Thermal Modeling of In-Depth Thermocouple Response in Ablative TPS Materials

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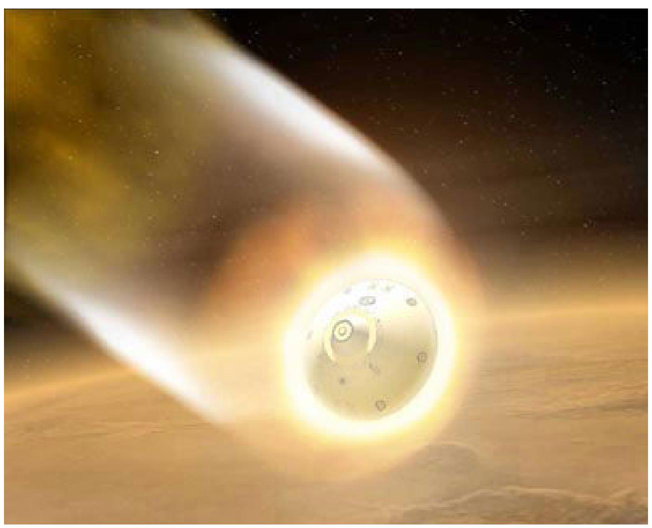
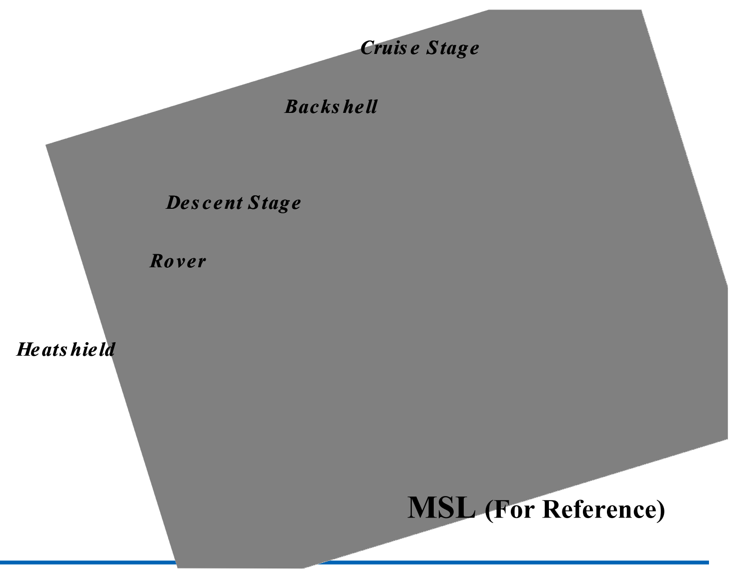
Outline

- Background and Scope
  - MSL, Entry, Descent, Landing Instrumentation (MEDLI)
  - MEDLI Instrumented Sensor Plug (MISP)
- Two dimensional thermal model
  - Boundary Conditions
  - Geometry
  - Case Studies
- Conclusions
- Future Work
- Acknowledgments

Background

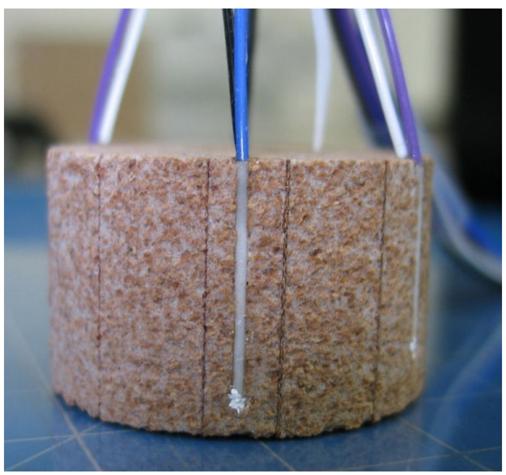
- MEDLI is an instrumentation suite installed in the heat shield of the Mars Science Laboratory (MSL) Entry Vehicle that will gather data on the atmosphere and on aerothermal, Thermal Protection System (TPS) and aerodynamic characteristics of the MSL Entry Vehicle during entry and descent **providing engineering data for future Mars missions**.
- MEDLI consists of 7 pressure ports and 7 integrated sensor plugs (containing four thermocouples and an isotherm sensor) all installed in the forebody heat shield of the MSL entry vehicle.





MEDLI Instrumented Sensor Plug (MISP)

- Sensor plug contains four in-depth Type K TCs 2.54 mm, 5.08 mm, 11.43 mm, and 17.78 mm from the surface
- One isotherm-following sensor to measure char depth
- Sensors located so as to provide enough information to recreate heat flux distribution on the centerline



MISP Locations:

1. Apex (reference heat flux)
2. Stagnation point
3. Windward heating augmentation
4. Leeward shoulder heating
5. Leeward shoulder heating
6. Transition onset cusp
7. Leeward acreage recession

