INFLUENCE OF TEST CONDITIONS AND VARIABILITY OF END-OF-LIFE SOLAR ABSORPTANCE OF THERMAL CONTROL MATERIALS

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ABSTRACT

This paper reports on 20-year ground test data of thermo-optical performance of MAP SG121FD/122FD and PSB/PSBN paints. It shows the influence of test parameters on test results and provides estimate of solar absorptance variability for these kind of coatings.

INTRODUCTION

Thermal control (TC) of spacecraft is based on critical surface coatings and devices as MLI assembly. Thermo-optical properties of these materials are of concern to design performant TC sub-systems all through the mission duration. Especially the capacity to reflect solar radiation and emit component heat is of prime importance to ensure spacecraft temperature will not exceed required limits. However, thermal control coatings (TCC) degrade with time in orbit and therefore control of spacecraft temperature within reasonable limits over long period of mission requires the (quantitative) knowledge of the performance change.
The solar absorptance α_s of materials is the critical property as well known to be sensitive to the harsh space environment due to radiation ageing.[1]
For instance, the surface dose expected for 15-year GEO mission is huge (>10^9 Gy (Al)) leading to surface discoloration (gradual and permanent solar absorptance increase with time) and potential long term mechanical damage (cracking).
The knowledge of End-Of-Life (EOL) solar absorptance is therefore of prime concern for the sizing of radiators. Change in absorptance has to be estimated from ground testing with representative test conditions. The norms [1] and common practice recommend accelerated combined particles/UV testing associated to in situ measurement (annealing mechanisms in presence of oxygen) for surface materials in order to approach realistic degradation mechanisms.

The SEMIRAMIS facility at ONERA DPHY allows for simulating GEO dose profile with electrons, protons and UV under vacuum with in situ reflectance measurement. Such combined testing requires complex test plan accounting for critical parameters such as:

- Dose profile : in GEO orbit surface dose is brought by protons and UV, bulk dose by electrons,
- Flux (dose rate) governs degradation kinetics (acceleration effects),
- Sequence is here important because of consecutive and not simultaneous exposure,
- Timing: high flux may induced over-degradation (acceleration effect) and delayed annealing mechanisms (timing effect).

Main limitations at facilities come from the absence of in situ measurement capabilities or limited acceleration. Indeed, at most laboratories full dose can be deposited with particles but only partial UV equivalent sun hours (ESH). Extrapolating EOL performance from partial mission dose data can be a solution provided that models can be applied. Thus (semi-)empirical fittings can be used [2]-[4]. However, this approach poses the problem of the uncertainties associated to $\Delta\alpha_s$ estimate including test parameters and batch-to-batch variation.

The last decades, TCC paints have been developed by CNES with the purpose to improve radiation stability. Ground testing of each new formulation has been performed at SEMIRAMIS with defined conditions (constant test plan over the last 20 years). Reference samples are used at each test campaign as witnesses to check for traceability and reproducibility of test conditions and thus ensure the ageing data on new developments can be compared to previous formulation.
This paper takes advantage of these 20-year CNES test data on witness samples to check for the relative influence of main test parameters and provides estimate on variability of EOL α_s for these pigmented coatings.

EXPERIMENTAL CONDITIONS

1.1 Test plan at SEMIRAMIS

As already mentioned, the ground testing of surface materials at SEMIRAMIS is performed combining electrons, protons and UV exposure under vacuum to reproduce the GEO dose profile (Fig. 1), in situ reflectance measurement and the monitoring of temperature [5].

[1] Contamination and thermal-cycling that also participate in the overall degradation and decrease of thermal performance are not addressed in this paper.

