Porous material Analysis Toolbox based on OpenFOAM

2023 AIAA SciTech

TP-18: Ablation Material Responses

NASA Ames Research Center
Entry Systems Modeling (ESM)

3D ablation modeling of silicone-coated heatshield compared to MEDLI2 in-flight data

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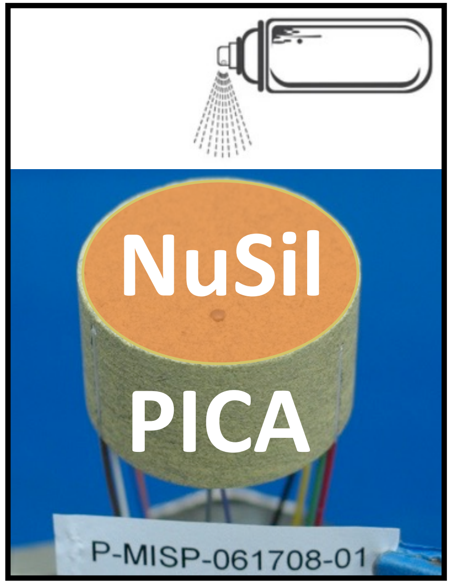
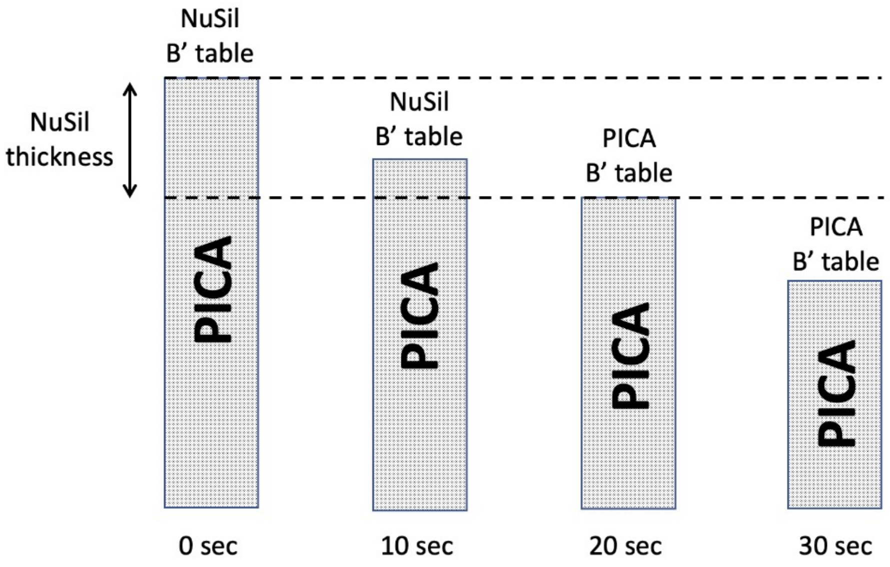
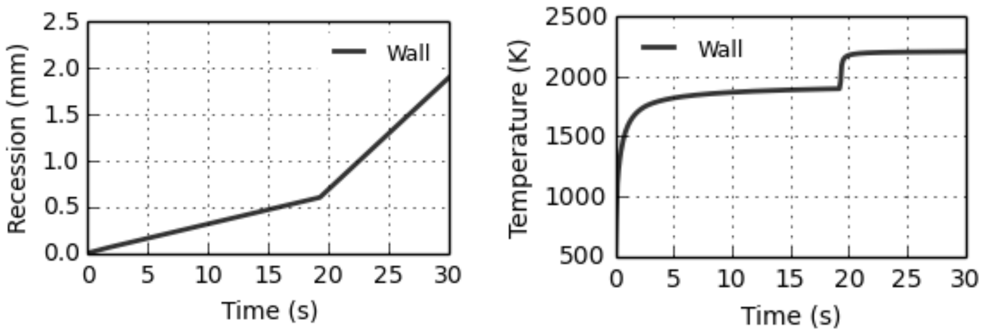
01/26/2023

Introduction of PICA-NuSil

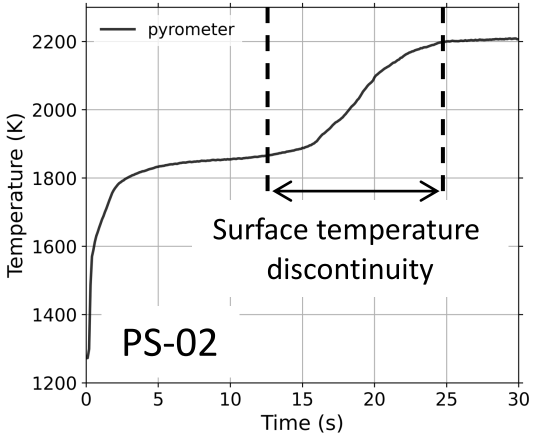


NuSil, a silicone-based overcoat, was sprayed onto the MSL and Mars 2020 heatshields including their in-depth temperature instruments (MISP) to mitigate the spread of phenolic dust from PICA. The behavior and material response of the PICA-NuSil (PICA-N) system consists an open problem in the literature [3,4].





In order to better understand the behavior of the NuSil coating, dedicated experimental campaigns have been conducted, with the first one taking place in NASA's Langley, HyMETS facility in March 2019 [1,2] and the second one in the AHF at NASA ARC in November 2020.



A novel Material Response (MR) model for PICA-N was implemented in PATO that accounts for the observed temperature discontinuity and change of recession rate [4].

PATO overview

Porous material Analysis Toolbox based on OpenFOAM

PATO [4] is a modular research and development platform designed to test innovative physics-based models for porous materials submitted to high-temperature environments at the macro-scale.

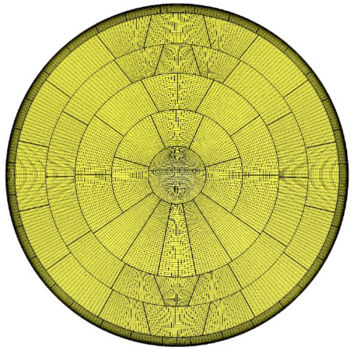
OpenFOAM

- Finite Volume
- PETSc
- I/O management
- Numerical schemes
- Massive MPI
- Fluid solvers
- Moving geometry
- Chemistry
- Basic mesh gen.
- Thermo/Transp.

