Clean Space Days 2024: Towards a Sustainable Future in Space

Composite degradation model for spacecraft oriented tool : ESA GSTP : NEVADA Project

Numerical and Experimental VAlidation of spacecraft Demise during Atmospheric re-entry

(Contract Ref: ESA AO/1-10448/20/NL/MG)

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October 8th 2024

Objectives & Approach

Objectives

- **To increase the knowledge of the degradation of space debris during re-entry.**
- **Enhance the predictive capabilities of the high-fidelity and spacecraft-oriented numerical tools**
- Numerically reconstruct data measured in high enthalpy facilities and reactors operated under representative flight conditions
- **Reduce the risk of casualties from uncontrolled** re-entry by reducing the amount of debris that survives re-entry.

Ti (up) and COPV (down) tanks found in India

Approach

- Various materials (including CFRP, AISI 304L steel, Haynes 25) will be tested and analysed to provide material properties and tools capable of modelling their atmospheric re-entry, as much of the debris found on the ground consists of these materials.
- A comprehensive experimental database will provide insight into degradation and fragmentation processes and enrich the current ESA ESTIMATE database.
- **Development of low cost, multi-physics, multi-scale methods capable of handling the demise of these materials for spacecraft-oriented tools.**

Objectives & Approach

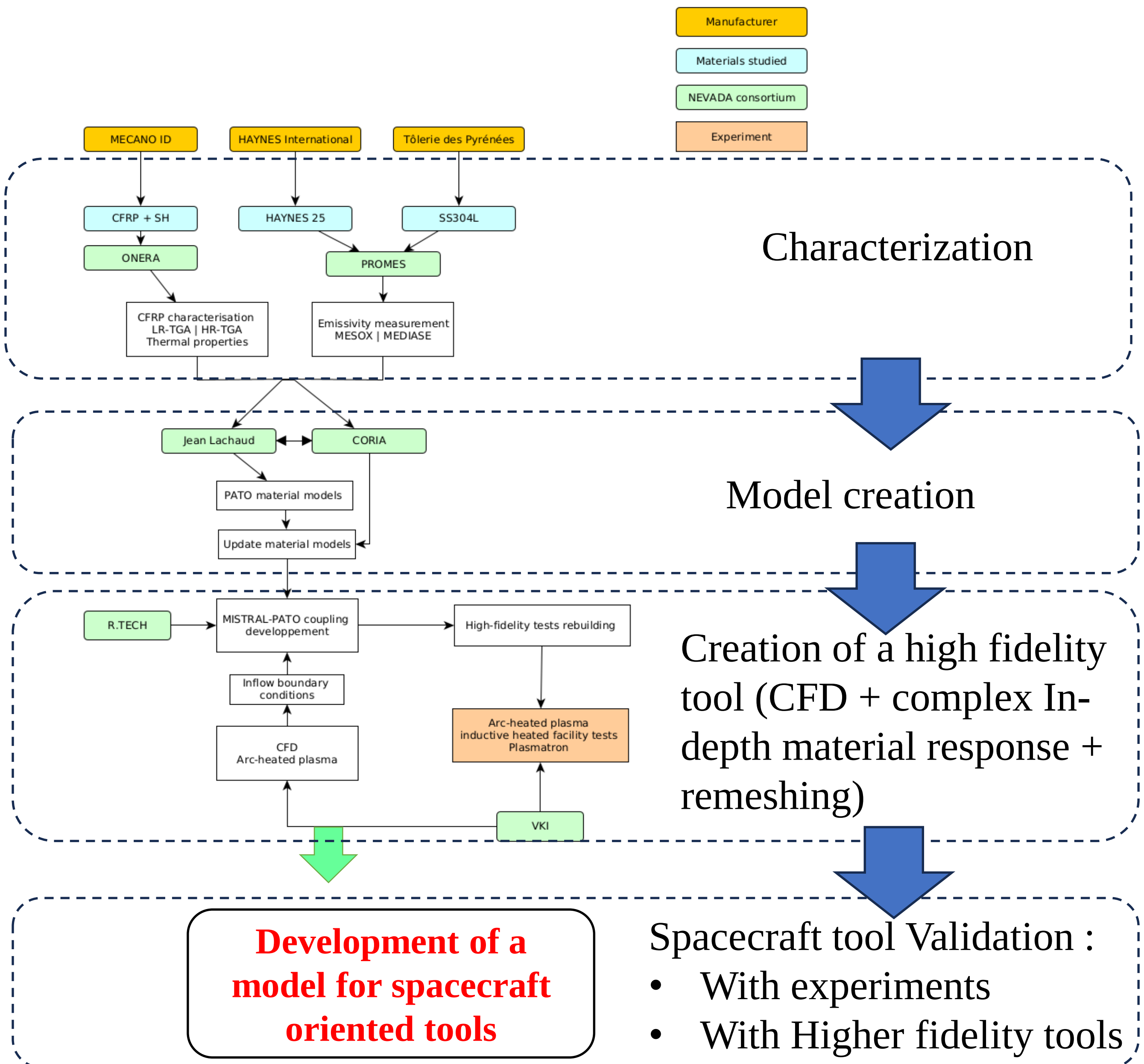
NEVADA project overview

GSTP 100% French :

→ French Consortium
With support VKI Belgium

CNES provides the Tool PAMPERO for this activity

PAMPERO



Test schedules

	PROMES	ONERA	VKI (flat plate)
CFRP		X	X
Haynes 25	X		X
SS 304L	x		X

Material models:

Porous Material :

- **Jean Lachaud** has established a CFRP properties data set base on those manufcature by **MECANO ID**

Spacecraft Oriented Tool

Objectives:

- **Development of cost-effective, multi-physics, multi-scale methods** able to handle the demise of these materials for **spacecraft oriented tools to strengthen the predictive capabilities of the debris reentry**

- Rebuild numerically the data measured in high-enthalpy facilities and reactors operated at representative flight conditions

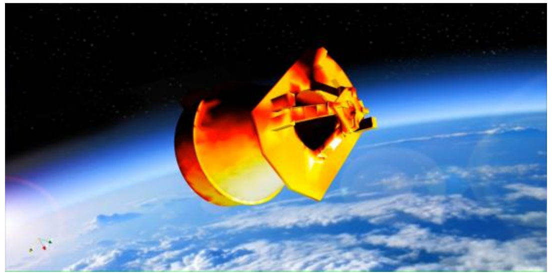
Target tool : PAMPERO : French spacecraft-oriented tool (100% CNES)

- **Perform computations for sensitive objects** reaching the ground close to the 14J limit

- Perform computations for very **complex objects** (not available within object-oriented tools)

- Perform **D4D computations** for future missions

- Support **experts** for the **fragmentation** modelling



AVUM re entry

PAMPERO

- Fast assessment
- Robust

} Simplified aerothermodynamics

- Integrated 6 Degrees of Freedom (6DOF)
- Integrated Thermal response 3D implicit+s2s
- Thermo mechanical Fragmentation (3D dynamic FEM)
- Ablation

} Shape change

- Integrated High-temperature material response
  - characterized Material through CNES data base
  - Melting
  - Pyrolysis, oxidation, etc.

TARANIS degradation

High-Fidelity CFRP model for PAMPERO

The main question : can we implement a high fidelity model inside a spacecraft oriented tool with in depth pyrolysis and 3D gas transport (instead of engineering correlations) → yes with several optimizations

Computational time reduced thanks to a 3D implicit resolution of the Mass/Momentum/Energy conservation → **5h for a full trajectory** simulation on a 400k cells mesh (300k **cells usually used to model a full satellite**)

The model is already in use for 2 CNES industrial projects :

- JASON demise analysis : 2 days of simulation on 32 cores with Solar panels and 2 dish antenna in CFRP
- EADS Tanks : preliminary study of the feasibility of aluminium liners in COPV tanks)

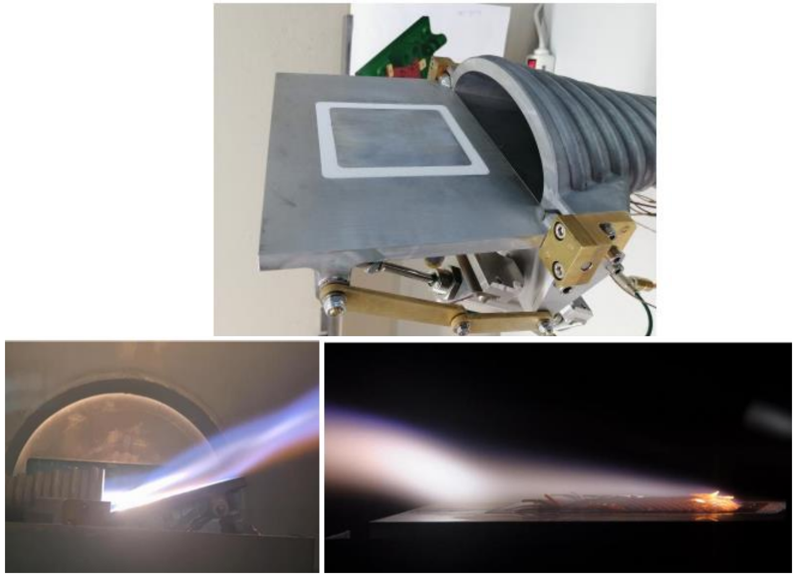
JASON degradation

Cfrp tank degradation

Aluminium Liner ablation

Experimental campaigns

VKI experiment

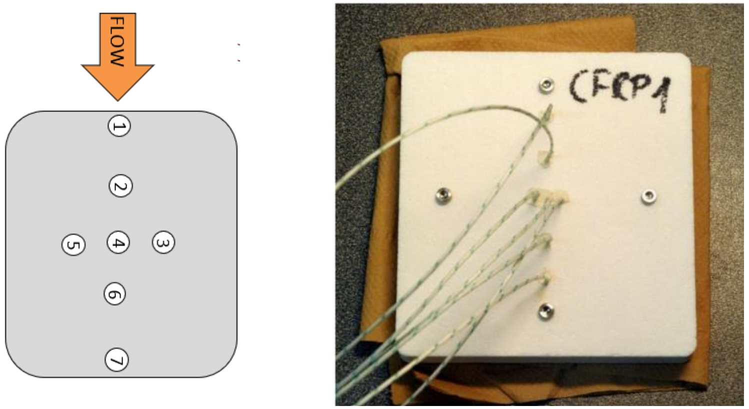


VKI experimental set up

Material	Angle of attack (°)	Mass flow (g/s)	Heating (s)
HAYNES	10	6	360
HAYNES	10	12	230
CFRP	10	6	600
CFRP	10	12	480
STEEL	10	6	600

