CMC Thermal Protection System for Re-Entry Demonstrator Pre-Development

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1 ABSTRACT

The Intermediate experimental Vehicle (IXV) atmospheric reentry demonstrator, developed within the FLPP (Future Launcher Preparatory Program) funded by ESA is now entering its detailed design phase. 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.

The development of this technology has been prepared for several years through national and European programs with the testing of key components in progressively more complex test campaigns, culminating with large-scale plasma wind tunnel tests of several completely representative TPS elements. In this paper are first presented the results obtained through these test campaigns. It then presents the current status of the technology for the IXV program and the main verifications that remain to be done through dedicated test campaigns during the continuing development of the IXV and its subsystems.

2 CMC TPS TECHNOLOGY EARLY DEVELOPMENT

Early development activities in this field were started beginning 2003 by Snecma Propulsion Solide, SAFRAN Group, with CNES support. The objective was to perform a series of test campaigns of TPS elements, in preparation of the development of an actual re-entry experimental vehicle. During this early phase, the main characteristics of the CMC TPS technology have been defined, starting from the basic principles established for the Hermes program.

These principles are shown on Figure 1. 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 material, and divided into several panels. This hot surface is supported by the vehicle inner structure ‚, and a lightweight, flexible insulation ƒ is installed beneath the hot surface to prevent the overheating of the internal structure and equipments. For the same reason, specific insulating stand-offs „ are used to attach the hot panels on the structure. Finally, a fibrous seal … is placed around each panel to prevent hot gases from entering through the gap between two adjacent panels.

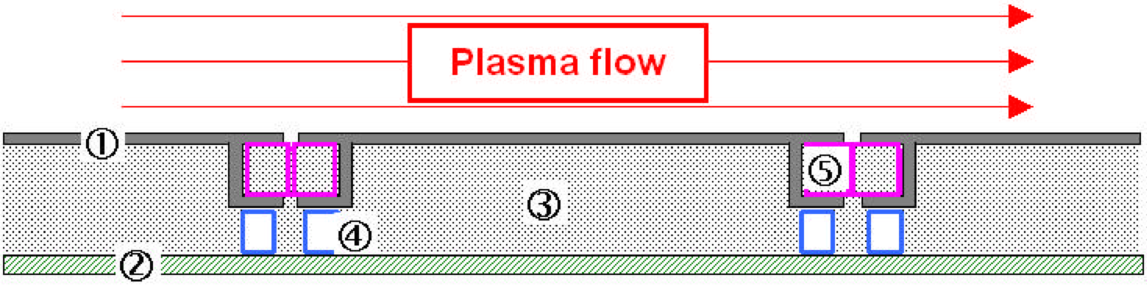

Figure 1 : CMC TPS principle

The early development program comprised many thermal, dynamic and thermomechanical development tests (cf. Figure 2) from small components level to large completely equipped TPS elements (the so-called "shingles"). These tests provided the necessary experimental data to better understand the knowledge of the TPS under a variety of representative environments. This activity also allowed the selection of the best suited materials for each subcomponent : C-SiC for the outer panels, silica-alumina fibres for the insulation and seal and superalloys for the mechanical attachment devices. A more detailed description of this early phase can be found in [1].

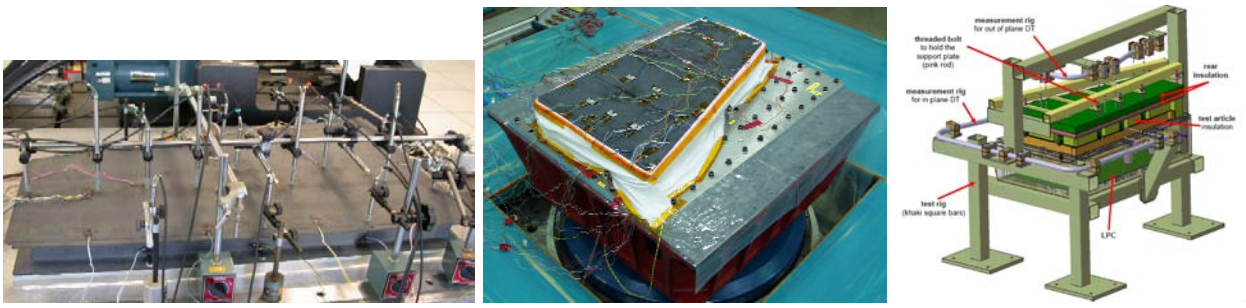

Figure 2 : Static (left), dynamic (middle) and thermomechanical (right) tests on full scale panel

3 SIMOUN PLASMA WIND TUNNEL (PWT) TEST CAMPAIGN

All the tests performed in the early development tasks allowed the acquisition of a large database for the sizing of CMC TPS for use on a typical re-entry vehicle. At this stage, it was then decided to move forward to a more representative, though more complex, type of test : Plasma Wind Tunnels tests. They are the only type of facility that can provide a high degree of representativity of the atmospheric reentry in terms of enthalpy and chemical composition of the airflow.

Though small coupons of CMC (C-SiC) material have been tested (cf. [2]) previously, the first PWT large scale test campaign was performed on an array of three parts of TPS elements in the SIMOUN arcjet (Astrium, France). Its purpose was to characterise the influence of a large number of geometrical parameters on the thermal field of the different components : influence of the steps (discontinuity between the surfaces of two adjacent panels) and of the gaps between the CMC panels, influence of the angle between junction line and flow direction, influence of the angle between two row of panels, influence of a triple point singularity between three panels.

