Review of End-of-Life Thermal Control Coating Performance

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Abstract

White thermal control coatings capable of long term performance are needed for Fission Surface Power (FSP) where heat from a nuclear reactor placed on the surface of the Moon must be rejected to the environment. The threats to thermal control coating durability on the lunar surface are electrons, protons, and ultraviolet radiation. The anticipated damage to the coating is a gradual darkening over time. The increase in solar absorptance would, in essence, add a cyclic heat load to the radiator. The greater the darkening, the greater the added heat load. The cyclic heat load could ultimately impart a cyclic influence on FSP system performance. No significant change in emittance is anticipated. Optical properties degradation data were found in the open literature for the Z-93 series of thermal control paints. Additional optical properties degradation data were found from the Lunar Orbiter V mission, the Optical Properties Monitor, and the Materials International Space Station Experiment. Anticipated end-of-life thermal control coating performance for a FSP installation is postulated. With the FSP installation located away from landing and launching areas, and out of line-of-sight, lunar dust from human activity may not be a threat. The benefits of investing in next generation thermal control paint chemistry are explored.

Introduction

The U.S. Space Exploration Policy includes returning to the Moon and establishing a manned outpost. Fission Surface Power (FSP) is being considered as a power source. Each FSP installation would be located remotely, perhaps 100 m to a kilometer away from the outpost's habitat, and would provide 6 kW of electric power. Up to five FSP installations are envisioned. Such an investment in outpost infrastructure would be expected to operate on the order of a decade or more. Although the energy conversion system has yet to be selected, radiators will play an important role in rejecting the waste heat from the reactor to the environment. A white thermal control coating will be needed on the radiator surface to minimize absorption of solar energy, and the coating will need to remain robust for the projected lifetime, at the desired operating temperatures, and in the midst of all the environmental threats found on the lunar surface. Not being considered are concepts that require an adhesive such as second surface mirrors or exotic concepts such as liquid droplet radiators.

Environmental threats include micrometeoroid impact, electrons, protons, ultraviolet radiation, neutrons, wide temperature swings, and lunar dust. To combat the threat of micrometeoroid impact, heat pipes will be utilized for redundancy to carry heat away from multiple cooling manifolds and light weight high thermal conductivity composite facesheets will be utilized to further distribute heat over a wide area, so that no single micrometeoroid impact will cause a single point failure. Candidate thermal control coatings are limited to the inorganic white paints owing to their high temperature of operation. The long term durability of the white thermal control coatings under lunar conditions are thought to be similar to those found in geosynchronous Earth orbit, determined in large part by electrons, protons, and ultraviolet radiation. Neutrons are an additional threat in the vicinity of the reactor depending on the amount of shielding around the reactor. Wide temperature operation is a concern as the FSP installation will require
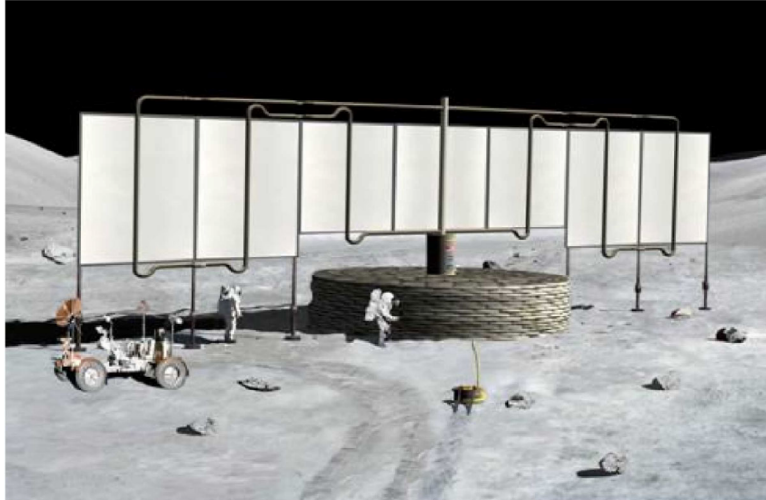
Figure 1.—Artist's rendition of a Fission Surface Power (FSP) installation on the Moon.

an initial cold soak in the dark for up to two weeks prior to deployment, followed by start-up and subsequent continuous operation at 125 °C for nearly a decade. Once operating, interruptions in service should be infrequent. Ground-based contamination should be minimal. Construction activities on the lunar surface offer the threat of contamination from lunar dust. Although the FSP installation is to be located away from a lunar outpost's launching and landing area, lunar dust from launching and landing may also offer a threat. Dust ejected on launch and landing may form a debris cloud that orbits the Moon. The perigee of the orbit would be near the surface where the launch or landing took place, pelting nearby structures with dust particles. Figure 1 shows an artists rendition of a FSP installation with radiators deployed.