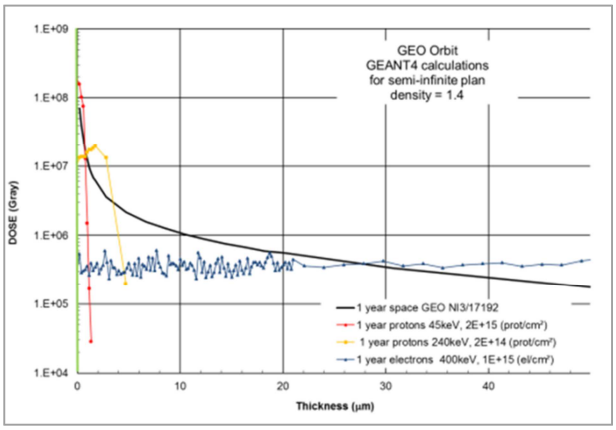

Fig. 1 – GEO dose profile at SEMIRAMIS combining electrons (bulk dose), protons and UV exposure (surface dose). Provided fluence here are calculated for a 1-year mission.

The UV facility makes use of Xenon lamp providing representative spectrum in the 200-400nm range with flux ranging from 3 to 7 suns.

The typical test sequence applied is disclosed in Fig. 2. Sequential exposure/measure steps are performed at increasing dose levels. In addition to the "irradiation phase", two transitions steps allow for evaluating outgassing effect (prior to irradiation sequence) and recovery at venting (after irradiation sequence).

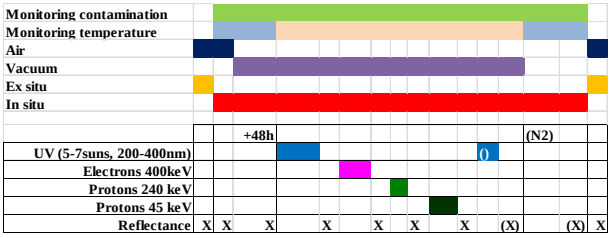

Fig. 2- Test sequence at SEMIRAMS alternating exposure and in situ reflectance measurement. Also includes two transition phases (into brackets).

This typical sequence may also include short UV final step (≈50esh UV) for promoting photo-annealing of short-life defects (small contributor to total degradation in orbit due to synergy of radiation and UV).

1.2 Samples description

The degradation of pigmented paints has extensively been investigated all through the years [6]-[9]. The samples used here as witnesses are:

- Silicones: SG121FD and SG122FD (non-conductive) paints from MAP,
- Silicates: PSB and PSBN paints from MAP.

The main degradation mechanisms observed are summarized here and shown in Fig. 3 and Fig. 4:

- both silicone paints are stable with UV, SG121FD is mostly sensitive to electrons while SG122FD to protons,
- Photo-annealing mechanisms (bleaching of color centers) is observed with SG121FD but not with SG122FD,
- Strong and rapid recovery at venting is linked to annealing of radicals.

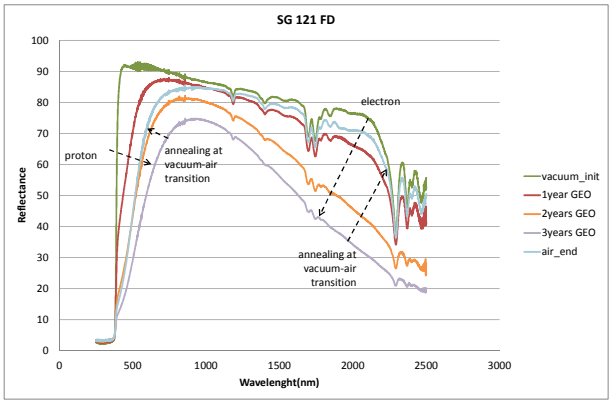

Fig. 3 - Reflectance curves at 1, 2 and 3-year GEO doses and after venting (air_end) for SG121FD (2016)

- PSB coating is sensitive to particles (electrons and protons) and stable with UV, whereas PSBN is mostly sensitive to electrons,
- Both are strongly sensitive to photo-annealing with UV whereas slight recovery is observed under vacuum and when exposed to oxygen (slow annealing rate).

