Material Response Analysis of a Titan Entry Heatshield

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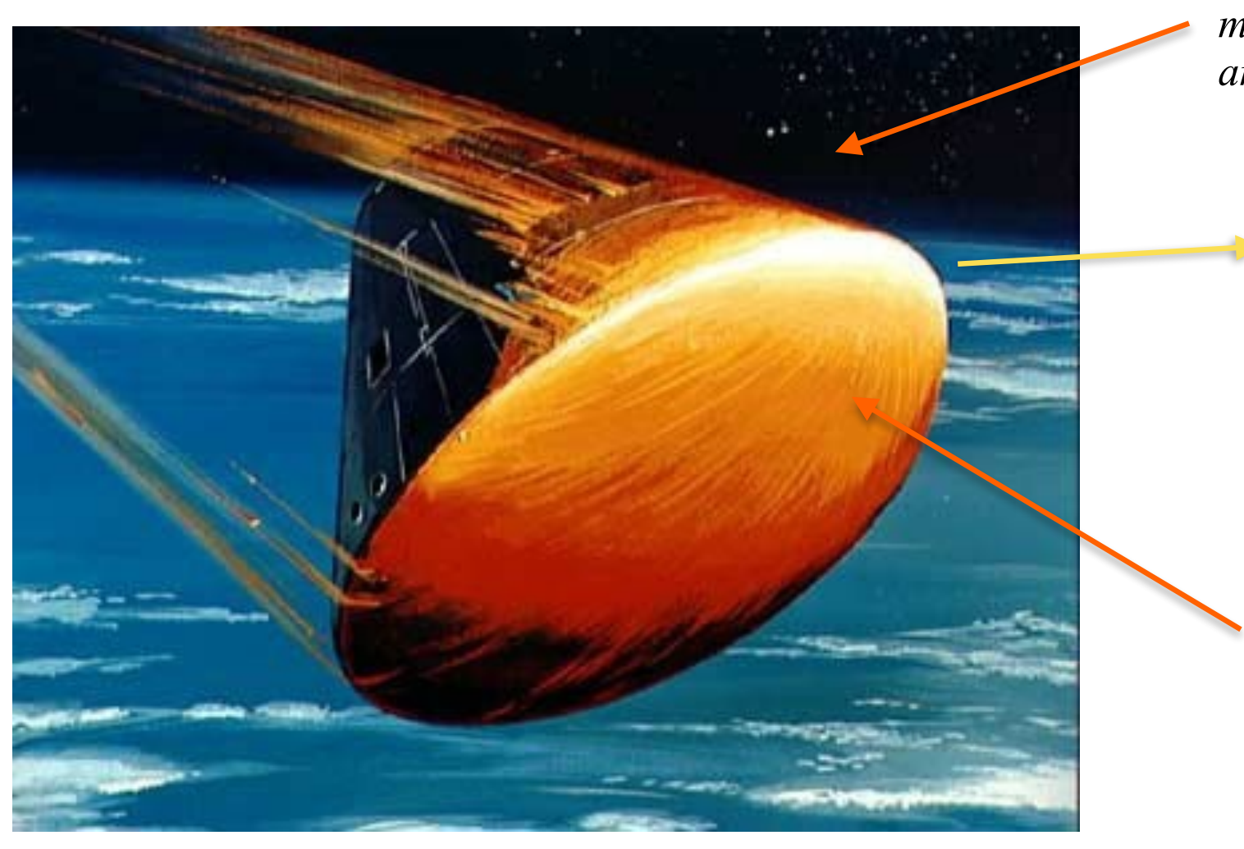
Abstract: Accurate calculation of thermal protection material response is critical to the vehicle design for missions to the Saturn moon Titan. In this study, Icarus, a three-dimensional, unstructured, finite-volume material response solver under active development at NASA Ames Research Center, is used to compute the in-depth material response of the Huygens spacecraft along its November 11 entry trajectory. The heatshield analyzed in this study consists of a five-layer stack-up of Phenolic Impregnated Carbon Ablator (PICA), aluminum honeycomb, adhesive, and face sheet materials. During planetary entry, the PICA outer layer is expected to undergo pyrolysis. A surface energy balance boundary condition that captures both time- and spatial-variance of surface properties during entry is used in the simulation.

