End-of-Life Optical Property Predictions of White Conductive Thermal Control Coatings through Analysis of On-Orbit and Ground Based Testing Data

Mark Hasegawa, Scott Freese, Lon Kauder, Jack Triolo

Degradation of thermal coatings has been a well observed and documented (Ref 1-3) phenomena that presents limitations to thermal engineering design of spacecraft. Observed spacecraft thermal coatings degradation based on thermal systems performance data from missions has been reported for a number of missions. Discrete calorimetric measurements of on-orbit degradation has been limited to few spacecraft in specific orbits, most of which are not in particle radiation environments. Few spacecraft experiments have had measurements conducted at geosynchronous orbital conditions over long durations and of these, none contain recently formulated conductive thermal control coatings. With these limitations on the amount of on-orbit data, most functions that predict optical property degradation relies on ground based test data. Ground based environmental testing has the difficulty of accurately accelerating the effects of the space environment on coatings and matching those results to observations on-orbit. Studies have approached this proper accelerated exposure by matching the expected lifetime dose as a function of depth for a given flux; however, the issues of matching degradation to on-orbit data still persist. These issues especially arise when the on-orbit data reflect degradation of coatings that may currently have different formulations or properties than when tested on-orbit. *Testing performed at NASA GSFC Code 546 Contamination and Thermal Coatings Branch attempts to develop end of life optical properties for a new, perspective white conductive coating, Z93C55 by relating ground based testing of historic samples from the era of the on-orbit testing to observed flight data. Testing includes exposure to electron fluences from 20KeV to 300KeV and proton fluences from 2KeV to 1.7MeV with and without UV radiation exposure. For this study, the end-of-life solar absorptance requirement was established to be less than 0.45.*

Introduction

New system requirements pertaining to thermal optical properties and coating electrical properties are commonly specified on non-low earth orbit missions. An increasing number of projects are specifying coatings with a surface resistivity of less than 1E-9 ohm/square to mitigate electrostatic charge buildup events over a range of operational temperatures. There are a limited number of coatings that meet these electrical property requirements while having flight derived optical properties in representative environments.

Goddard Space Flight Center Code 546, Contamination and Thermal Coatings Group has recently explored the variety of electrically conductive white coatings available through domestic vendors to evaluate properties to meet project requirements in a geostationary orbit. The lack of significant flight data in representative environments required the careful selection of samples in ground based tests to establish end of life thermal properties. Attention must be given to the origin and pedigree of samples used on past on-orbit experiments to insure that the present formulations for the materials are similar and will react in similar manner.

Optical Property Characterization

Thermal properties were established for a variety of conductive white coatings using ASTM E903-82 using a Cary 5000 UV/VIS/IR spectrophotometer and E408-71 using a Gier Dunkel DB100 IR reflectometer for solar absorptance and infrared normal emittance respectively. Hemispherical IR emittance was also measured using an Surface Optics SOC-100 Hemispherical Directional Reflectometer. These values are shown in Table 1.

Vacuum Surface and Bulk Resistivity Characterization

Samples were thermal cycled a minimum of 100 cycles at pressures less than 1E-6 torr between +130 and -170C prior to testing per STM S11/S12 under vacuum conditions. A concentric probe was used to measure current flow through the samples at various potentials. Samples were preconditioned under vacuum a minimum of 48 hours to remove water than cycled between +65C and -160C with resistances made at potential voltages of 10, 100, 150, 200, 250, 300, 350, and 500V at various temperatures. Surface and bulk resistivities were calculated during separate experimental runs. Figure 1 indicates results of the resistivity evaluation. The Alion Science and Technology material Z93C55 silicate demonstrated a low surface resistivity near or below the 1E9 ohm/sq.

Electrostatic Potential Evaluation

The GSFC Code 546 setup used previously to establish potential buildup in conductive coatings (Ref 1) was modified to use a low voltage non-contacting probe. Figure 2 shows the test setup with sample coupon. A 20 KeV electron source illuminates a sample coupon as a non-contacting probe measures the potential buildup relative to ground over the coupon. Electron energy and flux were varied between 2 and 20 KeV and 1-10 nA/cm^2, respectively. The sample and test setup temperatures ranged between 85C and -133C. Table 2 shows potential buildup in Z93C55 as a function of time, temperature and electron beam condition.