A complex test tooling, allowing the testing of a 300×300 mm TPS array was then designed (cf. Figure 3) in order to be able to tune the steps, gaps and angle parameters. It was protected from lateral heating by ceramic blocks (cf. Figure 4), in order to avoid parasite influence from the edges.

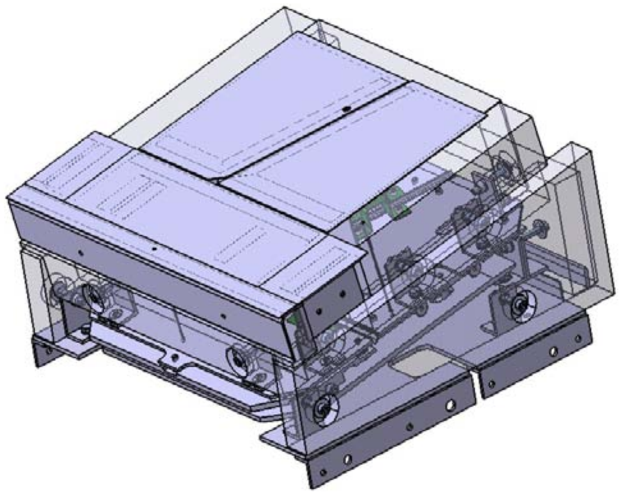

Figure 3 : Drawing of the SIMOUN plasma test article, and the tooling for configuration change

Figure 4 : Test article before set-up on SIMOUN plasma facility

A series of thirteen tests were performed, totalling more than 11 000 s under plasma flow. The calibrated heat flux was typically of 300 to 400 kW/m² near the triple point of the junctions between the TPS elements. The thermal data, acquired from in-depth thermocouples and surface IR camera, have shown that :

- The structure temperature is locally very sensitive to steps. Negative steps have little effect on the structure temperature, but positive steps of more than 1 mm have to be avoided as they lead to an overheating of more than 40°C (cf.Figure 5).

- On the contrary, the influence of the gaps on the cold structure temperature, measured for a gap range of 1 to 4 mm, is weak (about +/- 10°C).

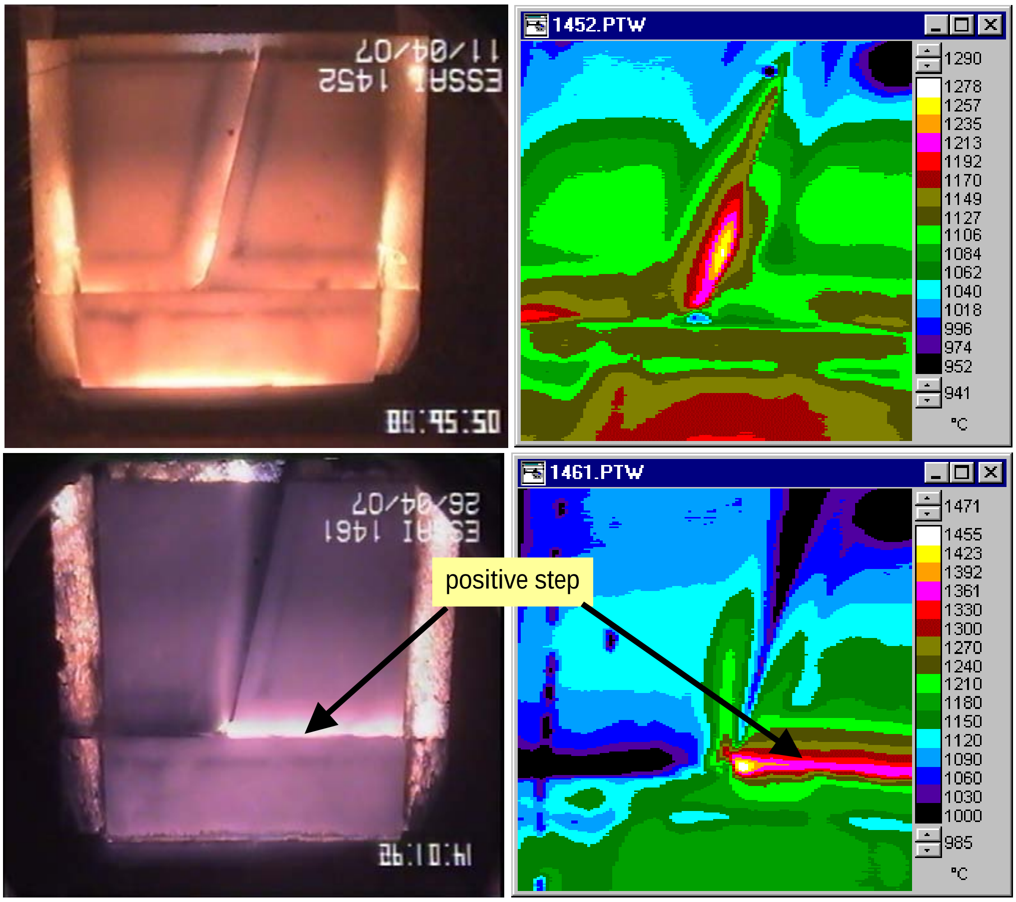

Figure 5 Visible and IR camera nominal configuration (above) and large positive step configuration (below)

The hardware has shown very good resistance. The post-test characterisation tests showed a nominal C-SiC material strength. However, some overheating generated by high positive step configurations (+1 mm or higher) at the edge of C/SiC panels led to local oxidation and small size damages. Morphological observations showed that this oxidation is limited to edge areas, hence it did not impact the mechanical health of the material in other areas, or the overall behaviour of the shingle.

