Windward and Nose Assemblies CMC Thermal Protection Systems for the IXV Re-entry Demonstrator - Technological Development Status

Thierry PICHON[1], Renaud BARRETEAU[2] and François BUFFENOIR[3]
Snecma Propulsion Solide, Safran Group, Le Haillan, France
thierry.pichon@snecma.fr
renaud.barreteau@snecma.fr
francois.buffenoir@snecma.fr

Abstract

The Intermediate experimental Vehicle (IXV) atmospheric re-entry demonstrator, developed within the FLPP (Future Launcher Preparatory Program) and funded by ESA, aims at developing a demonstration vehicle that will give Europe a unique opportunity to increase its know-how in the field of advanced atmospheric re-entry technologies. A key technology that will be demonstrated in real conditions through the flight of this ambitious vehicle is the CMC-based Thermal Protection System (TPS) that is the current baseline for the thermal protection of the windward area, as well as the nose assembly.

Ceramic Matrix Composite (CMC) TPS belong to the group of key technologies that will enable the IXV flight, as it will provide a high temperature resistant non ablative outer mould line for enhanced aerodynamic control. These thermo-structural composites have been developed in Europe for more than 20 years, and have reached a high Technology Readiness Level. Their maturity can now only be improved through an actual flight, which will precisely be made by the IXV.

The IXV vehicle is now well into its detailed design phase, with the vehicle Preliminary Design Review having successfully been achieved end of 2009, and with the vehicle Critical Design Review expected to be performed early in 2011.

Snecma Propulsion Solide, Safran Group, has already performed the preliminary design activities, which contributed to the successful completion of the system PDR, and to the demonstration that CMC TPS are well suited for the IXV mission. Refined design activities, including the definition of the components, detailed analysis and sizing, as well as technological testing to better determine the behaviour of the materials used, have been undertaken within phase C of the project. The results of these activities have been presented during the recent sub-system Critical Design Review.

The paper will describe the current technological achievements of the development of the Windward Assembly TPS and Nose Assembly, and the activities that are initiated and planned for the qualification and the delivery of the flight hardware.

1 IXV CMC TPS Development Overall Logic

The CMC (Ceramic Matrix Composite) TPS technology has initially been developed by Snecma Propulsion Solide, Safran Group, for the Hermès European shuttle programme in the late 80s. An improved version of this technology was developed in the beginning of the 2000s, with the introduction of more robust, less expensive materials in the design. Through the CNES-funded "Generic Shingle" programme [1,2], followed by the ESA-funded

[1] Programme Manager, High Temperature Composites for Space Applications
[2] Project Manager, IXV CMC TPS Development
[3] Design Lead Engineer, High Temperature Composites

"Future Launcher Preparatory Programme" [3], numerous tests have been performed prior to the start of the IXV detailed design phase (cf. Figure 1).

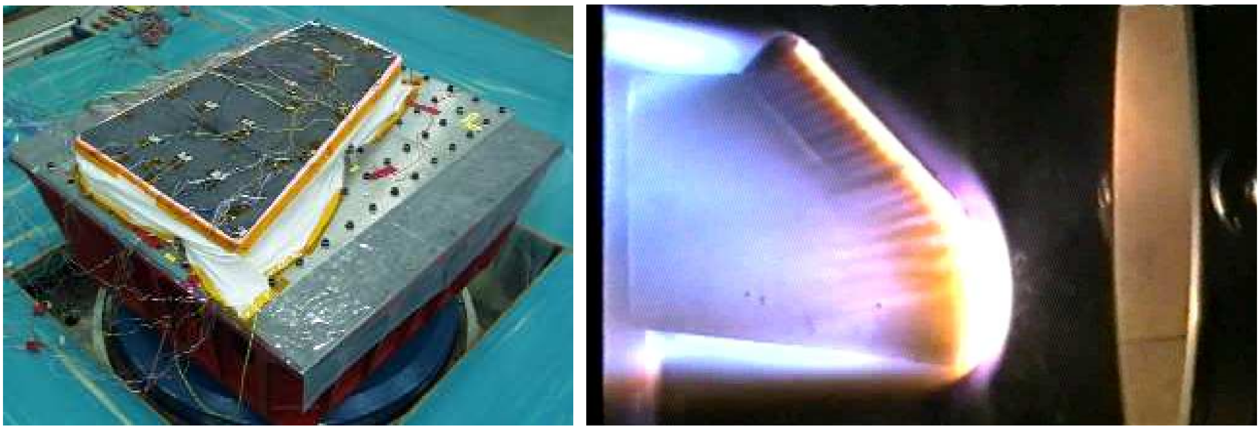


Figure 1 : Launch-representative dynamic test (left) and Plasma Wind Tunnel test in Scirocco facility (right)

The results of these tests confirmed the high potential of the CMC TPS technology for an application on a re-entry mission. Nevertheless, several technical subjects remained to be addressed during the development of the subsystems of the IXV, to include refined requirements issued at system level, or to perform design of additional features and verifications not covered by previous tests.

The most significant change at the beginning of the detailed design phase of the programme, was the incorporation of the vehicle nose assembly into the perimeter placed under the responsibility of Snecma Propulsion Solide. Although the environment of the nose is comparable in many ways to the conditions applied on the most solicited areas of the Windward TPS (heat flux, pressure, etc.), a preliminary trade-off was needed to adjust the main design parameters and specific engineering activities were performed to verify the feasibility of such a large, complex shaped, C-SiC part. This activity was introduced in the Consolidation Phase that initiated the detailed design phase, right after the Preliminary Design Review (PDR).

