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Evaluation of Thermal Control Coatings for Use on Solar Dynamic Radiators in Low Earth Orbit

Joyce A. Dever
*Lewis Research Center
Cleveland, Ohio*

Elvin Rodriguez
*Cleveland State University
Cleveland, Ohio*

Wayne S. Slemp
*Langley Research Center
Hampton, Virginia*

and

Joseph E. Stoyack
*LTV Missiles and Electronics Group
Grand Prairie, Texas*

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EVALUATION OF THERMAL CONTROL COATINGS FOR USE ON SOLAR DYNAMIC RADIATORS IN LOW EARTH ORBIT

JOYCE A. DEVER
NASA Lewis Research Center
Cleveland, OH 44135

ELVIN RODRIGUEZ
Cleveland State University
Cleveland, OH 44115

WAYNE S. SLEMP
NASA Langley Research Center
Hampton, VA 23665

JOSEPH E. STOYACK
LTV Missiles and Electronics Group
Grand Prairie, TX 75051

Abstract

Thermal control coatings with high thermal emittance and low solar absorptance are needed for Space Station Freedom (SSF) solar dynamic power module radiator (SDR) surfaces for efficient heat rejection. Additionally, these coatings must be durable to low earth orbital (LEO) environmental effects of atomic oxygen, ultraviolet radiation and deep thermal cycles which occur as a result of start-up and shut-down of the solar dynamic power system. Eleven candidate coatings were characterized for their solar absorptance, α_s , and emittance, ϵ , before and after exposure to ultraviolet (UV) radiation (200-400 nm), vacuum ultraviolet (VUV) radiation (100-200 nm) and atomic oxygen. Results indicated that the most durable and best performing coatings were white paint thermal control coatings Z-93, zinc oxide pigment in potassium silicate binder, and YB-71, zinc orthotitanate pigment in potassium silicate binder. Optical micrographs of these materials exposed to the individual environmental effects of atomic oxygen and vacuum thermal cycling showed that no surface cracking occurred.

Introduction

Power systems for the Space Station Freedom (SSF) must be able to reject their waste heat efficiently via radiator panels in order to maintain their prescribed operating temperatures. This requires the use of a coating on the surface of the radiator panels which reflects a large portion of incident sunlight and, therefore, has a low value of solar absorptance (α_s). In order to minimize the required surface area of the radiator panels for a specific radiant power, the coating must also have a maximum value of thermal emittance (ϵ).

In addition to meeting the power system requirements, the coating must meet requirements for durability to the low earth orbital (LEO) SSF environment including vacuum

ultraviolet radiation, atomic oxygen, thermal cycling and micrometeoroid/debris impacts.

The study summarized here is the result of a program which was initiated to evaluate the properties and characterize the performance of candidate SSF solar dynamic radiator (SDR) coatings. Since the requirements for the SDR coatings are similar to those for the photovoltaic radiator (PVR) coatings, as shown in Table I, this study is of relevance to both programs (E. P. Braunscheidel, 1990, Space Station Freedom Solar Dynamic Power System Branch, NASA Lewis Research Center, Cleveland, OH, personal communication; and K. A. White, III, 1990, Space Station Freedom Storage and Thermal Control Branch, NASA Lewis Research Center, Cleveland, OH, personal communication).

Candidate materials included white thermal control coatings, second-surface metallized Teflon coatings, sulfuric acid anodized aluminum, and a plasma sprayed aluminum oxide coating. The materials were tested for durability to ultraviolet radiation (200 to 400 nm wavelength range of radiation), vacuum ultraviolet radiation (100 to 200 nm wavelength range), vacuum thermal cycling and atomic oxygen.

White Thermal Control Coatings

Throughout the history of white thermal control paint coatings, extensive studies have been conducted to determine their space environmental durability, and much work has gone into their development.¹⁻⁸ The experiments performed as part of this effort will expand the existing data base, since the environmental effects testing performed here allows for comparison of the performance of these white thermal control paints with that of other types of thermal control surfaces tested in the same test facilities under identical conditions.

Three types of white thermal control paint coatings that have been developed by the Illinois Institute of Technology Research Institute (IITRI) were evaluated in

this study. One of these materials, Z-93, is the current baseline material for use on the solar dynamic and photovoltaic power module radiator surfaces. This material is comprised of zinc oxide pigment in a potassium silicate binder. It typically shows emittance values approximately 0.92 and absorptance values of 0.2 or less.

Other materials chosen as candidates are YB-71, which is comprised of zinc ortho-titanate pigment in a potassium silicate binder, and S13G/LO, a flexible white organometallic material comprised of zinc oxide pigment (each particle is encapsulated in potassium silicate) in a methyl silicone binder. Both show emittance values of approximately 0.9 and absorptance values of approximately 0.1.

For this testing, white thermal control coatings were deposited onto substrates by IITRI using an IITRI-developed turbine deposition process. Lewis Research Center provided the substrates which were 0.9" diameter disks of 0.032" thick aluminum alloy 6061-T6. The following are the coating thicknesses which provide minimum solar absorptance for each material: 4-5 mil for Z-93, 8-10 mil for YB-71, 4-6 mil for S13G/LO-41 and -51, and 8 mil for S13G/LO-1.

Second-Surface Metallized Teflon Coatings

Various types of second-surface silvered and aluminized Teflon thermal control coatings have been tested for space durability in flight tests and in the laboratory.^{4, 9} Thermal control materials developed by Sheldahl that were tested as part of this effort included layered thin film materials of second-surface metallized (aluminized or silvered) FEP Teflon, with silicon dioxide or cerium oxide protective coatings. Each contained FEP Teflon of 5.5 mil thickness. Mirror layers and protective coatings were of thicknesses such that they added negligible weight to the materials. Typical emittance values were less than 0.8, below the beginning-of-life requirement. Absorptance values of the SiO₂ coated metallized FEP materials were within the beginning-of-life requirements; however, the cerium oxide coated aluminized Teflon showed solar absorptance values of approximately 0.23 which did not meet the beginning-of-life requirement.