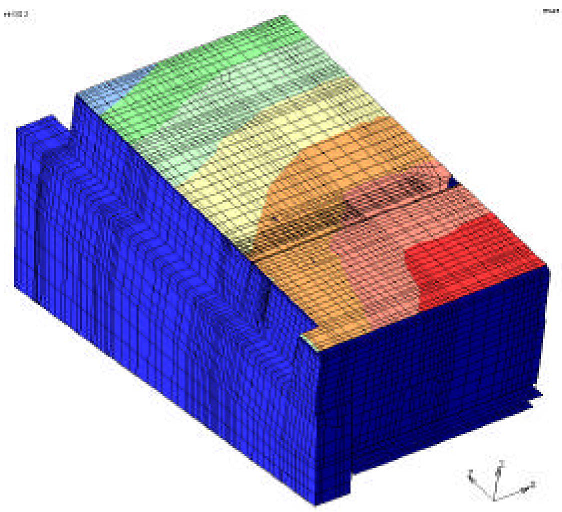

Figure 6 : 3D FEM thermal analysis

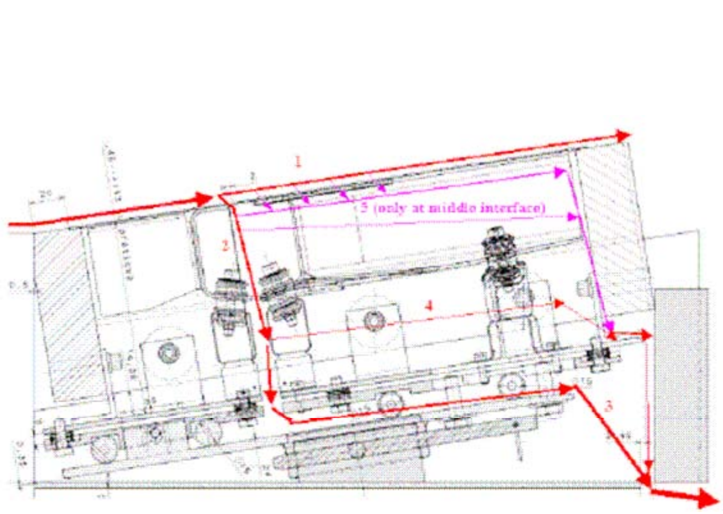

Figure 7 : Sneak flow path through test set-up

Extensive 3D thermal calculations (cf. Figure 6) have been performed in order to analyse the test results and enhance the calculations accuracy. These analyses allowed to establish that a sneak-flow (i.e. a hot gas infiltration) occurred during the tests (Figure 7). This sneak flow was nevertheless not accurately representative of the in-flight conditions because the particular architecture of the cold structure, which was designed to tune the geometrical parameters, allowed an easy circulation of the air with the back side of the test set-up. The possibility of sneak flow during flight cannot be excluded however, and will necessitate further investigations.

4 SCIROCCO PWT TEST

4.1 Demonstrator design

In the frame of the ESA FLPP 1 Material & Structure program, Snecma Propulsion Solide was entrusted by NGL Prime with the design, manufacturing and test of a large-scale CMC TPS demonstrator to be tested in the Scirocco facility (CIRA, Italy) The higher power of this facility allows to test larger articles. The purpose of this test was then to test complete C-SiC panels, equipped with insulation, seals and attachments.

A complete design has been studied with the following guidelines :

- The interfaces between the panels had to be representative of an application on the IXV vehicle. The interface between the two flat panels was to be placed in the test article's plane of symmetry, in order to represent the most unfavourable configuration found on a vehicle.
- The manufacturing process of the CMC panels had to be representative of a vehicle's TPS components.
- The materials used for insulation, seals and attachments were identical to those already used for the maturation of this CMC TPS technology.

The size of the TPS elements was essentially driven by the maximum frontal surface of the test article allowed by the Scirocco test facility. The surface of each of the three elements was about 400×200 mm, with an overall thickness of 110 mm. The curvature radius of the curved element was 250 mm.

Each TPS element (cf. Figure 8) included a stiffened panel of C-SiC material, four attachments made of Inconel 718 and Macor subcomponents, an internal insulation made of Zircar AB material, and a seal made of Zircar AB placed in a Nextel fibres braided envelope. All these materials are commercially available, except the C-SiC material produced by Snecma Propulsion Solide. This particular type of C-SiC, named L6, is made of several layers of undelaminable carbon-fabric, sewn together and shaped to form the skin and the integrated stiffeners. The layers are then densified through CVI process with a matrix of SiC. The SiC deposited on the surface also acts as an efficient oxidation protection system.

