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The SCX-01 atmospheric re-entry demonstrator and thermostructural ablative TPS flight experiment

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Abstract

Based on its long-lasting heritage on both rocket propulsion technologies and reentry vehicle, ArianeGroup developed since few years a novel family of 3D and versatile textile architecture. Once densified, the composite feature not only thermal and ablative properties but also thermostructural capabilities. This novel TPS concept will be tested on board the SCX-01 high speed re-entry demonstrator probe.

Keywords: *Space Case SCX-01, Naxeco©, reentry experiment*

Nomenclature

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TPS : Thermal Protection System

1. Space Case

1.1. Objectives

The SpaceCase project aims to propose a flexible and affordable in-flight test platform, as a reentry capsule, that shall allow leading experiments and technology validation of space components developed by Space stakeholders during a flight. A considerable panel of environmental solicitations can be proposed, as this SpaceCase capsule would be able to be integrated in heavy launchers as well as on sounding rockets, depending on the customer's experiment required environment and associated data needed to be recovered. The design of the customer's experiment itself could be supported by the SpaceCase project team.

Current opportunities to realize a space flight are few, expensive, and imply a very long lasting preparation. The SpaceCase project is the opportunity to propose a new test mean, which would fill this gap and be part of space actor's roadmaps when dealing with space products and technologies development, and be considered as a major partner for in-flight experimentations

Figure 1 : Artist view of a SpaceCase vehicle during Earth re-entry - Credit ArianeGroup

1.2. Atmospheric reentry experiments

ArianeGroup R&T initiated in 2021, with the support of the Aquitaine Region and the innovation center Way4Space the development of the first SpaceCase demonstrator. The SC-X01, for SpaceCase eXperiment number one (1), was designed to demonstrate the capability to consider this kind of space system as a passenger during a nominal launch. This demonstrator includes basic functions such as the ability to generate and retrieve through telemetry experimental data collected during the flight, the capability of the capsule-like platform to integrate new Thermal Protection System (TPS) material and architecture, and the compatibility with launcher interfaces and constraints, as well as regulation constraints (i.e. safeguard). SC-X01 development will be finalized 2nd semester 2022 and ready for the flight test.

Figure 2 : SpaceCase demonstrators

A second demonstrator (named SC-X02) is initiated via European partnership to develop additional functionalities linked to the commercial demand to physically recover the embedded payload. Then, the SC-X02 capsule will be the support for the development of parachute systems, among other capacities. It also aims at aligning proper objectives with environmental objectives, integrating materials whose manufacturing processes are constrained by specific "green" requirements. It is planned to validate the descent system with a drop test from a helicopter.

These two demonstrators would allow to validate the critical technologies needed for potential customers (agencies, private companies, laboratories and universities) to raise their own product Technology Readiness Level (TRL). In particular, the step to make from TRL6 to TRL7 implies an experiment in a realistic environment, which would be affordable thanks to the SpaceCase project.

1.3. SCX-01

The SC-X01 demonstrator is a 700 mm diameter and 300 mm height re-entry capsule weighing less than 45 kg and is one of the experimental payload selected by ESA on the 11th of February 2022 [1] to fly on Ariane6 inaugural flight. It will be separated from the launcher using an EOS BB8 ejection system from the French company MecanoID [2].
To reduce development schedule, the selected shape was initiated by a MuseC (Hayabusa) like shape that was also the selected frontshield shape made of Naxeco Resine® that was developed in cooperation with ESA during the PreHead [5] project aiming at demonstrating our capability to manufacture a carbon/resin structural frontshield in one single piece (see [3], [4], [5]).
The SCX-01 final aerodynamic shape is now called AGSCX1 aeroshape, deriving from the initial MuseC it features improved aerodynamic stability.
Moreover, such a heatshield is compliant with the stringent constraints of a Mars Sample return mission in terms of resistance to the most sever aeothermal environment but also in term of MMOD while optimized in mass.
Indeed, Naxeco Resine® has sufficient mechanical characteristics even at high temperature that allowed designing a structure-free front shield. The front heat shield has been thought in a way it can bear the reentry mechanical loads without the need of underlying cold structure. The mass saving and the assembly cycle reduction are obviously huge advantages compared to state of the art solution.

The SCX-01 will, then, be the first reentry capsule using a thermostructural ablative and charring shield connected to the rest of the vehicle thanks to titanium screws instead of being bonded on a substructure.

The backshield is made with the lightweight carbon resin Asterm® thermal protection glued onto an internal 3D printed structure. Asterm® was also specially developed by ArianeGroup in cooperation with ESA for sample return vehicles and can sustain heat-fluxes up to 15MW/m². The antennas are the same as the ones flying on Ariane launchers and are protected by radio-transparent Norcoat® 4000 thermal protection.
Even if SC-X01 re-entry velocity will be at about 7.8 km/s, such an architecture was selected as it is representative of a hypervelocity sample return capsule entering the atmosphere at 12 km/s. SC-X01 is thus a first step to prepare development of a hypervelocity re-entry vehicle in Europe such as the proposed demonstration mission HEARTED [6] proposed by ESA and supported by ArianeGroup.

The avionics package was designed internally and some parts (e.g motherboard) manufactured in the Aquitaine Region. SC-X01 will be turned ON just after release from Ariane6. Monitoring thermal protection will be done by Thermal Plugs embedded in the Naxeco® and Asterm® as well as recessions sensors. Trajectory will be monitored by an Inertial Measurement unit and a GPS system. Data will be hopefully recovered by telemetry using the Iridium system starting before Entry Interface Point, at 120 km altitude, and during the entry up to the splash down in the South Pacific Ocean. Communication black-out will be managed by on-board memories and by several stage re-emission for redundancy.

