Appendix Q

Multi-dimensional Ablation and Thermal Response Program for atmospheric entries

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Abstract

The method presented herein couples a reduced order aerodynamic model (HyFlow) and an ablative material response code (ARC) to produce three dimensional estimations of the external flow characteristics and the internal TPS behaviour during an atmospheric entry. Both codes have been internally developed at Strathclyde University.

The ablative material solver is a unidimensional code, based on the explicit finite difference method which has the capability of evaluating the internal temperature gradients, the pyrolysis phenomenon progression, the change of state and density in the material and the production of pyrolysis gases. If the material B tables are available, the code can also calculate the charred material mass flux and the material recession rate.

In this methodology, the ARC program is applied on a grid of points surrounding the entire geometry to produce an evaluation of the TPS behaviour on the whole spacecraft surface. The coupling of these two codes has been designed to produce fast three dimensional analyses to better evaluate the differences introduced by small changes in the spacecraft trajectory and geometry or in the TPS composition. This methodology has been previously utilized to evaluate both Earth and Martian entry trajectories (Stardust and Pathfinder missions). For this workshop, the study of the ARD re-entry is presented with a comparison against results generated by higher order codes and flight data. This case is of particular interest because it presents an angle of attack which makes the case non axis-symmetrical. The approach presented herein always performs three dimensional calculations of the atmospheric entry, therefore the symmetry of the flux or the lack of this symmetry does not influence the computational time. Consequently, complex non symmetric cases are just as easy to simulate as symmetric ones. The code is also able to simulate a capsule made by different TPS of different thickness. The entire re-entry trajectory run can vary from a few minutes to half an hour depending on the trajectory duration and the spacecraft mesh; the ARD re entry takes around 20 minutes for a trajectory duration of 240 s and for a mesh formed by around a thousand vertices.



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Multi-dimensional Ablation and Thermal Response Program for Re-Entry Analysis

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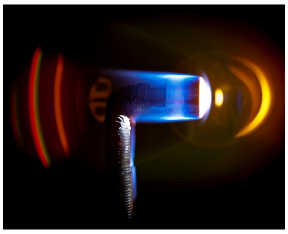
Non-Reusable Thermal Protection Systems: Ablative Material

- High number of different materials.
- Pyrolysis.
- Long and expensive design process.



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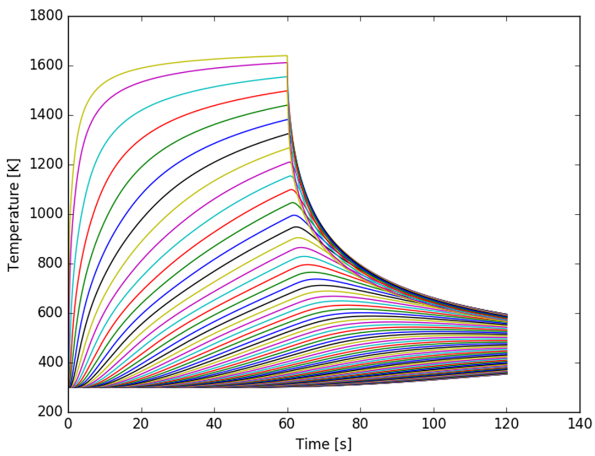
Material thermal response code (1/2)

- One-dimensional, based on finite differences.
- Calculates the temperature gradients.
- Evaluates the pyrolysis progression.
- Determines the change of state and density in the material.
- Computes the production of pyrolysis gases, the charred material mass flux and the surface recession rate.
- Applied on geometry vertices to produce three dimensional assessments.



