Overview of the material response code Icarus

Joseph Schulz, Georgios Bellas-Chatzigeorgis, Eric Stern, and Grant Palmer
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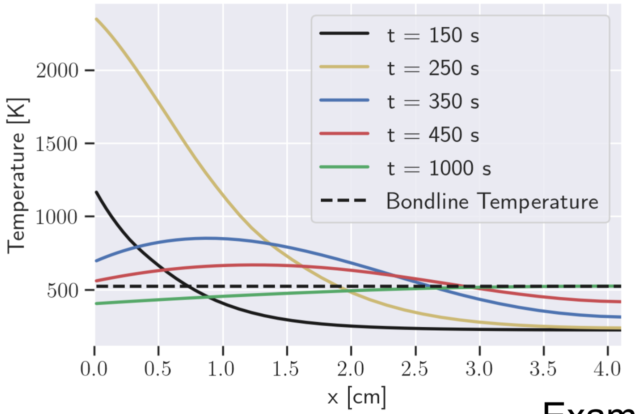
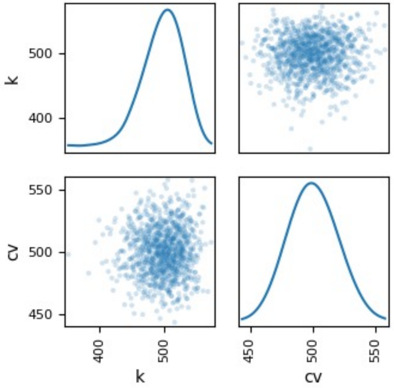
Icarus : Unstructured, 3-D Material Response

Retain ability of the heritage, 1-D design and analysis tools, e.g., FIAT

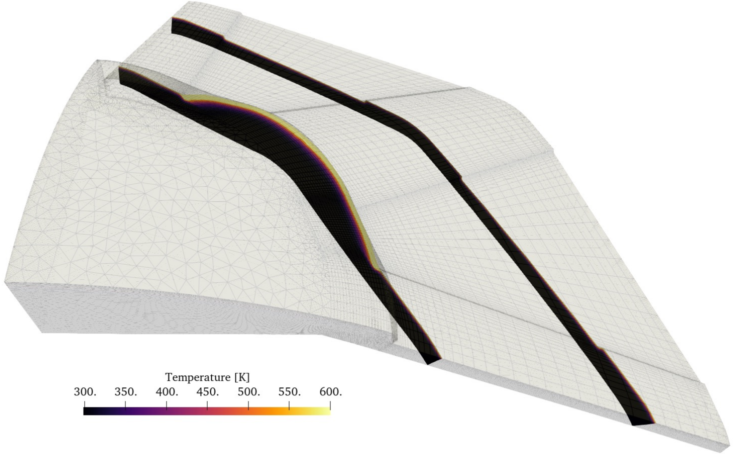
1. ***Extend analysis capability to complex, 3-D aeroshells with parallelization***
2. ***Interfaces for multi-physics coupling***





Iteration	Thickness	Max Temp.	Next Thickness
1	0.0508	453.85	0.0300
2	0.03	582.41	0.04040
3	0.0404	533.65	0.04264
4	0.0426	517.20	0.04182
5	0.0418	523.25	0.04184

Examples of heatshield sizing and uncertainty quantification capabilities



Governing Equations

$$\frac{\partial(\rho e)}{\partial t} + \frac{\partial}{\partial x_i}\left(\phi \rho_g h_g u_{g,i}\right) - \frac{\partial}{\partial x_i}\left(\kappa_{ij}\frac{\partial T}{\partial x_j}\right) = 0$$

Conservation of Energy

$$\frac{\partial \rho_{s,n}}{\partial t} = -k_n \rho_{v,n}\left(\frac{\rho_{s,n}-\rho_{c,n}}{\rho_{v,n}}\right)^{\psi_n} e^{\left(-T_{a,n}/T\right)}$$ where n = 1, …, N

$$\rho_s = \sum_{n=1}^{N} \Gamma_n \, \rho_{s,n}$$

$\Gamma_n =$ pseudo-volume fraction

$\phi =$ porosity

$$\rho = \phi \rho_g + \rho_s$$

Conservation of Mass

$$\frac{\partial(\phi \rho_g)}{\partial t} + \frac{\partial}{\partial x_i}\left(\phi \rho_g u_{g,i}\right) = \sum_{n=1}^{N} \Gamma_n \frac{\partial \rho_{s,n}}{\partial t}$$