The monolithic 3D printed refractory metal structure, as shown in the following picture, is used for transfering the loads from the ejection system to the vehicle during the ascent phase, support the back shell TPS and serves as interface for the avionic bay. The internal toroidal volume delimited by the 3D printed substructure can be filled with PU foam to insure floatability.

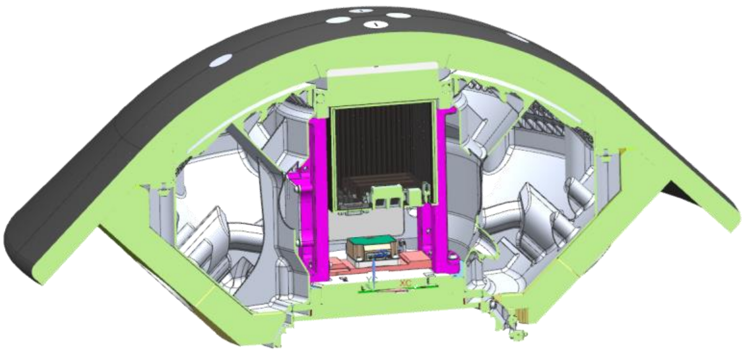

Figure 3: CAD model of the SC-X01 - Credit ArianeGroup

2. Thermostructural TPS

ArianeGroup developed since few years a novel family of 3D and versatile textile architecture for heatshield of atmospheric reentry capsules.
At the base of the composite materials, a 3D fibrous preform was selected to either follow carbon densification by chemical vapor infiltration or resin transfer molding accordingly to the severity or topology of the reentry mission.
The key feature of this technology is its ability to allow the manufacturing of a monolithic and structural heat shield which can offer new design approaches for Earth Reentry probes as well as probes for entry in more demanding environment such as for example a potential future Ice Giants mission One type of each material families was characterized under high velocity impact (HVI) shot and some impacted samples subsequently submitted to arc heated plasma torch testing. The paper describes the materials specificities and how a monolithic full-scale heat shield was manufactured, tested and prepared for a flight demonstrator on Ariane6 maiden flight with the SCX-01.

2.1. TPS Materials features

The material preform relies on an innovative and low cost technology called Naxeco® leading to 3 dimensional fibrous architectures. The fibers are taken from an aeronautic grade of synthetic ex-PAN (PolyAcriloNitrile) route, insuring a minimum of sustainability of the fiber production.
In the Naxeco® process, tows of carbon fibers are stretch-broken, then aligned to form layers which are webbed, one above the other, along two different directions (usually ± 45°, or 0-90°) to constitute rolls of raw material.
The Naxeco® preform consists in a stack of these raw layers constituting either flat plates or a stack of tape-wounded layers around an axi-symmetrical shape *or assemble as a flate plate preform*.

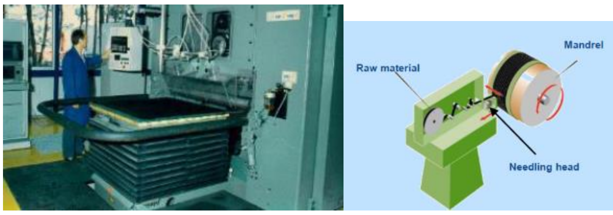

Figure 4: Genuine facility configurations for building flat Naxeco® preform (left) or axi-symmetrical parts (right)

As each layer is added, a needling board with hundreds of specific hook-fitted needles passes over the raw dual-layers felt and punches the tape to carry carbon filaments through and perpendicular to the stack up of layers, creating the third direction of reinforcement.

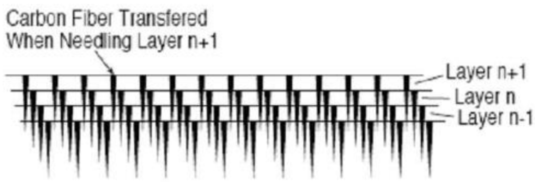

Figure 5: Generation of 3D carbon fiber architecture with a punch -needling process

Each volume of the preform has received the same amount of transferred carbon filaments providing the preform construction with good through-the-thickness homogeneity.

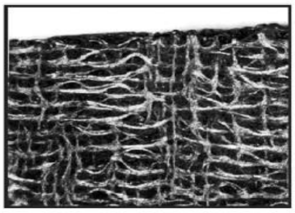

Figure 6: Micro-section of a 3D carbon fiber preform ([4])

During the ESA PREHEAD project, the needling process has been improved by a needle head automatic placement which allows the assembling of raw tapes on any 3D shape and even non-ruled ones.

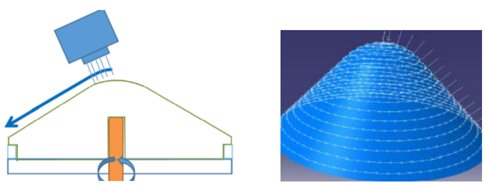

Figure 7: Newly developed automatic needle head placement (left) applicable for any 3D non-ruled heat shield shape (right)

The preparation of the machine trajectory commands for the punching head is done in the same design CAD environment, thereby allowing the simulation and the validation of a virtual manufacturing process prior to launching it in the physical world. This automatic raw carbon fabric assembling process was successfully demonstrated through the manufacturing of a scale-one (1m diameter) monolithic 45° sphero-conical heat shield preform at the near net shape level.
The second advantage of this 3D consolidated preform is its compatibility with two different densification routes namely:

- a polymeric thermoset transfer [10]:
- a chemical vapor infiltration (CVI)

detailed in the sections hereunder.

