Development and flight qualification of the C-SiC thermal protection systems for the IXV

François BUFFENOIR, Céline ZEPPA*, Thierry PICHON* and Florent GIRARD**
**HERAKLES – Safran Group*
Rue de Touban, Les Cinq Chemins - 33185 LE HAILLAN - France

Abstract
The Intermediate experimental Vehicle (IXV) atmospheric re-entry demonstrator, developed within the FLPP (Future Launcher Preparatory Program) and funded by ESA, 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, HERAKLES, Safran 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. The design and flight justification of these TPS has been achieved through extensive analysis and testing:

- Mechanical, Dynamical and thermo-mechanical analysis
- Coupons and technological tests
- Sub-scale tests specifically made to assess the behaviour of the TPS during re-entry.
- Full scale qualification tests that addresses the flight envelope of the vehicle :
  - Sine, Random and shock tests on nose and windward
  - Thermal test of the nose
  - Mechanical tests of nose and windward

This paper describes the Flight Model TPS design, as well as the development activities, tests and results that lead to the qualification of the nose and windward TPS assemblies.

1. Introduction

IXV is 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 is 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.

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

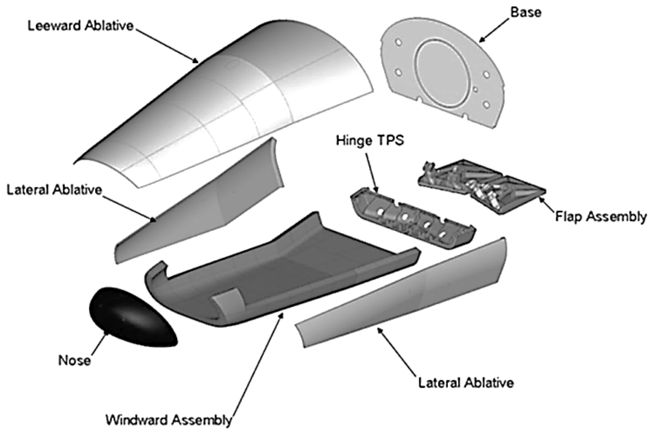

Figure 1 – IXV TPS assemblies

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 HERAKLES 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. And 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.

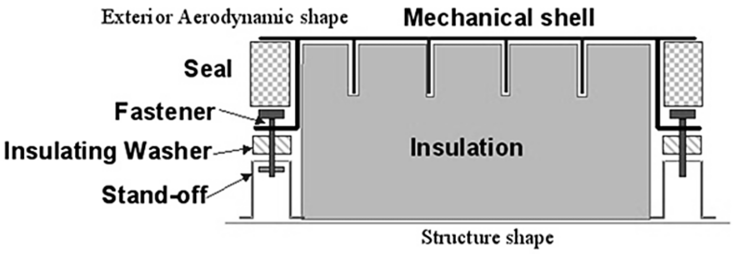

Figure 2 - TPS concept

3. IXV TPS description

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. Those layers are encapsulated in light polyimide films to prevent dust release, and have patterns that do not match the Windward pattern to prevent air infiltration from the airflow directly 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" (see Figure 4.) They are made of metallic parts, designed to accommodate thermal distortion of the panel, while withstanding re-entry mechanical loads. These stand-offs also have a fastening system with ceramic washers that act as a thermal barrier to prevent structure overheating. The nose is attached to a metallic ring using 16 stand-offs (see Figure 5.) These stand-offs are designed to accommodate thermal expansion of the nose while withstanding mechanical loads. A metallic dome is fastened to the ring, and provides support to the insulating layers. The ring is equipped with brackets, which are then used to attach the nose to the cold structure