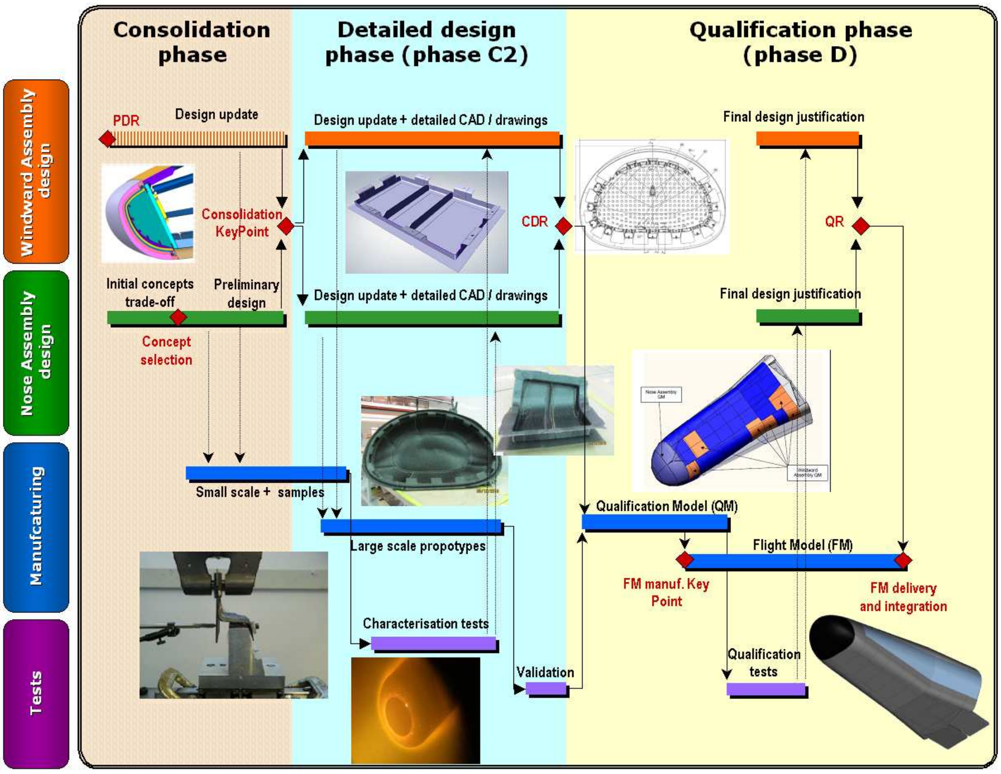


Figure 2 : Overall IXV Nose & Windward TPS Development Logic

The rest of the detailed design phase (phase C2) was dedicated to a very large spectrum of design and verification activities for both the Nose and the Windward subsystems, including :

- the adjustment of the design to the final requirements of the specification,
- dedicated thermal, thermo-mechanical, and dynamic justification analyses,
- several development test campaigns covering the elementary characterisation of the different components (C-SiC panels, ceramic internal insulation and seals, metallic attachment system),
- the verification of some critical issues, such as hot gas sneak flow assessment, maximum differential pressure during ascent, or the dynamic behaviour of subscale panels,
- the manufacturing of prototype C-SiC parts.

The Nose and Windward sub-system Critical Design Review (CDR) has been successfully cleared, and the system CDR recently held will formally authorise the start of the qualification phase of the vehicle, or phase D. This next phase will include the manufacturing of a Qualification Model, which will be made of one nose and a sample of the most critical panels of the Windward, its testing through the qualification test campaign, followed by the Qualification Review (QR). The manufacturing of the Flight Model will be started before the end of the qualification process due to vehicle schedule constraints. However, a manufacturing Key Point will ensure that the most important qualification results are available prior to this manufacturing. The phase will be concluded by the integration of this Flight Model on the vehicle.

Finally, phase E will include the actual flight preparation, launch and re-entry, followed by an expertise of the hardware after recovery of the vehicle.

2 Windward and Nose Current Design Status

The design of the Windward Assembly and of the Nose Assembly have been developed from the basis of the previous TPS programs. These principles are shown on Figure 3. The rigid surface that constitutes the aerodynamic mould line of the vehicle in contact with the plasma flow during the re-entry is made of a rigid, highly refractory CMC material, and divided into several panels. This hot surface is supported by the vehicle inner structure, and a lightweight, flexible insulation is installed beneath the hot surface to prevent the overheating of the internal structure and equipments. For the same reason, specific insulating mechanical stand-offs are used to attach the hot panels to the structure. Finally, a fibrous seal is placed around each panel to prevent hot gases from entering through the gap between two adjacent panels.

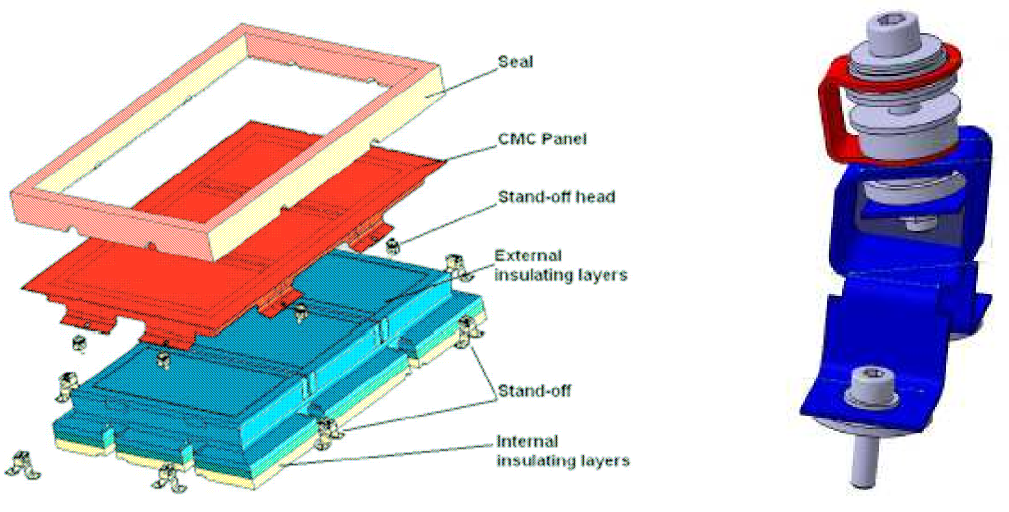


Figure 3 : Typical CMC TPS assembly design (left) and attachment device (right)

