channels embedded in the radiator panels. The surfaces of these panels, which contain coatings with a high thermal emittance, will then emit the waste heat to the space environment. These radiator coatings are also required to maintain a low solar absorptance to minimize heating by the sun which would reduce the radiator's efficiency in rejecting waste heat.

Candidate coatings for use in low Earth orbit (LEO) on the SSF power system radiators were screened for their durability to the various individual LEO environmental effects such as atomic oxygen, vacuum ultraviolet (VUV) radiation, and temperature cycling (Ref. 1). The environment which the coatings must be able to survive is described in Table I (Ref. 2).

TABLE I - SSF Thermal Control Coating Survivability Requirements

Design Life:	30 years
Beginning-of-Life Solar Absorptance: End-of-Life Solar Absorptance:	0.2 0.3
Thermal Emittance:	0.9
Atomic Oxygen Environment Flux: Fluence:	 3.55×10^{13} atoms/cm^{2}s 3.3×10^{22} atoms/cm^2
Solar Ultraviolet Radiation Environment	10,320 hours
Startup/Shutdown Temperature Cycles Number: Temperature Range:	 120 -77°C to +49°C

Candidate coatings chosen for their durability to individual LEO environments included white paint thermal control coatings, a second-surface silvered Teflon® coating and anodized aluminum. In order to make predictions of the on-orbit performance of these coatings, studies were conducted to evaluate their durability in simulated space environments which included synergistic effects. Samples were exposed to vacuum thermal cycling followed by exposure to environments containing atomic oxygen, VUV radiation and/or silicone contamination. An RF plasma asher

was used to expose samples to an equivalent lifetime (30-year) atomic oxygen fluence for the SSF photovoltaic radiator coatings. This environment also included intense VUV radiation, a by-product of the formation of atomic oxygen in the plasma asher (Ref. 3), and silicone contamination from a silicone adhesive used to bond the second-surface Teflon® sample to its aluminum substrate. Samples were also exposed in another facility which provides an electron cyclotron resonance (ECR) produced directed atomic oxygen beam combined with VUV radiation from deuterium lamps. This facility also contains an in situ reflectance measurement system to measure total hemispherical reflectance of exposed samples without breaking vacuum. It is further described in Reference 4.

THERMAL CONTROL COATINGS

Materials Tested

Candidate radiator coatings included Z-93 and YB-71, inorganic white paint coatings containing zinc oxide and zinc orthotitanate pigments, respectively, in a potassium silicate binder; sulfuric acid anodized (SAA) aluminum alloy 5657-H25; and SiO_x/FEP Teflon® (0.25 mm)/Ag/Inconel/Permacel P223 pressure sensitive adhesive, which will be referred to as SiO_x/FEP/Ag. Samples of the white paint coatings were prepared by IIT Research Institute in Chicago, IL and by Loral Vought Systems in Grand Prairie, TX. Samples of SAA aluminum were prepared by McDonnell Douglas Aerospace in Huntington Beach, CA. The SiO_x/FEP/Ag material was prepared by Sheldahl, Inc. in Northfield, MN. Z-93, YB-71 and SiO_x/FEP/Ag were applied to disks of aluminum alloy 6061-T6 of approximately 2.5 cm diameter and 0.79 mm thickness. SiO_x/FEP/Ag was applied to the substrates using the pressure sensitive adhesive. Z-93 and YB-71 were applied to the substrates using a low-pressure, high-volume spray, in thicknesses of 0.10 to 0.13 mm and 0.20 to 0.25 mm, respectively, to achieve the desired optical properties.

Damage Mechanisms to Coatings

White Paints Farley, Sancier and Morrison (Refs. 5-7) have described probable mechanisms of radiation damage in the semiconductor zinc orthotitanate (Zn_2TiO_4) and zinc oxide (ZnO) pigments based on observed paramagnetic centers. Such centers occur at point defects (i.e. anion or cation vacancies, interstitial atoms or molecules, impurity ions, etc.) which are local regions in the oxide lattice where the charge neutrality is not preserved. These defects are traps for electrons or holes (unfilled electron states) which could restore the neutrality. They result in discoloration of the originally transparent oxide material. These authors explained that ultraviolet radiation damage, resulting in color centers, occurs when the semiconductor oxide absorbs photons of energies greater than its bandgap energy (or of wavelengths less than its absorption edge). For zinc oxide and zinc orthotitanate,

the bandgap energies are approximately 3.8 eV and 3.3 Ev, respectively, which correspond to absorption edges at wavelengths of 325 nm and 380 nm, which are in the ultraviolet range. When photons of such energies are absorbed, electrons and holes are formed which can react with lattice ions and may lead to the formation of paramagnetic centers such as Ti^{3+} in zinc orthotitanate and interstitial zinc ions (Zn_i^+) in zinc oxide. Iyengar, et.al. (Ref. 8) found evidence of reversal, or bleaching, of the Ti^{3+} center upon exposure to oxygen.