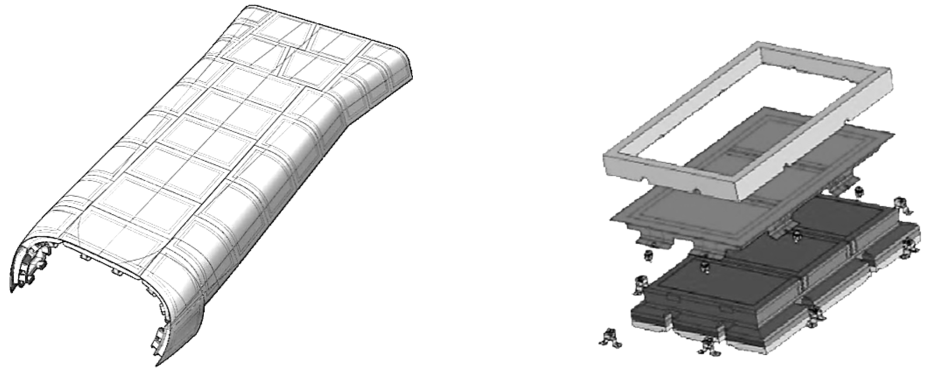

Figure 3 - Windward TPS and split view of a panel with insulation and seal

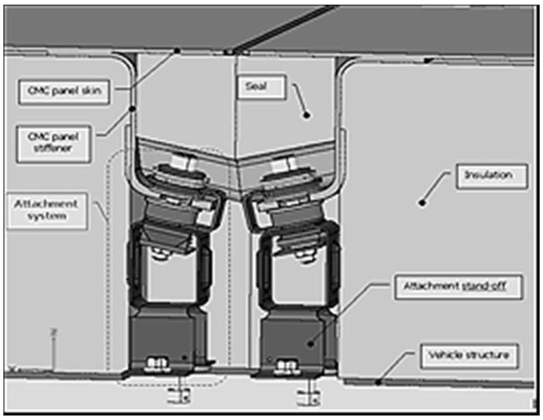

Figure 4 – Stand-offs assembly

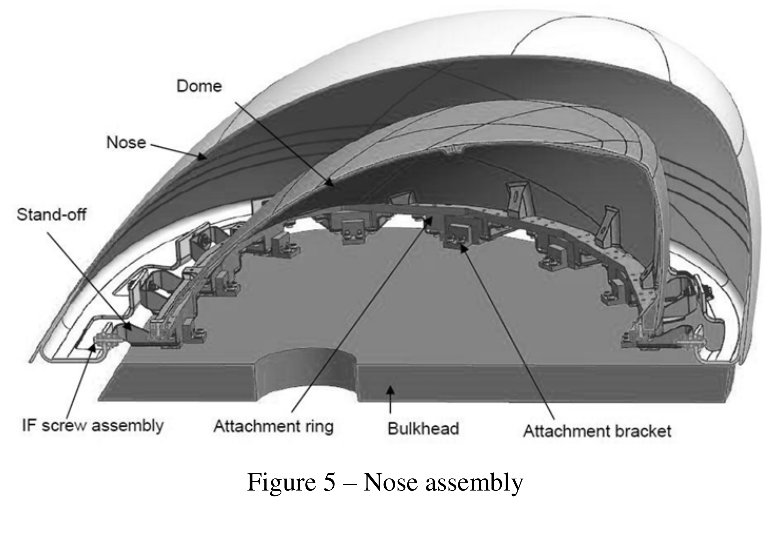

Figure 5 – Nose assembly

4. TPS Design for IXV

4.1. Main design drivers

IXV nose and windward TPS have been designed according to numerous load cases, which encompass its full mission. This paper focusses on the main design drivers, which are dynamic loads, which are more important during launch and descent (launcher acoustics and vibrations, fairing separation, parachute opening…), thermal loads, which are the key load cases during re-entry, and thermo-mechanical loads due to the distortion of the different components of the TPS, which are also key for the aerodynamics during flight (steps & gaps.)
Note: IXV nose and windward TPS have not been designed for splashdown loads, in agreement with TAS and ESA, since those severe loads would have required much heavier reinforced TPS, and additional weight at launch.

4.2. TPS Design for launch and descent environments

IXV TPS Design for dynamic loads has been based on FE models, which took into account the HKS experience on a full scale panel test made during the Shingle Generique (CNES – HERAKLES) program. It has also been based on sine, shock test and modal characterization on a fully equipped sub-scale shingle, which revealed that there is a high damping due to the insulating mattresses and a good behaviour of the panel components and attachment systems during these tests. Dynamical behaviour of the nose has also been based on those assumptions and a FE model since no past experience available at HERAKLES for such a part.
A full scale tests at ISQ of an assembly of 4 panels have been made to confirm the good behaviour of the windward and assess the influence of multiple panels. Modal, sine and random tests have been made on a shaker. All the frequencies were above the min specified of 120Hz, and no damage has been observed on the panel even after high level tests (up to 22,5g.) Shock tests have been performed on a dedicated device due to the weight of the assembly. The specification has been exceeded for low frequencies (under 400Hz), thus the test was deemed conservative by HERAKLES and TAS. Windward TPS has been then qualified by test for dynamic loads.
A full scale nose, fully equipped with metallic parts, insulating mattresses and flight instrumentation (pressure ports, thermocouples…) has been tested on a shaker at ISQ. Modal characterization revealed lower Eigen frequencies than predicted and a non-linearity of nose dynamic behaviour mainly due to insulation layers. Update of the FE model has been made to match accurately the test conditions and the nose behaviour so that an analysis of the complete vehicle could be performed, which confirmed that its dynamic behaviour is acceptable for flight. Specified levels have been checked with this updated model and sine, random and shock test resumed. Sine (up to 8,125g), random and shock loads have been applied without any damage. Thus, nose TPS has been qualified by test for dynamic loads.

