

FULL-SCALE MSL HEATSHIELD MATERIAL RESPONSE USING DSMC AND CFD TO COMPUTE THE AEROTHERMAL ENVIRONMENTS



IPPW-2018, June
University of Colorado Boulder
Abstract number: 639

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Introduction

During Mars atmospheric entry, the Mars Science Laboratory (MSL) was protected by a 4.5 meters diameter ablative heatshield assembled in 113 tiles [1]. The heatshield was made of NASA's flagship ablative material, the Phenolic Impregnated Carbon Ablator (PICA) [2].

Prior work [3] compared the traditional **one-dimensional and three-dimensional** material response models at different locations in the heatshield. It was observed that the flow was basically one-dimensional in the **nose and flank regions**, but three-dimensional flow effects were observed in the outer flank. Additionally, the effects of tiled versus monolithic heatshield models were also investigated. It was observed that the **3D tiled and 3D monolithic** configurations yielded relative differences for in-depth material temperature up to 18% and 28%, respectively, when compared to the a 1D model.

Aerothermal environments from SPARTA and DPLR

The MSL flight environment was simulated using the following assumptions for both the CFD and DSMC simulations:

- Super-catalytic wall BC: CO₂ and N₂ recombination to freestream mole fractions
- Radiative equilibrium wall with $\epsilon = 0.89$
- Mars atmosphere $y_{CO_2} \approx 0.97$ and $y_{N_2} \approx 0.03$
- 8 species and 24 reactions(12 forward + 12 backward): Mitcheltree model [6]
- Park hypersonics correction to vibrational relaxation