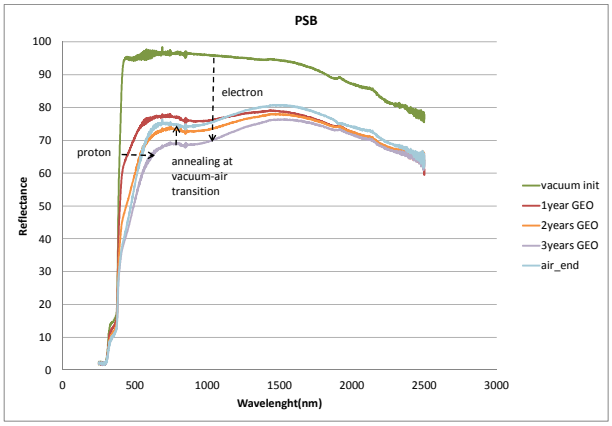

Fig. 4 – Reflectance curves at 1, 2 and 3-year GEO doses and after venting (air_end) for PSB (2016)

Next table summarizes the main characteristics of test campaigns and identifies the "witness" samples used. Typically data at 1-year and 3-year doses are available and allows for data comparison. Additional data can also be used at campaigns dedicated to the investigation of UV acceleration or spectrum and effect of sequence.

Table 1 – List of GEO test campaigns and associated witness sample. Main characteristics are provided with any deviation to the standard test plan (UV/e-/p+).

GEO dose (y = year)	ID	PSB	PSB N	SG121 FD	SG122 FD
0.9 year	1989, 1990	x			
UV acceleration	1991	x			
2.52 years	1991bis	x			
0.9 year	1992 1995_09	x			
1 year	1996	x			
0.9 year	1998	x			
0.9 year + optional UV	2000_09 2000_1 2002_09	x	x	x	
UV acceleration	2002ax	x		x	
3 years	2003	x	x		
5&10y p+/UV	2004	x	x		
5 years (no UV)	2006_5p	x	x	x	
UV spectrum	2006o 2006r	x		x	
1 year, T°	2007	x		x	x
8 years	2009	x	x	x	x
1year inverted sequence	2011i	x	x	x	x
3 years	2014	x	x	x	x
3 years	2016	x	x	x	x

1.3 Evolution of facility over the test period

Obviously, technical improvements have been brought to the facility over the years with the automation of accelerators and beam lines and new diagnostic tools for monitoring beams and dosimetry ….
These improvements have impacted on test plan mostly by modifying timing of applied test sequence with the more rapid turn-over between exposure and measure (reduced and optimized beam setup time) and shorter irradiation duration due to higher electron flux (x3-5) and UV acceleration (x2).
Both modification on UV spectrum and acceleration were validated (limited impact) on several materials (including our witness paints) [10].

1.4 Uncertainties on experimental parameters

Confidence on measured EOL solar absorptance relies on the representativeness and reproducibility of test conditions. However, it can be affected by batch-to-batch and campaign-to-campaign (uncertainties on test parameters).
Sample-to-sample variability is usually neglected as radiation response is mostly considered as process-dependent (no variation for a given formulation and manufacturing batch). That is why it is commonly admitted that only one sample per testing is enough (as disclosed in Table 1).
Uncertainties on critical test parameters mostly concern the dose at target level (uncertainties associated to solar absorptance measure is typically ±0.01 i.e. negligible in the overall uncertainties [11]). At SEMIRAMIS, dose uncertainties come from non-uniformity of beam (over the entire exposed area 12cm x 12cm) estimated with mapping at each irradiation step: typically 10% for electron and UV, 15-20% with protons. Finally, reproducibility of irradiation conditions is ensured by the application of the same procedure for beam setup.

MAIN RESULTS

Solar absorptance data have been analysed considering alpha change associated to a single irradiation step or cumulated steps (EOL–BOL α_s for full campaign). This approach allows for discarding any potential BOL data variability at BOL (batch-to-batch variability …).
This analysis is provided in the next section with emphasis on SG121FD and PSB paints for statistical reason (covered by more test campaigns).

2.1 UV results

SG121FD/SG122FD are stable with UV therefore any variability would mainly result from non-reproducibility of test parameters. As observed in Fig. 5, $\Delta\alpha_s$ for SG121FD is very limited and dose-independent.