The mode of degradation expected in Z-93 and YB-71 coatings from exposure to combined atomic oxygen and VUV radiation, which are expected to be present together in the plasma asher (Ref. 3) and in the ECR beam/VUV environments, is VUV-induced color center formation and atomic oxygen induced bleaching of this damage. In environments where the dose of VUV necessary to cause color center formation is much greater than the dose of atomic oxygen required to bleach the color center, discoloration is expected to be observed; however, in environments where there is a greater amount of atomic oxygen, less discoloration may be observed or the discoloration may be completely reversed. Because oxygen causes the reversal of color center formation, exposure to room air following VUV or combined VUV/atomic oxygen laboratory exposures may change the solar absorptance of the sample, causing measured damage to be less severe than the actual damage due to exposure to the atomic oxygen/VUV environment. For this reason, in situ optical properties measurement is important.

Because the balance between the amounts of ultraviolet radiation and atomic oxygen affect the extent of damage to these coatings, it is important in laboratory experiments to provide VUV and atomic oxygen proportions which are the same as those expected in the space environment.

Sulfuric Acid Anodized Aluminum Sulfuric acid anodized (SAA) aluminum materials have been known to discolor in ultraviolet radiation. There are a number of possible causes for this discoloration including the amount of sulfate in the coating, the amorphous structure of the surface oxide and color centers (Ref. 9). Because atomic oxygen may act to reverse some of degradation from ultraviolet radiation, and because both atomic oxygen and ultraviolet radiation are present in LEO, it is important to study the combined atomic oxygen and VUV effects.

SiOx/FEP/Ag FEP Teflon® is known to be damaged by atomic oxygen (Ref. 10) and by ultraviolet radiation (Ref. 11). Atomic oxygen causes oxidation of the polymer resulting in mass loss and texturing of the surface, and ultraviolet radiation may cause embrittlement, transmittance degradation, and mass loss over a long exposure duration. A coating of SiO_x, such as that which is used on the SiO_x/FEP/Ag thermal control coating, will provide a barrier to atomic oxygen attack of FEP. However, cracks in the SiO_x coating due to thermal cycling may provide locations where atomic oxygen and ultraviolet radiation may reach the FEP causing changes in the optical

properties and in the integrity of the coating. Further degradation to optical properties of the SiO_x/FEP/Ag coating may occur upon micrometeoroid and debris impact. Delamination of FEP from the underlying silver was observed on silvered Teflon® on LDEF in areas surrounding impact sites (Ref. 12). It is also possible that contaminating silicone adhesive could be exposed at an impact site. Atomic oxygen and ultraviolet radiation can act synergistically with silicones to produce a dark-colored contaminant deposit on nearby surfaces (Ref. 10).

EXPOSURE OF SAMPLES TO SIMULATED SPACE ENVIRONMENTS

Vacuum Thermal Cycling Exposure

All samples, unless otherwise noted, were exposed to 10 thermal cycles between -93°C and +49°C in vacuum at pressures between 0.013 and 1.3×10^{-4} Pa at Loral Vought Systems or at NASA Lewis Research Center prior to further testing. A Gier Dunkle MS-251 Reflectometer and DB-100 Reflectometer were used to measure solar absorptance and thermal emittance, respectively, before and after thermal cycling.

Exposure in an RF Plasma Asher

Samples of Z-93, YB-71, SAA aluminum and SiO_x/FEP/Ag were exposed in an RF plasma asher using oxygen as a feed gas. The asher produces a 13.56 MHz RF discharge of oxygen containing various species of ions, molecules and atoms. Samples located in the plasma may also be exposed to intense VUV radiation at the 130 nm resonance line for oxygen which is greatly exaggerated over that which would be expected in space at the same wavelength (Ref. 3). This is thought to account for the observed blue discoloration to YB-71 samples which was not observed in flight experiments or in exposure to moderate levels of VUV radiation from VUV lamps (Ref. 13). Z-93, YB-71 and SAA aluminum samples were exposed to a total effective atomic oxygen fluence of 3.4×10^{22} atoms/cm^2 based on the mass loss of Kapton®. The effective flux in the asher was approximately 10^{16} atoms/cm^{2}sec. The SiO_x/FEP/Ag sample was removed after a fluence of 1.1×10^{22} atoms/cm^2 due to severe degradation. Samples were visually inspected and analyzed for solar absorptance and thermal emittance at various increments of exposure. A Perkin Elmer Lambda-9 Spectrophotometer was used to measure spectral total hemispherical reflectance in air between 250 and 2500 nm, and these data were used to calculate solar absorptance. A Gier-Dunkle DB-100 Infrared Reflectometer was used to obtain the total normal thermal emittance in air between 5 and 25 μm at each increment.

Directed Atomic Oxygen/VUV Exposure Facility with In Situ Reflectance Measurement Capability

An electron-cyclotron resonance plasma source is used to generate a low-energy, high-flux directed atomic oxygen beam (figure 1a). This beam is also expected to provide intense VUV radiation at 130 nm, which may be 10 to 1000 times that of the sun as was found to be present in the plasma asher (Ref. 3). This was evidenced by samples of YB-71 being discolored in the beam in the same manner as YB-71 had discolored in the asher which was expected to be due to VUV-induced formation of the Ti^{3+} color center. If VUV-sensitive samples are to be evaluated for their space durability, it is desirable to protect them from this exaggerated level of VUV radiation. This can be accomplished by blocking the samples from line-of-sight exposure to the atomic oxygen beam using fused silica fixturing (figures 1a and b) and allowing samples to receive only scattered atomic oxygen off of these surfaces. Using this configuration, samples were exposed to a lower flux of atomic oxygen and did not receive this intense 130 nm VUV radiation.