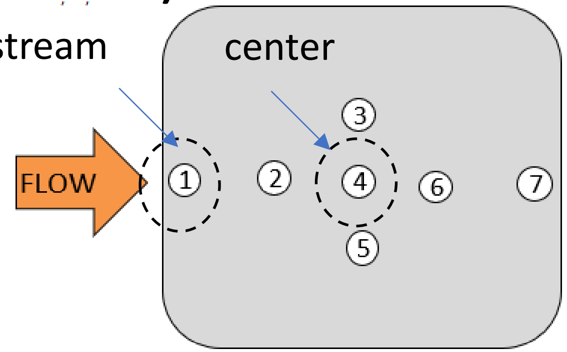
VKI experimental test cases

Thermocouple Layout



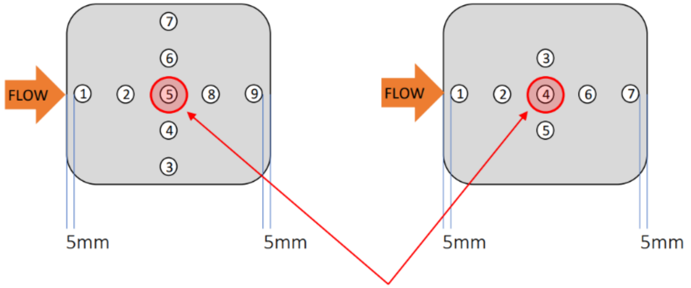
VKI experiments – thermocouples on the back face

Measured final recession :
(±10% error)

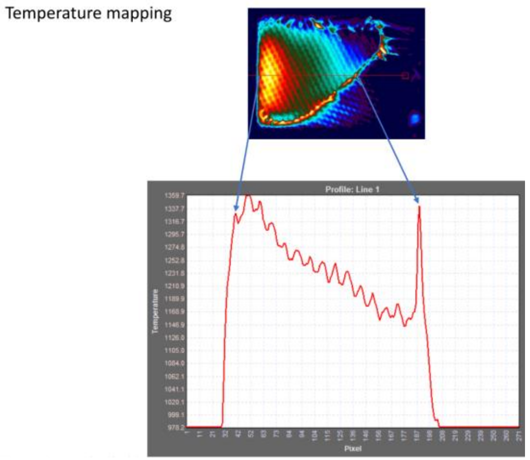


Recession points measurement

Front face temperature



Temperature at center of the plate



Temperature on the centerline at different timestep

Experimental campaigns

Materials: CFRP from MECANO ID (Toulouse France)

ONERA Facilities for the CFRP characterisation :

	Mettler Toledo TGA/DSC3+ with Adethec toolbox	HR-TGA	BLADE	Bruker-Equinox Lambda 1050
Facility specification	- Max Temp. 1100°C - Air/N2 Atmosphere	- Temperature up to 1500°C - Heating rate from 5°C/min to 1500°C/min - Helium Atmosphere	- LT : 20 – 80°C - HT : 60 – 600°C	- Ambient Temperature
Property measured	**Arrhenius model** for thermo-chemical reactions : • Resin pyrolysis • Char oxidation • Fiber oxidation	- **Mass loss rate** at high heating rates -> Arrhenius model	- 3 thermal conductivities k_x , k_y , k_z - Specific heat	- IR emissivity - UV/near-IR absoptivity
Sample	Virgin	Virgin	Virgin Degraded	Virgin Degraded

CORIA proposed to use its expertise in LIBS (Laser-Induced Breakdown Spectroscopy) to determine the **multi-elemental composition of the tested resin**

After processing the spectra, the following composition of the **pyrolysis gas** is deduced:

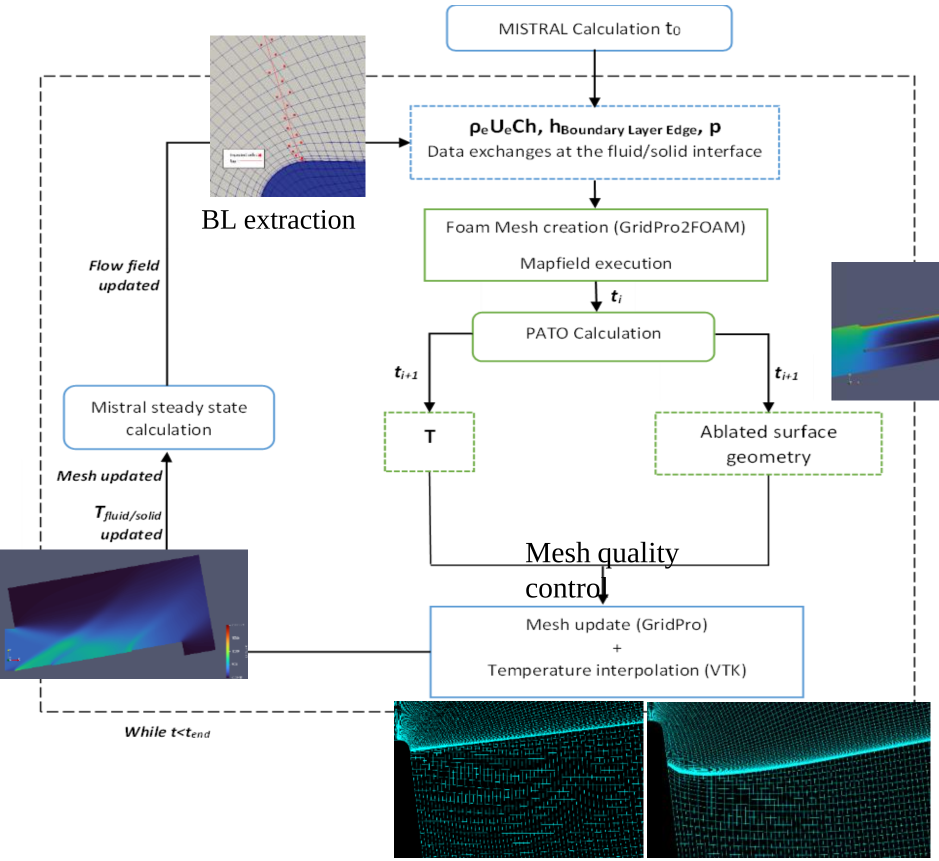
$$y_C = 48\ \%$$
$$y_H = 12\ \%$$
$$y_N = 8\ \%$$
$$y_O = 32\ \%$$

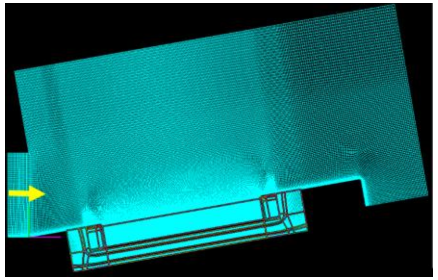
$$x_C = \frac{[C]}{[C]+[H]+[N]+[CO]} = 0.216$$
$$x_H = \frac{[H]}{[C]+[H]+[N]+[CO]} = 0.642$$
$$x_N = \frac{[N]}{[C]+[H]+[N]+[CO]} = 0.033$$
$$x_O = \frac{[O]}{[C]+[H]+[N]+[CO]} = 0.109$$

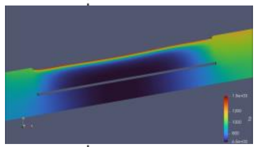
Composition of Pyrolysis Gas : uncertainty 8%

High Fidelity model

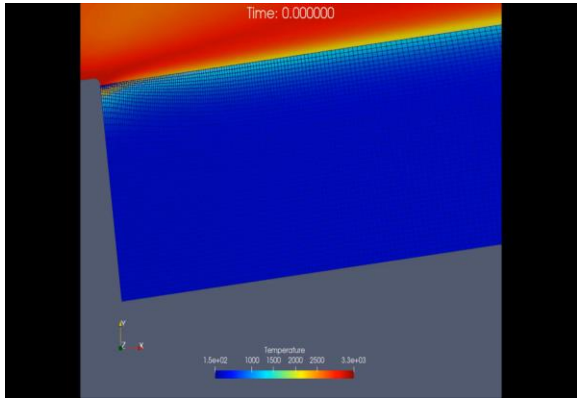
High Fidelity Coupling strategy overview (code NEVADA C.T. : NEVADA Coupling Toolbox)







Fluid/structure Mesh



Evolution of fluid/structure interaction

Fluid Modeling : MISTRAL

RTech in-house CFD tool

- **Navier-Stokes**
- **Non-equilibrium reactive chemistry**

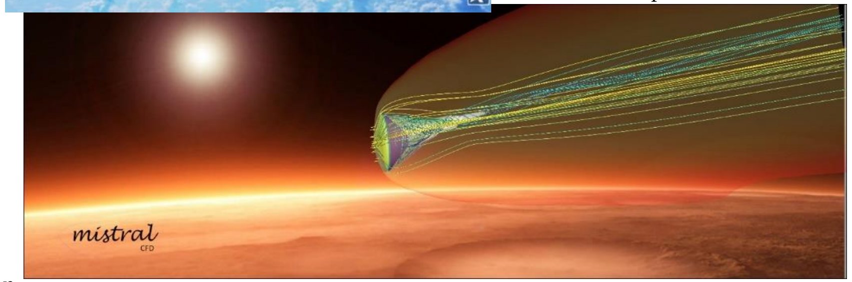
Physico-chemical models

Vibrational, electronic relaxation
High-temperature thermodynamics, transport
Homogeneous chemical kinetics (atmosphere)

Numerical schemes

Time integration: usual and in-house schemes
Space integration: usual and in-house schemes

Method: Finite volume integration: GMRES, inviscid fluxes: AUSM/VanLeer

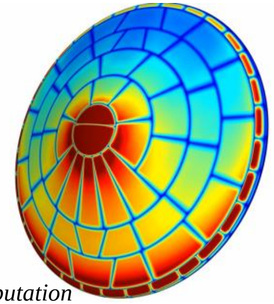


Mistral coputation

Solid modeling : PATO

Open source In-depth material response toolbox based on OpenFOAM

- Multiphase porous reactive materials
- Internal decomposition (pyrolysis, vaporization)
- Gas-gas and gas-solid chemical reaction
- Gas species transport (convection, diffusion)
- Solid morphology evolution (internal density change, surface ablation)