These film materials were mounted onto disks of 0.032" thick aluminum alloy 6061-T6 using pressure sensitive acrylic adhesive.

Sulfuric Acid Anodized Aluminum

Anodized aluminum materials have been developed and tested for consideration as thermal control surfaces.¹⁰⁻¹² Boundary Technologies, Inc. supplied samples of 10 mil thick aluminum alloy 5657-H28 with 0.5 mil oxide and with 1.0 mil oxide. Samples were 0.9" diameter with thin stems.

The anodization process included a 20 second bright dip at 97°C in a solution of 15% concentrated HNO₃/85% concentrated H₃PO₄. This was followed by anodization at 22°C and 15 volts in 19.9% H₂SO₄, and, finally, sealing for 5 minutes in 95°C water.¹²

For the 0.5 mil anodized material, typical emittance values were approximately 0.78 and absorptance values were greater than 0.2. For the 1.0 mil anodized material,

emittance values were between 0.82 and 0.84 and absorptance values ranged from 0.15 to 0.3.

Plasma Sprayed Alumina

LTV Missiles and Electronics Group has developed a method of plasma spraying an Al₂O₃ coating. LTV coated disks of 0.032" thick aluminum 6061-T6 with this material for testing. Typical beginning-of-life optical properties were emittance of 0.8 and solar absorptance of 0.3.

Performance and Durability Testing

Measurement of Optical Properties

The instruments used to measure optical properties of emittance and solar absorptance are shown in Table II.

Emittance Measurement Instruments:

The Hohlraum reflectometer (NASA Lewis Research Center) was used to measure spectral reflectance at room temperature from 1.7 to 14.7 μm, and the spectral reflectance values were then converted to spectral emittance. Total emittance was calculated by convoluting the spectral emittance into the room temperature blackbody distribution curve.¹³⁻¹⁴

The portable Gier Dunkle DB-100 infrared reflectometer (NASA Lewis Research Center, NASA Langley Research Center and LTV Missiles and Electronics Group) was used to measure total emittance in the wavelength region between 5 and 25 μm by using dual rotating cavities that reference sample radiation against an approximately room temperature blackbody.¹⁴ The accuracy of the DB-100 measurement is expected to be ±2%. Emittance of the sample at room temperature was measured in each case.

Absorptance Measurement Instruments:

The Perkin-Elmer Lambda-9 UV-VIS-NIR spectrophotometer with a 60 mm barium sulfate coated integrating sphere (NASA Lewis) was used to measure spectral reflectance over the wavelength range between 250 and 2500 nm. Total solar reflectance (ρ_s) within this wavelength range was calculated by convoluting the reflectance spectra into the air-mass-zero solar spectrum over the same wavelength range.^{14, 15} Total solar absorptance, (α_s), was calculated by:

$$\alpha_s = 1 - \rho_s$$

The accuracy is within ±2%, and the repeatability of the measurements is ±0.005.

The Beckman DK1-A with an 8" barium sulfate coated integrating sphere (NASA Langley) was used to measure spectral reflectance in the wavelength range between approximately 270 nm and 2300 nm. A similar method was used as with the Perkin Elmer Lambda-9 to obtain solar absorptance. The accuracy of the reflectance measurement is expected to be ±5%. The repeatability of measurements with this instrument is ±0.005.

The portable Gier Dunkle MS-251 (LTV) was used to measure total solar reflectance in the UV-VIS-NIR wavelength region. The expected accuracy is on the order of $\pm 1\%$.

Ultraviolet Radiation Exposure Testing

Ultraviolet radiation exposure with in situ absorbance measurement was performed on ten of the candidate materials at the NASA Langley Research Center facilities courtesy of Mr. Wayne S. Slemp (Materials Division). Materials were exposed to 500 hours of ultraviolet radiation (wavelength range 200-400 nm) produced by a 1000 watt xenon arc lamp at an acceleration level of 2 ultraviolet suns so that the total UV dose was 1000 equivalent sun hours (ESH). Solar reflectance was measured in situ before, during and after exposure using the Beckman DK-1A spectrophotometer.

Individual samples were mounted on a water-cooled substrate connected to a vacuum push-pull feedthrough in a small ion pumped vacuum chamber. Six of these chambers, each containing one specimen, surrounded the xenon lamp. For UV irradiation, the sample was exposed behind a UV transmitting quartz optical flat. For spectral reflectance measurement, the sample was translated using the push-pull feedthrough into a quartz test tube still in high vacuum of 10^{-8} torr. The entire exposure chamber and ion pump were removed from the UV exposure apparatus and placed on the Gier Dunkle integrating sphere. The quartz test tube, with the test sample, projected into the measurement position of the sphere. Corrections were made for the reflectance of the quartz test tube. Absorbance was calculated directly from corrected reflectance values. For the IITRI materials, emittance values of the unexposed samples were measured at Lewis using a Hohlraum reflectometer, and after exposure, emittance was measured by LTV using the DB-100 reflectometer. Because of a malfunction in Lewis's Hohlraum reflectometer, errors in the pre-exposure emittance values measured by the Hohlraum may be great. For the rest of the materials, each sample was measured for emittance at Langley using a DB-100 reflectometer before and after exposure.

Vacuum Ultraviolet Radiation Exposure

At the Lewis Research Center facilities, vacuum ultraviolet (VUV) radiation exposure was performed on eleven of the candidate materials. Materials were exposed to 333.33 hours of vacuum ultraviolet radiation (wavelength range 100-200 nm) produced by a 30 watt deuterium lamp with a magnesium fluoride window. The acceleration level was 3 vacuum ultraviolet suns so that the total VUV dose was 1000 ESH.