To understand and predict end-of-life optical performance for a FSP application, a literature study was conducted to identify the degradation of the Z-93 series of paints (defined here as Z-93, Z-93P, and AZ-93). Issues discussed in the literature include particle radiation, ultraviolet radiation, thermal cycling, contamination, atomic oxygen and other synergistic effects, and new technology development.

Ultraviolet Radiation, Protons, and Electrons

White thermal control coatings darken upon exposure to ultraviolet radiation, protons, and electrons. Various thermal control coatings, including Z-93, have been exposed to these threats in the laboratory, individually and synergistically. Y. Harada and R.J. Mell of IIT Research Institute and D.R. Wilkes of AZ Technology studied exposure of Z-93, a white thermal control paint consisting of zinc oxide pigment in a potassium silicate binder, to ultraviolet (UV) radiation alone and found that after 800 equivalent sun hours (ESH) of UV there was an increase in solar absorptance of 0.010. After exposure to 5000 ESH of UV, the increase in solar absorptance was 0.028. No change in infrared emittance was observed (ref. 1).

L.B. Fogdall and S.J. Leet, et al., of the Boeing Company, tested the effects of ultraviolet radiation, protons, and electrons on Z-93P and other coatings, individually and synergistically. Samples were bombarded with either 2400 ESH of UV, or 2400 ESH of UV along with a fluence of 2.3×10^{15} 40 keV electrons and a fluence of 7×10^{13} 40 keV protons. The experiment was to simulate a 12 year orbit life, at an altitude of 1375 km and an inclination of 85°. Table 1 shows the data for Z-93P only. The thermal emittance showed no change when exposed to the simulated space environment. The solar absorptance changed under UV exposure alone, with an increase of 0.011 to 0.013, and changed more when the sample was exposed to the combined effects, with an increase of 0.022. A sample that was allowed to recover in air showed no additional change in solar absorptance (ref. 2).

TABLE 1.—Z-93P EXPOSED TO ULTRAVIOLET RADIATION, ELECTRONS, AND PROTONS

Sample ID	Radiation exposure	Solar absorptance before irradiation, (in vacuum)	Solar absorptance after irradiation, (in vacuum)	Solar absorptance ~3 days after test, (in air)	Thermal emittance before irradiation, (in air)	Thermal emittance after irradiation, (in air)
Z-93P-2 and -3	e/p/UV	0.136 0.136	0.158 0.158	----- 0.157	0.921 0.919	0.919 0.919
Z-93P-6 and -1	UV only	0.136 0.136	0.149 0.147	----- -----	0.919 0.920	0.919 0.919

An experiment by C.A. Cerbus of the University of Dayton Research Institute and P.S. Carlin of the USAF Wright Laboratory Materials Directorate tested the effects of UV and electrons on Z-93 and YB-71. YB-71 consists of a zinc orthotitanate pigment in a potassium silicate binder. The experiment was done at the U.S. Air Force Research Laboratory Materials and Manufacturing Directorate's Space Combined Effects Primary Test Research Equipment Facility (SCEPTRE). Two tests were done on the samples, named 93QV01 and 93QV02, and lasted 1000 and 1265 hr, respectively. Exposures were accelerated slightly by selecting equivalent ultraviolet sun (EUVS) intensities greater than one sun, and were monitored with time up to 3000 ESH. Two electron energies were utilized, 1 and 10 keV representing trapped and solar wind electrons, accelerated by a factor of 5.5 compared to geosynchronous orbit, yielding fluences on the order of 10^{16} electrons/cm^2. Table 2 shows the results.

TABLE 2.—SOLAR ABSORPTANCE OF Z-93, YB-71, AND YB-71P

Material	EUVS, (250 to 400 nm)	1 keV fluence, (e-/cm^2)	10 keV fluence, (e-/cm^2)	Pretest solar absorptance, (in vacuum)	Posttest solar absorptance, (in vacuum)	Change in solar absorptance, (in vacuum)
93QV01 (1000 hr)						
Z-93	3.2	1.66E16	8.32E15	0.135	0.185	0.050
YB-71	2.6	1.66E16	8.32E15	0.087	0.232	0.145
YB-71	1.7	1.66E16	8.32E15	0.090	0.220	0.130
YB-71P*	2.1	1.66E16	8.32E15	0.089	0.282	0.193
YB-71P*	2.9	1.66E16	8.32E15	0.092	0.363	0.271
93QV02 (1265 hr)						
Z-93	1.2 (est.)	2.03E16	1.01E16	0.134	0.178	0.044
YB-71	2.8	2.03E16	1.01E16	0.097	0.297	0.200
YB-71P*	2.7	2.03E16	1.01E16	0.106	0.419	0.313
YB-71P	2.5	2.03E16	1.01E16	0.093	0.266	0.173
YB-71P	1.1 (est.)	2.03E16	1.01E16	0.097	0.233	0.136

*Suspected bad batch.

