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Selection of a PVD black coating for the thermal control of the Feedthroughs and Door Mechanisms in the Solar Orbiter Heat Shield

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ABSTRACT

The ESA Solar Orbiter is an interdisciplinary mission to the Sun. It consists of a single spacecraft which will orbit the Sun in a moderately elliptical orbit, using a suite of advanced Remote-Sensing and In-Situ instruments to perform a detailed observation of the Sun and surrounding space. SENER is contractor for the design and delivery of the FDMs subsystem (Feedthroughs, Door & Mechanisms), which consists on several through wall filters and six mechanism doors to protect the instruments in some operational conditions, all of them located in the Heat Shield of the satellite. The extreme environment which the FDMs will be subject to during the Mission, involves a challenge for the thermal design of the subsystem, mainly based on the passive thermal control, where the selected external surface finish plays a decisive role in the thermal behavior.

This paper briefly explains the trade-off performed for the selection of the coating of the FDMs during the initial phases of the project. This selection was tightly constrained by demanding requirements for operational temperatures (above 500ºC), cleanliness close to optical instruments, electrical resistivity and coating strength for AIT purposes. The finally selected coating is a special developed coating called ASTRO BLACK® based on the PVD technology. The coating has been submitted to a qualification test campaign whose results are also presented in the paper, together with the thermal analyses used for the design of the FDMs. Due to the good results achieved at analysis level, and during the tests performed throughout the project, SENER has considered the use of ASTRO BLACK® in other subsystems of the same mission which is responsible for, and also in other missions with highly demanding thermal environments.

Nomenclature

AAC = Aerospace & Advanced Composites
AU = Astronomical Units

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BOT = Begin of Test
EOT = End of Test
ESA = European Space Agency
ESD = Electro-Statical-Discharge
ESH = Equivalent Sun hours
ESTEC = European Space Technology and Research Centre
FDM = Feedthroughs and Door Mechanisms
FT = Feedthrough
I/F = Interface
NASA = National Aeronautics and Space Agency
PVD = Physical Vapour Deposition
SC = Solar Constant
SOLO = Solar Orbiter
STAR = Synergistic Temperature Accelerated Radiation facility
TEC-QTE = Materials Space Evaluation & Radiation Effects Section
TO = Thermo optical
UV = Ultra-Violet (radiation)
VUV = Vacuum ultra-violet (radiation)

I. Introduction

Solar Orbiter is a sun-observing satellite developed by ESA in collaboration with NASA, dedicated to solar and heliospheric physics. The satellite is designed to carry several scientific instruments for in-situ measurements at the closest ever sun environment, which will provide a critical step forward in understanding the origin of solar transient phenomena and their impact on the heliosphere. SOLO will have a highly elliptic orbit, between 0.9AU at aphelion and 0.28AU at perihelion, with a solar radiaton equivalent to 13 Suns at the minimum distance.

SENER is responsible for the delivery of the FDMs subsystem, which consist on several through wall filters located on the sunshield, in charge of protecting the satellite from the hardest environment. This subsystem provides the satellite with non-hermetic protective covering for its remote detection instruments.

Some of these feedthroughs (6) need a door cover to protect the instruments in some operational conditions. The door is located at the sun entrance side of the feedthrough and is actuated by a mechanism designed to rotate the door through a shaft, from closed to open position and from open to closed position.

The mechanisms and feedthoughs have the following elements:

Figure 1. *FDMs installed in SOLO Heat Shield (ESA)*

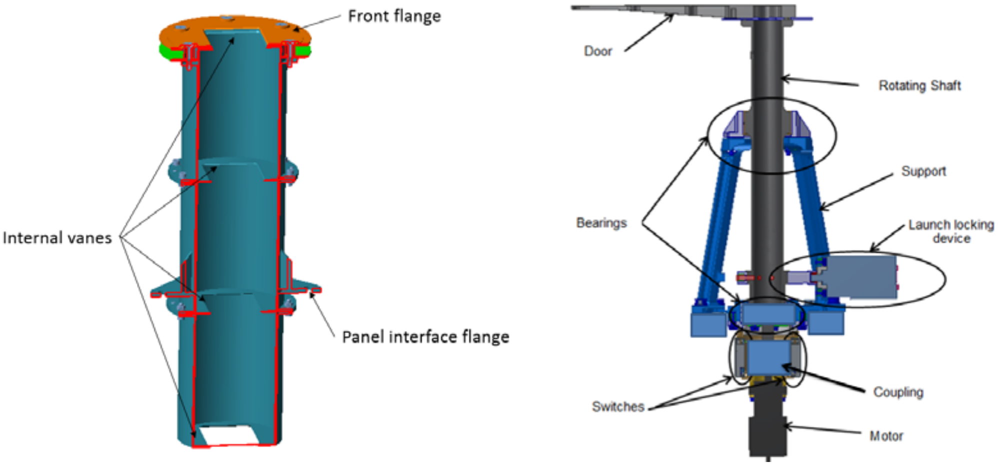


Figure 2. *Feedthrough (left) and Mechanism(right)*

II. FDMs Thermal Design Concept

The thermal analysis in this project has been taken as a challenge due to the proximity of the Spacecraft to the Sun, the closest ever (0.28AU). At the minimum distance, the satellite sets the heat shield of the spacecraft facing the Sun and, consequently, the highest temperatures, around 500ºC, are obtained at the door of the mechanism and at the front flange of the Feedthroughs.