PATO computation

PAMPERO Model

PAMPERO : CFRP model

The main question : can we implement a high fidelity model inside a spacecraft oriented tool with in deph pyrolysis and 3D gas transport (instead of engineering correlations) → yes with several optimizations

	density (kg/m3)	volume ratio
fibre	1800	0,56
resin	1280	0,43

Pyrolysis process and gas fluxes generation:

$$\pi_{tot} = \rho_{resine}\varepsilon_{resine}F\frac{\partial \xi}{\partial t}$$

$$\Delta m_{pg} = -\pi_{tot} \times V_p \Delta t$$

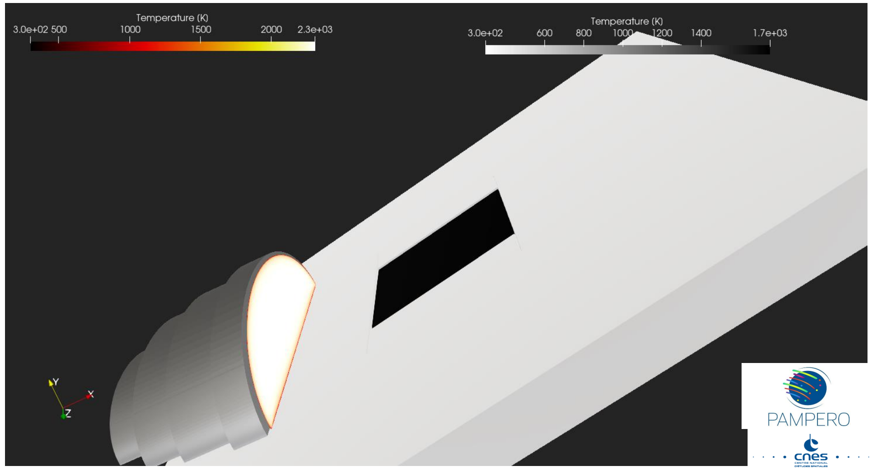
$$\frac{\partial \xi}{\partial t} = \mathcal{A}\, T_P{}^{\eta}\, exp\left(\frac{\mathcal{E}}{RT_P}\right)(1-\xi)^m$$

$$\varepsilon_g = \varepsilon_{resine}^{t0} \times \xi$$

with:

- ξ: Advancement of pyrolysis reaction (SI)
- T_P: Temperature at the current cell P where the reaction is computed (K)
- $\mathcal{A}$: Pre-exponential factor of pyrolysis reaction (SI)
- $\mathcal{E}$: Activation energy of pyrolysis reaction (J/kg)
- η: Calibration exponent
- m: Arrhenius law factor of pyrolysis reaction (J/kg)

Calibrated by Jean Lachaud with ONERA characterization → creation of an opensource tool for automatical calibration as function of burned gases



Préliminary computation NEVADA

Degradation (VOF analogy) :

$$m(t+dt) = m(t) + \Delta m_{pg}(t) + \Delta m_{ca}(t)$$

with :

- $\Delta m_{pg}(t)$, the mass lost through the pyrolysis of the epoxy resin
- $\Delta m_{ca}(t)$, the mass lost through chemical ablation of the char $C_{(s)}$

If $m(t+dt) \leq 0$, the cell is fully ablated and removed from the solid.

$$\nu_{fiber} = \frac{V_{fiber}}{V_{fiber} + V_{resin} + V_{gas} + V_{char}}$$

$$\nu_{fiber} + \nu_{resin} + \nu_{gas} + \nu_{char} = 1$$

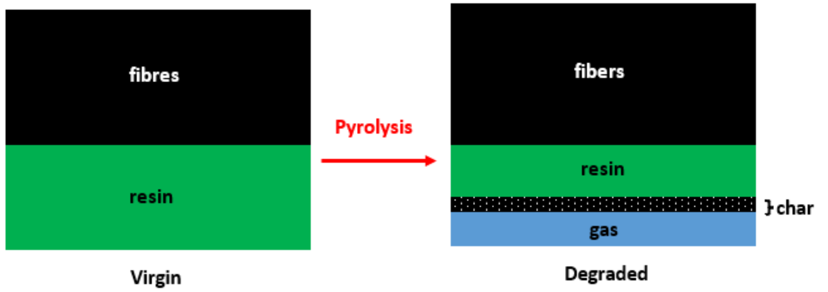


illustration of the different phases modelled for the composites in Pampero

PAMPERO Model

PAMPERO : CFRP model

The main question : can we implement a high fidelity model inside a spacecraft oriented tool with in deph pyrolysis and 3D gas transport (instead of engineering correlations) → yes with several optimizations

Gas Transport models through the Solid

Perfect Gas assumption :

$$\rho_g = \frac{M_g p_g}{R\,T_g}$$

ε_g : gas volume fraction
M_g : gas molar mass
Ks : permeability
μ_g : gas dyamic viscosity
π_{tot} : pyrolysis production rate kg.m^{-3}.

Mass conservation equation :

$$\frac{\partial \rho_g}{\partial t} + \frac{\partial(\epsilon_g \rho_g v_g)}{\partial x} = \pi_{tot}$$

Momentum equation (assumption of creeping flow in the continuum regime through the pores) :

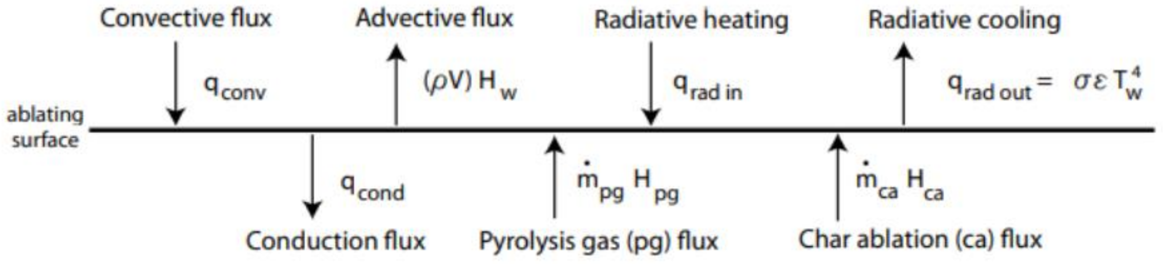
$$v_g = -\frac{1}{\epsilon}\left(\frac{1}{\mu}K_s\right)\frac{\partial(p_g)}{\partial x}$$

Solid Energy equation

$$\int_t^{t+\Delta t}\left[\int_{V_p}\frac{\partial(\rho(T)c_p(T)T)}{\partial t}dV_P\right]dt = \int_t^{t+\Delta t}\left[\int_{V_p}\vec{\nabla}\cdot(\kappa(T)\vec{\nabla}T)dV_p\right]dt + \int_t^{t+\Delta t}\left[\int_{V_p}\dot{E}_{pyrolysis}dV_P\right]dt + \int_t^{t+\Delta t}\left[\oint_{S_p}(\sigma\epsilon(T)T^4 + q_{conv} + q_{pyrolysis} + q_{ox})\vec{n}dS_p\right]dt$$

Surface balance :

$$q_{conv} - (\rho\, v)\, h_w + q_{rad,in} - q_{rad,out} - q_{cond} + \dot{m}_{pg}\, h_{pg} + \dot{m}_{ca}\, h_{ca} = 0$$



The surface energy balance at the wall

CFRP Models

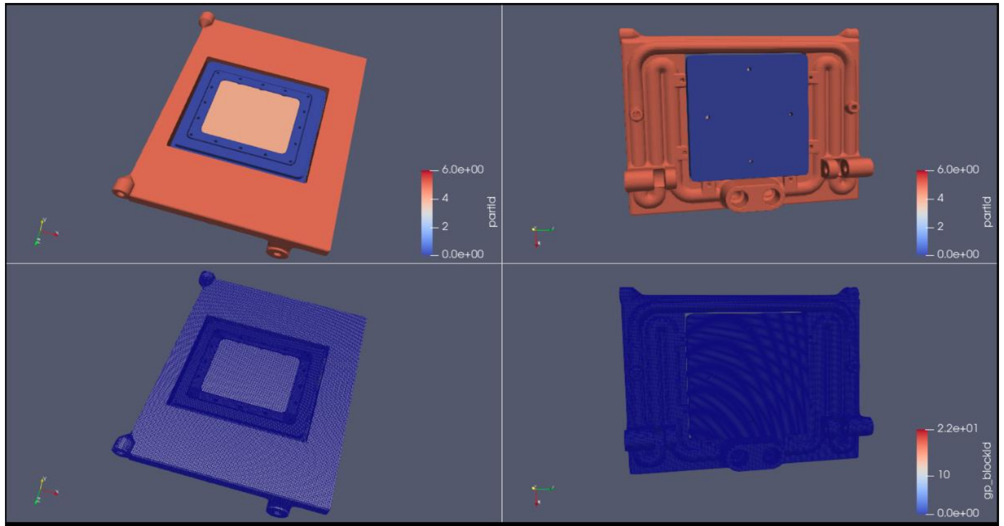
Simulations for rebuilding :

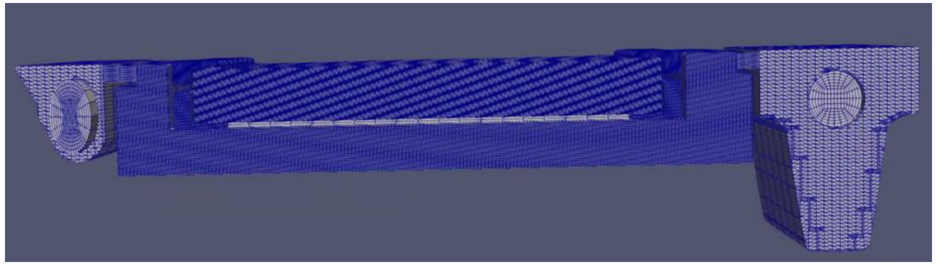
About 150 NEVADA C.T. simulations and >500 PAMPERO simulations have been launched during the project

Material	NEVADA C.T. (MISTRAL/PATO/GridPro/BLEED)	PAMPERO
Timestep	maximal timestep of 1e-4s for CFRP	timestep of 0,1 seconds (and 250 sub iterations for CFRP Gas Transport)
Computational time	**~month for CFRP (due to problem stifeness)**, days(5) for metals	**Days for CFRP (2 days),** hours for metals
Modeling	2D	3D
Recession	Mesh deformation	Pseudo VOF

Thanks to an R.Tech software named Zephyr (which can convert a step into a PAMPERO mesh), the real geometry can directly be used inside PAMPERO. The water has been modeled as a thermal sink and is meshed as well.