Darcy's Law: $u_{g,i} = -\frac{1}{\mu_g} K_{ij} \frac{\partial p}{\partial x_j}$

Implementation Details of Icarus

Finite-volume formulation: $\int \frac{\partial Q}{\partial t}\,\mathrm{d}V = \oint F \cdot \hat{n}\,\mathrm{d}A + \int \dot{S}\,\mathrm{d}V$

Conservatives:

$$Q = \begin{bmatrix} \rho_s \\ \phi\rho_g \\ E \end{bmatrix}$$

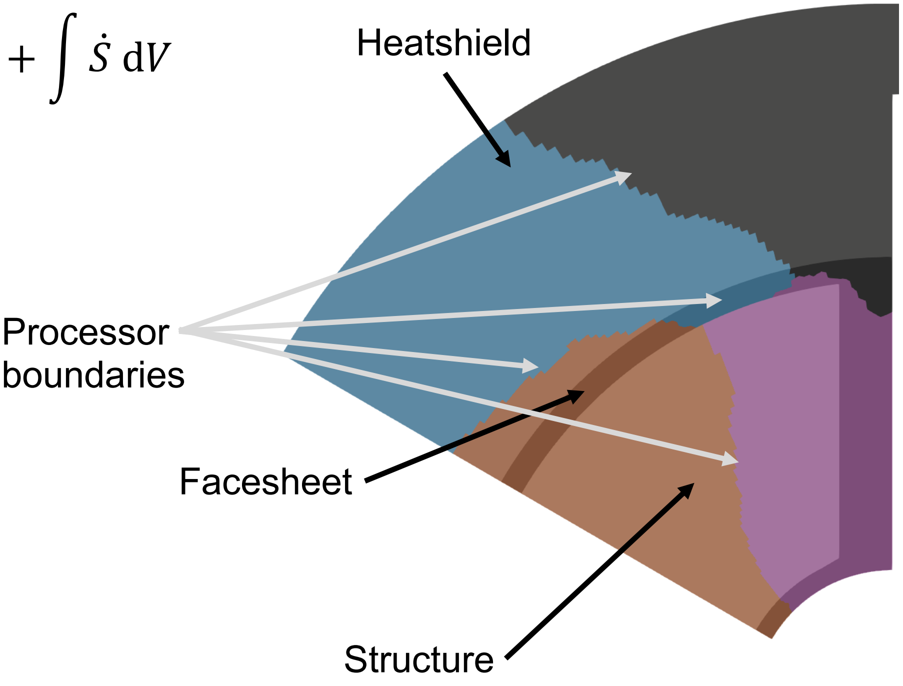
Primitives:

$$W = \begin{bmatrix} \rho_s \\ p \\ T \end{bmatrix}$$

Implicit Euler – Primitives

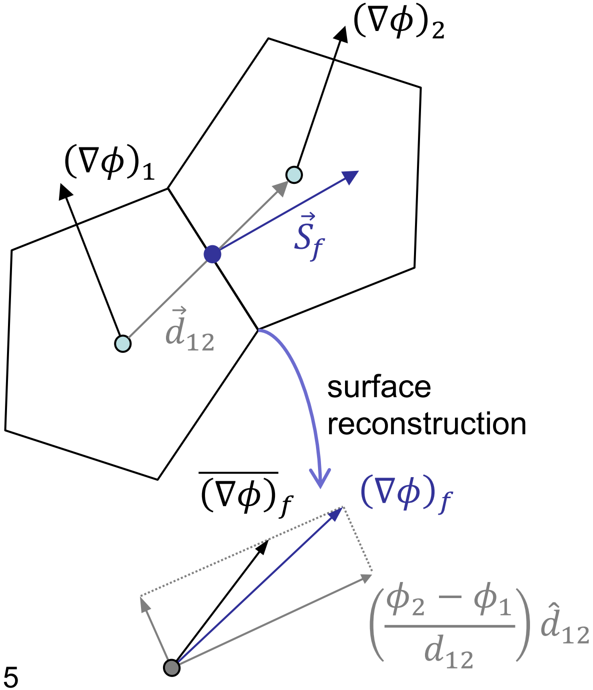
$$V_i \frac{\partial Q}{\partial W}\frac{\partial W}{\partial t} = \sum_{j \in V_i}^{N_f} F_j \cdot \hat{n}_j\, A_j + V_i \dot{S} = R_i$$