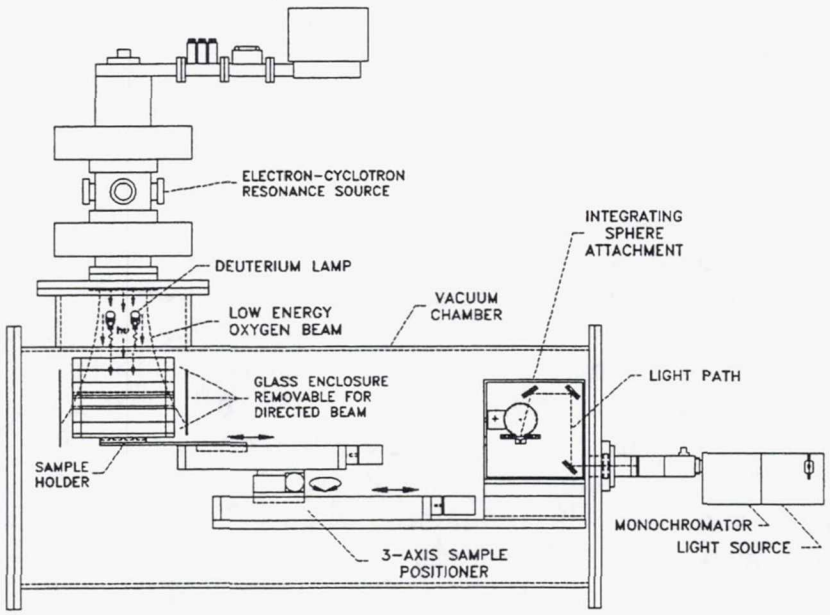

Figure 1a: Side view of atomic oxygen/VUV exposure facility.

Deuterium lamps with magnesium fluoride windows can be used to provide moderate intensity VUV radiation up to several suns between 115 and 200 nm. These were used in conjunction with the atomic oxygen ECR source (figure 1a) for performing synergistic studies. Two lamps are used to uniformly illuminate the four 2.5 cm diameter samples placed in a row on the sample holder, and a programmable logic controller (PLC) is used in this system to control the operation of two pairs of VUV lamps. In the side view of the system shown in figure 1b, each deuterium lamp actually represents a pair of lamps which can be seen on the front view shown in figure 1a. If one set of lamps fails, the PLC will send a signal to continue illumination of the samples with the other pair of lamps. If one lamp in the second set burns out, the PLC will check to see if a diagonal pair is available. If so, it will continue VUV illumination in this manner. If not, the PLC will operate with just one lamp

illuminated. The PLC can also be programmed to cycle the lamps on and off during a test so that the lamps will be on for a prescribed percent of the atomic oxygen exposure test time rather than being on for the full test time. This may be necessary to properly proportion the VUV and atomic oxygen doses for the particular spacecraft environment being simulated. Because surfaces in space are exposed to the sun for a portion of an orbit and are shadowed for the remainder of an orbit, cycling the VUV lamps on and off in this manner is an appropriate way to simulate the environment to obtain the desired amount of VUV radiation.

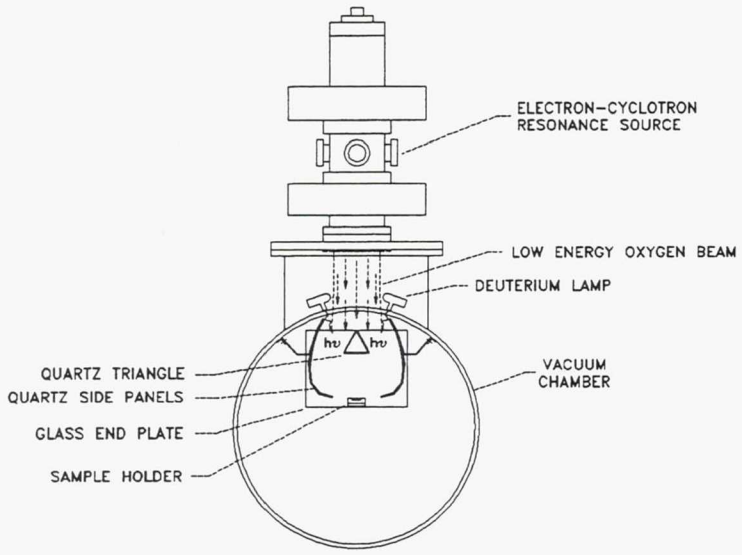

Figure 1b: End view of atomic oxygen/VUV exposure facility.

This facility also contains an Optronic Laboratories model 746 Reflectance Measurement System (RMS), shown in figure 1a, to measure reflectance of samples in situ. Samples are transported between the exposure and measurement environments by a three-axis positioning system. The RMS is capable of measuring total hemispherical reflectance between 250 and 2500 nm, and uses a 10.2 cm diameter integrating sphere with a detector assembly located inside of the vacuum system.