Therefore, the thermal design of the FDMs has been intended to minimize the thermal conductivity along the length of the FDMs, in order to reduce the heat fluxes transmitted to the support panel of the heat shield, as well as to ensure that the temperatures of the critical items of the mechanisms remain within their allowable operative temperature limits. This, involves important thermal gradients between the upper and lower parts of the FTs and Mechanisms.

For this purpose, the thermal design is based on a purely passive thermal control. Titanium (Ti6Al4V) has been selected as the material for all the structural parts due to the low conductivity and its capabilities to withstand the extreme temperatures foreseen. Reduced cross section of all structural parts is considered to decrease the heat flow downwards. Conductive decoupling is also required at interface with the supporting panel, which is achieved by means of Titanium thermal washers at the I/F bolts.

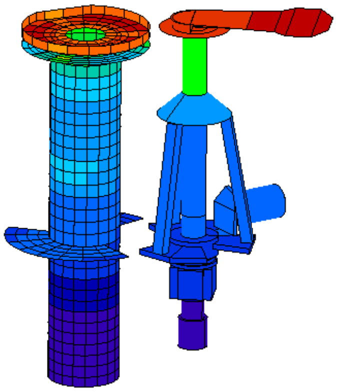


Figure 3. *FDMs thermal models*

Additionally, the surface finish selection is critical for the thermal behavior of the specimens:

- The external surfaces facing the sun in the hottest cases require a coating with a low absorptance to emissivity ratio. (yellow surfaces in Figure 4)
- The remaining external surfaces need a high emissivity finish to allow a large fraction of the heat to be radiated back to the deep space. (blue surfaces in Figure 4)
- The internal surfaces of the tubes demand specific optical properties, since they are aimed to provide the field of view of the instruments located inside the spacecraft. (orange surfaces in Figure 4)

However, the selection of the coating is not based only on the thermal purposes of the model, but must take into consideration also specific requirements coming from different disciplines.

Therefore, the extreme environments of the mission, as well several strong specific requirements involved that during the early stages of the project, the coating aspect was declared critical for the instrument needs. This led to an exhaustive coating trade-off prior to the official project launch.

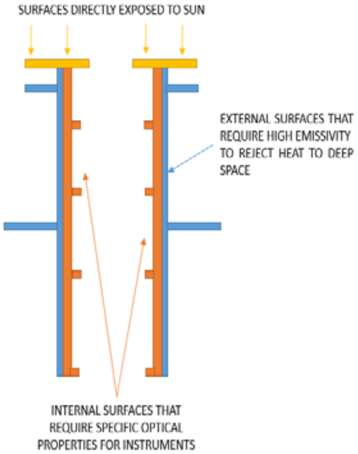


Figure 4. *FT external surfaces Thermo-optical properties needs*

III. Coating Selection Trade-off

During Phase 1 a baseline coating with an appropriate alpha/epsilon ratio value and the required high emissivity was selected, following SENER heritage with same surface finish in other applications. A batch of tests at coupon level was defined preliminarily, in order to verify as soon as possible the thermo-optical properties, capability to withstand the expected thermal environment, peeling resistance, superficial resistivity, proper stability to handing operations and cleanliness.

The coated samples were checked at different laboratories, performing the following tests:

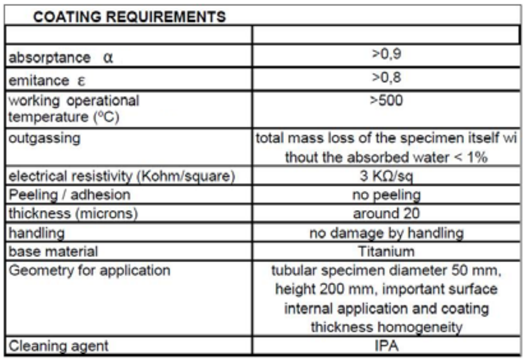
- Thermo-optical properties measurement
- Bake test at 500ºC
- Tape adhesion test
- Peeling test
- Electrical resistivity measurements

Although thermo-optical properties appeared consistent with the thermal needs, severe deviations identified after the thermal bake at 500ºC led to discard the pre-selected coating.

A development model was also produced during this preliminary phase, in order to verify proper applicability of the coating on the special geometry characteristics of the FTs (internal side of the tube, corners, edge of the vanes…) which was considered also critical. However, results showed that liquid electrochemical deposition process coating on the assembled parts of the complete model did not coat correctly and uniformly, leaving areas uncoated or partly coated. The coating appeared also extremely sensitive to handling, and several marks were observed after mechanical activities.

Although the test results were unsatisfactory for the preselected coating, lessons learnt from all the activities performed were highly determinant to continue the process of coating selection.

