Space Combined Environment Simulation Test on α_S Degradation of GEO Satellite Thermal Control Coatings

FENG Weiquan[1] , DING Yigang[1], YAN Dekui[1]，LIU Xuechao[2], WANG Wei[2]，LI Dongmei[2]
(1. *Beijing Institute of Spacecraft Environment Engineering*, *Beijing* 100094, *China*;
2. *China Academy of Space Technology*, *Beijing* 100094, *China*)

Abstract：GEO environmental degradation trend of 15years on solar absorptance for thermal control coatings such as S781 white paint, SR107-ZK white paint, silvered FEP, and OSR on the outer satellite are simulated by a combined low energy irradiation test. Severe degradation is found in organic white paint while OSR and silvered FEP remain quite stable. By comparison with flight test results, the effectiveness of the simulation method is shown. Based on the degradation trend data, the least squares regression method is used to obtain empirical formulas. The second order exponential decaying formulas are found quite good to fit degradation curves of four kinds of materials. Extrapolation for a longer test time is made and the results are verified. The error of using 8 years test results to extrapolate 15 year degradation is shown to be less than 1% .

Key words: combined simulation; low energy simulation; degradation; space radiation; solar UV; solar absorptance; in-situ measurement

CLC numbr: V416.5 **Document code: A** **Atricle ID:** 1673-1379（2007）01-0027-05

1 Introduction

Solar absorptance (α_s) is a very important parameter for surface properties of satellite. It represents the extent of solar energy absorbed by satellite. The degradation is represented by the increase of this parameter with the accumulated space environmental action. Temperature increase of satellite at the end of a long term mission is mainly caused by the degradation of surface thermal control coatings with respect to α_s. GEO satellite is vulnerable with respect to such degradation since there are a lot of low energy electrons and protons in the orbit. Low energy charged particles will deposit more energy in the surface layer and will damage surface properties seriously.

In order to simulate the degradation expressed by α_s of the thermal control coating on outer surface of satellite, a method of low energy combined environment test and the α_s in-situ measurement are applied. “Low energy” means that the energy of electron and proton is lower than 50keV. “Combined” means that electron, proton and UV irradiate the test samples together or in turns. “In situ measurement” means that α_s is measured during the testing without interruption of vacuum environment to avoid bleaching of coatings.

The test was performed on a Low Energy Combined Environment Test Facility built by Beijing Institute of Spacecraft Environment Engineering(BISEE). This facility can provide environments of low energy electrons, low energy protons, NUV, FUV or neutral plasma, thermal cycling and vacuum. The in-situ measurements of α_s or spectral reflectance or spectral transmittance or surface resistance or mechanical property for test specimens can be made inside the facility.

Fig1 Low energy combined environment test facility

An electron, proton and NUV combined test for the candidate thermal control coatings is performed to simulate 15 year of GEO orbit effects. There are 4 types of such materials as S781 white paint, SR107-ZK white paint, silvered FEP film, and OSR radiator. Our aim is to provide reliable simulation results for designing 15 year GEO satellite thermal control system in the orbital environment. Simulation results are compared with the flight experiment of these materials. In order to verify the UV degrading saturation, a 5000 ESH NUV test is performed. According to

收稿日期：2006-08-01；修回日期：2007-12-12
作者简介：冯伟泉（1956-），研究员，主要从事空间辐照环境地面模拟试验技术的研究工作。联系电话：86-10-68746635, E-mail: weiquan_feng@yahoo.com.cn.。

degradation trend, trend models are established and extrapolation predictions are made.

2 Test Conditions

2.1 Electron and proton irradiation

The most critical environments for α_s degradation of the 4 kinds of materials are electron and proton from the outer radiation belt and solar UV. The low energy electron and proton are most detrimental since they deposit their energy in a thin layer at the surface and α_s is mainly determined by properties of the thin layer materials.

The radiation models used for this study are AP8 model and AE8 model. Their lower ends of energy are, respectively, 100 keV and 40 keV. We extrapolate AP8 model and AE8 model down to the keV energy region. Therefore, the absolute values of the absorbed dose in the low energy region are not known accurately. The codes of ITS3.0 and SARIM are used for the dose profile matching calculation. The calculated electron and proton parameters for simulating α_s degradation of 15 year GEO environment on outer thermal control coatings are as follow: Electron: 40keV, 2.5×10^{16} e/cm^2;Proton: 40keV, 2.5×10^{15} e/cm^2. The dose – depth profile calculations for electron and proton are shown in Fig.1 and Fig.2.