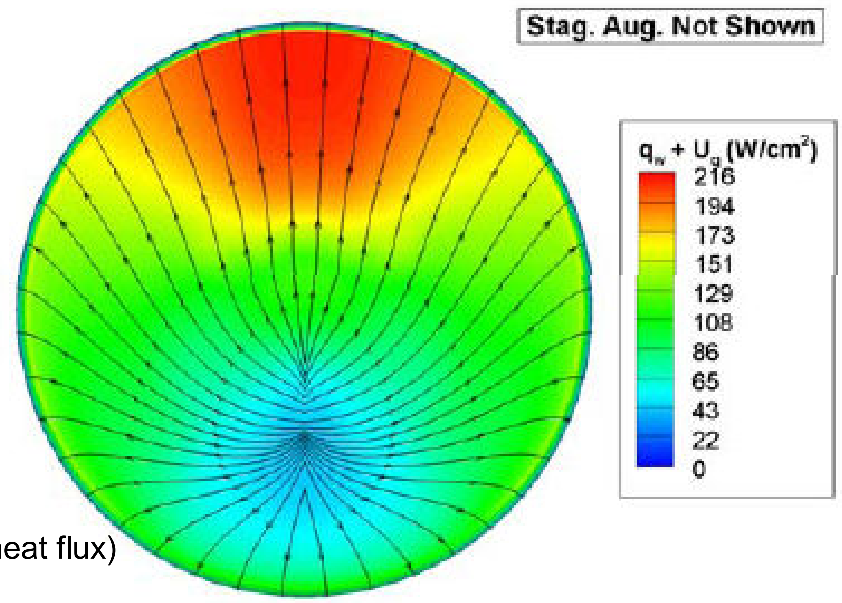
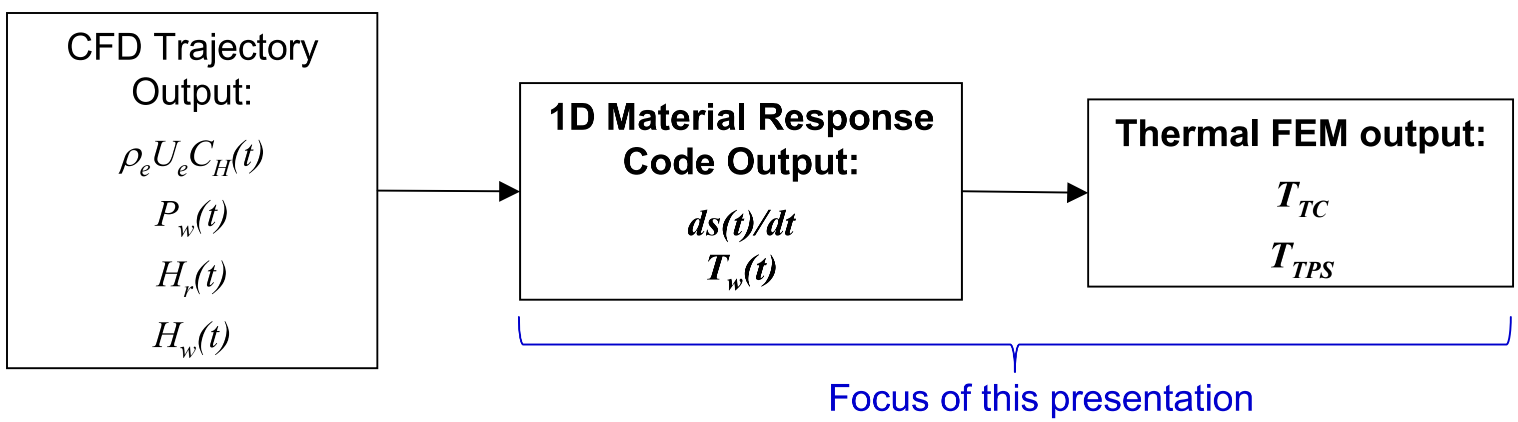


Figure courtesy K. Edquist (NASA LaRC) c/o R. Beck (NASA ARC)

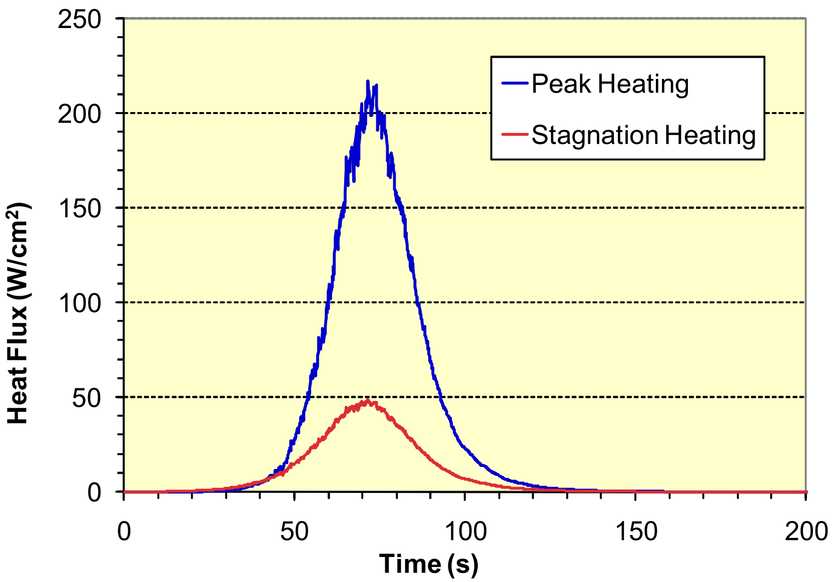
Problem Description and Solution Approach

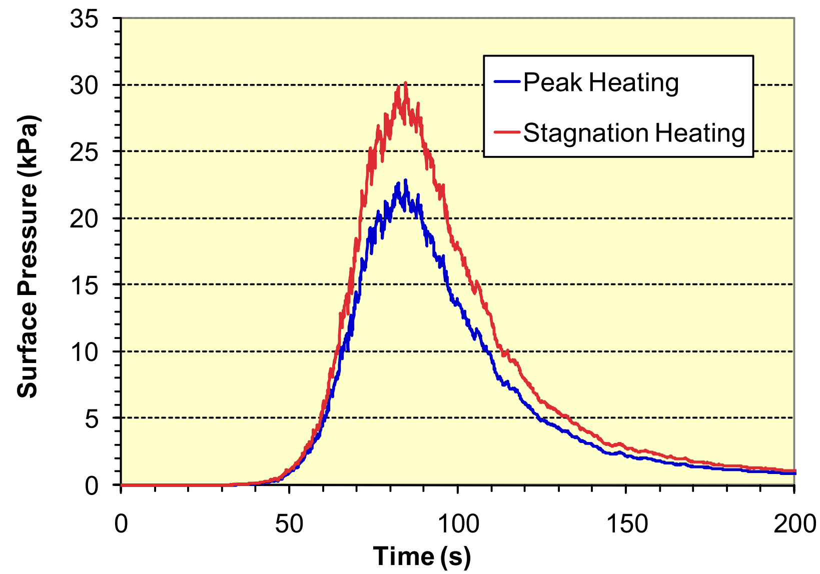
- How does one model the response of the thermocouples embedded in the fully decomposing thermal protection system material?
  - Existing material response codes do not account for multi-dimensional pyrolysis gas flow (even the available multi-dimensional codes still assume one-dimensional pyrolysis gas flow through the material)
- Conservative approach is taken:
  - Compute surface recession and wall temperature boundary conditions using a 1D material response program and input into a 2D thermal model of the instrumented sensor plug