Therefore, in order to investigate new additional coatings, a coating trade-off was launched. For this study, parameters in Table1 were selected, trying to concentrate the efforts on those strong coating performance requirements:



COATING REQUIREMENTS	
absorptance α	>0,9
emitance ε	>0,8
working operational temperature (ºC)	>500
outgassing	total mass loss of the specimen itself wi thout the absorbed water < 1%
electrical resistivity (Kohm/square)	3 KΩ/sq
Peeling / adhesion	no peeling
thickness (microns)	around 20
handling	no damage by handling
base material	Titanium
Geometry for application	tubular specimen diameter 50 mm, height 200 mm, important surface internal application and coating thickness homogeneity
Cleaning agent	IPA

Table 1 *Main requirements for coating selection*

For the trade-off a preliminary coating selection was performed, considering several well known coatings from different technologies. An exhaustive research was done in order to find the best candidates: one of them was considered based on SENER experience in thermo-solar area, while the remaining considered coatings were included in the final trade-off following the proposal of companies specialized in coatings development for space applications after being requested by SENER.

Considering the previous selection and taking into account Phase 1 experience tests, and advanced Phase 2 was launched. The idea was to test at coupon level all the potential candidates.

The tests performed in coupon flat specimens were:

- Absorptance and emittance at ambient temperature
- Absorptance and emittance after 24h bake test at 500ºC
- Absorptance and emittance after step 2 plus immersion in LN2
- Surface resistivity following ASTM D 257-07 Standard Test Methods for DC Resistance or Conductance of Insulating Materials
- Outgassing following ECSS-Q-ST-70-02C at 200ºC
- Peeling test method UNE-EN-ISO-2409/3M Scotch 810 tape adhesion test
- Knife edge microsections

In addition to the coupons test, in order to check geometry limitations in the coating application process due to the special geometry of the specimens several tubular parts were manufactured to be coated.

These verifications in the coating application process were determinant even for the specimens design. The major handicap encountered was the coating application on the internal walls of the tubular Feedthroughs, since for those

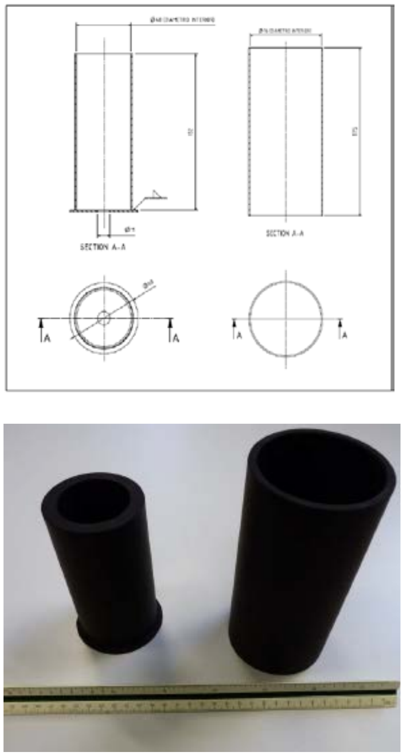


Figure 5. *Coating application verification with dummy models representing the Feedthroughs geometry (Sener copyright)*

geometries with smaller diameters, the process was limited to reach and cover all the internal areas in the total length of the tube.

For this purpose, several tubular geometries with different ratios diameter-length were manufactured. This was decisive for the design of some of the Feedthroughs. To simplify the manufacturing process just a single tubular piece would have been desired, but the limitations in the coating application on the internal parts, led to manufacture some of the Feedthroughs in split tubular parts bolted together.

The results from the amount of tests performed showed that finding a coating able to fulfill all the requirements did not look like to be feasible, therefore priority rank of the requirements should be defined and agreed taking into account additional aspects of existing heritage, coating supplier (for logistic purposes) and costs.

As a result of the trade off, some of the candidates were discarded due to not being compliant to the surface resistivity and/or outgassing requirements and finally a coating based on the PVD technology process was chosen.

The PVD coating selected was then submitted to a development process in which its composition was trimmed in order to improve the critical aspects identified at this early stage of the project: absorptance to emissivity ratio very close to the desired and homogeneity of the coating (constant thickness) during the application on the internal sides of the tubes.

IV. Coating performed tests

The PVD coating specially developed for FDMs application (Astro Black® registered mark by Metalestalki[1]) is a thin dark highly adherent film deposited by Physical Vapour Deposition. It is a stable ceramic coating that will not be affected by the extreme conditions and vacuum of space, as it can withstand temperatures in the range of 500ºC to -180ºC, and in addition of thermal properties, it guarantees extreme adhesion levels on Titanium substrate, cleanliness, excellent resistance to handling degradation and minimum outgassing levels.

During the project the coating was submitted to two test phases.

Initially, a confidence test campaign was performed under subcontract with AAC, in order to initially characterize the main coating properties and give evidence of coating behaviour.

The confidence tests were carried out in three different labs (AAC, NPL and TS-SPACE). The test plan is given:

TEST FACILITY	TEST PLAN
NPL	TIS
AAC	Surface Resistivity
	Thickness measurement (metallography)
	Peeling/ adhesion
	BOL Thermo-optical at ambient & high temperature
TS-SPACE	Particle & UV Radiation
AAC	MOL Thermo-optical properties at ambient temperature
	Thermal vaccum test [50;500]ºC 64 cycles
	Thermal vaccum test [-180;100]ºC 64 cycles
	EOL Thermo-optical at ambient & high temperature
	Thermoshock 64 cycles inmersion in LN2
	Peeling /adhesion EoL
	Stud/ adhesion

Table 2 *Test plan during coating confidence campaign*

Subsequently, a full qualification test campaign was performed under subcontract with ESA, in order to be finally accepted for the flight model.