PATO: material response

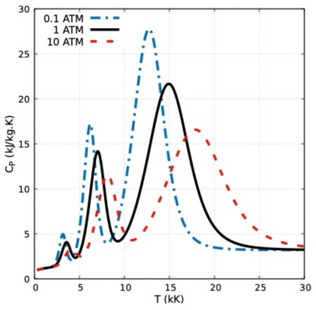
- *PATOx exectuable*
- *Pyrolysis*
- *libPATOx library*
- *Pure conduction*
- *Equilibrium chemistry*
- *1D/2D/3D mapping*
- *Finite-rate chemistry*
- *Multi-material*
- *Volume Ablation*
- *Fluid coupling*

Complex mesh generation



POINTWISE/GMSH

Thermo/Transport/ Chemistry

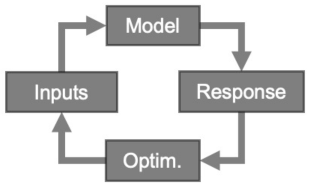


MUTATION++

Optimization/ UQ/SA/PE

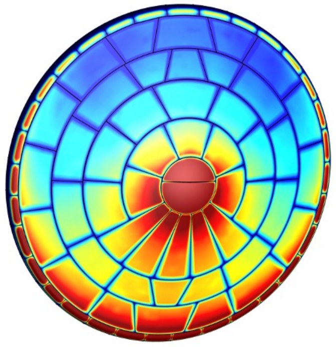
DAKOTA

Explore and predict with confidence.



DAKOTA

Post-processing 1D/2D/3D



FV/TEC

- **PATO website**
  http://www.pato.ac
- **Private GitLab**
  https://gitlab.com/PATO/PATO-dev
- **Installation**
  conda create --name pato
  -c conda-forge -c pato.devel pato
- **1D, 2D, 3D tutorials**
  $PATO_DIR/tutorials
- **NASA developers**
  Jeremie Meurisse, John Thornton, Georgios Bellas Chatzigeorgis & Sergio Fraile Izquierdo
- **Creators (2010)**
  Jean Lachaud & Nagi Mansour

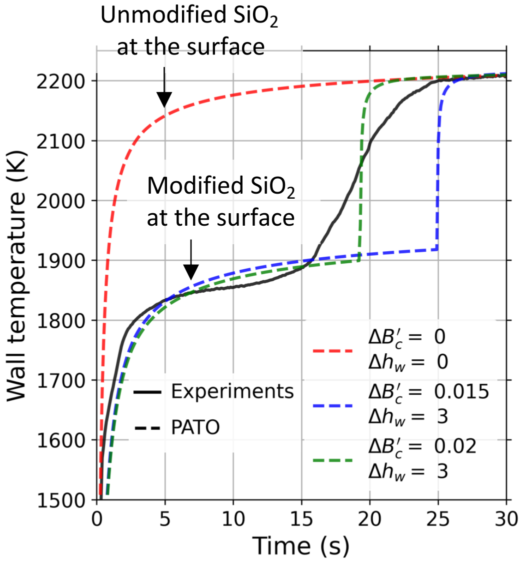
Surface modeling of the charred NuSil as pure silica

At first, the charred NuSil surface was modeled as pure silica (SiO_2) based on the observations of a glassy layer on the post-test coated samples [1,2]. The multiple components formulation of the surface mass balance was implemented in PATO to model the pure silica surface [3,4].

1. Pure silica

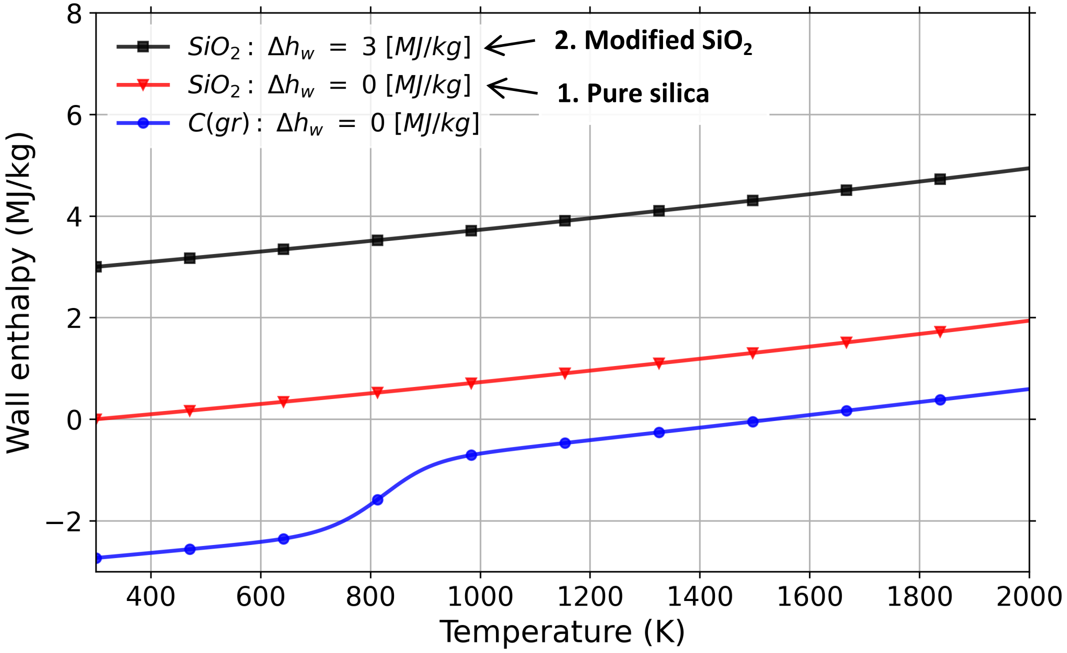
$$B'_c = \frac{\sum_{l=1}^{N_{el}^{s}} \left[B'_g \left(z_{l,pg} - z_{l,w} \right) + z_{l,e} - z_{l,w} \right]}{\sum_{l=1}^{N_{el}^{s}} \left(z_{l,w} - z_{l,ca} \right)}$$

$$\left[-\underline{\underline{\mathbf{k}}} \cdot \partial_x T \right] \cdot \mathbf{n} = C'_H (h_e - h_w) + \dot{m}_{ca} (h_{ca} - h_w) + \dot{m}_{pg} (h_{pg} - h_w) + q_{rad}$$



Then, the surface mass and energy balance equations were modified by adding a constant offset to the char blowing rate ($\Delta B'_c$) and the wall enthalpy (Δh_w) to reproduce the HyMETS experimental results [3,4].