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Material thermal response code (2/2)

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Main equations:

- Arrhenius equation: degradation

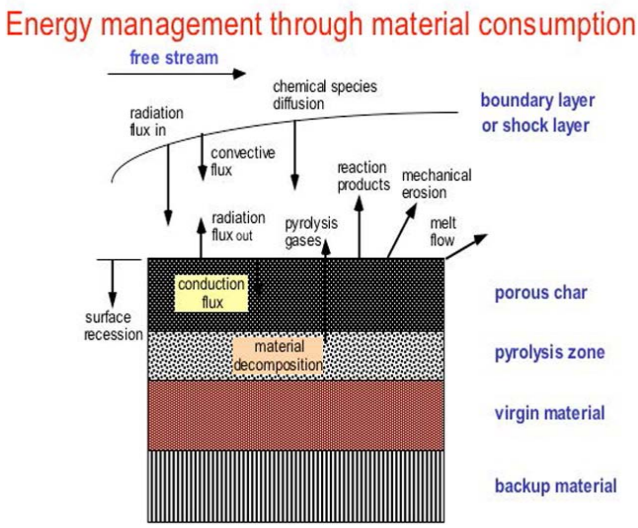
$$\frac{\partial \rho_i}{\partial t} = A_i \left(\frac{\rho_i - \rho_{ic}}{\rho_{iv} - \rho_{ic}} \right)^{\phi_i} e^{-E_i/T}.$$

- In depth energy balance:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x} \right) + (h_g - \bar{h}) \frac{\partial \rho}{\partial t} + \dot{S} \rho c_p \frac{\partial T}{\partial x} + \dot{m}_g \frac{\partial h_g}{\partial x},$$

- External surface energy balance:

$$\rho_e u_e C_H (H_r - h_{ew}) + \rho_e u_e C_M [\Sigma (z_{ie}^* - z_{iw}^*) h_i^{T_w} - B' h_w] + \dot{m}_c h_c + \dot{m}_g h_g + \alpha_w q_{rad} - F \sigma \epsilon_w T_w^4 - q_{cond} = 0.$$



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Aero-Thermodynamic Model

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- In house reduced order code instead of a more commonly used CFD tool.
- Based on a combination of compression and expansion panel methods.
- Assumption of thermally and calorically perfect gas.
- Can be used for the entire entry trajectory (prediction for both free-molecular flow and continuum flow conditions).
- The Reynolds analogy is employed for the determination of the heat flux on the entire geometry but the area around the stagnation point where the Fay-Riddell formula is utilized.

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Code Coupling

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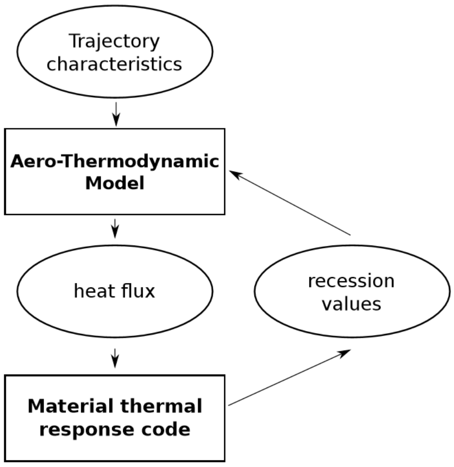
The steps in the simulations are:

- HyFlow estimates the three dimensional heat flux around the geometry for first time instance during entry.
- The one dimensional material code is applied on every geometry vertex.
- An evaluation of the material behaviour on the entire geometry is generated.
- The recession values are implemented and the new geometry is created.
- The same steps are repeated until the completion of the entry trajectory.



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Material model

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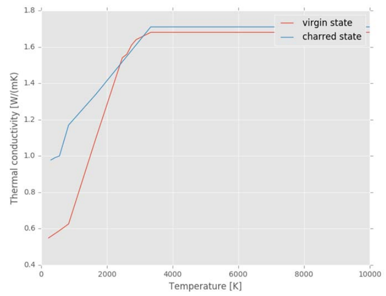
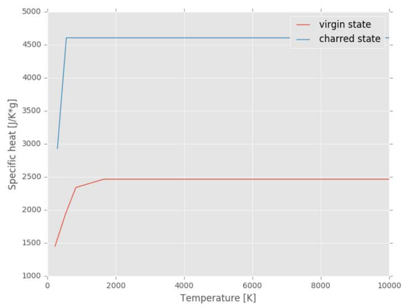
Thermo-chemical characteristics:

