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Combined Low-Energy Environment Simulation Test of Geosynchronous Satellite Thermal Control Coatings

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Geosynchronous orbit environment effects of 15 years on solar absorptance of thermal control coatings such as S781 white paint, SR107-ZK white paint, silvered fluorinated ethylene propylene F46, and optical solar reflectors on the outer satellite are simulated by a combined low-energy irradiation test. Severe degradation is found in organic white paint whereas optical solar reflectors and silvered fluorinated ethylene propylene F46 remains quite stable. By comparison with flight test results, the effectiveness of the simulation method has been shown. Based on the degradation trend data, the least-square regression method was used to obtain an empirical formula. The second-order exponential decaying formulas are found to be quite good to fit degradation curves of four kinds of materials. Extrapolation for a longer test time has been made, and the results have been verified. The error of using 8 year test results to extrapolate 15 year degradation is verified to be less than 1%.

I. Introduction

SOLAR absorptance (α_s) is one of the very important surface properties of a satellite. It represents the extent of solar energy absorbed by a satellite. The degradation of α_s is described by the increase of this parameter under the space environment. The temperature of a satellite will be increased due to α_s degradation of surface thermal control coatings. A GEO (geosynchronous orbit) satellite is very sensitive to such degradation because there are a lot of low-energy electrons and protons in the GEO orbit. Low-energy charged particles will deposit more energy in the surface layer and will damage surface properties seriously.

To simulate α_s degradation of thermal control coating on the outer surface of a satellite, a method of low-energy combined environment testing and α_s in situ measurement are applied. "Low-energy" means that the energy of electrons and protons is lower than 50 keV. "Combined " means that electrons, protons, and UV irradiate the test samples together or in turn. "In situ measurement" means that α_s is measured during the test without air exposure of samples in order to avoid bleaching of coating degradation.

The test was performed in a low-energy combined environment test facility built by Beijing Institute of Spacecraft Environment Engineering (BISEE), as shown in Fig. 1. This facility can provide environments of low-energy electrons, low-energy protons, NUV (near ultraviolet), FUV (far ultraviolet), or neutral plasma, thermal cycling, and vacuum. The in situ measurement of α_s, spectral reflectance, spectral transmittance, surface resistance, or mechanical properties for test specimens can be performed inside the facility.

An electron-, proton-, and NUV-combined test of the candidate thermal control coatings was performed to simulate degradation under 15 years of GEO environment. There were four types of such materials including S781 white paint, SR107-ZK white paint, silvered FEP (fluorinated ethylene propylene F46) film, and OSR (optical solar reflector) radiator. The test's aim was to obtain reliable degradation simulation results for thermal control design of a satellite. Simulation results were compared with the flight experiment results of these materials. A 5000 ESH (equivalent sunshine hours) NUV test was performed. According the degradation trend, trend models were established and extrapolation predictions were made.

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II. Test Conditions

A. Electron and Proton Irradiation

The severest environments for α_s degradation of test materials are low-energy electrons and protons from the outer radiation belt and solar UV. The low-energy electrons and protons are most detrimental to the surface because they deposit their energy at the surface and α_s is mainly determined by surface materials.

The radiation models used were the AP8 and AE8 models. To get low-energy data less than 100 keV for protons and 40 keV for electrons, we extrapolated AP8 and AE8 models to the kiloelectronvolt energy. The codes ITS3.0 and SARIM are used for calculation of the dose profile. After calculation, the electron and proton parameters for the simulating test are as follows: electrons 40 keV, 2.5×10^{16} e/cm^2, and protons 40 keV, 2.5×10^{15} e/cm^2. The dose-depth profile calculations for electrons and protons are shown in Figs. 2 and 3.

Flux is selected according to the acceleration factor of about 360, which is much less than the standard value of 1000. Thus, the accumulated time is 365 h for electron and proton irradiation. This rate corresponds to a flux of 3 nA/cm^2 for electrons and 0.3 nA/cm^2 for protons.