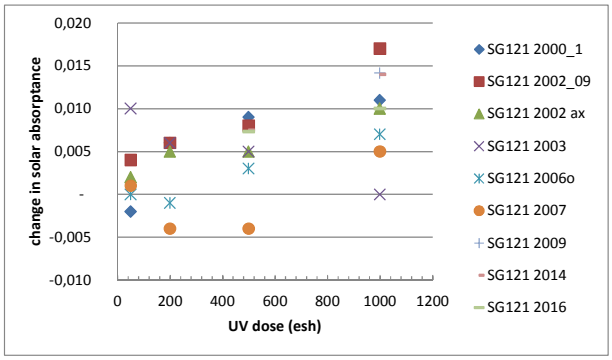

Fig. 5 - Change in solar absorptance of SG121FD with UV dose.

Upper bound limits and mean degradations are of same order of magnitude and standard deviation is close to measurement uncertainty (mean $\Delta\alpha_s$=0,011±0.004).

Contrary to SG121FD, PSB paint shows more sensitivity to UV with clearly dose dependence (Fig. 6).
Variability slightly increases with dose with most recent test campaigns providing upper and lower bound limits.
Note that data originating from test campaigns dealing with different UV spectrum (2006o) or acceleration (2002ax) are consistent with “standard conditions data” (no impact here).

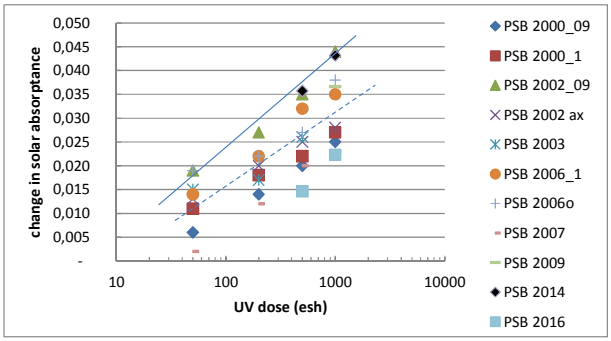

Fig. 6 - Change in solar absorptance of PSB with UV dose. Straight/dashed lines are respectively upper bound limit and mean degradation.

PSB	UV std-deviation	0,008 (24%)
	UV max	0,044
	UV mean	0,033
	UV min	0,022

2.2 Particles results

The following graphs provide change in solar absorptance after the 1-year electron and proton steps for both SG121FD and PSB.

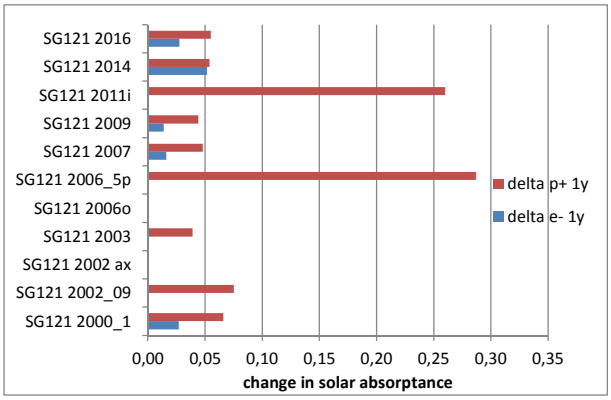

Fig. 7 – Change in solar absorptance after 1-year electron (e-) and proton (p+) doses for SG121FD.

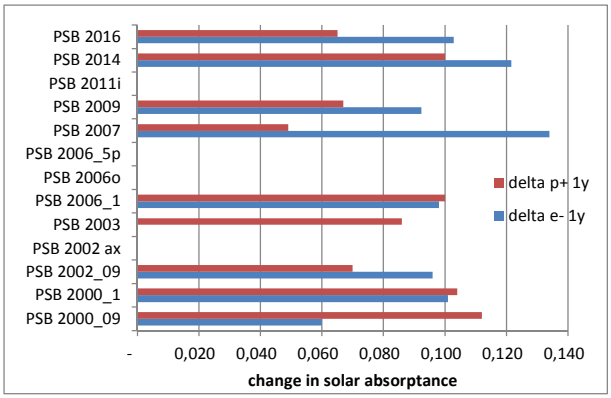

Fig. 8 – Change in solar absorptance after 1-year electron (e-) and proton (p+) doses for PSB.

