

# Full-scale Mars Science Laboratory Tiled Heatshield Material Response

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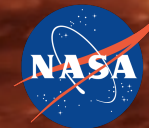
**Nagi N. Mansour<sup>2</sup>**

## 9<sup>th</sup> Ablation Workshop

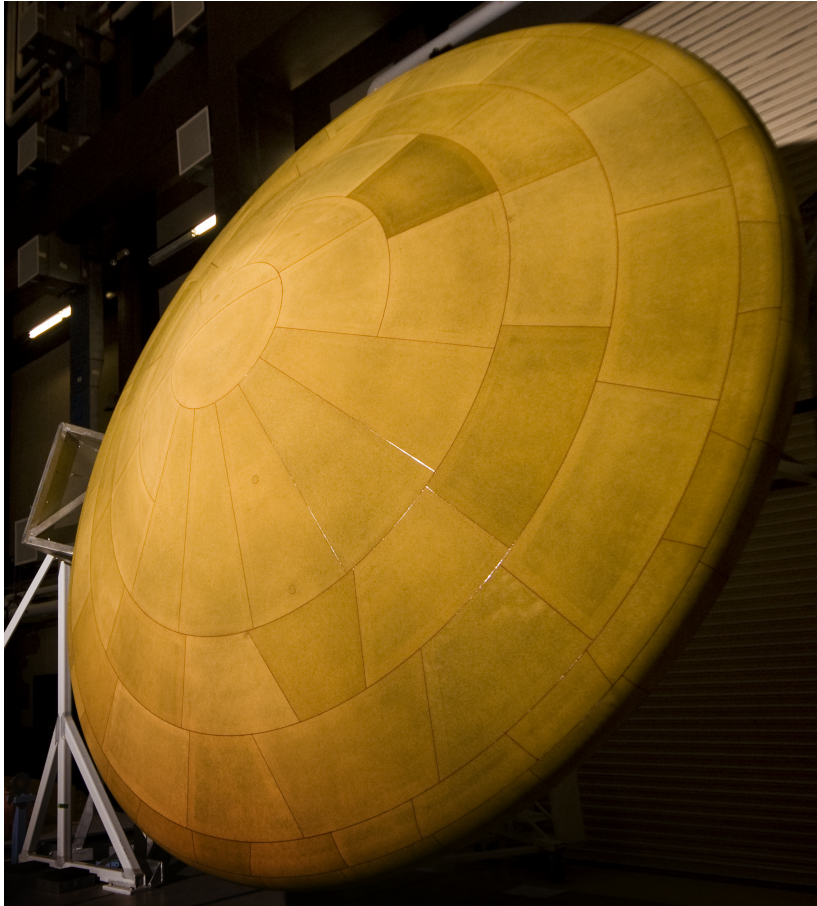
Montana State University, August 30<sup>th</sup> - 31<sup>st</sup>, 2017

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# Mars Science Laboratory landed Curiosity in 2012



tiled MSL PICA heatshield  
Lockheed Martin

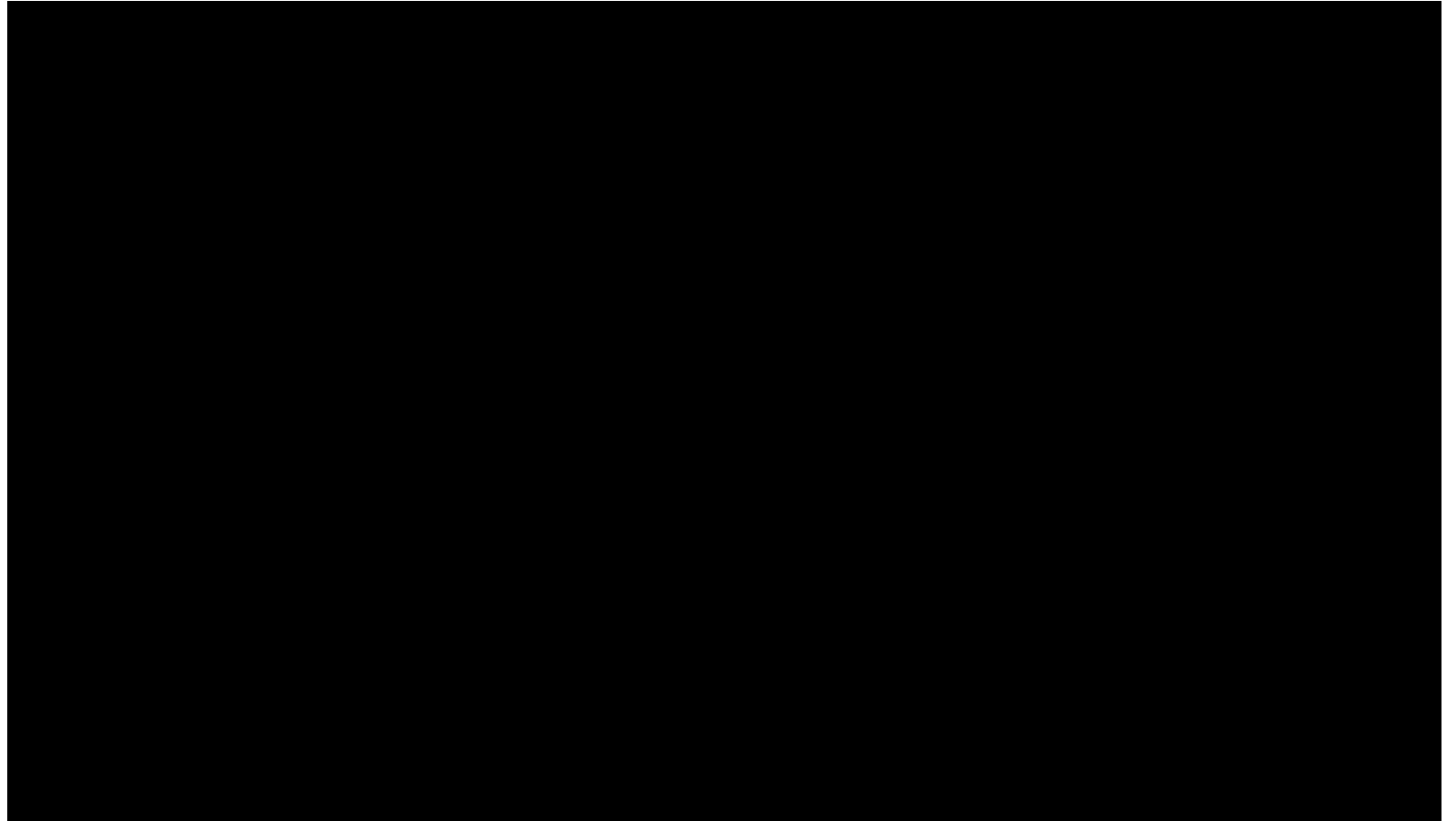
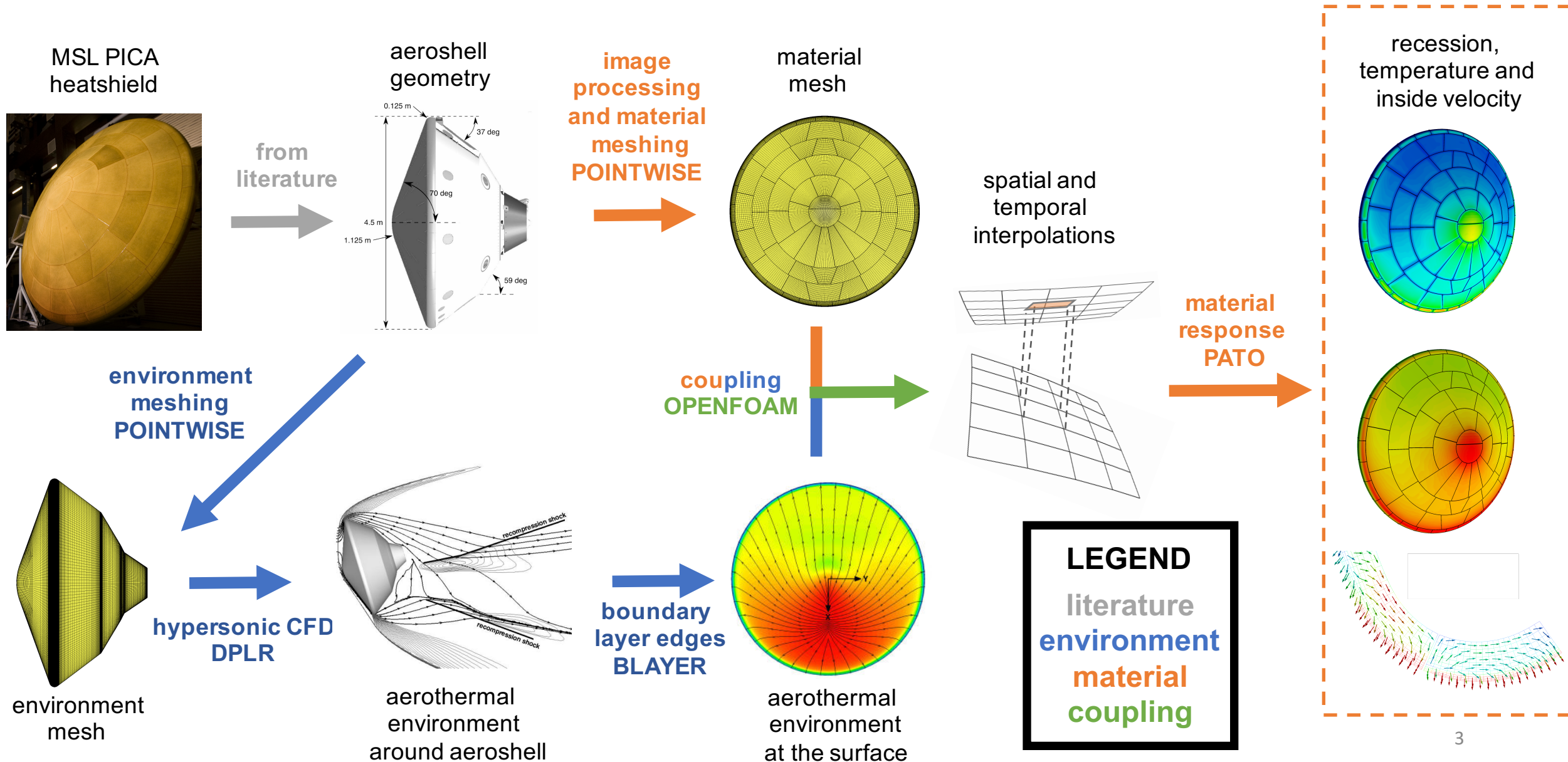