Motivations....

- Design and sizing of the thermal protection system (TPS) of an entry vehicle requires high-fidelity material response codes coupled to computational fluid dynamics (CFD) and full radiation transport.



Mass flow due to material decomposition and surface ablation

Shock layer radiation out to the surroundings

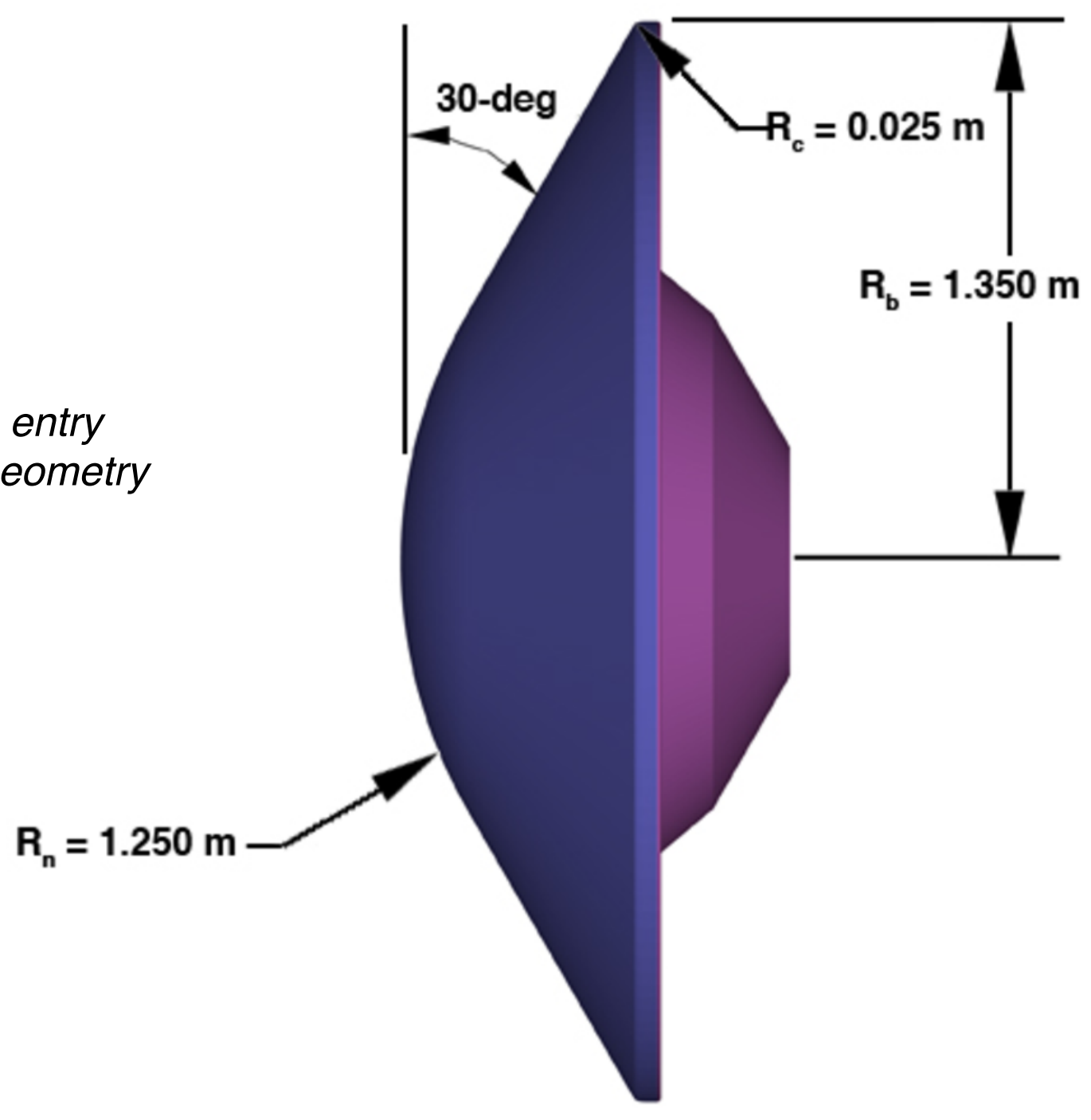
Strong convective and radiative heat flux to the surface