Proton, Electron, and UV Radiation Exposure

Radiation modeling using SRIM and ITS software was conducted to evaluate the expected dose vs. depth profiles for both electrons and protons in a zinc oxide – silicate based coating system. Proton and electron fluences based on observed 13 year geostationary environments (Ref 1) were used to create the baseline exposure profile. Figure 2 shows the modeled dose-depth profile for the Z93C55 coating and the expected deposition from a combined low and high energy particle exposure.

Samples from a number of conductive white coatings were exposed in the GSFC solar wind facility for simultaneous low energy proton, electron, and UV radiation exposure. The facility has been described in previous papers but should be noted that the facility has an in-vacuo solar absorptance measurement capability. Table 3 indicates the fluences and energy of protons, electrons, and UV radiation that the Z93C55 sample experienced during the initial solar wind exposure. Subsequent exposures were conducted in the Radiation Effects Facility with higher energy electrons and protons. Results are shown in Table 4. Solar absorptance degradation from initial conditions after exposure are shown in both Tables 3 and 4 for Z93C55 along with recently applied coatings of NS43G and NS43C, both heritage coatings from NASA with significant flight experience.

Samples were selected for higher energy proton and electron exposure based on available flight data. NS43G and NS43C samples from 1978 stored in the Code 546 sample library were selected for exposure along with samples of Z93C55 and current samples of available NS43C and NS43G. The heritage samples from 1978 were of the similar composition as those flown on long duration calorimetric studies. Exposure energies and fluences were selected to match SRIM and ITS models based on expected geostationary fluences. Table 4 indicates the proton and electron energies and fluences, as well as the coating degradation from initial conditions.

End-of-Life Optical Property Evaluation

The GSFC Coatings Committee evaluated the degradation of the Z93C55 coating relative to the changes observed in the historic 1978 coating samples and the present day samples. Samples from 1978 were selected because they represented the likely formulation of NS43C and NS43G that were part of the NTS experiment on OSO and on the SCATHA ML12 experiment , respectively. NS43C solar absorptance change after 1 year on orbit on OSO was 0.23 when contamination effects are subtracted from the optical solar reflector control. These results are shown in Table 5. The SCATHA experiment which contained NS43G indicated a change in solar absorptance estimated to be 0.13 after 15 years on orbit in a relatively contamination free environment. Estimated 15 year values are shown in Table 6. Comparison of the degradation of the NS43C and NS43G observed in the high energy electron and proton test indicated that the degradation was less rigorous than that experienced at 10 years on geosynchronous orbit. Changes in solar absorptance would be less than the sum of degradation expected from both low energy (electron only) and high energy proton and electron tests due to the presence of the UV component. It is hypothesized that the presence of UV interacts with color center formation to greatly reduce apparent electron damage as was apparent in test 1, 3, and 5 of the low energy test and the post UV exposure of samples from the high energy radiation test. Proton damage appeared to be negligible in these tests.

NS43G historic and present day samples degraded similarly in the high energy testing and thus are expected to degrade similarly in the low energy electron testing. Interestingly, the NS43G samples did degrade by 0.07 in low energy electron only exposures. The recovery of all samples in UV demonstrated the need to consider optical degradation of samples that included the UV component, as most external surface will be exposed to direct solar/UV at some point on orbit. Summing the degradation of the low energy combined environment with protons, electrons and UV and the high energy proton and electron exposure and enveloping maximum expected degradation, an end of life solar absorptance of less than 0.45 should be used by the project as a 15 year design value for thermal engineering.

Table 1 – Thermal Optical Properties

Coating	Measured Optical Properties		
	α	ε_n	ε_H
Z93C55	0.14	0.92	0.94
NS43G (2008 Formulation)	0.18	0.90	0.89
NS43C (2008 Formulation)	0.14	0.92	0.94
NS43G (1978 Formulation)	0.20		
NS43C (1978 Formulation)	0.19		

Table 2 - Observed Potential Buildup on Z93C55 during Electron Illumination

	2 KeV	**10 KeV**		**20 KeV**	
Temperature °C	**1nA/cm²**	**1nA/cm²**	**10nA/cm²**	**1nA/cm²**	**10nA/cm²**
-133 C	**+8 V**	**+7 V**	**+8 V**	**+10 V**	**+8 V**
+14 C	**+10 V**	**+2 V**	**+1 V**	**+3 V**	**+9 V**
+85 C	**+5 V**	**+5 V**	**+5 V**	**+5 V**	**+8 V**

