

Beta-Titanium Alloy Thermal Protection System for Re-entry Vehicles

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ABSTRACT

From the early beginning of space programs metallic Thermal Protection Systems (TPS) have been considered as promising technology to protect space vehicles against the severe aerodynamic heating encountered during re-entry into earth's atmosphere. The goal of "airplane-like" operations for future RLV's led to a renewed interest in TPS more durable than that developed for the space shuttle orbiter. This triggered the need for a development of metallic TPS which is expected to be also more robust than existing ones. Using the European IXV experimental vehicle concept as reference configuration ASTRIUM SPACE Transportation, Bremen was entrusted by NGL Prime for developing a metallic TPS called MERIT within the frame of the FLPP-1 M&S program. The development has been performed so far that the design for such a metallic TPS has been concluded and analytically verified. The next step was to verify the design and analytical work by ground tests. This has been done in two ways. A first test campaign was accomplished to verify points of special interest/performance in particular characterization. Next a panel array was tested in order to simulate so called TPS assembly conditions and to verify the TPS behavior from system point of view. For that vibration tests and thermal IR-tests have been executed. The objective of this paper is to provide a summary description of the development activities accomplished so far.

1 INTRODUCTION

Based on the overall requirements and needs for a future RLV TPS a detailed design trade-off has been performed within the frame of the pre-cursor project ULTIMATE. For that, various design principles like load and non-load carrying as well as box and stand-off designs have been studied in detail.

Finally the most promising concept was selected for the further development. This load carrying stand-off concept was designed in detail, thermo-mechanical analyses and ground test campaigns have been performed for the ULTIMATE project. All these works confirmed the excellent performance of the ULTIMATE metallic HC TPS design concept which was based on γ -TiAl HT components.

Since this material exhibits some disadvantages like low RT ductility for MERIT, a new beta-titanium alloy was selected. However, material properties are close together therefore the ULTIMATE design was adopted for MERIT.

In the following paragraphs the TPS panel design as well as the approach to verify the design and the performance of the metallic TPS by analyses and ground tests is described in some detail.

As already mentioned above, the European IXV experimental vehicle has been taken as reference configuration for the MERIT metallic TPS design. Based on heat fluxes derived from the aero-thermal analysis of the IXV trajectory and the maximum allowable surface temperature for the envisaged titanium alloy, possible MetTPS locations on the lateral surface of the re-entry vehicle have been identified (see red circle in Fig. 1 below).

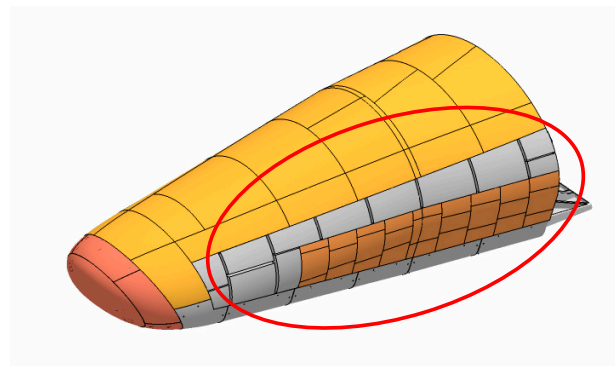


Fig. 1: IXV MERIT MetTPS Candidate Locations

METALLIC TPS PANEL DESIGN

The TPS panel design is based on a load carrying stand-off principle with a metallic casing (box) which forms the enclosure for the micro fiber insulation.

The outer surface is formed by a honeycomb sandwich panel with a total thickness of approx. 10mm and cubical cells made from thin foil gauges.

On two sides some overlapping of the outer face sheet material is foreseen to seal the panel interface in case of thermal expansion.

Ω -shaped stand-off's will introduce the outer mechanical loads into the substructure. This specific shape provides sufficient strength in normal direction and is somewhat smooth in lateral direction to allow for the relatively high thermal expansion of such large panel.

In the baseline design the stand-offs will be fixed by screws to the vehicle's substructure. Optionally a fixation by clip-on fasteners is being considered. Small tubes located in the inner part of the stand-offs are used to guide the tool screw locking.