2.2. Naxeco® Resin

Under the ESA PREHEAD project, ArianeGroup mainly focused on the improvement of an efficient resin transfer process, to create a new composite based on the 3D ex-PAN carbon reinforcement Naxeco® and a REACH-compliant proprietary phenolic resin to form the Naxeco Resin® material. The feasibility of this particular resin transfer process up to the curing cycle, with this specific phenolic resin was first validated and checked at a small scale with simple raw and thick plate.

Figure 8: RTM and curing cycle validation for the Naxeco® resin material at small scale and simple plate (material aspect right after curing cycle)

During this preliminary step different process parameters were explored (transfer time, resin mass rate, temperature cycle, vacuum pressure and number of pressure valves…) with the target to assess the effect on the final composite density and homogeneity. After several RTMs at different scale and on different aspect ratios and even 3D preforms, the process appears to be reproducible. Composite final density ranging from 1.0 to 1.4 g/cm^3 can be easily achieved. A through-the-thickness (TTT) density gradient can also be generated with a larger porosity on the inner face, thereby tailoring the material to optimize the heatshield thermal performance. Consequently, the outer face is presenting the larger density for better ablation performance coupled with lower conductivity on the inner side. The benefit on the mass budget compared to standard homogenous thermal protection system (TPS) is particularly interesting for high aerothermal energy mission.

Finally, thanks to the specific fibrous microstructure and a third direction reinforcement, the final Naxeco® Resin composite presents sufficient mechanical strength and rigidity up to the point that a load bearing structure is not required anymore. With the Naxeco® Resin composite enhanced thermomechanical properties new TPS architectures (mechanically functionalized) can be established with the sake of even better aerial mass performances compared to historical thermal protection materials.

Figure 9: Characterization of mechanical properties and assembling joints for the Naxeco® Resin

The preliminary design and laying out analysis also indicates that the thermo-structural Naxeco® Resin solution allows a reduction of integration complexity and cost while giving more internal volume for the payload with similar overall mass budget compared to state of the art heatshield architectures with an ablative material bonded onto a low density structure material.

2.3. Plasma test caracterisation

In order to evaluate the behavior of the Naxeco® based material and the benefit of the 3D reinforcement on the thermal and ablative behavior of pristine composite, arc heated plasma test campaigns was conducted at DLR's L3K torch under aerothermal stagnation point conditions representative of a Mars Sample Return mission on Earth, in ArianeGroup facility to test shear stress effect and at IRS facility for radiation and chemistry interaction studies.
Due to the criticality of potential MMOD impacts in view of planetary protection requirements for an Earth-return from Mars, the thermo-erosive behavior of pre-impacted samples (at Fraunhofer EMI, §3.) was also investigated.

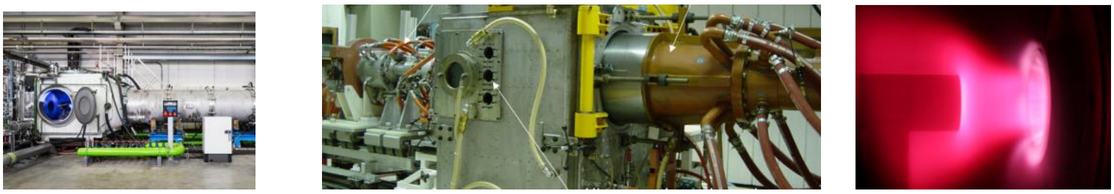

Figure 10: DLR L3K arc heater (credit DLR, left), ArianeGroup plasma torch (center), PWK1 (credit IRS, right), used to investigate the thermos-erosive behavior of the materials

The test conditions are summarized in Table 1.
The samples were equipped with type C and K thermocouples located at different depths. Precise thermocouple locations were confirmed by X ray photographs to rebuild the internal thermal gradient along the exposure and during the cooling down.

Table 1: Operated test conditions in the arc-heated plasma torch

Test ID	Duration (s)	Configuration	Stagnation pressure (bar)	Cold wall Heat flux (MW/m2)	Exposed Sample size (mm)
L3K-1	23	Stagnation point	2.1	6.1	50 diameter
L3K- 2	15	Stagnation point	9.1	13.6	50 diameter

The measurements in L3K showed good repeatability on both Naxeco materials which indicates a safe thermal and ablation response of the composites.
Even at high heat flux and flight representative heat loads the materials experienced a very small ablation compared to what was expected based on pre-test simulations. At high heat flux, the Naxeco Resin presented a superficial delamination due to the internal pyrolysis gas outgassing. This results in a localized swelling which ends with a spallation of the first layers only. The thermal shock at the entry of the sample in the plasma is likely to be the root cause of this phenomena. Under smoother flight kinematic conditions, the natural permeability of the charred material would be sufficient to avoid this internal pressure rise which was later confirmed by simulation.
For both pre-damaged materials, the impact crater remained geometrically stable and did not lead to amplification of the ablation neither to any tunneling effect (Figure).
Due to the lack of elementary characterization on virgin or charred materials, very preliminary thermo-ablative simulations were performed and were limited to a temperature driven approach.
The difference between the measured and calculated temperatures for a thermocouple (TC2) located at 6 mm depth is presented in Figure (where a positive delta-temperature corresponds to an underestimation of the model).

It is then noticeable that despite the presence of an off-centered crater, the larger over-estimation (around 100°C) of the model applied to the pre-impacted sample. This indicates that the damaged material is less conductive in the vicinity of the impact. This HVI effect on thermal diffusivity could be explained by local micro-cracking and matrix-fiber de-bonding.