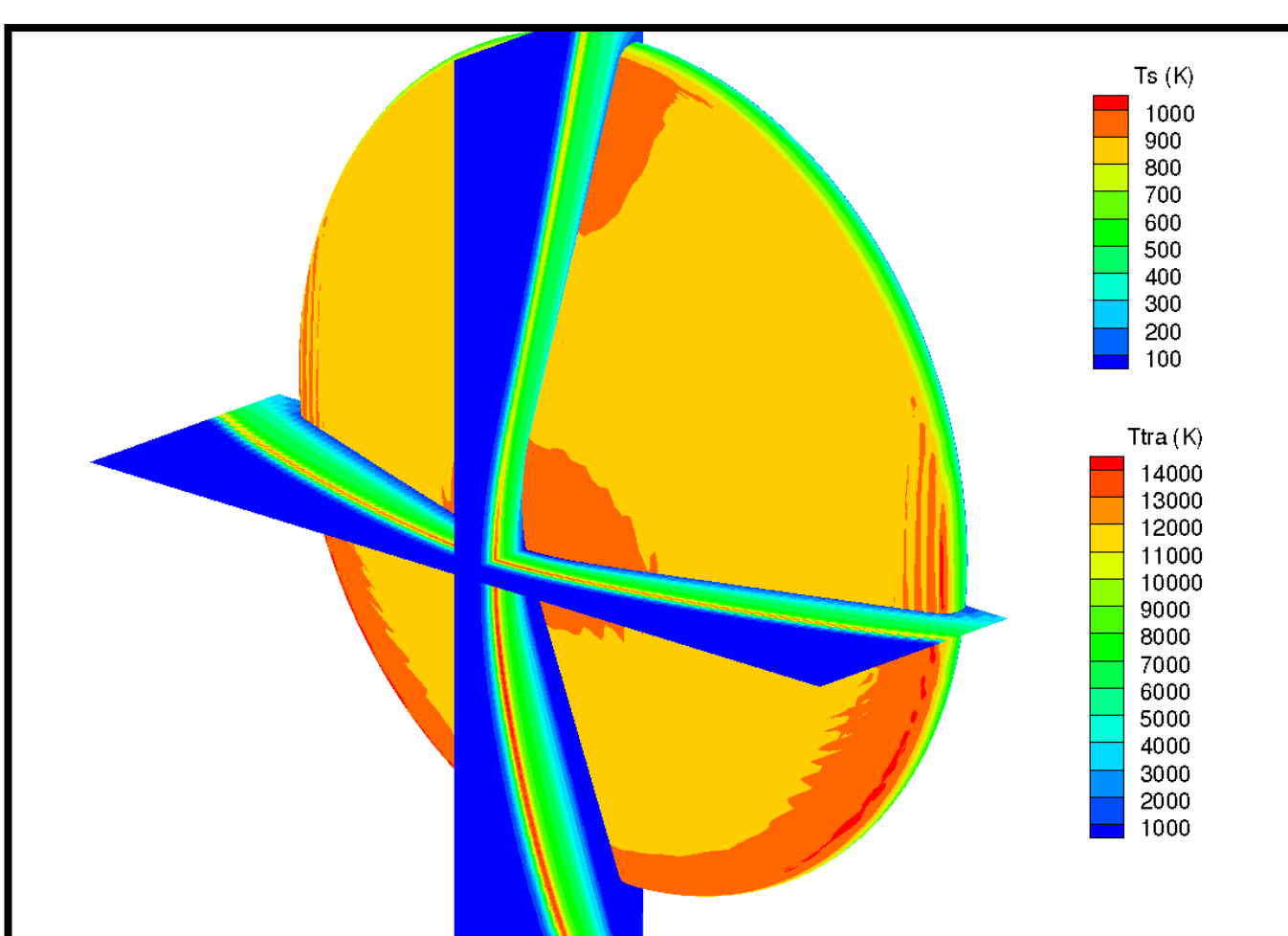


Fig. 1 Surface and translational temperature contours at 40 s of entry computed using DSMC

- Shock standoff distance decreases with decreasing altitude
- Strong non-equilibrium in shock at high altitudes
- Angle of attack varies from 30 deg at high altitude to 16 deg after 48 s of entry

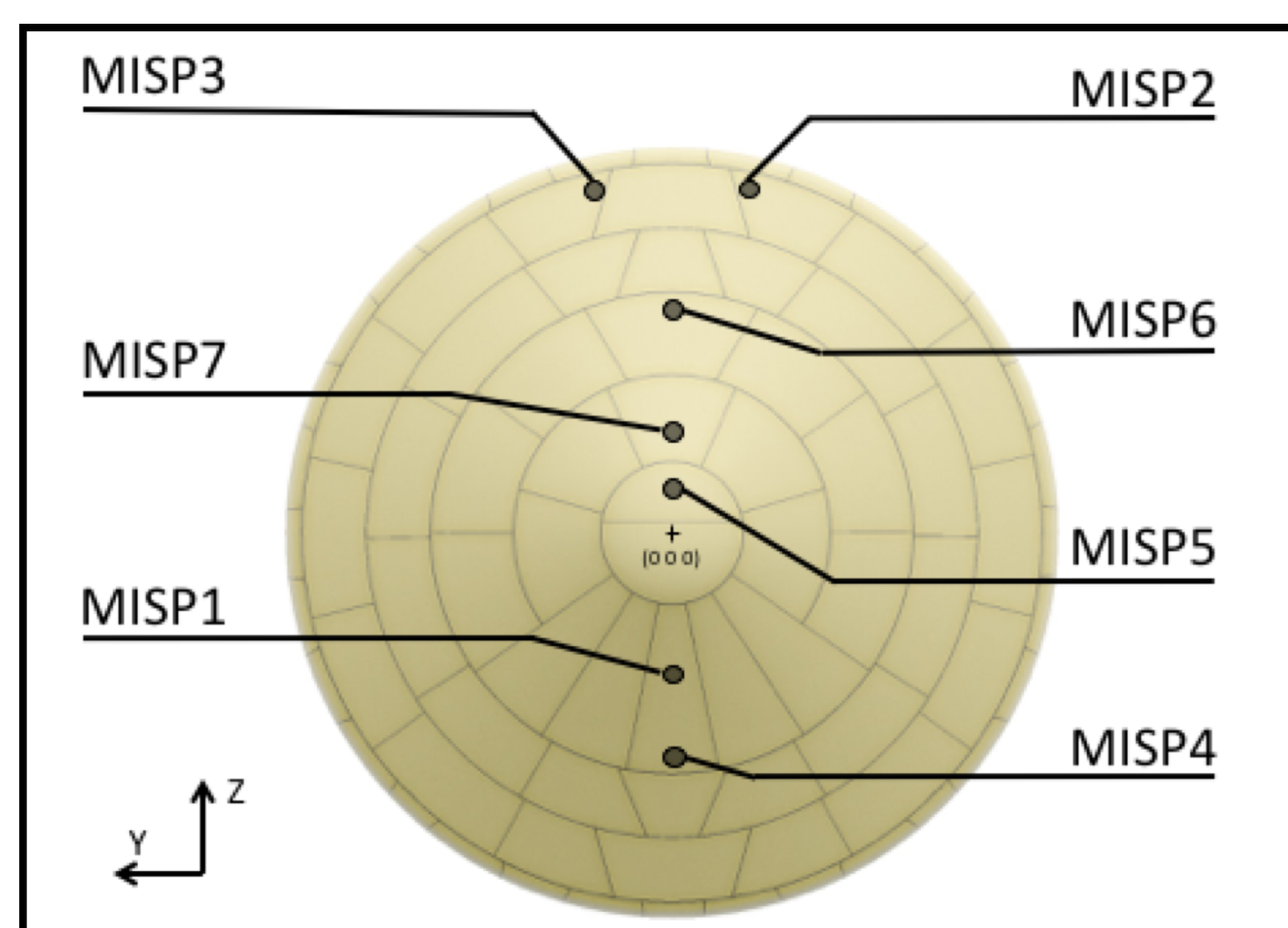


Fig. 2 MEDLI Integrated Sensor Plug (MISP) locations [3]