2. Modified SiO_2



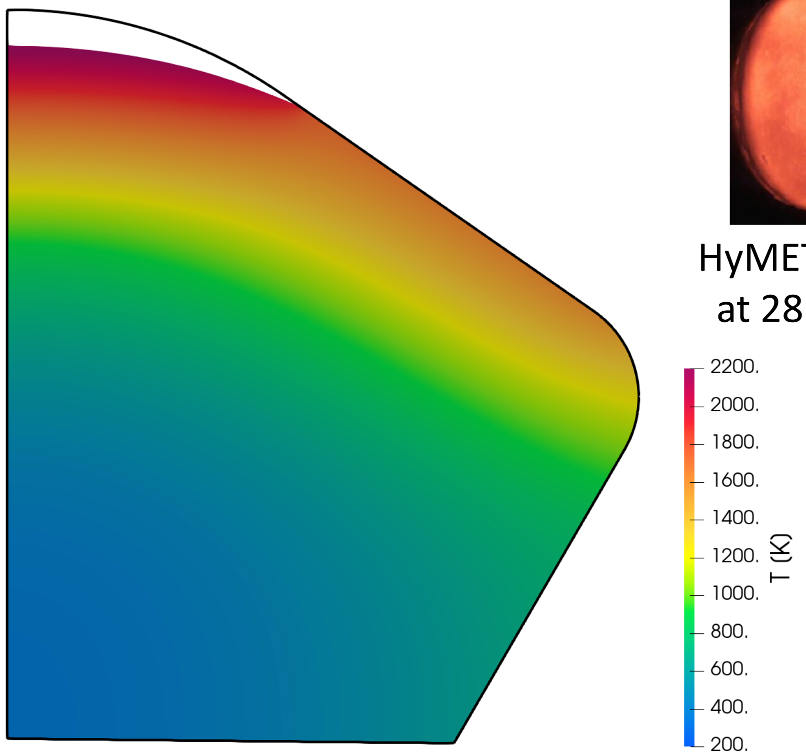
Ablation simulations in HyMETS using charred NuSil modeled as SiO_2

Material	Model	Atmosphere	Heat flux [W/cm²]	Pressure [kPa]
PICA-N	2	Earth	140	5.6

BLAYER: $p_w = 5.6\,kPa$ | $C_H = 0.18\,\frac{kg}{m^2 s}$ | $h_e = 9.7\,\frac{MJ}{kg}$

Recession: $r_{exp} = 1.93\,mm$ | $r_{pato} = 1.98\,mm$

Modified NuSil B' table: $\Delta B_c' = 0.0195$ | $\Delta h_w = 3\,\frac{MJ}{kg}$



HyMETS PS02 at 28 sec [1]

Fig. 1 Temperature and shape change at 30 sec [3,4].

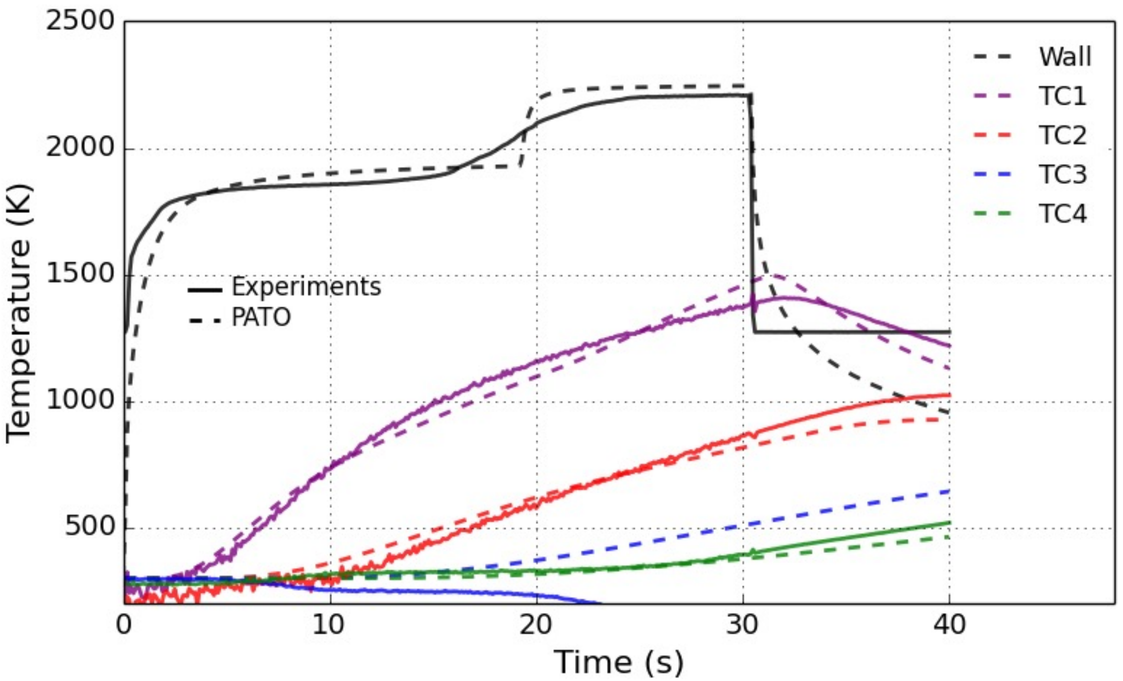
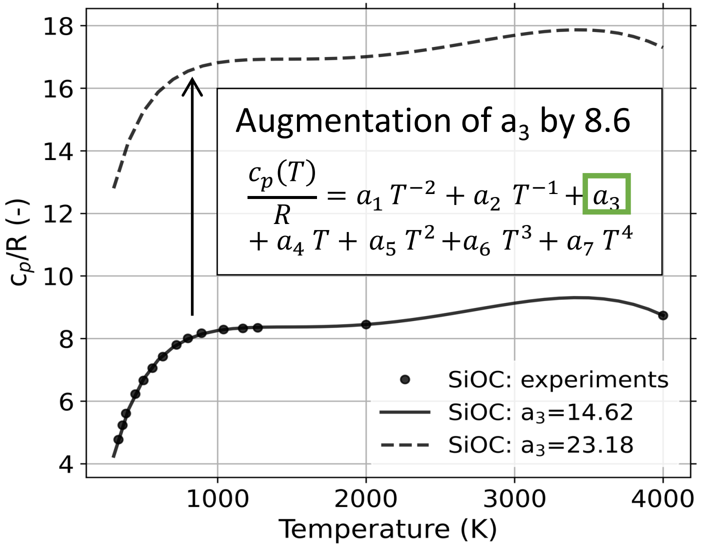


Fig. 2 Evolution in time of the temperature [3,4].

