Determination of Aerothermal Environment and Ablator Material Response using Inverse Methods

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Overview

The Mars Science Laboratory (MSL) was protected during entry into the Martian atmosphere by a thermal protection system that used NASA's Phenolic Impregnated Carbon Ablator (PICA) [1]. The heat shield of the probe was instrumented with the Mars Entry Descent and Landing Instrument (MEDLI) suite of sensors. MEDLI Integrated Sensor Plugs (MISP) included thermocouples that measured in-depth temperatures at various locations on the heatshield. The flight data has been used as a benchmark for validating ablation codes within NASA [2-4]. This work seeks to refine the estimate of the material properties for the MSL heat shield and the aerothermal environment during Mars entry using estimation methods in DAKOTA on the temperature data obtained from MEDLI.

Methodology

Inverse analysis is done with the DAKOTA software using a genetic algorithm for optimization [5]. This method launches populations of material response simulations using the Porous material Analysis Toolbox based on OpenFOAM (PATO). Between simulations, either material or environment properties are varied until the error between the computed temperatures and the MISP flight data is minimized.

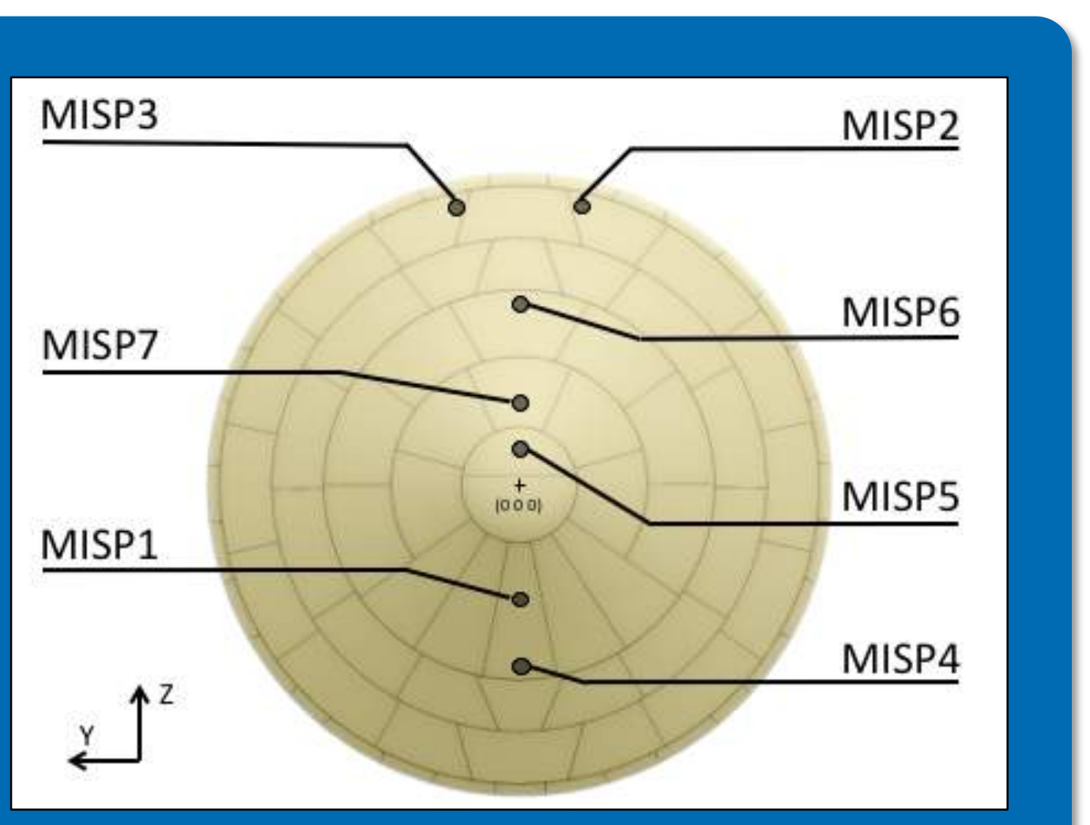
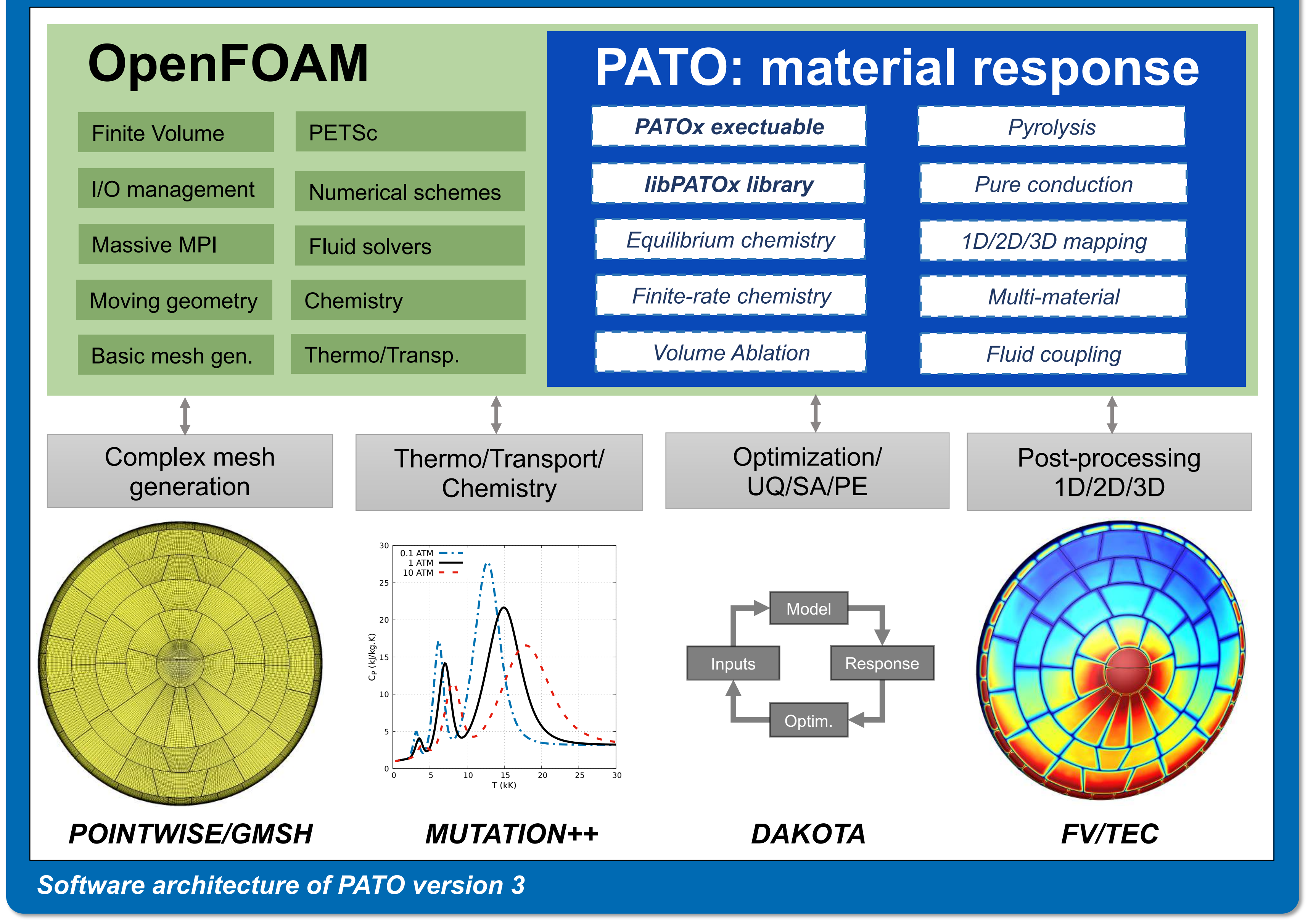


Diagram showing MISP thermocouple locations on MSL heat shield

Material Response Simulations using PATO

The material response of the heat shield is computed using PATO [6-8], a NASA software developed around the open-source computational fluid dynamics software, OpenFOAM. PATO uses a volume averaged approach to compute mass and heat transfer in porous media. Chemical reactions between solid and gas phases are modeled assuming local thermal equilibrium and equilibrium chemistry [8]. PATO uses Mutation++ to compute thermodynamic and transport properties [9].