- 7 plugs with 4 thermocouples each
- Nominal depth: TC1: 2.54 mm, TC2: 5.08 mm, TC3: 11.43 mm, TC4: 17.78 mm [8]
- MISP4 located at the stagnation point
- Assembly of 113 PICA tiles
- TACOT material properties used in PATO

DSMC

The objective of this work is to study the effects of the aerothermal environment on the material response. We extend prior work [3] by computing aerothermal environments using the direct simulation Monte Carlo (DSMC) code SPARTA [4] and the CFD code Data Parallel Line Relaxation (DPLR) [5]. SPARTA is used to compute environment in the **rarefied regime** prior to 48.4s of entry where the **Knudsen number** is such that the Navier-Stokes equations can be inaccurate. Similarly to previous work, the DPLR software is used to compute the hypersonic environment for a laminar boundary layer assumption from **48.4 s up to 100 s** after Entry Interface (EI) along the MSL 08-TPS-02/01a trajectory.

SPARTA: <https://sparta.sandia.gov>

DPLR: <https://software.nasa.gov/software/ARC-16021-1A>

PATO: <https://software.nasa.gov/software/ARC-16680-1>



Differences between CFD and DSMC:

- DPLR uses a 2 temperature model and SPARTA a 3 temperature model
- Laminar boundary layer model in DPLR
- Binary diffusion coefficients from Gupta collision integrals [7] in DPLR
- SPARTA uses Variable Soft Sphere (VSS) model with high temperature transport calibration
- Parker equation for rotational relaxation and Millikan-White equation + Park correction for vibrational relaxation in SPARTA