Table 3 - Solar Wind Proton, Electron, and UV Radiation Exposures

Test Material	20KeV Electrons e-/cm²	2 KeV Protons p+/cm²	NUV ESH	$\Delta\alpha$
Z93C55	9.30E+15	1.20E+16	1123	**0.051**
NS43G (new)	8.80E+15	9.10E+15	878	**0.028**

Table 4 Proton and Electron Radiation Exposures in GSFC Radiation Effects Facility

Test Sample	Protons	Electrons		Recovery	Post UV Recovery
		300KeV	100/50 KeV	4 hour in air	
	$\Delta\alpha$	$\Delta\alpha$	$\Delta\alpha$	$\Delta(\Delta\alpha)$	$\Delta\alpha$ from initial
Z93C55 #1	0.01	0.18	0.21	-0.01	0.16
Z93C55 #2	0.01	0.26	0.39	0.00	0.29
NS43G (New)	0.02	0.05	0.03	-	0.05
NS43C (New)	0.01	0.12	0.11	-0.01	0.07
NS43C (1978)	0.05	0.16	0.28	-0.02	0.09
NS43G (1978)	0.01	0.04	0.03	-	0.05

Table 5 NTS (1977) Geosynchronous Orbit Coatings Degradation

	BOL α	α (40 days)	α (337 days)	$\Delta\alpha$ (337 days)
NS43C	0.18	0.28	0.51	**0.33**
Ag/FEP (5mil)	0.08	0.14	0.26	**0.18**
OSR/CC	0.15	0.16	0.26	**0.11**

Table 6 SCATHA (1979) Geosynchronous Orbit Coatings Degradation

	BOL α	α (1 year)	α (10 years)	α (Estimated 15 years)	$\Delta\alpha$ (15 years)
NS43G	0.31	0.36	0.43	0.44	**0.13**
Ag/FEP (5mil)	0.11	0.16	0.34	0.36	**0.25**
OSR/CC	0.08	0.08	0.10	0.11	**0.03**