illustration of MSL Mars entry on August 2012  
credit: NASA JPL

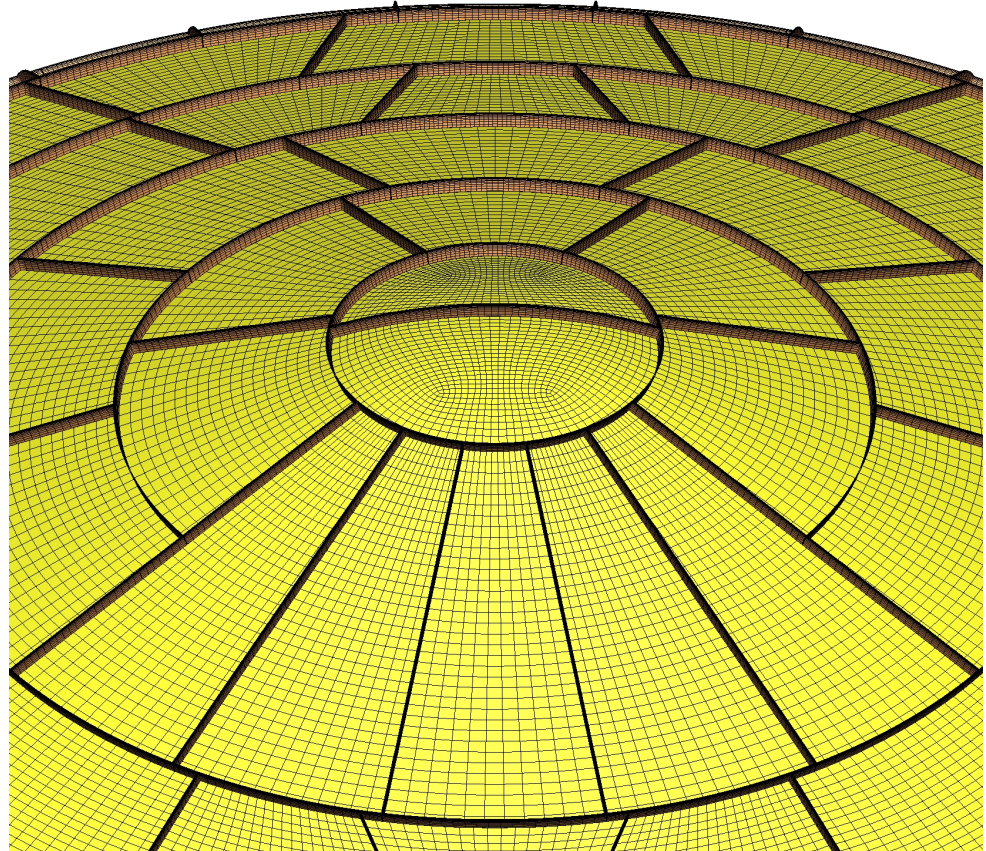
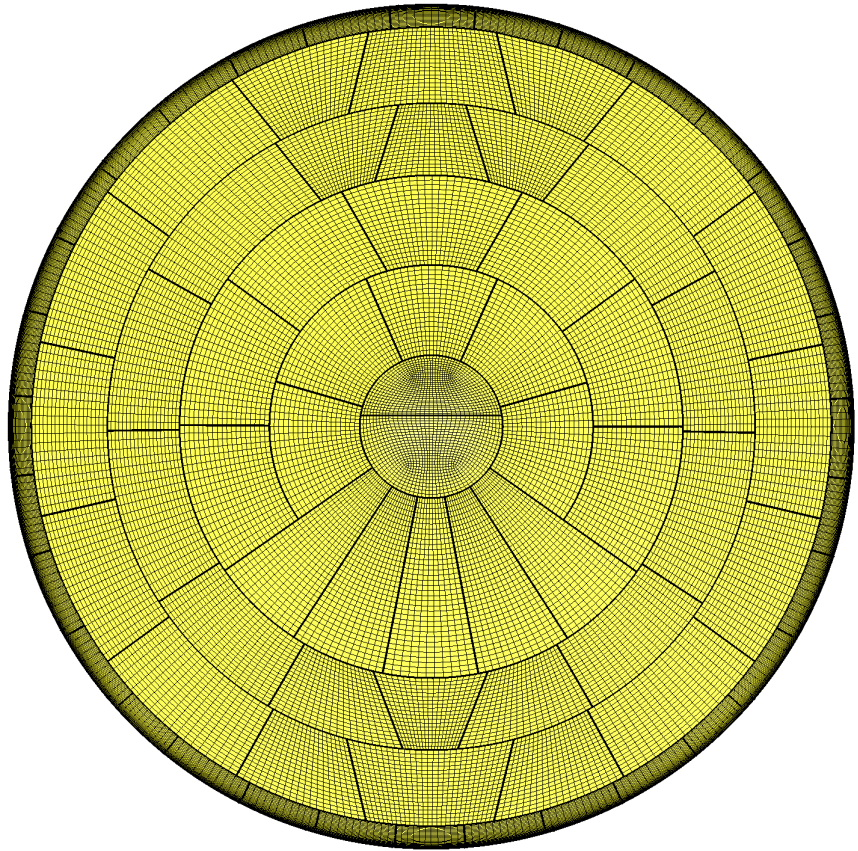
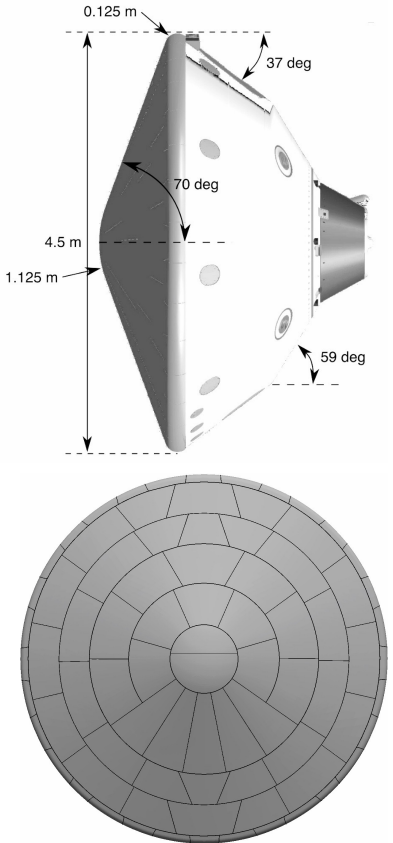


# Overview – coupling aerothermal environment and material response





# Computational domain of the entire MSL heatshield



aeroshell geometry with 113 PICA heatshied tiles

2 million cells mesh of the tiled heatshield

heatshield material in 2 regions  
bounding agent + porous tiles



# PATO\* is used for the material response model

## Pyrolysis

$$\partial_t \chi_{i,j} = (1 - \chi_{i,j})^{m_{i,j}} T^{n_{i,j}} A_{i,j} \exp\left(\frac{-E_{i,j}}{RT}\right)$$

$$\Pi = \sum_{i=1}^{N_g} \sum_{j=1}^{N_p} \sum_{k=1}^{P_j} \zeta_{i,j,k} \epsilon_{i,0} \rho_{i,0} F_{i,j} \partial_t \chi_{i,j}$$

## Mass and momentum conservation

$$\partial_t \left( \frac{\epsilon_g M}{RT} p \right) - \partial_x \cdot \left( \frac{pM}{RT} \left[ \frac{1}{\mu} \bar{K} + \frac{1}{p} \bar{\beta} \right] \right) = \Pi$$

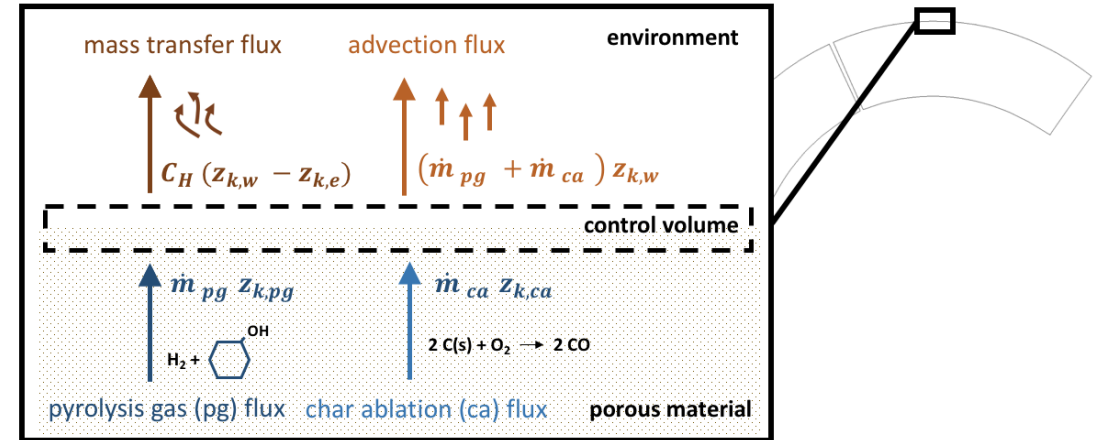
## Energy conservation

$$\sum_{i=1}^{N_p} [(\epsilon_i \rho_i c_{p,i}) \partial_t T] - \partial_x \cdot (\bar{k} \cdot \partial_x T)$$