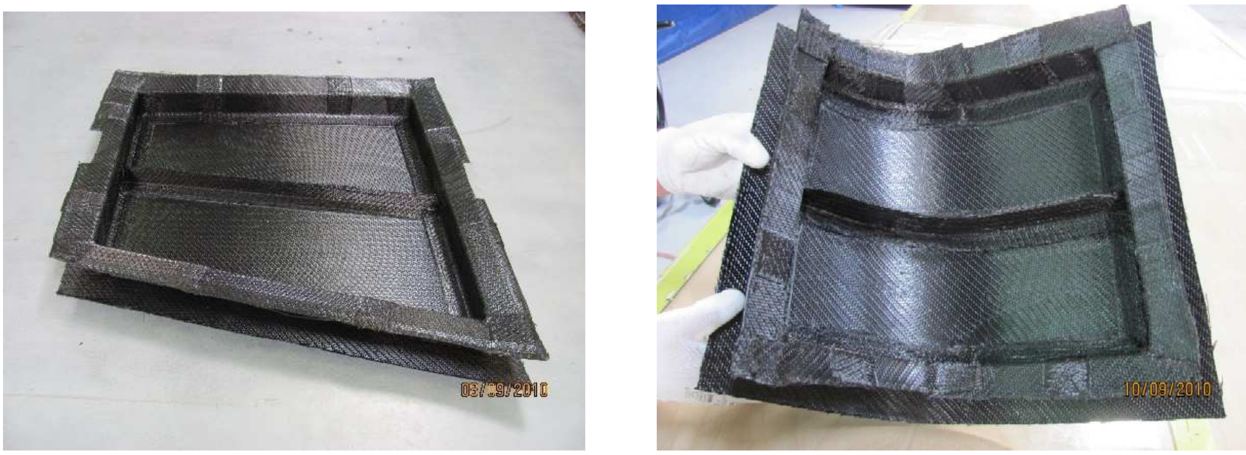


Figure 4 : Flat CMC feasibility panel (left) and curved CMC feasibility panel (right)

Nose cap and Windward panels share the same C-SiC material technology, including delamination-resistant multilayer weaving, lay-up, same sewing technique and Chemical Vapour Infiltration (CVI) densification processes.

For the Windward Assembly, which covers a large surface of the vehicle, the surface has been divided in 30 panels, making use of similar or even identical panels wherever possible, in the central flat areas. The panels on the sides are all unique due to the curvature evolution along the vehicle. The C-SiC panels are assembled onto the vehicle's cold structure by means of semi-flexible metallic attachments. The stiffness of these attachments has been adjusted to avoid the introduction of large stresses due to the significant thermal expansion of the panels when heated to very high temperatures. These attachment devices, shown on Figure 3 are also equipped with insulating ceramic washers in order to reduce the heat conduction towards the vehicle cold structure.

A ceramic, fibrous seal made of Zircar AB core and Nextel envelope is placed around the panels of the Windward, to prevent an excessive amount of gas from penetrating at the interface between two panels and overheat the structure. It is nevertheless permeable enough to allow the venting of the TPS volume during the launch phase.

The inner volume between the C-SiC parts and the cold structure is filled with lightweight ceramic insulation. The design of this insulation, made from commercially available products, has been significantly improved to cope with increased performance needs, and higher heat fluxes, and the stack-up of different layers of insulation now incorporate of alternative highly insulating materials, such as Pyrogel.

In the case of the Nose cap, shown on Figure 5, the largest (1.3 m wide) and most complex monolithic CMC part of both subsystems, the resulting design comprises eight "petals" of carbon fabric sewn together, forming the aero-shape, and 16 legs, also sewn onto the aero-shape, and that are designed to provide a mechanical interface for load transfer towards the structure. The resulting thickness of the preform ranges from 1.5 mm on the aero-shape up to 6 mm in the junction area between the aero-shape and the legs.

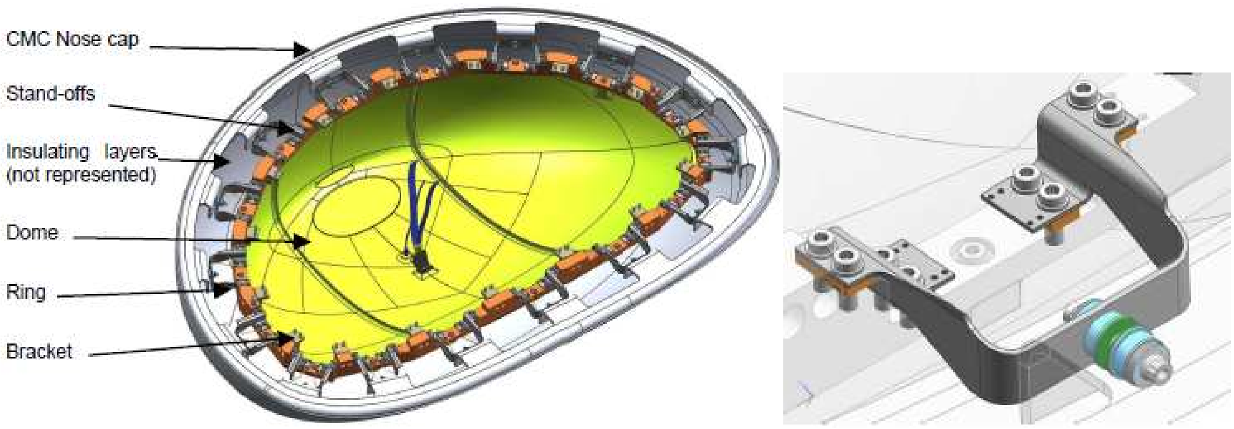
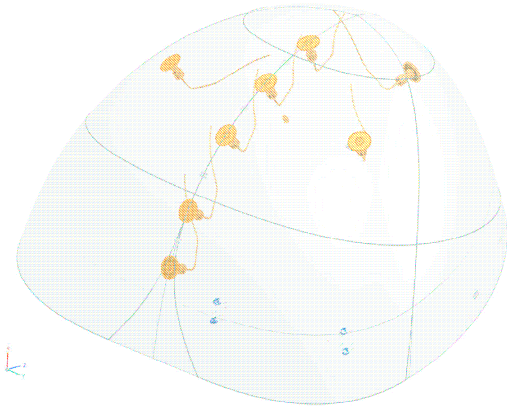


Figure 5 : CMC Nose assembly design (left) and attachment device (right)

Figure 6 : CMC nose feasibility part

Similarly, larger semi-flexible metallic attachments have been designed to transfer the loads from the 16 legs to the vehicle bulkhead via an interface ring. Again, the seal technology and internal lightweight insulation for the Nose Assembly is directly derived from the one used on the Windward CMC TPS, adjusted to the size and geometry of the nose.

For the IXV mission, a large number of inboard sensors is foreseen in order to collect data relevant to the re-entry environment. In particular, pressure measurements will be made through the TPS layer, both on the nose and in the windward area. In order to accommodate these sensors, a specific pressure port interface has been designed, with threaded C-SiC elements (screw and nuts), as shown on Figure 7. Eight of them will be integrated in the Nose cap alone, and 10 others will be placed on different panels of the Windward Assembly.