The combined effects of ultraviolet radiation and electrons showed for Z-93 an increase in solar absorptance in the range of 0.044 to 0.050. Figure 2 shows solar absorptance as a function of equivalent sun hours for all samples. Z-93 degraded less than every other case of YB-71, an indicator of its superior durability. In addition, the chart shows that the greatest degradation in solar absorptance occurs initially and tapers off with time (ref. 3). Indeed, for Z-93 the degradation reaches a plateau after 2000 ESH suggesting a Fission Surface Power plant would see no further degradation after this time.

Although Z-93 was first developed by the Illinois Institute of Technology Research Institute (IITRI) for use on aluminum, another manufacturer has emerged. AZ Technology now manufactures a version of the paint designated AZ-93. In addition, AZ Technology has developed a primer allowing their paint to be utilized on composite surfaces in addition to aluminum. D.A. Jaworske of NASA Glenn Research Center (GRC) studied the durability of AZ-93 and MLP-300 primer on carbon-carbon and carbon-polyimide composites to electrons. Electron exposure was accomplished at E-beam Services, Lebanon, Ohio, utilizing an industrial accelerator. In this facility, the electron beam passes through a titanium window and is rastored over samples placed on a conveyer system. For this study, 4.5 MeV electrons were used.
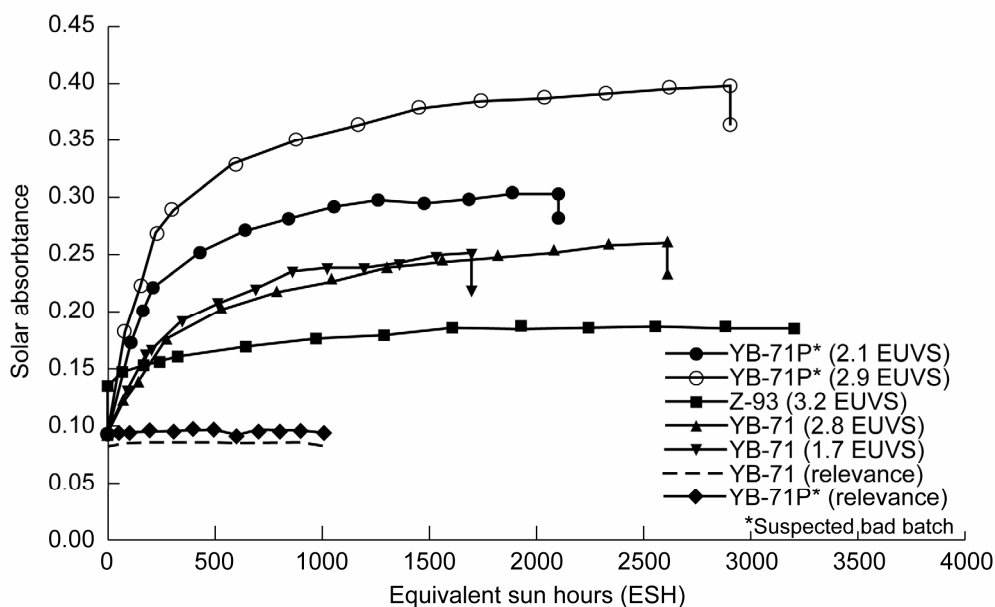
Figure 2.—SCEPTRE solar absorbtance history of Z-93P and YB-71, as-tested.

Repeated passes under the beam were arranged to yield a total exposure of 1010 MegaRads. The samples were purposely bagged in aluminized Mylar (Dupont Teijin Films) under inert gas while being exposed to the electron beam. Temperature strips placed nearby indicated that the maximum temperature did not exceed 125 °C. After electron exposure, the solar absorptance values of AZ-93 showed a slight increase in solar absorptance: with a change of 0.014 (0.119 to 0.133) for AZ-93 and epoxy primer on one carbon-carbon, 0.029 (0.118 to 0.147) for AZ-93 and epoxy primer on another carbon-carbon, and 0.038 (0.121 to 0.159) for AZ-93 and epoxy primer on carbon-polyimide. The infrared emittance values showed little change. Only trace peeling was observed after the ASTM D-3359 tape test, resulting in a value of 4A on a scale of 0A to 5A suggesting adequate bonding between paint and primer, and primer and composite (ref. 4).