Solar reflectance was measured by LTV Missiles and Electronics Group in air before and after exposure using an MS-251 Mobile Solar Reflectometer. Solar absorbance values were calculated from the reflectance values. Post-exposure solar reflectance was also measured for some samples at Lewis using a Perkin-Elmer Lambda-9 UV-VIS-NIR spectrophotometer. Emittance of each VUV exposed sample was measured at LTV using a DB-100 reflectometer.

The difference between UV exposure and VUV exposure refers to the wavelength range of the radiation. Although there is a negligible percent of solar radiation in this shorter wavelength range (below 200 nm, intensity ≤ 3 W/m²) as compared to the whole ultraviolet wavelength range (up to 400 nm, intensity = 123 W/m²), VUV provides higher energy radiation and its effect on materials in the space environment must be evaluated.⁹

Atomic Oxygen Exposure

Materials were exposed in a plasma asher (SPI Plasma Prep II), that was run with a background gas of air.

Samples were exposed to an effective fluence of 2×10^{21} atoms/cm² based on the mass loss of Kapton. Effective flux during ashing varied between 4.5×10^{15} and 7×10^{15} atoms/cm²sec.

Ram atomic oxygen fluence on Space Station Freedom surfaces in a constant density orbit over a period of 30 years is expected to be approximately 1.5×10^{23} atoms/cm².¹⁶ The orientation of the SDR surfaces is ideally expected to be edge-on, 90°, to the ram direction. An estimate of the amount of atomic oxygen that surfaces in this orientation will experience is 4.4% of the ram fluence.¹⁷ However, a conservative estimate of the error in this anticipated orientation may be 5° off in either direction from the edge-on orientation which would cause the radiator surfaces to vary between 85° and 95° with respect to ram. In this case, the average amount of atomic oxygen fluence these surfaces will experience is 5.7% of the ram fluence.¹⁷ Using this assumption, the expected atomic oxygen fluence on SDR surfaces is expected to be 8.6×10^{21} atoms/cm² over 30 years. Therefore, the exposure level used in these experiments, 2×10^{21} atoms/cm², represents approximately 23% of full life or 7 years in the Space Station Freedom environment. In order to assure durability, however, surfaces are to be designed to be durable to conditions of much greater fluence. The SDR surfaces are to be designed for exposure to an atomic oxygen flux of 3.35×10^{13} atoms/cm²s, which represents a fluence of 3.36×10^{22} atoms/cm² over 30 years.¹⁸ So the exposures performed here represent only 6% of the design life.

The atomic species in the air plasma are at thermal energies, approximately 0.1 eV. This is considerably lower than the energy of oxygen atoms colliding with the orbiting Space Station, approximately 4.5 eV. Also, the directionality of attack of the atomic species in the plasma asher is random, whereas the Space Station Freedom orbit for the radiator surface allows for a sweeping ram direction of attack. Chemically, the processes of atomic oxygen damage have been observed to be similar between the asher environment and the space environment; materials which survive the asher usually survive the LEO environment, and materials which degrade in the asher undergo degradation in LEO. However, the results of asher exposures are qualitative rather than quantitative, so that the asher is a good instrument to use for determining whether or not a material will degrade, but not for quantitative determination of the rate of degradation.

Prior to ashing, Kapton witness coupons were dehydrated for at least two days in a desiccator at a pressure of approximately 60 mTorr so that the measured mass would not be in error due to absorbed moisture. Before

and after exposure, solar reflectance and emittance of the samples were measured at LTV using a MS-251 Mobile Solar Reflectometer and a DB-100 Reflectometer, respectively. Optical micrographs were also taken of the samples after exposure.

Vacuum Thermal Cycling

Samples were vacuum thermal cycled for 10 to 15 cycles between -100°F and +300°F, with a 15 minute "soak" during which the sample remained at temperatures between +297°F and +304°F. The temperature was measured by using a thermocouple embedded and epoxied in the surface of a representative sample. Optical micrographs of the samples were taken before and after vacuum thermal cycling to observe cracking or other macroscopic surface morphology changes. Samples that did not show cracking were vacuum thermal cycled for additional cycles up to 25.

Results

Tables III, IV and V show changes in optical properties due to UV exposure, VUV exposure and plasma ashing, respectively. In discussing the changes in optical properties, measurements which were made using the same instrument both before and after exposure will be compared. Additional measurements are provided to show the agreement of results among various instruments.

UV Exposure

Table III shows the summary of changes in optical properties for the materials that were exposed to UV radiation. Among the white paint coatings, Z-93, YB-71 and the S13G/LO materials, the post-exposure emittance values were acceptably within the 0.9 requirement. These materials showed changes in the in situ-measured solar absorptance values of 0.02 or less upon exposure to UV as shown in Figure 1a. The only exception was a YB-71 sample that showed an increase in solar absorptance of 0.09. This was considered to be anomalous, so a second sample of YB-71 was tested. This sample showed a lower initial value solar absorptance and a negligible change in solar absorptance.

The second-surface metallized Teflon coatings, silicon dioxide coated silvered Teflon ($\text{SiO}_2/\text{FEP}/\text{Ag}/\text{Inconel}$), silicon dioxide coated aluminized Teflon ($\text{SiO}_2/\text{FEP}/\text{Al}$) and cerium oxide coated aluminized Teflon ($\text{CeO}_2/\text{FEP}/\text{Al}$) showed negligible changes in emittance, but slight changes in solar absorptance as shown in Table III and Figure 1b. The solar absorptance of silicon dioxide coated silvered Teflon increased by 0.05, and the silicon dioxide coated aluminized Teflon increased by 0.04 upon exposure to 1000 equivalent sun hours (ESH) of UV radiation. The cerium oxide coated aluminized Teflon showed the largest increase in solar absorptance of 0.09 from 0.23 to 0.32. At this level of exposure, the changes in solar absorptance do not appear to level off indicating that there may be continued change with further exposure.