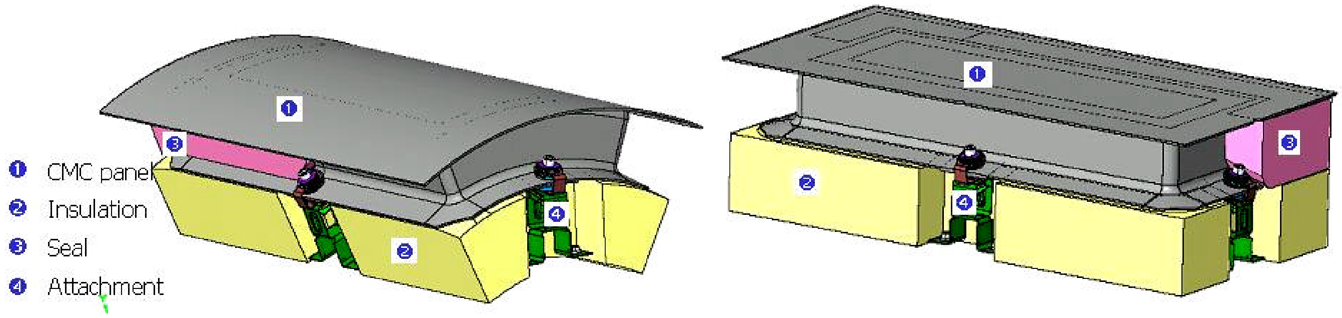

Figure 8 : Curved and flat TPS elements (seal partly cut to show the shape of the stiffeners)

4.2 PWT test set-up

In order to achieve the required heat flux, the flat surface of the demonstrator is tilted relatively to the nozzle axis with a 45° angle of attack. To support the three TPS elements, to protect their sides from the heat flux, and to provide the necessary access and interfaces for integration with the Scirocco test facility, Snecma Propulsion Solide has designed a specific test rig. This rig was made of a robust stainless steel welded frame. The sides were closed by steel sheets supporting Superwool 607 lightweight ceramic insulation blocks. On the front face, the sides of the three CMC TPS elements were protected by carbon-phenolic blocks. The choice of this ablative material, also produced by Snecma Propulsion Solide, was driven by the high thermal loads expected on the rounded edges near the stagnation point.

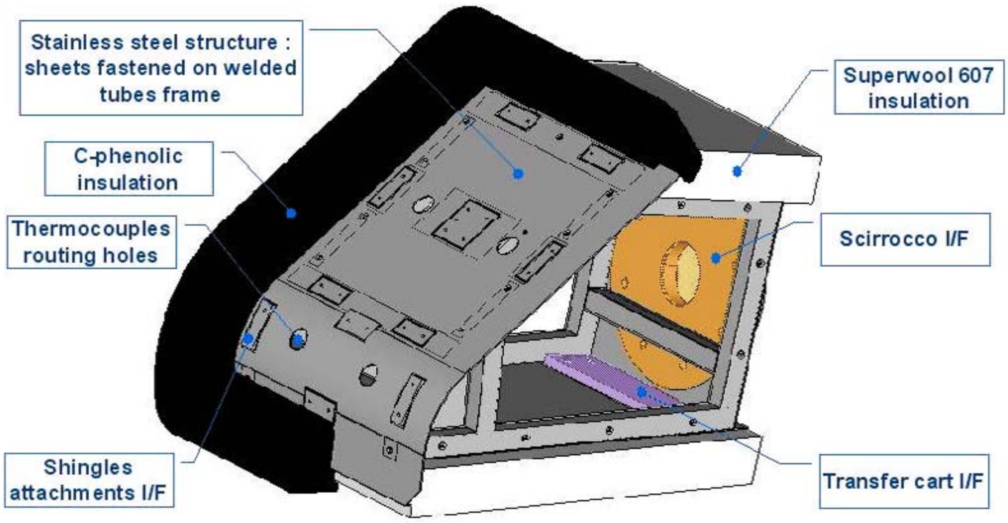

Figure 9 : Scirocco test rig

4.3 Test conditions

One test was performed in Scirocco PWT facility. In order to collect as much information as possible during this single test, it was decided to divide it in three successive steps of constant heat flux.

- A first step of 680 s was performed in order to simulate a complete re-entry on the hottest part of the flat panels (corner near the triple point), considered as the reference location. There, the heat flux (cold-wall, full-catalytic) computed by CIRA in CFD analysis was ~350 kW/m², similar to the heat flux applied in the SIMOUN test. The duration of 680 s corresponds to the time at which the cumulated energy applied at these locations equals the energy of the specified re-entry.
- A second step of 110 s with a heat flux 28% higher than the first step (~450 kW/m² at the reference location)
- A third step of 110 s with a heat flux 41% higher than the first step (~500 kW/m² at the reference location)

The purpose of the last two steps was to demonstrate a sufficient robustness of the technology. For the second step, the predicted heat flux gradients on the surface of the demonstrator are shown on Figure 10. The predicted pressure was 35 mbar at the stagnation point, and 20 mbar on the flat panels.