In short, these laboratory test results offer the best glimpse on how Z-93P might respond to a FSP application on the lunar environment for a decade. Anticipated degradation in solar absorptance would likely be in the range of 0.010 to 0.050 and the rate of degradation would be greatest initially, tapering off quickly with time. Infrared emittance would likely remain unchanged.

Neutrons

C.L. Bowman, D.A. Jaworske, and M.K. Stanford of NASA Glenn Research Center and J. Persinger and T.E. Blue of The Ohio State University studied durability of the AZ-93 and MLP-300 primer system on carbon-carbon and carbon-polyimide composites under high energy, fast spectrum neutrons. Two neutron fluences were selected, 1.83×10^{13} neutrons/cm^2 and 1.74×10^{15} neutrons/cm^2, obtained at reactor operating powers of 3 and 100 kW, respectively. This range of neutron fluence was selected based on estimates of 10^{11} to 10^{12} neutrons/cm^2 for the Jupiter Icy Moons Orbiter heat rejection system (based on a shielded 500 KW$_{thermal}$ reactor). No observable discoloration was observed in the post-irradiated coupons and all coupons appeared congruent to their pristine counterparts. Although qualitative, no change in appearance to the unaided eye suggests little to no change in the solar absorptance of the thermal control paint under the given neutron irradiation conditions. Infrared emittance, as measured, showed no change. For the lower neutron fluence, all coupons had adhesion characteristics similar to their pristine counterparts, all at an ASTM D-3359 tape test value of 4A. For the higher neutron fluence, the adhesion

strength decreased, all to an ASTM D-3359 tape test value of 3A. The results indicated that the adhesion strength of thermal control paint is unaffected by the lower neutron fluence level, and the adhesion strength is affected by the higher neutron fluence level (ref. 5).

For a FSP application having reactor shielding comparable to the Jupiter Icy Moons Orbiter, or better, the impact of neutrons on the optical properties and adhesion characteristics of AZ-93 and MLP-300 primer applied to composite radiator panels should be negligible.

Atomic Oxygen and Contamination

Although oxygen is absent at the lunar surface, studies of Z-93 in the low Earth orbit environment are numerous and several are included here for completeness. Contamination is inseparable from the atomic oxygen discussion. In 1992, M.M. Hasegawa and H.W. Babel of McDonnell Douglas Space System Company estimated the optical properties of Z-93 after 30 years for the Space Station Freedom project. Estimations were carried out using a maximum expected value for the amount of outgassed contamination from the station and a docked orbiter. Ultraviolet radiation and bipropellant contamination were also considered. The calculated values included the predicted value of solar absorptance (α) after 30 years and the change in solar absorptance in that time. A typical beginning of life solar absorptance of 0.150 was used, and is best obtained at a paint thickness of 0.15 mm (0.006 in.) and above. The model summed contributions from: ground contamination, UV exposure during the first few thousand equivalent sun hours when contamination is low, in space outgassing contamination (based on Skylab contamination data), and bipropellant deposition. Figure 3 summarizes the contributions of each over time (ref. 6).
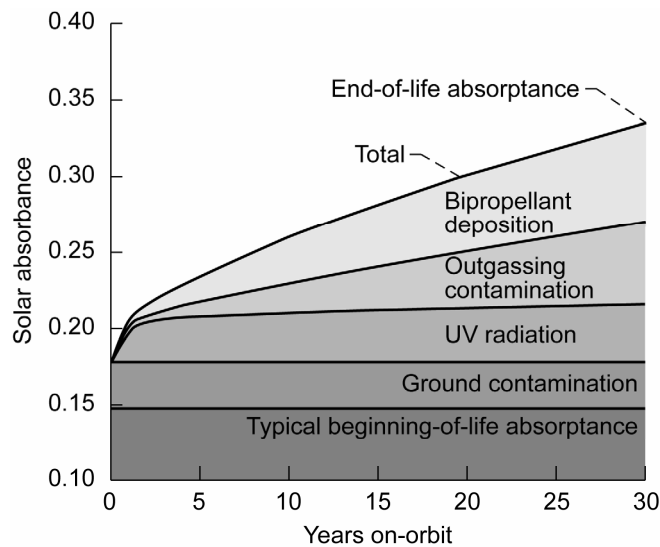

Figure 3.—Calculated change in the solar absorptance of Z-93P on International Space Station, with contributions separately identified.