Exposure to the ECR Beam with Silicone Contaminant Present Samples of Z-93, YB-71 and SAA aluminum were exposed to the directed atomic oxygen beam, without fused silica fixturing and without deuterium lamps, along with samples of Kapton® coated with McGhan NuSil CV-2502, a silicone adhesive used for cladding solar array blanket materials; Kapton® coated with McGhan NuSil CV-1147, a glass frit-filled silicone which is a candidate for atomic oxygen protection; silicone tape adhesive; silicone sandwiched between two layers of SiO_x-coated Kapton®; SiO_x-coated Kapton®; bare Kapton®; fused silica; sapphire and pyrolytic graphite. After long-term exposure in LEO, solar array blankets containing silicone adhesive between two layers of Kapton® are likely to erode, exposing the silicone adhesive. The CV-2502-coated Kapton® samples emulated this long-term space exposure. Because silicones were observed to cause contamination of nearby surfaces on LDEF (Ref. 10), there is a concern that exposed silicone adhesive from atomic oxygen-eroded solar array blankets may contaminate nearby surfaces. Such contamination effects were examined by exposing the radiator coatings to this environment in the presence of silicones. Samples were exposed for a total effective (Kapton®-measured) atomic oxygen fluence

of $5.3x10^{21}$ atoms/cm^2, at a flux of approximately $2x10^{15}$ atoms/cm^{2}s. Samples received line-of-site exposure to the atomic oxygen beam, which also is likely to provide high intensity 130 nm VUV radiation.

Exposure to ECR Beam Combined with Vacuum UV Radiation Lamps

Test I: Line-of-Site ECR Exposure Combined with VUV Lamp Exposure In the first test of combined exposure to atomic oxygen and VUV radiation, samples of Z-93, YB-71 and SAA aluminum were exposed simultaneously to the atomic oxygen beam in a line-of-site configuration, and to VUV radiation provided by two deuterium lamps (figure 1a). Note that the fused silica fixturing, shown in the figure, was not used in this test. Samples received a total atomic oxygen effective fluence of $2.0x10^{21}$ atoms/cm^2 at an average effective flux of approximately $2x10^{15}$ atoms/cm^{2}sec and a total VUV lamp exposure of 668 equivalent sun hours at approximately 4.5 suns between 115 and 200 nm. The number of 130 nm VUV sun hours contributed by the ECR source is unknown, but it is expected to be on the order of 10 to 1000 times that of the sun as was found to be the case for the plasma ashers (Ref. 3). Incremental reflectance measurements were made in situ.

Test II: Exposure to ECR Configured with Fused Silica Fixturing and VUV Lamps In the second test of combined atomic oxygen and VUV exposure, samples of various formulations of Z-93 and a sample of SAA aluminum, not previously thermal cycled, were exposed to atomic oxygen and VUV radiation in the configuration shown in figures 1a and b with the fused silica fixturing in place and with the deuterium lamps on. Samples received only scattered atomic oxygen from off of the fused silica surfaces, and did not receive the intense 130 nm VUV radiation from the ECR source. Samples were exposed to a total atomic oxygen effective fluence of $3.6x10^{21}$ atoms/cm^2 at a flux of approximately $5x10^{15}$ atoms/cm^2 and to a total VUV radiation exposure between 600 and 700 equivalent VUV suns at 2 to 5 equivalent suns, dependent on sample location and duration of operation for each VUV lamp.

RESULTS AND DISCUSSION

Effects of Vacuum Thermal Cycling on Thermal Control Coatings

The results reported in figure 2 were obtained by Loral Vought Systems for thermal cycling of typical samples of Z-93, YB-71, SAA aluminum and SiO_x/FEP/Ag between -93°C and +49°C for 10 cycles in a vacuum chamber at a pressure of 0.013 Pa. For the SAA aluminum, results showed a significant increase in solar absorptance due to thermally-induced cracking of the surface oxide and a small, but measurable, degradation in thermal emittance. A handling-induced scratch was observed on the surface of this sample after exposure; however, it is not felt that this was the cause for such significant optical properties degradation. The SiO_x/FEP/Ag sample showed a small increase in solar absorptance after thermal cycling and a negligible emittance

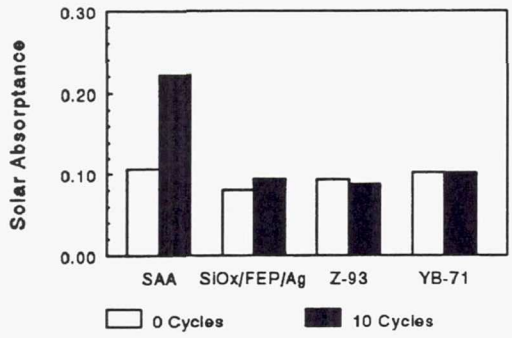

Figure 2a: Solar absorptance of thermal cycled coatings.

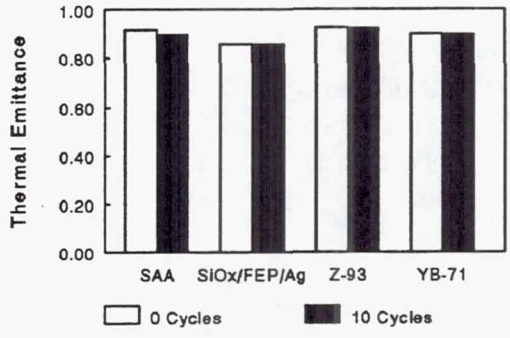

Figure 2b: Thermal emittance of thermal cycled coatings.

decrease. Z-93 showed a negligible change in emittance and a small reduction in solar absorptance after thermal cycling which may be due to water loss upon dehydration prior to thermal cycling. YB-71 shows negligible changes in solar absorptance and thermal emittance upon thermal cycling.