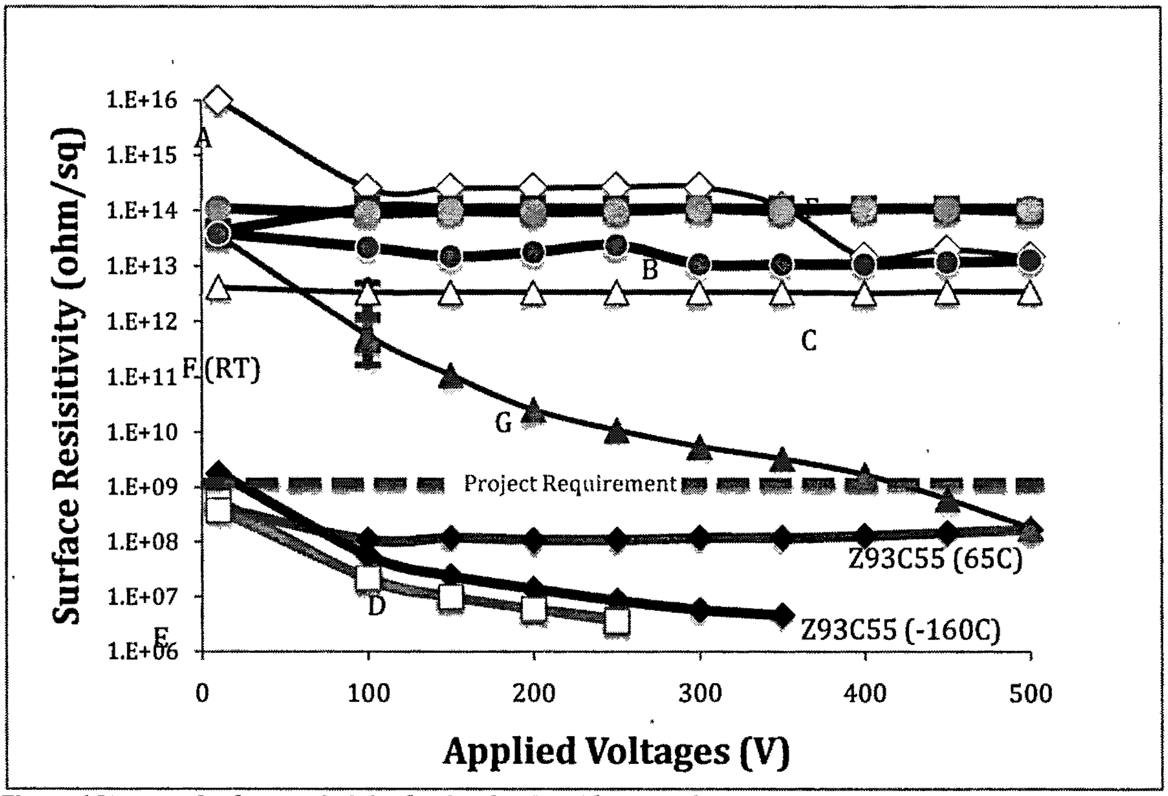
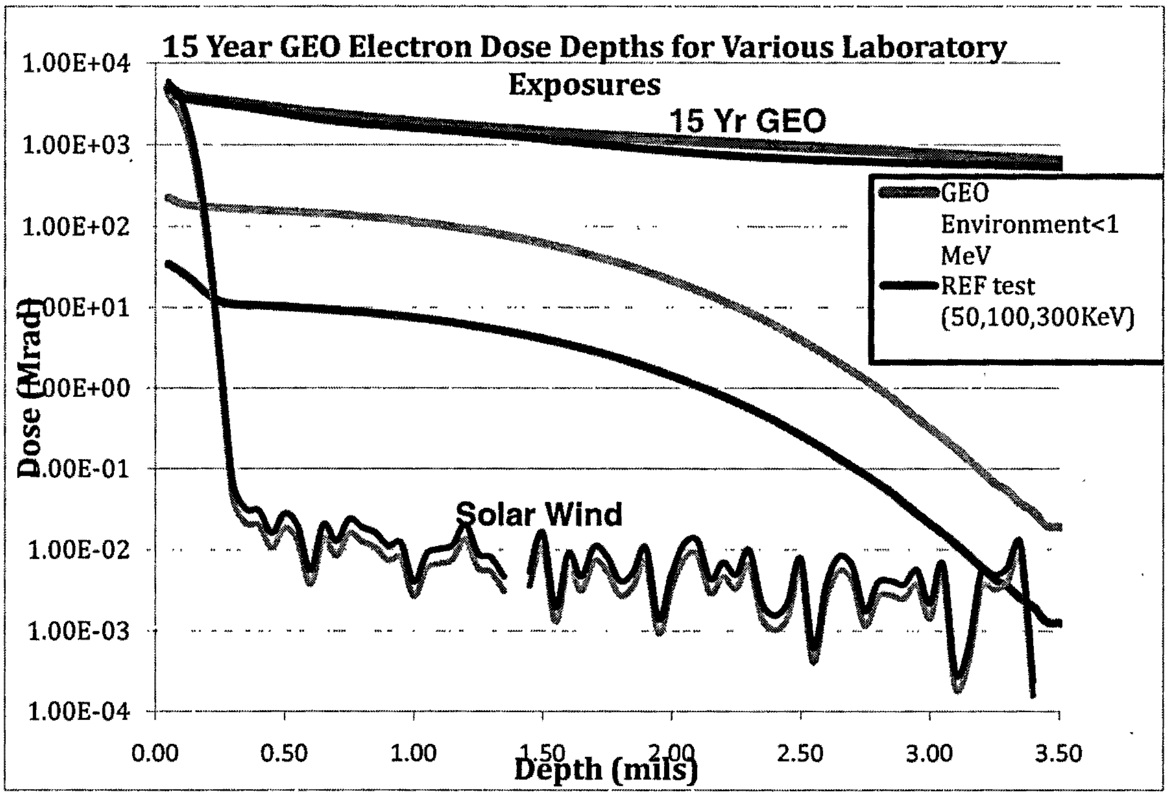


Figure 1 Vacuum Surface Resistivity for Conductive White Coatings


15 Year GEO Electron Dose Depths for Various Laboratory Exposures
15 Yr GEO
Solar Wind
GEO Environment<1 MeV
REF test (50,100,300KeV)
Dose (Mrad)
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
Depth (mils)

References

1. Hall, D. F., Fote, A. A., Thermal Control Coatings Performance at Near Geosynchronous Altitude, J. Thermophysics and Heat Transfer, 1992 Vol 6, Issue 4, p665

2. Jaworske, D. A., Kline, S. E., Review of End-of-Life Thermal Control Coating Performance, NASA/TM 2008-215173

3. Bever, R. S., Kauder, L. Spacecraft Charging Tests of COBE Outer Cover Materials

4. Thomsen, M. F., Statistics of Plasma Fluxes at Geosynchronous Orbit Over More Than a Full Solar Cycle, Space Weather, VOL. 5, 2007