M. Finckenor, of NASA Marshall Space Flight Center (MSFC), and J. Visentine, of Boeing, et al., exposed Z-93P and other materials to contamination, UV, and atomic oxygen (AO) (ref. 7). UV exposure was carried out at two different locations, Boeing-Huntington Beach, and AZ Technology. The AO exposure was carried out at MSFC. The two types of contamination were RTV-560 silicone and Tefzel (DuPont Company), which represented silicone-based and carbon-based outgassed materials, respectively. RTV-560 forms a silicate when in contact with AO. Tefzel is eroded by AO. Table 3 summarizes the data for Z-93.

TABLE 3.—OPTICAL PROPERTIES OF SILICONE AND ORGANIC CONTAMINATED Z-93P

Sample	Contamination	UV-HB, (ESH)	UV-AZ, (ESH)	AO-MSFC atoms/cm^2	Solar absorptance, (α)				
					Baseline	Post contamination	Post UV-HB	Post UV-AZ	Post-AO exposure
Z-93 P#058	None	0	1000	3.04E20	0.152	-----	-----	0.156	0.145
Z-93 P#054	None	0	1060	2.94E20	0.154	-----	-----	0.163	0.122
Z-93 P#030	RTV560	0	1000	3.74E20	0.148	0.154	-----	0.158	0.160
Z-93 P#020	RTV560	2000	1060	2.23E20	0.165	0.178	0.180	0.215	0.188
Z-93 P#031	Tefzel	0	1000	2.87E20	0.156	0.170	-----	0.264	0.169
Z-93 P#021	Tefzel	2000	1060	2.34E20	0.153	0.171	0.197	0.307	0.182 0.217

UV darkening was observed in all of the contaminated samples, with those contaminated by Tefzel exhibiting the greatest darkening. Sample Z-93 P#021 has two post-AO exposure values for solar absorptance because there were significant variations in the sample, and the values represent the maximum and minimum values of solar absorptance. All but sample Z-93 P#030 showed a recovery of optical properties after AO exposure.

R.R. Kamenetzky, J.A. Vaughn, M.M. Finckenor, and R.C. Linton of Marshall Space Flight Center tested the effects of simultaneous ultraviolet radiation and atomic oxygen on Z-93 and other thermal control coatings. It was found after exposure to 7.2×10^{20} atoms/cm^2 of atomic oxygen and 8000 ESH at 130 nm that both solar absorptance and infrared emittance of Z-93 were not significantly affected by the AO/UV exposure, remaining unchanged at 0.150 and 0.920, respectively (ref. 8).

In short, atomic oxygen and contamination are of concern in low Earth orbit. In the absence of outgassing and bipropellant contamination, modeling suggests a degradation in solar absorptance near 0.050, with greatest degradation initially and tapering off quickly with time.

Flight Data

Calorimetric studies have been conducted by tracking the increase in satellite temperatures with time, thereby deriving thermal control coating durability information. However, satellite calorimetric data must be considered cautiously. Contamination adds uncertainty to the observed temperature increases. In 1968, W.S. Slemp and T.W.E. Hankinson of NASA Langley Research Center (LARC) released a comparison of flight data from three different flights, the Orbiting Solar Observatory (OSO) experiments, the Lunar Orbiter missions, and the Mariner series. Z-93 was flown on OSO-III, Lunar Orbiter V, and Mariner IV. OSO-III was launched into a 550 km low Earth orbit, Lunar Orbiter V was in a near elliptical polar lunar orbit, and Mariners IV and V conducted flybys of Mars and Venus, respectively. No change was observed after 1000 ESH on OSO-III. The OSO experiments were located under the protective Van Allen belts, which would protect the samples from being exposed to ionizing radiation. An increase of 0.060 was observed after 1500 ESH on Lunar Orbiter V and an increase of 0.120 was observed after 3000 ESH on Mariner IV (ref. 9).

Optical studies have been conducted by tracking the change in solar absorptance of coatings before and after flight, or during flight, utilizing spectral reflectance measurements. Both Z-93 and Z-93P were first developed by the Illinois Institute of Technology Research Institute (IITRI) for use on aluminum. AZ Technology manufactures a version of the paint designated AZ-93 and a primer designated MLP-300 allowing the paint to be utilized on composites. There are two recent on-orbit sources of optical properties data for AZ-93 with MLP-300 primer (1) the Optical Properties Monitor (OPM) Experiment flown on space station Mir, and (2) the Materials International Space Station Experiment (MISSE 1&2) flown on International Space Station. Table 4 summarizes the optical properties observed.

