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IXV Thermal Protection System Post-Flight Preliminary analysis

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Abstract

The Intermediate experimental Vehicle (IXV) atmospheric re-entry demonstrator, developed within the FLPP (Future Launcher Preparatory Program) and funded by ESA, was aimed at developing a demonstration vehicle that gave Europe a unique opportunity to increase its knowledge in the field of advanced atmospheric re-entry technologies. A key technology that has been demonstrated in real conditions through the flight of this ambitious vehicle is the Thermal Protection System (TPS) of the Vehicle. Within this program, ARIANE Group, has been in charge of the TPS of the windward and nose assemblies of the vehicle, and has developed and manufactured SepcarbInox® Ceramic Matrix Composite (CMC) protection systems that provided a high temperature resistant non ablative outer mould line (OML) for enhanced aerodynamic control.
After the successful flight of February the 11th, 2015, the vehicle has been recovered and the excellent behaviour of the TPS to the thermal loads of re-entry has been assessed [1]. Recorded data have also been retrieved, which allows performing a preliminary analysis of this flight.

This paper describes the first findings and conclusions made on this historical IXV flight, based on the thermocouples and displacement sensors measures. It also describes some of the foreseen activities for the development of the Space Rider TPS, which will be largely based on the IXV proven technology.

1. Introduction

IXV was an ESA program for the acquisition of in-situ data for a lifting body vehicle during re-entry and in-flight validation of critical technologies, such as Thermal Protection Systems (TPS). The prime contractor was Thales-Alenia Space, and the vehicle has the following main dimensions and characteristics:

- Length : 4.40 m + 0.66 m (flaps)
- Width : 2.24 m
- Height : 1.54 m
- Mass: about 1.9 t.

ARIANE Group has been in charge of the design and manufacturing of the windward assembly and nose TPS (see Figure 1.)

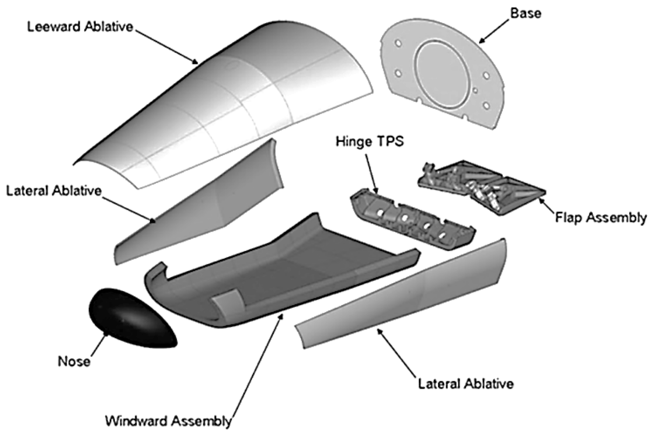

Figure 1 – IXV TPS assemblies

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The IXV mission is representative of a Low Earth Orbit return, with a Mach number of about 28 at 90-100 km altitude, and max heat flux specified at 650 kW/m². This led to an estimated max temperature on TPS outer skin of 1650°C. The duration of the re-entry is 20 minutes, during which the acoustic load is 70dB, and deceleration is 3g.

2. TPS concept

The TPS concept proposed by ARIANE Group is based on the "shingle design", which dissociates thermal and mechanical functions. A thin, heat resistant shell made of ceramic matrix composite (CMC) is designed to withstand mechanical loads due to extreme heat fluxes while maintaining the outer aerodynamic line of the vehicle. In addition, layers of insulation material underneath this skin absorb the heat load, and protect the cold structure from high temperatures (see Figure 2.)
The 2 main advantages of this concept are that the CMC is heat resistant, and thus re-usable (Shingles TPS can withstand many re-entries), and CMC and insulations mattresses are light-weight materials, which guarantees low weight TPS for the vehicle.