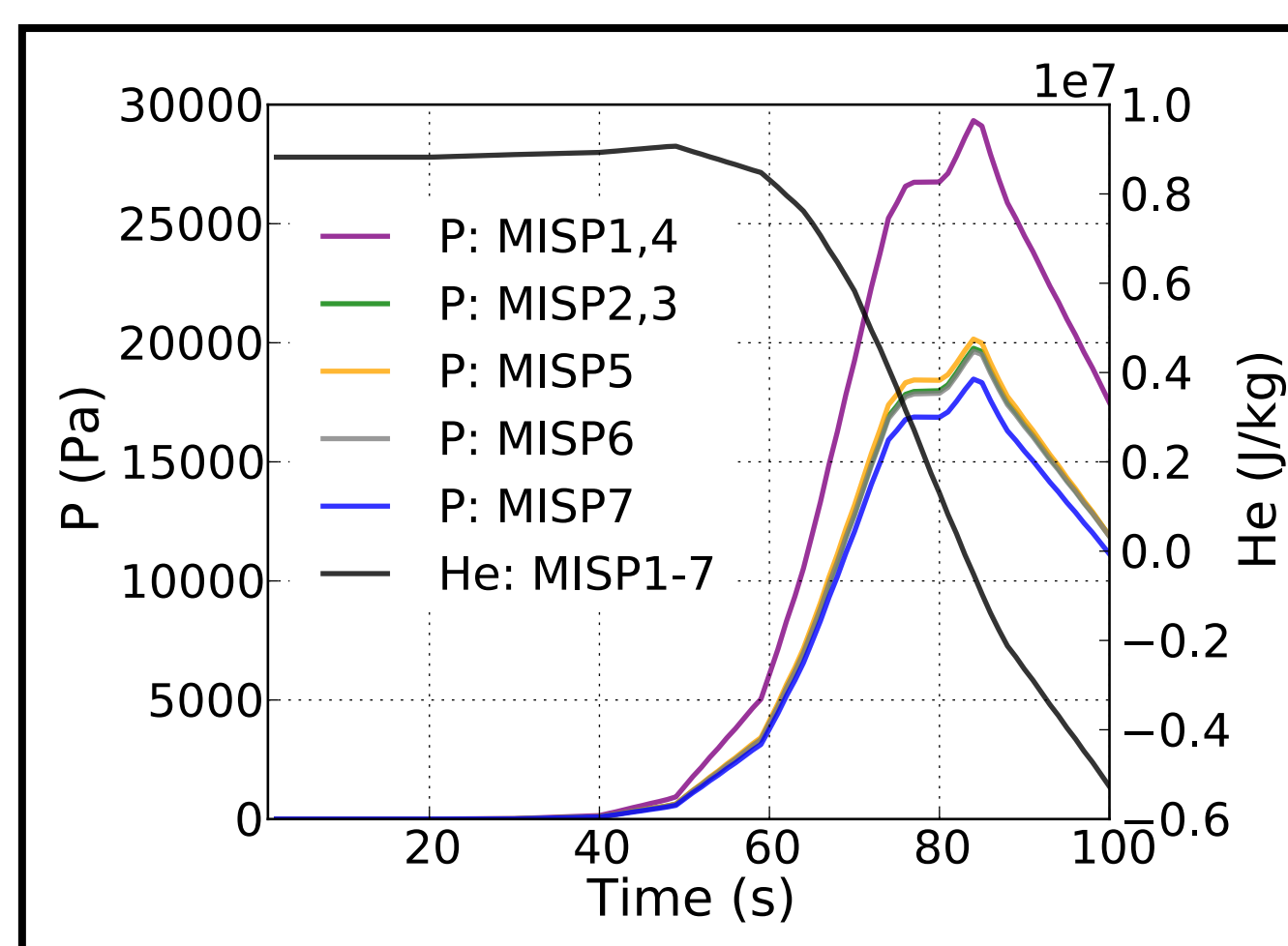


Fig. 3 Evolution in time of pressure (p_w) and BLE enthalpy (h_e) at the front surface

- Peak of pressure occurs around 84 s, highest at plugs 1 and 4, close to stagnation point
- BLE enthalpy is high until 60 s then sharply drops to negative values after 84 s