Surface modeling of the charred NuSil as silicon oxycarbide

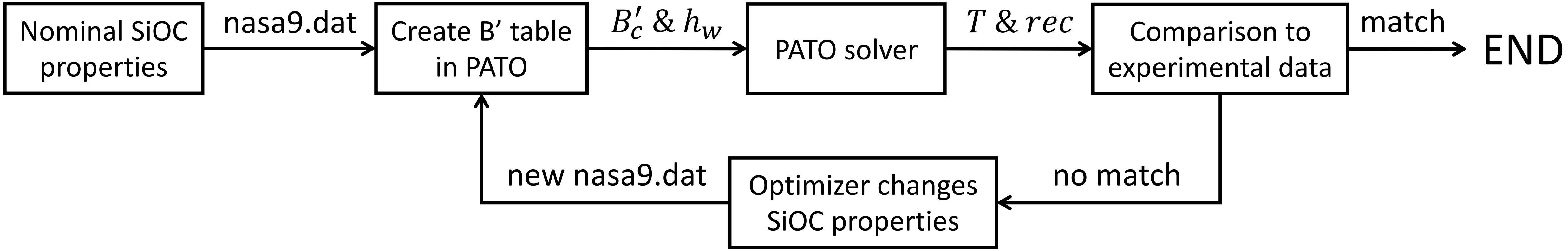
Here, the charred NuSil surface was modeled as SiOC with initial thermal properties found in the literature [5]. Parameters of heat capacity, enthalpy, and entropy were optimized using a multi-o[illegible]n. The simulated temperature results were compared to PICA-N arc jet test cases (HyMETS and AHF-346). Note: The SiOC phase change was not included. The optimization solution was not unique.

3. Optimized SiOC



4. SiOC based on exp.

Differential Scanning Calorimetry (DSC) was performed to analyze post-test sample surfaces from the HyMETS test campaign. The heat capacity of the charred NuSil surface was measured as a f[illegible]bout 1800 K. The heat capacity values were then used to build the latest surface model of the charred NuSil based on SiOC measured properties.

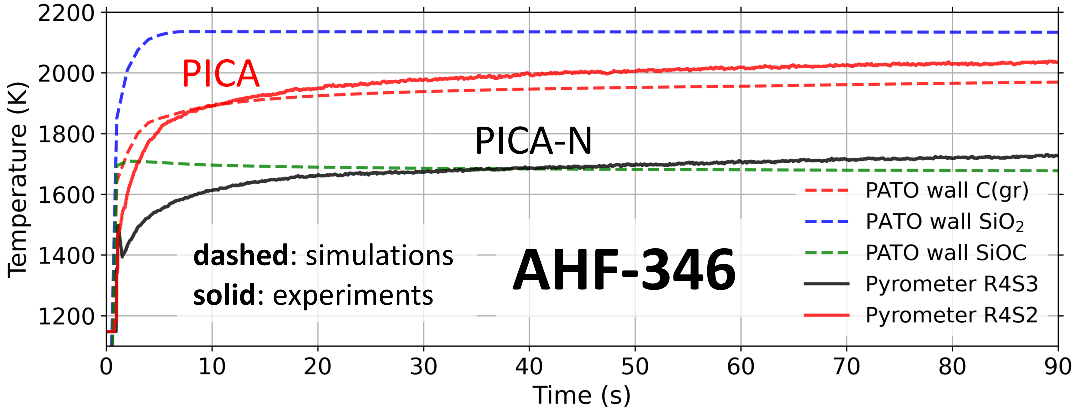


Ablation simulations using charred NuSil modeled as optimized SiOC

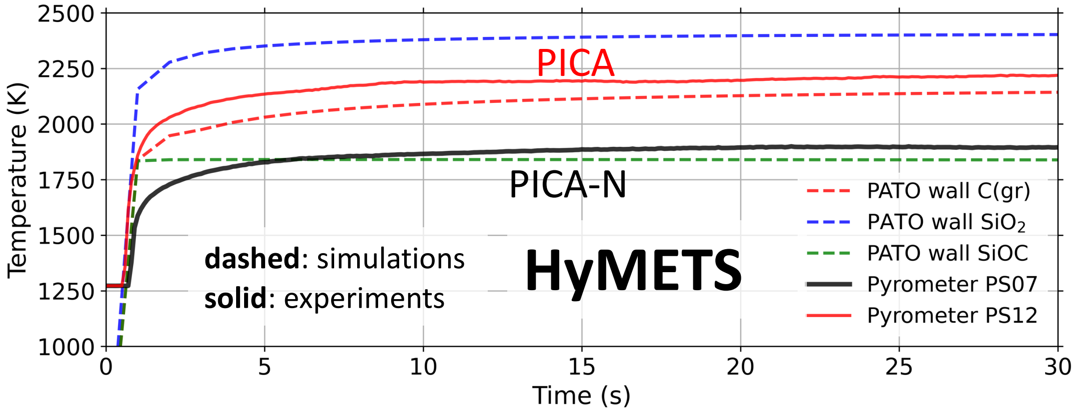
NASA9 database: solution of the parameters optimization for the SiOC properties at the surface								
a_1	a_2	a_3	a_4	a_5	a_6	a_7	b_1	b_2
2.741895240e+05	-3.757811021e+03	2.318030056e+01	-2.890504258e-03	-5.487137170e-07	6.627457661e-10	-1.055953088e-13	-5.497138874e+04	-1.394824571e+02

The properties of the NASA9 database (c_p , h and s) were used in the Mutation++ library [6] to compute the equilibrium of the mixture which directly impacts B_c' and h_w. The PATO ablation simulations using the optimized SiOC properties for the charred NuSil surface model were compared to HyMETS and AHF-346 data.