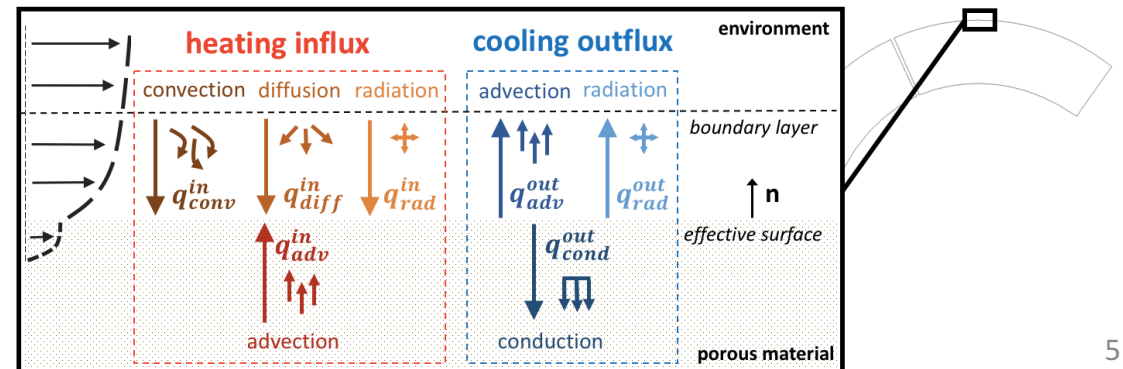
$$= \sum_{i=1}^{N_p} [h_i \partial_t (\epsilon_i \rho_i)] - \partial_t (\epsilon_g \rho_g h_g - \epsilon_g p) + \partial_x \cdot (\epsilon_g \rho_g h_g v_g)$$

\* PATO = Porous-material Analysis Toolbox based on OpenFOAM

## Surface mass balance $\longrightarrow h_w \dot{m}_{ca}$



## Surface energy balance $\longrightarrow T_w$



# A new GUI implemented in PATO

PATO (Porous-material Analysis Toolbox based on OpenFOAM)

1. Set Case

2. Environment

3. Regions

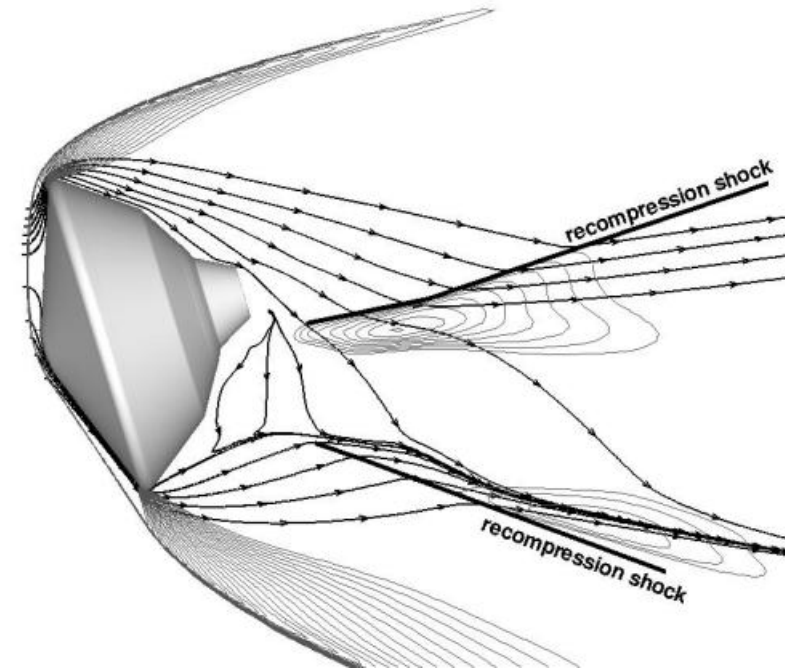
case definition	constant/setCase
<input checked="" type="checkbox"/> boundaryLayerApprox	<b>constrainedEquilibrium yes; // reaction-limited surface oxidation rate – only with mutationBprime ('on-the-fly')</b> // yes: finite-rate, available C+O->CO (using rate of Park, bounded by equilibrium) // no: equilibrium
<input type="checkbox"/> failureFraction	
<input checked="" type="checkbox"/> physicsBasedErosionModel	wallSpeciesDiffusion 1; // this coefficient can take any number; diffusion enthalpy flux = - rhoeUeCh * h_w * wallSpeciesDiffusion // 1 : State-of-the-art approximation for species diffusion // 0 : Diffusion neglected
model# (Press enter) <input type="text" value="1"/>	// 1-b) Options for axi-symmetrical heat fluxes - radial evolution factor read from file 'constant/environmentProperties/fluxFactorMap' axiSymmetricalFlux no; // "no" for uniform heat load (value inputed in 'constant/environmentProperties/boundaryConditions' is used uniformly) // "yes" for axiSymmetrical heat load, the three following fluxFactors are used: // 1- choose normal to directions along which the flux varies (e.g. axis of an IsoQ sample for example). Use X= (1 0 0), Y= (0 1 0), or Z= (0 0 1): fluxFactorNormal (1 0 0); // 2- choose center of axi-symmetry fluxFactorCenter (0.0 0.0 0.0); // 3- choose type of projection fluxFactorProjection no; // yes: projection on the plane perpendicular to the Normal and passing by the center (recommended for plane surfaces: e.g. top of a cylinder); // no: projection directly on the Normal itself; that is, the distance from the center is directly computed by projection on the Normal (recommended for convex surfaces, e.g. IsoQ samples). // **** End Options for axisymmetrical heat fluxes
<input type="checkbox"/> volAblation	
<input checked="" type="checkbox"/> constrainedEquilibrium	
<input checked="" type="checkbox"/> wallSpeciesDiffusion	
<input type="checkbox"/> axiSymmetricalFlux	
fluxFactorNormal <input type="text"/>	
fluxFactorCenter <input type="text"/>	
fluxFactorProjection <input type="text"/>	
<input type="checkbox"/> finiteRate	// Step 2 - Set in-depth model (all no = type 2 base model) finiteRate no; // no: Equilibrium chemistry is used based on the elemental fractions of the pyrolysis gases. // yes: Finite-rate chemistry based on species fractions (species production in the pyrolysis reactions, finite-rate chemistry mechanism) // The chemistry mechanisms and their chemistry databases are selected in file 'thermophysicalProperties'. // Set initial gas composition in directory 'U' (Update O2, N2, files may be added as necessary for other species present at t=0).
<input type="checkbox"/> multiComponent	multiComponent no; // yes: Multicomponent diffusion is used - Average diffusion coefficients are computed with Mutation++ and Fick's law is used // Only available when mutationTT is switched to 'yes' - defaults to 'multiComponent = no' otherwise. // Option available in finite-rate chemistry mode only (finiteRate=yes).
<input type="checkbox"/> elementConservation	// no: Binary diffusion is used - an equal diffusion coefficient D is used for all molecules (update D in 'constant/porousMat/constantProperties')
<input checked="" type="checkbox"/> mutationTT	
<input checked="" type="checkbox"/> mutationBprime	
<input type="checkbox"/> detailedSolidEnthalpies	elementConservation no; // yes: Element conservation equation is solved in equilibrium mode. // Reduce the max time step to 1e-4 to prevent instability. // no: Used when element fraction is constant (e.g. type 1 and 2 models), and in finite-rate chemistry mode (species conservation is automatically used).
<input checked="" type="checkbox"/> readBoundaryTecplotTable	



# Aerothermal environment computed from DPLR\*

## DPLR assumptions

- laminar boundary layer
- chemical and thermal non-equilibrium
- radiative equilibrium
- super-catalytic wall
- non-blowing & smooth wall
- 12 reactions & 8 species
- Mars atmosphere:  $y_{\text{CO}_2} = 0.97$ ,  $y_{\text{N}_2} = 0.03$

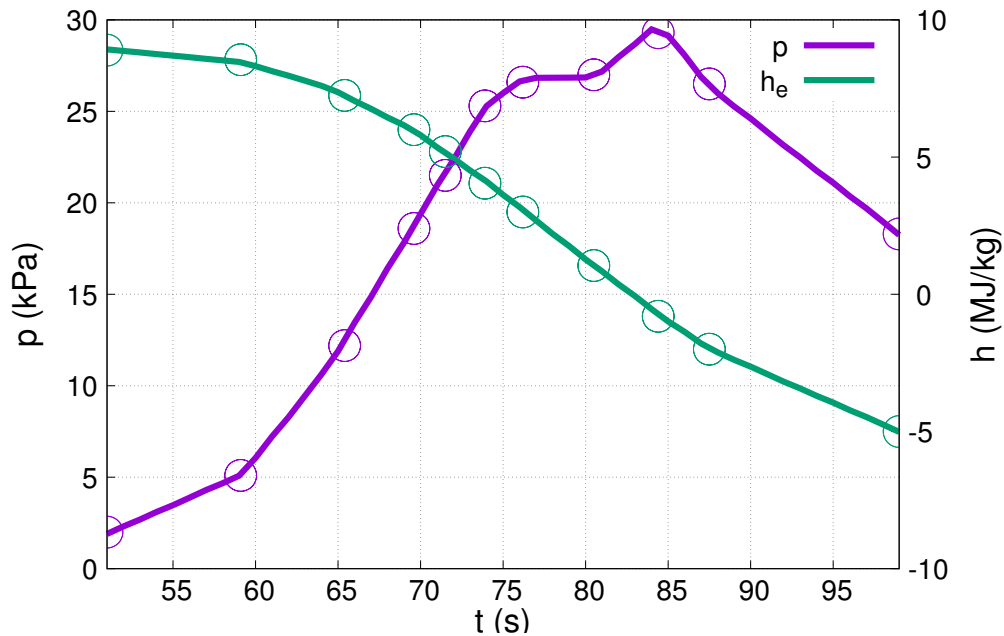


**BLAYER** calculates the **boundary layer edges** using a curvature-based method

**surface pressure  $p_w$ , heat transfer coefficient  $C_H$  and enthalpy  $h_e$  at the boundary layer edges** are used as inputs in the **material response code: PATO**