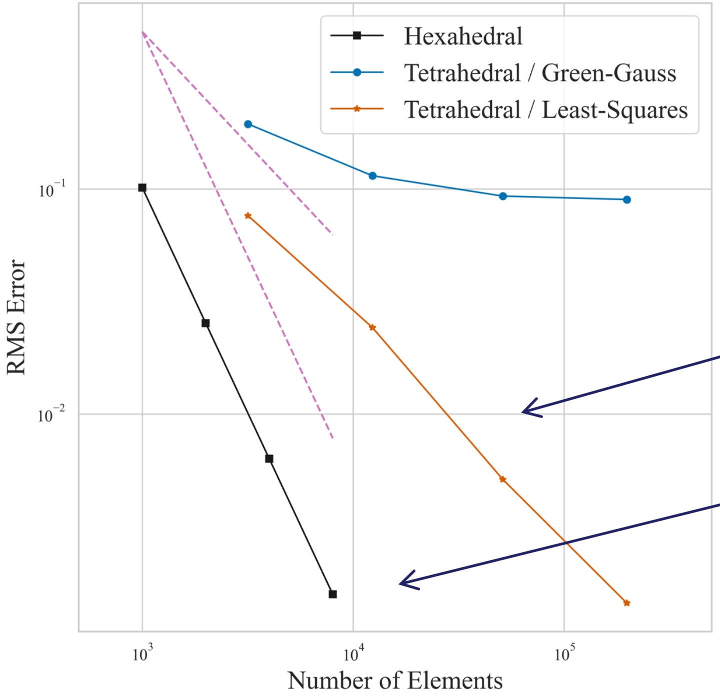
$$\sum_k \left[\frac{V_i}{\Delta t}\left(\frac{\partial Q}{\partial W}\right)\delta_{ik} - \left(\frac{\partial R_i}{\partial W_k}\right)^n \right] \delta W_k^{n+1} = R_i^n$$



Gradient Reconstruction

- Flux evaluation requires surface gradients





Grid Convergence Study

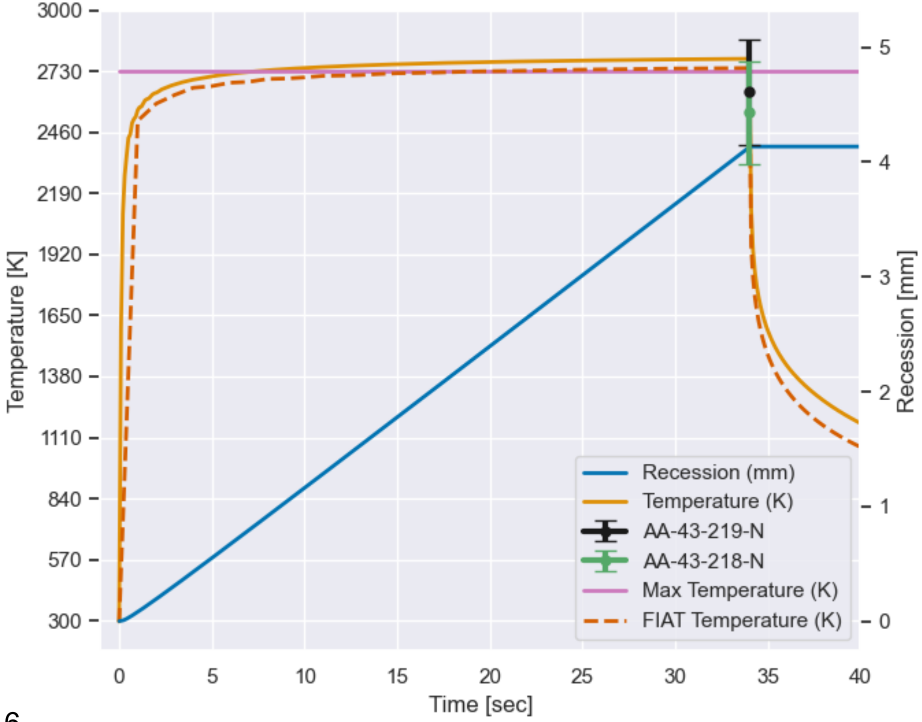
- Constant material properties
- Heat conduction only
- Uni-directional heating
- Isothermal / Adiabatic

