PLASMA WINDTUNNEL TESTS AT P A R E S THERMAL PROTECTION SYSTEM

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OVERVIEW

With the announced retirement of the US shuttle in 2010, the need for an own download capability from the ISS for Europe becomes more and more important in order not to loose the attractivity of the ISS as research facility.
The capability to download processed or collected samples has to be guaranteed further on. As Soyuz does not offer sufficient possibilities, ESA decided to investigate complementary systems for ISS logistics which can take over essential tasks. The ATV, Progress and HTV based PARES (payload retrieval system) capsule can provide a frequent download capability for small and medium sized samples and equipment from ISS [2].
The PARES re-entry trajectory is designed such that, of course, a collision with the carrier vehicle or even its debris is avoided. This causes loads which are highly demanding for the Thermal Protection System (TPS).
This paper describes the overall TPS & hot structures concept and focuses on plasma wind tunnel tests performed to verify critical issues for the wall TPS, nose and the stabiliser part of the system.
These tests were performed within the frame of phase B of the PARES project and were conducted recently at several facilities like L3K-DLR Cologne, PWK1&2-IRS Stuttgart and COMETE of ASTRIUM Aquitaine.

1. INTRODUCTION

Minimizing the capsules net weight may be among others achieved by a minimization of TPS mass. The thermal protection mass is directly linked to the heat input, which is primarily defined by the entry conditions, i.e. entry speed and entry angle. However, the entry state is provided by the carrier vehicle and may therefore not be influenced by PARES itself. But the TPS mass may be optimized such that the local TPS thickness is adjusted to the local heat flux conditions. This requires having the vehicle's nose during the hot hypersonic phase always pointing more or less into the flight direction, which ensures having the stagnation point heat flux always been located at the nose. In contrast, allowing any orientation during re-entry would lead to a relatively thick and heavy TPS on the capsules surface. With respect to payload requirements, an undefined attitude is also not desirable as rapid attitude variations may cause unwanted angular rates and accelerations.

For that reasons the PARES TPS has been somewhat highly optimized to be in-line with the stringent mass and performance requirements. This causes high demands especially for the nose, stabiliser and the wall TPS. To reduce the risk resulting thereof critical issues have been verified by 4 plasma wind tunnel test campaigns which were performed therefore already in phase B of the project.

2. OVERALL TPS CONCEPT

Fig. 1 below defines the main parts constituting the Thermal Protection System (TPS) of the PARES capsule, according to the baseline for phase B.

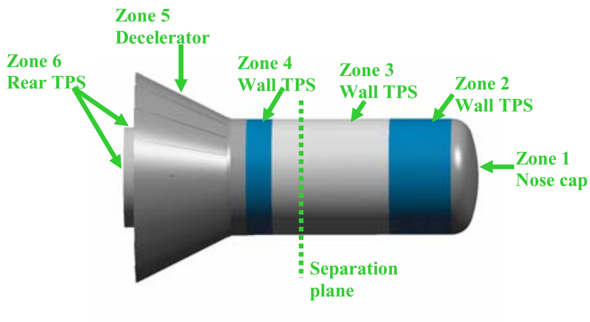

FIG 1. Different Zones of the PARES TPS

The specific TPS applied on the single zone depends on the environmental loads especially the max. thermal load during re-entry. For that reason and based on thermal analysis the following TPS pattern has been selected [1].

- Zone 1: C/SiC nose cap (see para. below)
- Zone 2: Surface Protected Flexible Insulation (SPFI)
- Zone 3: Flexible External Insulation (FEI-1000)
- Zone 4: SPFI
- Zone 5: C/SiC stabiliser (see para. bolow)
- Zone 6: Internal Flexible Insulation (IFI-1000)

For zone 2 SPFI has been selected because of the high thermal loads just behind the nose and due to the small AoA expected. The SPFI is a windward-side TPS which blocks hot gas penetration which can occur in this area. This is realized by the CMC cover which constitutes the outer surface.