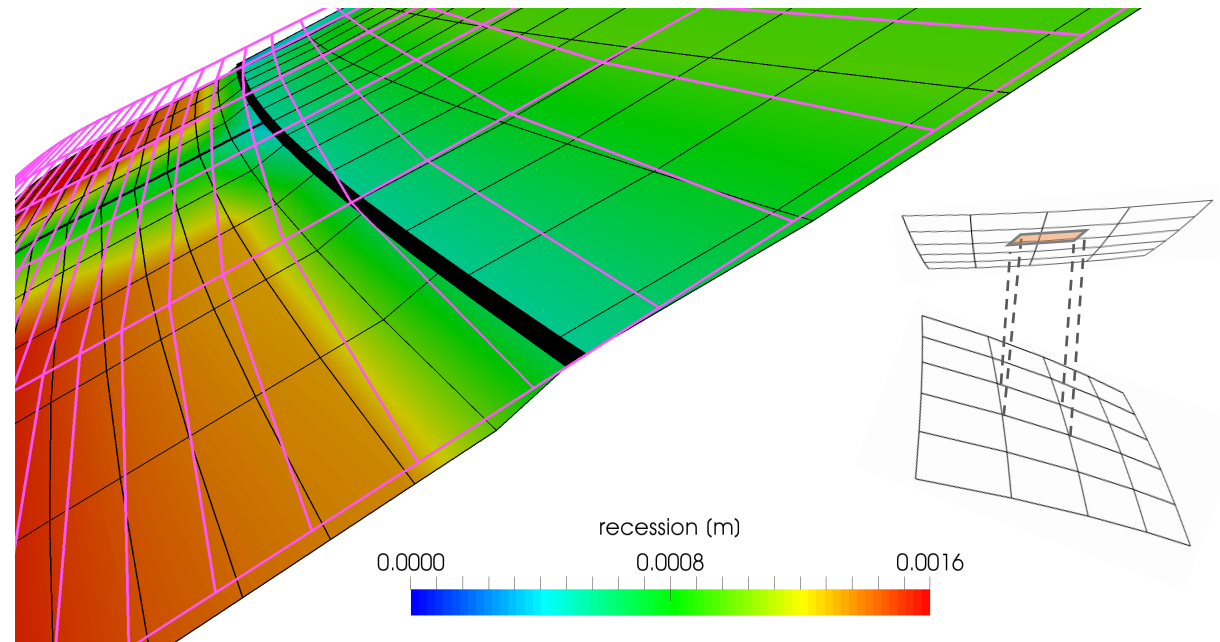
# Temporal and spatial interpolations

## temporal interpolation



11 **discrete** times  
(50s to 100s of MSL entry)  
**linear** interpolation

## spatial interpolation

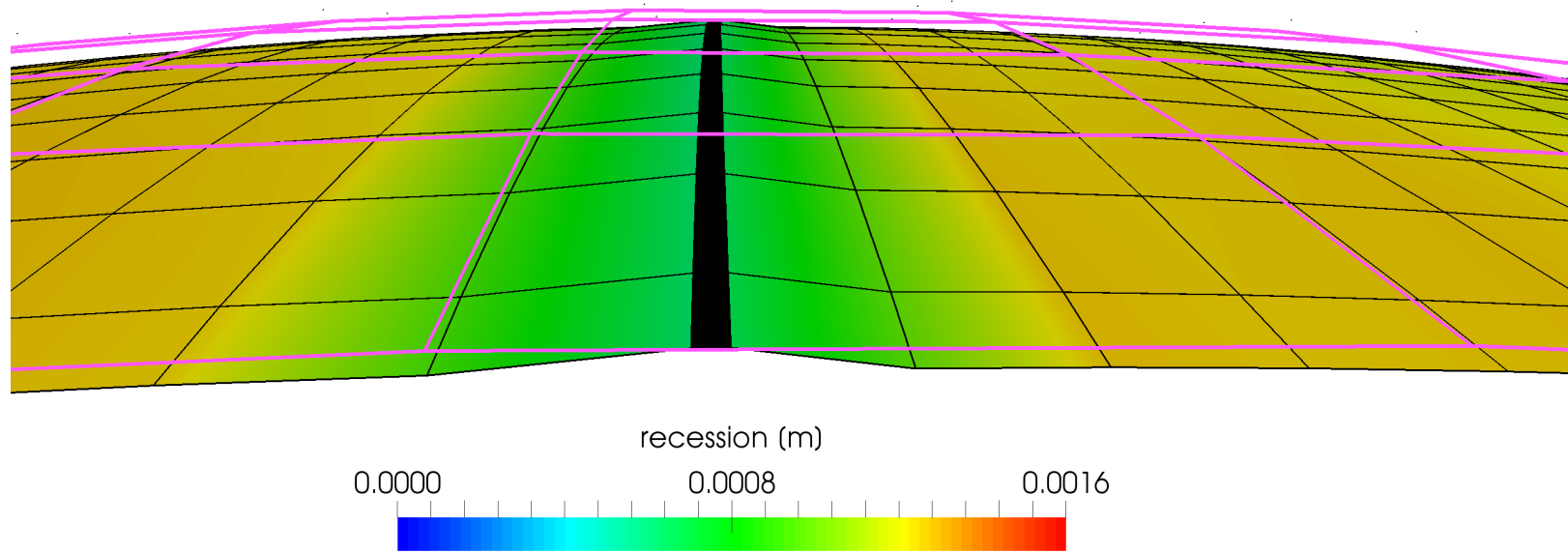


separate mesh regions are numerically **connected** by  
the **Arbitrary Mesh Interface (AMI)** utility using local  
**Galerkin projection** implemented in **OpenFOAM**

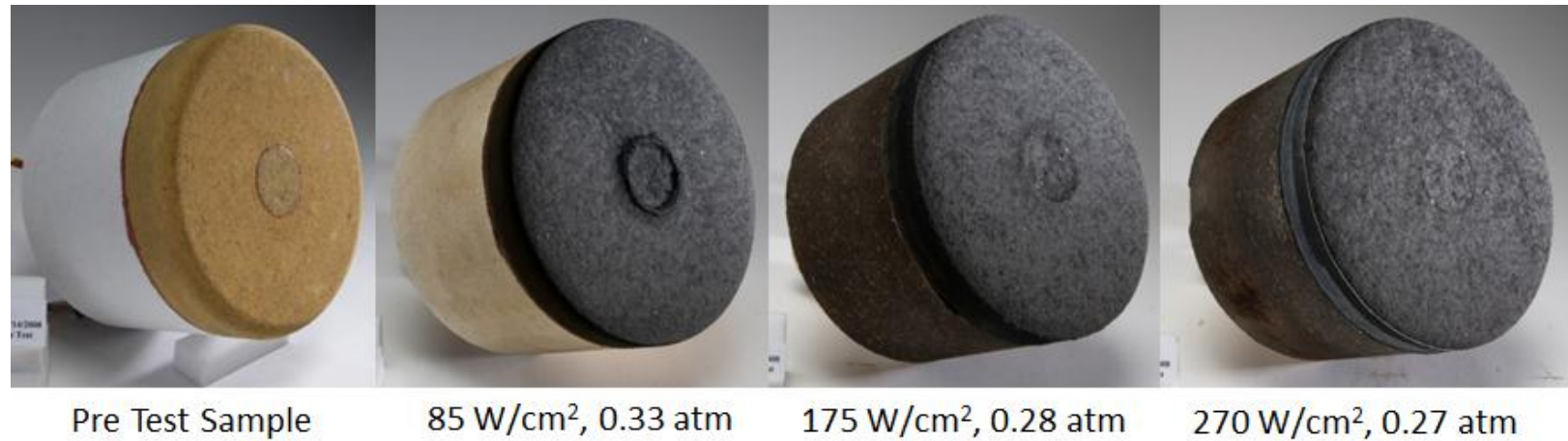


# “Fencing” effect at tiles interfaces

**MSL heatshield  
front surface  
at the nose**



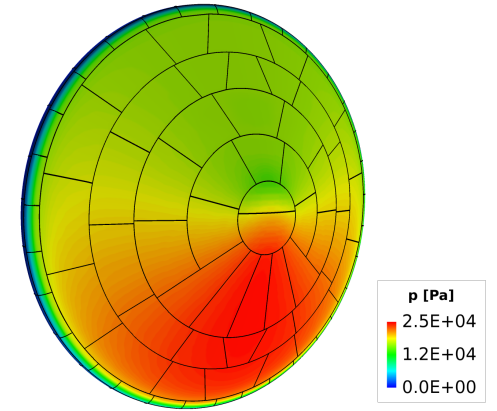
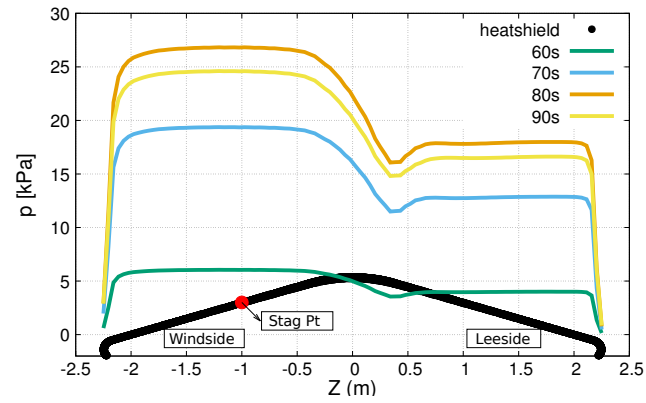
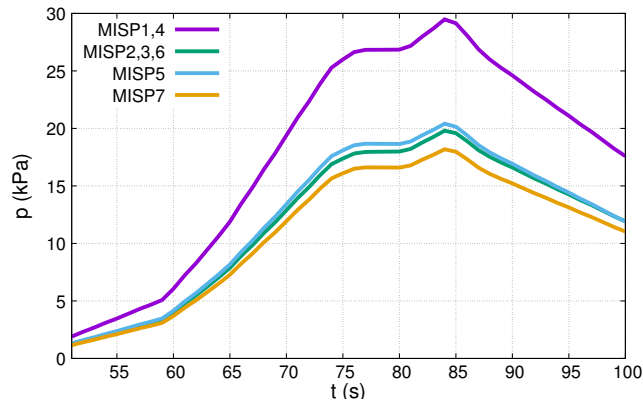
**Post-test  
arcjet coupons**