For PVD Astro Black coating qualification, 18 samples Ti6Al4V 1mm thickness were employed. The dimension was selected to be compatible with STAR chamber, where UV & Particle radiation test were planned to be performed, leading to 19x19mm square samples.

The samples were coated on one side following the same process as the one applied to the fly parts.

The following flowchart compiles the activities performed by ESTEC to the set of samples previously described:

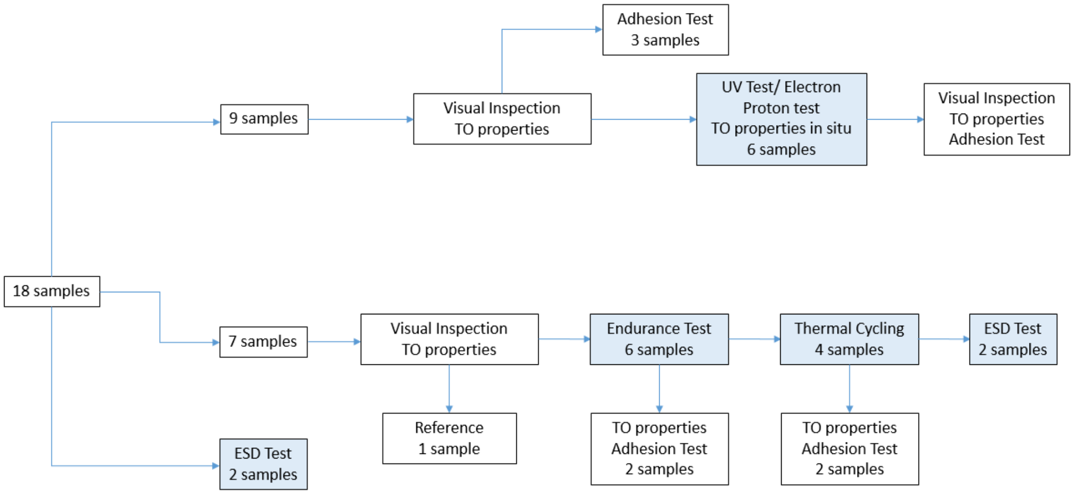


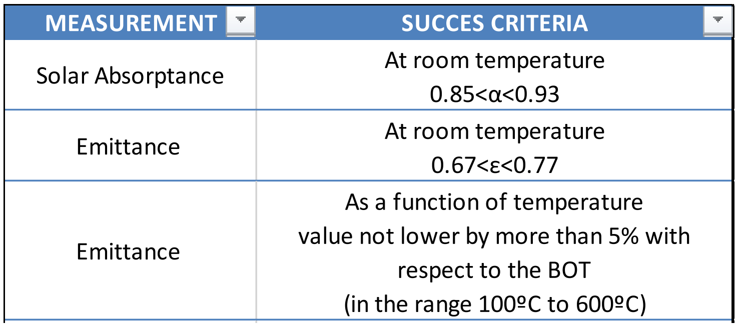
Figure 6. *Astro Black qualification test campaign flowchart*

The main tests were all performed in different ESTEC ESA facilities:

TEST FACILITY	TEST PLAN
ESTEC TEC-QTE lab STAR facility	Electron, Proton and UV irradiation
ESTEC TEC-QTE lab ESD Facility	ESD Test
CRYO40K facility of the Mechanical Systems Laboratory in Ek 121 ESTEC	Cold Thermal Cycling
XTES facility	Hot Thermal Cycling
XTES facility	Thermal Endurance

Table 3 *Tests and facilities during the coating qualification campaign*

For the samples characterizations performed throughout the test the following acceptance criteria was defined:



MEASUREMENT	SUCCES CRITERIA
Solar Absorptance	At room temperature 0.85<α<0.93
Emittance	At room temperature 0.67<ε<0.77
Emittance	As a function of temperature value not lower by more than 5% with respect to the BOT (in the range 100ºC to 600ºC)

Table 4 *Success criteria for samples characterization*

Thermal endurance Test

Prior to the Thermal Cycling, several samples were previously subject to the SOLO Thermal Endurance test campaign, comprising a total of 960h at 576°C.

The purpose of the test was to examine the effect of long term exposure to high temperature on the performance of the Astro Black®.

Several inspection points were performed during the long term test at specified exposure times (170h, 180h, 350, 960h - EOT). During the intermediate inspections, several characterizations took place: mass measurements, solar absorptance, emittance, emittance as a function of temperature. For this purpose, the furnace was naturally cooled down to ambient temperature to allow ex-situ sample characterization.

The following table summarizes the achieved results with respect to the acceptance criteria.