The anodized aluminum samples (0.5 mil and 1.0 mil oxide) showed negligible changes in emittance and solar

absorptance upon exposure to 1000 ESH of UV as shown in Table III and Figure 1c.

VUV Exposure

The results of these tests are shown in Table IV. Z-93, YB-71 and the S13G/LO materials showed changes in emittance within 0.02 which is within instrument accuracy. Exposure to VUV radiation caused significant increases in the solar absorptance of the S13G/LO materials. The increases for the -41, -51 and -1 were 0.19, 0.29 and 0.29, respectively, so that the final solar absorptance values were at or above the requirement for solar absorptance values of ≤ 0.3 . Appearance of the S13G/LO coatings changed from white to tan in color as a result of the VUV exposure. The Z-93 sample showed a decrease of 0.05 in solar absorptance. A decrease in solar absorptance is not considered to be damaging to the optical performance of the material. The YB-71 showed an increase of 0.06 in its solar absorptance value from 0.08 to 0.14, still well within the ≤ 0.3 requirement. Visual inspection of the Z-93 and YB-71 showed that the coatings were slightly yellowed as a result of exposure.

The second-surface metallized Teflon materials $\text{SiO}_2/\text{FEP}/\text{Ag}/\text{Inconel}$ and $\text{SiO}_2/\text{FEP}/\text{Al}$ showed negligible changes in emittance but large increases in solar absorptance of 0.11 and 0.12, respectively. The cerium oxide coated aluminized Teflon showed a 0.01 decrease in emittance, which is considered to be negligible, and a 0.08 increase in solar absorptance giving a final solar absorptance value of 0.31. This is higher than the end-of-life maximum solar absorptance requirement for the radiator surfaces.

The anodized aluminum materials (0.5 mil and 1.0 mil oxide) showed negligible changes in emittance. The 0.5 mil anodized aluminum showed a decrease of 0.08 in solar absorptance which is not considered to be damaging to the optical performance of the surface. The 1.0 mil anodized aluminum maintained its solar absorptance value of 0.21.

The plasma sprayed alumina coatings showed a negligible change in emittance but an increase in solar absorptance of 0.05, from 0.28 to 0.32, beyond the end-of-life maximum requirement of 0.3.

Atomic Oxygen Exposure

The results of these tests are shown in Table V. The white paint coatings, Z-93, YB-71 and the S13G/LO materials, showed negligible changes in emittance upon exposure in the air plasma asher. Z-93 and the S13G/LO materials showed solar absorptance changes within instrument accuracy. By far, the most significant change in optical properties was observed with YB-71. Upon visual inspection the color of the coating had changed from white to bluish gray. Because of this result, another YB-71 sample was exposed to a plasma asher run with oxygen feed gas. This sample showed a significantly lower solar absorptance change upon exposure to a greater value of fluence as shown in Figure 2 and Table V.

The second-surface metallized Teflon materials, $\text{SiO}_2/\text{FEP}/\text{Ag}/\text{Inconel}$ and $\text{SiO}_2/\text{FEP}/\text{Al}$ showed negligible changes in emittance. An increase in solar absorptance of 0.05 was observed for $\text{SiO}_2/\text{FEP}/\text{Al}$, while the change for $\text{SiO}_2/\text{FEP}/\text{Ag}/\text{Inconel}$ was within instrument accuracy.

CeO₂/FEP/Al showed an increase in emittance of 0.02 and an increase in solar absorptance of 0.05 upon exposure in the asher.

The 0.5 mil and 1.0 mil anodized aluminum samples and the plasma sprayed alumina samples showed negligible changes in emittance and absorptance upon exposure in the air plasma asher.

Surface Morphology Changes due to Vacuum Thermal Cycling and Atomic Oxygen Exposure

Optical micrographs of unexposed samples of the white paint thermal control coatings Z-93, YB-71, S13G/LO-1 and S13G/LO-41 are shown in Figure 3a-d. In comparing the surface morphology of the as-received materials at 8x magnification, Z-93 showed a more homogeneous appearance and a finer texture than the S13G/LO materials. As-received YB-71 showed the finest texture and the most homogeneous appearance of the white thermal control coatings. These materials and the plasma sprayed alumina coating (Figure 3e) showed no spalling or surface cracking due to exposure to 25 vacuum thermal cycles or 2×10^{21} atoms/cm² effective fluence of atomic oxygen exposure. S13G/LO-51 appears to undergo slight cracking upon exposure to air plasma as shown in Figure 3f.

The SiO₂/FEP/Al and SiO₂/FEP/Ag/Inconel samples contained surface scratches prior to thermal cycling as shown in Figure 3g-h. With the optical microscope, the scratches appeared when the sample was in a specific orientation with respect to the illumination lamp used while taking the micrograph. These scratches were all uniform and nearly parallel to one another. Before thermal cycling, these scratches were the only surface details observed for these samples. After 15 vacuum thermal cycles, a variety of surface defects appeared on the SiO₂/FEP/Aluminum as shown in Figure 3g, and cracking was observed on SiO₂/FEP/Silver/Inconel as shown in Figure 3h. In order to show these defects and cracks in the micrographs, it was necessary to orient the sample with respect to the illumination source such that the original scratches were not observed. Ashing also caused surface cracking of the SiO₂/FEP/Aluminum and the SiO₂/FEP/Silver/Inconel as shown in Figure 3g-h; however, this cracking appeared to have a minimal effect on optical properties, since the changes in emittance and solar absorptance were small as shown in Table V.