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

Complex mesh generation
Thermo/Transport/ Chemistry
Optimization/ UQ/SA/PE
Post-processing 1D/2D/3D

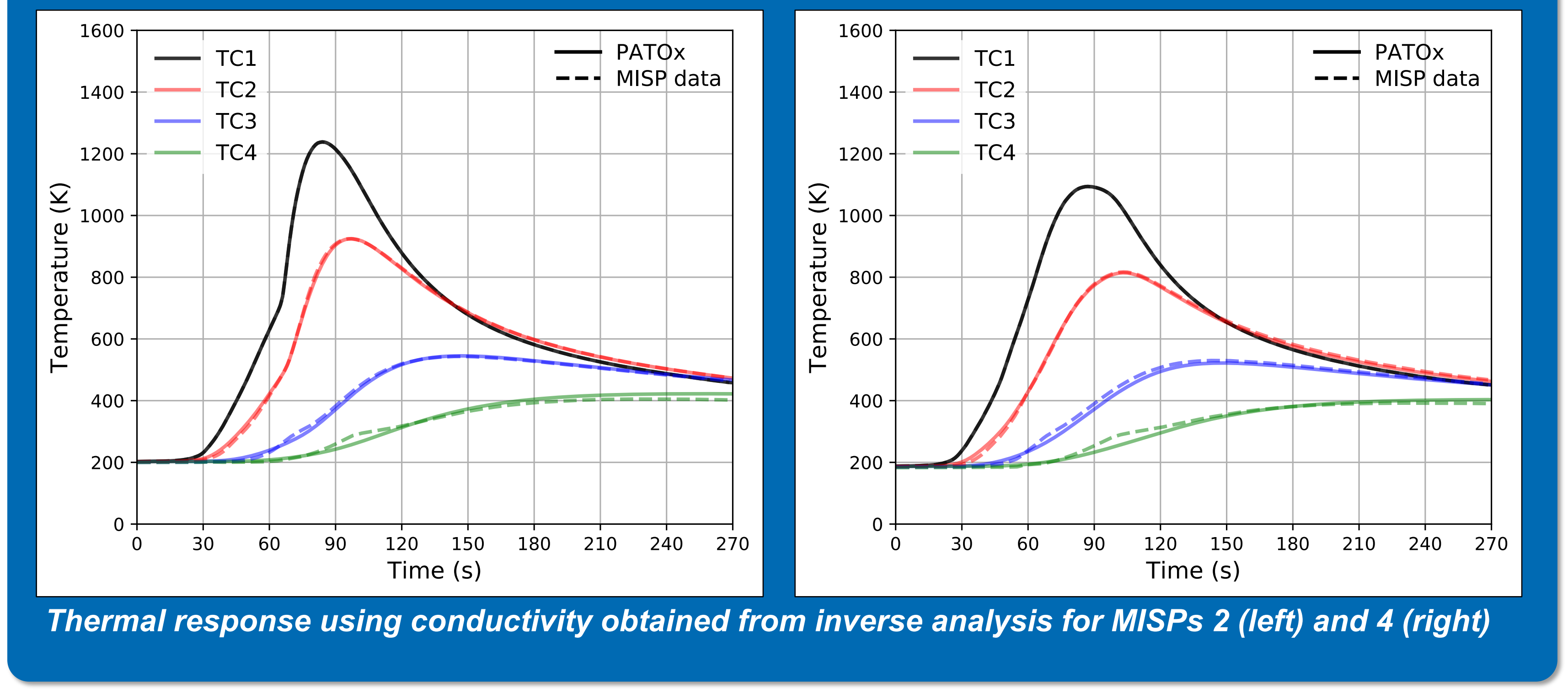
Model
Inputs
Response
Optim.

POINTWISE/GMSH
MUTATION++
DAKOTA
FV/TEC

Software architecture of PATO version 3

Estimation of Thermal Conductivity

In estimating thermal conductivity, the temperature profile obtained by the shallowest thermocouple at each MISP location was used as a boundary condition. The thermal conductivity was then varied in order to minimize the error between measured and computed temperatures for the other 3 thermocouples.