# Interpolated inputs from BLAYER to PATO

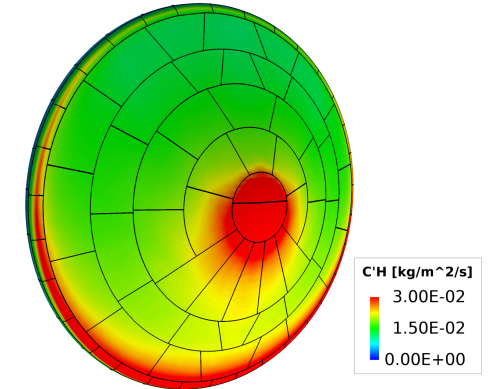
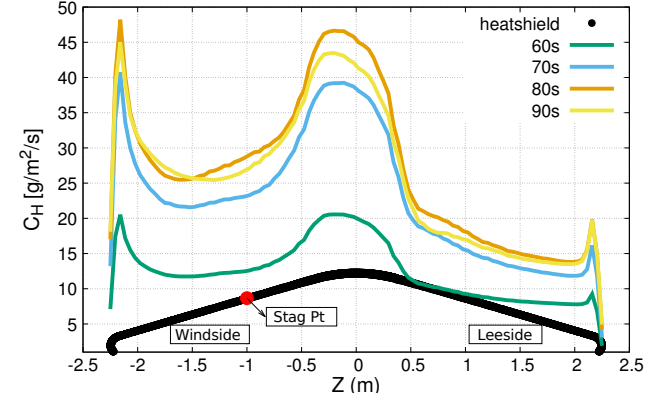
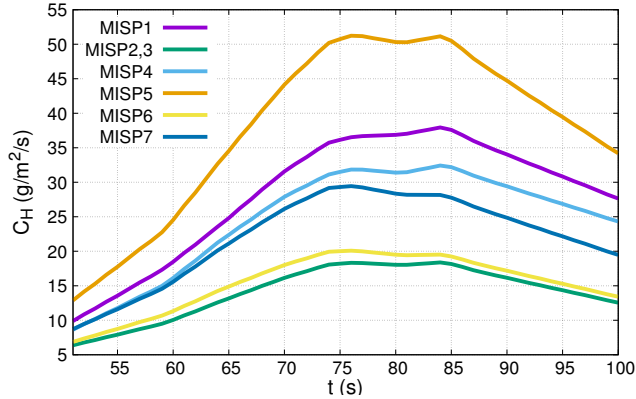
surface pressure

$$p_w$$



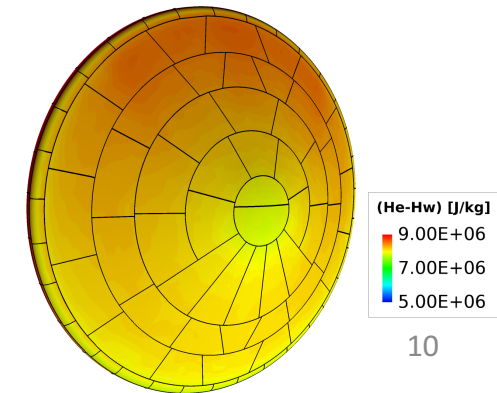
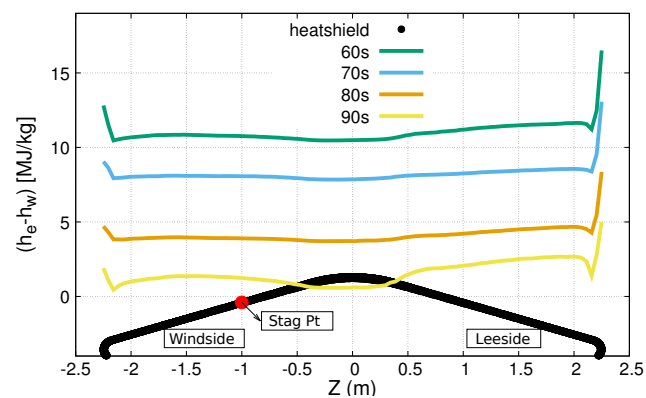
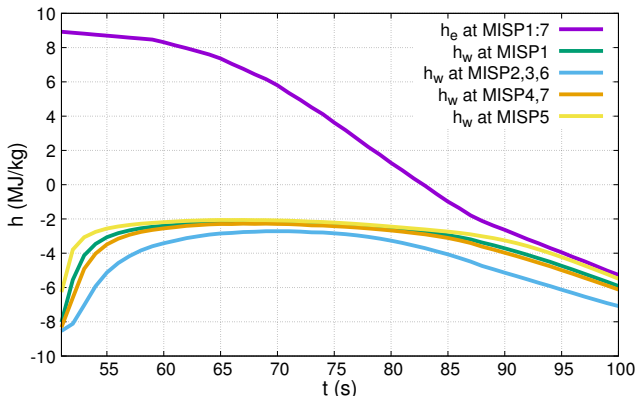
heat transfer coefficient

$$C_H$$



edge enthalpy

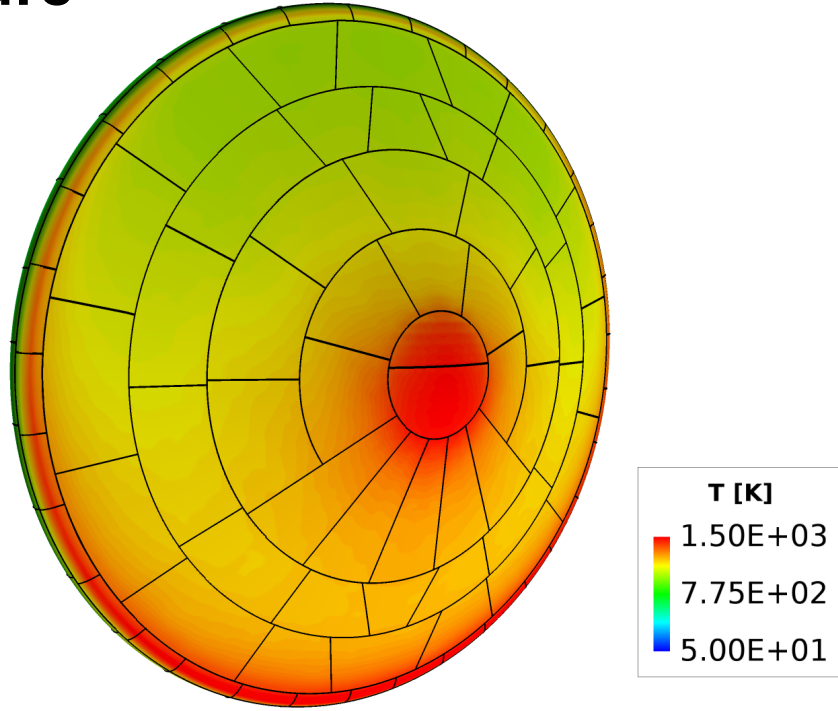
$$h_e$$



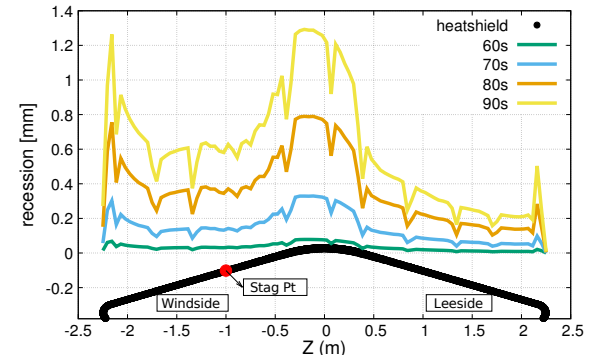
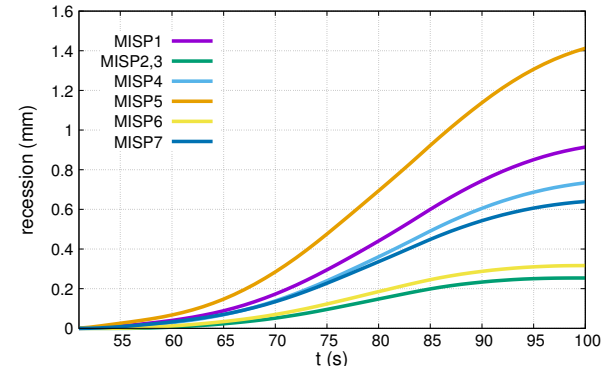
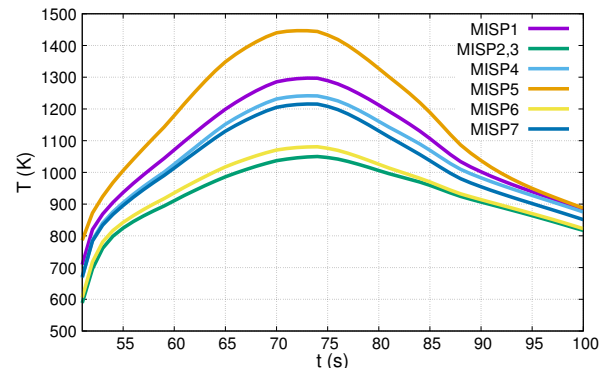
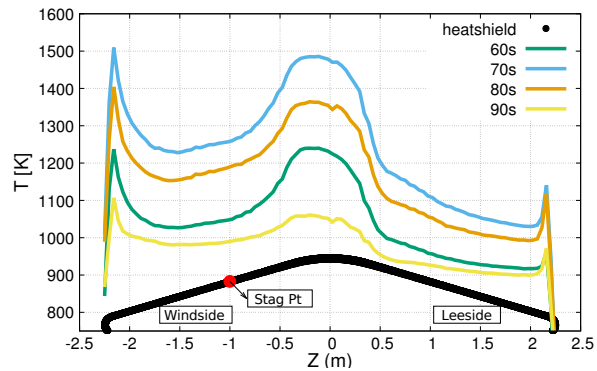
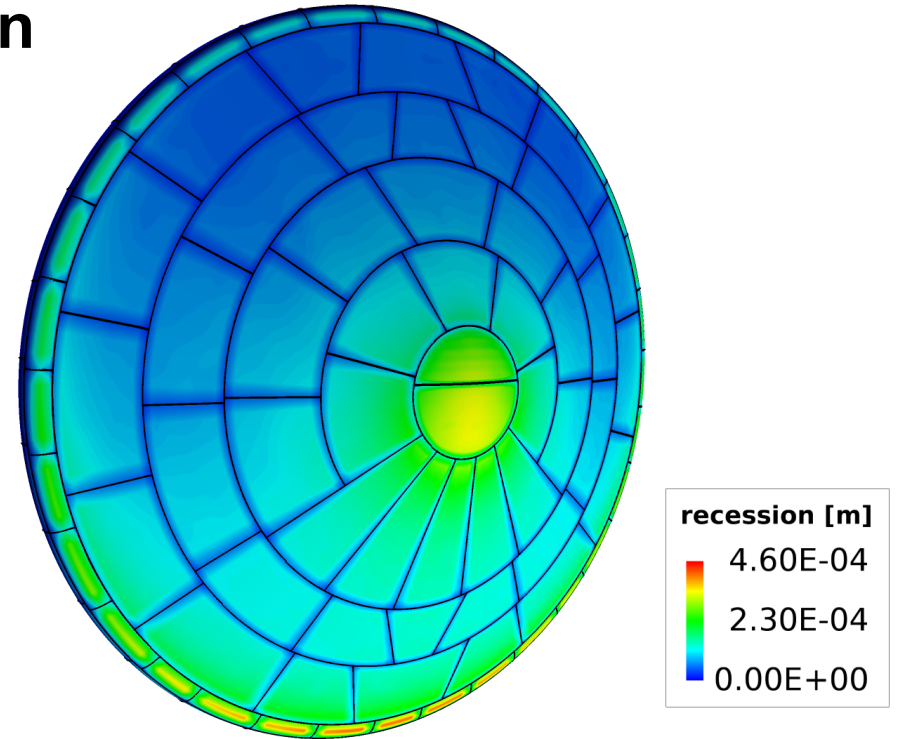