RF Plasma Asher Effects on Coatings

Figure 3 shows the results of exposure of Z-93, YB-71, SAA aluminum and SiO_x/FEP/Ag to oxygen plasma ashing to an equivalent 30 year atomic oxygen fluence

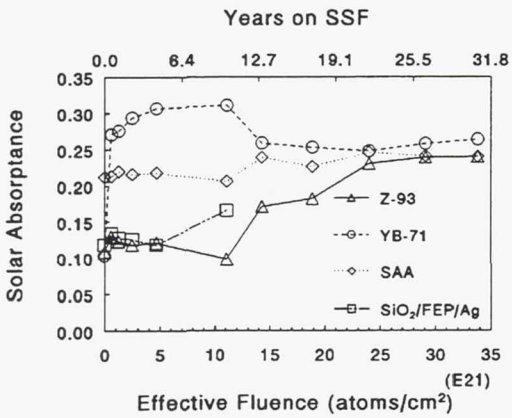

Figure 3a: Solar absorptance of RF plasma ashed coatings.

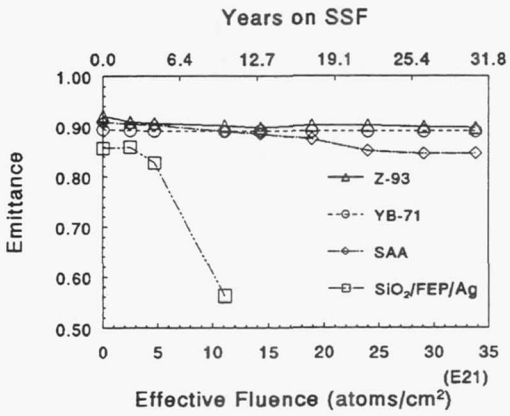

Figure 3b: Thermal emittance of RF plasma ashed coatings.

of 3.3 x 10^{22} atoms/cm^2. Samples were exposed to 10 vacuum thermal cycles, described above, prior to plasma ashing. Figure 3a shows the solar absorptance (α) history during this testing. Note that YB-71 shows a significant α increase at the first increment. Visual observations show a blue-gray discoloration of the initially chalk-white coating which is likely due to the formation of the Ti^{3+} color center in the zinc orthotitanate pigment due to intense 130nm VUV radiation which is a side-product of the plasma formation (Ref. 3). This effect has not been observed for YB-71 on space flight experiments such as LDEF and is likely an anomaly of the simulated environment.

The SiO_x/FEP/Ag sample showed an increase in solar absorptance and a dramatic decrease in thermal emittance (figure 3b) at an exposure level of 1.1x10^{22} atoms/cm^2. This sample, which initially looked like a diffuse mirror, had taken on a black tar-like appearance which started as a ring on the edge of the sample and moved toward the center with increasing exposure (figures 4a and b). This is likely due to oxidation of the silver and the silicone adhesive from the edges of the sample which were unprotected. Because the asher provides a random-directional attack, and because this sample was small and the edges were not protected, this sample showed damage which was not representative of that which would have occurred in space where the edges would likely be shielded. Furthermore, in space, atomic oxygen attack occurs as a directed or sweeping beam whereas in the asher atomic oxygen attack is random

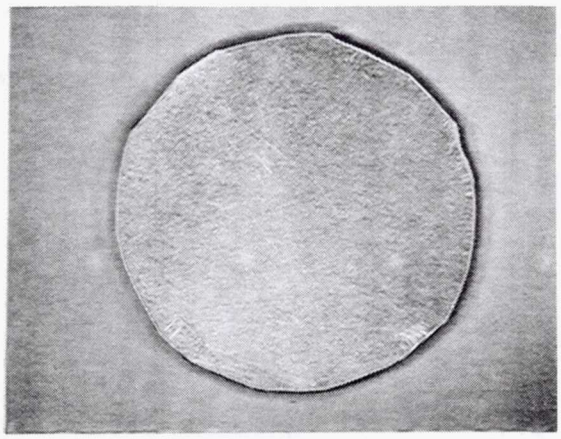

Figure 4a: Unexposed sample of SiO_x/FEP/Ag.

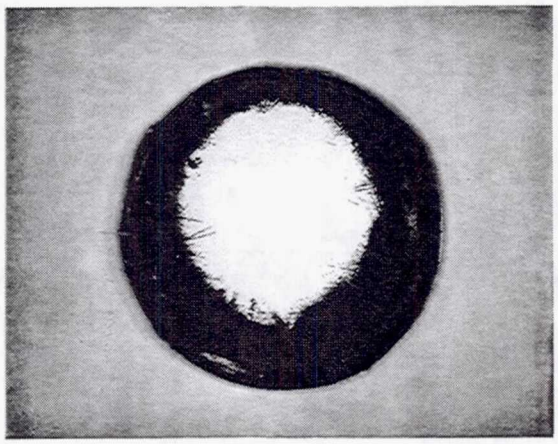

Figure 4b: RF plasma ashed sample of SiO_x/FEP/Ag.

directional resulting in potentially greater damage. However, this result does raise concern over the degradation of surface optical properties upon micrometeoroid or debris impact. Silvered Teflon® exposed on the Long Duration Exposure Facility

(LDEF), which was damaged by impacts, showed complete delamination of the Teflon® from the silver in areas extending to more than an inch away from the impact sites (Ref. 12). Oxidation of the silver and/or silicone adhesive would result in a darkened area much larger than the area of the impact thus locally affecting the solar absorptance.