PAMPERO Mesh





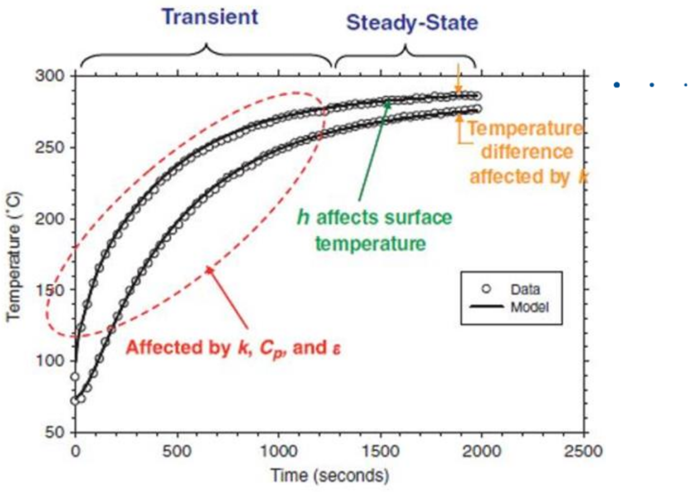
PAMPERO Mesh

Sensitivity analysis

Uncertainties and Sensitivity analysis :

The analyzed uncertainties are the following : 500< PAMPERO Computations

- **Numerical methods uncertainties**
- **Freestream condition**
- **Glued thermocouple could impact the results**
- **Pre-heated plate**
- **Boundary conditions**
- **Equipments Contacts**
- **CFRP material properties**
- **Material Degradation**
- **Turbulence**
- **Mesh convergence**
- **Catalycity**



Theoritical influence of each thermal parameter on front and back face temperature [1]

Lack of DATA at high temperature : The conductivity/heat capacities have been measured at relatively low temperatures (up to 450°K for virgin and 300°K for degraded CFRP) to avoid any degradation during the characterization

Degradation modelling

Some material degradations are not taken into account by the simulation models:

- **Swelling for CFRP**: it has been shown that it could have a strong impact on the temperature prediction in [1]
- **Delamination for CFRP**: it has been shown that it could have a strong impact on the temperature prediction in [1]

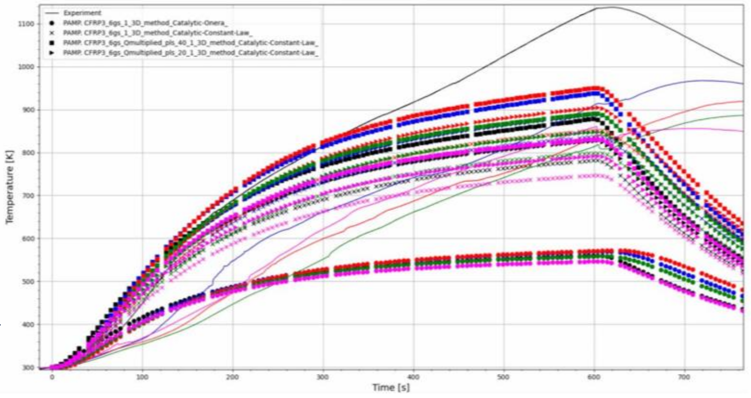
swelling observed on CFRP plate at 10°

NEVADA Approach

PAMPERO model validation with Higher Fidelity tools : NEVADA C.T. : Successfull

Uncertainty analysis on 1st VKI test case 12g/s

Rebuilding on 2nd VKI test case 6g/s



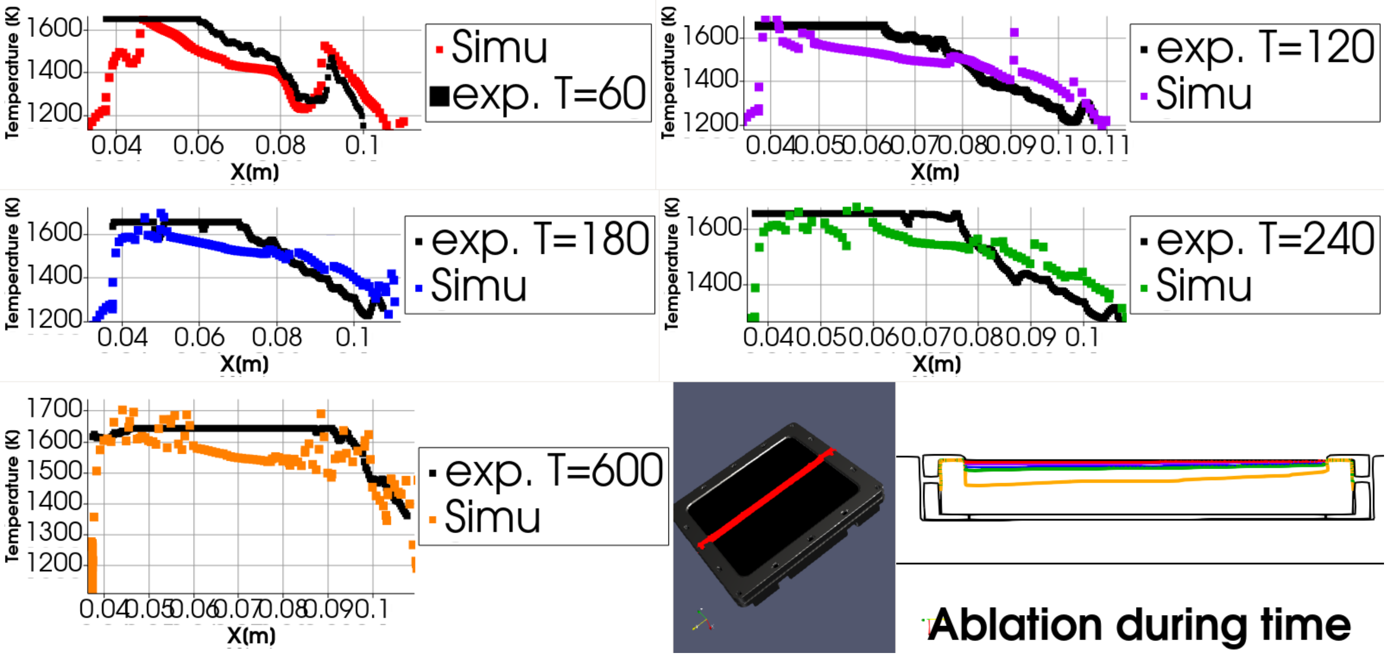
One of the variation with PAMPERO of material properties at high temperature – Back Face Thermocouples

[1] X. Wang, *Modelisation of the thermal degradation of composites in order to predict their fire reaction when they are exposed to flames*, https://theses.hal.science/tel-04269903, 2023.

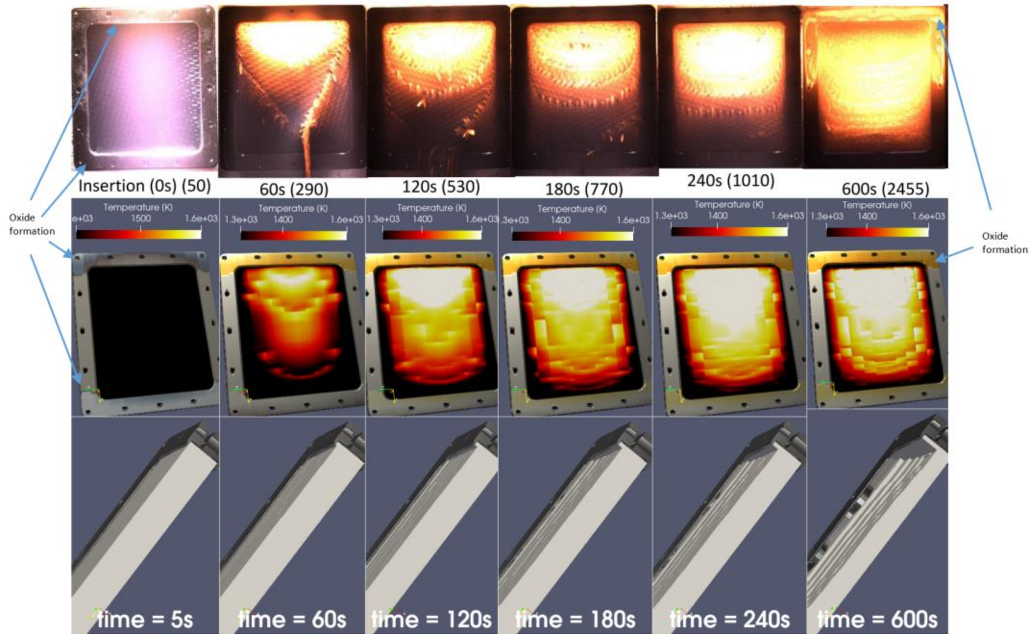
Results : Temperature

Results : CFRP 6gs

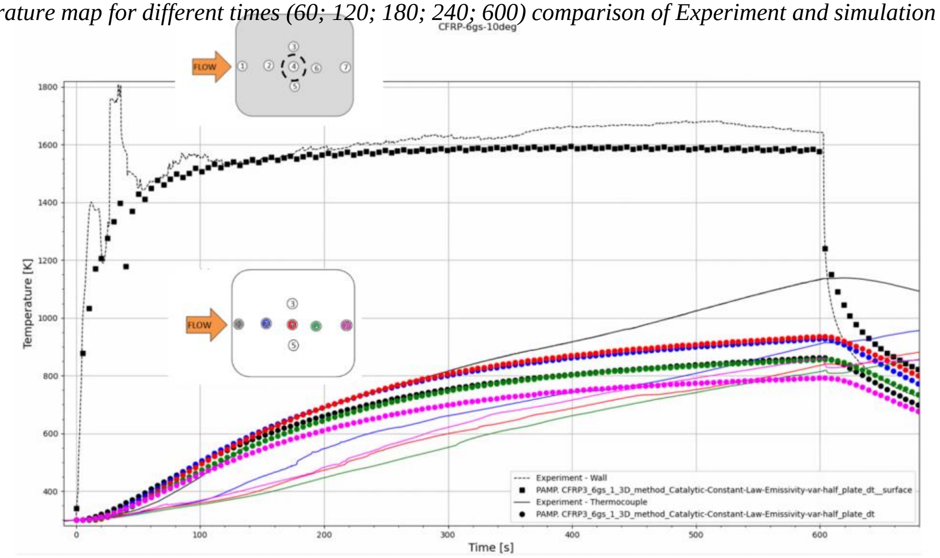
Front Face Temperature



Front face temperature at centerline for different times (60; 120; 180; 240; 600) comparison of Experiment and simulation



Temperature map for different times (60; 120; 180; 240; 600) comparison of Experiment and simulation



Front and back Temperature as function of time. comparison of Experiment and simulation

The temperature distribution over the plate is similar.