Zone 3 has significant lower thermal loads therefore FEI-1000 can be applied here with the advantage of lower cost due to lower manufacturing and integration effort. A further advantage of FEI is that here the "soft" interface for the separation plane can be made. A tight TPS interface is designed by over sizing neighbouring blankets at that plane which will be compressed/pressed against each other during mounting of the both capsule halves.

For zone 4 SPFI is foreseen since particularities are here expected coming from vortices in front of the stabiliser which might require a pressure tight surface.

Zone 6 underneath the stabiliser and the backside is protected by IFI-1000 since in this leeward area such insulation blankets are considered to be sufficient and are the most lightweight and low cost option.

3. NOSE & STABILISER TPS

3.1. Nose Cap Design

The Nose Cap design fulfils most suitably the design driving system requirements which are the aero-thermal loads during re-entry and the mass limitations. The heat flux for the stagnation point area did not change compared to the stabiliser area, but is with about 1700°C still very high, even for a CMC hot structure concept.

For this reasons a relatively thick wall of the Nose Cap around the stagnation point has been selected to use the ceramic material as 'heat sink' device for the short peak temperature during re-entry. By doing so, the temperature for the complete Nose Cap can be reduced, but what is also important, to have an inner surface temperature reaching a non critical value concerning oxidation and to have some high margins against possible oxidation erosion of the outer surface, which has been assessed and justified by plasma erosion testing described in the following.

The maximum thickness at the centre of the axis symmetrical shell is 18 mm and stepwise reduced down to 3.2 mm at the cylindrical part of the Nose Cap.

The Nose Cap consists of the following components:

- 1 C/SiC shell with stiffening ring, CVD coating and SiC closure caps for fastener accessibility
- 12 Metallic Attachment brackets (PM1000) as interface and connection to the cold structure
- 12 Metallic Bolts and self locking nuts (PM1000) with thermal stress free concept to attach the Nose Cap to the attachment brackets
- 24 Metallic fastener to attach the metallic brackets to the cold structure
- Insulation between Nose Cap and cold structure to reduce the temperature for the cold structure to the required level.

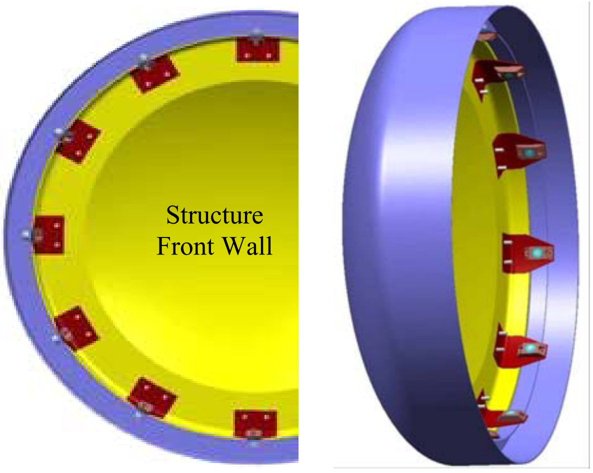

Figure 2: Nose Cap Assembly CATIA Image

3.2. Stabiliser Design

The foldable stabiliser is composed of 18 panels which form in unfolded condition a closed conical and axis symmetrical aeroshell. The 18 stabiliser segments are designed as ultra-light-weight thin walled and stringer stiffened panels. The selected material is a C-fibre reinforced ceramic composite (C/SIC) and is suitable for a hot structure design application.

The hinges at the root of the stabiliser panels and the support brackets are laid out as hot structure metallic material which can withstand the high thermal conduction generated by the non-insulated panel rear surfaces.

The deployment mechanism can be divided into the structural deployment and support elements, the support struts and the support ring and the deployment actuators with the locking devices.

Fig. 3 shows the stabiliser in deployed position with the stabiliser structural elements and the deployment mechanism elements.