Surface Boundary Conditions to CMA04 Material Response Program

- Time-dependent input heating and surface pressure profiles (trajectory considered early in the design of the MSL heat shield)

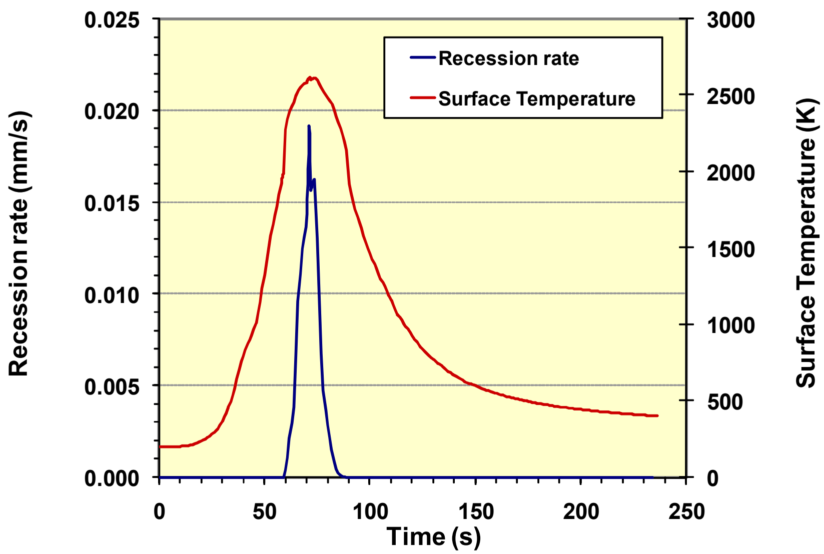




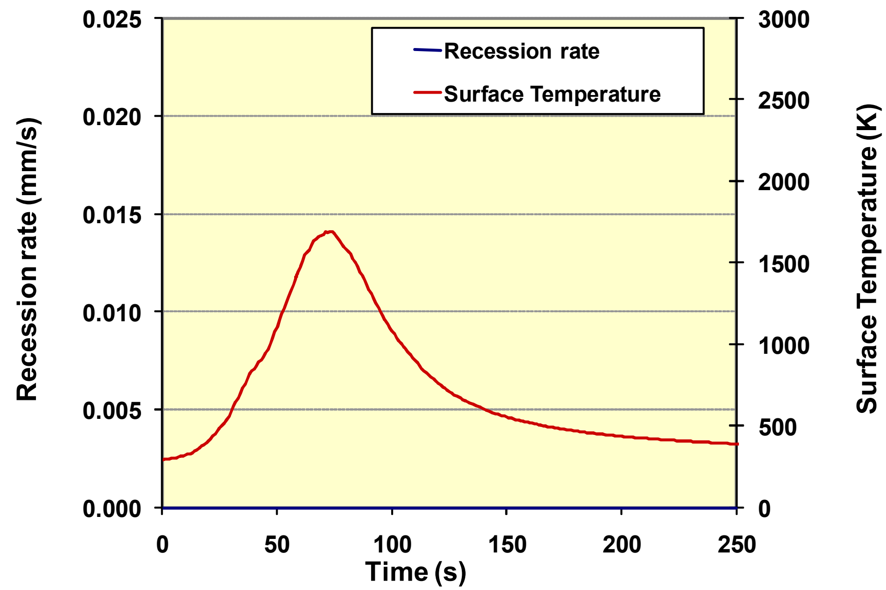
- Peak heating profile: q_{max} = *217 W/cm²*, P_{max} = *23 kPa*
- Stagnation point heating profile: q_{max} = *48 W/cm²*, P_{max} = *30 kPa*

2D Heat Conduction Model Boundary Conditions

- CMA04 material input file
  - SLA-561V High Fidelity Response Model (HFRM), peer reviewed at NASA ARC, and Mars "B prime tables" (dimensionless mass surface flux) are used
- Computed wall temperature and recession rate time histories:



Peak Heating Profile

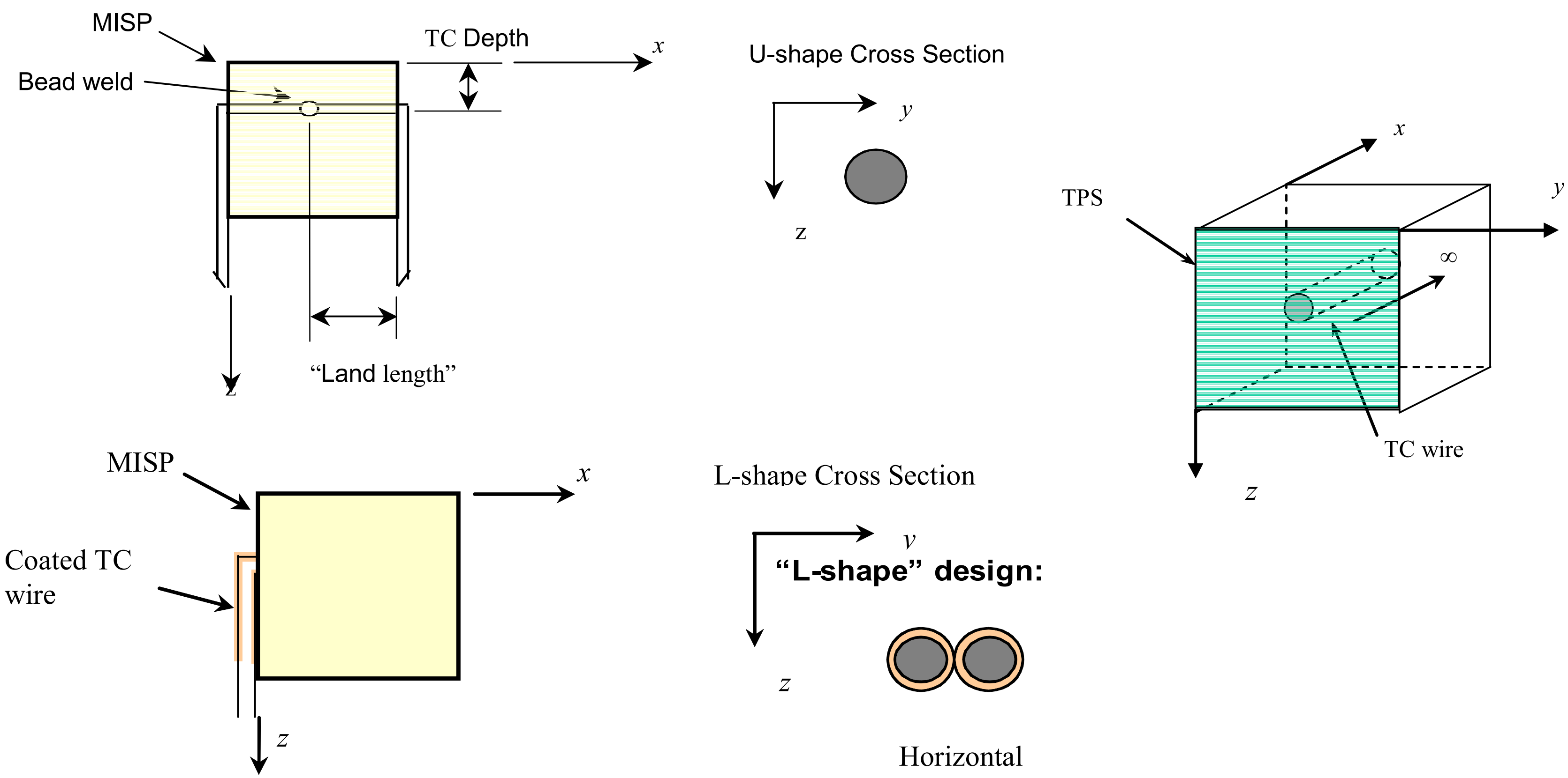


Stagnation Point Heating Profile

- Predicted total recession in peak heating case is only 1.22 mm; consequently, no thermocouples burn through
- No recession is predicted for the stagnation point

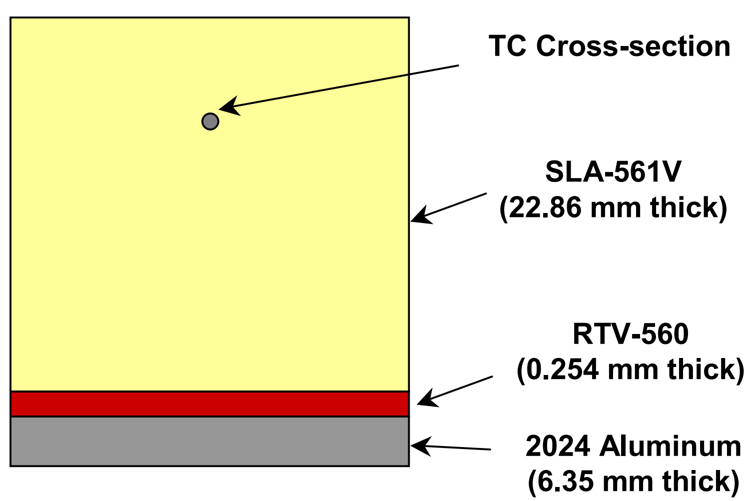
Geometry for 2D Thermal Model

- Thermocouple is modeled as a two-dimensional object based on its cross-section



Construction of Thermal Model

- 2-D Boundary conditions for side and back walls
  - Insulated side walls are assumed
  - Radiation from back wall to an ambient temperature of 203 K (-70 °C)
- Initial conditions
  - All materials are set to 203 K at time zero
- Material properties are input as functions of temperature
  - Virgin properties of SLA-561V from the High Fidelity Response Model developed at NASA ARC are used
- Material Stack-up:



$$\rho_{eq} = \frac{\sum_i A_i \rho_i}{\sum_i A_i}$$

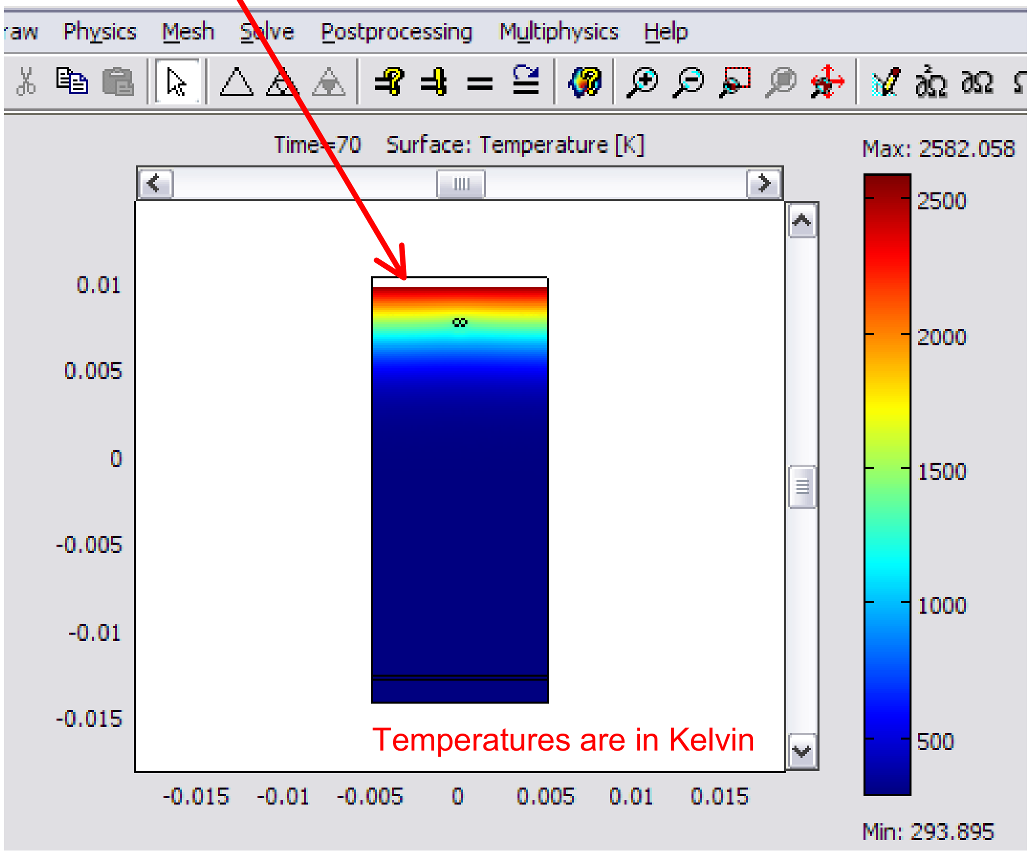
$$k_{eq} = \frac{\sum_i A_i k_i}{\sum_i A_i}$$

$$C_{p,eq} = \frac{\sum_i A_i \rho_i C_{p,i}}{\sum_i A_i \rho_i}$$

Thermal Model Details (cont'd)