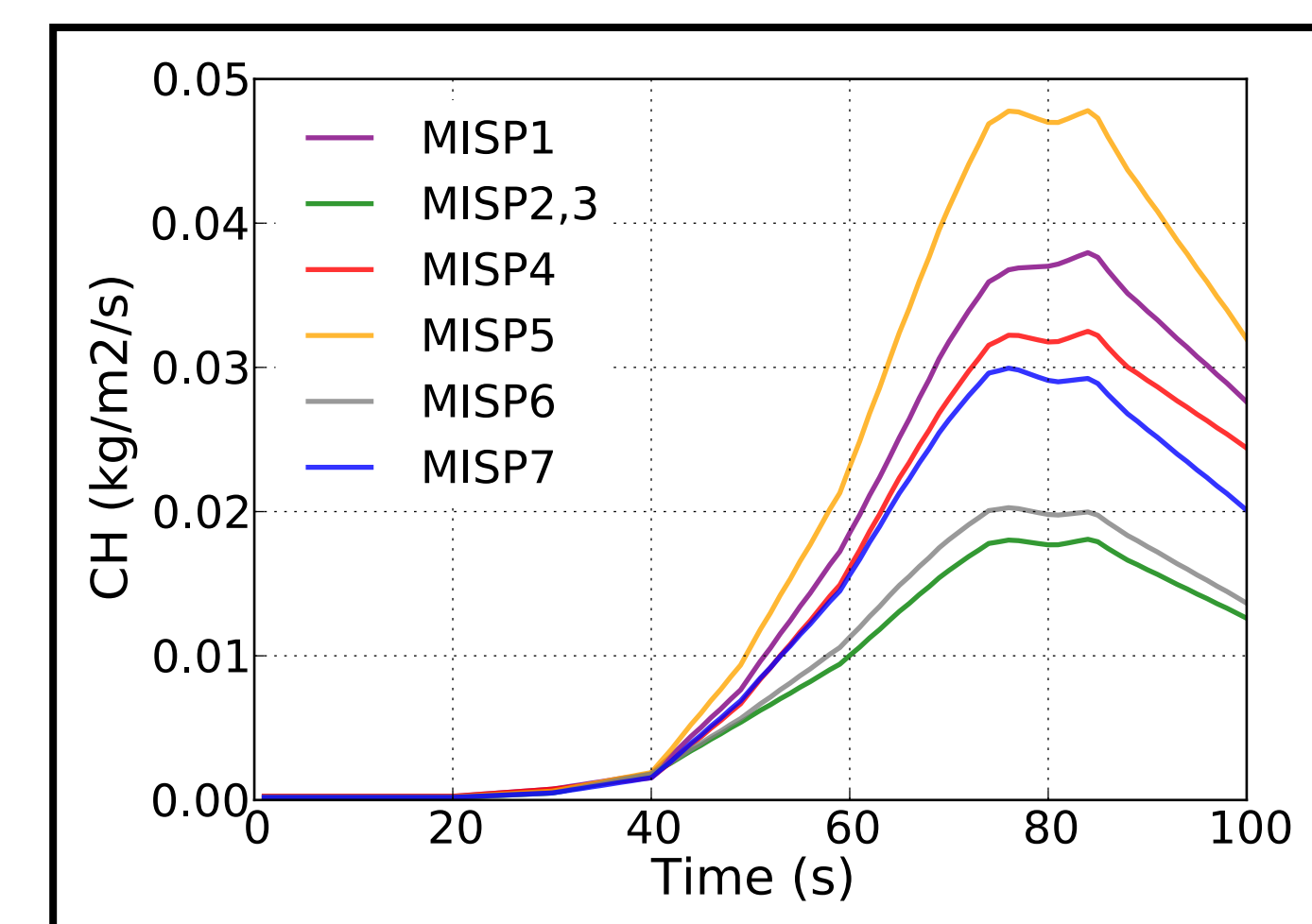


Fig. 4 Evolution in time of heat transfer coefficient (C_H) at the front surface

- C_H computed from PATO Boundary Layer utility and BLAYER [9] as ratio of q_w to $(h_e - h_w)$
- Two peaks in heat transfer coefficient appear around 75 s and 85 s
- Maximum heating occurs at MISP5

Material response from PATO

The Porous material Analysis Toolbox based on OpenFOAM (PATO) [10, 11] is used for the material response calculations. The governing equations are volume-averaged forms of solid mass, gas mass, gas momentum and total energy conservation, including pyrolysis gas production. The thermodynamics and chemistry properties are computed using the **Mutation++** library [12]. The boundary conditions at the heatshield front surface are interpolated in time and space from the aerothermal environment at discrete points of the MSL trajectory [3], using a Galerkin projection. For this study, the Theoretical Ablative Composite for Open Testing (TACOT) database developed by the TPS community was used to define the porous material properties. TACOT is a fictitious material that was inspired from low density carbon/phenolic ablators. The boundary layer edge (BLE) quantities from DPLR are extracted using a curvature-based method with the **BLAYER** code [9]. For the DSMC results, a Boundary Layer utility was created in PATO and an edge-based method is used (location of BLE such that $h_e = 99.5\%$ of $h_{e,\infty}$). At 40 s after EI, the peak pressure value computed from SPARTA is reached in the stagnation point region (MISP4) around 150 Pa (Fig. 5). We compute the PATO material response of the MSL heatshield in a **monolithic 3D configuration**, with the Martian aerothermal environments derived from **DPLR only** and **DSMC+DPLR**. For both cases, a uniform initial temperature is imposed. The addition of the DSMC results modifies the **temperature prediction** for the first 60 s after EI (Fig. 6). For MISP4, in-depth thermal effects are as important as surface thermal effects especially before 60 s (Fig. 7). Fig. 8 shows the **surface recession** computed in PATO with the highest recession at MISP5 as expected for a **laminar aerothermal environment**. Almost no recession is observed before 60 s due to the low heat flux. Only subtle differences in the recession are found between DPLR only and DSMC+DPLR derived environments.