It is expected that oxidized silicone from the SiO_x/FEP/Ag transported to the other samples exposed in the asher and contaminated them. A more dramatic change in α is observed for the other samples during the increment immediately following the severe degradation of the SiO_x/FEP/Ag sample at $1.1x10^{22}$ atoms/cm^2 as shown in figure 3. It is likely that this represents silicone contamination to the surfaces and that further changes in the optical properties of the rest of the samples were influenced by this contamination.

Effects of Atomic Oxygen, Intense VUV Radiation and Silicone Contamination on Coatings

Figures 5a and b show the changes in solar absorptance and thermal emittance of Z-93, YB-71 and SAA aluminum due to exposure to line-of-site atomic oxygen from the ECR source, which is also likely to contain high intensity VUV radiation, in the presence of the silicone-containing samples as described earlier. The changes in α for the samples exposed in this environment were significant while the changes in emittance were very small. Solar absorptance increases were attributed to two causes. First, a yellow-brown discoloration was observed on all the samples which was likely

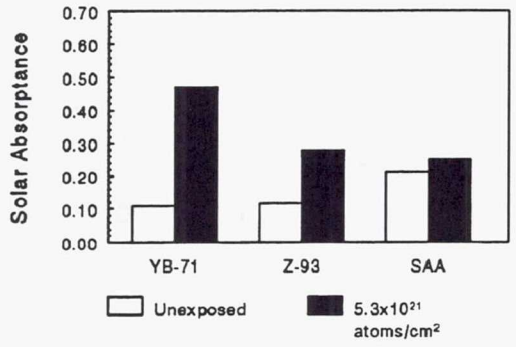

Figure 5a: Solar absorptances of coatings exposed to the ECR beam in the presence of silicone.

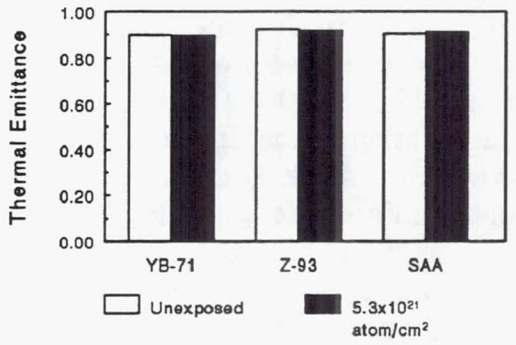

Figure 5b: Thermal emittances of coatings exposed to the ECR beam in the presence of silicone.

to be due to silicone contamination deposited onto the thermal control coating samples which was "fixed" by atomic oxygen with intense 130 nm VUV radiation. Second, a blue-gray discoloration was observed for the YB-71 sample in addition to the degradation due to contamination. This is the same type of discoloration observed in the plasma asher which was attributed to the formation of the Ti^{3+} color center in zinc orthotitanate from the intense 130 nm VUV radiation produced during the formation of atomic oxygen. The solar absorptance degradation observed here for Z-93 and YB-71 is much more severe than degradation observed with these types of samples in space. However, the results do raise concern that samples exposed to atomic oxygen and VUV in space in the presence of silicones may become discolored due to contamination.

Effects of Atomic Oxygen and VUV Radiation on Coatings

Test I: Line-of-Site ECR Exposure Combined with VUV Lamp Exposure The first test of combined atomic oxygen and VUV radiation exposure with in situ reflectance measurement was performed with the facility in the configuration shown in figure 1a with no 130 nm blocking fixturing and using the VUV lamps. The atomic oxygen fluence and the VUV equivalent sun hours (ESH) for each increment were proportioned for the Space Station Freedom environment being simulated. For example, the atomic oxygen and VUV radiation exposure levels for these coatings are $3.3x10^{22}$ atoms/cm^2 and 10,320 ESH, respectively, for 30 years in LEO. Therefore, the ratio of $3.3x10^{22}/10,320$ or $3.2x10^{18}$ atoms/cm^2·ESH was targeted for each increment of exposure. The VUV equivalent sun hours were calculated only for the VUV lamps and not for the 130 nm intense VUV expected from the ECR source. The results for exposure of Z-93, YB-71, SAA aluminum and a new formulation of Z-93, referred to as Z-93-P, are shown in figure 6a and are representative of 22 months in space. The Z-93-P sample behaves similarly to the YB-71 sample in that both show severe degradation at the first increment, probably due to the formation of color centers, then the solar absorptance levels off with continued exposure. It is likely that the severity of degradation was influenced by the strong VUV from the ECR source and is unrealistic. Also, it is unknown why the Z-93-P sample showed this severe degradation at the first increment, whereas the original formulation of Z-93 did not; however, it is likely to be due to differences in processing parameters. All data was obtained in situ except the last data point which was obtained several hours after air had been admitted to the chamber. There was a dramatic reduction in solar absorptance for the YB-71 and Z-93-P samples, a moderate reduction in solar absorptance for the Z-93 sample, and a negligible change in solar absorptance for the aluminum sample after being exposed in room air after testing. This shows the importance of performing solar absorptance measurements in situ for the white paint coatings, and it shows that the anodized aluminum does not undergo significant bleaching in air. The negligible emittance changes, measured in air, for the samples exposed in this test are shown in figure 6b.