Planetary Entry Environment

The goal of the current work is to apply the Icarus material response code to compute the in-depth material response of a multi-layer TPS material stack-up along a representative Titan entry trajectory.

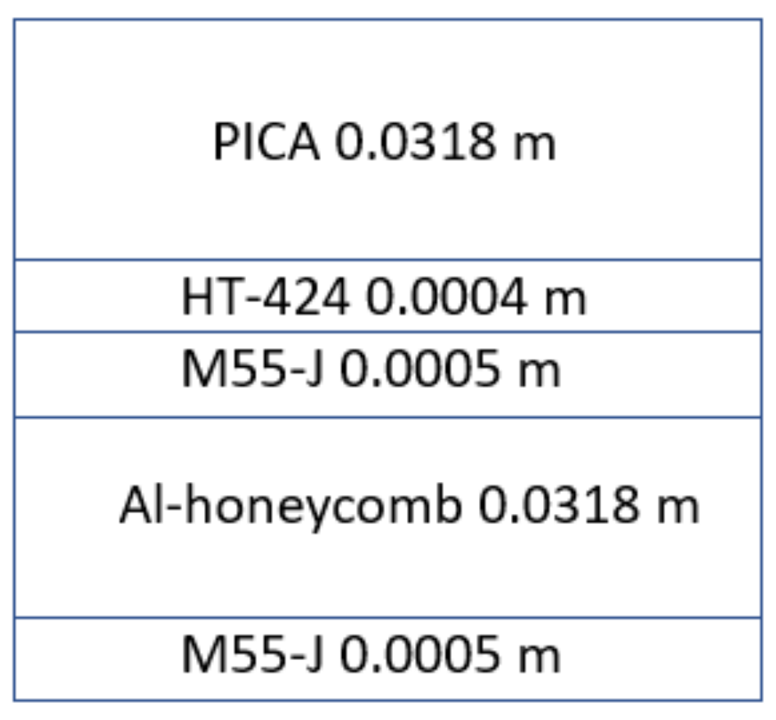
Huygens Vehicle Geometry and TPS Material Stack-up

- The Huygens probe was a 60-deg half-angle sphere-cone with a 2.7 m base diameter and a 1.25 m nose radius.