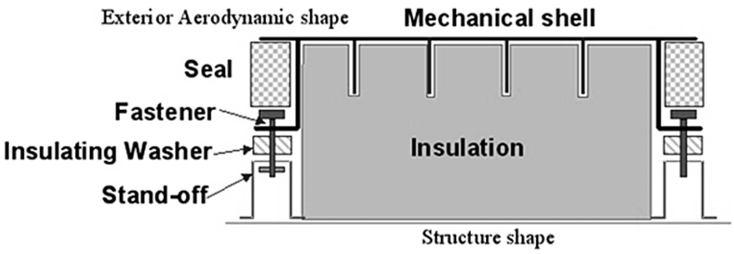

Figure 2 - TPS concept

TPS of the IXV are made of three main components: CMC skins, insulation material and attachment system. The outer skin of the TPS is made of Carbon – Silicium Carbide (C-SiC) material. There are 30 panels for the windward (see Figure 3), made of a thin outer layer with integrated woven stiffeners and attachment legs and one very large (>1.3 m wide), monolithic C-SiC part for the nose with integrated stiffener and attachment legs.
Each panel, and the nose, is equipped with insulating materials. Different materials are used, selected for their density, maximum allowable temperature and efficiency, from alumina blankets close to the outer surface to silica aerogels close to the cold structure. Interfaces between panels are filled with peripheral seals, made of alumina fibres encapsulated in a braided heat-resistant sleeve made of ceramic fibres.
The Panels are attached to the cold structure using specially designed "stand-offs." They are made of metallic parts, designed to accommodate thermal distortion of the panel, while withstanding re-entry mechanical loads.

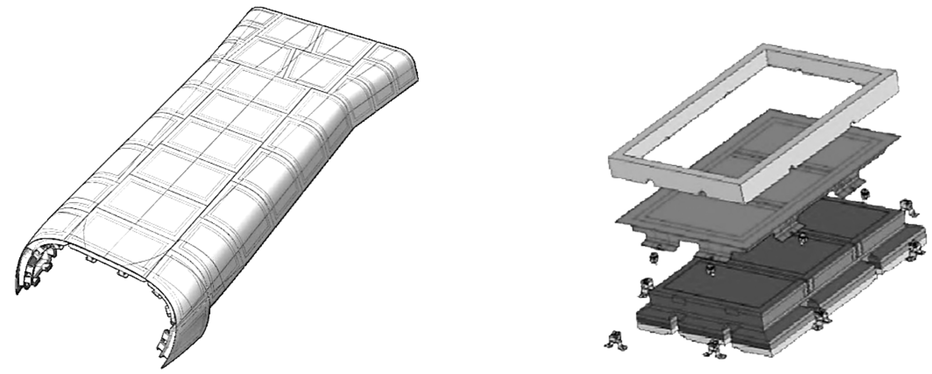

Figure 3 - Windward TPS and split view of a panel with insulation and seal

3. IXV Instrumentation and flight

Since this vehicle was designed for the acquisition of in-situ data for a lifting body, it has been equipped with 300 sensors. Windward and nose TPS were equipped with thermocouples, pressure probes, displacement sensors and strain gages