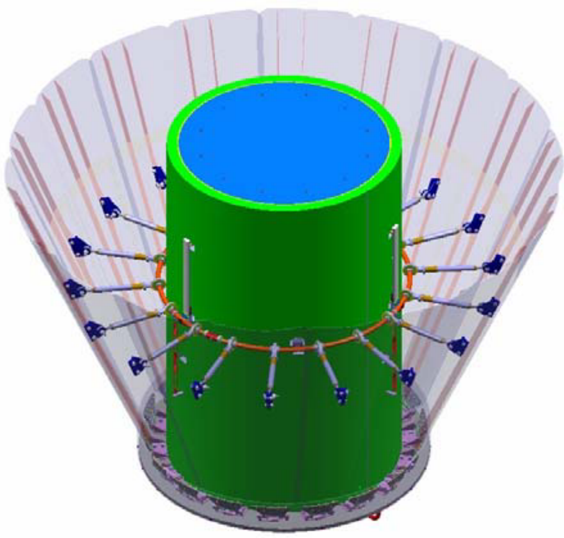

FIG 3. CATIA view cut open with C/SiC Panels and metallic Brackets and Hinges

4. VERIFICATION OF CRITICAL ISSUES

4.1. General

The entire plasma test verification in project phase B was subdivided into two parts corresponding to the most critical TPS issues identified during the foregoing study. Part 1 was performed as one test campaign in one test facility whereas part 2 was performed in three campaigns at two different facilities.

- Investigation of the influence of panel gaps at stabiliser panels and interface between wall TPS and stabiliser called "stabiliser plasma test" hereafter
- Investigation of nose cap integrity and nose cap erosion rates called "nose cap plasma test" hereafter

The above points are means to verify early on the project critical design issues [4] and minimise risk for cost and schedule for the further phase C/D.

4.2. Stabiliser Plasma Test Campaign

The TPS concept of the PARES design has been thermally tested in DLR's arc heated facility L3K. The main objective of the campaign was the experimental investigation of structural and material integrity of the PARES design, in particular of a potential gap between overlapping parts of the stabilisers, when subjected to high thermal loads within a high enthalpy flow field. In total eleven tests were performed at two different flow conditions.

4.2.1. Test Set-up, Instrumentation and Conditions

The size of the plasma torch in such facilities usually limits the size of the model to be tested. In case of PARES stabiliser the transition area from the wall TPS to the stabiliser panels were chosen to be realized in the model. The model forebody represents the wall TPS and two panels with the dedicated angle and overlapping represent the stabiliser panels. This allows testing the wall TPS transition to stabiliser, the seal between wall TPS and stabiliser panels and the gap between two stabiliser panels itself as well as the underlying internal insulation. The most critical issue was though to be the possible gap between adjacent panels which may lead to high temperatures of the stabiliser structural elements and insulation. Such gaps might cause by manufacturing tolerances, integration irregularities and failed correct adjustment of panels during stabiliser opening.

Fig. 4 shows the model used for this test campaign.

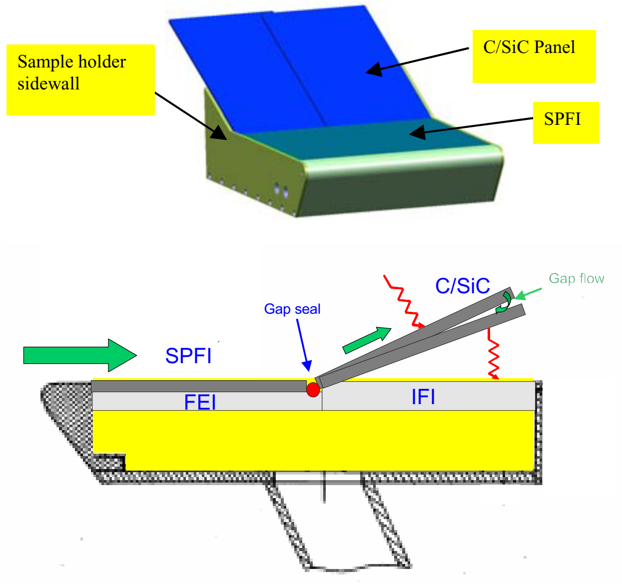

FIG 4. Stabiliser Plasma Test Model

For instrumentation several temperature measurement techniques were applied. The surface temperature was measured globally using an infrared camera system as well as locally at three different spots by pyrometers. In total, 16 thermocouples were used to measure the temperature development at various locations inside the model.