- Arrhenius equation terms (pre-exponential factor, activation energy, decomposition reaction order).
- Virgin and charred density.
- Virgin and charred thermal conductivity as a function of temperature.
- Virgin and charred specific heat as a function of temperature.
- Enthalpy of formation and pyrolysis





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Test case: The Atmospheric Re-entry Demonstrator ARD

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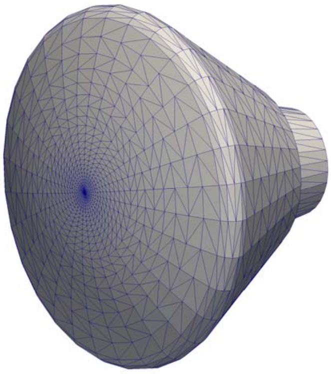
- Material: ALEASTRASIL
- Thickness: 20 mm

Time instances for the entry trajectory:



time (s)	velocity (m/s)	altitude (km)
4886.56	7554.83	78.7536
4912.72	7470.65	74.4595
4930.99	7329.8	71.4605
4952.04	7073.58	68.0047
4970.82	6786.07	64.9223
4990.45	6467.55	61.7003
5012.07	6097.09	58.1505
5021.5	5924.88	56.603
5040.82	5514.98	53.4314
5060.58	4949.71	50.1874
5078.88	4338.34	47.1828
5096.83	3733.77	44.2373
5116.45	3074.3	41.0169
5133.22	2526.46	38.263
5155.41	1851.32	34.6205
5178.19	1266.9	30.8815
5198.89	838.137	27.4829
5218.11	547.725	24.3278
5237.66	310.017	21.1195
5262.31	199.981	17.0727
5273.39	173.541	15.2532

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Results: Heat Flux

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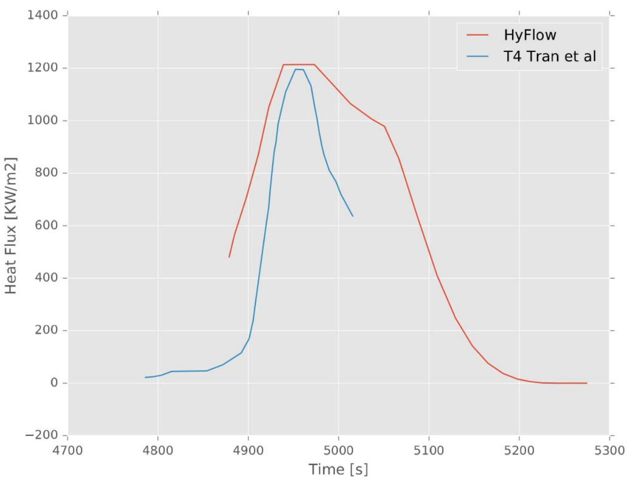

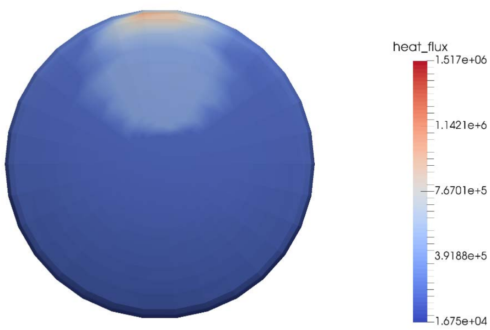

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Results: Temperatures (1/2)