Fig.2 Electron dose near surface(KAPTON)

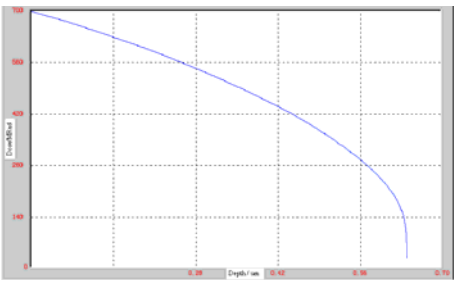

Fig.3 Proton dose near surface(KAPTON）

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

2.2 UV exposure

NUV irradiation is 5000ESH. The acceleration factor is about 4. The accumulated irradiation time is about 1250 hours. The real NUV irradiation time for 15 years is certainly much more than 5000 ESH. As a combined accelerating test for simulating a long mission α_s degradation, the electron and proton play a much more important role than UV. We have performed a 5000 ESH NUV irradiation test for the same materials and it is found that α_s degradation is saturated long before 5000 ESH as seen in Fig.3. NUV irradiation in a long time combined irradiation test acts as a background environment.

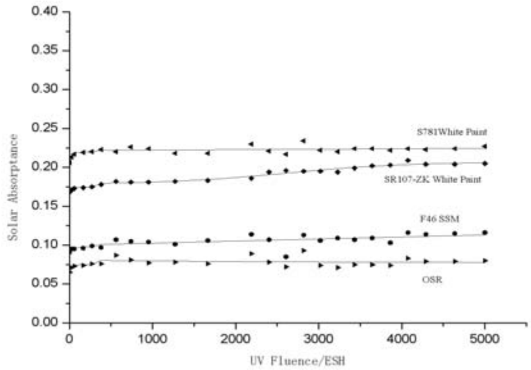

Fig.4 NUV irradiation test

2.3 Temperature and Vacuum

The temperature of samples is controlled by a good thermal contact with the metal plate support. The plate support is maintained at a specific temperature of 20 ℃ to ensure the sample temperature being kept at less than 50 ℃. Too low temperature is harmful to the sample contamination control. The facility's shroud temperature is controlled at -35 ℃, which ensures the sample temperature being much higher than the shroud temperature. Vacuum systems consist of turbo-molecular pumps and mechanical pumps. Vacuum is better than 3×10^{-3} Pa during the whole test period.

2.4 Irradiation/Measurement Sequence

For all samples, we have performed α_s in-situ measurements before test to ensure the accuracy and reliability of the measurement system. Electron and proton current were calibrated by Faraday cup to acquire the relations between the current on the samples and the current on the monitor. Vacuum, temperature, electron, proton and NUV are monitored by computer during the test time.

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

2.5 Contamination Control

α_s is a kind of surface properties which is sensitive to contamination. Contamination of test samples must be minimized to prevent erroneous results. In this test, several measures are taken to control the sample contamination such as low contamination vacuum system, cryogenic shroud, sample's high temperature and material control inside the facility. In order to monitor the contamination inside the facility, a TQCM(Temperature-controlled Quartz Crystal Miro-balance) is placed in the test chamber in 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.

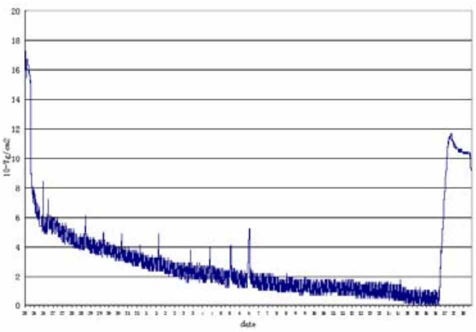

Fig.5　Mass change measured by TQCM

As can be seen from Fig.5, the mass on TQCM decreases all the time in the vacuum environment. It means that the contamination of the test chamber during test could be neglected.

3 Samples Description

The test samples are S781 white paint, SR107-ZK white paint, silvered FEP and OSR. S781 white paints are a kind of organic paints with ZnO pigment and S781 silicone resin. α_s of S781 white paint is about 0.18 and its emissivity about 0.87. SR107-ZK white paint's pigment is ZnO treated by potassium silicate. SR107-ZK white paint's binder is SR107 silicone rubber. α_s of SR107-ZK white paint is about 0.17 and its emissivity 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 aluminium substrate. OSR is a quartz plate(0.2 mm) coated with silver on one side and ITO film on the other side. Aluminium substrate is 28 mm in diameter. Three samples of each material are mounted on the target for irradiation test at the same time.