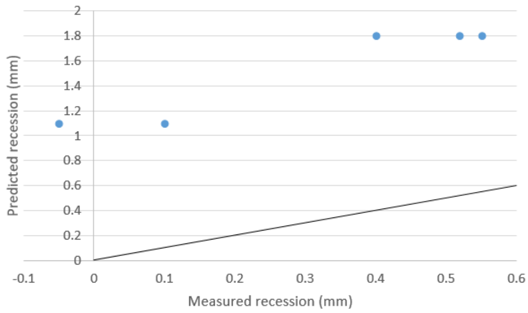

Figure 11: Correlation between predicted and observed recession according to a preliminary thermos-erosive model

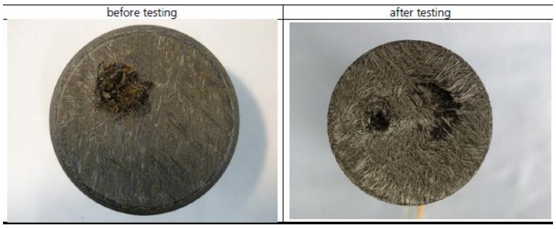

Figure 12: Comparison of pre-damaged L3K sample with HVI of the exposed surface before the plasma exposure (left) and after plasma exposure (right)

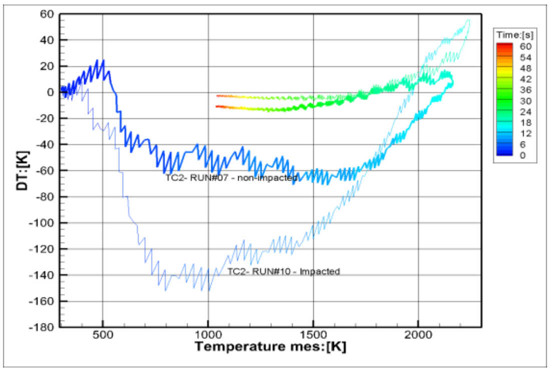

Figure 13: Measure-Simulation comparison for a 6 mm depth thermocouple (TC2) of impacted and non-impacted sample

3. Scale 1 Monolithic Heat shield manufacturing for a flight demo

The ESA PREHEAD demonstrator was initially manufactured to be representative of a Sample Return mission reentry capsule and adopted a 45° sphere-conical shape with a 1m base diameter as depicted in *figure 14.* Further, the preform was densified with proprietary phenolic resin and the transfer process to constitute a 3D reinforced Naxeco Resin thermos-structural heat shield. For the SCX01 application a 700mm-diameter heatshield will be cut out of the original heatshield demonstrator.
Ariane 6 maiden flight will deliver the SCX01 demonstrator on a reentry trajectory with velocity of the class of 8km/s at 120 km of altitude and shallow flight path angle. The expected conditions will obviously not be in the range of interplanetary reentry ones, but will constitute a challenging proof of

concept not only of a monolithic Thermo-Structural Protection-System (TSPS) but also of the end-to-end vehicle design and production.

Figure 14: ESA PREHEAD's 1m base diameter heat shield 3D fibrous preform demonstrator after needling consolidation

Figure 15: ESA PREHEAD's 1m base diameter heat shield 3D fibrous preform demonstrator after phenolic resin transfer

4. Numerical analysis

4.1. Model characteristics

The Front Shield-Backshell and structure are justified with a thermoablative-mechanical analysis using a 3D finite element simulation on a 30° section of SC-X01.

The Naxeco Resine® Front Shield, the insulating foam, the Inconel structure, Asterm® back cover parts and the glue, Fly-Away part of the EOS, cover of the avionics bay and the Norcoat liege® thermal protection at the base of SCX-01 are included in the sectorial finite element model.

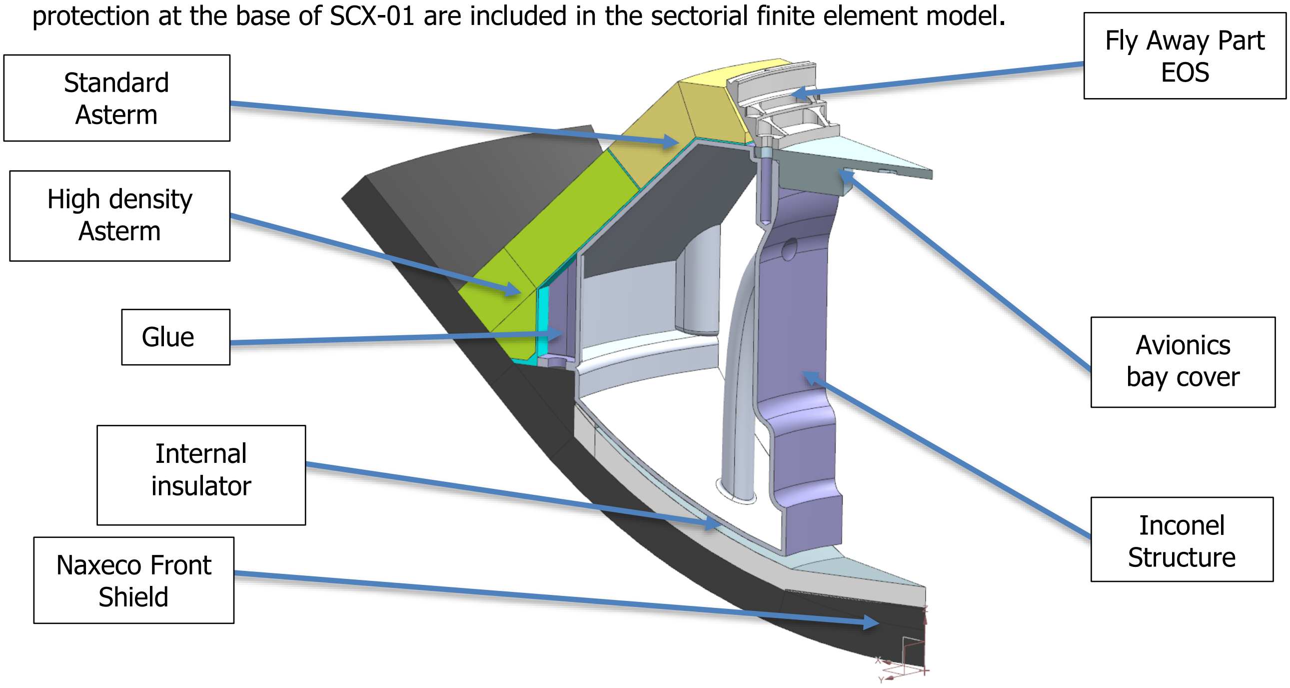

Figure 16: SC-X01 re-entry model

Applied fluxes are computed using the thin film coefficient approach [7] estimated all along the expected trajectory.