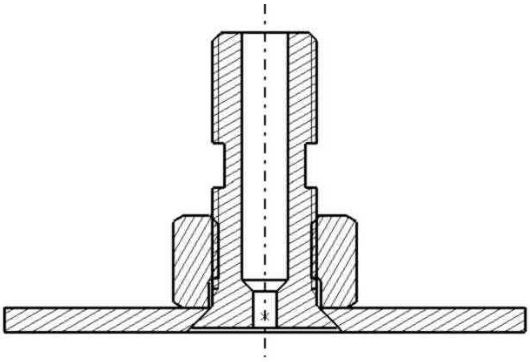


Figure 7 : Pressure ports in the Nose (left), and detailed design of the C-SiC pressure port (right)

3 Windward and Nose Current Justification Status

3.1 Analyses

The CMC TPS technology basic performances had been verified through previous programmes. However, entering into a detailed design phase for an actual spacecraft implies thorough justification activities, with analyses based on mathematical models, and development test to collect experimental data for correlation purposes.

A very detailed thermal analysis on the nose and on the most heated Windward panels has been performed on large 3D models (cf. Figure 8), representing all the components, and the underlying cold structure.

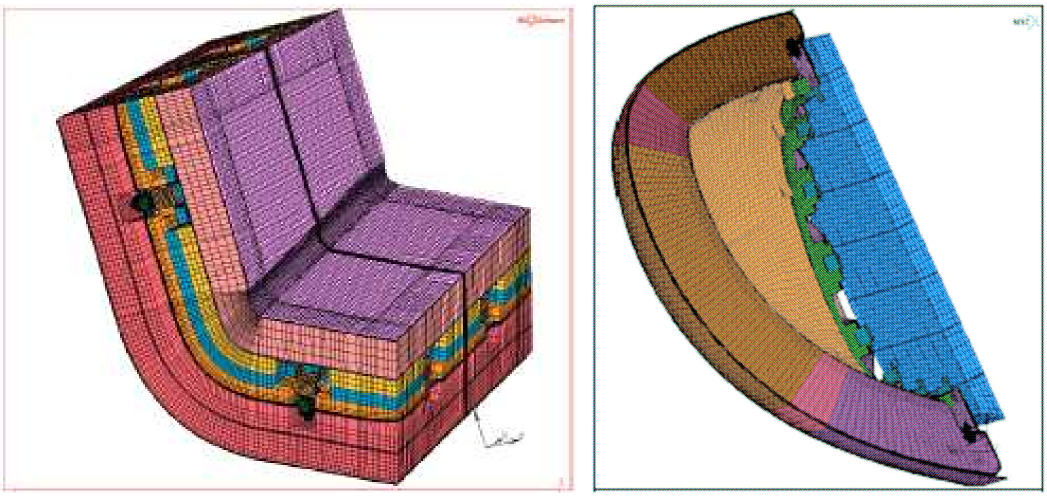


Figure 8 : Windward panel (left) and nose assembly (right) thermal models

The temperature evolution computed for the most loaded areas (for instance for the Windward area panel, shown on Figure 9) confirms the good insulation properties of the system, as the temperature drops from just below 2000 K beneath the surface to less than 450 K at the interface with the cold structure. It can also be observed that the cold structure temperature only increases after more than 10 minutes into the re-entry.

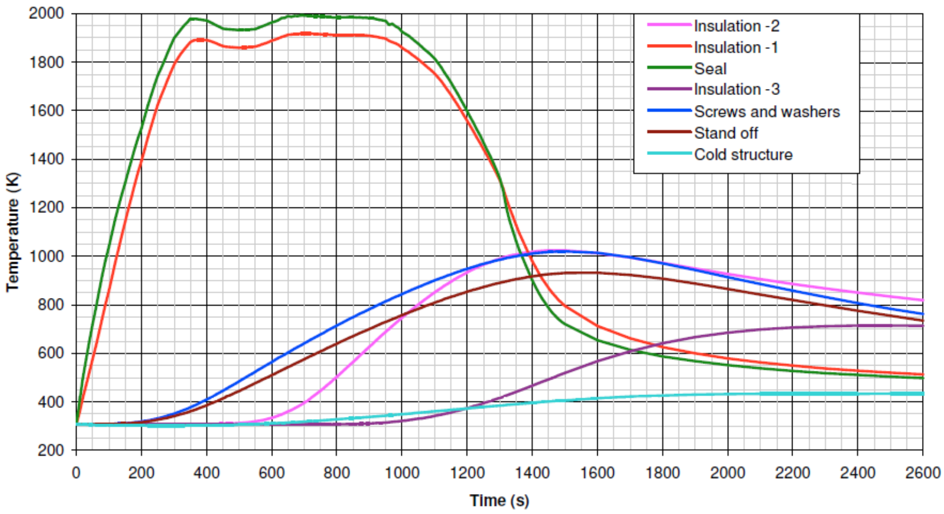


Figure 9 : : Temperature evolution inside the Windward TPS most loaded panel

In parallel, a detailed thermo-mechanical analysis was performed to compute the maximum stress and deformations of both TPS subsystems. The finite element models represented each individual fabric layer for better accuracy, as shown on Figure 10. These calculations have shown an overall adequate sizing of the CMC parts, although some local peaks of stress remain to be evaluated in the light of the recently updated heat-flux sizing trajectory, the reduction of mechanical loads, and of the validation tests still to be performed.