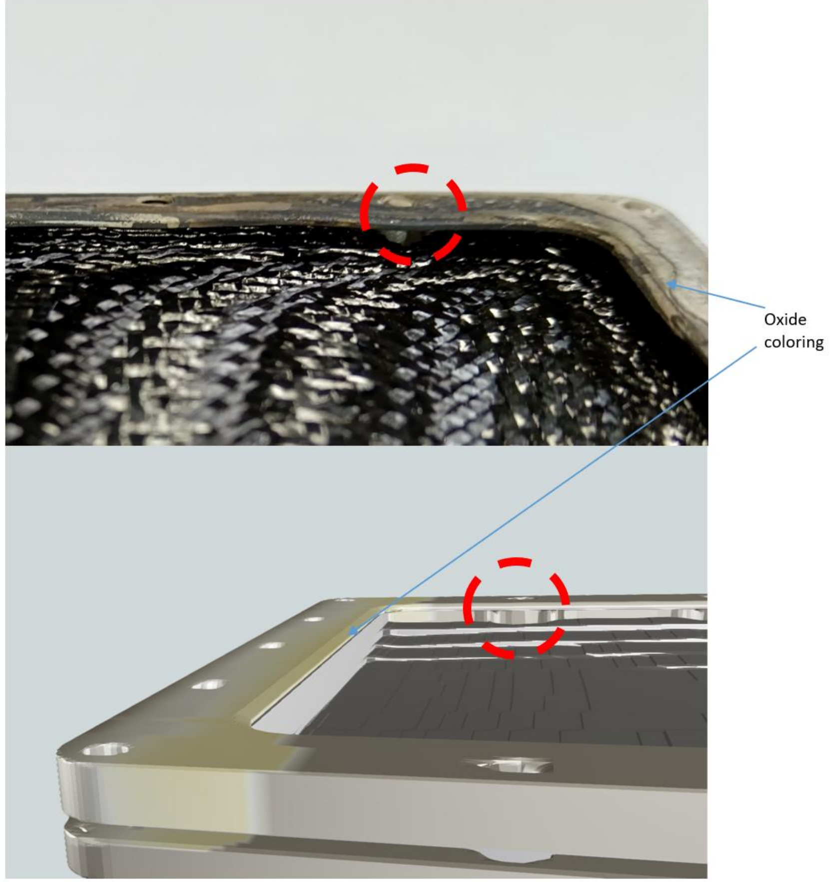
The degradation occurs also the same way between PAMPERO and the experiments

Results : Degradation

Results : STEEL 6gs

Ablation

The degradation is about **78% of the initial mass in simulation compared to the experimental material degradation about 78%.**

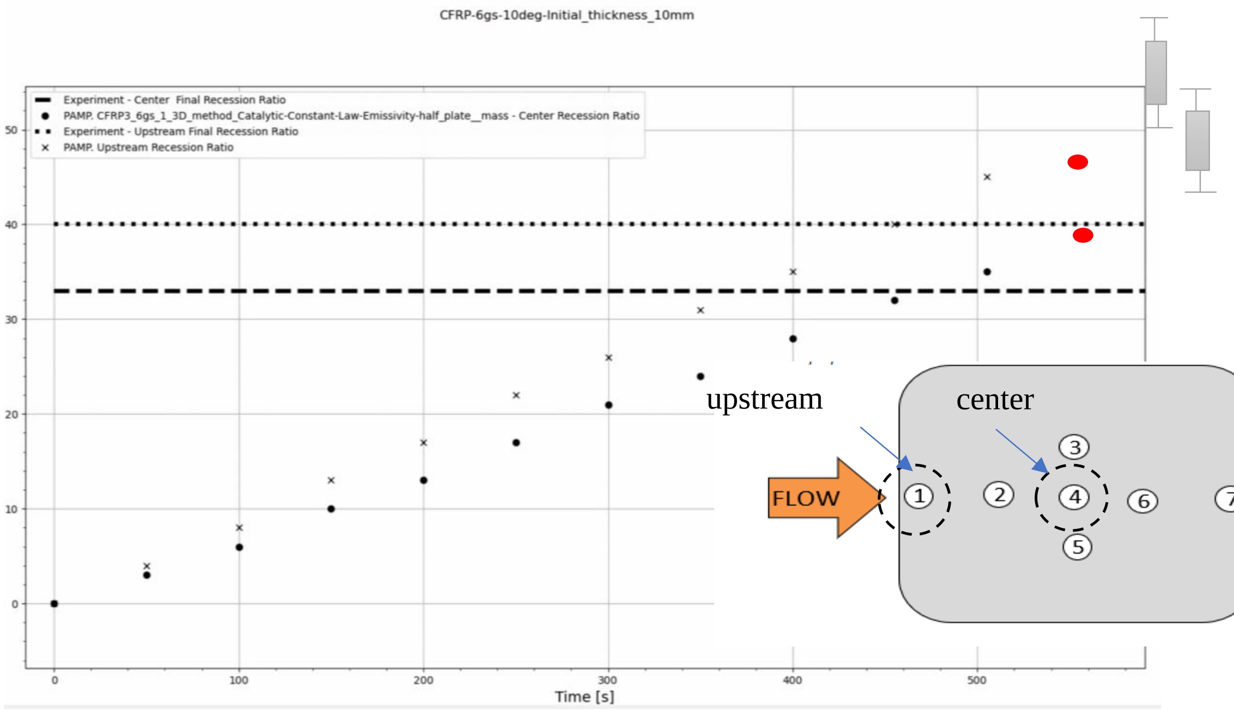


Screenshot of the final degradation of the sample. Experiment (up) and Simulation (down) - CFRP - 10deg - 6g/s

PAMPERO

In the comparison of the final sample to the sample at the end of the simulation we can observe a **similar ablation behavior and a similar recession :**

3,9 mm in simulation and 3,3 mm in the experiment at center of the plate (the small discrepancy → swelling ?)



Recession ratio evolution compare to final recession ratio - CFRP - 10 ° - 6g/s

Conclusion and Perspectives

The objectives of the current study were successfully met :

- To improve the knowledge of the degradation of space debris during re-entry
- Strengthen the predictive capabilities of the high-fidelity and spacecraft-oriented numerical tools currently in use.
- **Numerically reconstruct data measured in high-enthalpy facilities and reactors operated under representative flight condition**

An explicit coupling strategy (called NEVADA C.T.) of RTech's in-house high-fidelity tool Mistral with the OpenFOAM-based material response solver PATO was then developed to provide a cross-check verification code for the spacecraft-oriented tool and to numerically rebuild the experiments in the VKI facilities.

Extensive efforts were made to develop such tools/models in terms of **accuracy and CPU optimization**. The reconstruction activity has allowed the improvement of our tools, in particular the new version v3 of PAMPERO shows **good agreement with the experiments in terms of mass, recession rate and front and back surface temperature.**

NEVADA C.T. and PAMPERO show good agreement and PAMPERO allows a **great speed-up for the calculation of the thermal response** (**1-2 months** calculation for NEVADA C.T. against **2 days for PAMPERO**), allowing to handle industrial cases.

The final objective, to provide a code to reduce the uncertainties on the risk of casualties from uncontrolled re-entry, was fully **achieved during this activity**.

Conclusion and Perspectives

The study shows that **significant effort is still required** to correctly characterize the **thermal properties of composite** (especially in a degraded state at high temperature) and to take into account **phenomena such as swelling and delamination which has to be modelled to properly model an atmospheric re-entry of such materials**

Further effort will be made on to these points in order to assess the full degradation process of industrial geometries.

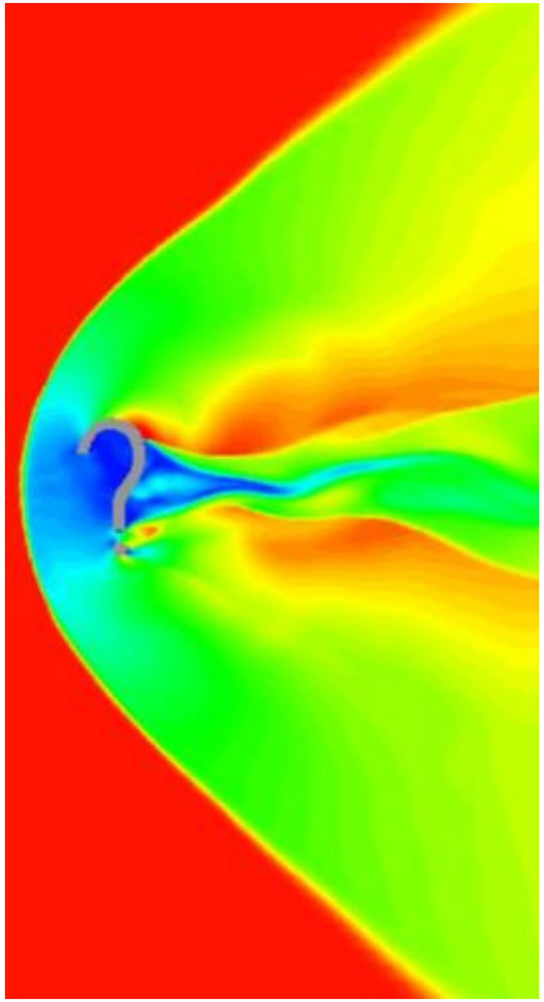
- ☐ *To do so* ***several characterization are still required (at iso – fluxes)*** *for* ***char and virgin*** *materials in order to correctly assess CFRP material properties. This would ensure the thermal behavior of such material during heating phase/pyrolysis.* ***A coupling of PAMPERO and Dakota could be used to fit the material properties at really high temperature***