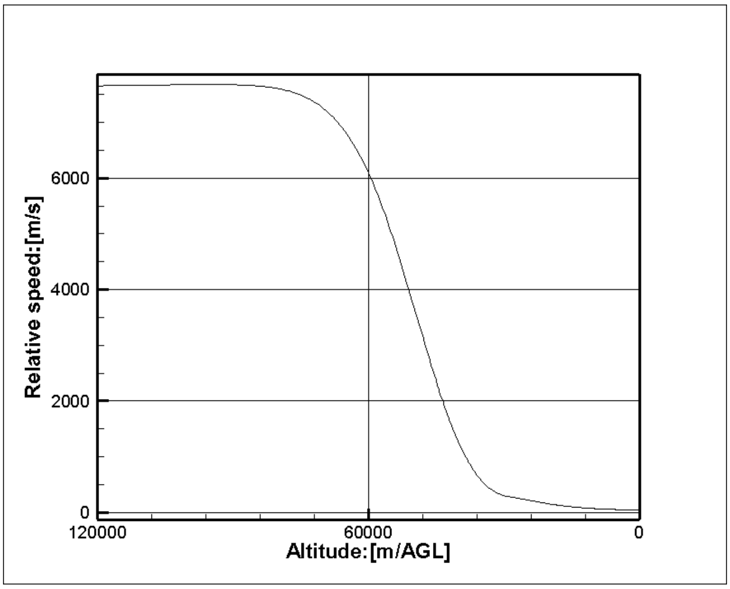

Figure 17: Expected re-entry trajectory

The dimensional mass and heat transfer coefficients at the wall are then given by:

$$C_M = \rho_e u_e St_M$$

$$C_H = \rho_e u_e St_H$$

where ρe and ue are the density and velocity at the boundary layer edge, and StM and StH are the Stanton numbers for mass and heat transfer. In a simplified approach, the environment and material response are estimated in an uncoupled way. The dimensional heat transfer coefficient

is then corrected to account for blockage induced by pyrolysis and ablation gas blowing of Naxeco Resin® or Asterm® materials.

The correction is applied in Samcef Amaryllis with the nonblowing environments from in-house engineering aerothermal simulation. The blowing correction follows from [8]:

$$C'_H = C'_H \frac{\ln(1 + 2\lambda B'_c)}{2\lambda B'_c}$$

where $C'H$ is the corrected heat transfer coefficient, and λ is the blowing reduction parameter. B'c

is the dimensionless blowing rate of the pyrolysis gases and ablation products and is given by

$$B'_c = \frac{\dot{\mathrm{m}}\mathrm{c}}{C_M}$$

where mc is the mass flow rate, λ is set to 0.5 for laminar flow as done in previous studies [9].

The wall temperature (Tw) is computed with a surface energy balance model as illustrated below:

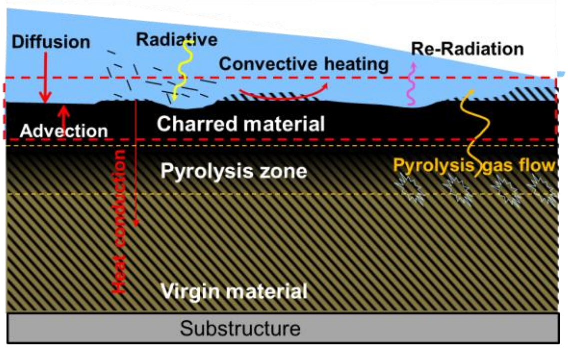

Figure 18: Surface energy balance scheme

Heating and cooling energy fluxes from the environment and the material are shown. The surface energy balance at the wall by:

$$q_{cond}^{out} = q_{conv}^{in} + q_{diff}^{in} + q_{adv}^{in} + q_{rad}^{in} - q_{adv}^{out} - q_{rad}^{out}$$

where $q$out cond is the conductive heat flux from the surface into the material, $q$in conv is the convective heat flux from the boundary layer to the surface, $q$in diff is the heat flux due to diffusion from the boundary layer to the surface, $q$in adv is the advective heat flux due to the transport of pyrolysis and ablation products gases from the material to the surface, $q$out adv is the advective heat flux due to transport of gases to the boundary layer, $q$in rad is the radiative heat flux on the surface from hot gas in the boundary layer and the environment, and $q$out rad is the radiative heat flux emitted from the heat shield surface. The resulting conductive entry flux in the heat shield is:

$$-(\overline{\overline{k}}.\overrightarrow{\nabla T}.\overrightarrow{n}) = C'_H(Hr - Hw) + \dot{m}c(hc - Hw) + \dot{m}g(hg - Hw) + \alpha q_{rad}^{in} - \varepsilon w\, \sigma\, T_w^4$$

The surface energy and mass balances allow for the computation of Tw and Hw. In the B′ based boundary condition, CH, hr, $q$rad, and the pressure at the wall (pw) are obtained from the aerothermal uncoupled engineering method.The pyrolysis mass blowing rate ($\dot{m}g$) is computed by integrating the pyrolysis mass, and transport equations by the thermal response code. The pyrolysis enthalpy ($h$pyro) is computed under chemical equilibrium given the elementary composition of the pyrolysis gas.