B. UV Exposure

The NUV irradiation test had 5000 ESH. The acceleration factor was about 4. The accumulated irradiation time was about 1250 h. NUV irradiation time for 15 years is certainly much more than 5000 ESH. But, low-energy electrons or protons have much higher degradation effects on thermal control coatings than UV. We performed a 5000 ESH NUV irradiation test for the same materials as those in the combined irradiation environment test. α_s degradation curves were stabilized early during the 5000 ESH test as shown in Fig. 4. Thus, we think that the function of NUV irradiation in a long time combined irradiation test is like a background environment.

C. Temperature and Vacuum

The temperature of samples was controlled by fixing them on a big metal plate whose temperature was maintained at about 20°C to

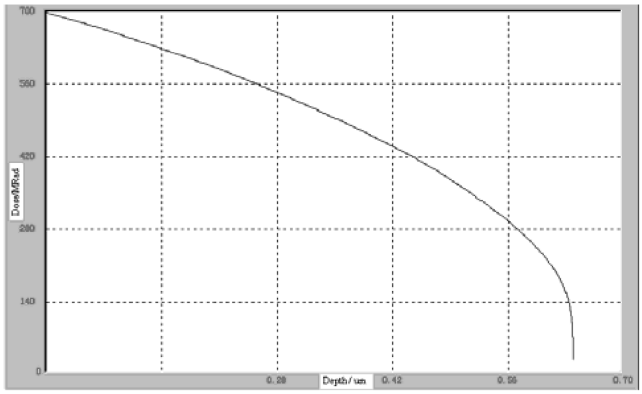

Fig. 1 Proton dose near the surface (KAPTON).

Fig. 2 Low-energy combined environment test facility.

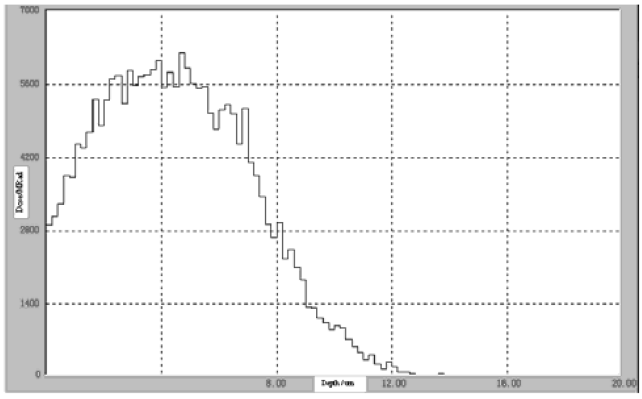

Fig. 3 Electron dose near the surface (KAPTON).

ensure the sample temperature was less than 50°C. Too low of a temperature is harmful to the sample's contamination control. The facility's shroud temperature was controlled at −35°C. The sample temperature needs to be much higher than the shroud temperature. Vacuum systems consisted of a turbo-molecular pump and mechanical pump. The vacuum was better than 3×10^{-3} Pa during the whole test period.

D. Irradiation/Measurement Sequence

We performed α_s in situ measurement before testing in order to ensure the accuracy and reliability of the measurement system. Electron and proton currents were calibrated by a Faraday cup to acquire the relations between the current on samples and the current

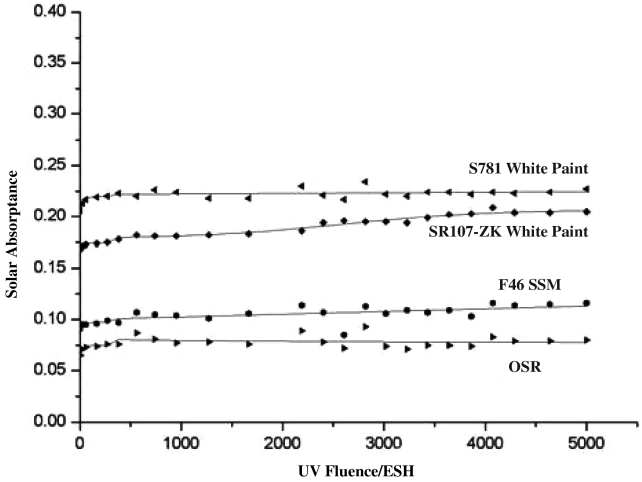

Fig. 4 NUV irradiation test.

on the monitor. Vacuum, temperature, electrons, protons, and NUV were monitored by computer during the test.