A lower frame will provide a rigid interface to the substructure enabling to introduce here a sneak flow barrier and to fasten the sidewalls and the stand-offs accordingly.

Fig. 2 below shows the detailed design of a single TPS panel. This sketch is depicting the panel from the backside, i.e. from the substructure side without micro fiber insulation installed in the casing of the panel and with removed back-side wall.

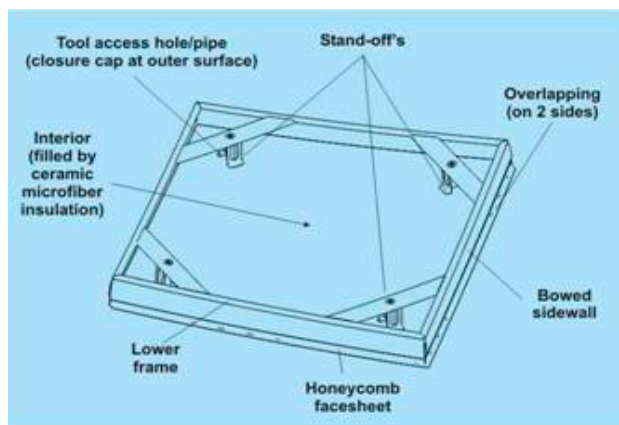


Fig. 2: MetTPS Panel Design

VERIFICATION APPROACH

For the MERIT metallic TPS development it was decided to verify the design and performances by analysis and additionally by testing.

Within the first development phase verification by analysis has been performed. The second step has been concluded recently which comprises the ground testing campaign.

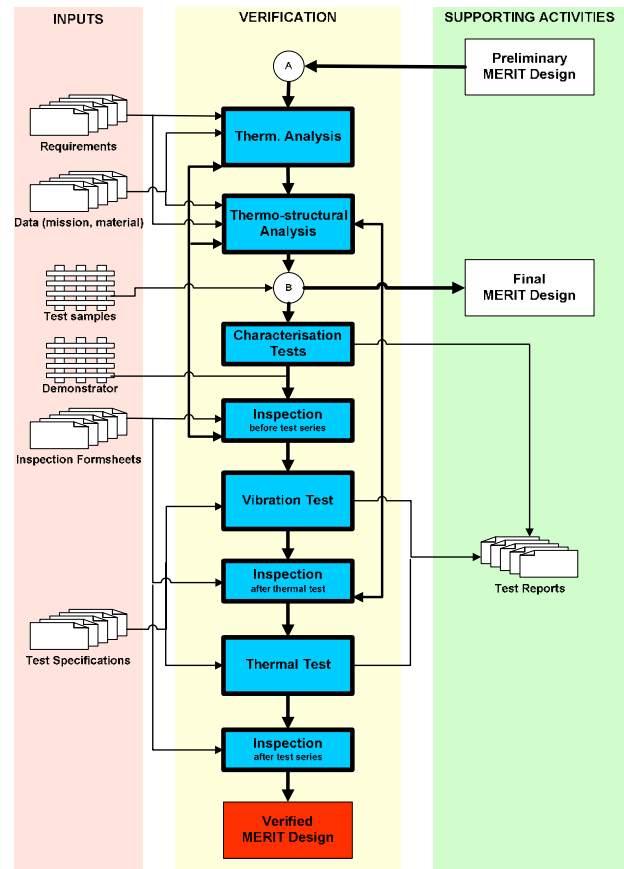


Fig. 3: Verification Sequence

The new β -titanium alloy which was selected for MERIT was characterized in the past only for temperatures up to around 600 °C. Therefore characterization tests were executed first to generate sufficient data for the range up to 900 °C as required for MERIT.

For ground verification the loads introduced by the most severe environments for such a TPS were checked. This was done in a sequential order, i.e. mechanical testing has been performed first and was followed by thermal ones.

Based on ULTIMATE experience the definition of ground tests on panels grouped as assembly (the so-called IXV demonstrator) has been done in order to verify the design and performance under realistic constraints, i.e. influence of neighbouring panels, heat transfer in lateral direction et cetera were investigated.