# Temperature and recession from PATO

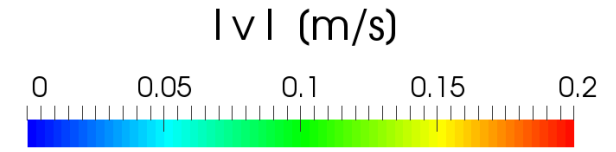
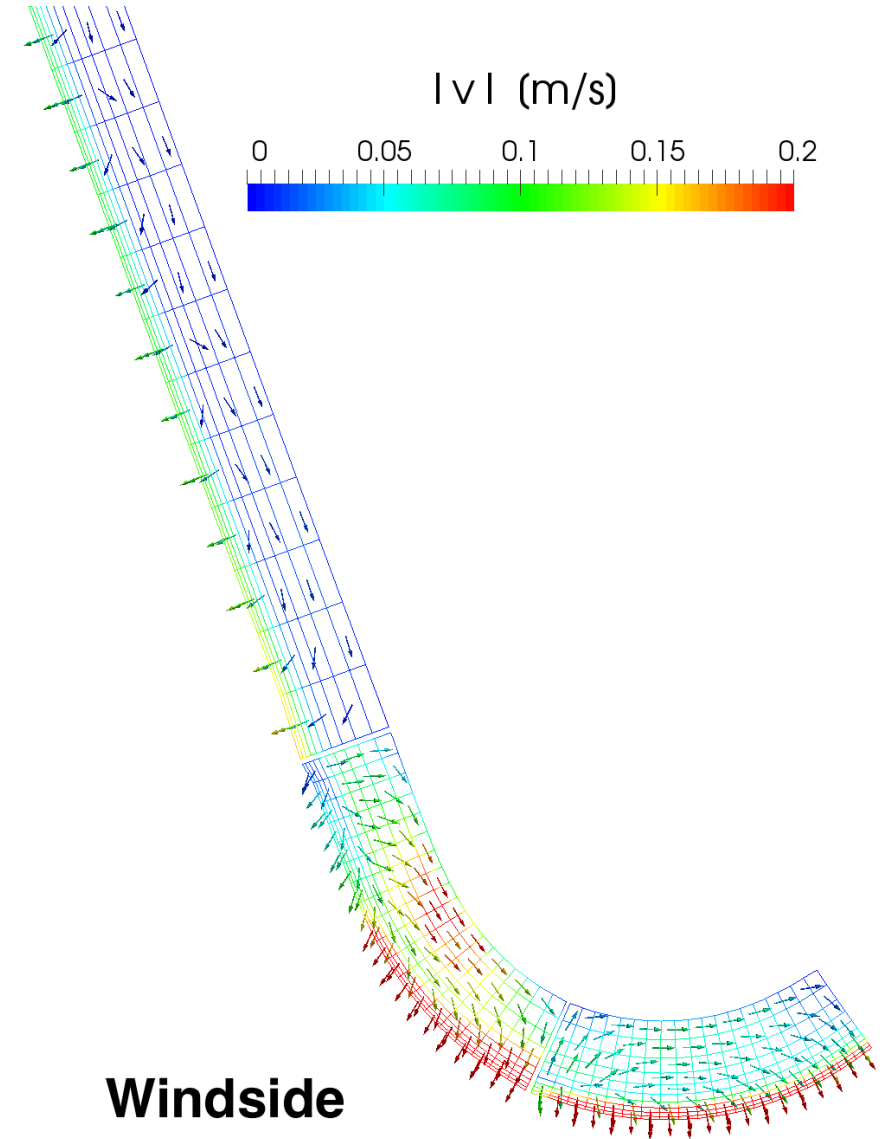
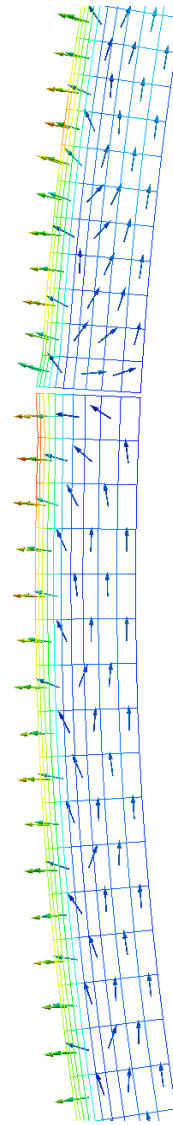
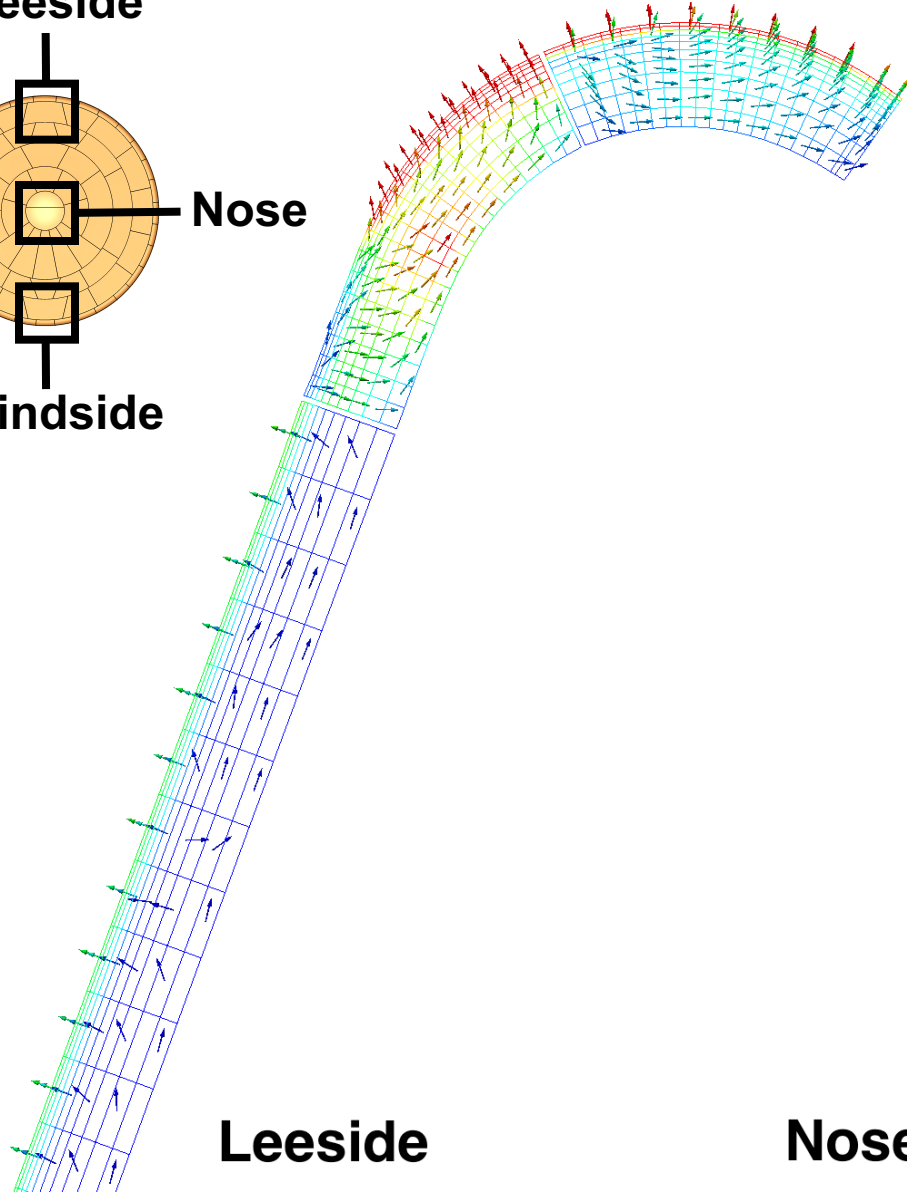
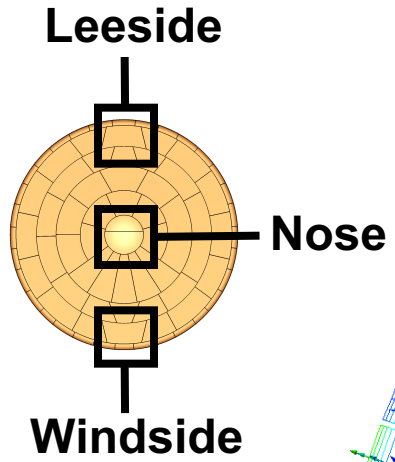
temperature