- ☐ ***To address swelling****, a development on PATO is on-going but on material such as wood. A development/validation with tests of the swelling for CFRP during atmospheric re-entry is required to evaluate with accuracy the thermal raise.*

- ☐ ***To address delamination, a complet strategy is under reflexion for another GSTP including more test cases and Simulations***

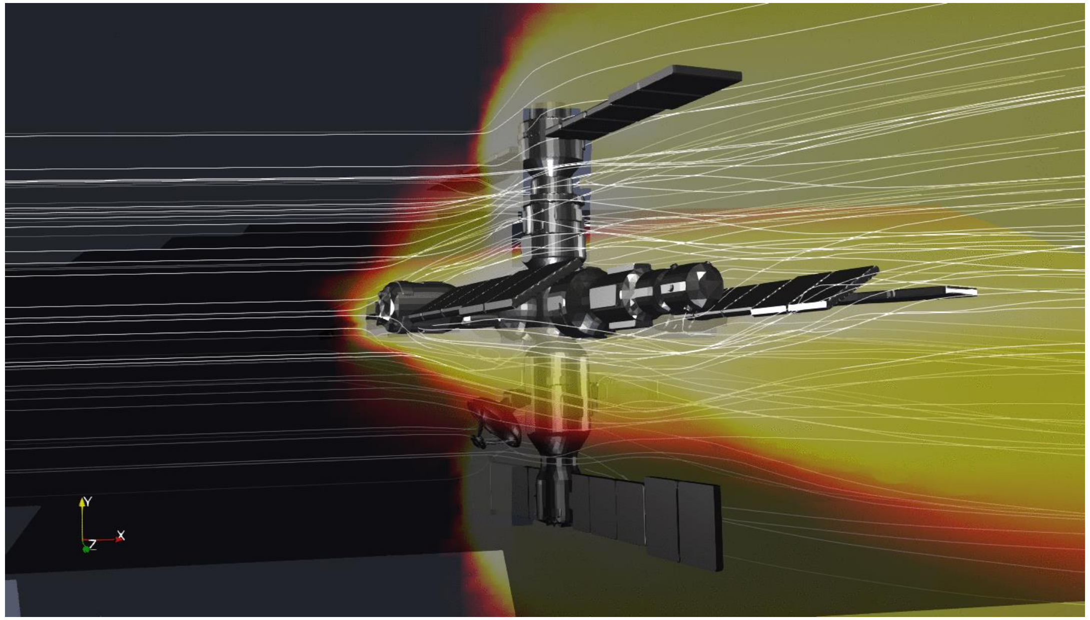
These 3 developments would ensure a correct estimation of thermal raise in satellite equipment's during re-entry once such phenomena (swelling/Pyrolysis/delamination) occur

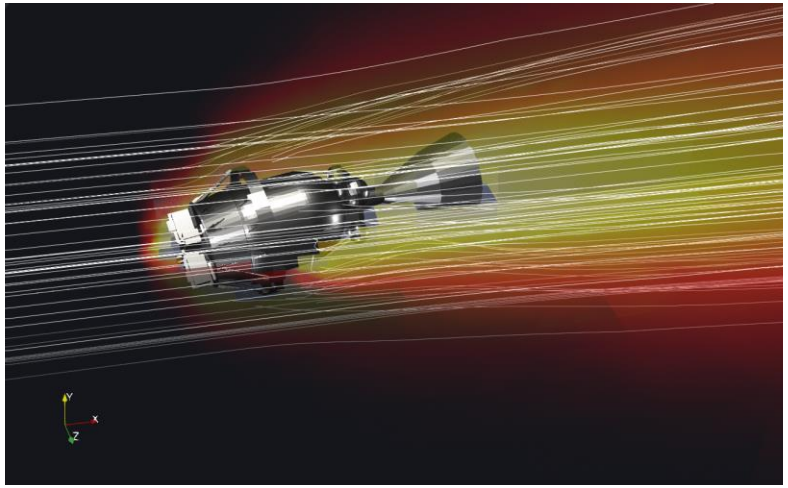
Questions



Upcoming :
New release of
PAMPERO :

PAMPERO Hi-Fi





Back Up

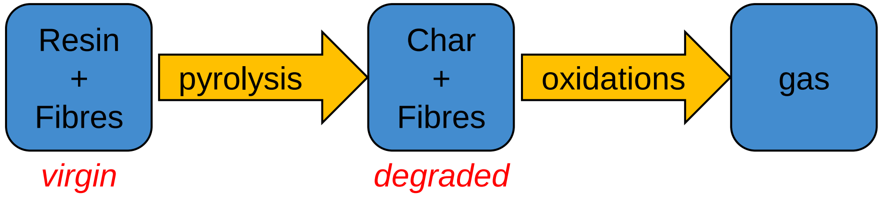
Experimental campaigns

TGA/DSC3+

- Assess simultaneously mass loss and reaction enthalpies during the decomposition process

- Tmax = 1100°C
- Air/N2 atmosphere

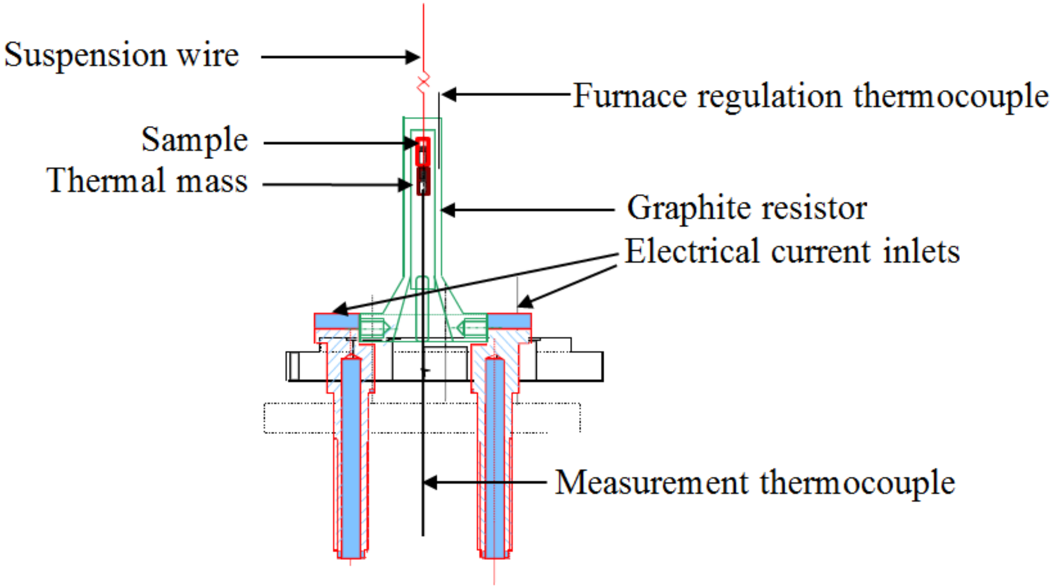
- ADETHEC toolbox
  - Analyse and model thermo-chemical reactions
  - n solid species and r reactions
  - **3 stage Arrhenius model for TGA fitting of a CFRP decomposition**



Experimental campaigns

HR-TGA

- Identification of degradation kinetics at high heating rates
- Temperature up to 1500°C
- Heating rates from 5°C/min to 1500°/min
- Helium atmosphere
- **Mass loss rate** measured with Setaram CS32 balance
    - Up to 400mg relative mass loss
    - 6µm precision



Optical suface properties

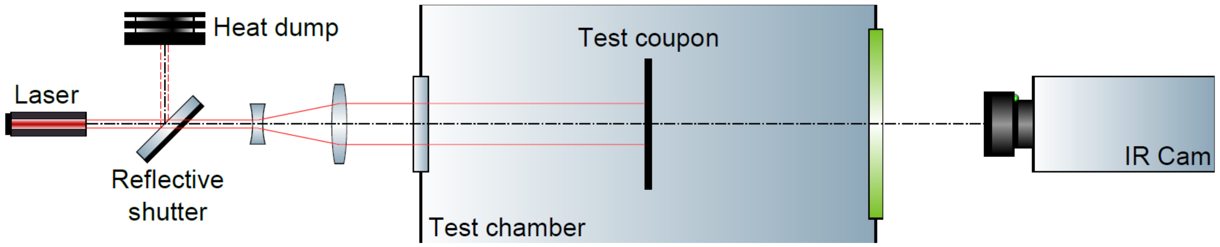
- **Spectral emissivity** measurements :
  - Ambient temperature
  - Bruker-Equinox => IR: 1.3-27 µm
  - Lambda 1050 from Perkin-Elmer => UV/near IR: 175-2500 nm

- 2 material states
- Virgin (initial): resin + fibres
- Degraded: char + fibres

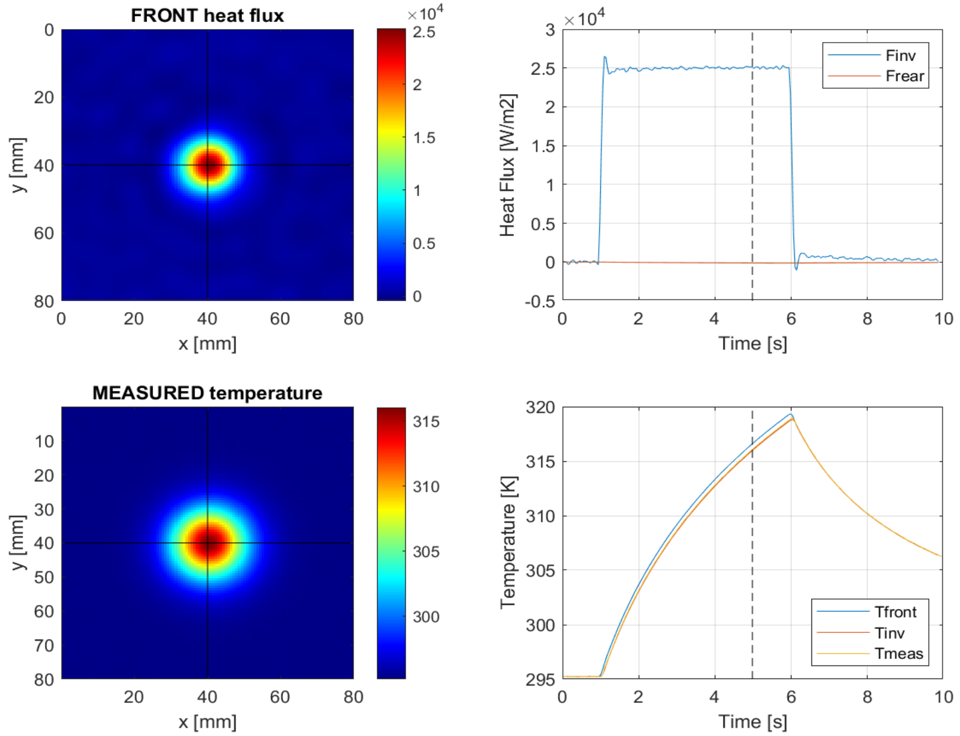
Experimental campaigns

BLADE

- BLADE-LT
  - Range 20-80^{o}C
  - Sample size 80x80 mm²



- BLADE-HT
  - Range 60-600^{o}C
  - Sample size 100x100 mm²
- **Properties**
  - 3 thermal conductivities: k_x,k_y,k_z
  - specific heat
  - as a function of temperature
- 2 material states
  - Virgin (initial): resin + fibres
  - Degraded: char + fibres