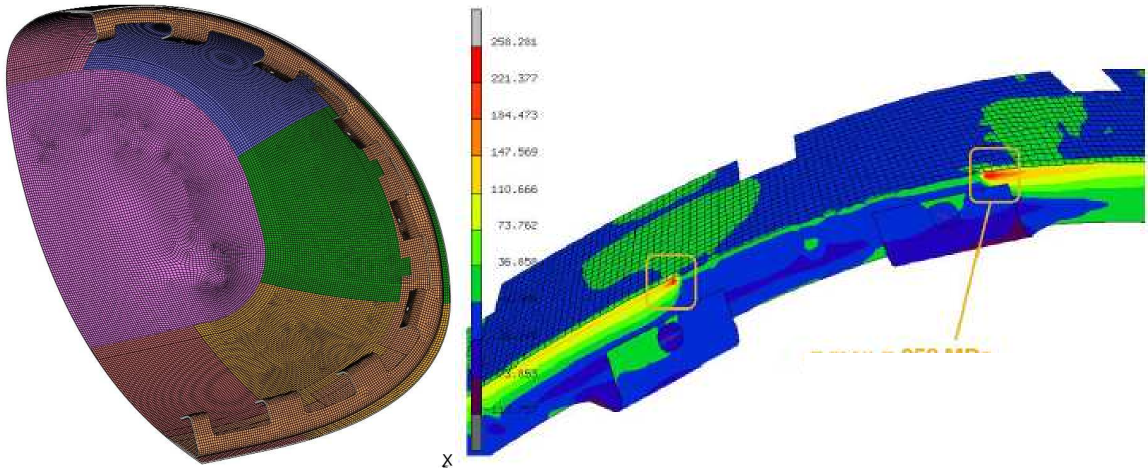


Figure 10 : Thermo-mechanical FEM model (left) and most stressed areas (right)

In addition, mechanical dynamic analyses have been performed in order to verify the sizing of the TPS against the launch phase vibratory environment. The results of these analyses confirmed the fact that it is the re-entry and not the launch that is the most sizing load case.

3.2 Technological and development tests

The IXV nose TPS and windward TPS assembly are not only designed using mechanical and thermo-mechanical analysis, but also using the results of development and technological tests. Among those tests, some are specifically made to assess the behaviour of the TPS during re-entry.

3.2.1 Insulation layers characterisation

The insulation materials used for IXV TPS to protect the cold structure were subjected to a test campaign at ISQ, Portugal, to assess their actual thermal conductivities and their specific heats, and to compare them with the available commercial data. The tested insulation materials were Pyrogel, WDS, Zircar AB and Zircar Mat. For each of these materials, samples were tested at temperatures from 20 to 1600°C maximum, and at pressures ranging from 10 mbar to 100 mbar, to represent as best as possible the re-entry conditions. As an example, tests results for Pyrogel demonstrate that the thermal conductivity increases with temperature, while remaining constant with pressure, as depicted on Figure 11. The increase in conductivity with temperature has been measured at 3.8E-5 W/m/K/Pa. Moreover, measured thermal conductivities have bee found to be lower than those given by supplier data at high temperature. As a consequence, the thermal analyses performed for IXV TPS substantiation which was based on supplier data provided conservative results.

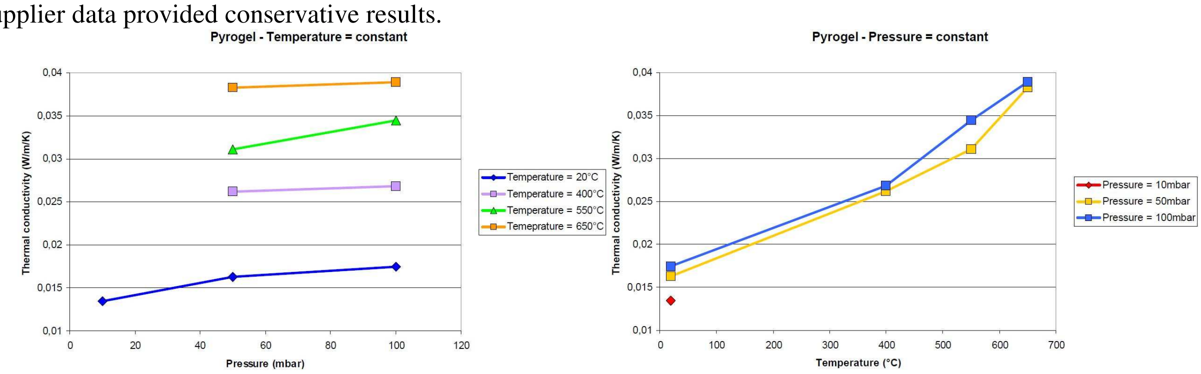


Figure 11 : Pyrogel Thermal Characterisation

In addition to the same elementary characterization of the other insulation materials, similar tests will be performed again with assemblies of 2 insulation materials, in order to assess the thermal contact resistance between two different insulation materials.

3.2.2 Active oxidation assessment of the CMC during re-entry

CMC material which sustains high heat flux with low pressure levels can encounter active oxidation. To determine the threshold between passive and active oxidation, C/SiC CMC samples were subjected to a plasma thermal test campaign at VKI, Belgium. These samples have been exposed to heat fluxes representative of the re-entry, at various pressure levels from 1300 Pa to 5000 Pa. An example of the behaviour of a sample during test is shown on Figure 12.