Surface defects and cracks appeared upon exposure of the CeO₂/FEP/Aluminum material to 15 vacuum thermal cycles as shown in Figure 3i. Air plasma ashing appeared to cause significant erosion of the cerium oxide surface layer of this coating exposing much of the FEP Teflon underneath. Optical micrographs of the sample exposed to air plasma ashing showed some spalling and removal of the cerium oxide coating exposing the surface of the Teflon as shown in Figure 3i. The cerium oxide appears as the smoother surface at the top of the photograph of the ashed sample. These results indicate that this material would not be durable in the atomic oxygen environment of LEO, since the protective coating erodes exposing Teflon, a potential contaminant to nearby surfaces. Surface cracks appeared on both the 0.5 mil and 1.0 mil anodized aluminum coating as a result of exposure to 15 thermal cycles as shown in Figure 3j-k. However, the anodized coating appears to be intact;

no flaking of the oxide was observed. Air plasma ashing did not cause any surface morphology changes in the anodized aluminum materials.

Discussion

White Thermal Control Coatings

The white thermal control coatings, Z-93, S13G/LO-41, S13G/LO-1, S13G/LO-51 and YB-71 maintained emittances which were within the ≥ 0.9 requirement upon exposure to UV, VUV and atomic oxygen exposure as shown in Tables III, IV, and V, respectively. Of the materials tested in this effort, these were the only ones which met this emittance requirement.

The solar absorptance change for the oxygen plasma ashed YB-71 sample was small, whereas the air plasma ashed YB-71 sample showed a large solar absorptance increase. The reason for the difference in results between the air plasma and oxygen plasma exposed samples appears to be a result of a reaction of the pigment with the nitrogen present in the air plasma asher. Since the amount of nitrogen present in LEO is very small, this magnitude of degradation is not expected to occur in LEO. In general, the oxygen plasma asher exposure more closely simulates the LEO atomic oxygen environment; however, air plasma is used normally for convenience. In this testing, YB-71 appears to be the only nitrogen sensitive material, since all other materials showed insignificant changes in optical properties upon air plasma ashing.

The white paint coatings appeared to be durable to vacuum thermal cycling since cracking was not observed. The S13G/LO-51 and -1 materials did not appear to be durable to exposure to VUV radiation (100-200 nm wavelength), since their solar absorptance values after exposure were not within the end-of-life solar absorptance requirement of ≤ 0.3 . The S13G/LO-41 material showed a solar absorptance value of 0.30 upon exposure to 1000 ESH VUV which is within the requirement; however, the level of testing here did not represent the full 30 year life, and if the solar absorptance were to increase with further testing, the requirement would not be met. These materials showed durability to UV radiation (200-400 nm wavelength), however. Additionally, the S13G/LO-51 underwent slight cracking upon air plasma ashing which may indicate a lack of durability in the atomic oxygen environment.

Based on this testing, Z-93 and YB-71 were the best performers with respect to optical properties and LEO environmental durability.

Second-Surface Metallized Teflon Coatings

SiO₂/FEP/aluminum and SiO₂/FEP/silver/inconel showed negligible changes in emittance upon exposure to UV, VUV and air plasma ashing; however, their emittance values did not meet the beginning-of-life requirement. These samples showed a lack of durability to VUV exposure as evidenced by solar absorptance changes. Only small changes in solar absorptance were observed for samples exposed to UV and air plasma ashing.

Despite cracking of the SiO₂ surfaces upon exposure to air plasma ashing and vacuum thermal cycling, the integrity

of these coatings did not appear to be compromised. No loss of the cracked SiO₂ coating was observed using optical microscopy, and only small areas of FEP were exposed between the cracks. This SiO₂ coating, even with cracks, would be necessary in order to keep the underlying FEP from becoming a contaminant to surfaces near the radiator in LEO.

The CeO₂/FEP/Aluminum sample showed negligible changes in emittance upon exposure to UV and VUV and an increase in emittance of approximately 0.03 upon exposure to air plasma ashing. Solar absorptance of the as-received material was greater than the beginning-of-life requirement of ≤ 0.2 and, upon exposure to the simulated LEO environments, increases in solar absorptance resulted in final values of solar absorptance close to or above the end-of-life requirement of ≤ 0.3 . Visual inspection of this sample after ashing showed a great loss of cerium oxide from the surface and texturing of the underlying Teflon surface, which is characteristic of atomic oxygen exposed Teflon.^{19, 20} This texturing of Teflon would likely be the reason for the increase in emittance of 0.03. Because of the loss of the CeO₂ coating upon exposure to atomic oxygen, and because the solar absorptance increases to values near or greater than 0.3 upon exposure to LEO simulation environments, this material would not be appropriate for use on radiator surfaces in LEO.

Sulfuric Acid Anodized Aluminum

The anodized aluminum materials showed negligible changes in emittance and solar absorptance increases of 0.03 or less upon exposure to the simulated LEO environments of UV, VUV and air plasma ashing. Although the surfaces of these samples underwent cracking upon exposure to 15 vacuum thermal cycles, the anodized coating still appeared to be intact.

Overall these materials appeared to be durable to the simulated LEO environmental effects although their emittance values did not meet the ≥ 0.9 requirement.

Plasma Sprayed Alumina

Samples of plasma sprayed Al₂O₃ showed negligible changes in emittance and small changes (≤ 0.03) in solar absorptance upon exposure to VUV and air plasma ashing; however, the emittance values did not meet the ≥ 0.9 requirement.

Performance of Candidate Radiator Materials

It is necessary to consider the mass per unit area of the radiator coatings when evaluating their performance. Table VI includes measured values of mass/area after air plasma ashing, vendor specifications for the unexposed coatings, emittance after ashing and solar absorptance after VUV exposure for each. The post-exposure emittance and solar absorptance values are given to show the greatest amount of damage to optical properties observed in this testing. The materials are listed in order of decreasing post-ashing emittance values. Z-93 has the highest emittance value so that the least amount of surface will be needed to provide the required thermal control, and it has a relatively low mass per area. YB-71 has the highest value of mass per

area, greater than three times that of Z-93, and the emittance is slightly lower than Z-93 so that a slightly greater amount of surface area will be required to provide the same thermal control. The lowest mass per area values are for the 0.5 mil and 1.0 mil aluminum anodize coatings. However, because they have emittance values which are considerably lower than Z-93, a substantially greater amount of surface would be needed to provide the same thermal control.