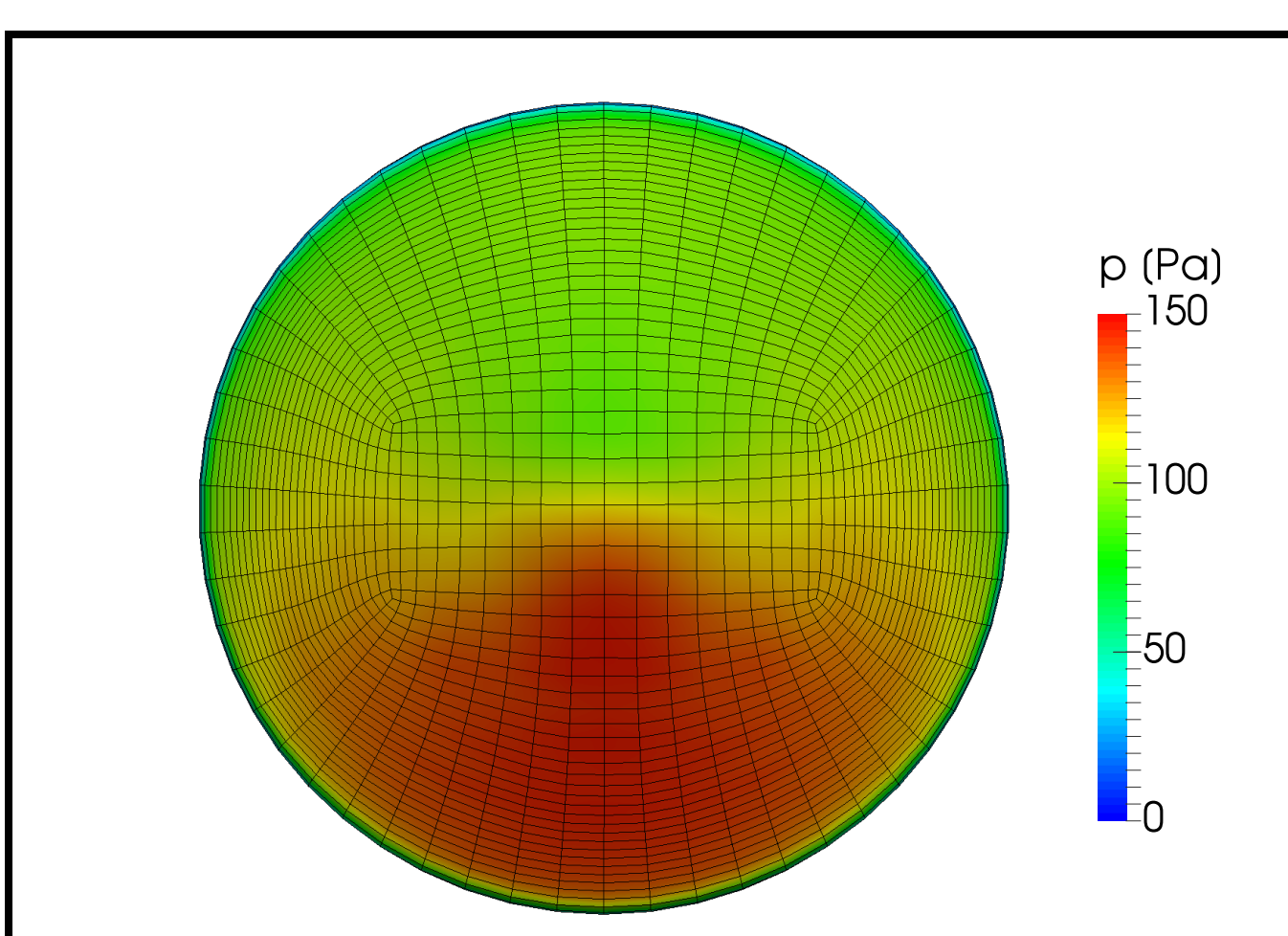


Fig. 5 3D-view of PATO input (pressure p_w) heat shield front surface (40s of MSL entry)