One can notice in Fig. 7 the worst-case (WC) solar absorptance measured on SG121FD at test campaign 2014 with electrons. This "excessive" degradation is assumed to be due to the timing of the sequence (no latency after the end of irradiation and prior to measurement). This point will be discussed later.
With protons, WC is achieved at test campaigns 2011i and 2006_5p, each time in absence of UV exposure prior to particles irradiation (non-standard condition). Excluding these two configurations, discrepancy between data is smaller for proton than electron for SG121FD (standard deviation respectively 23% and 34%) and SG122FD (only 9% found with protons).

Discrepancy between data for PSB is more limited (Fig. 8, lower overall sensitivity). The WC data at campaign 2014 is observed again but also with 2007 data for electrons and 2006_1 and 2000s data for protons. The similarity between 2014 and 2007 test campaigns can explain the WC degradation with electrons: in both cases here again no latency between irradiation and measurement, contrary to other campaigns.
This timing effect is confirmed with the proton 2007 data due to a 12-day test interruption due to technical failure: strong recovery under vacuum is clearly observed during this interruption with α_s lowering from 0.21 to 0.15.
The mean and standard deviation associated with PSB paint is therefore 0.101±0.022 (22%) and 0.084±0.022 (26%) respectively for electron and proton testing. More discrepancies are found with PSBN mostly due to statistical reason.

2.3 Overall discrepancies on alpha degradation

The following table summarizes variability measured after 1- and 3-year GEO doses. These results exclude test campaigns whose conditions deviate from standard conditions (timing and sequence) i.e. 2014, 2006_5p and 2011i.

Table 2 –Mean and standard deviation for change in solar absorptance for all witness samples at GEO doses.

sample	1 year GEO	3-year GEO
PSB	0.218 ± 0.024 (11%)	0.298 ±0.033 (11%)
PSBN	0.123 ± 0.021 (17%)	0.223 ±0.067 (30%)
SG121FD	0.089 ±0.018 (21%)	0.224 ±0.036 (16%)
SG122FD	0.067 ± 0.009 (13%)	0.201 ±0.048 (24%)

A smoothing effect is observed: variability at step level (UV, electrons or protons) lies in the 15-35% range whereas 10-20% at combined 1-year GEO. Degradation and annealing compensate along the successive steps.

Finally, variability seems not dependent on final dose but rather to material sensitivity (see SG121FD and PSB data that exhibit good statistics).

DISCUSSION AND PARAMETRICAL ANALYSIS

Considering the testing approach at SEMIRAMIS (successive exposures), it is assumed that total $\Delta\alpha = \Sigma\alpha_i$ by step. The importance of timing is mentioned to explain WC data in 2014 for instance. Indeed, timing is important because in such accelerated testing, it may impact on results in two different ways namely dose rate and timing effects (Fig. 9).

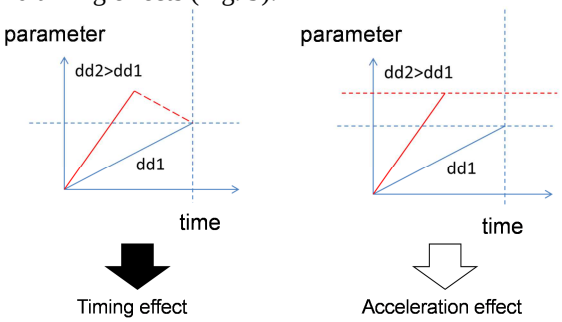

Fig. 9 – Timing effect leads to delayed annealing whereas acceleration effect results in over-degradation here.