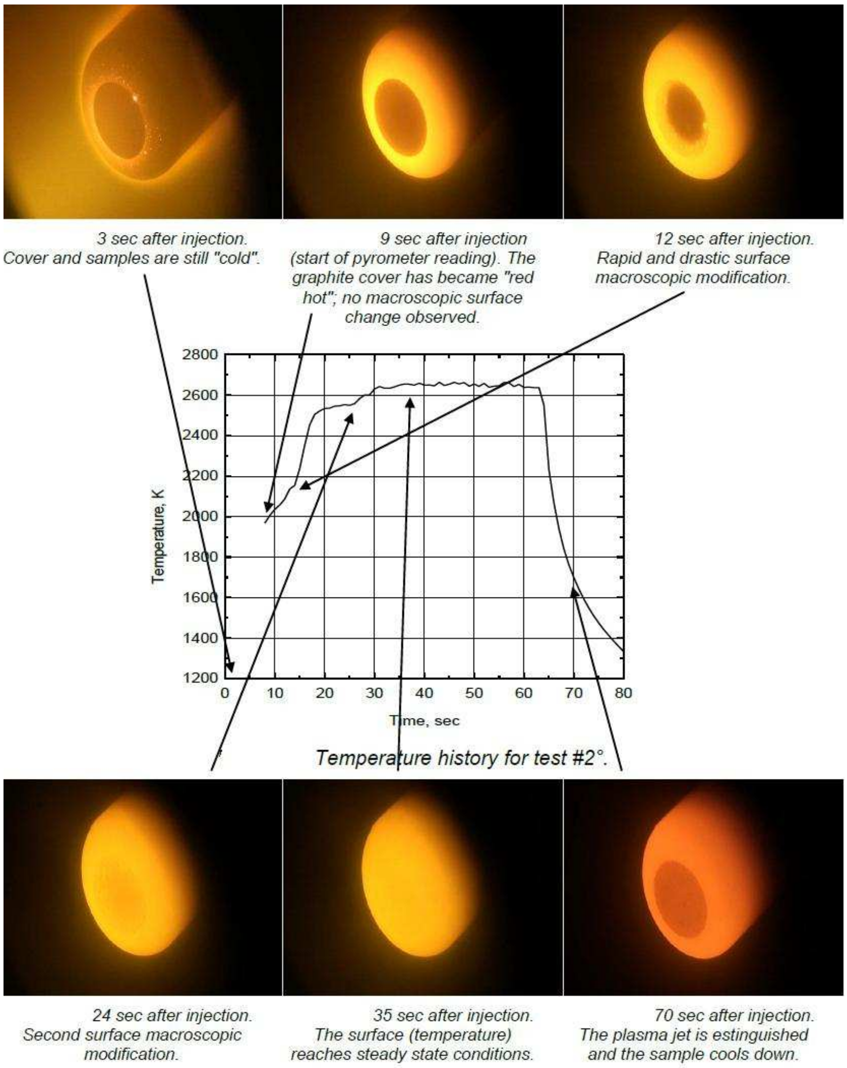
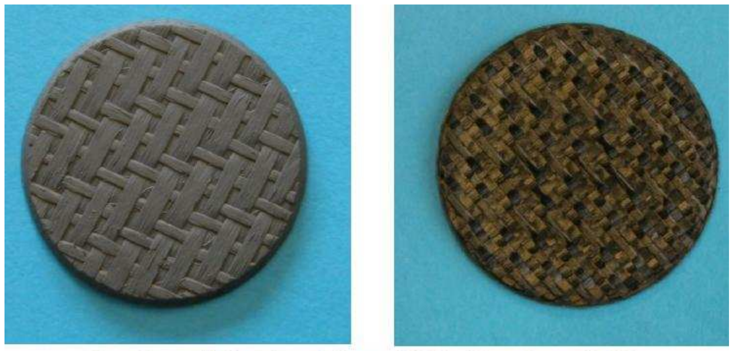


Figure 12 : CMC sample behaviour during plasmatron testing

After each test, the mass loss of each sample has been measured. The average weight loss was between 22% and 37%, which means that the samples lost 1/4 to 1/3 of their weight in about 30 seconds. In order to assess the origin of these weight losses, the samples have been visually inspected. Inspection of the samples seem to indicate that they sustained more than just passive oxidation (see Figure 13). However, this inspection was not sufficient to assess the actual nature of the oxidation, and morphological analysis of the samples has been performed.



Pre-plasma (left) and post-plasma (right) picture of sample O3.

Figure 13 : CMC sample before and after test

Morphological analysis of the sample allowed to know if the weight loss was due to carbon oxidation only, SiC passive oxidation or SiC active oxidation. The morphological analysis of the samples demonstrated that:

- below 1200K, no oxidation was present,
- above 2478K, all the samples encountered severe degradation , at all pressure level
- between 1600K and 2000K, Carbon oxidation is observed on all the samples, with SiC passive oxidation for those tested at total pressures over 2000 Pa

The test results were then compared with the active oxidation curve of SiC material used for the IXV, and confirmed that the curve is accurate for IXV TPS conditions (see Figure 14).

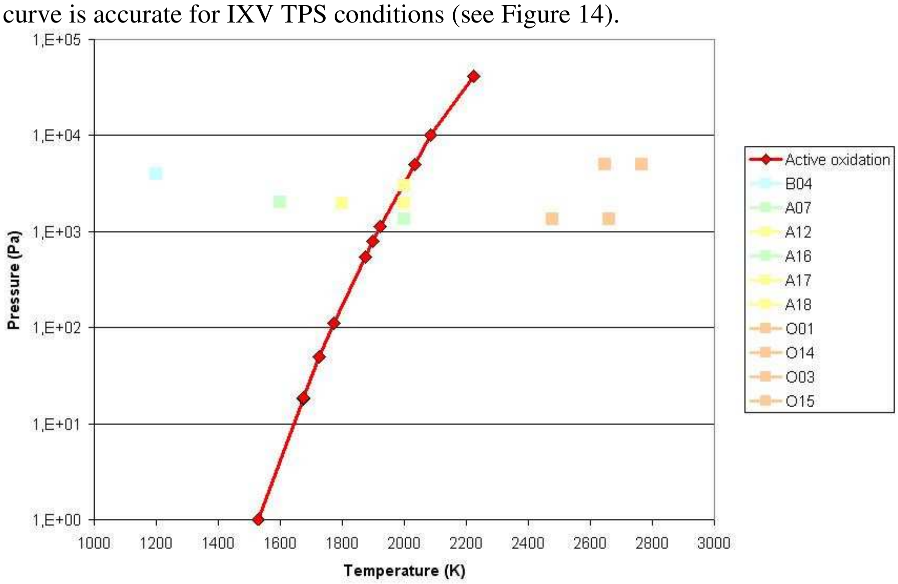


Figure 14 : Active oxidation curve used for IXV TPS CMC material

3.2.3 Catalycity assessment of the CMC material

Catalycity tests have been performed at VKI, Belgium. Catalytic behaviour of the CMC TPS can influence significantly the heat transfer and therefore the surface temperature of the heat shield. Conservatively, heat-fluxes are typically specified in fully catalytic conditions. However, in extreme conditions, this may prove to be over-conservative. Thus, the aim of the test is to assess the recombination efficiency for the surface material, based on a Local Heat Transfer Simulation method. The procedure combines experimental test results coming from the Plasmatron facility and numerical data coming from VKI in-house developed CFD codes.

Before performing emissivity measurement of the CMC samples, the plasma flow is calibrated using a copper water cooled probe: the measured heat fluxes on the test probe is compared to the estimated corresponding full catalytic calculated heat fluxes, based on a numerical model made by VKI. Once it has been demonstrated that the applied heat flux is similar to the calculated heat flux, the emissivity of the CMC samples is measured. Then, using Stefan-Boltzman's law, the emissivity values are used to estimate the re-emitted heat flux, which is then used to assess the amount of heat flux actually absorbed by the CMC material. The measurements made and calculations performed are given in Figure 15.