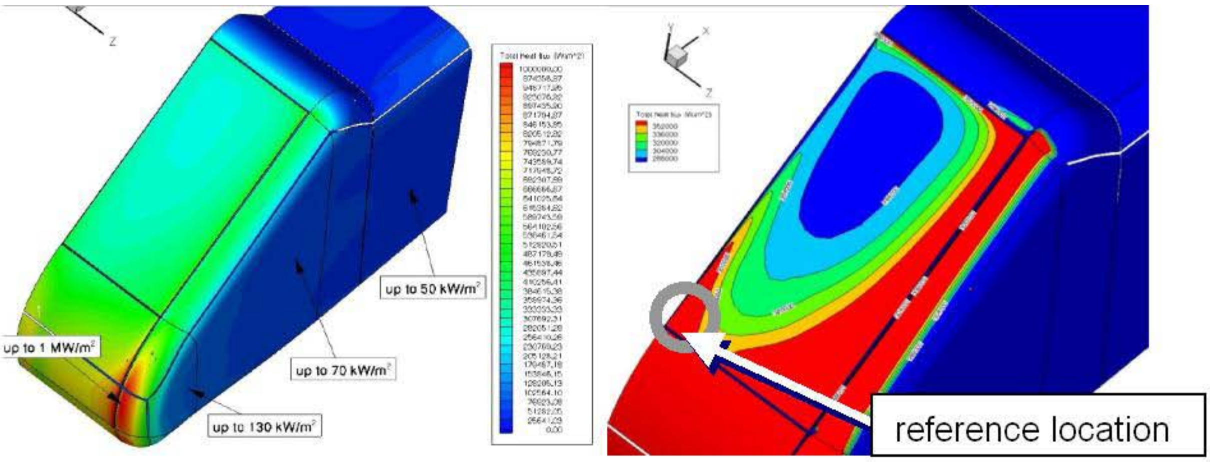

Figure 10 : Predicted full-catalytic cold-wall heat flux for second step (CIRA)

4.4 Test results

The test was performed as expected, the total duration reaching 905s. The video did not provide any particular indication of a potential degradation of the demonstrator or of the surrounding thermal protection blocks.

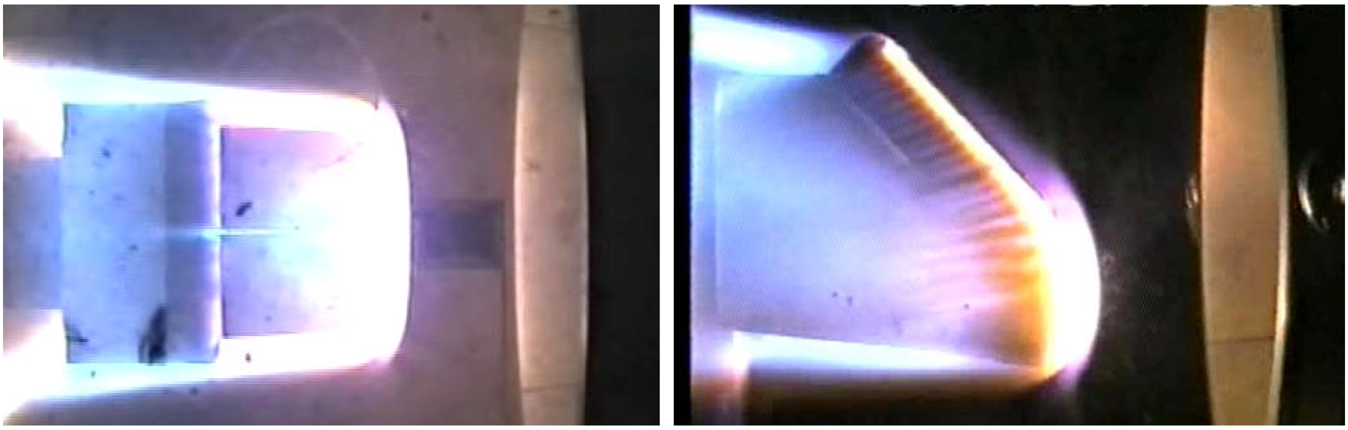

Figure 11 : Video recording of the test article during the plasma test (CIRA)

The in-situ post-test inspection showed that the test article had survived the severe environment without visually detectable damage, such as the loss of one part, or the deterioration of the CMC panels surface. Due to normal passive oxidation of the SiC surface, iridescent colours were observed on all the three panels, particularly the curved panel.

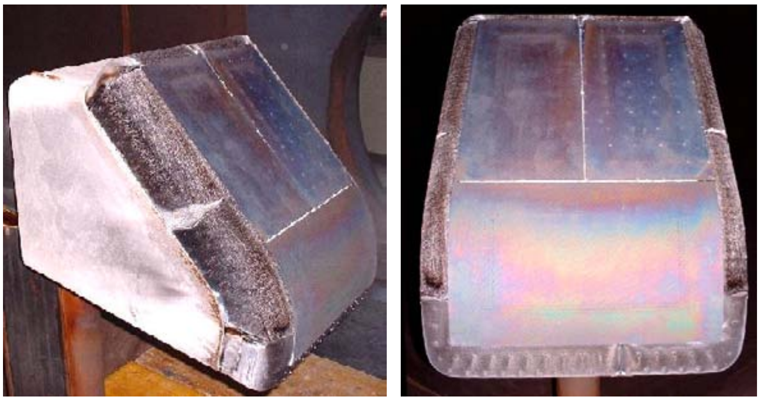

Figure 12 : Overview of test article front face after test

After the disassembly, the visual inspection showed that the CMC panels were in excellent condition. This was confirmed by IR thermography and microscopic inspection of the hottest areas, which revealed no trace of in-depth oxidation. The attachments were also in very good condition, and it was verified that they could be dismounted from the outside without any difficulty, as they would in the case of a RLV application. The insulation and seal were in good shape. They were slightly polluted by the condensation of outgassed products from the carbon-phenolic ablator. This was however not representative of the final application, as the ablator was specific to the test set-up.