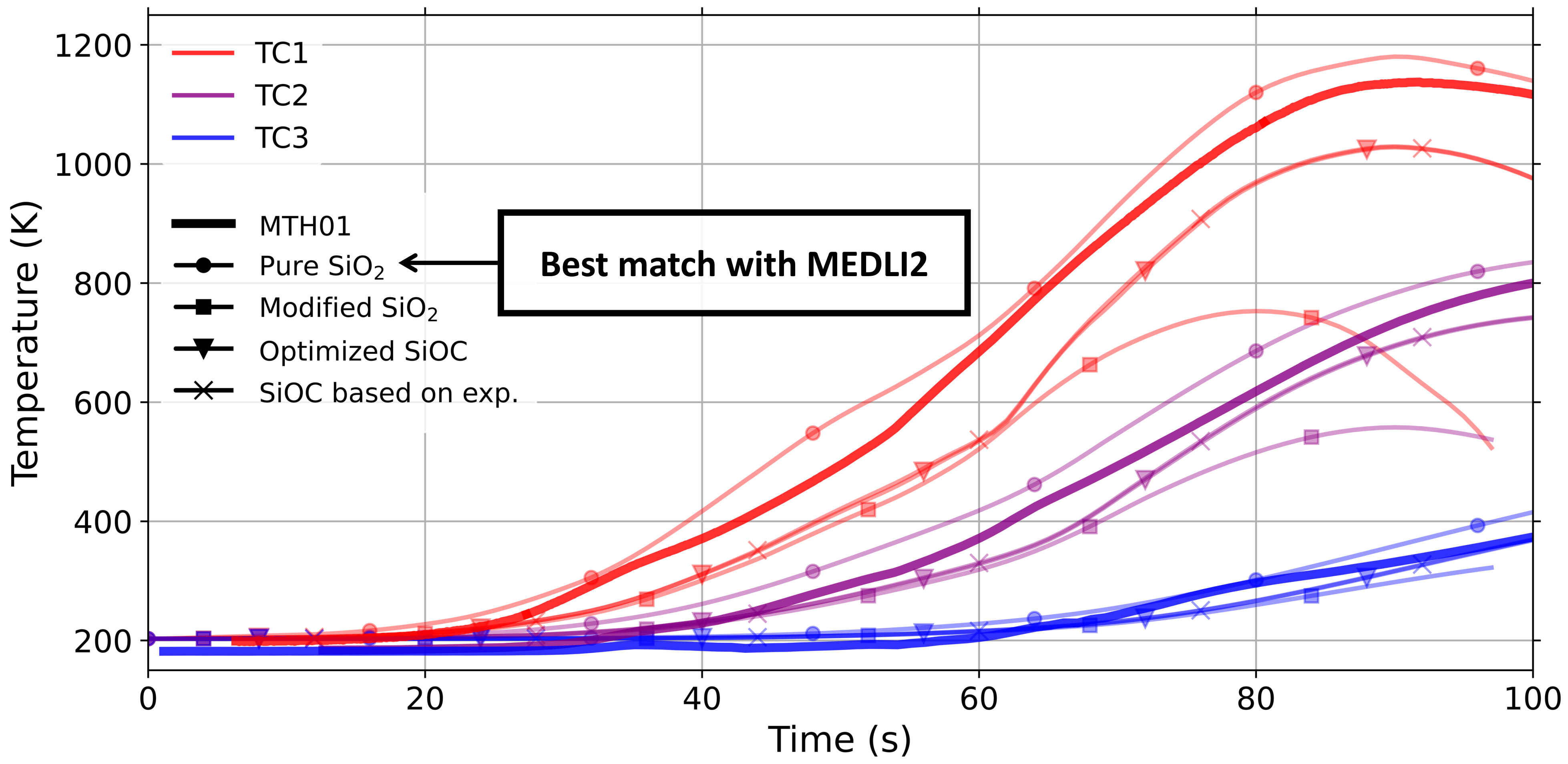
Model	Material	Atmosphere	Geometry	Q [W/cm²]
R4S2	PICA	Earth	4” sphere cone	100
R4S3	PICA-N	Earth	4” sphere cone	100



Model	Material	Atmosphere	Q [W/cm²]	P [kPa]
PS07	PICA-N	CO_2	127	5.2
PS12	PICA	CO_2	126	5.3



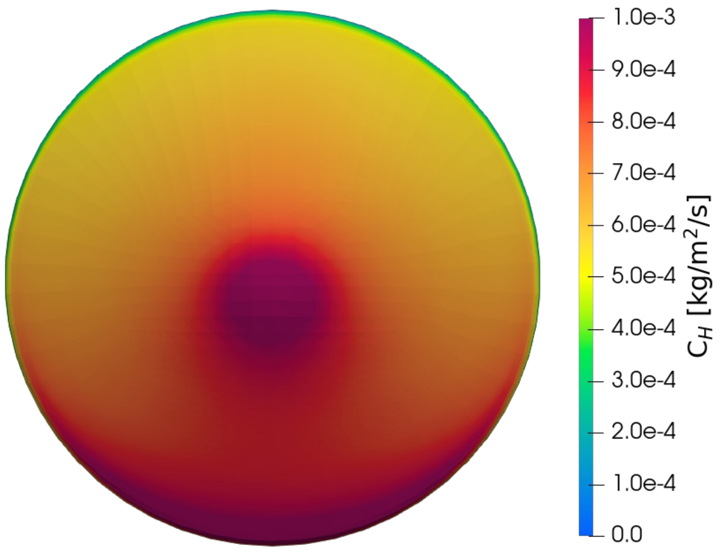
Comparison between the surface charred NuSil models and MEDLI2



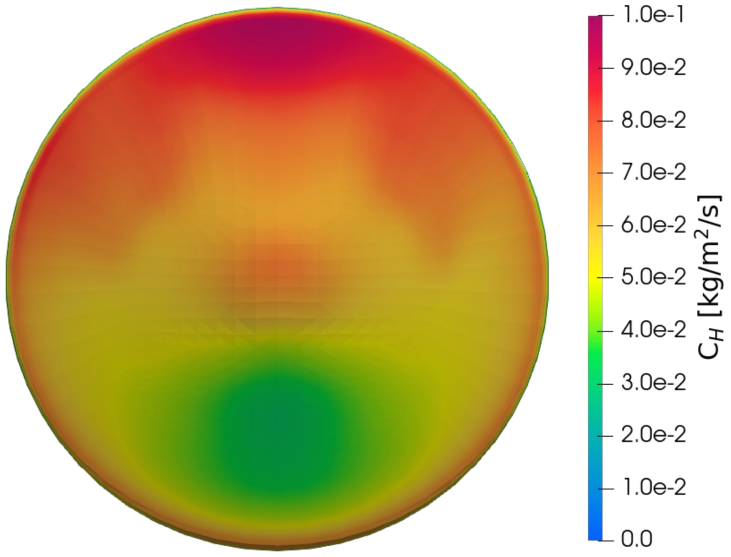
The 1D simulated temperatures using the charred NuSil surface modeled as **pure silica** showed the best agreement with the flight data from the thermal plugs MTH of the MEDLI2 suite [7]. Hereafter, this surface model will be used in the different PICA-N ablation simulations.