Measured Heat-Flux (kW/m²)		Pressure (Pa)				
		1300	2000	3000	4000	5000
Temperature (K)	1200	195	185	180	175	160
	1400	360	385	410	375	390
	1600	745	735	810	745	700
	1800	1150	1250	1280	1300	1215
	2000	1510	1490	1570	1655	1775

Calculation Heat-Flux (kW/m²)		Pressure (Pa)				
		1300	2000	3000	4000	5000
Temperature (K)	1200	179	161	152	146	129
	1400	350	366	381	342	355
	1600	772	729	790	707	656
	1800	1251	1302	1302	1285	1286
	2000	1700	1572	1593	1646	1757

Stefan-Boltzmann Heat-Flux (kW/m²)		Pressure (Pa)				
		1300	2000	3000	4000	5000
Temperature (K)	1200	92	88	89	89	85
	1400	172	174	192	176	187
	1600	316	316	334	334	320
	1800	494	524	524	530	524
	2000	662	690	717	744	717

Heat-Flux absorbed (kW/m²)		Pressure (Pa)				
		1300	2000	3000	4000	5000
Temperature (K)	1200	87	73	63	57	44
	1400	178	192	189	166	168
	1600	456	413	456	373	336
	1800	757	778	778	755	762
	2000	1038	882	876	902	1040

Figure 15 : Heat flux and emissivity assessment of catalycity tests

The comparison between applied and absorbed heat flux demonstrates that the heat flux decrease due to catalycity is at least 30% in stagnation point conditions, and increases with temperature. Thus, a heat flux decrease curve is proposed, as depicted on Figure 16.

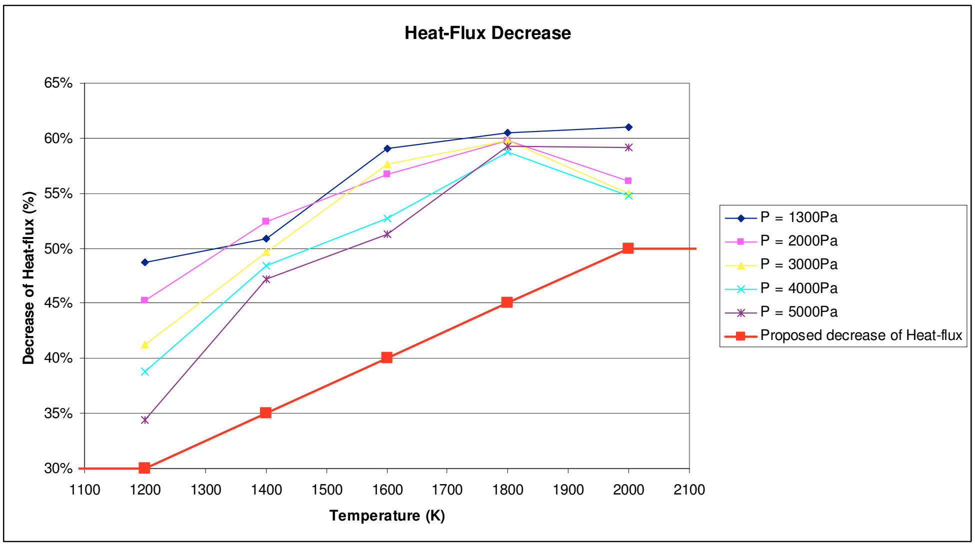


Figure 16 : Heat flux decrease due to catalycity in stagnation point conditions

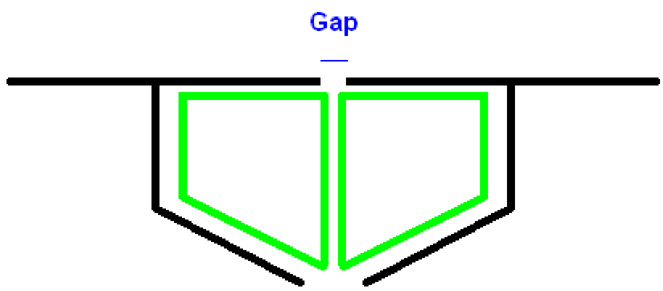
Based on these tests results, a significant catalycity relief is possible for use in the IXV Nose TPS thermal analysis, since the nose is in similar conditions with regards to the heat flux, at stagnation point, as the tested samples. This catalycity relief allows to reduce the over-conservatism in the evaluation of the thermally induced strain.

3.2.4 Permeability and venting tests

The TPS panels are surrounded by seals, which provide sealing between adjacent panels. These materials are not airtight and their permeability varies according to the following parameters:

- the gap between two panels,
- the temperature of the gas,
- the state of the seal (intact or damaged),
- the shape of the panel.

The permeability of the seal is an influent parameter for sneak flow and thermal analysis. To better assess the influence of this parameter, characterisation of the seal permeability has been performed at ISQ, Portugal on specific test samples. Each test sample is made of two panels representative of the interface between two TPS panels, and a portion of seal between them (cf. Figure 17). Different configurations of gaps, panel geometry and seal state have been tested. Most of the permeability tests have been performed with metallic panels for sake of simplicity, but the influence of the panel material, metallic or CMC, has also been measured.



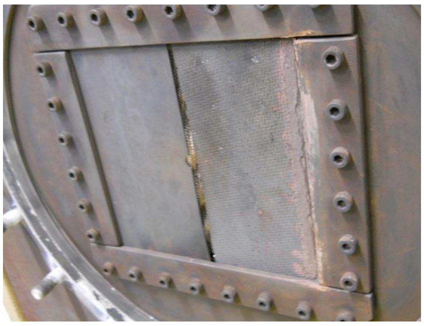


Figure 17 : Test configuration for permeability test

Tests results show that the seal permeability decreases with the decrease of the gap between panel when less than 3 mm wide, but is little affected when the gap is above 3mm (cf. Figure 18). The effect of temperature has been measured with metallic panels, and as such limited to 600°C. However, tests results have been analysed and extrapolated to calculate permeability values higher temperatures with CMC panels, based on the gap evolution due to material thermal expansion. Analysis results demonstrate that the seal permeability remains constant with temperature, the prevailing effect being the width of the gap. The influence of the state of the seal has been measured by performing tests with an intact seal, a drilled seal and a torn seal (only the sleeve of the seal and the superficial layers of the inside material were torn.) Tests results demonstrated that a torn seal conserves the same permeability characteristics as an intact seal, while a drilled seal has a permeability higher by approximately 30%. IXV TPS panel seals are held by the panels stiffeners, which have a "S" shape, or a "G" shape, as depicted in Figure 19. Even though the permeability tests have mostly been made with "S" shaped stiffeners, the influence of a "G" shape stiffener has also been tested, which demonstrated that the permeability are similar using "S" and "G" shaped stiffeners.