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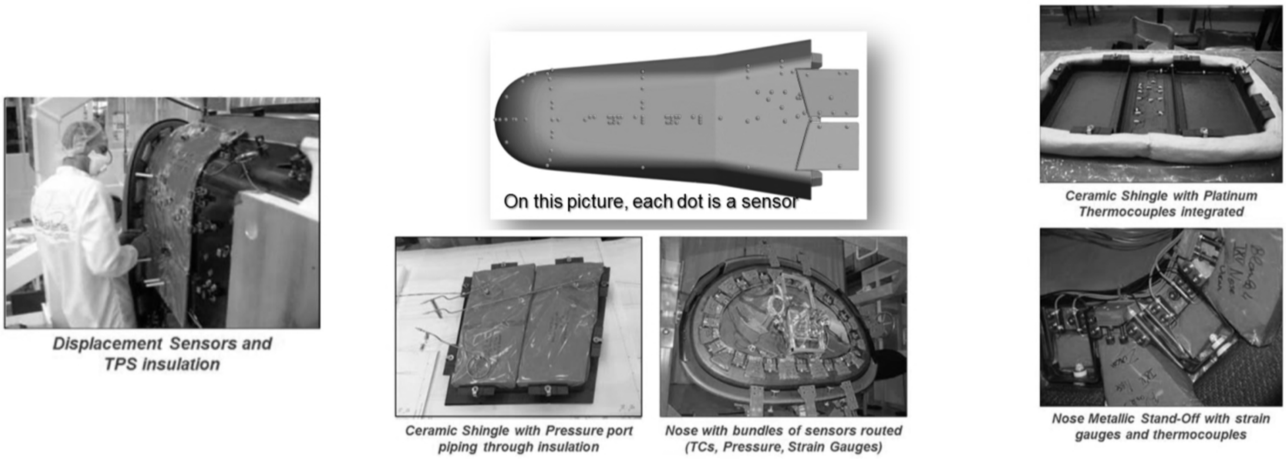

Figure 4 – TPS instrumentation for IXV

IXV successfully flown on February, 11th 2015. Performed trajectory was close to the nominal one and the TPS were sound after re-entry. A huge amount of data is available after this flight. However, the analysis presented in this document is focused on the first visual inspection, thermocouples and displacement sensors analysis.

4. Post flight findings and analysis

4.1. Visual inspection

The first visual inspection shows that the C-SiC outer skins are in very good shape. The visual aspect of the CMC panels matches their pre-flight visual aspect. Interfaces are also in very good shape. Some panels are covered with sea-water salt, leading to the white colour marks that can be seen on the TPS.

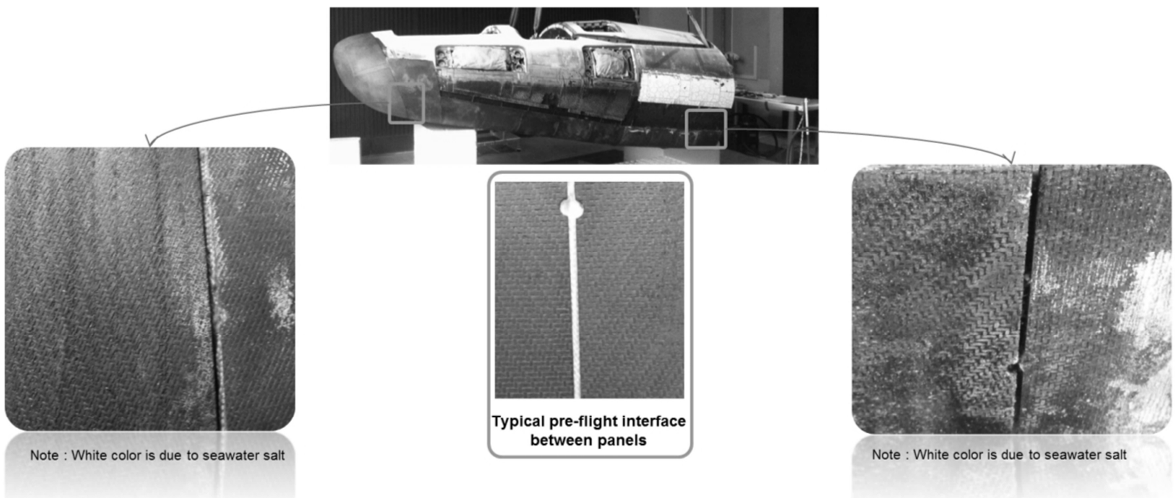

Figure 5 – Visual inspection of TPS after re-entry

4.2. Thermocouples analysis

Recorded temperatures show a 200K to 600K difference between measures and predictions (see Figure 6.) also, difference between maximum and minimum temperatures on the windward seems less severe in reality than predicted.