Huygens entry vehicle geometry

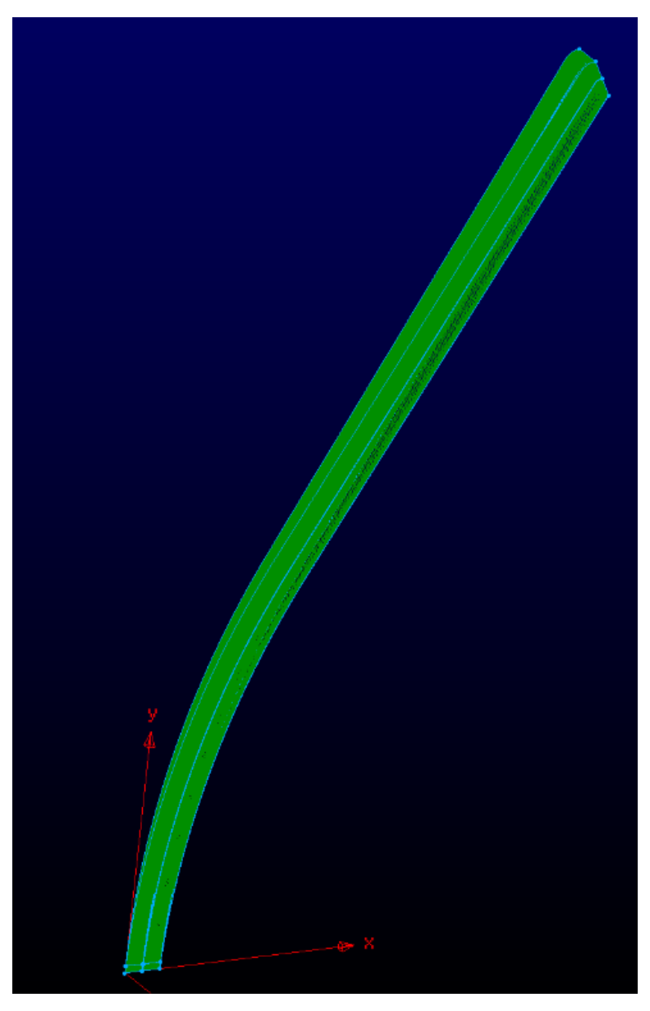
- For this study, a 5-layer TPS material stack-up was modeled:
  - 0.0318 m PICA outer layer
  - 0.0004 m HT-424 adhesive
  - 0.0005 m M55-J face sheet
  - 0.0318 m layer of aluminum honeycomb
  - 0.0005 m M55-J face sheet



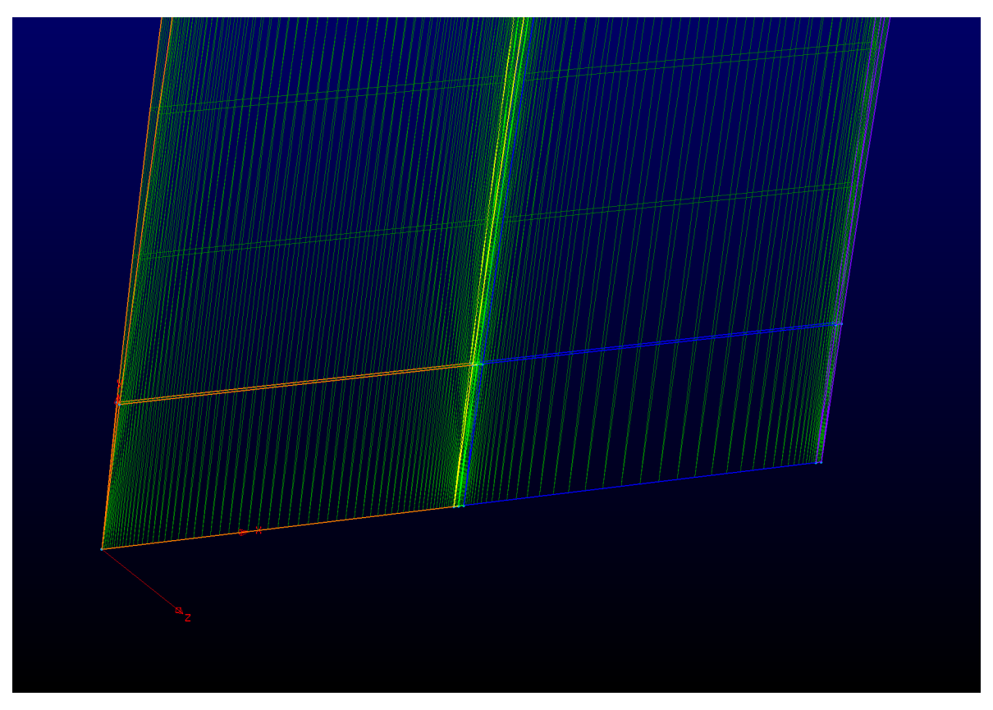
TPS material stack-up for Titan entry vehicle

Icarus

- Icarus is a 3-D, finite-volume, unstructured material response code.
- Can model ablating, pyrolyzing, melting, or vaporizing materials subject to a wide range of surface boundary conditions.
- Icarus grid of Huygens entry vehicle is a 3-D wedge with a mixture of hexahedral and prismatic grid elements.