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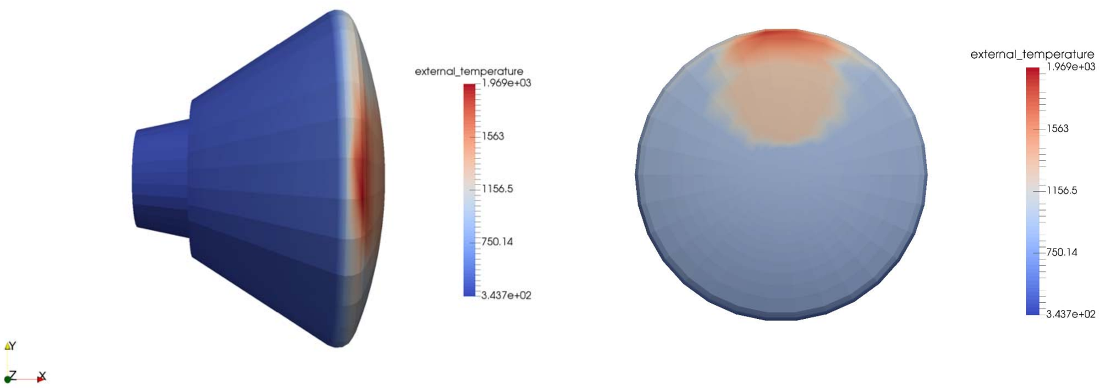

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Results: Temperatures (2/2)

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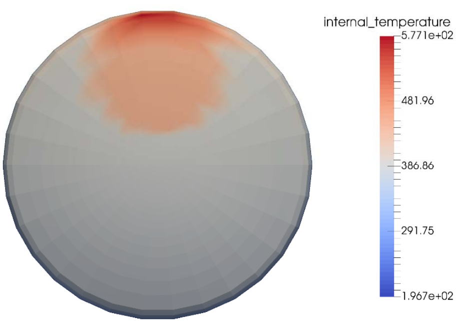

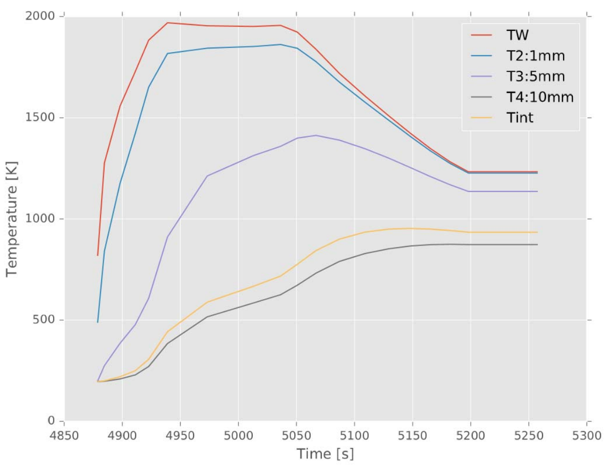

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Results: Recession

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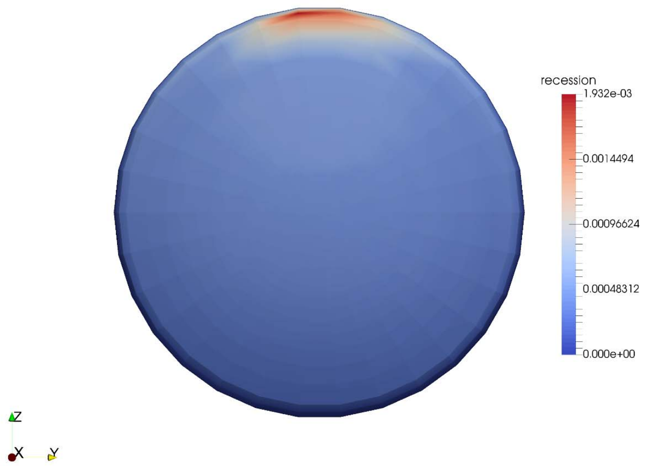

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Conclusions & future work

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Conclusions:

- The results presented show that it is possible to use the presented approach to evaluate the internal material behaviour and external flux aerodynamics during the atmospheric entry phase of a space mission in three-dimensional space.
- Short computational time: from 4 minutes to half an hour depending on the geometry and the re-entry duration.