The test matrix for characterization and ground verification testing on assembly level is shown in Tab. 1 below. Fig. 3 above shows the entire verification sequence.

For analysis existing data for the lower temperature range were extrapolated and later verified by characterization testing.

	Test	Objective(s)	Test Article	Test Conditions
Characterization Tests	Emittance measurements	Determine integral emittance of panel surface	samples 20x20 mm	RT extrapolated for up to 900°C by a verified ASTRUM algorithm
	Bulging strength tests	Verify thermal resistance at high temperatures	samples ~100x100 mm	20 cycles of $T_{max} = 900^{\circ}\text{C}$
	Face sheet tensile strength	Determine mech. characteristics	Adapted standard samples	RT to 900°C
	SW Compression Tests	Determine SW compression characteristics	SW samples (standard)	RT to 900°C
	SW Bending Tests	Determine SW bending characteristics	SW samples (standard)	RT to 900°C
Demonstrator	Vibration (Array)	Determine resonant frequencies and verify mechanical behavior under vibration loads	7-panel array of 200x200 mm panels with 'T' interfaces	1g Sinusoidal sweep from 30 -2000Hz in two axes, and typical random launch power spectral density (PSD) as loading
	Thermal (Array)	Verify thermal behavior under simulated re-entry loads and measure global characteristics (of interfaces and sealing)	7-panel array of 200x200 mm panels with 'T' interfaces	20 cycles of $T_{max} = 900^{\circ}\text{C}$

Tab. 1: Ground Test Matrix

VERIFICATION BY ANALYSIS

THERMAL ANALYSIS

Objectives - There are two main objectives for the thermal analysis:

- Verification of the selected insulation system:

Here, the main focus was put on the substructure temperatures. The analysis' aim was to demonstrate that the substructure maximum allowable temperature is not exceeded for the given mission profile and flight trajectory.

- Input for thermo-mechanical analysis:

In order to support the thermo-mechanical analysis, the calculated temperatures were transferred to the structural (I-DEAS) model of the MERIT panel.

Requirements - The given requirements for the thermal analysis were:

- Maximum service temperature for HT-Ti alloy: $T_{max} = 900^{\circ}\text{C}$

This requirement is taken into account by choosing the appropriate location on the vehicle and using the respective heat fluxes, taken from the IXV aerothermodynamical analysis, presented below.

- Maximum service temperature for the fuselage shell: $T_{max} \sim 150^{\circ}\text{C}$

Thermal Loads and Environment

- The aero-thermal heat flux and pressure timeline used for the thermal analysis are presented in Fig. 4 (re-entry).
- Initial conditions for re-entry: 25°C

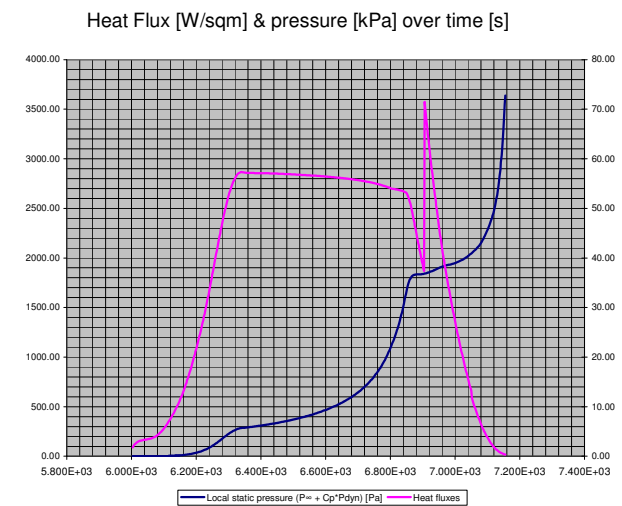


Fig. 4: Aero-thermal Heat-flux and Pressure Timeline

Thermal Simulation Tool - For the thermal analysis, the ESATAN software package was used to establish the MERIT TMM.

Thermal Modelling and Node Distribution - A three dimensional thermal mathematical model (TMM) was developed according to the panel design as described above.

For the fibrous insulation specific subroutines for this ASTRUM material were used.