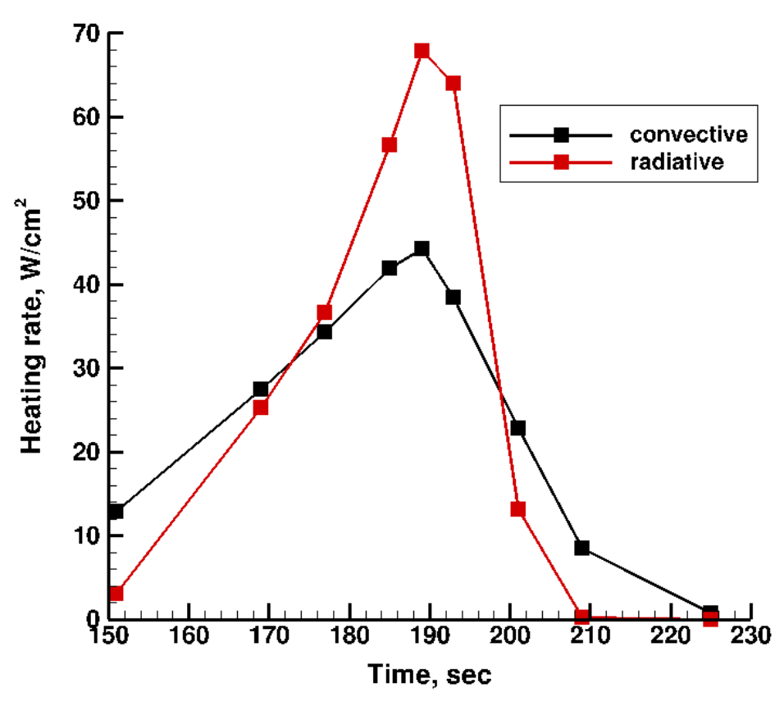
3-D wedge grid of Huygens heatshield



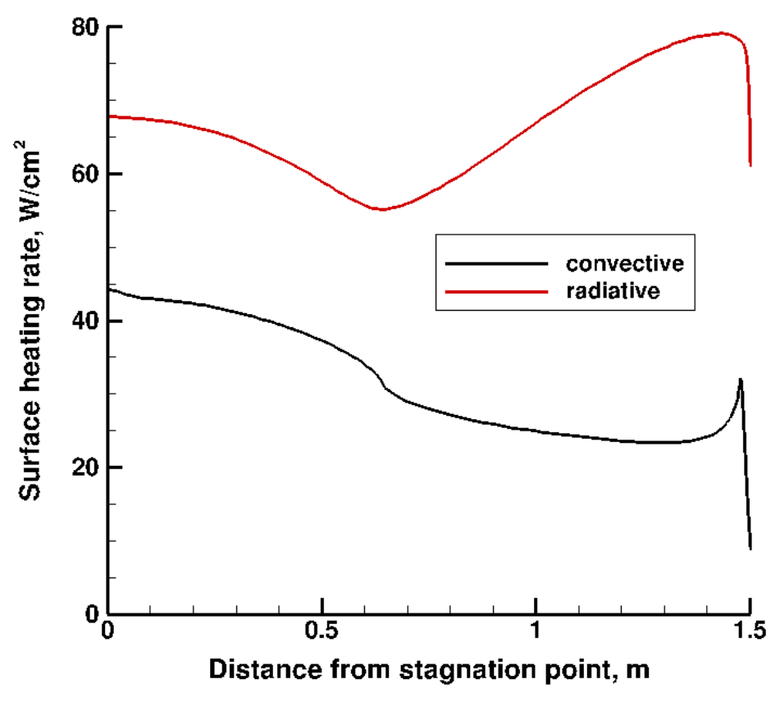
Close-up of stagnation line showing 5-layer stack-up