4 Test Results

The total 15 GEO environmental doses are divided equally into 15 years (the first year has two measurement points, one for a half year). The solar absorptances for 3 samples of each material are measured and the average value is taken as the α_s value for that material. "0" year means the original value of α_s. "Air" means that α_s is measured after the test chamber is exposed to one atmosphere at the end of test.

The test results are listed in Tables 1 through 4.

a. OSRs

Table 1　OSR α_s degradation

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

b. S781 white paint

Table 2　S781α_s degradation

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

c. SR107-ZK white paint

Table 3　SR107-ZK α_s degradation

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

d. Silvered FEP

Table 4　Silvered FEP film α_s degradation

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

As shown in the test results, the OSRs are the least degraded and the organic white paint the most degraded. All four types of materials show a bleaching effect. A comparison of the degradation extent is shown in Fig.6.

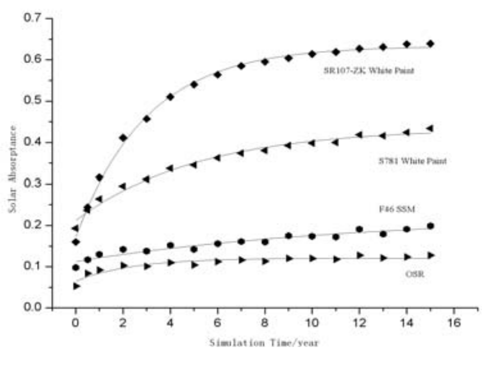

Fig.6　Solar absorptances degradation

5 Comparison with Flight Results

GEO in-flight experiment〔1〕 for monitoring a_s degradation of S781 white paint, silvered FEP and OSR (without ITO) was performed many years ago. The a_s degradation was calculated through the temperature changes of a thermal housekeeping box.

Table 5 S781 white paint comparison

Time	12 h	0.5 y	1y	2y	3y	4.3y
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_s for flight is 0.241. △a_s for test is 0.128.

Table 6 Silvered FEP comparison

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

△a_s for flight is 0.162. △a_s for test is 0.038.

Table 7 OSRa_s comparison

Time	12h	1y	2y	3y	4.3y
Flight	0.122	0.134	0.139	0.139	0.139
Test	0 0.056	0.092	0.103	0.101	0.110

△a_s for flight is 0.017. △a_s for test is 0.054.

As shown in Table5~Table7, the ground test degradation is in general close to the flight results. The degradation of S781 white paint and aluminized FEP is more severe than that of the simulation test sample. The reason is maybe due to a less contamination in ground test samples. The OSR samples in test are ITO coated while the flight OSR samples are not. That is why degradation of the OSR samples in test is more severe.

6 Extrapolation

As shown in Fig6, 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 becomes necessary. We have applied the least square regression to the degradation curves to get empirical formulas. The following second-order exponential decaying formula is found to be very close to all test result points .

$a_s = C+A\exp(-t/\theta1) + B\exp(-t/\theta2)$ 。

There are 5 parameters (C, A, θ_1, B, θ_2) to be determined by the least square regression method. a_s degradation regression 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 are used, the bigger the error at the 15 year point as shown in Table 8. a_{s0} of SR107-ZK white paint for combined simulated 15 years is 0.639.

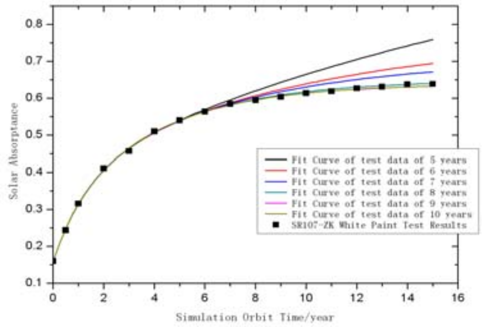

Fig.7 Extrapolation for SR107-ZK degradation

Table 8 Error of extrapolated degradation

simulated time (year)	Prediction of a_s at 15years	Error relative to test a_{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%

As shown in Table 8, if we use 8 year points, the 15 year prediction accuracy is less than 1% which is good enough for engineering applications. It means that for a long life degradation simulation, extrapolation by using empirical formulas will be very economical.