Aerothermal environments for the Mars 2020 heatshield

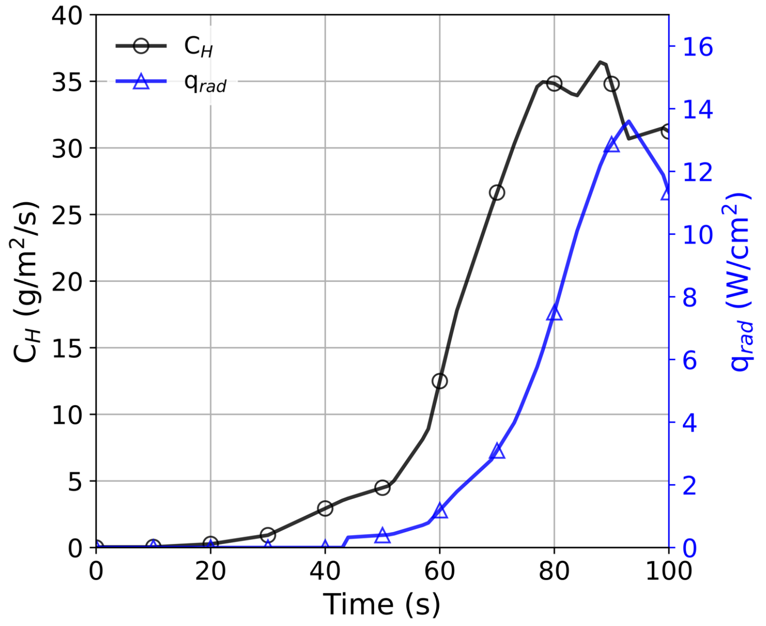
Rarefied regime: *SPARTA [8]*



Continuum regime: *DPLR [9]*



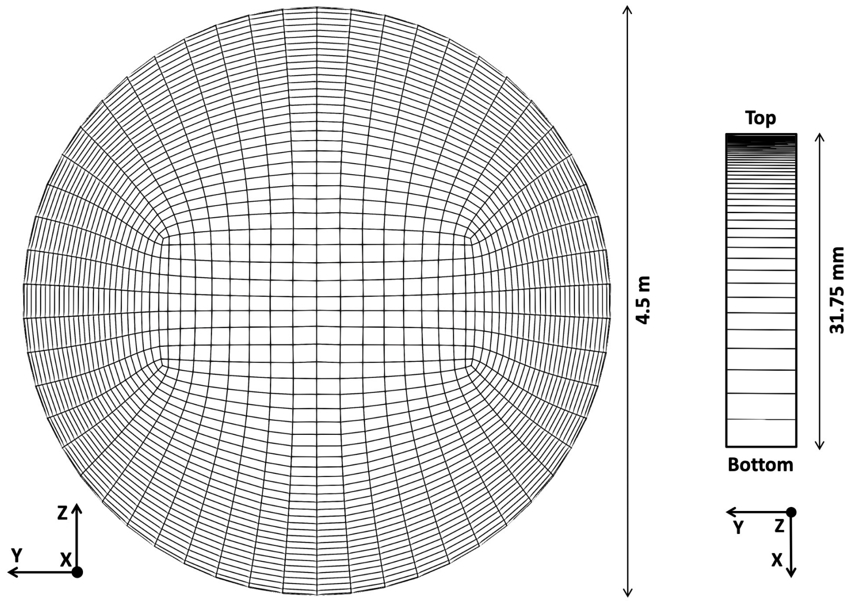
Radiation: *NEQAIR [10]*



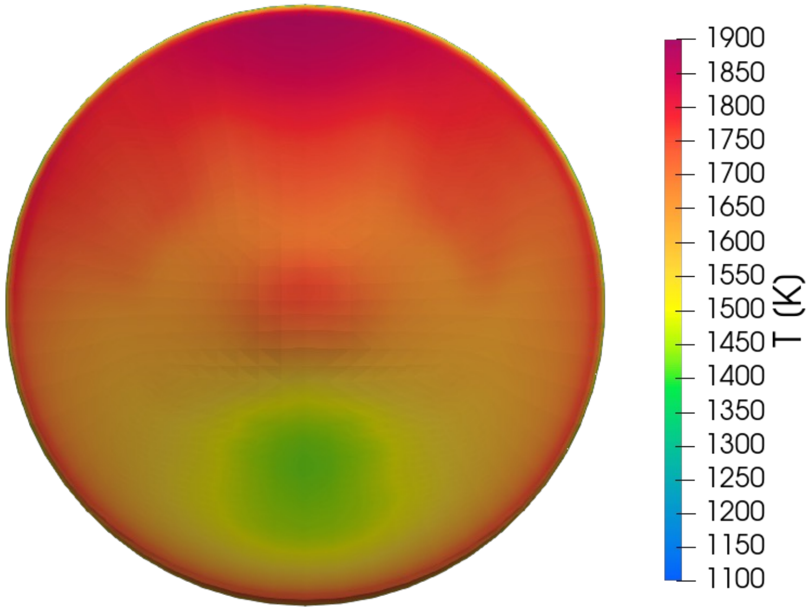
DSMC **SPARTA** code was used to compute the environment in the rarefied regime from 0 to 43 sec. **DPLR** code was used to compute non-equilibrium supersonic and hypersonic flows around the aeroshell from 43 to 130 sec. Radiative heating was computed over the entire heatshield using the **NEQAIR** program on each CFD points. The convective peak heating occurred at 80 sec followed by the radiative one at 90 sec.