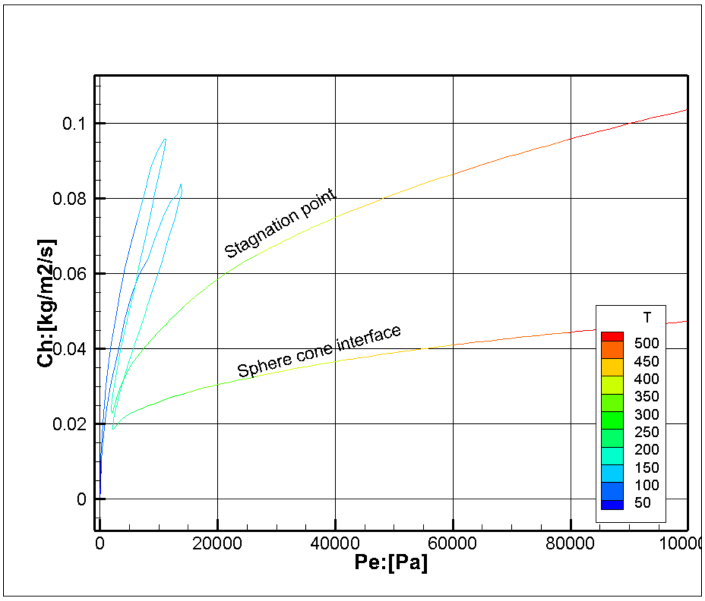

Figure 19: Heat transfer coefficient and BL edge pressure at stagnation point and at the sphere cone interface on the front shield

The following hypotheses used for the thermoablative study are:

- Naxeco and Asterm are modelled using a pyrolysis behavior
- The Naxeco Front Shield as well as Asterm are considered ablative (chemical ablation modelled)
- Back cover aerothermal fluxes are applied to the external face of both ASTERM pieces and EOS.
- Radiative contact between structure and insulative foam

4.2. Thermochemical results

The temperature field at maximum of dynamic pressure and at splashdown is given in the following figures.

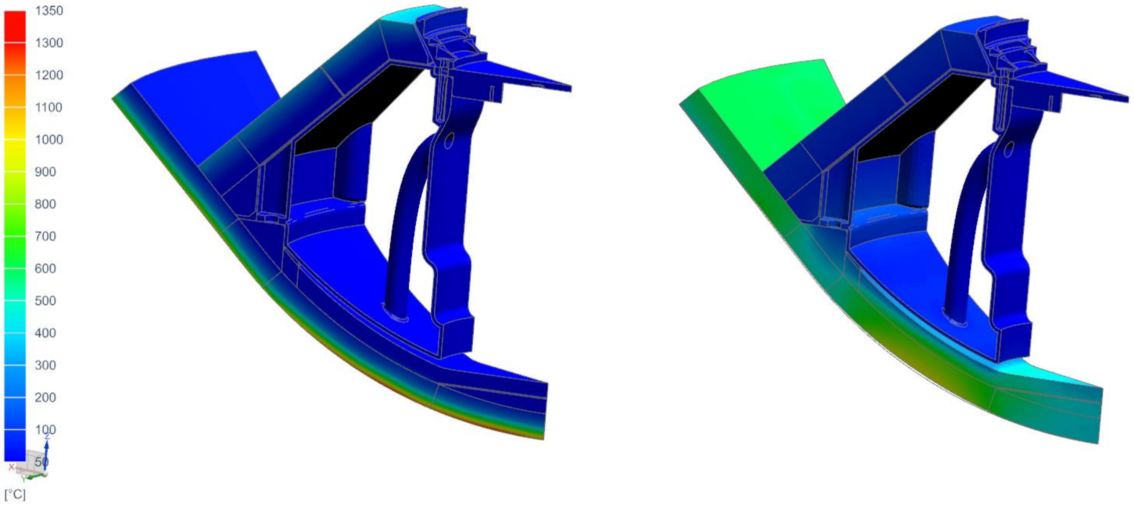

Figure 20: Temperature mapping at maximum dynamic pressure (left) and at the end of the mission (right)

Under the aerothermal loads the resin will start to decompose and volatize leaving a dense charred layer. This pyrolysis phenomenon is taken into account through a simplified decomposition mechanism and the resulting density of the material can be predicted. The following figures focus on the generalized density gradient inside the front shield maximum of dynamic pressure and at splashdown.
The generalized density variable represent the pyrolysis index and is expressed as follow:

$$\xi = \frac{\rho - \rho_c}{\rho_v - \rho_c}$$

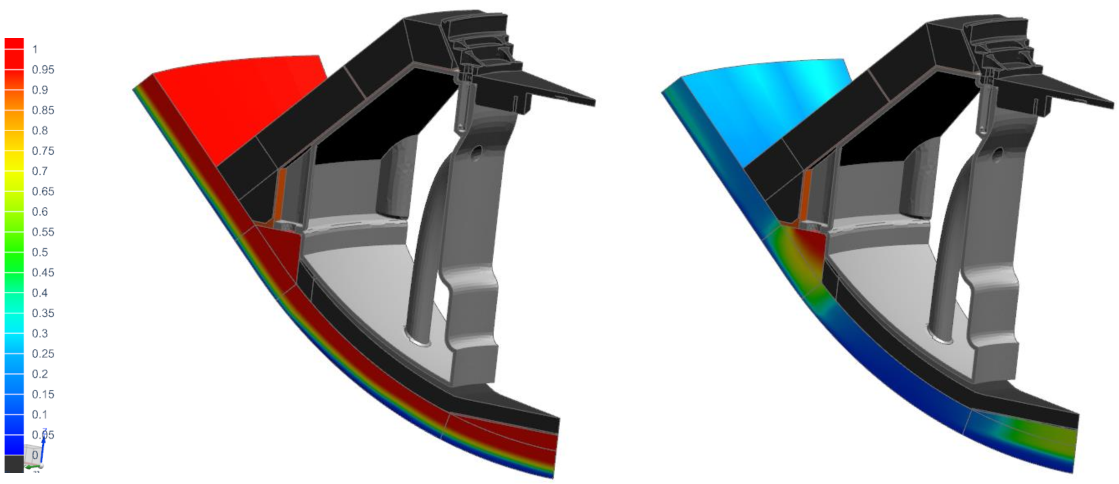

Figure 21: Generalized density mapping at maximum dynamic pressure (left) and at the end of the mission (right)

At the altitude of maximum dynamic pressure and therefore mechanical loads, the region of the mechanical interface of the front shield remain virgin and at relatively low temperature insuring a safe behavior of the assembly.
In parallel of the pyrolysis, a chemical interaction between the material surface and the plasma takes place which is described here as oxidation and carbon volatilization. It results a surface recession whom the rate depend on the oxygen mass flux, surface temperature and pressure.
The maximum ablation occurs downstream the sphere cone transition due to a slight increase of the heat transfer coefficient with coincide with the reacceleration of the flow.

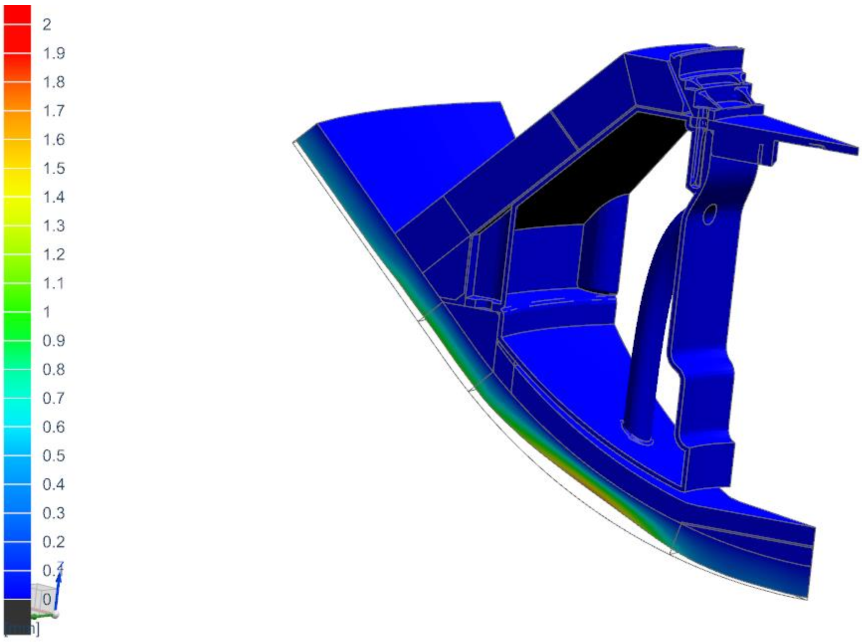

Figure 21: Chemical recession field at the end of the mission (X5 amplification coefficient is applied to the surface displacement)

4.1. Thermomechanical results

Among the various flight-worthiness justification of the capsule during the ascent phase and reentry, on major concern was the behavior of the mechanical junction between the ablative front heat shield and the back cover structure.
The junction design between the Naxeco Resine® front shield and the substructure had to:

- account for the different thermal expansion of the two parts as the internal temperature is rising
- resist to the longitudinal expansion of the material stack
- allowing relative sliding during re-entry phase without any radial blockage
- avoid any longitudinal gapping during dynamic loads of the ascent phase

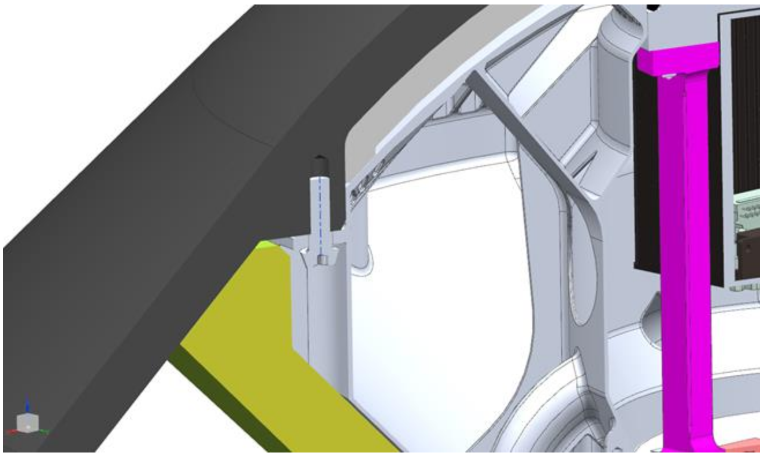

Figure 22: Close view on the mechanical interface between the substructure and the Naxeco Resin® heatshield)

On top of the internal constraints, the whole capsule must withstand the outer mechanical loads:

- longitudinal and lateral aerodynamic acceleration
- non uniform pressure loads on the front shield

Through a one way coupling thermal-mechanical scheme, the 2 latest opposite requirements could be met by a fine-tuning of the screw tightening. This numerical analysis have been fed by elementary (tensile test) and technological characterization (torque-tension-relation) to investigate:

- tensile behaviour and strength
- friction coefficient between screw and Naxeco Resin®
- long term creeping

Moreover, the design of the radial gap between the structure and the Front heat shield has been set so that the predicted radial displacements between the two parts is smaller than the minimum gap accounting for manufacturing tolerance and a dedicated policy margin.