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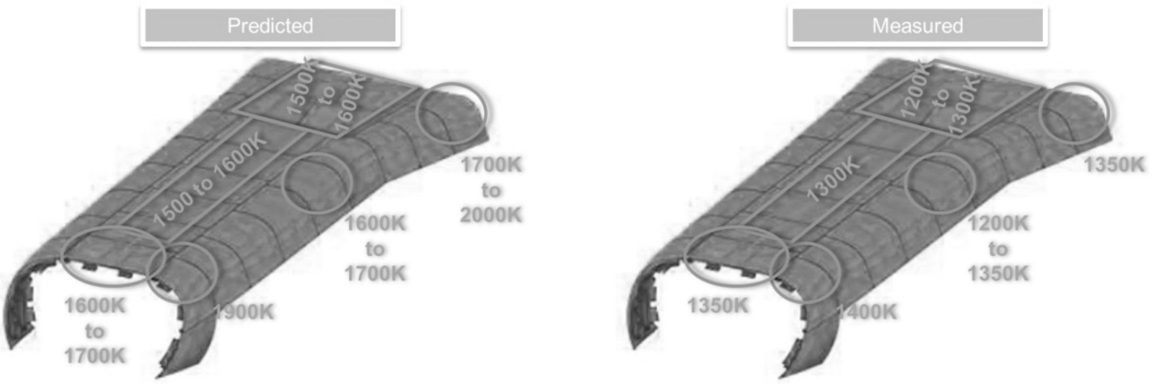

Figure 6 – comparison between predictions and measures

This comparison of temperatures is interesting for panel 27, since it was predicted as one of the most loaded panels during re-entry. If we take a look at the recorded and predicted temperature curves, we can observe that the heating slopes are similar. The heating duration and beginning time for cooling down are also similar. However, the measured temperatures for WT80 (hottest sensor of panel 27) are 600K cooler than calculated temperatures for this sensor.