recession

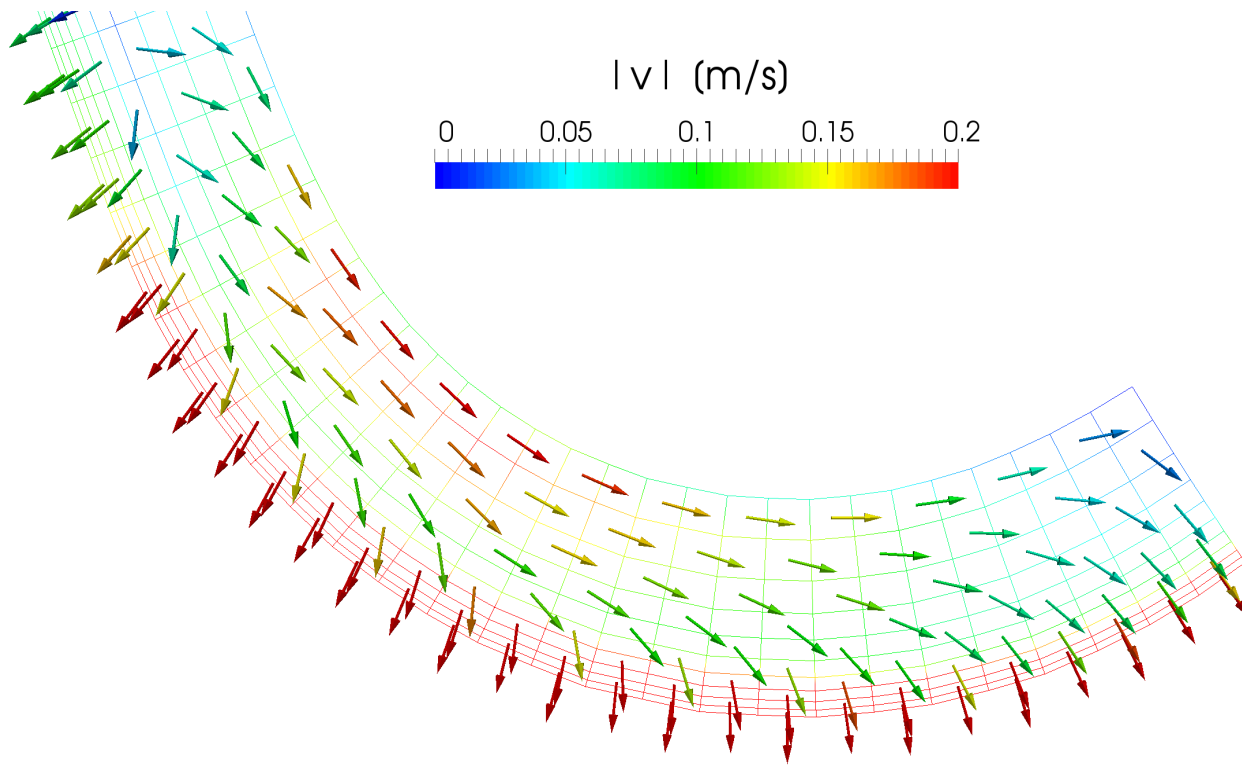


# Velocity inside the porous material

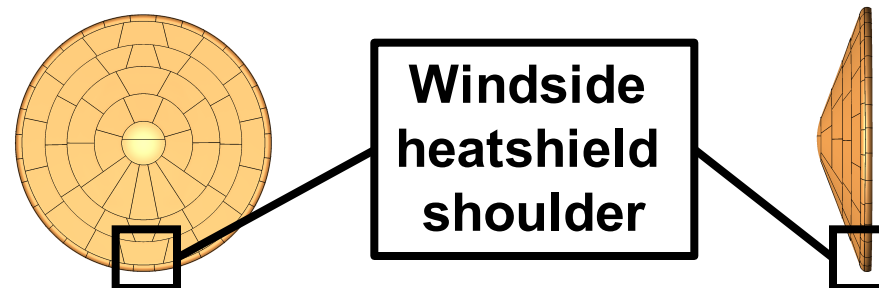
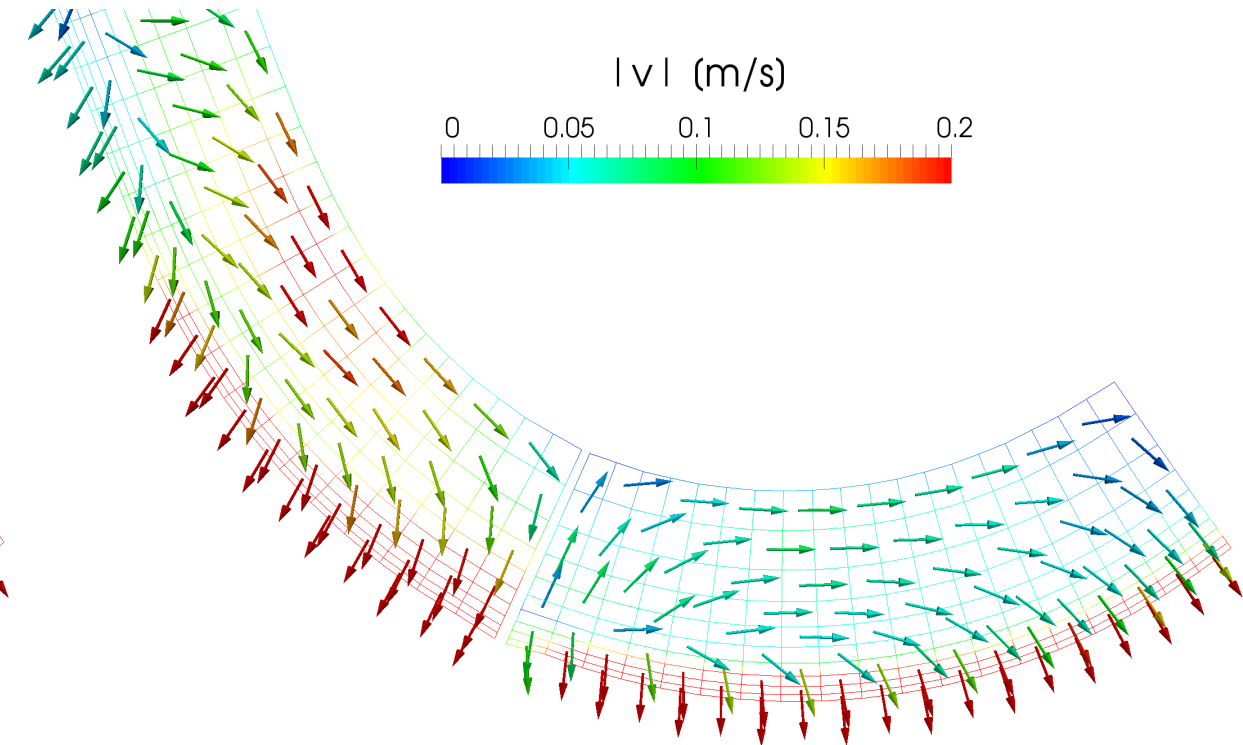


# Tiled configuration changes the flow inside the material

non-tiled configuration

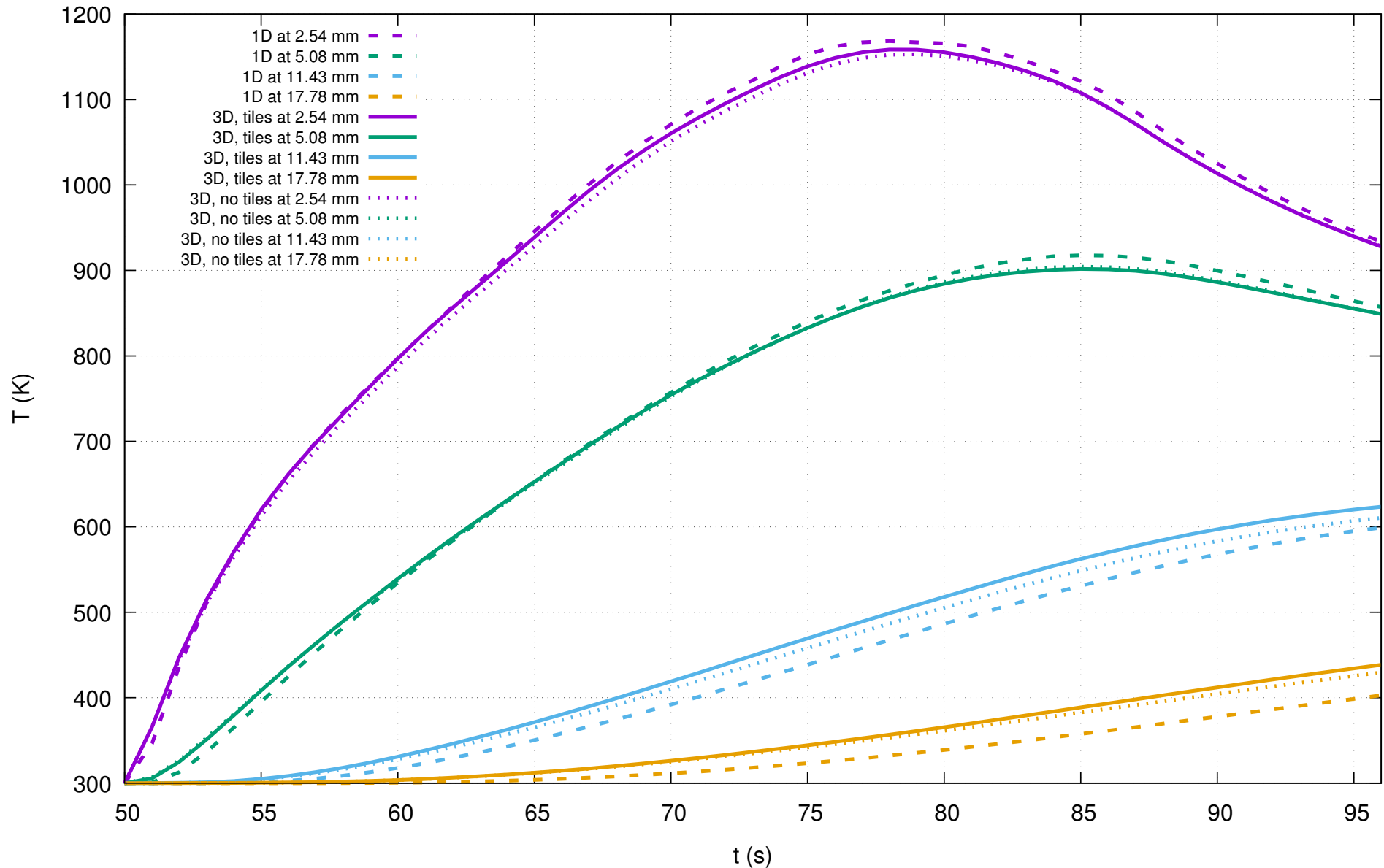
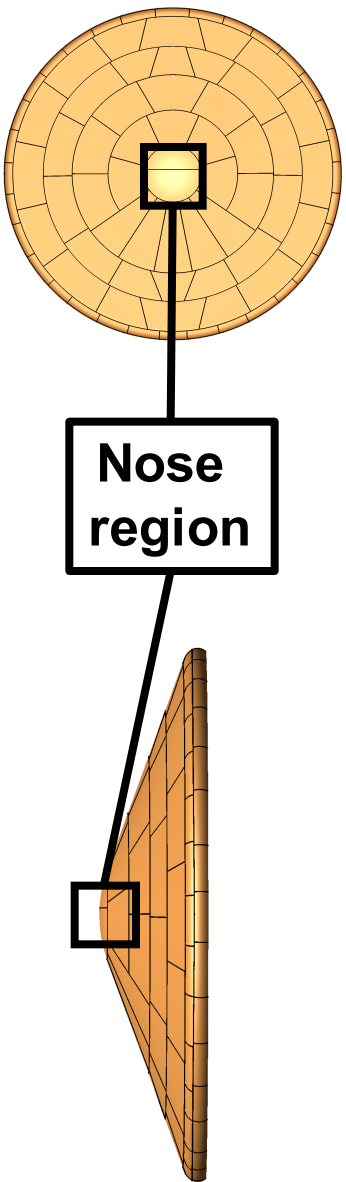