CHARACTERISTIC	Test Results	Acceptance Criteria
α	Stable, between 0.87 and 0.88	Passed
ε	Stable, between 0.7 and 0.77	Passed
ε (T)	Did not lower with respect to the BOT, in the range 100ºC to 600ºC	Passed

Table 5 *Thermal endurance test summary results*

Thermal cycling Test

Several coupons from the thermal endurance test were afterwards submitted to thermal cycling

The required extreme temperature range (+550°C / -196°C) could not be covered in a unique test due to facility limitations. So, it was decided to split the temperature cycle into a hot cycle and cold cycle with an overlapping temperature at (45±10)°C

- 20 Hot cycles between 40ºC and 550ºC in the XTES facility
- 20 Cold cycles between -196ºC and +50ºC in the CRYO40K facility

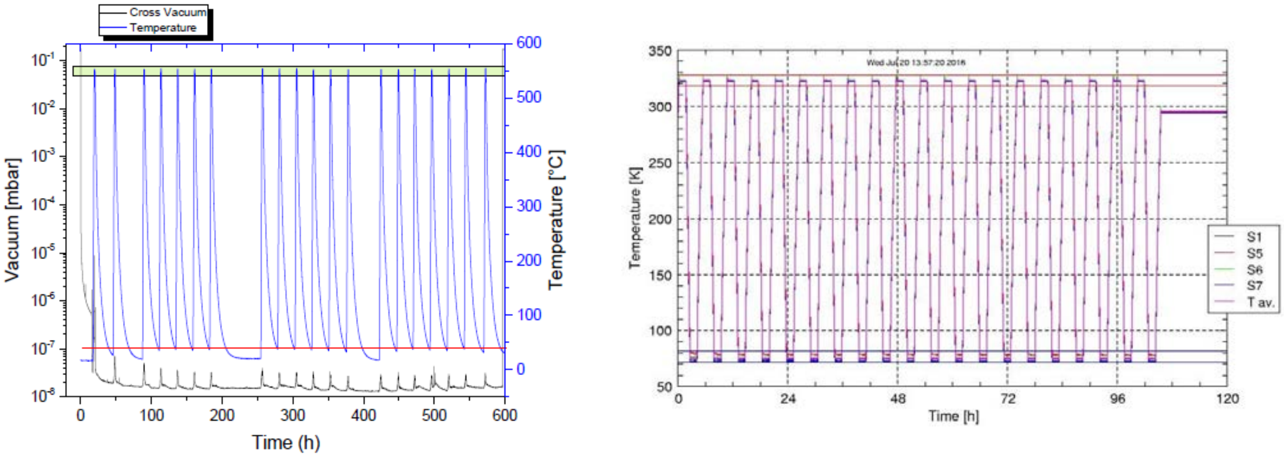


Figure 7. *Hot (left) and cold (right) thermal cycles performed during qualification campaign*

One inspection point was performed during the Thermal Cycling, at the transition from the hot cycles to the cold cycles.

Several characteristics were analysed, namely: solar absorptance, emittance (measured with the portable equipment), and emittance estimated as a function of temperature.

The cold TV cycling test was performed after the hot TV cycling test. Both of them were conducted successfully.

The following table summarizes the achieved results with respect to the acceptance criteria.

CHARACTERISTIC	Test Results	Acceptance Criteria
α	Stable, between 0.87 and 0.88	Passed
ε	Stable, between 0.73 and 0.74	Passed
ε (T)	Did not lower with respect to the BOT, in the range 100ºC to 600ºC	Passed

Table 6 *Thermal cycling test summary results*

ESD Test

The electrostatic charging properties of the Astro Black were tested under different temperature conditions at the beginning of life and after Thermal Endurance + Thermal Cycling tests.

During the test, different samples were exposed to electron radiation at temperatures under high vaccum conditions.

All tests were performed at ESTEC in the ESD Test facility, which enables simultaneous irradiation of temperature controlled-samples to electrons (5 to 60 KeV) and vaccum UV (110-200nm), which permitted evaluation of the charge/discharge characteristics of the different (pristine and tested) samples.

Test results performed at room temperature and at low temperature (-180ºC, considered worst conditions) evidenced no charging.

UV & Particle Test at elevated Temperatures

The test objective was to irradiate the test samples with Astro Black thermal coating under UV & particle radiation in order to characterise their degradation during the exposure.

During the test, different samples were exposed to proton and electron radiation and UV/VUV radiation at high temperature (<500ºC). The exposed duration lasted aproximately 2500 hours with several intermediate inspection points.

The following test conditions were used:

- Test duration: 25000 ESH assuming alpha measurement accuracy is 1% or better
- Intensity (200nm-400nm): 11 ±3 SC
- Temperature: 575ºC ± 40ºC
- VUV intensity (115nm – 320nm): 10±4 SC
- Vaccum: better than 5* 10-6 mbar
- Proton radiation / 60KeV: 1h @ 2.5nA / cm2
- Electron radiation /60KeV: 240 hrs @ 0.5 nA /cm2

The following table summarizes the achieved results with respect to the acceptance criteria.

CHARACTERISTIC	**Test Results**	**Acceptance Criteria**
α	Stable, between 0.88 and 0.89	Passed
ε	Stable, between 0.73 and 0.76	Passed
ε (T)	Did not lower with respect to the BOT, in the range 100ºC to 600ºC	Passed

Table 7 *UV & particle radiation test summary results*

Thermo-optical properties measurements

One of the critical aspects of the coating qualification test campaign was the thermo-optical properties determination.

In order to evaluate the potential change in the absorptance and emittance values of the coating after the extreme conditions of the tests, several in-situ and ex-situ measurents were undertaken throughout the complete test campaign.