4.2.2. Test Performance and Results

The first tests were run at closed gap varying test duration and model inclination. The desired surfaces temperatures of 1125°C could be reached with an angle of attack of 10° and a testing time of 180 s. The corresponding test with closed gap served as reference for the tests with open gap.

No significant temperature gradients were observed on the panels when the gap was closed. Only very near to the transition between the panels higher temperatures were measured indicating intensified heating. After opening the gap to 0.8 mm no significant differences to the closed gap configuration could be identified. Locally, at the transition point between panel 1 and panel 2 the peak temperature increased, but the affected area did not significantly enlarge. No significant temperature increase was observed at the pyrometer spots, which had a distance of about 10 mm to the transition point. In the model's interior as well, no significant differences were observed.

The situation changed when the gap width was gradually increased to 1.8 mm and 2.8 mm. The area with intensified heating in the overlapping region of the panels enlarged and at the pyrometer spots as well an influence of the open gap could be measured.

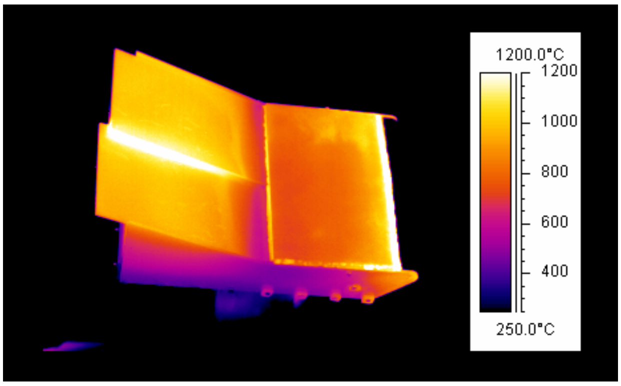

FIG 5. Temperature Distribution for max. Gap Conditions

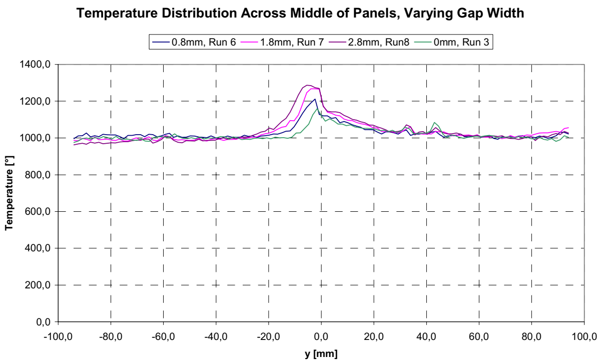

FIG 6. Temperature Distribution across the Panels

In the cavity under the panels an intensified heating could be observed only for the widest gap. The rates of temperature increase as well as final temperatures were remarkably higher as for the 1.8 mm gap. Nevertheless, no indication of material or structural damage could be observed.

The last tests of the campaign were performed at a different flow condition (FC II) which generated a higher stagnation pressure at the model location. The higher pressure level caused an increase of surface temperature of about 50°C all along the model. The effects of intensified surface heating could clearly be observed at all thermocouple location. In the cavity on top of the IFI layer, the temperature increased faster compared to FC I and the final temperatures increased by about 60°C, i.e. it exceeded the level of additional heating to the surface. But even for this configuration, no indication of material or structural damage was observed.

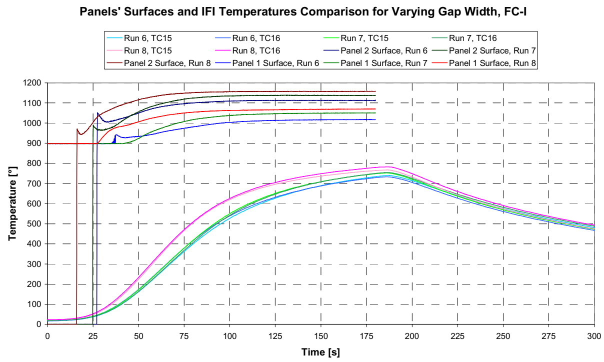

FIG 7. IFI Temperatures for different Gaps

4.3. Nose Plasma Test Campaigns

4.3.1. Plasma Erosion Tests

The plasma erosion tests were intended to provide:

- Erosion determination for PARES nose area and typical re-entry duration
- Determination of passive/active oxidation behaviour (if any)

4.3.1.1. Test Set-up, Instrumentation and Conditions

Two temperature levels representing fully and partly catalytic TPS materials have been chosen as test conditions based on CFD results for PARES re-entry. These values 1930 and 1830°C correspond to the peak values during PARES re-entry.

As in most cases the plasma generators used were not able to generate the combination of high enthalpy/high pressure conditions as calculated for the real re-entry (270hPa at the point in time where the max. heat flux of 1.2 MW/m² occurred).

Instead around 95hPa and 81hPa were applied for plasma test facility I (IRS) combined with high enthalpy flow. For facility II (COMETE) high pressure conditions up to 500 hPa with lower enthalpy flow have been applied.

Lower pressure values are more critical in view of passive/active oxidation transition [3] and are considered as a certain kind of worst case conditions. The risk of passive/active oxidation transition was accepted for this kind of testing.

For both facilities identical test set-ups have been used, i.e. 30mm dia CMC samples (two kinds of fibre lay-up unidirectional and cross layer) of 18mm thickness were installed in stagnation point flow configuration.

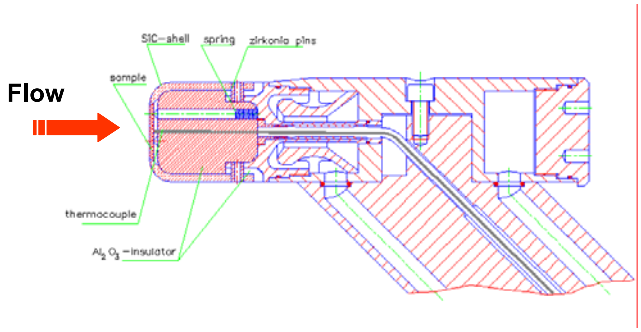

FIG 8. Plasma Erosion Test Set-up

The instrumentation comprised thermocouples installed at the back side of the sample and a pyrometer measuring the sample front side temperature. Besides facility related special measurement equipment was used to determine the plasma flow conditions.

4.3.1.2. Test Performance and Results

4.3.1.2.1. IRS Campaign

The first two tests are dedicated to a comparison of the unidirectional quasi-isotropic and the cross layer sample at the same exposure time (130 sec) and at the same temperature (1830 °C).

Test 03 was performed using a unidirectional sample at the same exposure time of 130 seconds and an increased temperature of 1930°C. This sample went active during the test.

The last erosion test was performed at an increased duration of 600 seconds (corresponding to 5 re-entries) and at a temperature of 1830°C. No active oxidation has been observed.

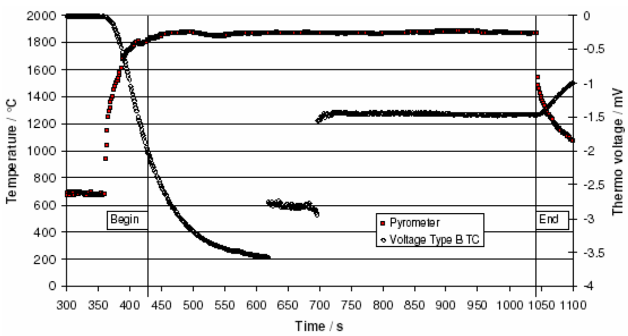

FIG. 9. Temperature Profile for Erosion Test

For the 3 samples which remained passive practically no weight loss and therefore no erosion occurred. No difference concerning erosion for the different lay-ups can be stated.

The sample subjected to the higher temperature value went after 2/3 of the test duration active which causes a drastically temperature rise and an increased erosion rate. Around 6 layers of the lay-up were eroded.