Surface Environments and Boundary Conditions

- The DPLR CFD code and NEQAIR line-by-line radiation codes were used to compute surface heating rates and pressure.
- 13-species gas chemistry model: CH4, CH3, CH2, N2, C2, H2, CH, NH, CN, N, C, H, Ar.
- N2: 0.970, CH4: 0.023, Ar: 0.007 by mole fraction
- Surface heating dominated by radiative component.
- Radiative heating increases along flank towards shoulder due to CN levels in shock layer.



Convective and radiative heat pulse at the stagnation point.



Surface heating rates, t = 189 second trajectory point.

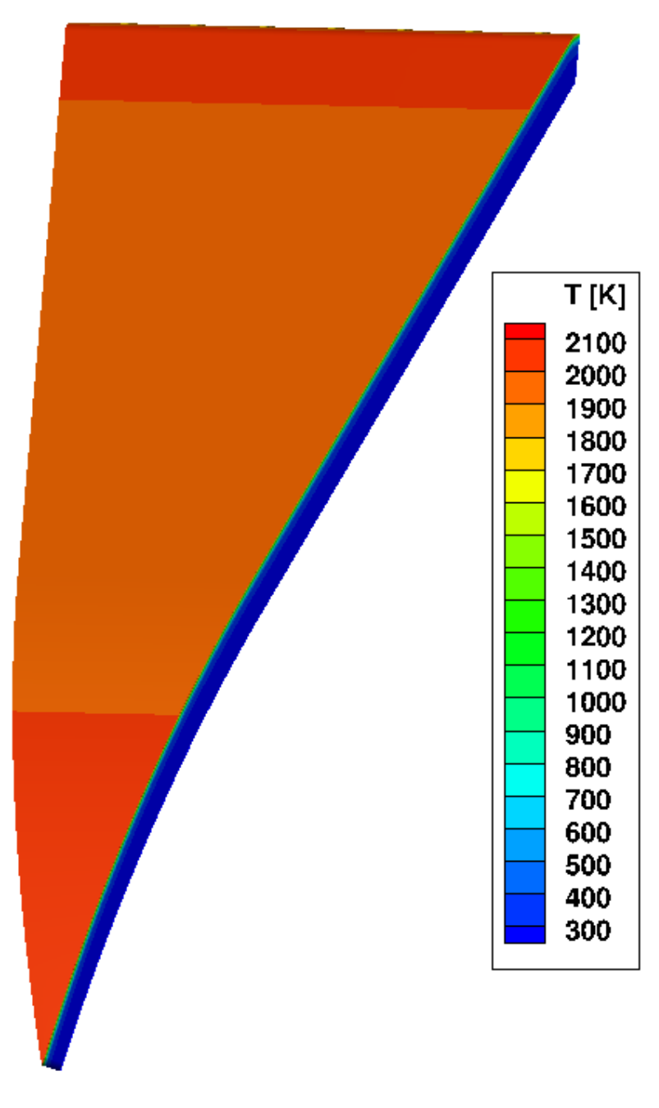
- DPLR/NEQAIR solutions at 9 points along Huygens November 11 trajectory (time = 151 - 225 sec) used to create time- and spatially-varying boundary conditions.
- An aeroheating surface energy balance (SEB) boundary condition is used in Icarus.

$$\dot{q}_{cond} = C_H\left(h_{rec} - \left[1 + B'_c + B'_g\right]h_w\right) + \dot{m}_c h_c + \dot{m}_g h_g + \alpha \dot{q}_{rad} - \sigma\left(\epsilon T_w^4 - \alpha T_\infty^4\right)$$