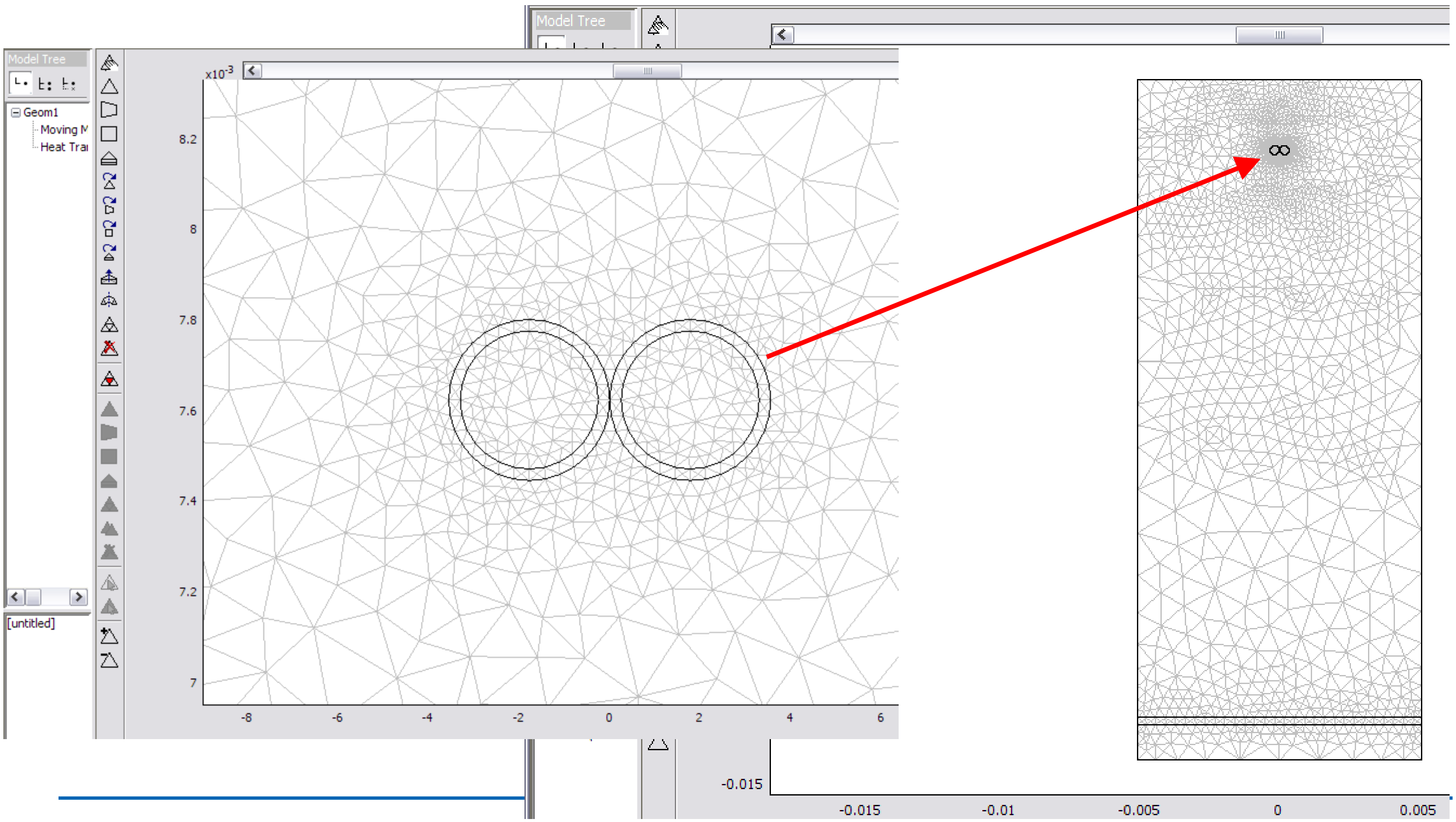
- Computational tool for 2D model: COMSOL Multiphysics
  - Commercial finite-element package
    - User may use pre-defined physics modules (transient conduction) and/or input differential equations in coefficient or general form
  - Arbitrary Lagrangian-Eulerian (ALE) moving boundary is used to provide recession rate and surface temperature boundary conditions as a function of time
  - Multiphysics capability of COMSOL couples moving mesh with heat conduction in a solid material

Screenshot showing surface recession of L-shape TC configuration at time *t* = 70 sec of the peak heating profile



Thermal Model Details (cont'd)