3D ablation simulations of the Mars 2020 heatshield

Material response mesh: ***Pointwise***



Surface temperature: ***PATO [11]***

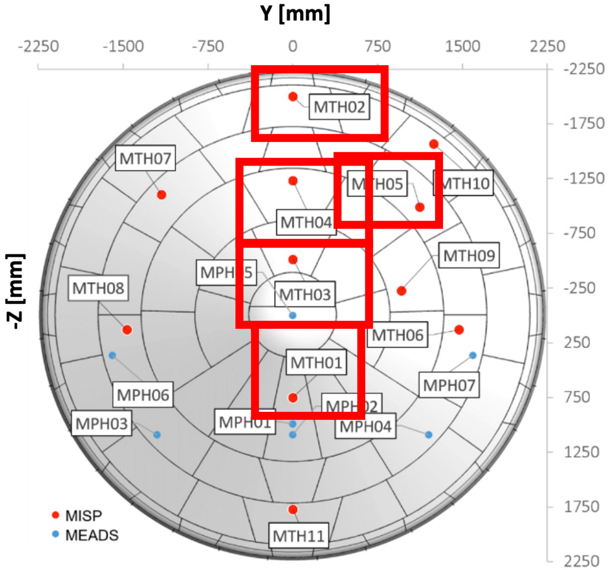


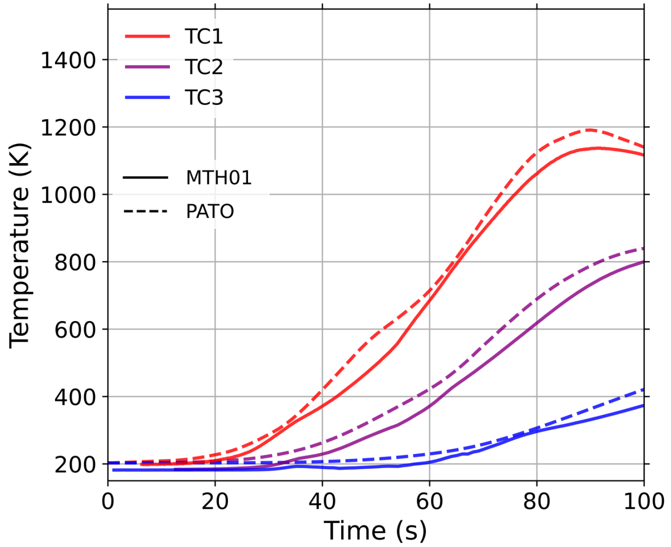
Surface recession: ***PATO***

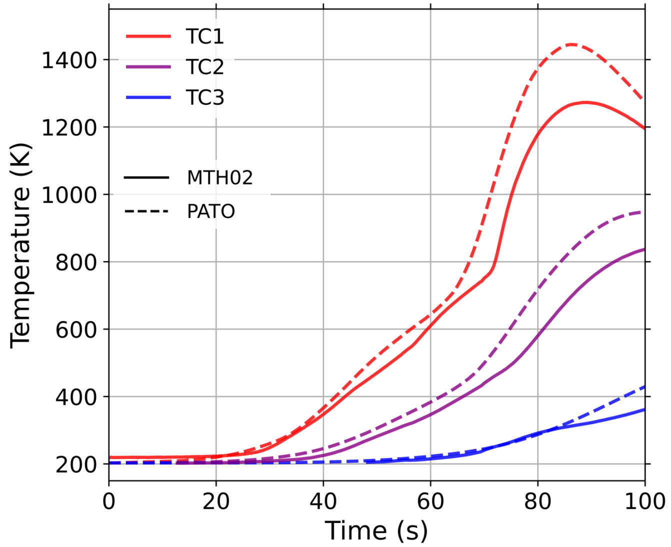
Thermal sensors	Recession [μm]
MTH01	3.82
MTH02	1.80
MTH03	1.21
MTH04	2.44
MTH05	3.22
MTH06	5.86
MTH07	3.21
MTH08	5.59
MTH09	3.20
MTH10	2.95
MTH11	6.02

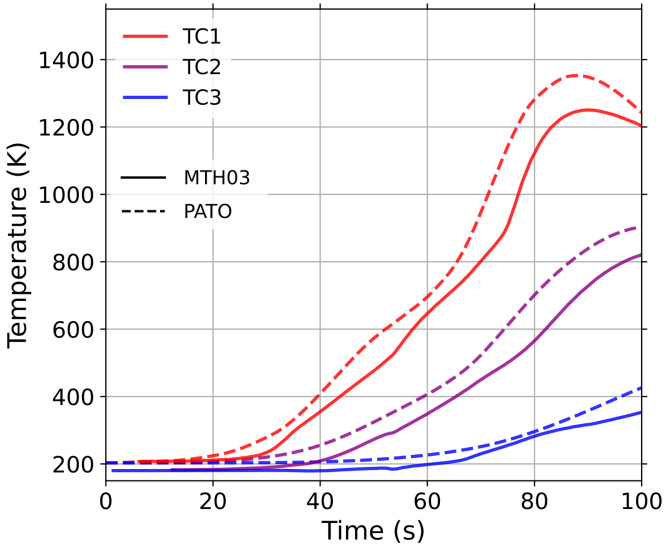
The heatshield geometry was discretized with an unstructured grid (100k cells including 60 in-depth). 3D PATO material response of the Mars 2020 heatshield using the charred NuSil **surface modeled as pure** $\mathbf{SiO_2}$. The total coating thickness was estimated to be 200 µm. The surface recession results indicate that the heatshield was **still fully covered by a layer of charred NuSil** after the Martian atmospheric entry.

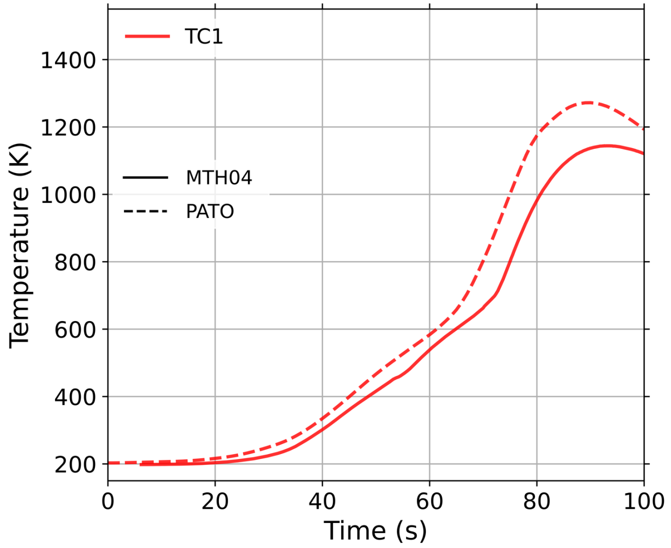
PICA-NuSil model compared to MEDLI2 flight data