Test II: Exposure to the ECR Configured with Fused Silica Fixturing and VUV Lamps
The second test of combined atomic oxygen and VUV radiation exposure was performed with fixturing to block samples from the 130 nm VUV radiation from the ECR source and with VUV deuterium lamps on as shown in figures 1a and b. Samples of various formulations of Z-93, referred to as Z-93, Z-93-P and Z-93-2135, and a sample of SAA aluminum were exposed. These samples were not vacuum thermal cycled prior to this testing. The proportion of 3.2×10^{18} atoms/cm^2·ESH was not maintained, because the VUV intensity of the lamps was not adjustable, a greater flux of atomic oxygen was measured after a facility repair, and it was not possible to cycle the atomic oxygen source on and off to maintain the prescribed atomic oxygen-to-VUV proportion. Also, a facility malfunction caused the VUV lamps to rapidly burn out. Because each lamp in the system is slightly different in intensity, and various combinations of the four lamps were used due to the rapid rate of lamp failure, gradients occurred in the number of sun hours received by the samples. Each increment gave different intensities of VUV received by each sample resulting in the levels of atomic oxygen and VUV being independent of one another. Therefore, the results shown in figure 7a have been plotted on a three-dimensional graph which

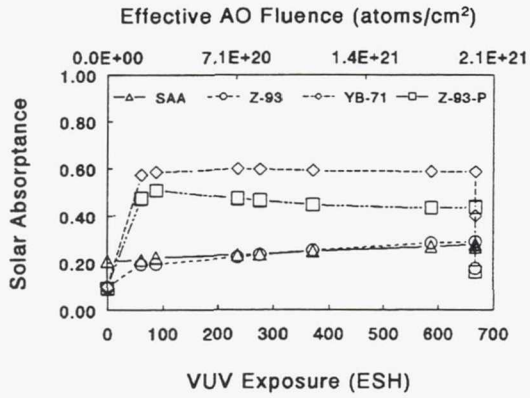

Figure 6a: Effects of ECR beam/VUV lamp exposure on solar absorptance of coatings.

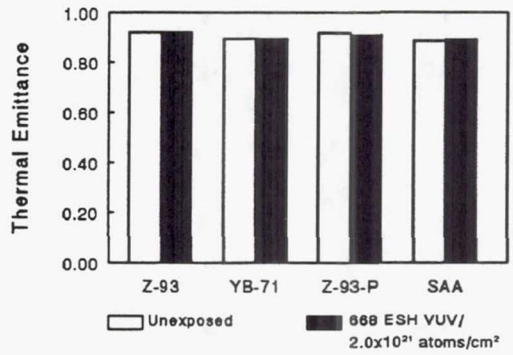

Figure 6b: Thermal emittance of ECR beam/VUV lamp exposed coatings.

permits the number of sun hours and the atomic oxygen fluence to be shown as independent. A trend is observed for this test which is similar to that observed for Test I; a significant α increase is observed at the first increment, and further degradation is much less severe. For Test II, there was a reduction in solar absorptance between the first and second increments and relatively small changes in solar absorptance with further exposure. It is unknown at this time why this behavior was observed, but it is likely due to facility exposure parameters. The degradation at

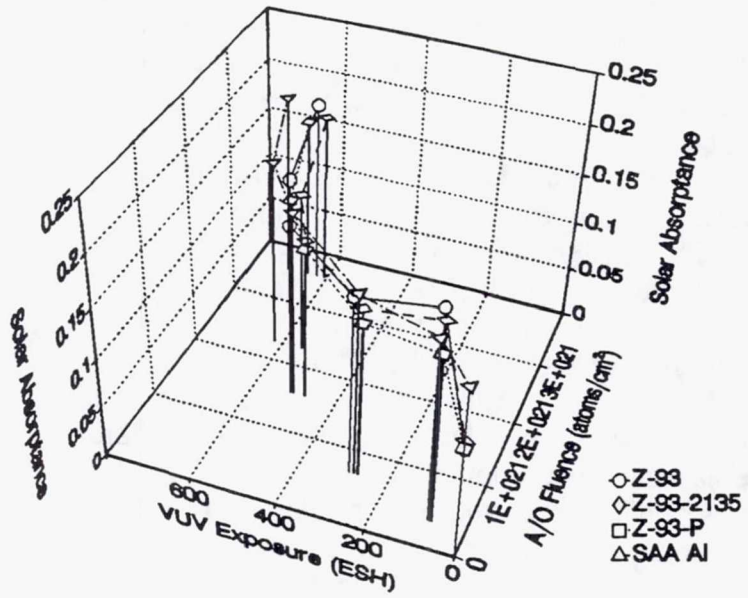

Figure 7a: Effects of ECR produced atomic oxygen (130 nm radiation blocked) and VUV lamp exposure on solar absorptance of coatings.

the first increment in Test II where the 130 nm blocking fixtures were used was not nearly as dramatic as that observed in Test I where the blocking fixtures were not used. This confirms that the fused silica fixturing is effective in blocking the undesirable severe 130 nm radiation produced by the ECR source, and that testing performed where samples are exposed to the line-of-site ECR beam result in different damage mechanisms to the white paint coatings than those which occur in space. Furthermore, in Test II, as in Test I, the anodized aluminum showed the least change in solar absorptance of all the materials tested. Also as in Test I, samples showed negligible changes in emittance as measured in air (figure 7b).