tiled configuration

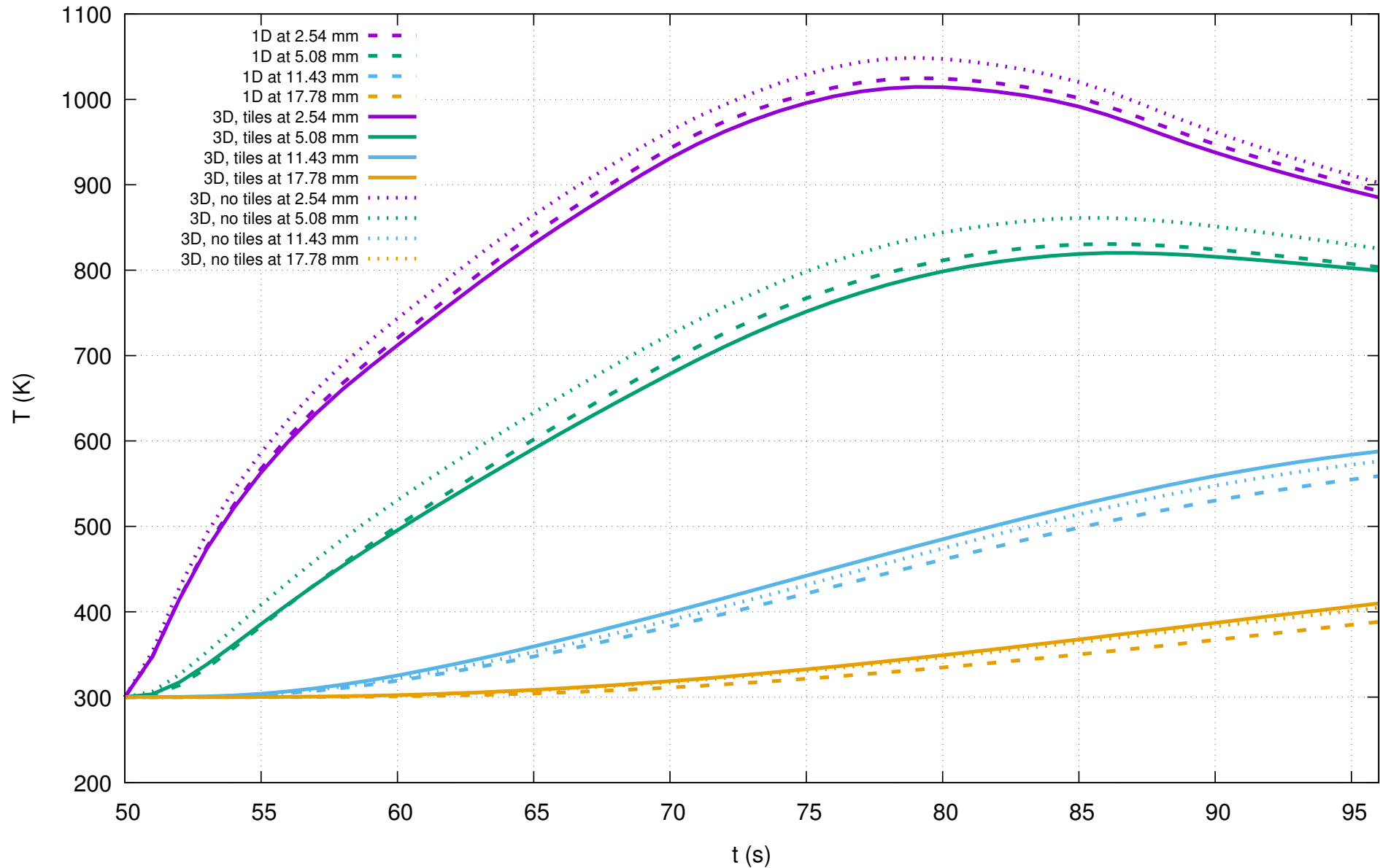
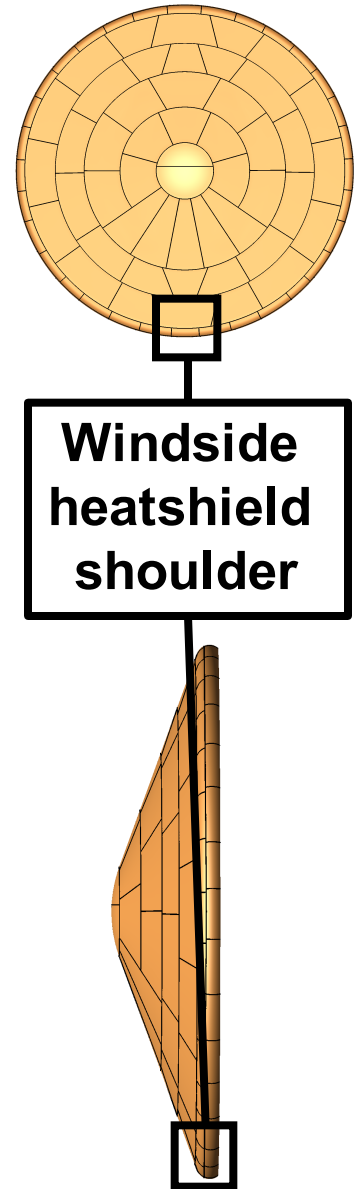




# 1D and 3D material response comparison – nose



# 1D and 3D material response comparison – shoulder



# Conclusion and future work

## hypersonic environment (DPLR)

- laminar
- super-catalytic wall
- non-blowing
- 8 species & 12 reactions

↓ **impacts**

- 2020 mission
- MISP locations
- “fencing” effect
- tiled configuration

## coupling



Linear in time  
Conservative in space by  
local Galerkin projection



Future work includes  
blowing from pyrolysis &  
moving mesh from recession

## porous material response (PATO)

- equilibrium
- pyrolysis
- CMA-type BL approx.
- no finite-rate, no oxidation

↓ **outputs**

- temperature
- recession
- heat fluxes
- inside velocity

## impacts

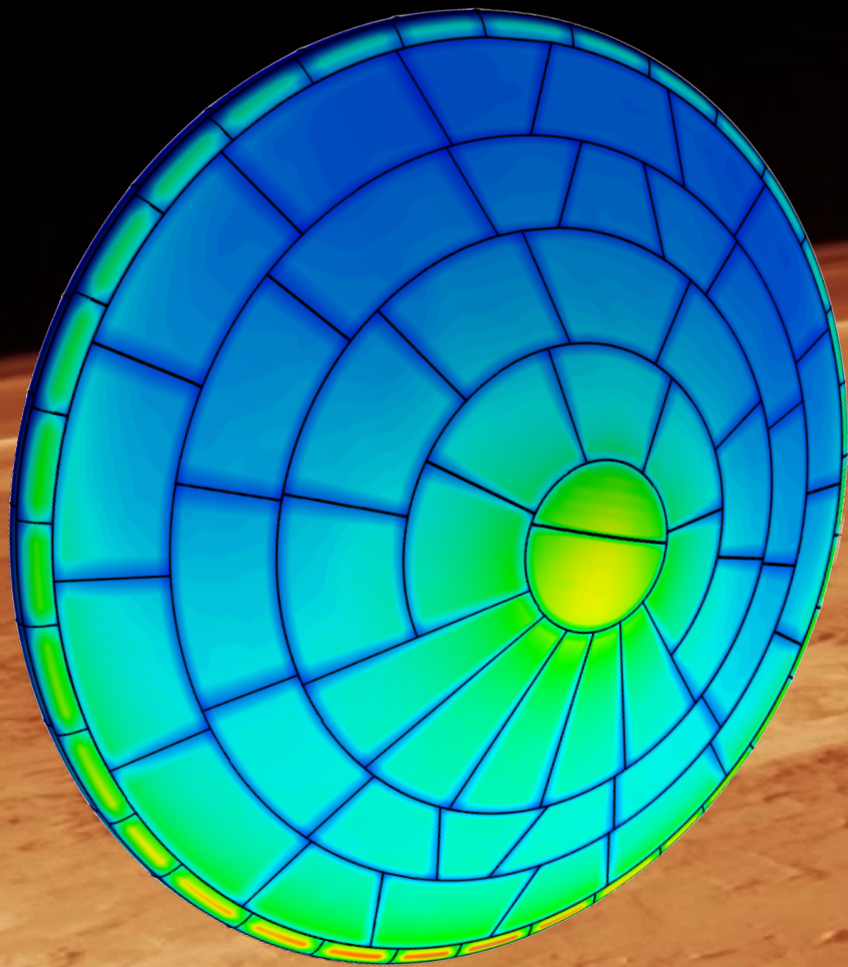


PATO is a useful tool  
to predict material response  
for future entry missions



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# Questions ?

## 9<sup>th</sup> Ablation Workshop

Montana State University, August 30<sup>th</sup> - 31<sup>st</sup>, 2017

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