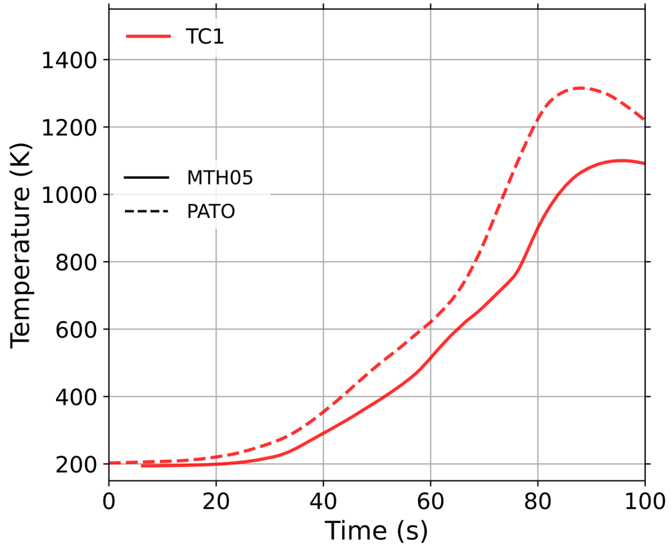






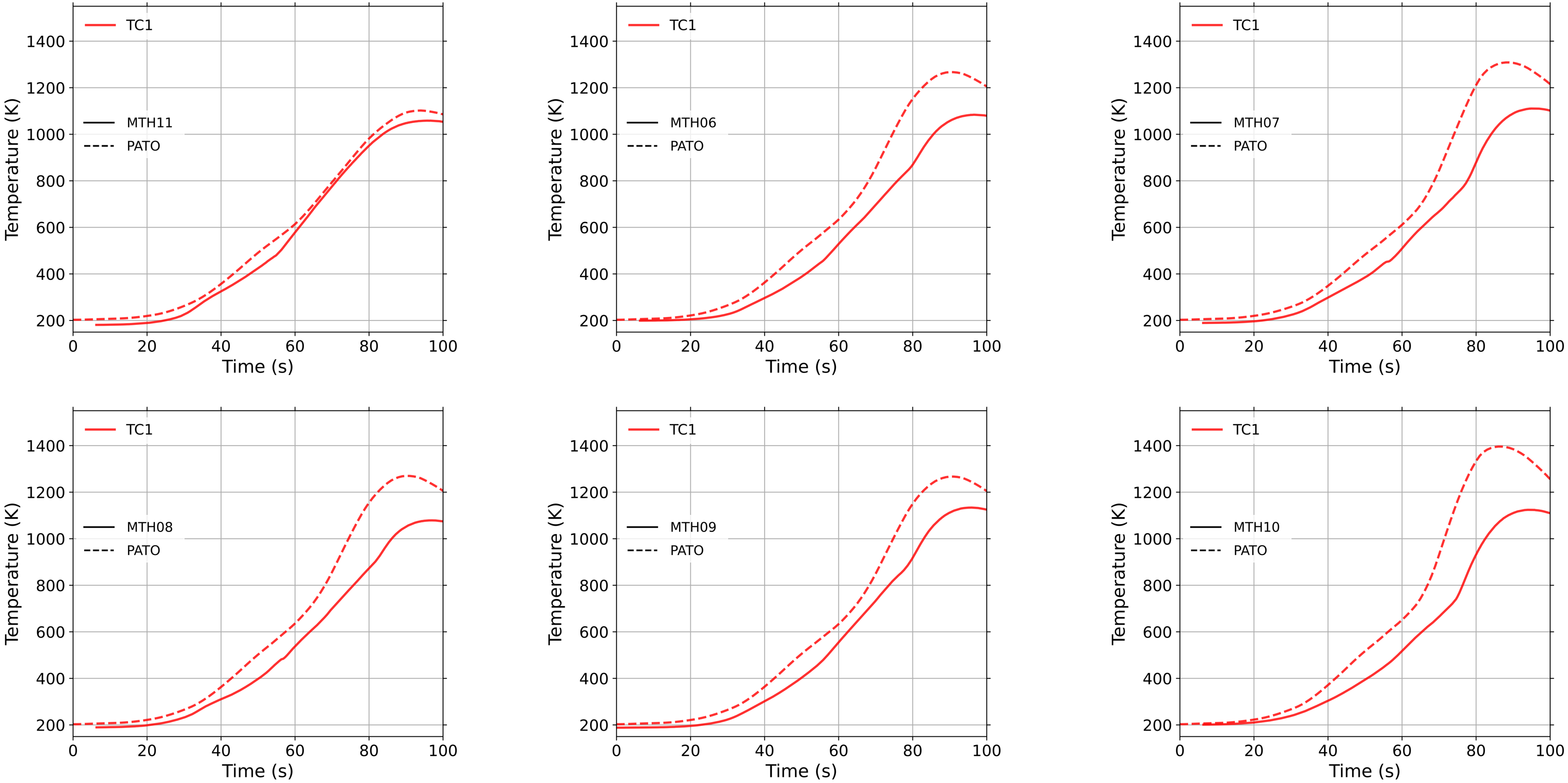






PICA-NuSil model compared to MEDLI2 flight data

Y [mm]



Summary of the PICA-NuSil model

Conclusion

- 4 charred NuSil surface models developed:
  1. ***Pure silica*** **:** best match with MEDLI2 data.
  2. ***Modified SiO_2*** **:** match HyMETS exp.
  3. ***Optimized SiOC*** **:** match HyMETS/AHF exp.
  4. **SiOC based on exp. :** match optimized SiOC.

- 3D ablation simulations for Mars 2020:
  - ***SPARTA****:* rarefied regime using DSMC [0-43] sec.
  - ***DPLR****:* CFD in fully turbulent regime [43-130] sec.
  - ***NEQAIR****:* Radiative heating at each CFD points.
  - ***PATO****:* 3D material response (T & rec.) using the charred NuSil surface modeled as pure silica.
  - Model indicates that the Mars 2020 heatshield was still fully covered by a NuSil layer after entry.
  - Good agreement was found between the PICA-N model (pure SiO_2) and the MEDLI2/MTH plugs.

Future work

- Development of a new model that couples pyrolysis and char blowing gases between DPLR and PATO.

- 3D ablation simulations of the Mars 2020 heatshield using the PICA-N model that will include the coupling of blowing gases. Results will be compared to MEDLI2 flight data.

- Further studies are needed to have a better understanding of the transition from laminar to turbulent.

References

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