The mass measurements showed no significant mass variation for the CMC panels and the attachments, and very small mass loss for the seals (~1%). No accurate mass measurement of the insulation could be performed due to the outgassed products condensation.

The test article had been extensively instrumented with thermocouples, in order to assess the applied heat flux and to measure the heat transfer through the TPS elements. In addition, a pyrometer and two infrared cameras were used to get additional information on the surface heat flux. The maximum temperature measured under the skin of the CMC panels by thermocouples was about 1430°C and 1220°C for the curved and the flat panels, respectively.

The analysis of the surface temperatures measured by the pyrometer, the cameras and the thermocouples allowed to estimate the heat flux reduction due to partial catalycity of the CMC panels and hot-wall effect. Although not very accurate, due to the uncertainties associated with each type of sensor, the heat flux estimation indicates roughly a 30% decrease due to catalycity and 10% more due to hot-wall effect.

In-depth, it was observed that the thermal conduction in the CMC panel and the attachments was well predicted, particularly on the flat panels, as shown on Figure 13. This means that the heat transfer in these components is well characterised.

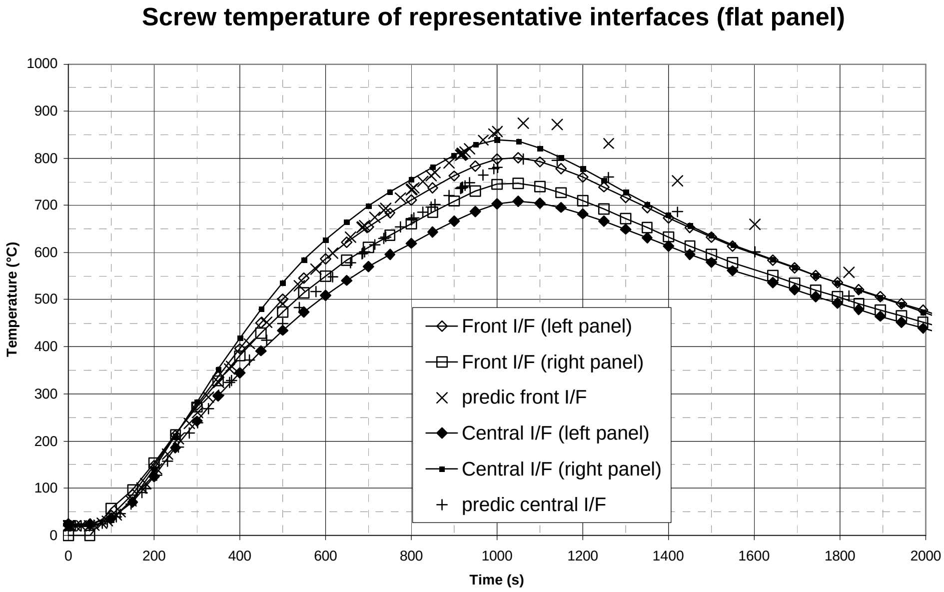

Figure 13 : Thermocouples measurements on flat panels screws at representative interfaces

On the structure, the largest differences between prediction model and measurements occurred in the non-representative areas close to the ablative carbon-phenolic blocks, which particular thermal behaviour was not accurately represented in the model. During the test, the maximum temperature on the structure in the representative area (far from the carbon-phenolic blocks) was 141°C. In this area, the correlation between predictions and thermocouples was fair (cf. Figure 14), with one exception, at the thermocouple located at the triple point between the three panels, suggesting a particular behaviour in this area. This singularity is assumed to be caused by a limited amount of hot gas (sneak-flow) that can more easily penetrate under the CMC panels through the triple point junction, due to the lower compression of the seal at this location.