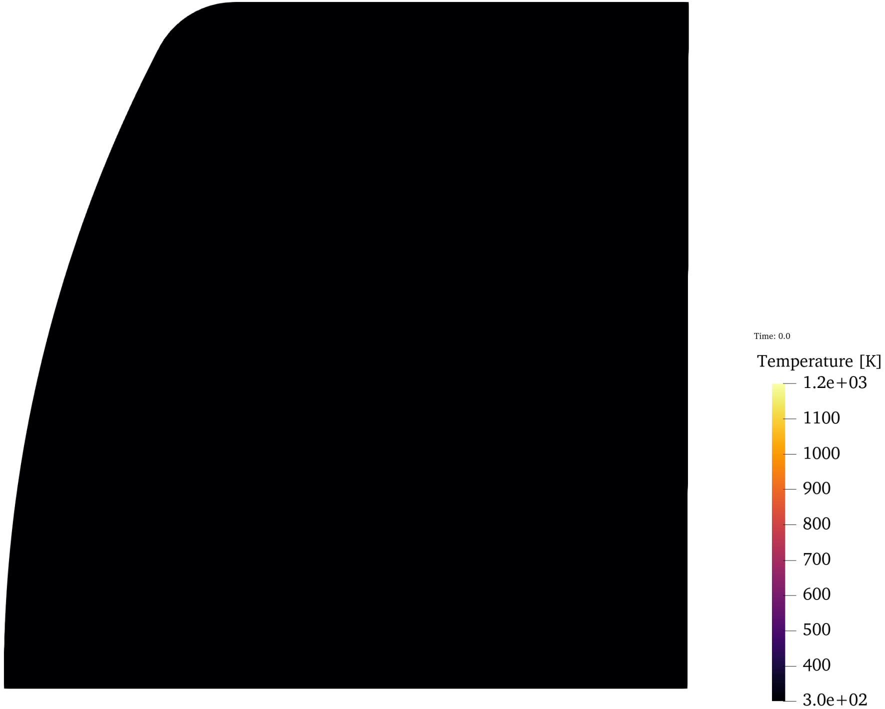
Worst-case:
Many non-orthogonal elements

Best-case:
Mesh is orthogonal to $\nabla\phi$

Arcjet Validation

Milos, F.S. and Chen, Y.-K. “Ablation and Thermal Response Property Model Validation for Phenolic Impregnated Carbon Ablator”, AIAA-2009-262