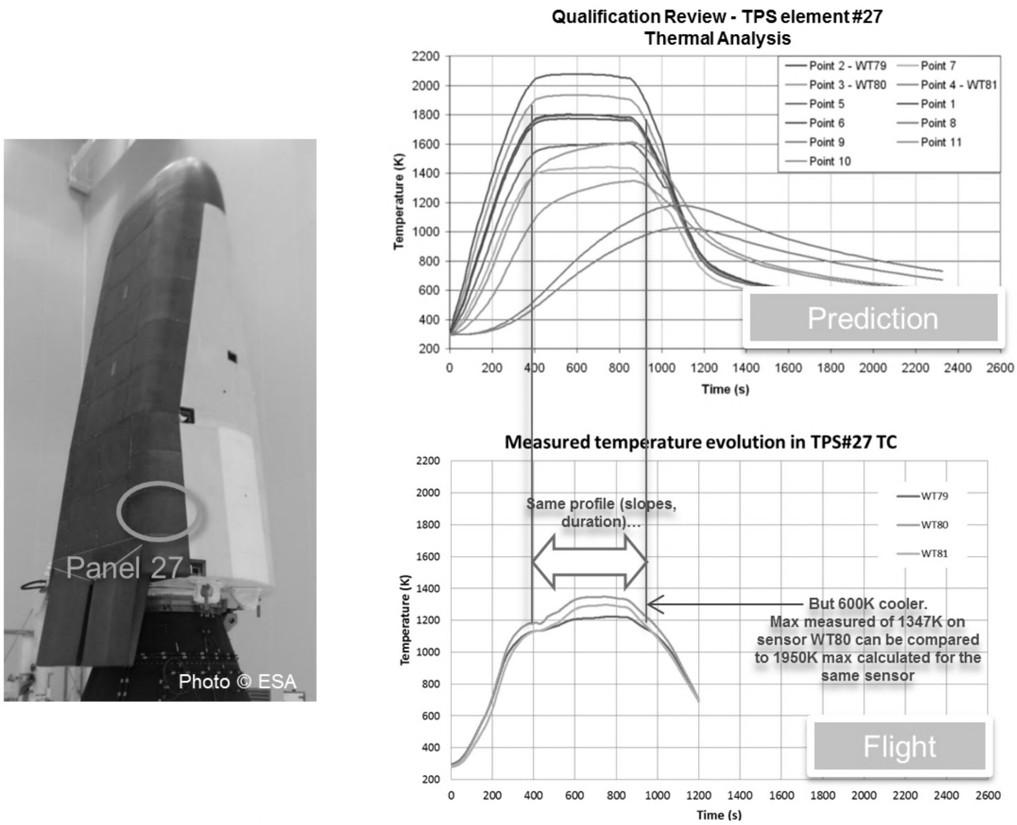

Figure 7 – comparison between predictions and measures for panel 27

Similar findings can be seen for nose measures. The measured and predicted heating slopes are similar for the hottest area of the nose. And measured temperatures for NT2 (hottest sensor of nose) are in fact 400K cooler than predicted. Top of nose is also cooler than predicted: 539K instead of 800K and heats up slower.

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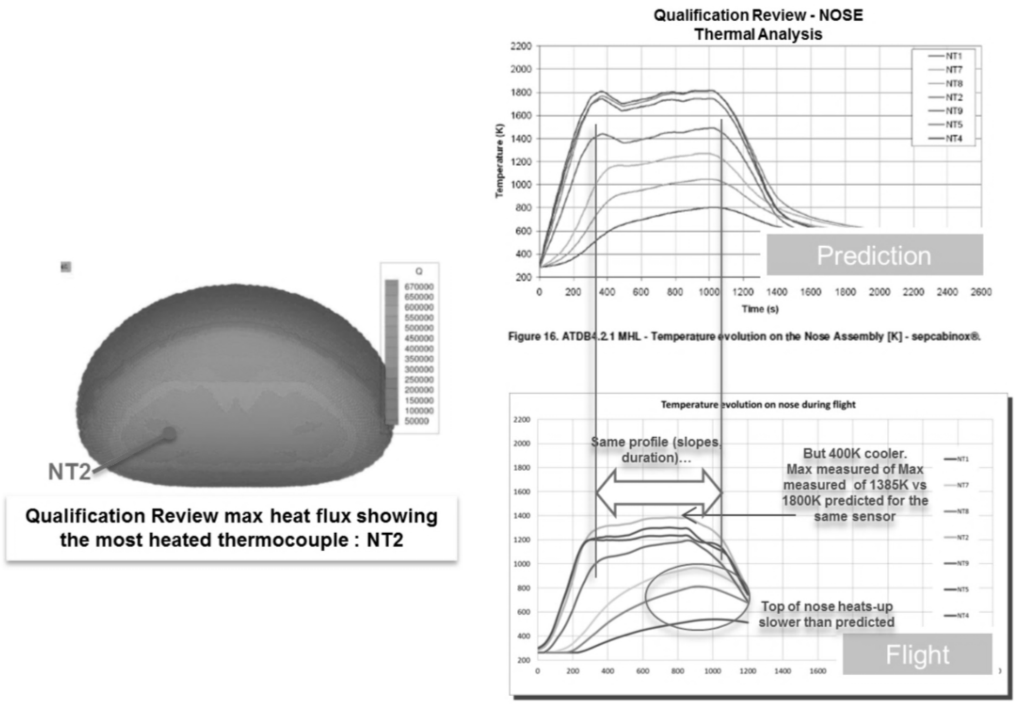

Figure 8 – comparison between predictions and measures for panel 27

Thus, for both nose and panel 27, max temperatures are lower than expected. Measures vs predictive analysis suggests a 25% to 40% heat flux level decrease (to be confirmed by analysis.) The possible origins for those differences are that the flown trajectory has been nominal vs extreme trajectories considered for predictive analysis, and the material catalytic behaviour of the CMC (which lowers heat flux level, as seen during sample testing.)