4.3. TPS Design for re-entry environment

An extensive characterization campaign for mathematical models construction and verification has been made during the IXV program. For the C-SiC material, thermo-mechanical characterisations have been performed (> 100 samples) up to 1500°C, C-SiC legs ultimate and fatigue tests have been made, a CMC pressure port has been thermally tested and measurement of catalytic and emissivity properties has been made on C-SiC samples, which were also used for the verification of degradation under air plasma up to 1700°C. Finally, a C-SiC test article with seal, metallic stand-off and insulation has been brought up to 1300°C to test the complete shingle assembly under temperature.
Metallic parts have been also tested with fatigue resistance tests of metallic stand-offs (4 times nominal mission) and strength and stiffness measurements of attachment parts up to 1000°C. Verification of thermal properties of insulation materials has been made, and seals have been tested: measurement of permeability of seals between panels and hot gas infiltration “sneak flow” tests.
With those characterizations, models of the nose and windward have been built. The HERAKLES TPS for IXV being made of 30 panels and a nose, each made of many components in CMC, metal or insulation, designing each one of these elements is a too long process. Thus, the analysis of thermal mapping and deformation during flight has been used to select 3 panels, which behavior are representative of the complete windward. This selection also took into account the singularities on panels such as pressure ports.
Thermal analysis of the nose and selected panels representatives of the entire TPS has been made by building FE models taking into account past experience and material characterization. Thermal margins were assessed using a very conservative approach: conservative trajectory (Thermal Data Base), and no catalytic effect of the C-SiC material, even if measured during component tests. Active oxidation margins have been assessed using a less severe trajectory, even if still conservative. Thermo-mechanical analyses of the nose and panels have been made with the

same assumptions as for thermal analysis for thermal input. Detailed FE models of panels representatives of the entire TPS for windward margins assessment and a detailed FE model of the nose have been made, plus local refined models of the nose CMC legs, due to critical local shear modes in this area, for nose margin assessment. A complete simplified model of the windward has also been built for Steps & gaps assessment.