- Thermo-optical properties were measured at the reception of the samples.
- During UV testing, alpha and epsilon values were measured in situ at representative temperature, and after UV and particle radiation, all samples were measured again.
- Regarding those samples that were submitted to endurance and thermal cycling, several samples were measured after endurance test, and same samples after thermal cycling.

All the measured information regarding the thermo-optical properties of the PVD coating is provided in the following graphics:

The measured thermo-optical properties at specific points during the thermal endurance test performed during the qualification campaign are provided:

SOLAR ABSORPTANCE					
sample	BOT	Phase A EOT	Phase B EOT	Phase C EOT	Phase D EOT
#10	0.88	0.88	0.88	0.88	0.88
#11	0.88	0.87	0.87	0.87	0.87
#12	0.87	0.87	0.87	0.87	0.87
#14	0.88	0.88	0.88	0.87	0.87
#15	0.88	0.88	0.88	0.88	0.88
#16	0.87	0.87	0.87	0.87	0.87

Table 8 *Solar Absorptance measuments during thermal endurance test phases*

EMITTANCE (room temperature)					
sample	BOT	Phase A EOT	Phase B EOT	Phase C EOT	Phase D EOT
#10	0.7	0.71	0.72	0.73	0.73
#11	0.74	0.73	0.73	0.73	0.73
#12	0.74	0.74	0.73	0.74	0.73
#14	0.72	0.74	0.74	0.74	0.74
#15	0.69	0.73	0.73	0.73	0.73
#16	0.77	0.74	0.74	0.74	0.74

Table 9 *Emittance measuments during thermal endurance test phases*

The measured thermo-optical properties at specific instants during the thermal cycling performed after the endurance test are provided:

SOLAR ABSORPTANCE			
sample	Thermal Cycling BOT	Intermediate Inspection (after hot cycles)	Thermal Cycling EOT
#10	0.88	0.88	0.88
#11	0.87	0.87	0.87
#12	0.87	0.87	0.87
#16	0.87	0.87	0.87

Table 10 *SolarAbsorptance measuments during thermal cycling test phases*

EMITTANCE (room temperature)			
sample	Thermal Cycling BOT	Intermediate Inspection (after hot cycles)	Thermal Cycling EOT
#10	0.73	0.73	0.73
#11	0.73	0.73	0.74
#12	0.73	0.74	0.74
#16	0.74	0.74	0.74

Table 11 *Emittance measuments during thermal cycling test phases*

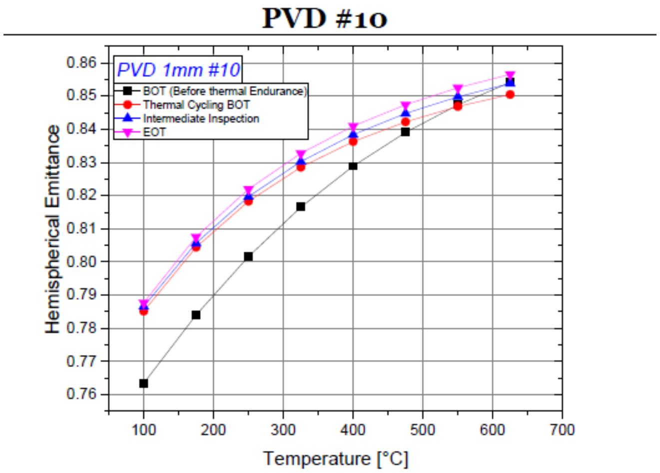


Figure 8. *Hemispherical emittance measured after thermal cycling tests*

The measured thermo-optical properties at specific instants during the UV & Particle radiation testing are provided:

SOLAR ABSORPTANCE								
sample	0h	100h	200h	800h	1500h	2600h	1h p+	240h e-
1	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88
2	0.88	0.88	0.88	0.89	0.89	0.88	0.88	0.88
3	0.88	0.88	0.88	0.89	0.89	0.88	0.88	0.88
4	0.88	0.88	0.88	0.89	0.88	0.88	0.88	0.88

Table 12 *SolarAbsorptance measurements during UV & particle radiation test phases*

EMITTANCE (room temperature)		
sample	BOT	EOT
1	0.74	0.73
2	0.74	0.76
3	0.74	0.73
4	0.73	0.73