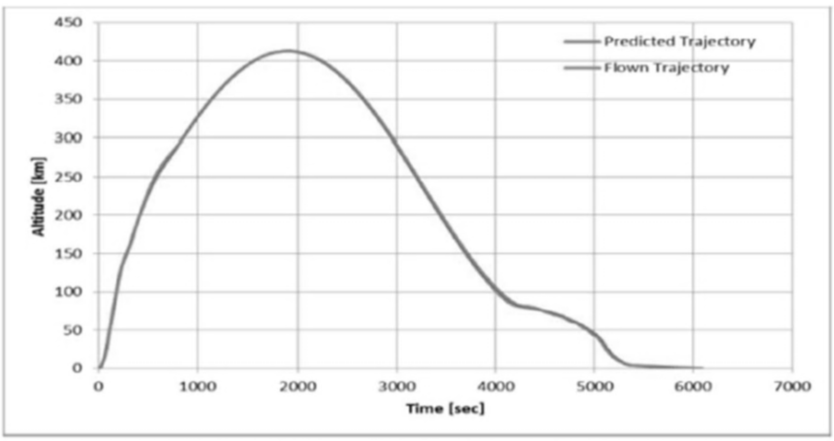

Figure 9 – Flown vs predicted trajectory of IXV

4.3. Perspectives for Space Rider TPS Design

The Space Rider vehicle will able to carry payloads and will be heavier than IXV (also thanks to VEGA C increased performance.) First assessments suggest sizing fluxes that would be higher than for IXV. However, the 25% to 40% difference estimated between predicted and measured fluxes on IXV, such as explained in the previous chapter, suggests that IXV TPS configuration is suitable for Space Rider. Thus, based on the IXV flight experience and

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preliminary space Rider specifications, the TPS configuration chosen for Space Rider is for now considered equal to the one flown on IXV (same materials and insulation stack-up.)

4.4. Displacement sensors analysis

The displacements sensors that have been installed on IXV TPS enabled the measure steps depicted in Figure 10.

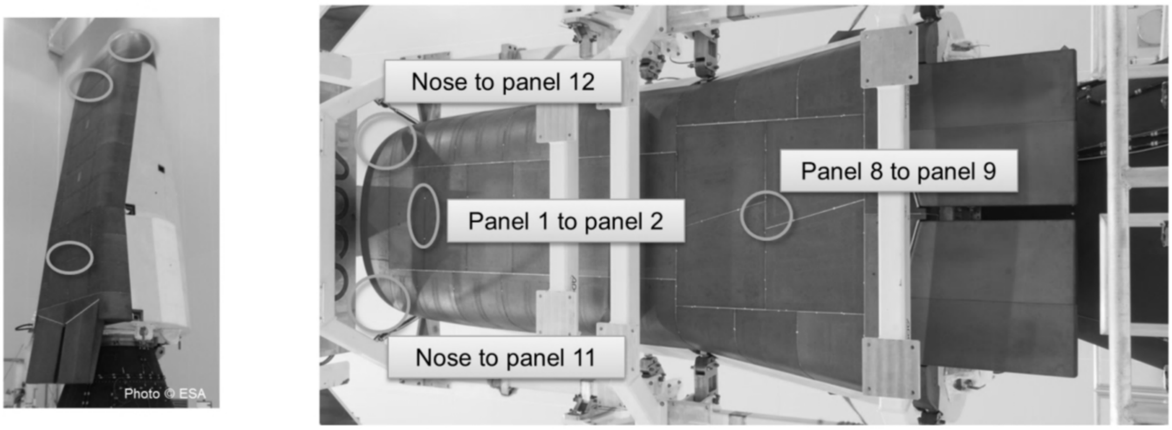

Figure 10 –IXV TPS Displacement sensors

These displacement sensors recorded data have been adjusted with actual steps measurements made on the vehicle before flight. This has been done in order to reconcile the location of sensors and the max step predicted location. The comparison of predicted vs measured steps is revealing strong discrepancies:

- 0.05 to 3.8mm differences between predicted and measured steps. Moreover, some steps measured positives while predicted as negatives
- Measures reveal that steps do not change much during flight. Less than 0.1mm for panels and less than 1 mm between nose and side panels.