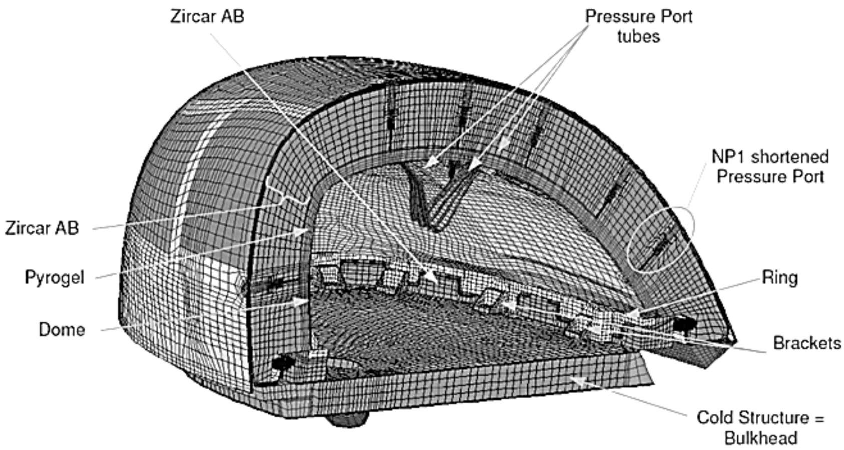

Figure 6 – Nose Thermal FE Model

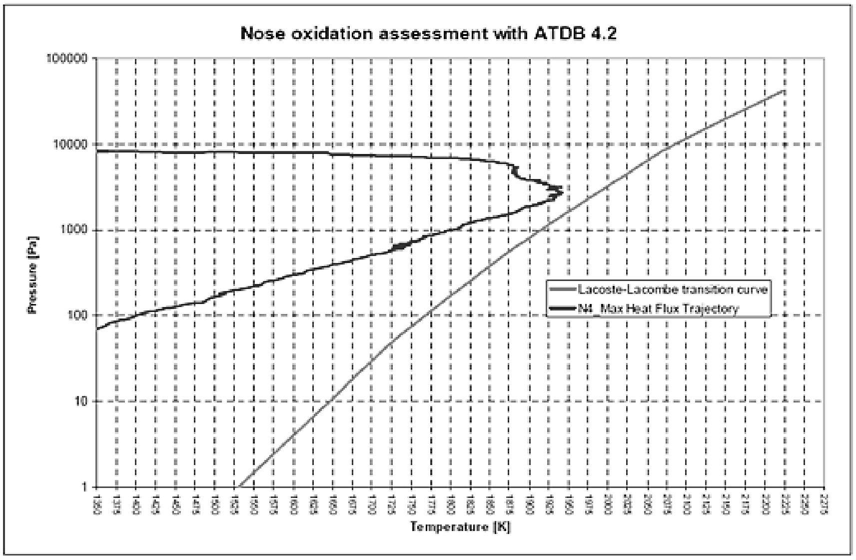

Figure 7 – 50K margin vs active oxidation using specified thermal data base, without knock-down factor due to catalytic effect

Thus, all these FE models and analysis have been used to assess thermal and thermo-mechanical margins during re-entry. In addition, tests have been used to validate these analyses:

- Thermal tests from past HERAKLES experience for TPS behaviour under extreme heat loads
- Mechanical or thermo-mechanical qualification tests on full scale TPS components for CMC parts behaviour

4.4. Thermal Tests of the TPS

TPS behaviour under heat flux has been assessed by a CIRA plasma wind tunnel test made during FLPP program [1]. This test was made with similar insulation and C-SiC stack-up vs IXV. More than 900s under heat fluxes of 500 KW/m² to 750 kW/m² were performed, and the test was successful: good behaviour of the C-SiC and Insulation. Steps & gaps influence has been assessed with SIMOUN tests made with 3 panels at 390 kW/m², during Shingle Generique program [2]. Different steps & gaps have been evaluated, with heat flux influence assessment.

4.5. Thermo-mechanical qualification tests of the TPS

A Nose thermal test has been performed. 800°C gradient were created between outer skin and inner parts of the C-SiC nose, which allowed the verification of the resistance of the Nose Assembly to this gradient, and substantiation of FE model by comparison of the measured and calculated displacements.
Nose mechanical test were made on nose legs loaded with actuators to simulate re-entry legs displacements. Shear loads in legs have been identified, and local FE models have been adjusted with tests results to match actual nose behaviour. Nose mechanical behaviour was then substantiated with those updated FE models
Panels mechanical tests have been made by using pressure, that pushes the panels skin outwards, loading the C-siC legs so that the stress level relative to the room temperature max allowable level matches the flight margins.
One flat and one curved panel have been tested, demonstrating good behaviour of the panels: no damages after tests.

5. Conclusion

The Qualification tests and analysis activities described in this paper led to the validation of the TPS design during the September 2014 Qualification Review. The successful February 11th 2015 flight demonstrated the performance of the Shingle C-SiC concept for re-entry. The IXV has been successfully protected during re-entry by HERAKLES nose and windward TPS:

- Nominal trajectory and manoeuvers
- Internal temperatures within the limits of the operating ranges of the avionics components
- Fulfilment of all experimentation objectives

The first visual inspection of the TPS is showing that the C-SiC outer skins are in very good shape, confirming the successful design of the TPS manufactured by HERAKLES.

References

[1] R. Barreteau, T. Pichon, M. Lacoste, F. Girard, HERAKLES – Safran Group - CMC Thermal Protection System for Re-Entry Demonstrator Pre-Development. In 3rd European Conference for AeroSpace Sciences - Versailles, France, 6-9 July 2009

[2] P. Soyris, R. Barreteau, T. Pichon, M. Lacoste, HERAKLES – Safran Group, Y. Prel, CNES – Generic Shingle Developments for Re-entry Vehicle TPS. In 2nd International ARA Days, Atmospheric Reentry Systems, Missions and Vehicles, Arcachon, France, 21 - 23 October 2008