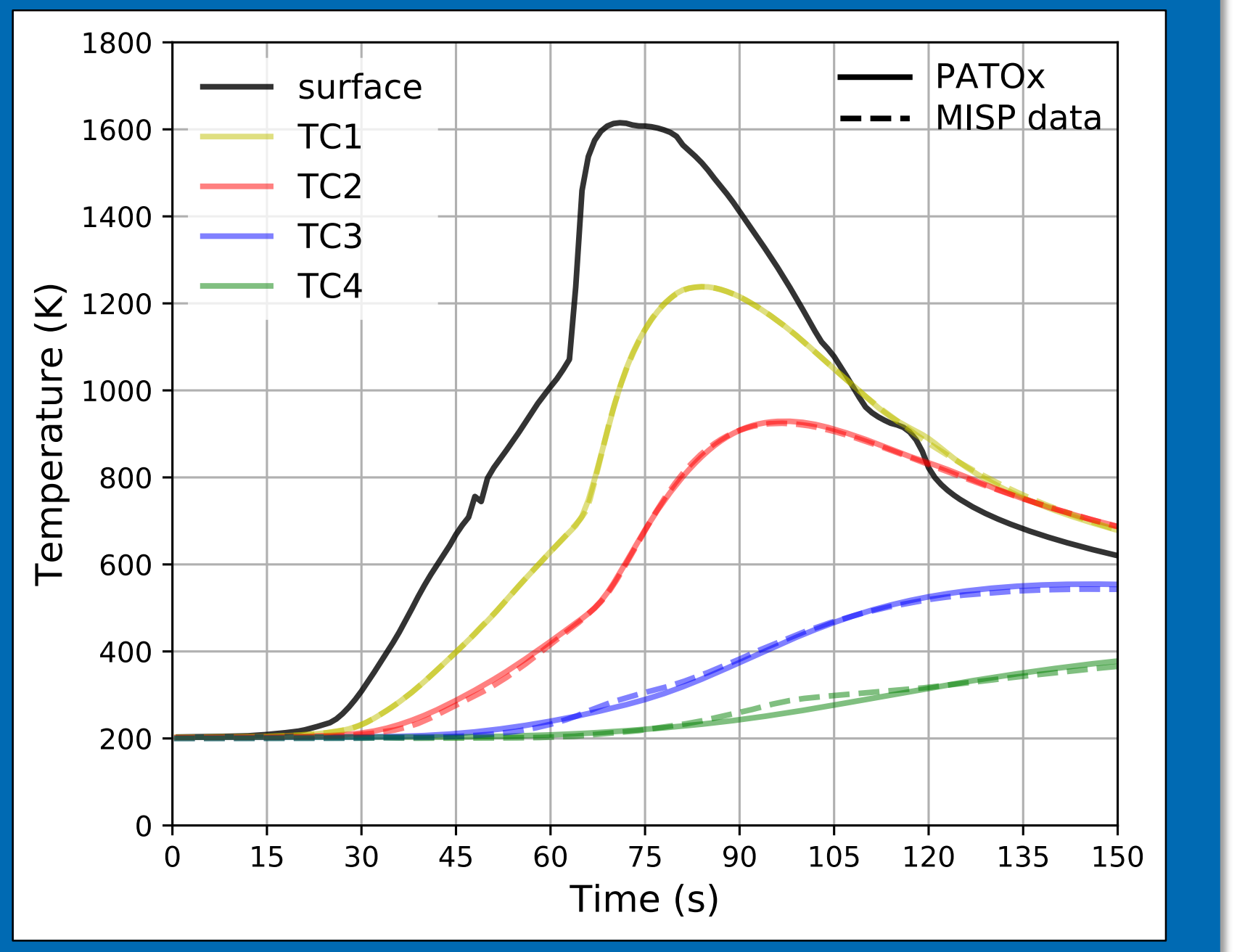
Thermal response using conductivity obtained from inverse analysis for MISPs 2 (left) and 4 (right)

Estimation of Aerothermal Environment

With the thermal conductivity values obtained from the previous analysis, estimates of the heat transfer coefficient ($\rho_e u_e C_H$) and specific enthalpy at the boundary layer edge (h_e) were computed. These parameters influence the convective heat flux at the surface (q_{conv}). As with the thermal conductivity, the error between measured and computed temperatures for the thermocouples was minimized.