Table 13 *Emittance measuments during UV & particle radiation test phases*

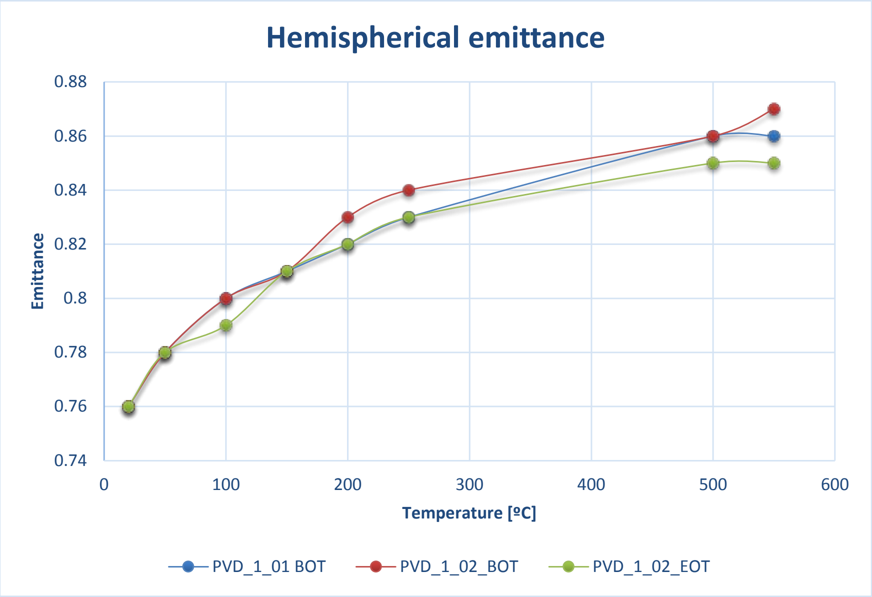


Figure 9. *Hemispherical emittance measured after thermal cycling tests*

Note: The error of the thermo-optical measurements in all the tests performed is 0.04K

V. Lessons learnt. PVD in SENER projects

As mentioned, SENER was responsible for the design, so for the thermal analysis of the FDMs. The preliminary thermal analysis performed showed that the design was strongly dependent on the thermo-optical properties of the selected coating. After several tests, Astro Black was finally selected as the best compromise fulfilling all requirements.

The initial thermo-optical properties (provided by Metalestalki) considered and absorptance value of 0.85, and an emissivity value of 0.66, providing a ratio absorptance to emissivity of 1.28, adjusted later on.

An improvement in thermo-optical properties was achieved after the composition of the coating was modified and thus has been proven via the confidence and qualification test campaigns.

The information coming from the measured data was useful for the thermal analysis as could be seen in the following figures where the temperature of one of the feedthroughs and its corresponding mechanism before and after the thermal properties update is shown:

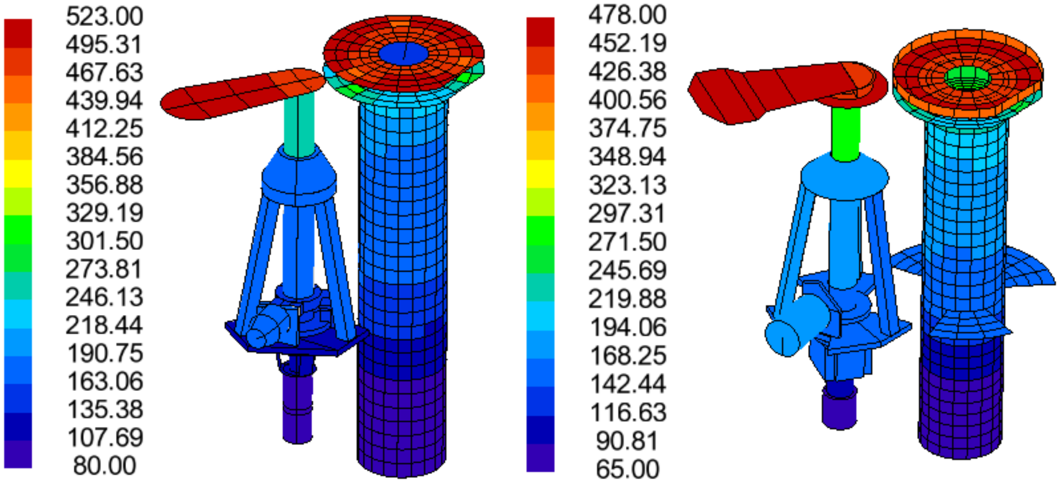


Figure 10. *Thermal results before (left) and after (right) TO properties update throughout the project*

The temperatures have evolved positively throughout the project, mainly impacted by the updates in the thermo-optical properties. The values measured during the qualification test campaign are particularly beneficial for the FMDs since, considering the emittance increase with temperature, for those areas facing the sun where the higher temperatures are obtained, the emissivity increases in almost a 15%, making decrease the ratio alpha-epsilon to values close to 1.

The decrease in temperatures in the hottest areas of the FDMs was also helpful to decrease temperatures all along their bodies, although the thermal gradient along them remains similar, as it depends also on the thermal environment created by the layers of the heat shield.

The thermo-optical properties values coming from the qualification test campaign were also useful and benefitial for the thermal model correlations that were performed on some of the Feedthroughs after dedicated thermal balance tests.

The test configuration was exactly the same for all the thermal balance test performed:

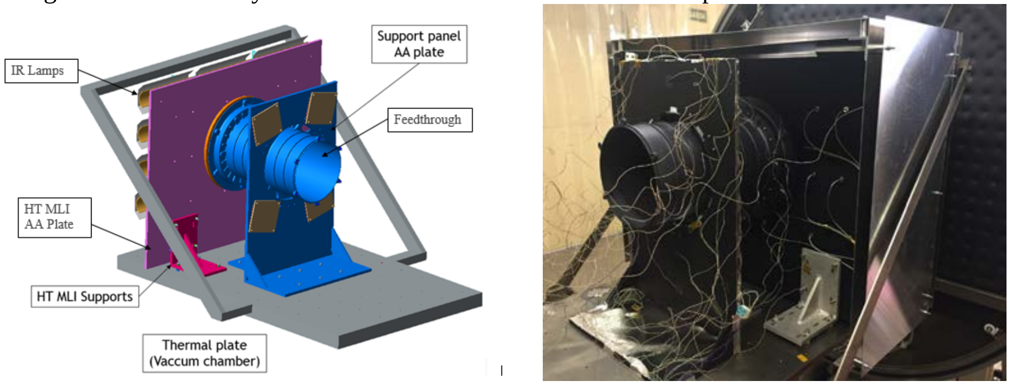


Figure 11. *Thermal balance tests configuration*

A high temperature shield (HT MLI) heated by infrared lamps was used during the test to radiatively create a thermal gradient along the Feedthrough, in order to simulate a similar temperature variation that the specimen has in flight from the top to its bottom part.