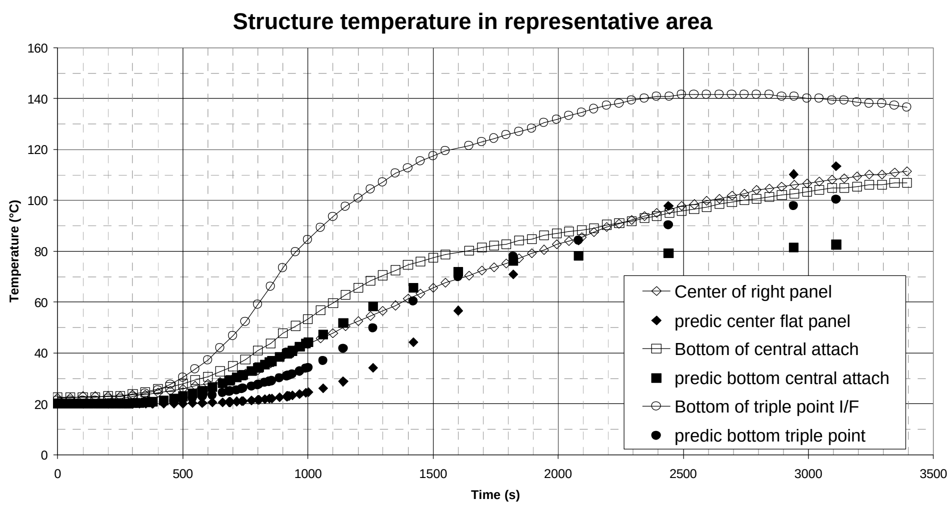

Figure 14 : Structure thermocouples in the representative area

4.5 Thermal analysis

A thermal analysis of the re-entry loadcase of the actual IXV TPS (based on the knowledge of the aerothermodynamic environment available at the time) was made on a model representing 1/4th of a panel. The objective was to update the in-flight performance prediction of the thermal protection system by taking into account the experience from the PWT test. Then, an increased insulation conductivity has been introduced, due to the slightly faster temperature rise measured on the demonstrator structure compared to the initial predictions. As for the heat flux, a decrease due to partial catalycity was applied to take into account the significant effect demonstrated by surface temperature measurements. The decrease was conservatively limited to 25%.

This analysis showed (cf. Figure 15) a maximum temperature of 1216°C on the CMC outer skin, 697°C in the metallic screws and 167°C on the cold structure at 2000 s after the beginning of the reentry (specified landing time).

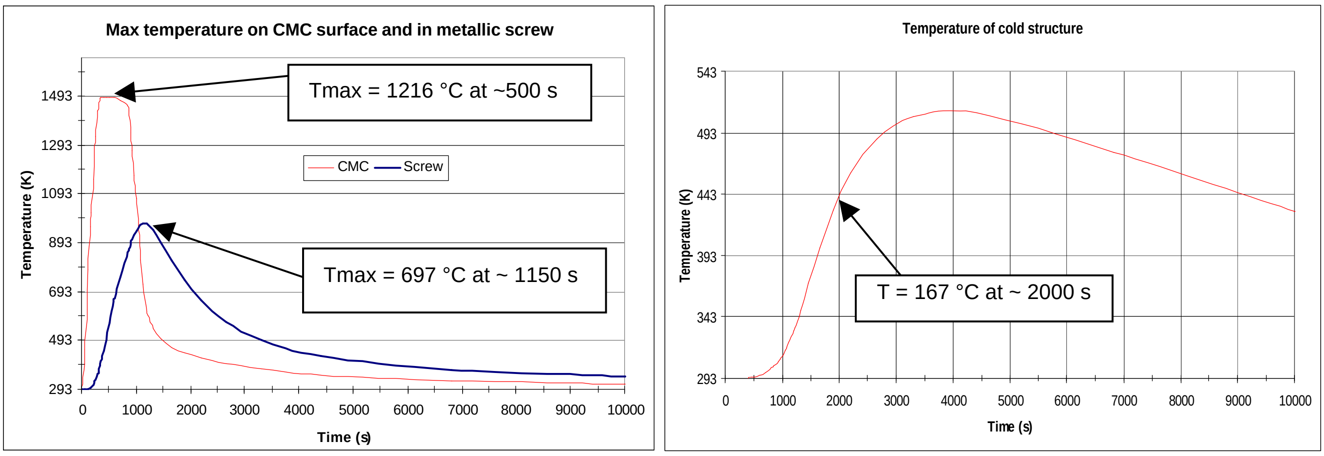

Figure 15 : Temperature evolution during re-entry on surface and attachment screws (left) and internal structure (right)

5 CMC TPS TECHNOLOGY CONTINUED DEVELOPMENT

From the experience acquired through the development tests, including the large scale PWT tests, a high maturity level has been achieved for the CMC TPS technology. Its current Technological Readiness Level is assessed to 6 and it is then ready to be used in an actual vehicle development. This technology was then selected to cover the entire IXV windward area (cf. Figure 16), and was included in the preliminary design phase of the IXV development (phase B2/C1).

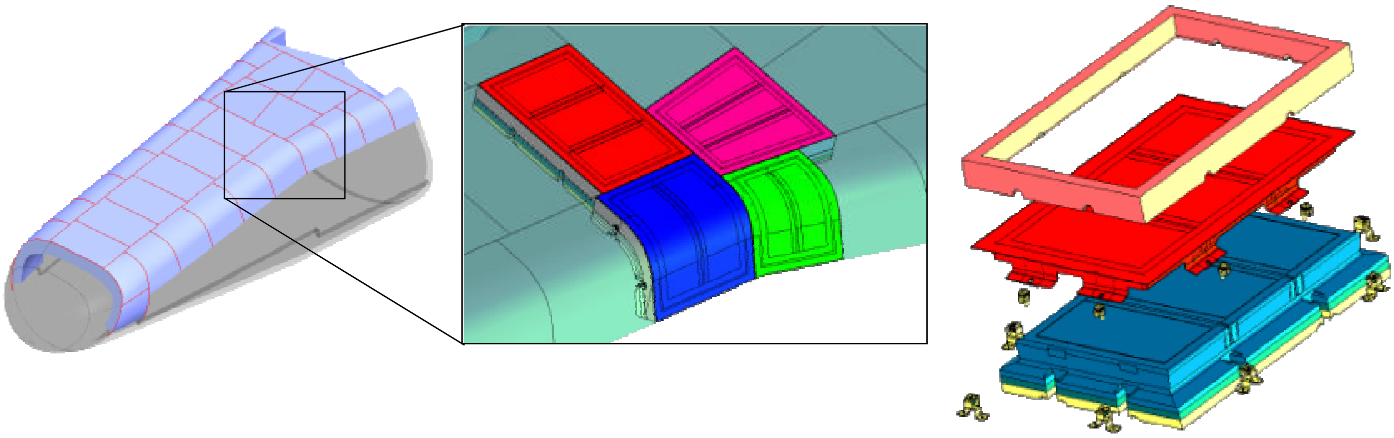

Figure 16 : Overview of windward area CMC TPS pattern on IXV (left) and detailed design of windward TPS elements (middle and right)