$$q_{\text{conv}} = \rho_e u_e C_H' (h_e - h_w)$$

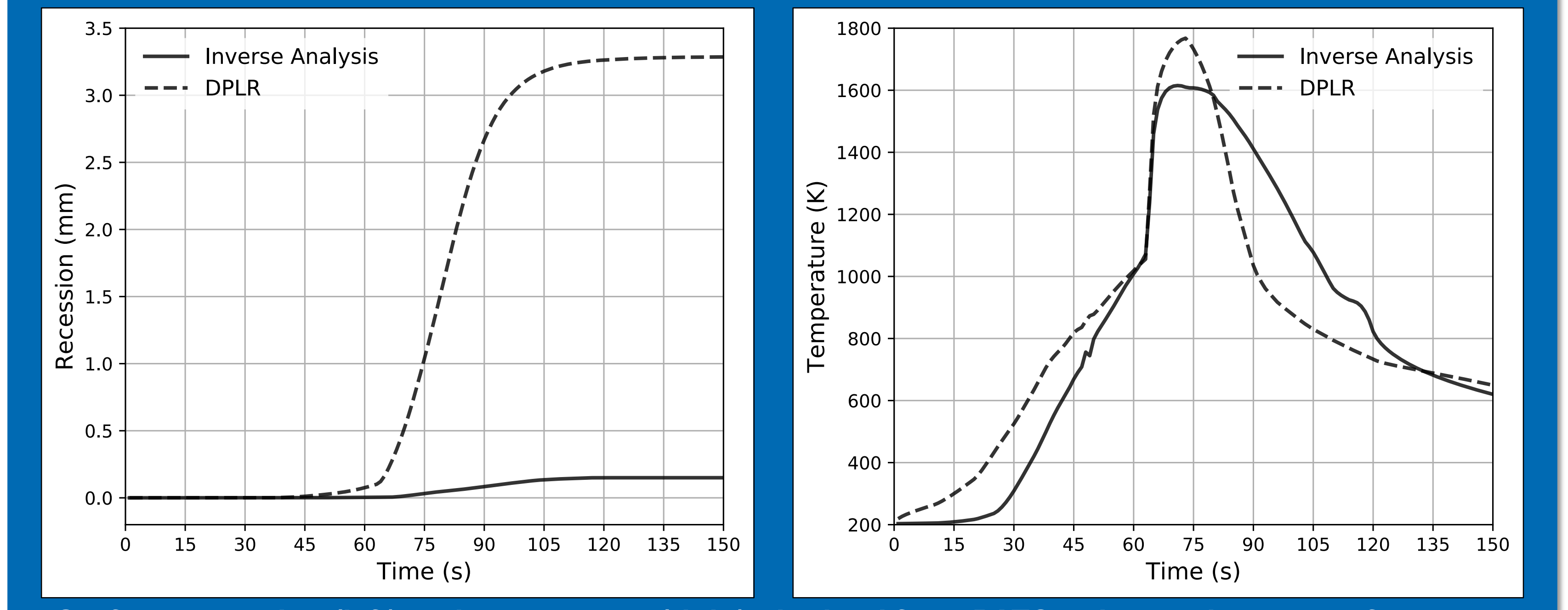
ρ_e density at boundary layer edge
u_e velocity at boundary layer edge
h_w specific enthalpy at the wall
C_H' modified Stanton number to account for blowing



Thermal response using environment obtained from inverse analysis for MISP 2

Comparison to Environment from CFD

Aerothermal environments obtained using the Data Parallel Line Relaxation (DPLR) code [10] have been compared to those obtained from the inverse analysis. Environments from the inverse analysis predict lower temperatures and much lower recession at MISP 2.



Surface recession (left) and temperature (right) obtained from PATO using environments from DPLR and inverse analysis for MISP 2

Conclusion

For the material properties and environment, the optimizer was able to find parameters such that the computed temperature profiles from PATO matched the MISP flight data. The thermal conductivity values match reasonably well with expected values for PICA. Computed surface temperature profiles using the estimated environment parameters look qualitatively good as well apart from some noise. Future work will involve constraining the edge enthalpies and Stanton numbers to specific functions in order to produce more physical values. Additional work should be done to add the effect of NuSil and finite-rate chemistry to the analysis.

References

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