TABLE 4.—OPTICAL PROPERTIES OF AZ-93 ON MLP-300 EPOXY
OBSERVED FROM ON-ORBIT EXPOSURE

	OPM	MISSE 1&2
Exposure duration	237 days	3.956 years
Solar exposure	832 ESH	5545-5931 ESH
Pre flight solar absorptance	0.160	0.156
Pre flight emittance	0.906	
$\Delta\alpha$ after 0 days	0.001	
$\Delta\alpha$ after 237 days	0.005	
$\Delta\alpha$ post flight	0.005	0.001-0.003
Post flight emittance	0.904	

The OPM Experiment was carried to Mir on STS-81 in January, 1997. It was deployed on the exterior of the Mir Docking Module on April 29, 1997. OPM operated until January 8, 1998. OPM was retrieved from the Docking Module on January 9, 1998 and returned on STS-89 (ref. 10). MISSE 1&2 were deployed on August 16, 2001 on STS-105 and retrieved on July 30, 2005 on STS-114, yielding an exposure period of approximately 4 years (ref. 11). In general, AZ-93 held up well in the low Earth orbit UV environments of space station Mir and ISS. AZ-93 applied using MLP-300 AZ primer, in particular, showed no measurable change in optical properties after either a 237 day or a 3.956 year exposure.

In short, the Lunar Orbiter V results offer a glimpse on how Z-93 might respond to the lunar environment for a decade based on flight experience, though clouded by the uncertainty of contamination. Degradation in solar absorptance would likely be on the order of 0.060.

Pigment and Binder Chemistry

C. Tonon, C. Duvignacq, and M. Dinguirard of ONERA/DESP, and G. Teyssedre, of Laboratoire de G´enie Electrique studied the irradiation-induced degradation of zinc oxide paints as well as zinc oxide pigment and poly(dimethyl siloxane) resin individually. It should be noted that although the Z-93 series utilizes a zinc oxide pigment, it utilizes a potassium silicate binder rather than a siloxane resin. Samples were irradiated with 45 keV protons, 400 keV electrons, and ultraviolet radiation. The change in the optical properties of the paint were dominated essentially by the pigment. Degradation in the 380 to 600 nm region was irreversible and was attributed to radiation-induced displacement of oxygen atoms close to the grain surface in the pigment, independent of the nature of the ionizing radiation. They speculated that pigment particles coated with an oxide layer would be much more stable, compensated by oxidation (ref. 12).

D.A. Jaworske and J.A. Dever of NASA Glenn Research Center and M.S. Deshpande of Applied Material Systems Engineering, Inc., describe the development of new multi-functional thermal control coating systems that are being pursued to address the needs of high-temperature composite radiators to be used for long durations. These systems are being pursued through development of next generation pigment and binder chemistry at Applied Material Systems Engineering, Inc. (AMSENG) under the NASA Small Business Innovative Research program to achieve electrostatic charge mitigation and long term durability in a space radiation environment. AMSENG's innovations are based on molecular dynamics calculations for alkali silicate glass structures (i.e., oxide layers as discussed above) and a

random network model that essentially predicts the aggregation of modifying ions in channels lined by non-bridging oxygen atoms. AMSENG models indicate that appropriately tailored lithium silicate, lithium/sodium silicate, or lithium/potassium silicate will form pores and channels and these structures will help to achieve in thermal control materials the required surface charge and bulk charge buildup mitigation utilizing the interconnecting pores and channels as percolation paths. AMSENG is also developing passivation techniques using mixed alkali silicate microgels to prevent pigment degradation at elevated temperatures. Self assembled nanoclusters incorporated into the coating, where aluminum is partially substituted by zinc, provide the chemical compatibility to anchor to negative coefficient of thermal expansion structures resulting in thermal shock resistance.

The benefit of investing in next generation thermal control paint chemistry to FSP is to improve the long term durability of pigments to UV, electron, proton, and elevated temperature exposure. The ultimate goal is to incorporate the pigments and binders into thermal control coating products applicable to high temperature composite radiator systems (ref. 13).

The FSP radiator demonstration panels now under study utilize composite facesheets. It should be noted that the upper temperature limit of the AZ-93 and MLP-300 primer system is bounded by the MLP-300 primer, 177 °C. Recently developed annealed pyrolytic graphite radiator panels having an aluminum skin would utilize traditional Z-93P or AZ-93, would not require a primer layer, and would not be limited to the upper temperature limit of 177 °C.