Experimental campaigns

BLADE

- BLADE-LT
  - Range 20-80°C
  - Sample size 80x80 mm²

- BLADE-HT
  - Range 60-600°C
  - Sample size 100x100 mm²
- **Properties**
  - 3 thermal conductivities: k_x,k_y,k_z
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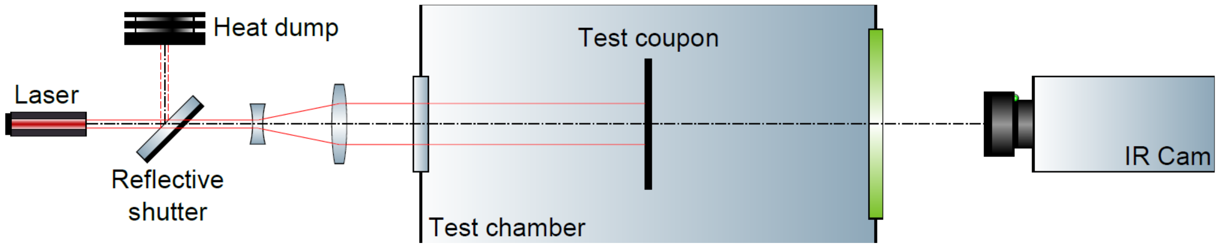
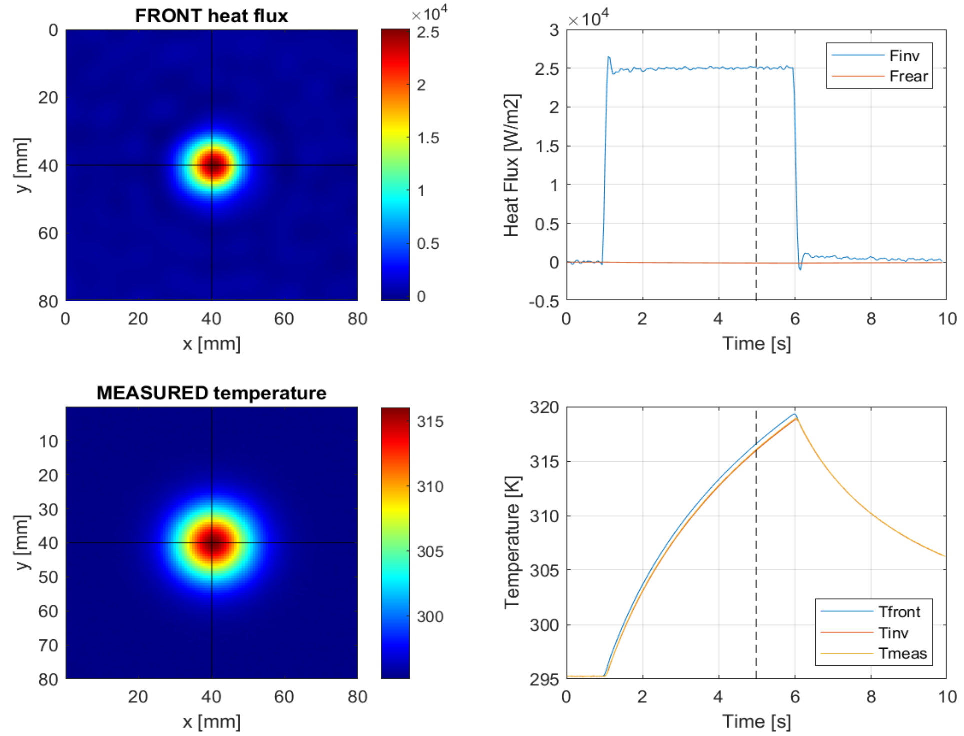


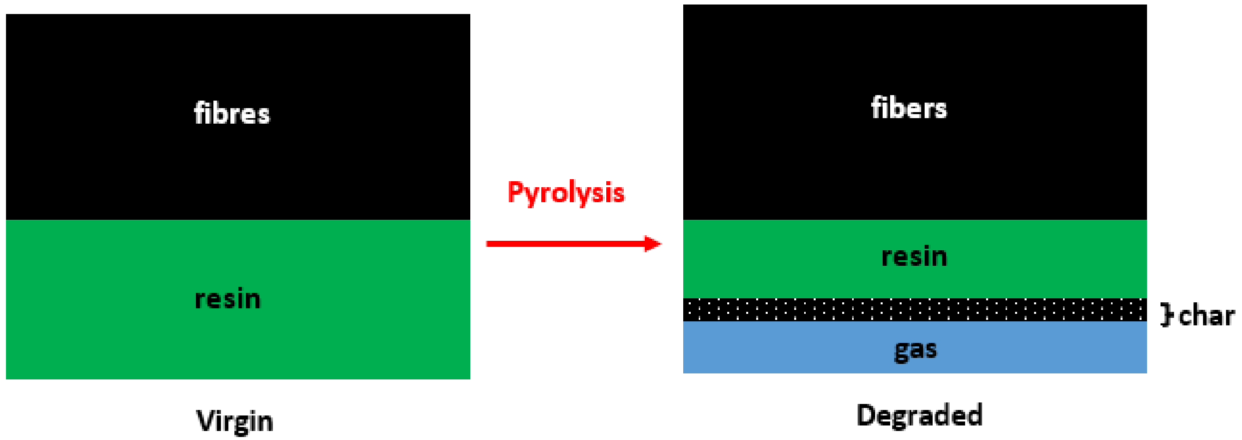


PAMPERO : CFRP model : VOF analogy

	density (kg/m3)	volume ratio
fibre	1800	0,56
résine	1280	0,43

$$\nu_{fiber} = \frac{V_{fiber}}{V_{fiber} + V_{resin} + V_{gas} + V_{char}}$$

$$\nu_{fiber} + \nu_{resin} + \nu_{gas} + \nu_{char} = 1$$



$$(c_p(T))_{degraded} = (1 - \xi)\ (c_p(T))_{virgin} + \xi\ (c_p(T))_{graphite}$$

ε is the advancement rate of the pyrolysis reaction, see next section Pyrolysis reaction

PAMPERO : CFRP model : VOF analogy

	density (kg/m3)	volume ratio
fibre	1800	0,56
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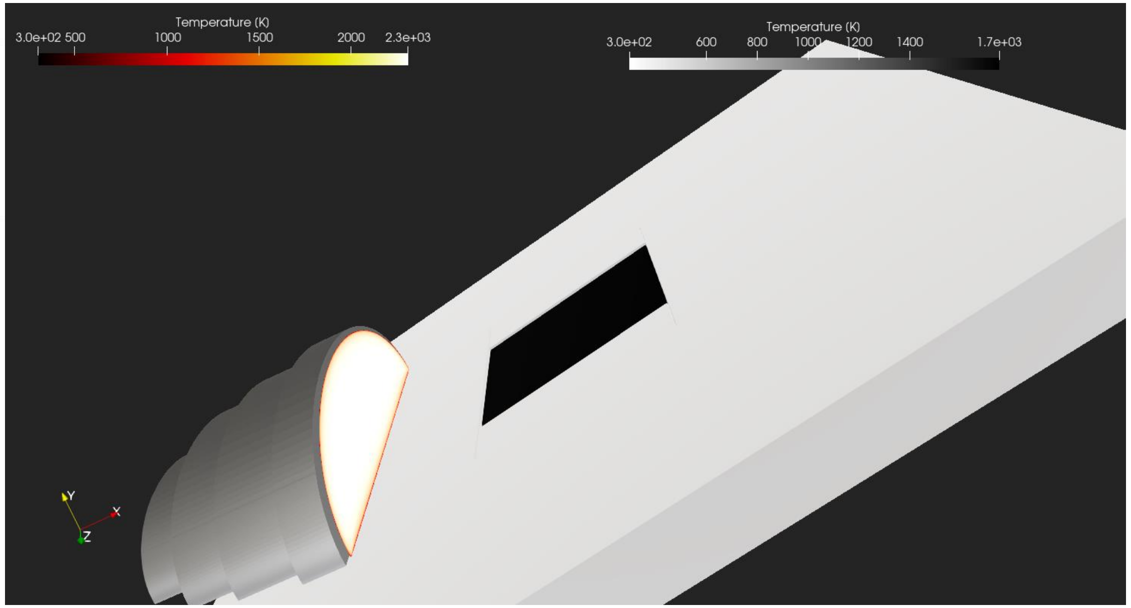
$$m(t+dt) = m(t) + \Delta m_{pg}(t) + \Delta m_{ca}(t)$$

with :

- $\Delta m_{pg}(t)$, the mass lost through the pyrolysis of the epoxy resin
- $\Delta m_{ca}(t)$, the mass lost through chemical ablation of the char $C_{(s)}$

If $m(t+dt) \leq 0$, the cell is fully ablated and removed from the solid.