The fluence of electrons and protons was divided into 15 equal sections. Each section represents 1 year GEO irradiation. NUV irradiation was performed in all the section periods. NUV was combined with electron irradiation at the first half period and proton irradiation on another half period. In every interval between the two sections, there were about 20 min for α_s measurement of every sample without interruption of the vacuum.

E. Contamination Control

α_s is a kind of surface property that is sensitive to contamination. Contamination of test samples must be minimized to prevent erroneous results. In this test, we took several measures to control sample contamination, such as a low-contamination vacuum system, cryogenic shroud, the sample's high temperature, and material selection of the test facility. To monitor the contamination inside the facility, a TQCM (temperature-controlled quartz crystal miro-balance) is placed in the test chamber for the whole test period to measure changes in mass as shown in Fig. 5. The accuracy of TQCM is 1.8×10^{-8} g/cm^2.

As we can see from Fig. 5, the mass on TQCM is decreased all the time in a vacuum environment. It means that the contamination of the test chamber during the test is very small.

III. Samples Description

The test samples are S781 white paint, SR107-ZK white paint, silvered FEP, and OSR. S781 white paint is a kind of organic paint with ZnO pigment and S781 silicone resin. The α_s of S781 white paint is about 0.18, and its emissivity is about 0.87. SR107-ZK white

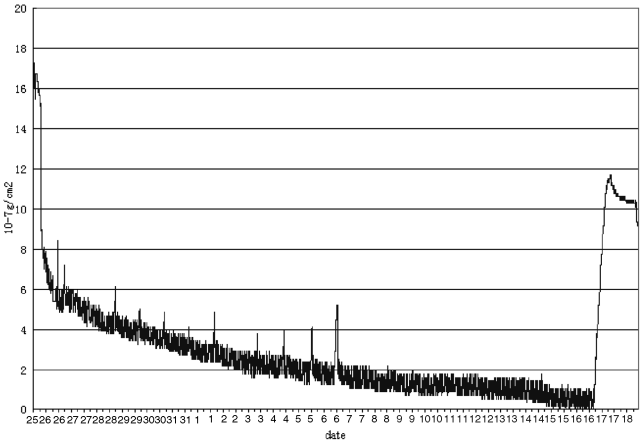

Fig. 5 Mass change measured by TQCM.

paint's pigment is ZnO treated by potassium silicate. SR107-ZK white paint's binder is SR107 silicone rubber. The α_s of SR107-ZK white paint is about 0.17, and its emissivity is about 0.87. The sample of silvered FEP is an FEP (0.1 mm) film coated with silver on one side. The silvered side is bonded on the round aluminum substrate.

OSR is a quartz plate (0.2 mm) coated with silver on one side and ITO (indium tin oxides) film on other side. The aluminium substrate is 28 mm in diameter. Three samples of one material are mounted on the target for irradiation tests.

IV. Test Results

Test time was divided equally into one year increments (the first year has two measurement points, one for a half year) to represent 15 years. The solar absorptances for three samples of one material are measured and averaged. 0 year data represent the original value of α_s. "Air" means that α_s is measured after the test chamber is exposed to air.

A. OSRs

Table 1 shows the test results for OSRs.

B. S781 white paint

Table 2 shows the test results for S781 white paint.

C. SR107-ZK white paint

Table 3 shows the test results for SR107-ZK white paint.

D. Silvered FEP

Table 4 shows the test results for silvered FEP.