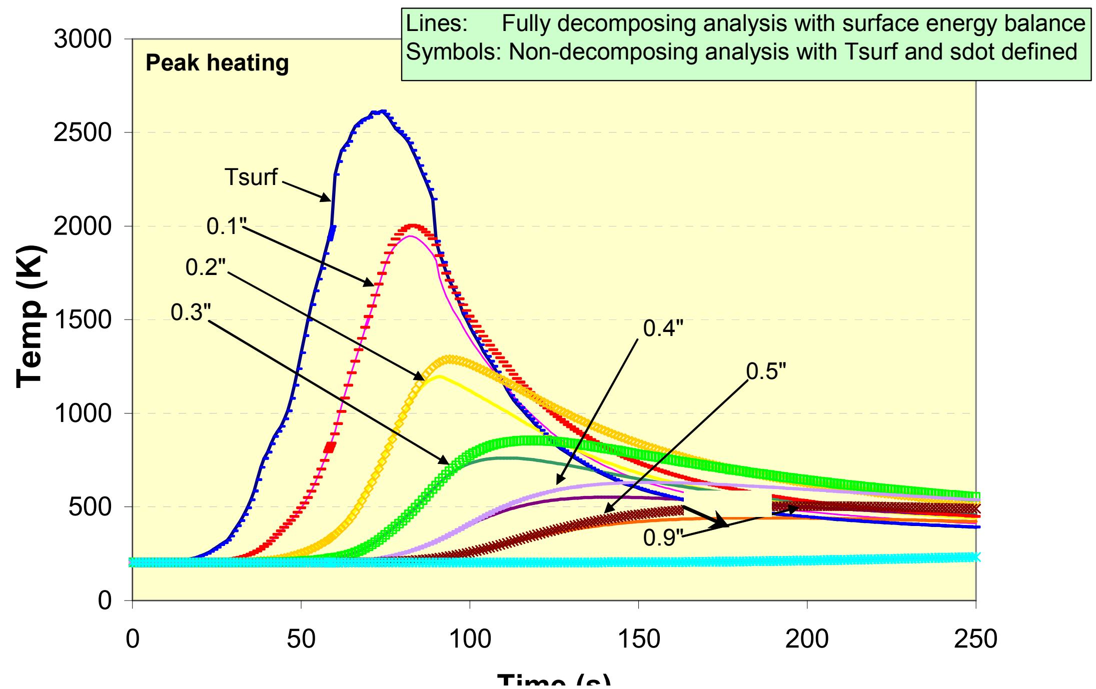
- Mesh construction
  - Approx. 4000 triangular elements total
    - ~ 75 elements for the alumina coating
    - ~ 140 elements for the thermocouple wire



Examination of 2D Assumptions

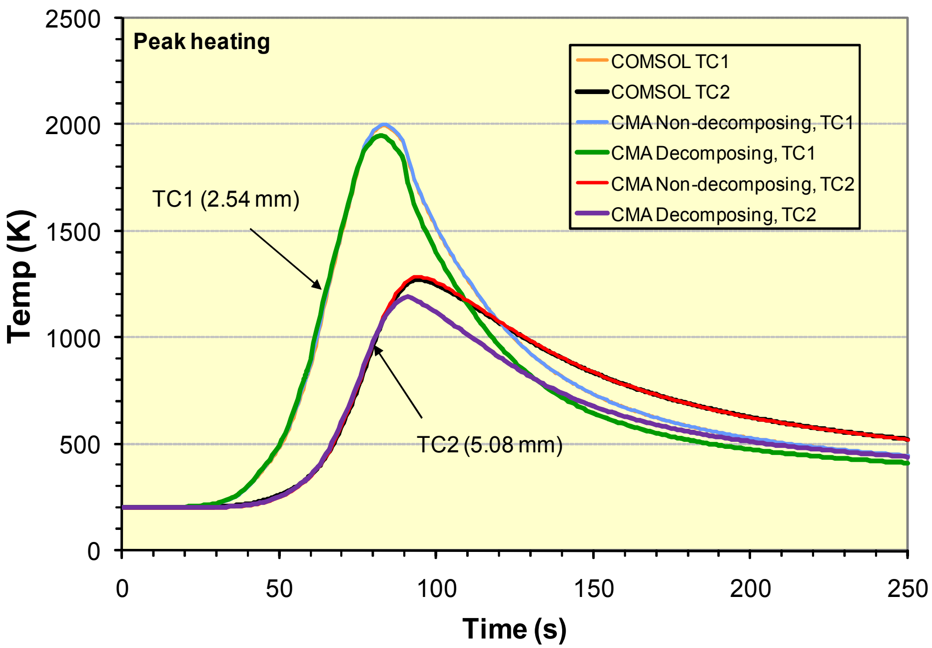
- Assumption of no internal decomposition examined with 1D dimensional CMA04 analysis
- CMA04 code is run for two cases with different boundary conditions:
  - No decomposition – time-dependent surface temperature and recession rate
  - Fully decomposing – $\rho_e U_e C_H(t)$, $P_w(t)$, $H_r(t)$, $H_w(t)$ taken from CFD

- Fully decomposing trace lags behind the non-decomposing result
- Expect 2D non-decomposing thermal model to be conservative: actual thermocouple response time should be faster than what the computations predict

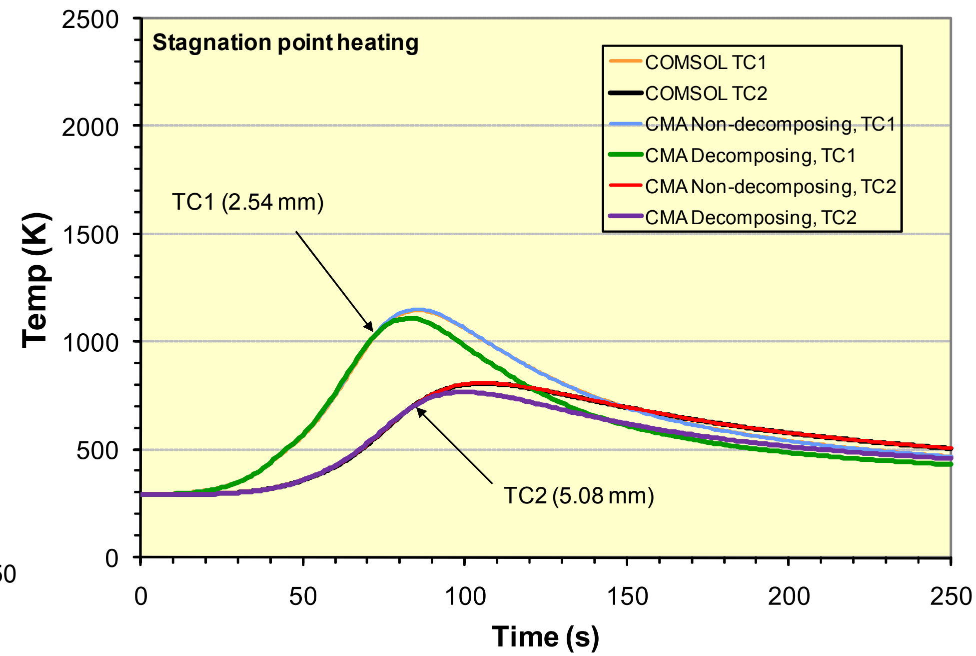


Model Traceability

- Comparison of COMSOL predicted in-depth temperatures with CMA04 non-decomposing analysis:



Peak Heating Profile



Stagnation Point Heating Profile

Test Cases

- Analysis Matrix (valid for both peak heating and stagnation point heating profiles):

	0.165 mm	0.305 mm	0.396 mm	No TC
U-shape	×	×	×	×
L-shape		×		×

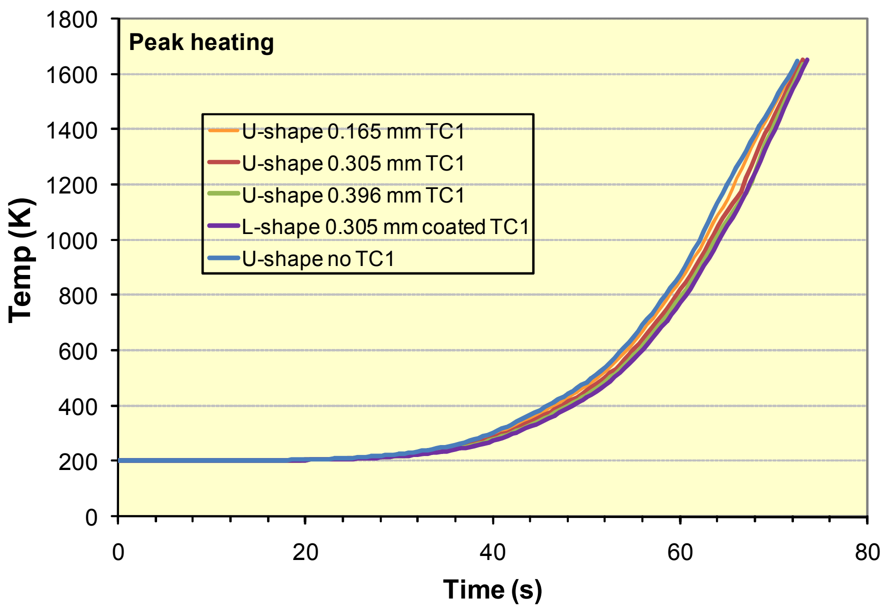
- Thermocouple error is relative to the temperature the TPS would achieve in the absence of instrumentation and subjected to the same boundary conditions

$$\%Error = (T_{TPS} - T_{TC}) / T_{TPS} \times 100$$

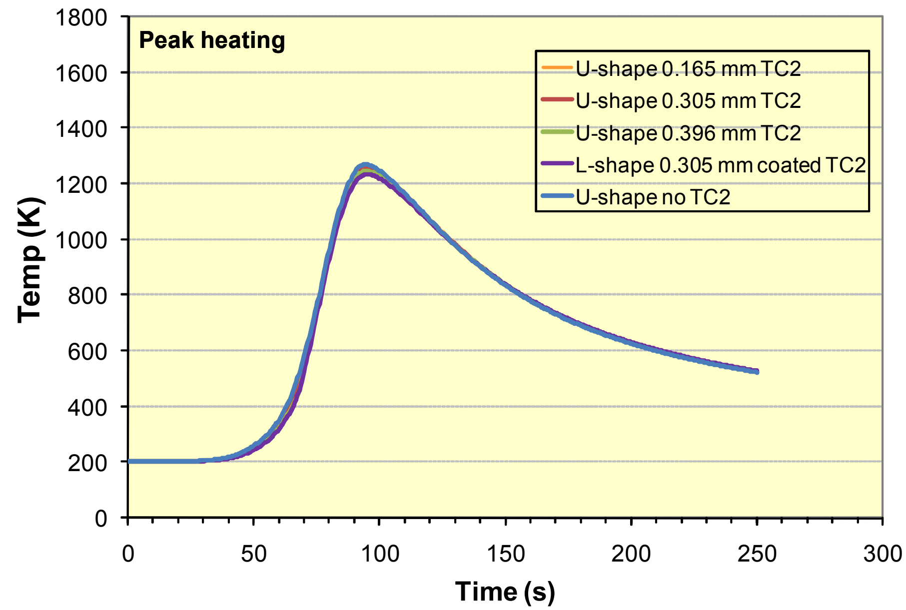
- Analysis focuses on locations of TC1 and TC2: 2.54 mm and 5.08 mm, respectively, from the top surface of the sensor plug
  - Since negligible error (< 3 K) is seen at the TC3 location (11.43 mm depth), analysis of TC4 (17.78 mm depth) was not considered
- Aluminum back plate, RTV-560 bonding agent remained isothermal

Thermal Model Simulation

- Temperature-time histories for peak heating profile:



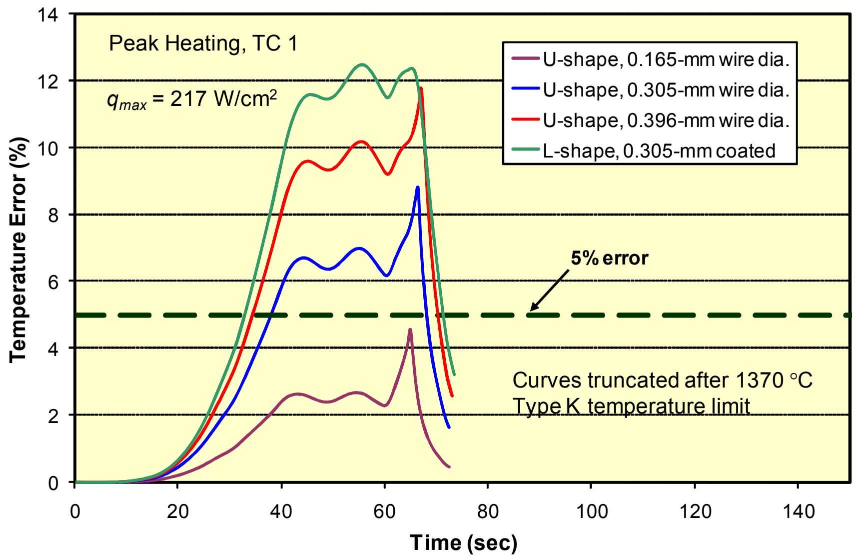
TC 1 Depth of 2.54 mm from Surface

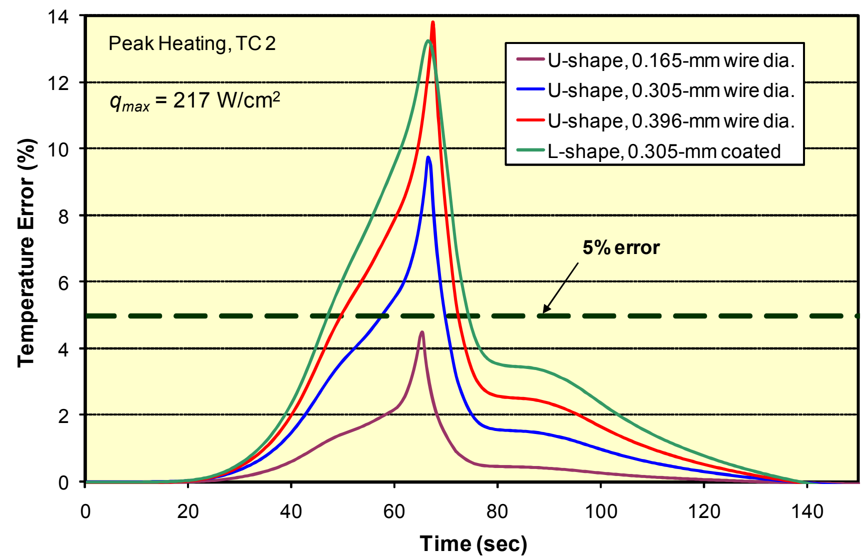


TC 2 Depth of 5.08 mm from Surface

Results – Peak Heating Profile

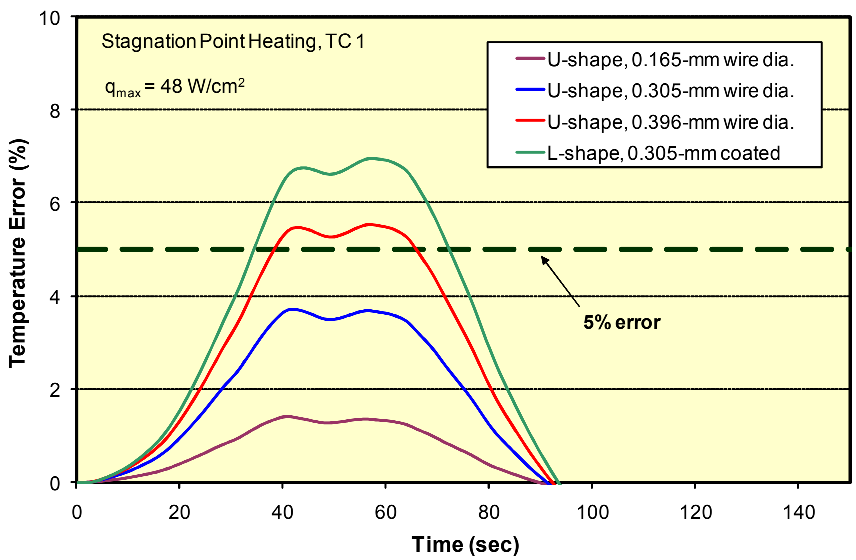
- Results of parametric studies run to determine effect of wire diameter and thermocouple installation method

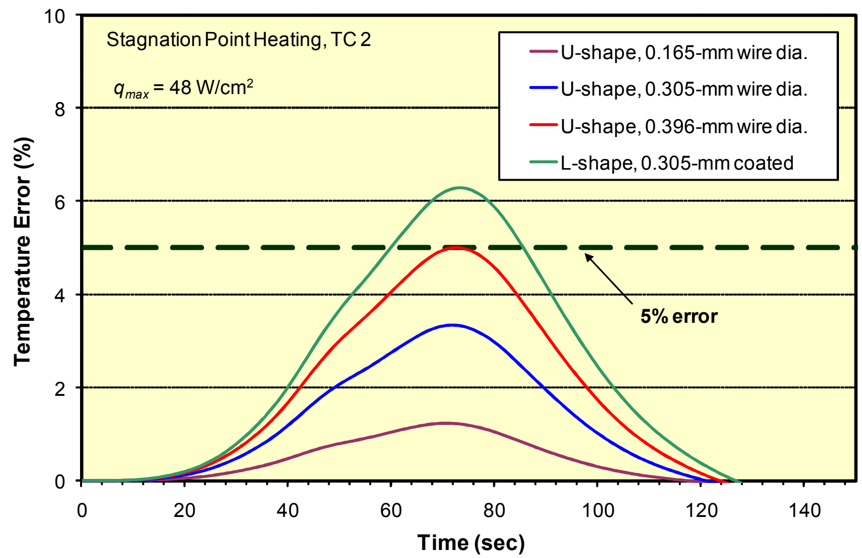




- Only the 0.165 mm diameter wire maintains an error below 5% for the entire duration of the trajectory
- In the case of the thermocouple located 5.08 mm from the surface, the error peaks at the time of peak heating

Results – Stagnation Point Heating Profile





- Lower overall heating at the stagnation point significantly reduces error for thermocouple configurations
- Only the 0.165 mm and 0.305-in diameter bare wires remain below an error of 5%

Conclusions

- 2D finite element model constructed in COMSOL Multiphysics has been developed to estimate the error associated with thermocouple lag and allows for rapid turnaround of trade studies
- Moving boundary achieves excellent agreement with CMA04 for a non-decomposing analysis
- Peak heating location produces larger errors than the stagnation point (low heating) profile
- Bare wire (uncoated) thermocouple diameters of 0.165 mm and 0.305 mm consistently achieved the best results among the configurations considered
- No significant thermal lag is predicted with this model for in-depth thermocouples located at depths 11.43 mm and below

Future Work

- Determine the effect of one thermocouple on another as a function of separation distance
- Run the model for other trajectories and TPS materials
- Relax the perfect thermal contact assumption and model the gap between the thermocouple and TPS material
  - Radiation between wire and TPS
  - Gas flow
- Develop model to account for internal decomposition with multi-dimensional pyrolysis gas flow

Thermal Model

(Videos)

Acknowledgments

- MSL, Entry, Descent, Landing Instrumentation (MEDLI) project for funding this work
- Dr. Michael J. Wright (NASA-ARC) for providing the CFD trajectory data input as boundary conditions into the CMA04 calculations

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