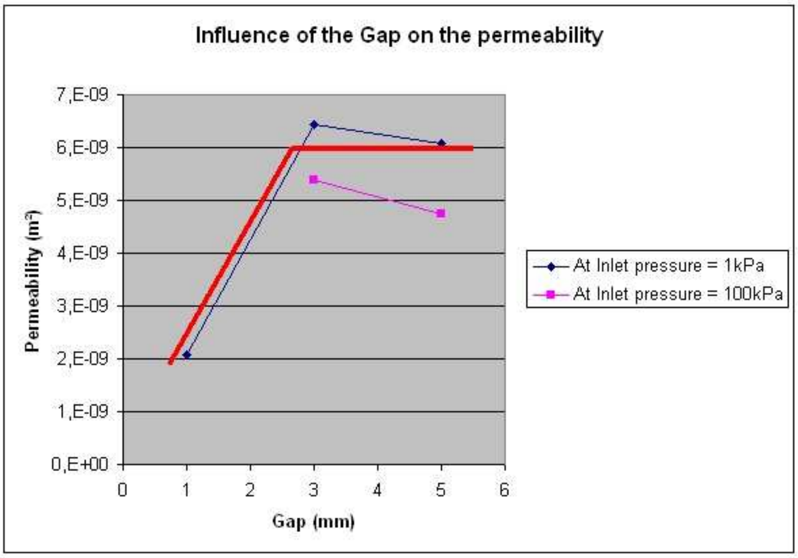
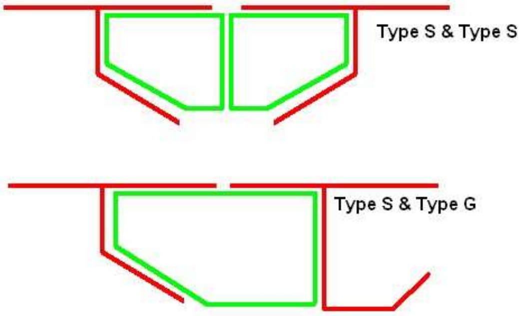


Figure 18 : Influence of the TPS panel gap value on seal permeability



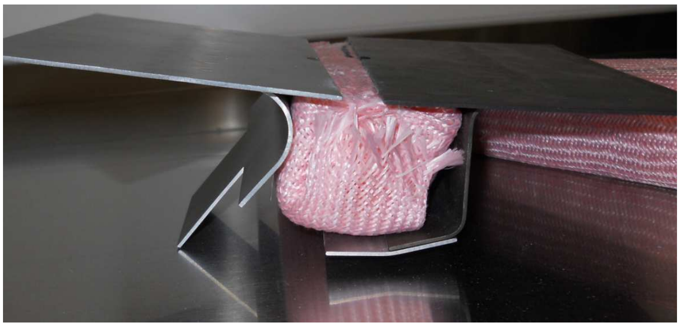


Figure 19 : TPS panels stiffener geometry

3.2.5 Sneak flow tests

This test is complementary to the permeability tests. It will be made at ISQ (Portugal) and aims at characterising the sneak-flow effects, i.e. the hot gas infiltration under the panels of the TPS which overheats the cold structure by convection. In addition, a sneak flow characterization approach is developed. 3 panels representative of TPS panels will be assembled in a test chamber. A gas flow will be injected in the test chamber, and two main configurations will be tested. For the first configuration, an additional separation, placed on the second panel, will force the gas flow through the gap between the first two panels and out through the second gap. For the second configuration, there will be no additional separation so that the amount of gas going outside or inside the gap will depend solely on the gas flow and test sample configuration (cf. Figure 20). These test results will be used, along with venting tests results and permeability tests results, as input data for specific TPS thermal analysis, which will assess the cold structure temperature increase due to sneak flows.

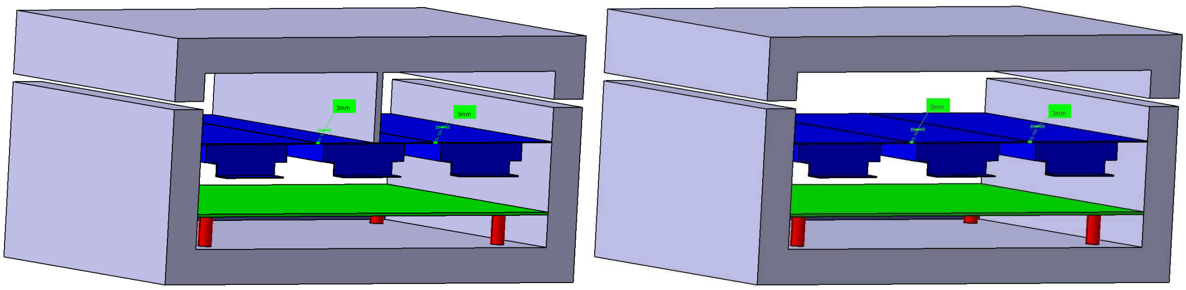


Figure 20 : Sneak flow test chamber configurations with and without additional separation

4 Conclusion

The detailed design phase of the Nose Assembly and the Windward TPS assembly of the IXV has just been completed. Following a consolidation phase dedicated to concept selection and preliminary design of the Nose Assembly, the detailed design phase encompassed a very large spectrum of activities. The design has been refined to take into account the specificities of the IXV mission, for instance the higher heat flux level, the interface with on-board experiments, mass budget, cleanliness constraints, etc. This design has been justified through thermal, mechanical and thermo-mechanical analyses, with FEM models calibrated during previous TPS programmes.

The justification effort is being supported by numerous test campaigns, from elementary characterisation samples to fully equipped subscale TPS panel, with the aim of verifying mechanical allowable characteristics, heat transfer characteristics, compatibility with launch and re-entry environment.

Full scale prototype parts are also being manufactured using industrial processes, and should be completed soon. They will provide the necessary experience to start the Qualification Model manufacturing right from the beginning of the Qualification phase.

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