Pyrolysis process and gas fluxes generation:

The physic taken into account is :

$$\pi_{tot} = \rho_{resine}\varepsilon_{resine}F\frac{\partial \xi}{\partial t}$$

$$\varepsilon_g = \varepsilon_{resine}^{t0} \times \xi$$

$$\Delta m_{pg} = -\pi_{tot} \times V_p \Delta t$$

Calibrated by Jean Lachaud with ONERA characterization

PAMPERO : 2 implemented Gas Transport models through the Solid

Perfect Gas assumption :

$$\rho_g = \frac{M_g p_g}{R\,T_g}$$

Mass conservation equation :

$$\frac{\partial \rho_g}{\partial t} + \frac{\partial(\epsilon_g \rho_g v_g)}{\partial x} = \pi_{tot}$$

Momentum equation (assumption of creeping flow in the continuum regime through the pores) :

$$v_g = -\frac{1}{\epsilon}\left(\frac{1}{\mu}K_s\right)\frac{\partial(p_g)}{\partial x}$$

ε_g : gas volume fraction
M_g : gas molar mass
Ks : permeability
μ_g : gas dyamic viscosity
π_{tot} : pyrolysis production rate $kg.m^{-3}.s^{-1}$

PAMPERO : 2 implemented Gas Transport models through the Solid

1D solution – velocity assumption :

$$v_g = 1D\ approximation$$

$$v_g = -\frac{1}{\epsilon}\left(\frac{1}{\mu}K_s\right)\frac{\partial(p_g)}{\partial x}$$

Pressure computation from velocity

$$\rho_g = \frac{M_g p_g}{R\ T_g}$$

Density computation from pressure

3D solution – system resolution:

Gas Transport

$$\begin{cases} \rho_g = \dfrac{M_g p_g}{R\ T_g} \\ \dfrac{\partial \rho_g}{\partial t} + \dfrac{\partial(\epsilon_g \rho_g v_g)}{\partial x} = \pi_{tot} \\ v_g = -\dfrac{1}{\epsilon}\left(\dfrac{1}{\mu}K_s\right)\dfrac{\partial(p_g)}{\partial x} \end{cases}$$

PAMPERO : 2 implemented Gas Transport models through the Solid

1D solution – velocity assumption :

$v_g = 1D\ approximation$ based on PATO results

$$V_g = V_0\left(1 - \frac{d}{d_{max}}\right)e^{-Ad}$$

$v_g = v_0$ on external surface and 0 at the limit of pyrolyzed cell

3D solution – system resolution:

Semi-implicite resolution on ρ_g with sub iterations

Time step : t

Pyrolysis

Gas Transport

$$\Delta m_{pg} = -\pi_{tot} \times V_p \Delta t$$

$$\frac{\partial \rho_g}{\partial t} + \frac{\partial(\epsilon_g \rho_g v_g)}{\partial x} = \pi_{tot} \qquad \rho_g = \frac{M_g p_g}{R\,T_g}$$

$$v_g = -\frac{1}{\epsilon}\left(\frac{1}{\mu}K_s\right)\frac{\partial(p_g)}{\partial x}$$

Energy computation / surface recession

Time step : $t + \Delta t$

PAMPERO : 2 implemented Gas Transport models through the Solid

1D solution – velocity assumption :

Pyrolyszed

Non-Pyrolyzed

$$V_g = V_0\left(1 - \frac{d}{d_{max}}\right)e^{-Ad}$$

3D solution – system resolution:

Semi-implicite resolution on ρ_g with sub iterations

Time step : t

Pyrolysis

Gas Transport

$$\Delta m_{pg} = -\pi_{tot} \times V_p \Delta t$$

$$\frac{\partial \rho_g}{\partial t} + \frac{\partial(\epsilon_g \rho_g v_g)}{\partial x} = \pi_{tot} \qquad \rho_g = \frac{M_g p_g}{R\,T_g}$$

$$v_g = -\frac{1}{\epsilon}\left(\frac{1}{\mu}K_s\right)\frac{\partial(p_g)}{\partial x}$$

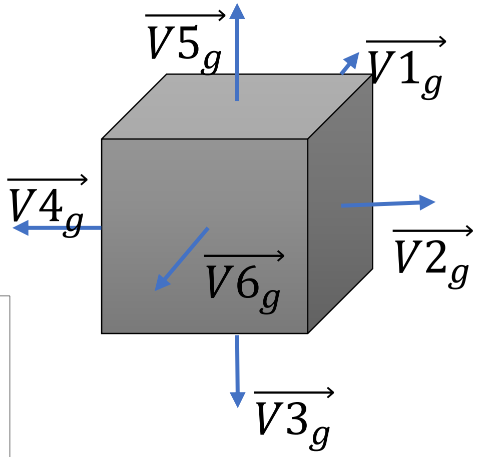
Energy computation / surface recession

Time step : $t + \Delta t$

PAMPERO : 2 implemented Gas Transport models through the Solid

1D solution – velocity assumption :

Ray – Casting in each face direction to build a 1D connectivity through all cells of the mesh



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Ray – Casting in each face direction to build a 1D connectivity through all cells of the mesh

$$V_g = V_0\left(1 - \frac{d}{d_{max}}\right)e^{-Ad}$$

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PAMPERO : CFRP – Energy computation

Energy equation :

PAMPERO : CFRP – Energy computation

Energy storage term :

PAMPERO : CFRP – Energy computation

Pyrolysis energy flux term :

pyrolysis energy flux is expressed as

Pyrolysis gas convective heat flux density term :

the convective heat flux density transported by the pyrolysis gas throughout its way out of the material

***Bprime* model was developed in the 1960s** by the Aerotherm Company under **NASA funding.**

It is a state-of-the-art model for reactive boundary **layers to couple material and flow simulation.**

Surface recession : B' Model

Surface balance :

Bprime model was developed in the 1960s by the Aerotherm Company under NASA funding. It is a state-of-the-art model for reactive boundary layers to couple material and flow simulation.

<u>Surface recession</u> : B’ Model

Surface balance :

The corrected Stanton number takes the form :

With :

$$B'_{ca} = \frac{\dot{m}_c}{\rho_e u_e Ch}$$

$$B'_{pg} = \frac{\dot{m}_{pg}}{\rho_e u_e Ch}$$

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Surface recession : B' Model

Surface balance :

$$B'_{ca} = \frac{\dot{m}_{ca}}{\rho_e u_e Ch}$$

$$B'_{pg} = \frac{\dot{m}_{pg}}{\rho_e u_e Ch}$$

A thermo-chemical equilibrium and element conservation is considered in a closed control volume

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Surface recession : B' Model

Surface balance :

$$B'_{ca} = \frac{\dot{m}_{ca}}{\rho_e u_e Ch}$$

$$B'_{pg} = \frac{\dot{m}_{pg}}{\rho_e u_e Ch}$$

A thermo-chemical equilibrium and element conservation is considered

obtained with assumptions from atmospheric model

obtained by experimental analysis of the elemental composition of the resin

Momentum and mass transport

=1 as the char contains only carbon element

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Surface recession : B’ Model

Surface balance :

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$$B'_{pg} = \frac{\dot{m}_{pg}}{\rho_e u_e Ch}$$

Equation could be solved with mutation ++

Bprime model was developed in the 1960s by the Aerotherm Company under NASA funding. It is a state-of-the-art model for reactive boundary layers to couple material and flow simulation.

Surface recession : B' Model

Surface balance :

$$B'_{ca} = \frac{\dot{m}_{ca}}{\rho_e u_e Ch}$$

$$B'_{pg} = \frac{\dot{m}_{pg}}{\rho_e u_e Ch}$$

For Pampero, a utility from open-source software PATO is used to generate a Bprime interpolation table.

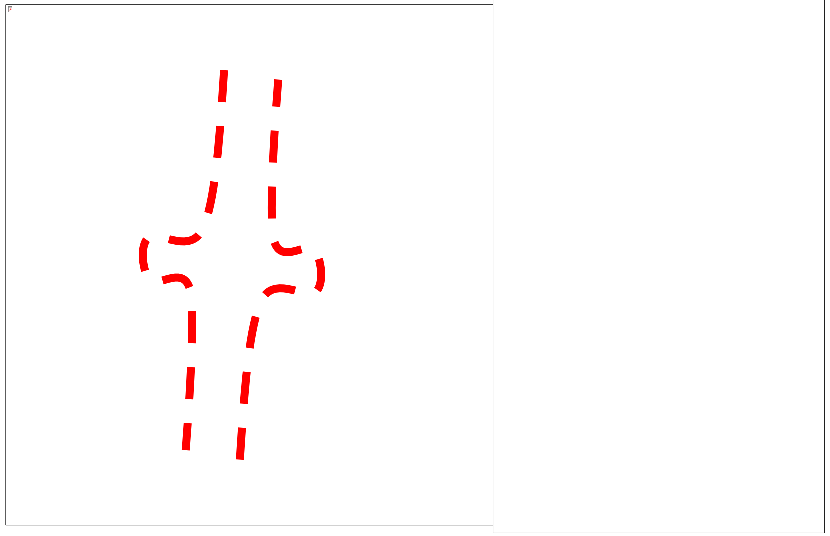
From this table can be interpolated as a function of (T, p, Bpg') the dimensionless mass transfer for char Bca' and the wall enthalpy hw. This utility calls Mutation ++ to generate the table with Bprime coefficients and wall enthalpy hw for a range of pressures and temperatures.

Using the interpolation table rather than solving the chemical equilibrium composition decreases the computational time.

Uncertainties and Sensitivity analysis : thermocouple

The presence of adhesive mounting of the sensors could disturb the measurement which in results impact the comparison with the simulations

Back face of CFRP plate before (left) and after (right) test



Observed CFRP Pyrolyze pattern compared to thermocouple position

Uncertainties and Sensitivity analysis : Material properties

The emissivities have been studied up to high temperatures but are slightly different from VKI measurements

Sample characterized at ONERA

Emissivities measured at ONERA (left) VKI (right)

Both emissivities has been used

Uncertainties and Sensitivity analysis : Material properties

The conductivity/heat capacities has been measured at relatively low temperatures (up to 450°C for virgin and 300K for degraded CFRP) to avoid any degradation during the characterization

Sample characterized at ONERA

Conductivities/heat capacity measured at ONERA

Uncertainties and Sensitivity analysis : Degradation modelling

Some material degradations are not taken into account by the simulation models:

- **Swelling for CFRP:** it has been shown that it could have a strong impact on the temperature prediction in [1]

A **sensitivity analysis** has been conduct with the effect of the step on the **heat fluxes** : the heat fluxes can see **+50% by changing the step.**

Swelling can impact the dimension of the step.

Step of 1mm

Step of the original plate

Effect of the step on the heat flux

[1] X. Wang, *Modelisation of the thermal degradation of composites in order to predict their fire reaction when they are exposed to flames*, https://theses.hal.science/tel-04269903, 2023.