Table 1: predicted vs measured steps

	Max In-flight step (positive = step up / negative = step down)			
	Nose to windward		Windward fwd	Windward aft
	Nose to panel 11	Nose to panel 12	panel 1 to panel 2	Panel 8 to panel 9
Predicted	-1,86 mm	-1,86 mm	1,03 mm	0,14 mm
Measured	1,90 mm	1,06 mm	-0,11 mm	0,09 mm

	Step variation during flight (= max step - min step)			
	Nose to windward		Windward fwd	Windward aft
	Nose to panel 11	Nose to panel 12	panel 1 to panel 2	Panel 8 to panel 9
Measured	0,95 mm	0,60 mm	0,06 mm	0,09 mm

For example, these measures suggest that steps between nose and side panels 11 and 12 were positive whereas expected negative from analysis. However, post-flight visual inspection shows no evidence of edge deterioration due to positive steps on flight hardware. Note that similar max steps were tested at component level (SIMOUN tests with 3 panels at 390 kW/m² made during Shingle Generique program 2002 – 2007.)

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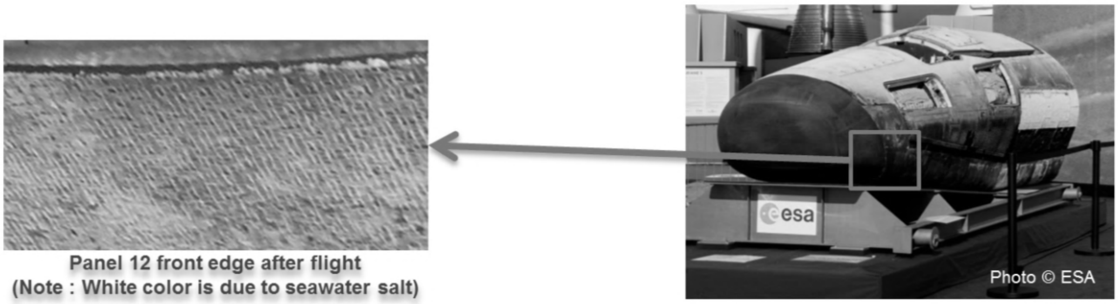

Figure 11 –Panel 12 front edge after flight

These flight measures reveal that steps did not change much during flight. Panel to panel steps moved by less than 0.1mm, and nose to windward steps moved by less than 1mm, whereas higher values were expected from analysis. This leads to the conclusion that actual temperature gradients were surely smoother than expected. Steps between nose and side panels have been positive whereas expected negative from analysis. However, it was acceptable since there is no visible damage due to positive steps after flight on those panels. But it leads to the conclusion that even if appropriate for temperature analysis, extreme trajectories lead to overestimated steps and panels deformations.

4.5. Conclusion

It can be concluded from this post flight analysis that the heat fluxes were lower by 25 to 40%, which is just an estimate and has to be confirmed by heat flux analysis. Possible causes can be that the flown trajectory was the nominal one vs extreme trajectories considered for analysis, and the material catalytic behaviour of the CMC. Moreover, the temperature gradients on the outer skin were smoother than expected. This analysis also reveals that the steps evolutions during flight were predicted with extreme trajectories, but that actual flown trajectory leads to different steps values. However, predictions were conservative for windward, and nose to windward steps were still within past experience (Shingle Generique program.)
The successful February 11th 2015 flight demonstrated the performance of the Shingle C-SiC concept for re-entry and this initial analysis suggests re-entry conditions were less severe than predicted. Preliminary data suggest that IXV TPS are suitable for Space Rider.

References

[1] F. BUFFENOIR, C. ZEPPA, T. PICHON and F. GIRARD, ARIANE Group - Development and flight qualification of the C-SiC thermal protection systems for the IXV, in 6TH European Conference For Aeronautics And Space Sciences- 29 June - 3 July 2015, Krakow