Thermal Cycling on Composites

D.A. Jaworske of NASA Glenn Research Center evaluated the thermal cycling durability of a variety of thermal control coatings, including the AZ-93 and MLP-300 primer system, on carbon-carbon and carbon-polyimide composites. The specimens coated with the AZ-93 and MLP-300 primer system and thermal cycled to a hot end temperature of 177 °C showed no substantial change in solar absorptance or infrared emittance. They were found to have only trace peeling with very little material actually removed, as determined by the ASTM D-3359 X-cut tape test (ref. 14). These represent the best thermal control paint on composite results to-date, with samples achieving a rating of 4A on a scale of 0A to 5A (ref. 15). For samples prepared on isocyanate ester composite, both the AZ-93 and MLP-300 primer system and AMSENG's heritage zinc oxide pigment coated with a glass frit in a newly developed lithium/sodium silicate binder, with negative coefficient of thermal expansion nanoclusters, showed no substantial change in solar absorptance or infrared emittance. The AZ-93 and MLP-300 combination showed minor microscopic cracking after thermal cycling, while the AMSENG product showed no microscopic cracking. Solar absorptance and infrared emittance for the AZ Technology and AMSENG product lines, before and after thermal cycling, are shown in table 5.

TABLE 5.—AZ-93/MLP-300 AND AN AMSENG DEVELOPMENTAL PAINT ON CARBON-ISOCYANATE ESTER

	Before vacuum exposure at 177 °C	After vacuum exposure at 177 °C
AZ-93/MLP-300 Solar absorptance	0.122	0.129
AZ-93/MLP-300 Infrared emittance	0.916	0.913
AMSENG Solar absorptance	0.122	0.116
AMSENG Infrared emittance	0.913	0.912

For an undisturbed FSP application operating continuously, microscopic cracking of the paint should make no difference in the optical performance of the paint.

Lunar Dust

C.M. Katzan and J.L. Edwards separated lunar dust threats into two categories, natural mechanisms for lunar dust transport, and dust suspension caused by human activity (ref. 16). Natural mechanisms include micrometeoroid impact and an electrostatic effect at the Moon's sunset terminator. Lunar dust transport by micrometeoroid impact is negligibly small. At the terminator, charged particles hop 3 to 30 cm from the lunar surface, churning the lunar soil. This movement of lunar fines due to electrostatic transport is thought to be different at the equator (where the height of hopping is low) compared to the poles (where the height of hopping may be significant). Dust suspension caused by human activity includes, in ascending order, suspension from walking, rover operations, mining operations, and spacecraft operations. Spacecraft ascent and descent are the most significant of all the anthropogenic sources. With an ejection angle near zero, modeling of the dust distributed by launch and landing indicates a mean velocity of 70 m/s while a small fraction of the dust travels at velocities in excess of 2000 m/s. Escape velocity is 2.37 km/s. Hence Katzan and Edwards conclude that every landing will launch some lunar particles into orbit. All nearby surfaces are subject to pitting (ref. 16).

J.R. Gaier and D.A. Jaworske discussed lessons learned from Apollo (ref. 17). Heat rejection from second surface mirrors used to cool the batteries on the Lunar Roving Vehicle (LRV) were subjected to dusting. Although brushing dust off the mirrors with a nylon bristle brush removed large particles, the small particles remained and affected subsequent battery temperatures. After four hours into an Extra Vehicular Activity, Apollo 17 LRV battery temperatures exceeded their maximum operating temperature. By six hours, the batteries had reached their maximum survival temperature. Lunar dust under lunar surface conditions is much more adherent than terrestrial simulation conditions implied, particularly for the finest fraction of dust which was not removed at all by brushing.

For a FSP installation located two meters above the surface, lunar dust from the terminator will likely not present a problem. Radiators will be folded during the excavation activities needed to install a FSP system, providing some protection. Pelting of the radiator surface from dust ejected upon launch or landing activities is problematic based on location and line of sight. An installation a hundred meters away from the launching site and within line of sight will be pelted by high velocity dust particles while an installation a kilometer away and out of line of sight may be shielded. Dust particles launched into orbit would have a perigee near the surface where the launch or landing took place.

Future Work

Additional coating work is planned in support of FSP heat rejection system risk reduction. New product development continues at AMSENG, with emphasis placed on plasma spraying, SCEPTRE testing, and scale-up. MISSE 6, scheduled for launch in 2008, will carry aloft the first samples of AMSENG's next generation white thermal control coatings based on tailored lithium silicate pores and channels for charge buildup mitigation. Additional electron exposure work is planned at NASA Glenn Research Center and will identify the degradation in optical properties as a function of both electron fluence and elevated temperatures. Additional radiator panel testing is also planned, including several new panel concepts being developed under the Small Business Innovative Research program.