Table 1 OSRα_s degradation data

Year	0	0.5	1	2	3	4
α_s	0.053	0.084	0.092	0.103	0.101	0.110
Year	5	6	7	8	9	10
α_s	0.104	0.112	0.116	0.113	0.120	0.120
Year	11	12	13	14	15	Air
α_s	0.118	0.191	0.179	0.191	0.199	0.175

Table 2 S781 α_s degradation data

Year	0	0.5	1	2	3	4
α_s	0.193	0.237	0.264	0.295	0.311	0.337
Year	5	6	7	8	9	10
α_s	0.345	0.362	0.374	0.380	0.392	0.398
Year	11	12	13	14	15	Air
α_s	0.400	0.418	0.416	0.424	0.434	0.374

Table 3 SR107-ZK α_s degradation data

Year	0	0.5	1	2	3	4
α_s	0.160	0.244	0.316	0.411	0.457	0.510
Year	5	6	7	8	9	10
α_s	0.540	0.564	0.585	0.595	0.604	0.614
Year	11	12	13	14	15	Air
α_s	0.619	0.627	0.631	0.638	0.639	0.590

Table 4 Silvered FEP film α_s degradation data

Year	0	0.5	1	2	3	4
α_s	0.098	0.117	0.130	0.142	0.138	0.152
Year	5	6	7	8	9	10
α_s	0.142	0.112	0.161	0.160	0.175	0.174
Year	11	12	13	14	15	Air
α_s	0.172	0.191	0.179	0.191	0.199	0.175

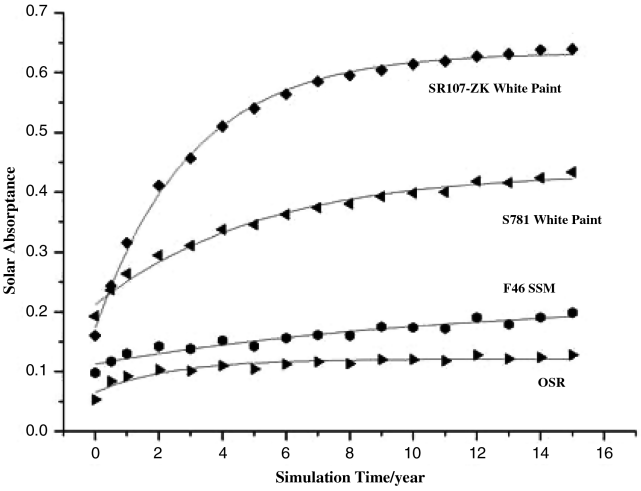

Fig. 6 Solar absorptance degradation curves.

E. Discussion

As shown in the test results, the OSRs are the least degraded, and the organic white paints were the most degraded. All materials show a bleaching effect. All degradation curves were shown in Fig. 6.

V. Comparison with Flight Results

A GEO in-flight experiment [1] for monitoring α_s degradation of S781 white paint, silvered FEP, and OSR (without ITO) was performed before. The α_s degradation was calculated through the temperature changes.

As shown in Tables 5–7, the ground test degradations for the four materials are quite close to the flight results. The degradation of S781

Table 5 S781 white paint comparison[a]

Time	12 h	0.5 yr	1 yr	2 yr	3 yr	4.3 yr
Flight	0.241	0.332	0.378	0.444	0.476	0.519
Test	0.212	0.237	0.264	0.295	0.311	0.340

[a]$\Delta\alpha_s$ for flight is 0.241. $\Delta\alpha_s$ for test is 0.128.

Table 6 Silvered FEP comparison[a]

Time	12 h	0.5 yr	1 yr	2 yr	2.5 yr
Flight	0.153	0.199	0.241	0.287	0.315
Test	0.099	0.117	0.130	0.142	0.137

[a]$\Delta\alpha_s$ for flight is 0.162.$\Delta\alpha_s$ for test is 0.038.