7 Conclusion

The geostationary environmental effects of 15 years on a_s degradation of S781 white paint, SR107-ZK white paint, silvered FEP, OSR at the outer surface of satellite are simulated by a combined low energy irradiation simulation test methods. The comparisons between the simulation test and flight test were made to show the effectiveness of the simulation test method. According to the degradation trend, a least square regression methods are used for obtaining empirical formulas. The second order exponential decaying formula is found reasonably good to fit the degradation curves. Severe degradation is found in organic white paint while OSR and silvered FEP remain quite stable. Extrapolation method for a long simulation test time is verified. For samples of SR107-ZK white paint, with 8 years of simulation test points, extrapolation values at 15 years are very close to the 15 year test values with less than 1% discrepancy.

References

[1] Feng Weiquan. Study on long term degradation of solar absorptance properties of geostationary satellite thermal control coatings[J]. Chinese Space Science and Technology, 2005, 34(25)

[2] Marco J. Evaluation of thermal control materials degradation in simulated space environment[A]. ESA SP 540, Proceedings of the 9th International Symposium on Materials in Space Environment[C]. Noordwijk, The Netherlands, 2003-6-16～20. 2003-9

GEO 卫星热控涂层 α_S 退化空间综合环境模拟试验

冯伟泉[1]，丁义刚[1]，闫德葵[1]，刘学超[2]，王 伟[2]，李冬梅[2]
（1. 北京卫星环境工程研究所，北京 100094；2. 中国空间技术研究院，北京 100094）

摘要：文章用综合低能辐照试验模拟 15 年地球同步轨道环境对热控材料 S781 白漆、SR107-ZK 白漆、镀银 FEP、OSR 片的太阳吸收率退化趋势。有机白漆有严重退化，而 OSR 和 镀银 FEP 材料退化较少。通过与飞行试验结果比较，证明了本次模拟试验的有效性。通过利用退化趋势的试验数据，应用最小二乘法获得退化数学模型。二次指数退化模型与 4 种材料退化曲线符合较好。更长试验时间结果可以通过数学模型外推的方法获得。经试验验证，用 8 年试验数据外推 15 年数据误差不超过 1%。

关键词：综合模拟；低能模拟；退化；空间辐射；太阳紫外；太阳吸收率；原位测量

～～

中 国 的 深 空 探 测

深空探测是当今世界科技发展的前沿领域，具有很强的基础性、前瞻性、创新性和带动性，对于理解保护地球、探索生命起源、引领科技发展、培养尖端科技人才具有十分突出的作用。深空探测的 4 个重点是月球探测、火星探测、巨行星探测、小行星及彗星探测等。20 世纪 90 年代初，我国开始月球探测工程的有关论证。2004 年 1 月，以“嫦娥工程”命名的绕月探测工程正式启动，标志着继发射人造地球卫星和突破载人航天之后，探月将成为我国向深空探测进军的起点。

人类月球探测活动大致可分为“探”、“登”、“驻”三个阶段，我国目前开展的月球活动处在“探”的阶段，分“绕”、“落”、“回”三期实施。绕月探测工程由月球探测卫星、运载火箭、发射场系统、测控系统和地面应用系统 5 大部分组成，这个综合性工程系统将使用中国自己的技术、产品、设计、条件完成。探测用仪器和设备的工作特性满足工程需求，其可靠性要满足一年的连续观测。

据欧阳自远院士介绍，“嫦娥一号”绕月卫星精选 4 大科学目标:

(1) 获取月球表面三维立体影像（用可见光立体成像仪和激光高度计）;

(2) 分析月球表面有用元素含量和物质类型的分布特点（用干涉成像光谱仪、X 射线谱仪等）;

(3) 探测月壤厚度（用微波探测器）;

(4) 探测地球至月球 4×10^4~4×10^5 km 的空间环境（用太阳高能粒子探测器和低能粒子探测器）。

研制和发射“嫦娥一号”卫星需要攻克的 4 大主要技术难点:

(1) 卫星轨道设计和飞行程序控制设计（轨道加速，轨道调整，近月点制动）;

(2) 远距离测控和数据传输（保证地面实时进行卫星测控、监视及数据传输）;

(3) 制导、导航与控制（保持对月、地、日 3 个天体定向）;

(4) 热控技术（应对两次月蚀环境，-170~+130℃温差）。

下一步探月二期的总体科学目标是“月球软着陆和月球车巡视勘察”，届时我国将使用空间光学望远镜、极紫外相机、低频射电设备等在月球上进行天文观测，以探寻太阳系外行星。

[闫德葵　摘编]