Future work:

- The verification of the method on a real TPS structure: different materials for different parts of the spacecraft geometry and different thicknesses.
- Coupling of the thermal response code with a more precise/reliable aero-thermodynamic model: on-going.

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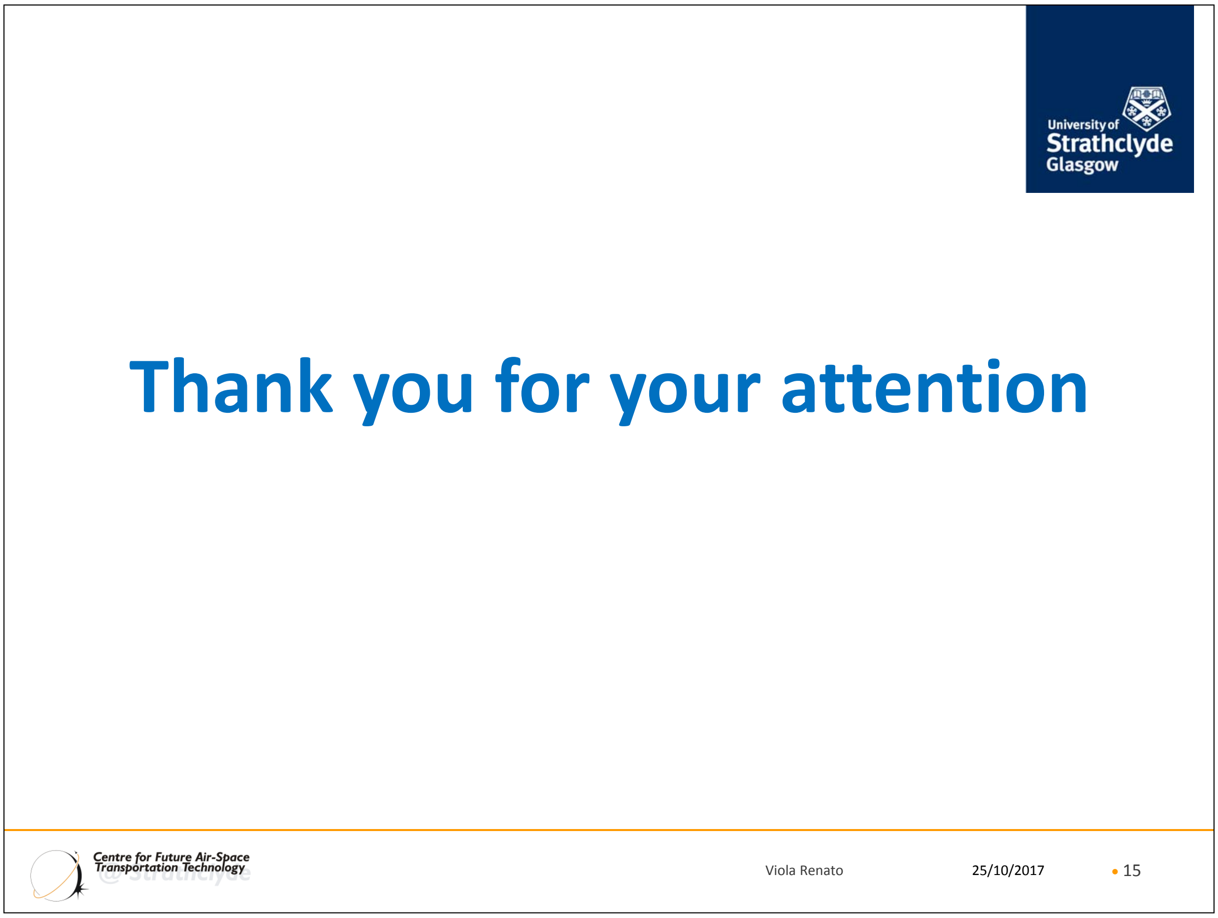
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