In order to take into account the increased severity of the phase B2/C1 requirements, when compared to previously specified re-entry environments, and more specifically its increased heat fluxes, an adaptation of the generic design developed so far has been done. In particular, the insulation had to be improved by more efficient materials. In addition, the CMC panels have been modified in order to increase their flexibility and reduce their sensitivity to thermomechanical stress.

The development of this technology is then in the short term linked to the development of the IXV itself. In order to verify and qualify the design of the CMC TPS for the IXV, a significant number of development and qualification tests are foreseen, as shown in the table hereafter.

These tests are divided in development (#1 to 9) and qualification tests (#9 to 11). The first ones are dedicated to acquiring experimental data on features that have not been tested previously, while the second type is necessary for the final verification of the design before the flight. A significant number of them (#2, #6 and #7) are dedicated to the permeability of the seals and to the characterisation of the corresponding potential sneak-flows. Others are necessary due to possible modification of the design (design adaptation and change of material for insulation and / or attachment) due to the increased severity of the current requirements compared to those used for the Simoun and Scirocco tests (#4, #5 and #6).

#	Type of test	Description	Objective
1.	Plasma Wind Tunnel	CMC Oxidation tests on small CMC coupons and Catalycity tests	Refine the active / passive oxidation limit and obtain a reference catalycity measurement, to refine heat flux specifications
2.	Permeability	Seal permeability (measure of pressure and flow rate on seal coupon)	Obtain characteristics for venting and sneak flow assessment
3.	Mechanical	CMC technological mechanical tests on singular areas samples	Assessment of the strength of the most critical areas of the panels such as stiffener, if design and / or loads differ from previous experience
4.	Mechanical and thermal	Attachment device (screw and stand-off) mechanical and thermal tests	Verify the fatigue behaviour of the attachment. Characterise static strength and conductance of modified versions of the attachments (replacement of Inconel for instance) if necessary for the IXV application.
5.	Thermal	Insulation properties characterisation	Verify the performance of the optimised insulation stack-up (different from the one used for Scirocco or Simoun)
6.	Pressurization test	Venting : pressurisation and depressurisation of the CMC TPS elements	Characterise the pressurization / depressurisation characteristics of the whole CMC shingle stack-up, using up to three shingles assembled representatively.
7.	Pressurization test	Sneak flow test. These tests will be performed in a pressurized chamber.	Characterise the mass flow rate circulating under the CMC skin and the thermal transfer between the flow and the TPS
8.	Assembly test	Assembly of an array of CMC TPS to components of the TPS :	Verify that the components can be mounted and dismounted easily from the outside. This will be used to define and validate the best assembly procedures.
9.	Plasma Wind Tunnel	PWT of TPS panels with singularities like interface area, local damage, or instrumentation (pressure port).	Singularities validation in re-entry environment
10.	Thermo-mechanical	Thermo-mechanical test of an array of 3 or 4 shingles	Qualification wrt re-entry environment to validate the deformation prediction and verify the strength of the panels
11.	Dynamic	Dynamic test of an array of 3 or 4 shingles	Qualification wrt launch environment to verify the strength of the panels

(in white : development tests ; in blue : qualification tests)

6 CONCLUSIONS

All the tests performed in the CMC TPS development activities have provided essential experimental data to consolidate the CMC TPS technology for future application on re-entry vehicles. The activities have also provided valuable experience for complex testing activities, both in terms of test article design, and in terms of facility operations, that will be highly profitable for future development and qualification tests of the TPS of a re-entry demonstrator.

As a general statement, all the components of the CMC TPS technology successfully sustained the different tests. This means that all the components were able to fulfil their function up to the end of the tests, thus demonstrating a high level of confidence in the possibility to develop a full TPS system based on this technology for future vehicles, such as the IXV. In particular, the CMC panels made of L6 material, specifically developed to meet the severe requirements of reusable launch vehicles have demonstrated a remarkable resistance to the severe re-entry environment.

However, some characteristics still need to be investigated, such as the occurrence and effects of sneak-flows on the thermal behaviour of the TPS. In addition, the most recent evolutions of the IXV specifications are significantly more severe, in particular for the heat flux requirements, than those considered for the technology development through the Simoun and Scirocco test campaigns. This means that design adaptations are likely to be necessary, along with the corresponding re-verification through experimental tests.

Finally, in the long term, with the more distant perspective of the use of this technology for a future reusable launch vehicle program, the CMC TPS development effort will have to be continued in order to validate features that will not be addressed by the IXV, such as the lifetime or overhaul procedures for this kind of system.

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