Concluding Remarks

In terms of performance and durability upon exposure to the simulated LEO environments, the most appropriate coatings for use on solar dynamic power module radiator surfaces of those tested in this effort were Z-93 and YB-71, since they maintained their superior optical properties upon exposure to UV radiation, VUV radiation and atomic oxygen and did not show cracking upon atomic oxygen exposure and vacuum thermal cycling.

This comprehensive screening effort gives an indication of the durability and performance of radiator materials upon being subjected to the individual environmental effects of solar ultraviolet radiation, atomic oxygen and thermal cycling. These results alone are not adequate for determining the overall LEO durability of radiator coatings. It is also important to determine the effects of other environmental hazards such as micrometeoroid and debris impacts and contamination. Additionally, the most promising coatings should be tested in longer duration exposures to a combination of LEO simulated environments to allow predictions to be made regarding performance and durability over their anticipated 30-year lifetime.

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TABLE I - REQUIREMENTS FOR SOLAR DYNAMIC AND PHOTOVOLTAIC RADIATOR COATINGS

	Photovoltaic Power Module	Solar Dynamic Power Module
Life	30 years	30 years
Solar Absorptance		
Beginning of life	0.2	0.2
End of life	0.2	0.3
Emittance		
Beginning of life	0.9	0.9
End of life	0.9	0.9
Operating Surface Temperature Range	-25°F to -10°F	250 ± 3°F
Operating Thermal Cycle Requirements	175,320 cycles	175,320 cycles
Startup and Shutdown Temperature Range Requirements	-107°F to -120°F	-100°F to -250°F
Startup and Shutdown Thermal Cycle Requirements	100 cycles	100 cycles
Vacuum Ultraviolet Radiation Durability Requirements		10,320 equivalent sun hours
Atomic Oxygen Durability Requirements		3.36 x 10 ²² atoms/cm ² with average flux of 3.35 x 10 ¹³ atoms/cm ² · s

TABLE II - INSTRUMENTS FOR OPTICAL
PROPERTIES MEASUREMENT

Test Site	ε Measurement	α Measurement
NASA Lewis	1. Hohlräum Reflectometer 2. DB-100	Perkin-Elmer 9 Spectrophotometer
NASA Langley	DB-100 Reflectometer	Beckman DK-1A Spectrophotometer
LTV M&E Co.	DB-100 Reflectometer	MS-251 Mobile Solar Reflectometer

TABLE III - EFFECTS OF UV EXPOSURE
ON OPTICAL PROPERTIES

1000 ESH, 2 Solar Constants

Material	Emittance		Absorptance	
	Before	After	Before	After
Z-93	0.92*H	0.92** 0.92*	0.17* 0.18	0.11** 0.17 0.13*
Si3G/LO-41	0.90*H	0.89** 0.90*	0.16* 0.16	0.11** 0.17 0.13*
Si3G/LO-1	0.91*H	0.90** 0.91*	0.19* 0.18	0.13** 0.20 0.15*
Si3G/LO-51	0.88*H	0.89** 0.89*	0.15* 0.15	0.11** 0.16 0.12*
YB-71	0.90*H	0.89** 0.89*	0.11* 0.10	0.09** 0.19
	0.89	0.89 0.90*	0.07	0.07 0.07*
CeO ₂ /FEP/Al	0.80	0.81 0.81*	0.25* 0.23	0.29* 0.32
1.0mil Anodized Al	0.83	0.83 0.84*	0.20* 0.18	0.20* 0.19
0.5mil Anodized Al	0.78	0.78 0.80*	0.17* 0.15	0.19* 0.17
SiO ₂ /FEP/Al	0.76	0.76 0.76*	0.08	0.10 0.11*
SiO ₂ /FEP/Ag/Inc	0.76	0.76 0.76*	0.12	0.17 0.19*

Measurements made at Langley (DB-100, DK-1A)
unless otherwise noted

* Measured at Lewis (DB-100, PE Lambda-9)

** Measured at Lewis (Hohlräum)

*** Measured at LTV (DB-100, MS-251)

TABLE IV - EFFECTS OF VUV EXPOSURE
ON OPTICAL PROPERTIES

1000 ESH, 3 Solar Constants

Material	Emittance		Absorptance	
	Before	After	Before	After
Z-93	0.92	0.92 0.93*	0.22	0.17 0.18*
Si3G/LO-41	0.90	0.89 0.90*	0.11	0.3 0.34*
Si3G/LO-1	0.91	0.89 0.90*	0.12	0.33 0.37*
Si3G/LO-51	0.89	0.88 0.88*	0.10	0.39 0.41*
YB-71	0.90	0.89 0.90*	0.08	0.14 0.11*
CeO ₂ /FEP/Al	0.81	0.80 0.81*	0.23	0.31* 0.28
1.0mil Anodized Al	0.83	0.82 0.85*	0.21	0.25* 0.21
Plasma Sprayed Al ₂ O ₃	0.80	0.80 0.80*	0.28	0.32 0.33*
0.5mil Anodized Al	0.78	0.78 0.81*	0.30*	0.22* 0.22
SiO ₂ /FEP/Al	0.76	0.75 0.76*	0.13	0.25 0.26*
SiO ₂ /FEP/Ag/Inc	0.76	0.75 0.76*	0.05	0.16 0.20*

* Measured at Lewis (DB-100, PE Lambda-9),
all others measured at LTV (DB-100, MS-251)