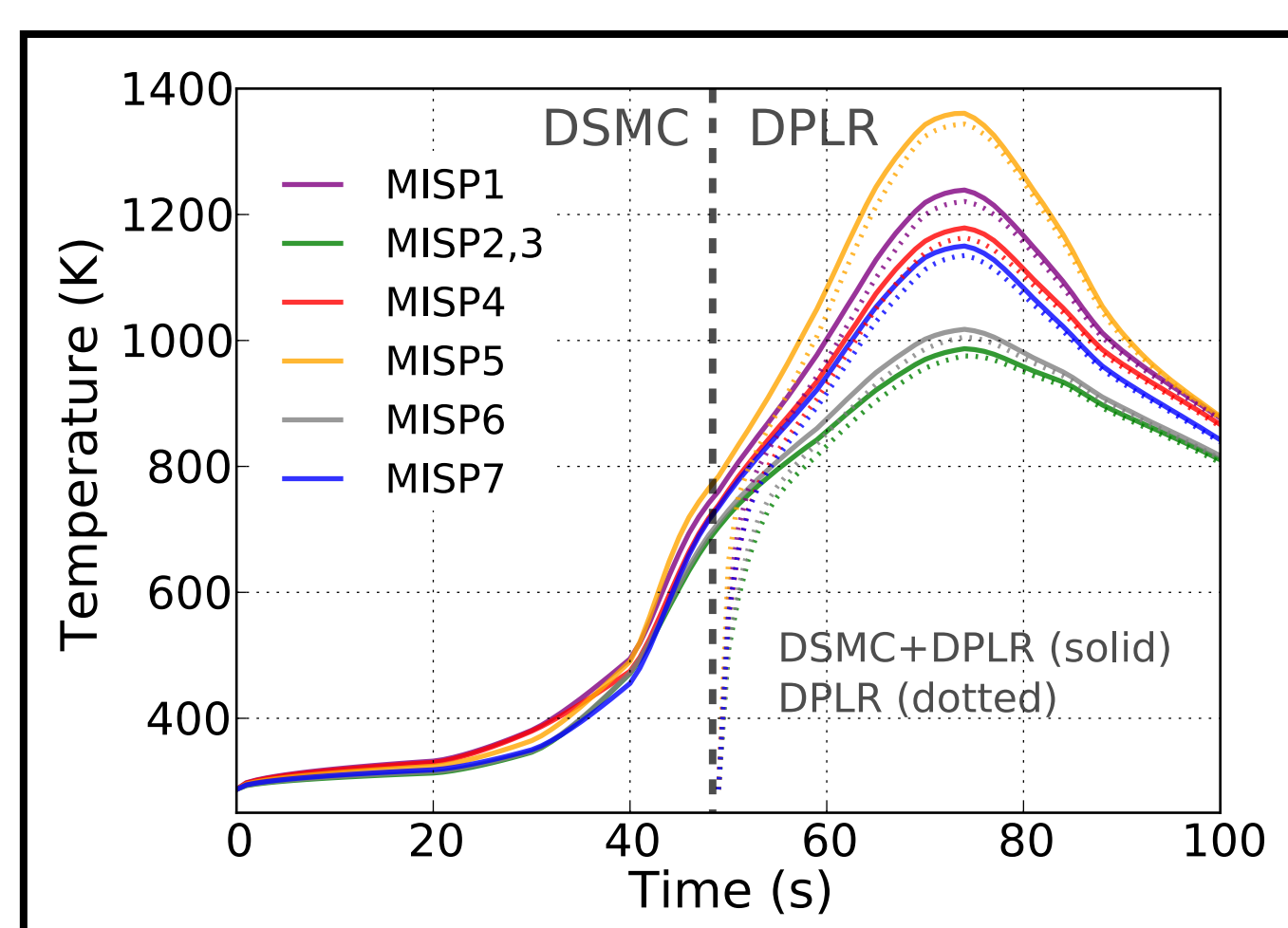


Fig. 6 PATO surface thermal response at the MISP locations

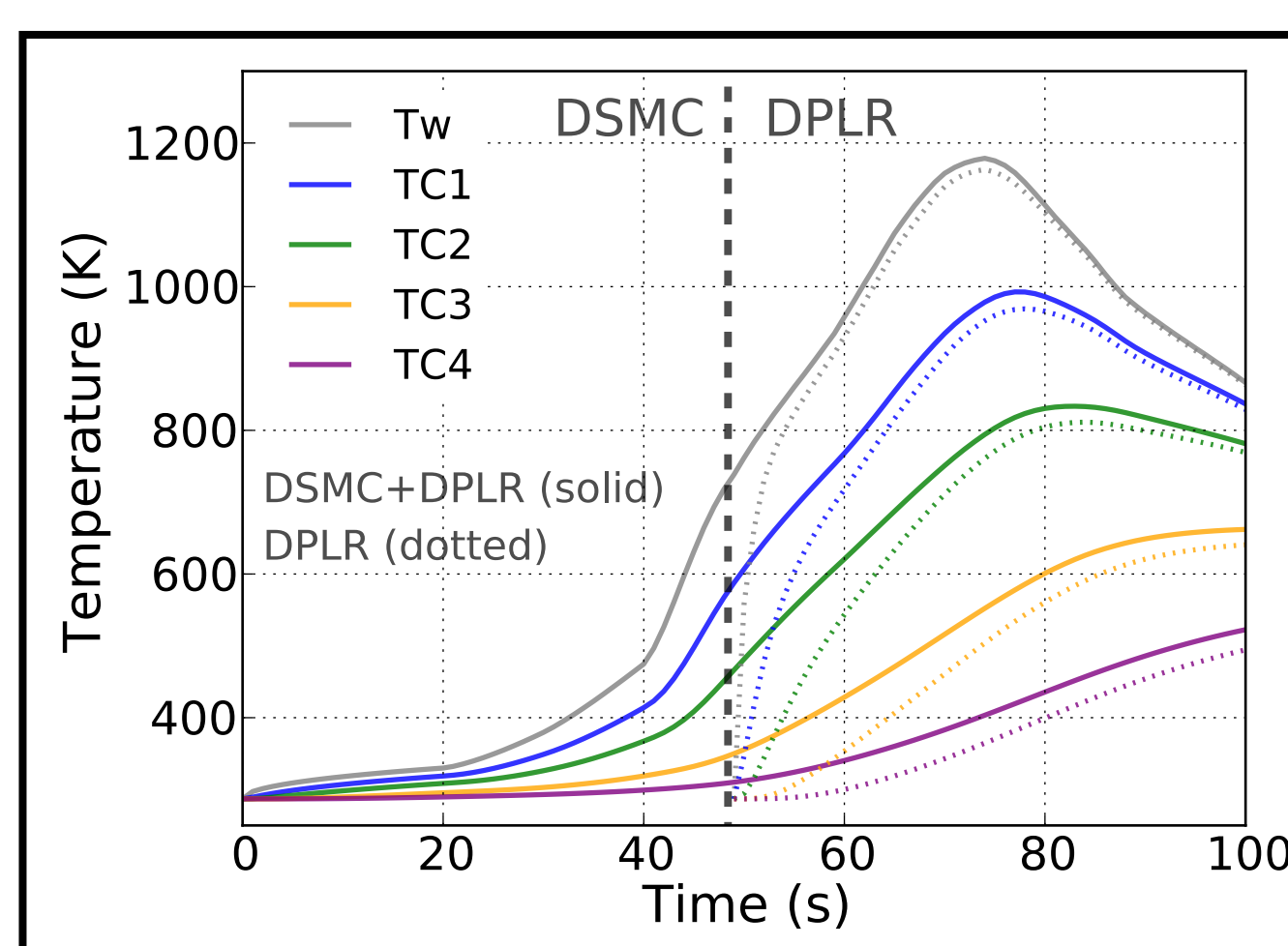


Fig. 7 PATO surface and in-depth