Summary

The solar absorptance of white thermal control paint is likely to change over the lifetime of a Fission Surface Power installation. Darkening of the coating will likely be a consequence of the combined effects of ultraviolet radiation, electrons and protons, brought about by radiation-induced displacement of oxygen atoms close to the grain surface in the zinc oxide pigment particles. The increase in solar absorptance would, in essence, add a cyclic heat load to the radiator. The greater the darkening, the greater the added heat load. The cyclic heat load could ultimately impart a cyclic influence on FSP system performance.

Utilizing end-of-life Z-93 performance values developed for International Space Station would be inappropriate because end-of-life optical property values predicted for International Space Station are dominated by contamination. Utilizing end-of-life optical property values obtained from the Lunar V mission may offer a narrow glimpse on how Z-93 might respond to the lunar environment for a decade, but are clouded by uncertainty. Ground testing utilizing combined effects offers the best glimpse on how Z-93P might respond to the lunar environment for a decade. Anticipated degradation in solar absorptance would likely be in the range of 0.022 to 0.050 and the rate of degradation would be greatest initially, tapering off with time. With shielding, neutron exposure should not impact the optical properties. No significant change in emittance is anticipated.

For Fission Surface Power radiators having composite facesheets, AZ-93 combined with an MLP-300 epoxy-based primer offers optical properties analogous to Z-93P along with an interface suitable for use on composites. The AZ-93/MLP-300 primer system has flight heritage and offers adhesion characteristics that are robust for both paint and primer. Microcracking is observed upon thermal cycling owing to the mismatch in coefficients of thermal expansion, however, the microcracking should not present a problem to a continuously operating radiator panel. The AZ-93/MLP-300 primer system is bounded by the design limit of the epoxy primer, 177 °C.

Next generation white thermal control paints specifically designed to reduce radiation-induced displacement of oxygen atoms in zinc oxide pigment particles are being developed and may offer improved long term optical properties durability. These coatings can be applied by either traditional water-based spraying methods or recently developed plasma spraying methods having potential cost benefits. Qualification testing is under way and initial samples are scheduled for launch in the near future. Self assembled nanoclusters incorporated into the coating, where aluminum is partially substituted by zinc, provide the chemical compatibility to anchor negative coefficient of thermal expansion structures resulting in thermal shock resistance, as observed by minimal microcracking upon thermal cycling. With compatible coefficients of thermal expansion between coating and composite, continuous operation of the FSP radiator panel could be relaxed. Scale-up remains a challenge.

For Fission Surface Power radiators having facesheets composed of annealed pyrolytic graphite encapsulated by aluminum, Z-93P or AZ-93 applied to the aluminum skin in the heritage fashion should impart standard optical properties having the robust interface to aluminum that is common with the Z-93 paint series.

Of all the lunar dust issues, dust from launch and landing activities represent the greatest threat to FSP radiators. Depending on distance and line of site considerations, lunar dust may pelt the radiator with each launch or landing, or the radiator may be shielded from dust by natural obstructions by blocking line of sight dust impact.

Future work is planned to study the degradation in optical properties as a function of both electron fluence and elevated temperatures. Such synergistic testing should provide guidance on optical properties durability under conditions that better approximate the operating temperatures of a FSP installation. Additional radiator panel testing is also planned, including several new panel concepts currently being developed.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
White thermal control coatings capable of long term performance are needed for Fission Surface Power (FSP) where heat from a nuclear reactor placed on the surface of the Moon must be rejected to the environment. The threats to thermal control coating durability on the lunar surface are electrons, protons, and ultraviolet radiation. The anticipated damage to the coating is a gradual darkening over time. The increase in solar absorptance would, in essence, add a cyclic heat load to the radiator. The greater the darkening, the greater the added heat load. The cyclic heat load could ultimately impart a cyclic influence on FSP system performance. No significant change in emittance is anticipated. Optical properties degradation data were found in the open literature for the Z-93 series of thermal control paints. Additional optical properties degradation data were found from the Lunar Orbiter V mission, the Optical Properties Monitor, and the Materials International Space Station Experiment. Anticipated end-of-life thermal control coating performance for a FSP installation is postulated. With the FSP installation located away from landing and launching areas, and out of line-of-sight, lunar dust from human activity may not be a threat. The benefits of investing in next generation thermal control paint chemistry are explored.

15. SUBJECT TERMS
Thermal control coatings; Solar absorptance; Infrared emittance

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