TABLE V - EFFECTS OF PLASMA ASHING
ON OPTICAL PROPERTIES

Total Fluence = 2×10^{18} atoms/cm²

Material	Emittance		Absorptance	
	Before	After	Before	After
Z-93	0.93	0.92 0.92*	0.12	0.15 0.14*
Si3G/LO-41	0.90	0.90 0.90*	0.12	0.12 0.13*
Si3G/LO-1	0.91	0.90 0.90*	0.13	0.15 0.17*
Si3G/LO-51	0.89	0.89 0.90*	0.11	0.12 0.12*
YB-71	0.90	0.89 0.90*	0.08	0.44 0.36*
YB-71 (Oxygen Plasma, 3.5×10^{18} atoms/cm ²)			0.08*	0.14*
CeO ₂ /FEP/Al	0.81	0.83 0.85*	0.23	0.28 0.26*
1.0mil Anodized Al	0.82	0.82 0.84*	0.21	0.21 0.20*
Plasma Sprayed Al ₂ O ₃	0.80	0.80 0.81*	0.27	0.26 0.26*
0.5mil Anodized Al	0.78	0.78 0.80*	0.17	0.20 0.18*
SiO ₂ /FEP/Al	0.76	0.77 0.78*	0.13	0.18 0.18*
SiO ₂ /FEP/Ag/Inc	0.76	0.76 0.76*	0.05	0.06 0.07*

* Measured at Lewis (DB-100, PE Lambda-9)
all others measured at LTV (DB-100, MS-251)

TABLE VI - PERFORMANCE OF CANDIDATE RADIATOR COATINGS

Material	Emittance After Ashing	Solar Absorptance After VUV Exposure	Mass/Area (g/cm ²)	
			Measured (after ashing)	Vendor Specs. (unexposed)
Z-93	0.920	0.18	0.018±0.0014	0.0162
S13G/LO-41	0.901	0.34	0.036±0.0014	0.0376
S13G/LO-1	0.898	0.37	0.054±0.0014	0.0561
S13G/LO-51	0.893	0.41	0.041±0.0014	0.0413
YB-71	0.887	0.14	0.060±0.0014	0.0572
CeO ₂ /FEP/Al/Isotac	0.834	0.25	0.031±0.0014	0.036
1.0 mil Anodize (on Al)	0.816	0.33	---	0.0069
Plasma sprayed Al ₂ O ₃	0.804	0.33	0.054±0.0014	---
0.5 mil Anodize (on Al)	0.779	0.22	---	0.0034
SiO ₂ /FEP/Al/Isotac	0.770	0.26	0.035±0.0014	0.036
SiO ₂ /FEP/Ag/Iconel/Isotac	0.760	0.20	0.032±0.0014	0.036

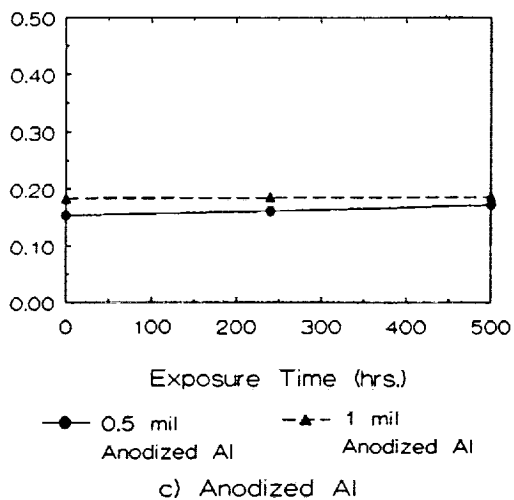
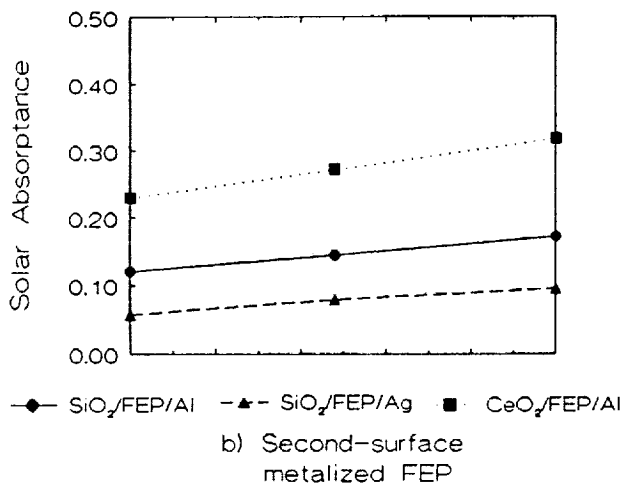
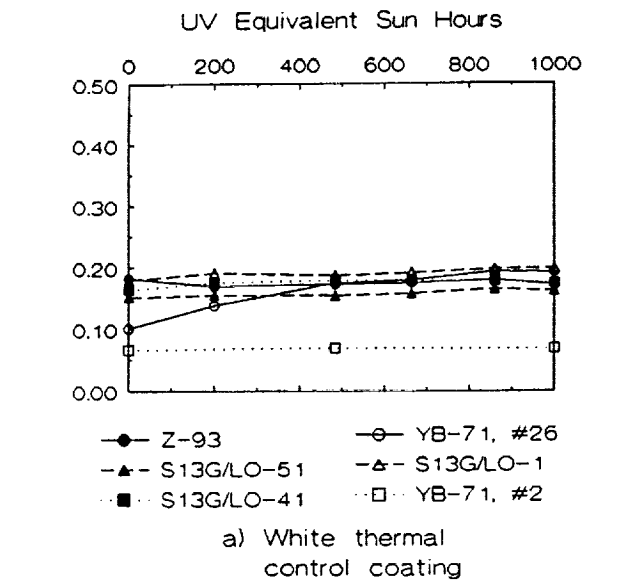