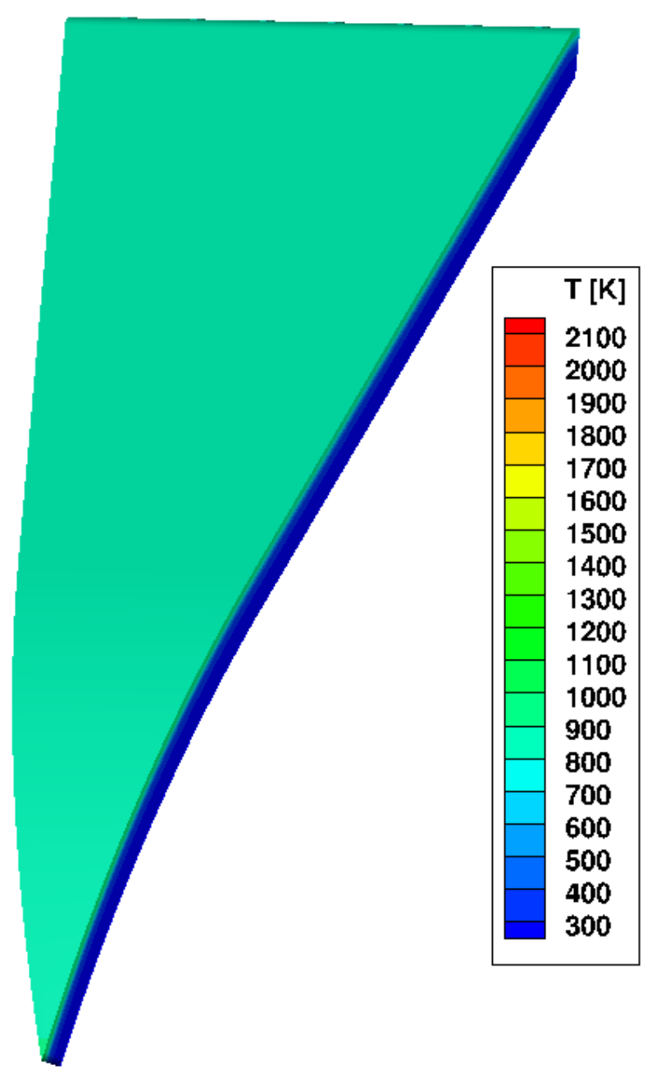
- Normalized char mass flux computed using a 45-species PICA-Titan GSI gas mixture.
- Pyrolysis gas mass flux computed using a 39-species PICA pyrolysis gas mixture.

Results

- Icarus computation run for 100 seconds of simulation time starting at the 151 sec trajectory point conditions. Zero-heating cool-down conditions were applied after 225 sec.
- Surface boundary conditions were both time- and spatially-varying during the simulation.
- Surface temperatures reach a peak value of 2068 K at t = 189 sec. Surface then starts to cool as external heating rates decrease. Peak temperature at t = 225 sec is 1003 K.
- Because radiative heating increases along flank towards the shoulder, surface temperatures on the upper flank region are similar to stagnation point values.