In a scenario where timing effect occurs:

$$\Delta\alpha = \Sigma\alpha_{i\_degradation} + \Sigma\alpha_{i\_annealing} \qquad (1)$$

(opposite signs for degradation and annealing). It was shown for these materials that annealing kinetics under vacuum follows and exponential law **Erreur ! Source du renvoi introuvable.**[5]

$$\alpha_s = A * exp\left(-\frac{t}{\tau}\right) + B \qquad (2)$$

with relaxation time dose-dependent: typically τ~16days at 1-year GEO and τ ~2.5 days at 8-year GEO for PSB/PSBN, and very slow annealing at 1 year GEO and τ~3.5days at 8-year GEO for SG121FD/122FD. Table 3 provides "corrected" figures for data 2014 accounting for vacuum annealing (1-day latency).

Table 3 – Change in solar absorptance of PSB and PSBN paints at campaigns 2014 and 2016. Effect of vacuum annealing (timing of the test sequence).

	Change in α_s			
	2014	2014 + 1-day latency		2016
		p+ step	e- & p+ steps	
PSB	0.27	0.24	0.19	0.19
PSBN	0.23	0.21	0.21	0.14

One can notice that for PSB, 2014 and 2016 data are equal considering vacuum annealing at each particle step (0.19). The corrected delta alpha for PSBN remains much too large and a 4-day annealing is necessary to "lower" the degradation to the 2016 level.

The impact of variability on extrapolation of EOL solar absorptance is then estimated using the 8-year test campaign data (Fig. 10). The solar absorptivity degradation fitting is here based on semi-empirical models i.e. sum of two saturated exponentials

$$\alpha_s = \alpha_{sat} * (1\text{-}exp(-t/\tau)) \qquad (3)$$

±20% constant variability is assumed here at each step (1/3/5/6.5/8-year steps).

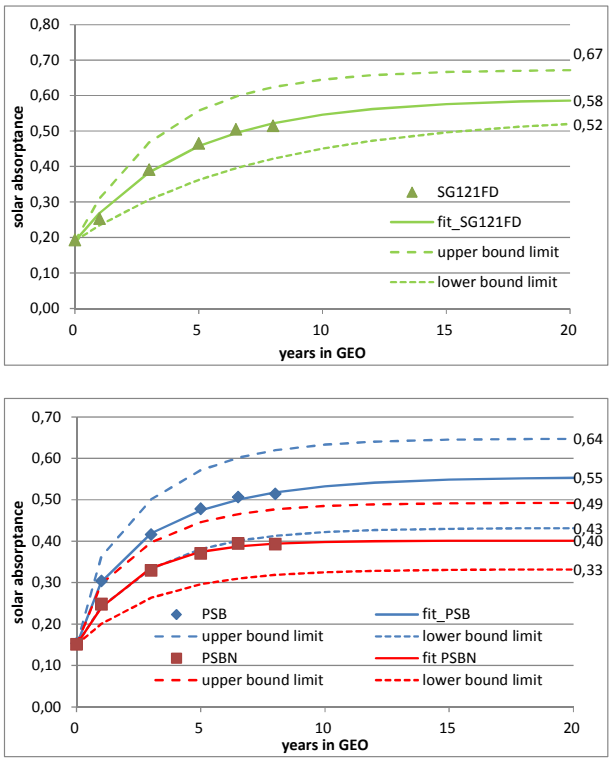

Fig. 10 – Extrapolated solar absorptance of SG121FD (top) and PSB/PSBN (bottom) accounting for variability of data.

CONCLUSIONS

The analysis of 25-year of CNES test campaigns data on reference materials samples have been performed to investigate variability in EOL performance of white paints.

Variability on change in solar absorptance for 1-year GEO dose, including process-to-process and campaign-to-campaign variabilities, is lower than ±20%. This figure is consistent with experimental uncertainties (dose non-uniformity) and is quite constant with dose (1 and 3 years GEO).

Timing effect is critical especially with high acceleration factors. The testing approach at SEMIRAMIS (successive exposures) induces a smoothing effect i.e. degradation and annealing compensate over the long term. Adequate test plan shall therefore include latency times (under vacuum) to allow

for (delayed) annealing mechanisms to take place. Final UV step to accelerate and promote short-life defects annealing can also be added or true synergy applied with simultaneous UV and particles exposure.

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