Figure 1: Solar absorbance as a function of UV exposure

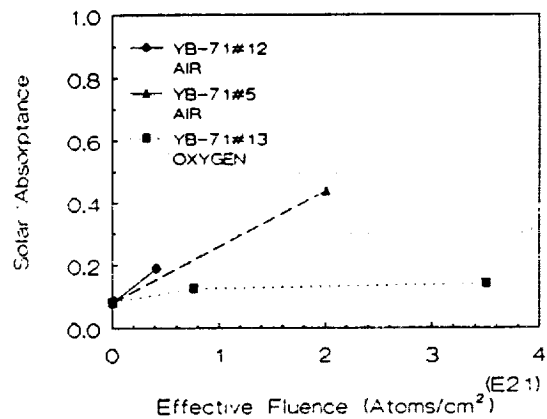


Figure 2: Solar absorbance of YB-71 as a function of oxygen and air plasma ashing

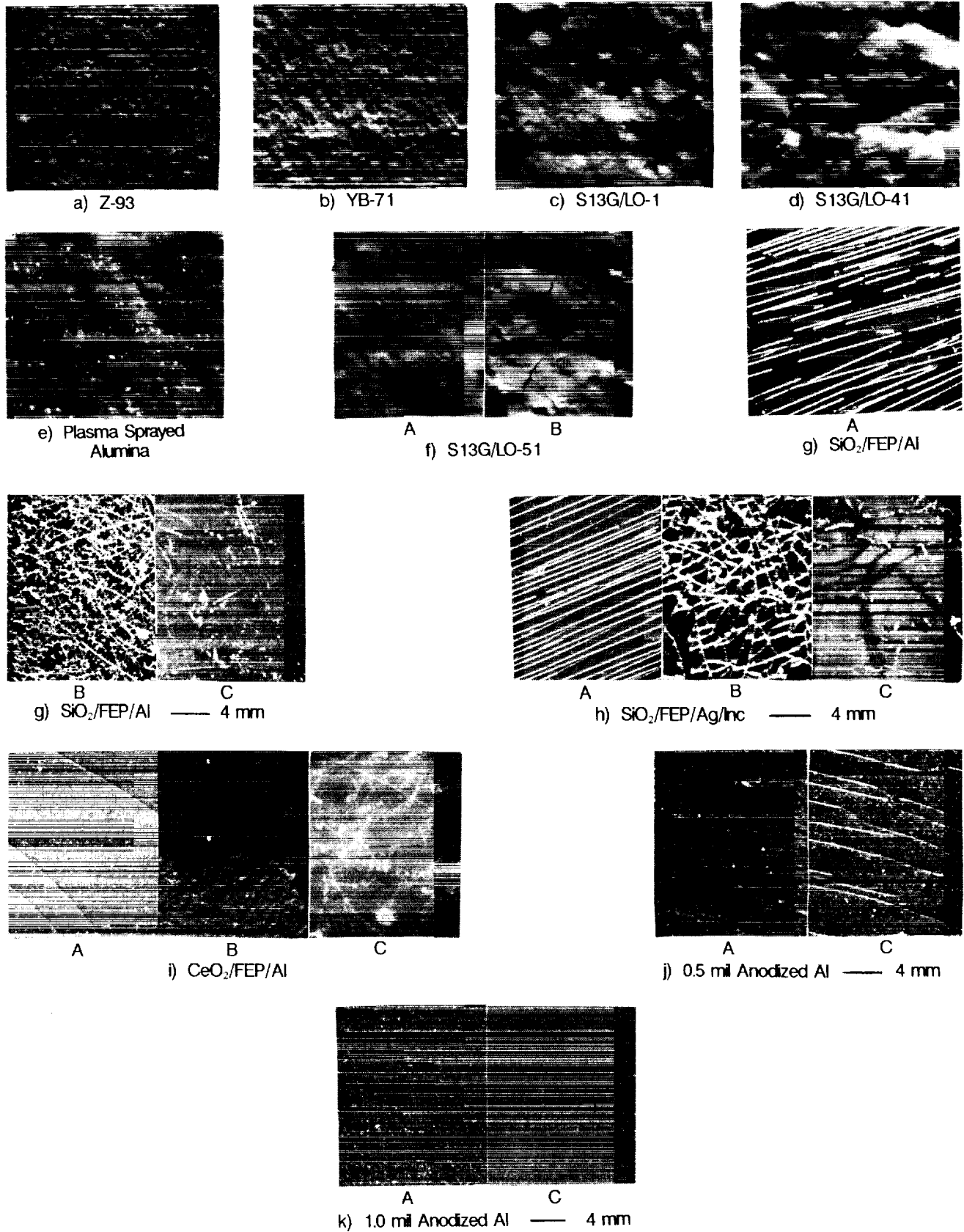


Figure 3: Effects of air plasma ashing and thermal cycling on surface morphology of candidate radiator materials (A: unexposed, B: air plasma ashed, C: thermal cycled) Scale — 1mm, except where noted



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16. Abstract Thermal control coatings with high thermal emittance and low solar absorptance are needed for Space Station Freedom (SSF) solar dynamic power module radiator (SDR) surfaces for efficient heat rejection. Additionally, these coatings must be durable to low earth orbital (LEO) environmental effects of atomic oxygen, ultraviolet radiation and deep thermal cycles which occur as a result of start-up and shut-down of the solar dynamic power system. Eleven candidate coatings were characterized for their solar absorptance, α_s, and emittance, ϵ, before and after exposure to ultraviolet (UV) radiation (200-400 nm), vacuum ultraviolet (VUV) radiation (100-200 nm) and atomic oxygen. Results indicated that the most durable and best performing coatings were white paint thermal control coatings Z-93, zinc oxide pigment in potassium silicate binder, and YB-71, zinc orthotitanate pigment in potassium silicate binder. Optical micrographs of these materials exposed to the individual environmental effects of atomic oxygen and vacuum thermal cycling showed that no surface cracking occurred.					
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