CONCLUSIONS

Exaggerated amounts of VUV from exposure in an RF plasma asher or in an ECR beam environment may produce damage mechanisms which are different than those which would occur in space. This testing shows that it is desirable to prevent samples from receiving this intense VUV in order to obtain more realistic results. In the ECR facility, fused silica fixturing may be used to block the samples from line-of-site ECR beam exposure. Samples exposed in such a fashion received scattered atomic oxygen, and results indicated that they did not receive the intense VUV radiation.

Exposure of thermal control coatings to the ECR beam in close proximity to a silicone adhesive showed considerable degradation, and, although some blue-gray discoloration was observed, due to intense VUV radiation in the ECR beam, the brownish discoloration from silicone contamination was great. Furthermore, silicones exposed in the asher caused contamination of nearby surfaces as evidenced by significant changes in solar absorptance. These data imply that exposed silicone surfaces in the LEO environment may severely contaminate nearby surfaces.

Because of the competition between formation of color centers due to ultraviolet radiation and reversal of color centers due to oxidation, it is important to maintain realistic proportions of atomic oxygen and ultraviolet radiation in ground-laboratory tests and to use in situ reflectance measurement methods, particularly for white paint coatings.

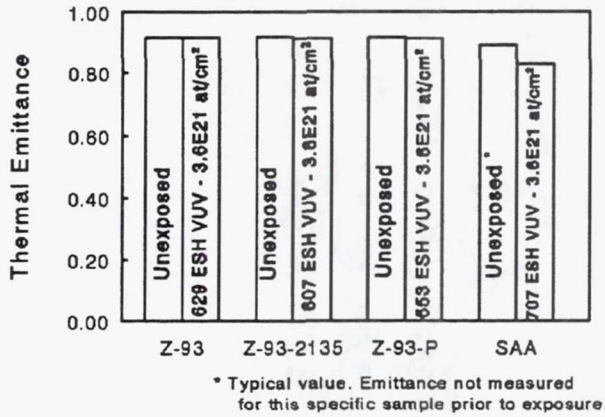

Figure 7b: Thermal emittance of coatings exposed to ECR-produced atomic oxygen (130 nm radiation blocked) and VUV lamps.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Bruce Banks and Alan White of NASA Lewis Research Center for their technical counsel during this work. Also, thank you to Phyllis Ellingboe, Sheldahl, Inc.; Yoshiro Harada, IIT Research Institute; Huong Le, McDonnell Douglas Aeronautics and Joe Stoyack, Loral Vought Systems Corp. for providing samples of coatings and technical assistance.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 1993	Technical Memorandum

4. TITLE AND SUBTITLE

The Effects of Simulated Low Earth Orbit Environments on Spacecraft Thermal Control Coatings

5. FUNDING NUMBERS

WU–474–46–10

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–7829

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM–106146

11. SUPPLEMENTARY NOTES

Prepared for the 38th International SAMPE Symposium and Exhibition sponsored by the Society for the Advancement of Materials and Process Engineering, Anaheim, California, May 10–13, 1993. Joyce A. Dever and Sharon K. Rutledge, NASA Lewis Research Center; Eric J. Bruckner, Cleveland State University, Cleveland, Ohio 44115; Curtis R. Stidham and Thomas J. Stueber, Sverdrup Technology, Inc. Lewis Research Center Group, 2001 Aerospace Parkway, Brook Park, Ohio 44142; and Roy E. Booth, Loral Vought Systems Corporation, P.O. Box 65003, Dallas, Texas 75265–0003. Responsible person, Joyce A. Dever, (216) 433–6294

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Categories 14, 18, and 23

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

Candidate Space Station Freedom radiator coatings including Z-93, YB-71, anodized aluminum and SiO_x coated silvered Teflon® have been characterized for optical properties degradation upon exposure to environments containing atomic oxygen, vacuum ultraviolet (VUV) radiation and/or silocone contamination. YB-71 coating showed a blue-gray discoloration, which has not been observed in space, upon exposure in atomic oxygen facilities which also provide exaggerated VUV radiation. This is evidence that damage mechanisms occur in these ground laboratory facilities which are different form those which occur in space. Radiator coatings exposed to an electron cyclotron resonance (ECR) atomic oxygen source in the presence of silicone-containing samples showed severe darkening from the intense VUV radiation provided by the ECR and from silicone contamination. Samples exposed to atomic oxygen from the ECR source and to VUV lamps, simultaneously, with in situ reflectance measurement, showed that significantly greater degradation occurred when samples received line-of-site ECR beam exposure than when samples were exposed to atomic oxygen scattered off of quartz surfaces without line-of-site view of the ECR beam. For white paints, exposure to air following atomic oxygen/VUV exposure reversed the darkening due to VUV damage. This illustrates the importance of in situ reflectance measurement.

14. SUBJECT TERMS

Thermal control coatings; Simulated space environments

15. NUMBER OF PAGES

18

16. PRICE CODE

A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	