Due to the predominant radiative behavior of the test specimen, the temperature dependant emissivity values measured during the coating qualification test campaign were also important to reach successful correlations.

The preliminary tests and verification phases carried out on the coating, along with the confidence and qualification test campaigns assessed during the FDMs project have helped to remark the good characteristics of the coating: low ratio alpha/epsilon that increases with temperature favouring the thermal control of the externally exposed surfaces in hot extreme environments, low contamination levels, it does not contain any type of adhesive, and is a hard coating that suffers no damage when handling. All this make Astro Black the appropriate candidate for the thermal control of subsystems highly exposed to the space environments.

Apart from the FDMs, SENER is responsible for other susbsystems that have also selected Astro Black for the surface finish of the exposed surfaces.

Figure 12. *Door mechanism and Feedthrough of FDMs (Sener copyright)*

Some of them, as it is the case of SOLO High Gain Antenna or MCAP release mechanism, are subsystems of the same mission and have been already submitted to their corresponding qualification and acceptance test campaigns showing no problems at all with the coating.

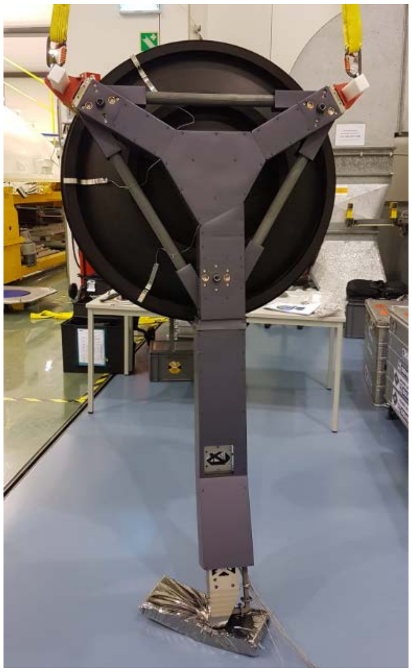


Figure 14: *High gain antenna for SOLO mission (SENER copyright)*

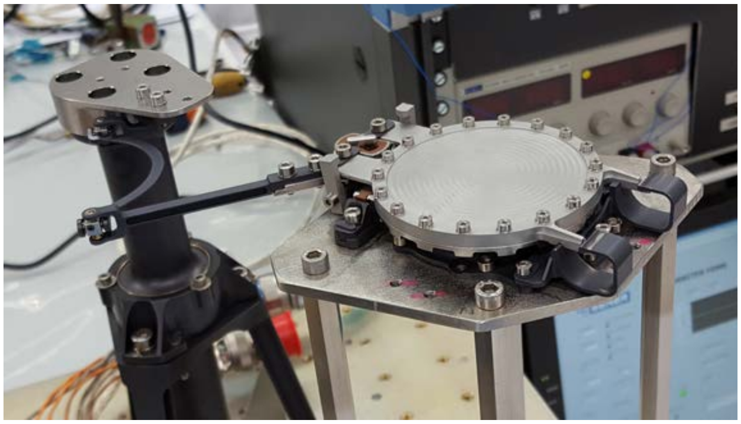


Figure 13. *MCap release mechanism for SOLO mission (SENER copyright)*

Other subsystems belong to missions that are still in design phases (Medium gain antenna in JUICE), but based on the FDMs good results, also rely on the PVD coating for the thermal control of the mechanism.

VI. Conclusions

- When considering critical aspects, as it is the case of the coating in FDMs project, it is worth investing time and money in performing preliminary tests to identify and detect potential failures, which in case of being detected during advanced phases of the project could results catastrophic.
- When several strong design requirements coming from different disciplines need to be taken into account, performing a trade-off results to be determinant to reach a compromise solution.
- Limitations encountered during the coating application process on the internal tubular parts were decisive for the mechanical design of the specimens. The problem was detected and solved during the preliminary tests that were performed during the initial phases.
- Since an appropriate coating was not find at the end of the trade-off, a new PVD coating was research, developed qualified and produced for the Solar Orbiter project. Astro Black coating was able to provide a solution in conditions that cannot withstand commercial paints used for the earth orbiting satellites.
- When using coatings, the characterization of their thermo-optical properties is very important for an accurate correlation since its emissivity is, in this case, one of the main drivers of the temperatures of the model. The successful correlations achieved for different thermal models during the project took advantage of the TO measurements performed during the full coating qualification campaign that was carried out.

References

[1] Metalestalki.Development, Qualification and Application of a Thermal Protection PVD coating Designed for the solar Orbiter Project