Overall, the thermal FEM model contains a total of approx. 400 nodes. An example of the node distribution at the panel corner is given in Fig. 5 below.

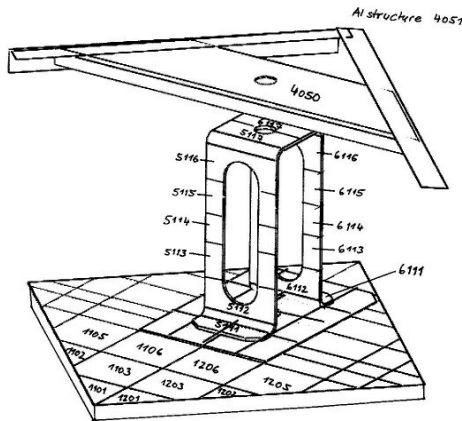


Fig. 5: Node Distribution (example)

Thermal Conductivity of fibrous Insulation Material - The thermal conductivity within the fibrous insulation material is calculated by approximation functions taking into account

- solid conductance within the fibres
- radiative heat transfer between the solid fibres as a function of temperature
- gas conductance in between the fibres as a function of temperature and pressure

These functions are based on thermal conductivity measurements performed in vacuum and different air pressures in the temperature regime from RT to 1300°C.

External Interfaces - Only the sub-structure area immediately underneath the MERIT panel was included. The interfaces to adjacent panels or sub-structure areas were considered to be adiabatic boundaries.

Boundary Temperatures - In the thermal analysis transient runs (for actual IXV mission) were conducted. The following boundary conditions were applied:

- SW upper face sheet: T_{initial} = 25°C
- TPS radiates against environment temperature of 269°C

Thermal Analysis Results

Maximum Temperatures - The maximum temperatures during the mission are reached on the outer face sheet of the upper honeycomb panel. Fig. 6 shows the temperature timelines for selected nodes.

The maximum calculated temperature is:

$$T = \sim 820^{\circ}\text{C at } t = 6900 \text{ s}$$

This temperature is below the specified maximum operational temperature for the β -Ti alloy (900°C).

Substructure Temperatures - The maximum substructure temperatures are reached shortly before the end of the mission. Fig. 7 shows the temperature timelines for selected nodes.

The maximum calculated substructure temperature is:

$$T = \sim 135^{\circ}\text{C at } t = 7800 \text{ s}$$

This temperature is below the specified maximum operational temperature for the vehicle's substructure (150°C), leaving a margin of 15 K.

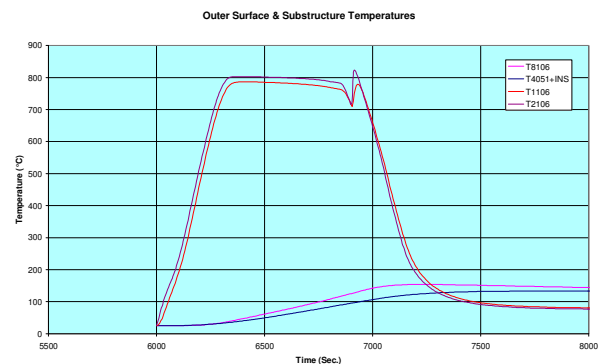


Fig. 6: Temperature Timeline (outer facesheet nodes)

The temperature gradient along the S/O for the point in time where the maximum temperatures occur is shown in Fig. 8.

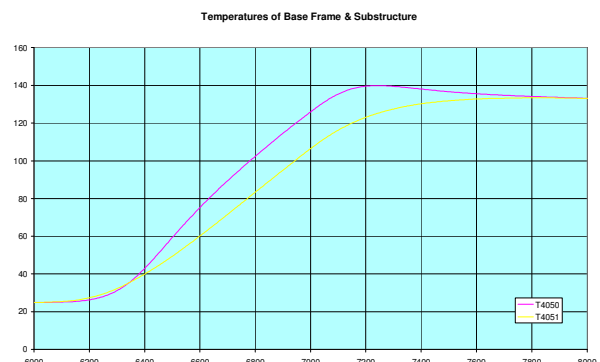


Fig. 7: Temperature Timeline (substructure and base frame)