The one way coupling algorithm transfer the temperature and the pyrolysis index to the mechanical solver so that it was possible to capture the nonlinear behavior of the Naxeco Resine material. As the temperature is increasing, the material tends to expand as due to the temperature effect but once the resin reaches its first decomposing plateau, the material start to shrink. This phenomenon, which overlaps with the surface recession, is shown on figure 23.

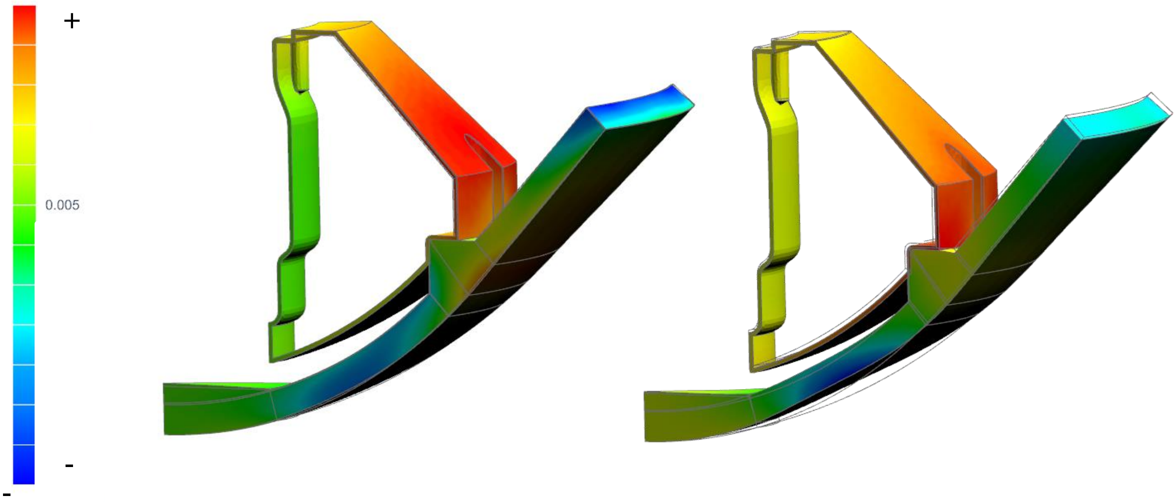

Figure 23: Thermomechanical radial displacement after the pic heating (left) and at the end of the mission (right) (x10 amplification factor is added to the displacement field)

5. Flight experiments and perspectives

The SCX-01 as the first flight demonstrator of future microgravity and reentry experimental flight bed system will be capable of monitoring the environment but also the material response through a dedicated avionic and sensors package. Indeed, the front heat shield is embedding 2 thermal plugs with 2 thermocouples each and 2 recession electrical sensors (supplied by Demokritos). The back cover in Asterm® will receive a unique plug with four thermocouples so that heat loads can be precisely monitor in case of an inverse reentry.

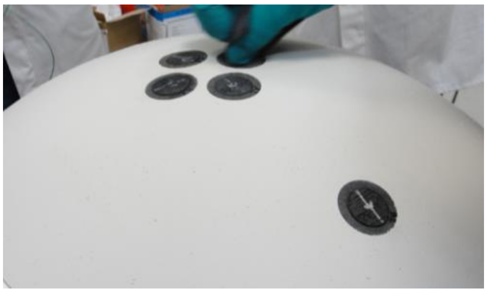

Figure 23: Integration of the thermal sensors on the front shield

For Ariane 6 maiden flight, on which SCX-01 will take place, the conditions at separation and subsequently the reentry trajectory could not be negotiated with the launcher operator. The telemetry scenario is therefore based on a satellite communication with the Irridium constellation.
The following communication timeline has been optimized minimize the risk to lose data packet. The different TM modes will use of the on board memories capabilities but the black out and the final descent phase might not play in the favor of an high telemetry quality signal.
That's why, AGS is already working on two aspect for the future SCX-02 experimental platform:

- Avionic miniaturization and efficiency
- Parachute system

The latest is of interest for either recovering the capsule and its experimental payload or increasing descent time for increased transfer data budget.

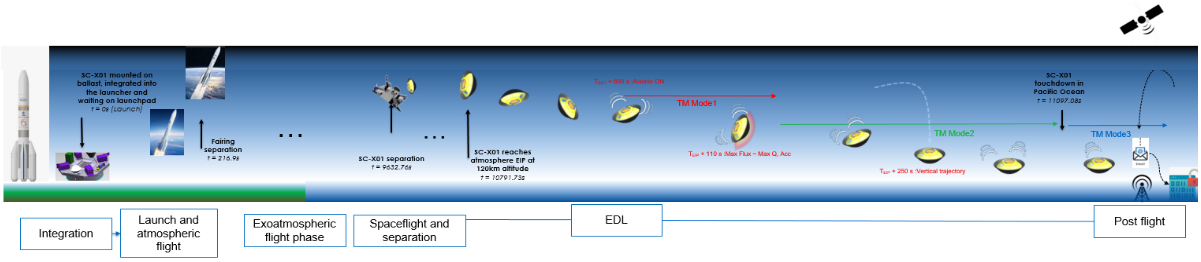

Figure 24: Telemetry timeline optimization

Figure 15: Final phase of integration for the SCX-01 flight re-entry demonstrator embedding a thermostructural TPS on Ariane6 FM1

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