thermal response at MISP4

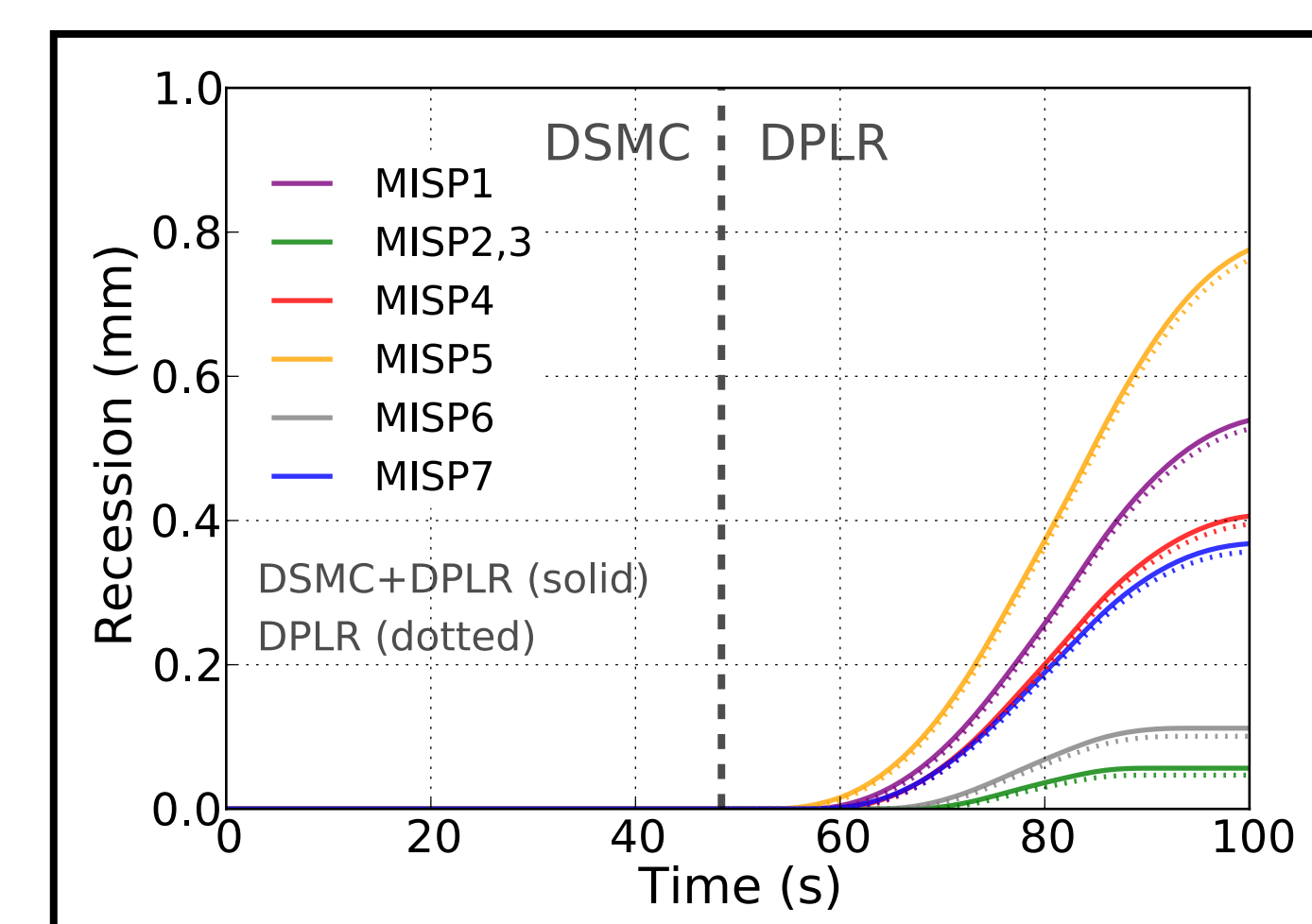


Fig. 8 PATO surface recession at the MISP locations

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