FIG. 10. Sample after Erosion Test

As conclusion can be stated that nominal conditions causes no criticality w.r.t. passive/active transition. Even for the fully catalytic conditions the erosion is low and by far below the value which is the maximum tolerable.

4.3.1.2.2. COMETE Campaign

In general the COMETE test campaign was a repetition of the previous described IRS campaign. The same test configuration and samples were used. The difference was that COMETE is able to simulate higher pressures. Draw back of this facility is that the enthalpy is somewhat lower. Therefore it was decided to test the lower PARES heat flux conditions (~1830°C) corresponding to a partly catalytic surface.

The results of the COMETE campaign confirmed in general the results of the IRS campaign, i.e. very low erosion rates were measured even at active oxidation conditions. None of the samples have been destructed or damaged.

It turned out that the active oxidation transition occurred at lower heat fluxes for higher pressures in the range of 250 to 500 hPa (see Fig. below).

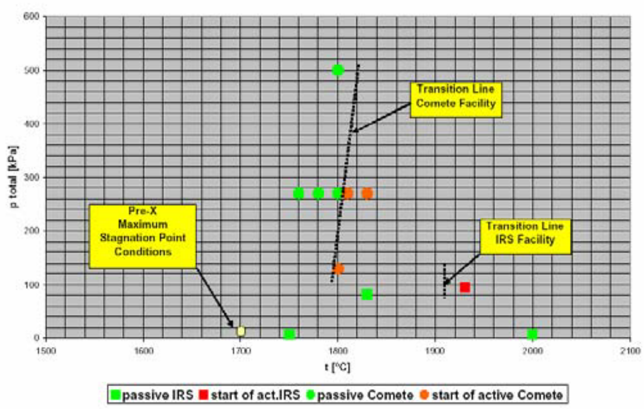

FIG 11. Comparison of IRS/COMETE Measured Passive/Active Oxidation Transition

4.3.2. Nose Integrity Plasma Tests

This test campaign was conducted in order to verify the PARES design concept, by:

- justification of the thermal gradients as input to the thermo-mechanical analysis,
- confirmation of the selected thickness needed for the 'heat sink' concept,
- measurement of erosion rates for maximum pressure and temperature conditions,
- enlargement of the thermal data base as input for the detailed design in Phase C/D.

4.3.2.1. Test Set-up, Instrumentation and Conditions

A temperature level representing partly catalytic TPS materials have been chosen as test condition based on CFD results for PARES re-entry. This value of 930kW/m² ≈1830°C corresponds to the peak value during PARES re-entry.

As in most cases the magneto plasma generator used was not able to generate the high pressure conditions as calculated for the real re-entry (270hPa at the point in time where the max. heat flux occurred). Instead around 8hPa (centre of sample) was applied.

This value is more critical in view of passive/active oxidation transition and is considered as a certain kind of worst case condition. The risk of passive/active oxidation was accepted for this kind of testing.

Two kinds of fibre lay-up unidirectional and cross layer were tested under those conditions.

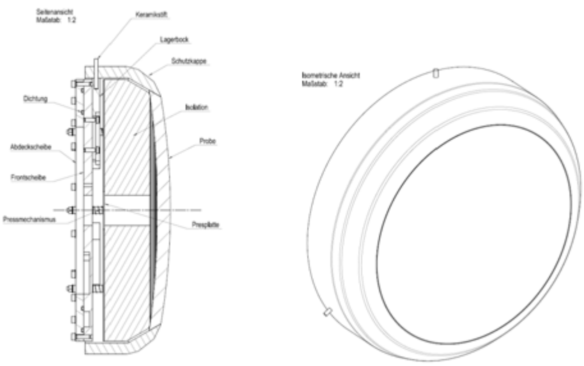

FIG 12: Nose Integrity Test Set-up

The instrumentation comprised 11 thermocouples installed at the back side of the sample and a pyrometer measuring the sample front side temperature. Besides facility related special measurement equipment was used to determine the plasma flow conditions.

4.3.2.2. Test Performance and Results

The temperature gradient along the surface of the samples was quite large and amounts to around 400K from stagnation point to sample border. This large gradient will not occur during PARES re-entry. However, the larger gradient causes higher tension compared to the real re-entry and is therefore considered as much more demanding.