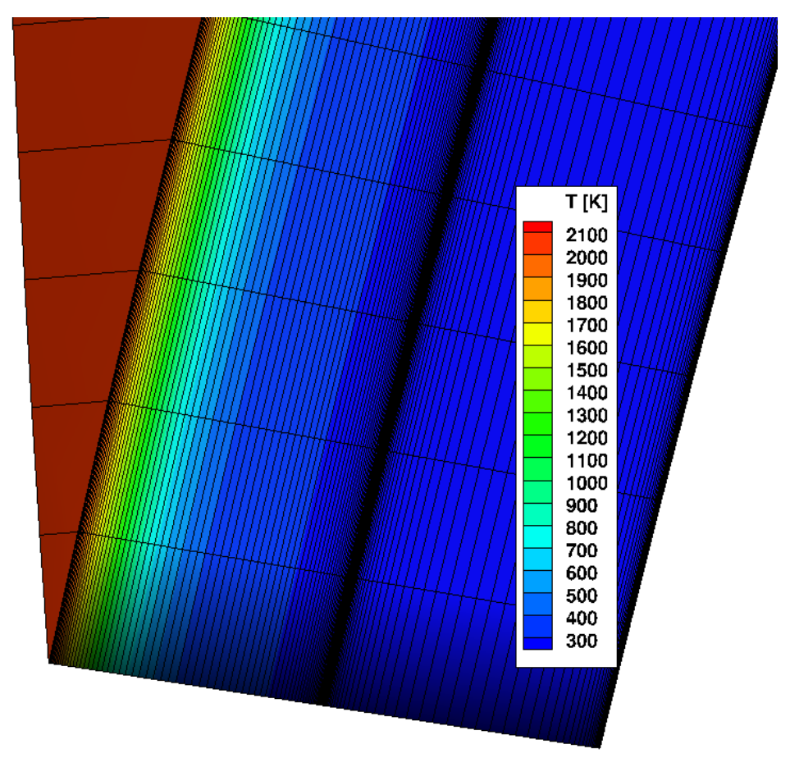


Surface temperatures, t=189 sec

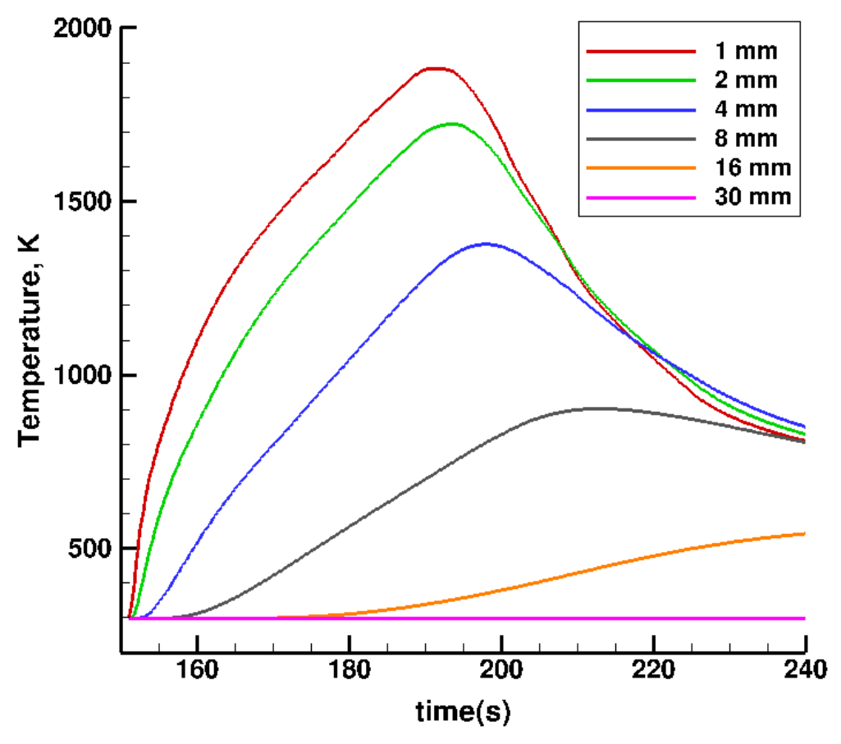


t=225 sec

- In-depth temperature profiles indicate heat soak does not reach the PICA backface at the 100 second simulation time cut-off.



In-depth temperature contours at t = 189 sec.



Time history of stagnation point temperature at various depth locations.

Summary/Conclusions

- Icarus material response solver demonstrated ability to compute in-depth material response of Huygens probe heatshield during an entry into Titan. The 100 second simulation time captured the entire entry heat pulse.
- Five-layer material stack-up was modeled.
- DPLR/NEQAIR simulations used to create 4-D, time- and spatially-varying surface boundary conditions

Future Work

- Implement Stanford/DLR dust particle model into Icarus for Mars entry simulations.
- Apply Icarus to other planetary entry scenarios.

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References:

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