Table 7 OSRα_s comparison[a]

Time	12 h	1 yr	2 yr	3 yr	4.3 yr
Flight	0.122	0.134	0.139	0.139	0.139
Test	0.056	0.092	0.103	0.101	0.110

[a]$\Delta\alpha_s$ for flight is 0.017. $\Delta\alpha_s$ for test is 0.054.

Table 8 Error of extrapolated degradation

Simulated time, yr	Prediction of α_s at 15 yr	Error relative to test α_{s0}
5	0.759	18.8%
6	0.694	8.6%
7	0.672	5.2%
8	0.641	0.3%
9	0.635	−0.6%
10	0.637	−0.3%

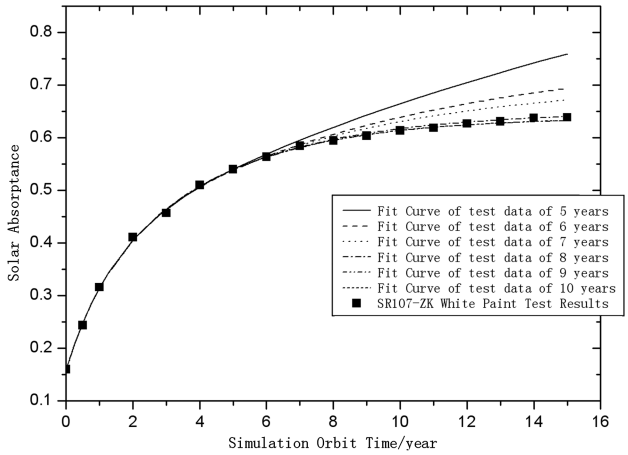

Fig. 7 Extrapolation for SR107-ZK degradation.

white paint and aluminized FEP is more severe than that of the simulation test sample. The reason maybe is due to less contamination in ground test samples. The OSR samples in the test were ITO coated whereas the flight OSR samples were not. That is why degradation of the OSR samples in the test was more severe.

VI. Extrapolation

As shown in Fig. 6, the degradation trend is slowed down as the environmental dose accumulates. So it is possible to use the extrapolation method for a longer simulation exposure [2]. A process known as regression or curve fitting was used. We applied the least-square regression to the degradation curves to get empirical formulas. The following second-order exponential decaying formula was found to be very close to all test result points:

$$\alpha_s = C + A\exp(-t/\theta 1) + B\exp(-t/\theta 2)$$

There are 5 parameters $(C, A, \theta 1, B, \theta 2)$ to be determined by the least-square regression method. A α_s degradation regression example for SR107-ZK white paint is shown in Fig. 7. The predictions of end of life of 15 years from different number of points are displayed. The less the points that are used, the bigger the error at 15 years, as shown in Table 8. α_{s0} of SR107-ZK white paint for a combined simulated 15 years is 0.639.

As shown in Table 8, if we use 8 year test results, the accuracy for 15 year degradation prediction is better than 1%. It means that for a long life degradation simulation test, using the extrapolation method will be very economical to test.

VII. Conclusions

The geostationary environmental effects of 15 years on α_s degradation of S781 white paint, SR107-ZK white paint, silvered FEP, and OSR at the outer surface of satellite are simulated by a combined low-energy irradiation simulation test method. The comparisons between the simulation test and flight test were made to show the effectiveness of the simulation test method. A least-square regression method is used for obtaining empirical formulas to predict degradation trends. The second-order exponential decaying formula is found to be reasonably good to fit the degradation curves. Severe degradation is found in organic white paint whereas OSR and silvered FEP remain quite stable. The extrapolation method for a long time test has been verified. For examples of SR107-ZK white paint, with 8 years of simulation test results, extrapolation values at 15 years are very close to the 15 year simulation test results.

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[2] Marco, J., "Evaluation of Thermal Control Materials Degradation in Simulated Space Environment," *Proceedings of the 9th International Symposium on Materials in Space Environment*, SP 540, ESA, Noordwijk, The Netherlands, Sept. 2003.

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Associate Editor