FIG. 13. Nose Cap in Plasma Wind Tunnel

Both kinds of samples behave generally in the same way, i.e. no active oxidation or significant erosion was observed.

The structural integrity was kept even under extended (600s) test duration. No damage or significant degradation has been observed.

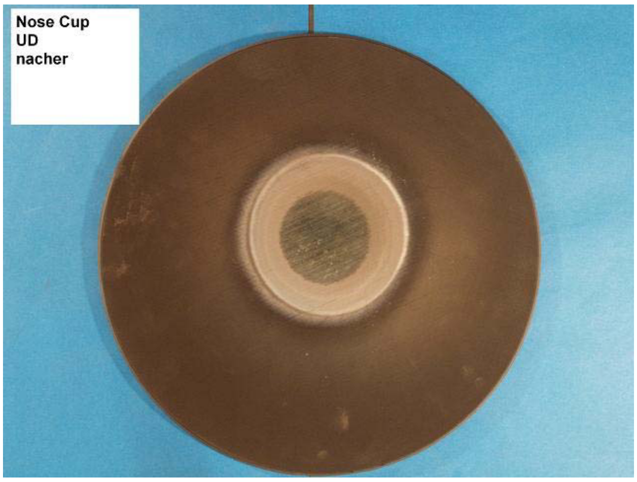

FIG 14. Nose Cap UD Probe after Test

Decolourisation around the stagnation point is an indication that some chemical processes took place but the CVD coating remains intact even under this very hard test conditions.

The high temperature insulation HTI was still intact after test without damage or degradation of insulation function. There was just some decolourisation observed but without any influence on performance.

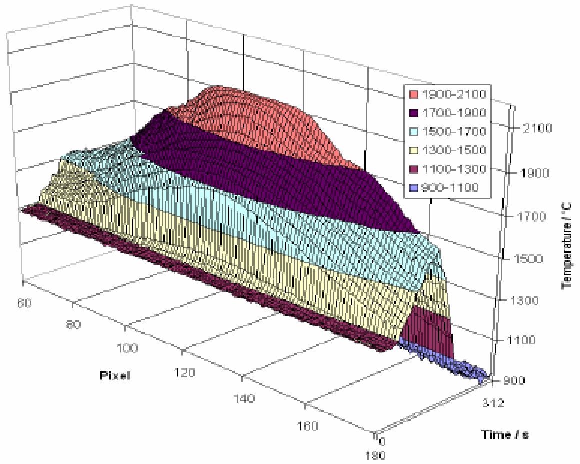

FIG15. Test Temperature Profile

The HTI insulation was inspected after test and neither destruction nor degradation was found (see Fig. 14 below). Only a certain decolourisation at the side facing the nose cap sample occurred due to carbon particles released from the C/SiC surface.

FIG 16. HTI Appearance Before and After Test

5. CONCLUSION

The paper provides an overview about the TPS design and focuses on verification performed for PARES in phase B.

Design and analysis of the TPS was successfully concluded for this phase of the project.

Critical issues have been identified for the nose and stabiliser areas due to the high thermal loading.

It has been proposed to verify the design w.r.t. these criticalities by plasma wind tunnel tests.

The corresponding tests have been prepared, performed and evaluated.

Results show that a high margin of safety is left for both areas so that the design is appropriate or thickness of nose cap can be even reduced.

6. ACKNOWLEDGEMENT

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7. REFERENCES

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8. CONTACT

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9. ACRONYMS & ABBREVIATIONS

ATV Automated Transfer Vehicle

C/SiC Carbon fiber reinforced Silicon-carbide Ceramic

CFD Computed Fluid Dynamics

CVD Chemical Vapour Deposition

FEI Flexible External Insulation

HTI High Temperature Insulation

IFI Internal Flexibel Insulation

I/F Interface

IR Infrared

ISS International Space Station

RT Room Temperature

SPFI Surface Protected Flexible Insulation

TPS Thermal Protection System