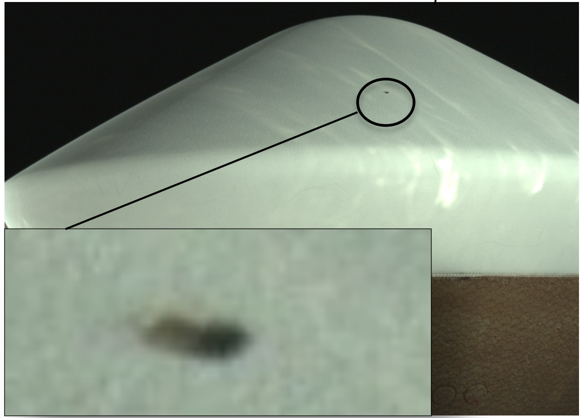


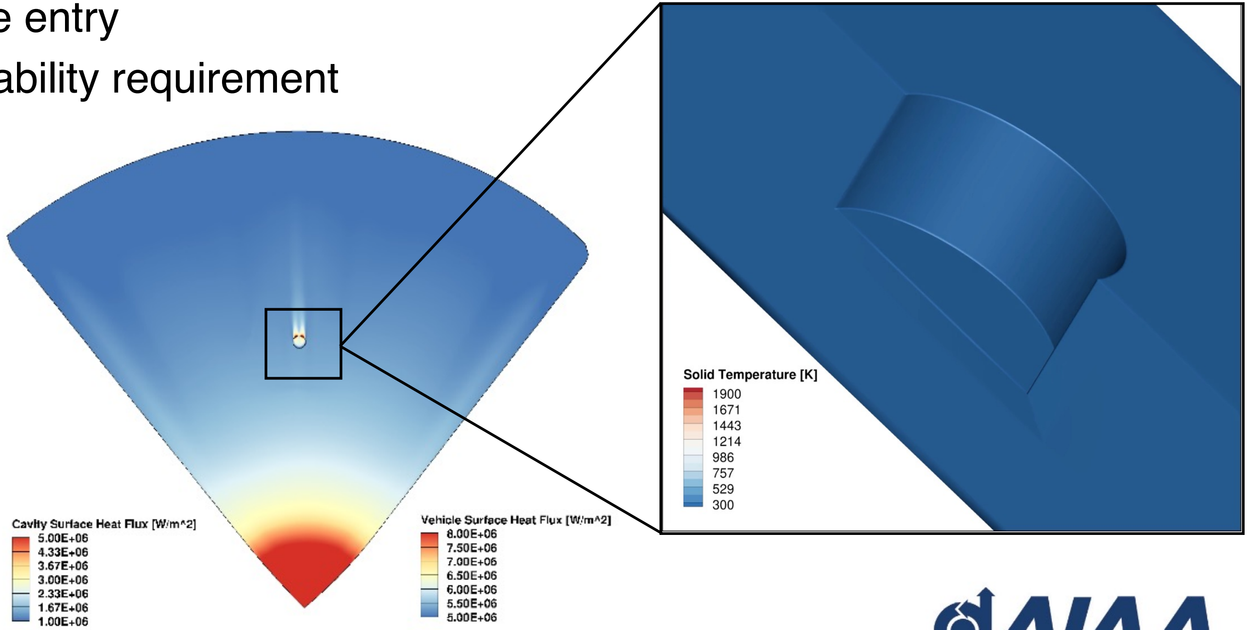


Application: MMOD Impact TPS

- Micro-meteorite / orbital debris (MMOD) impacts
  - Mars Sample Return (MSR) / Earth Entry System (EES) will have to pass through the orbital debris field before entry
  - EES has a stringent reliability requirement

Osiris-Rex MM impact



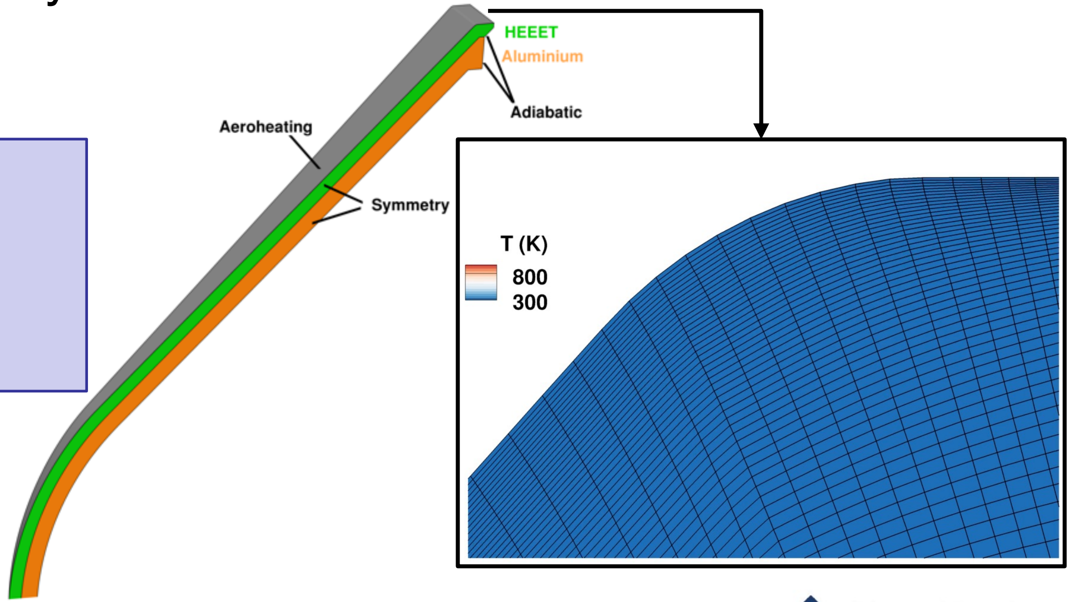


Application : MSR-EES Shoulder Recession

- Safety and aerodynamic stability/control affected by ablation at the shoulder during a flight trajectory

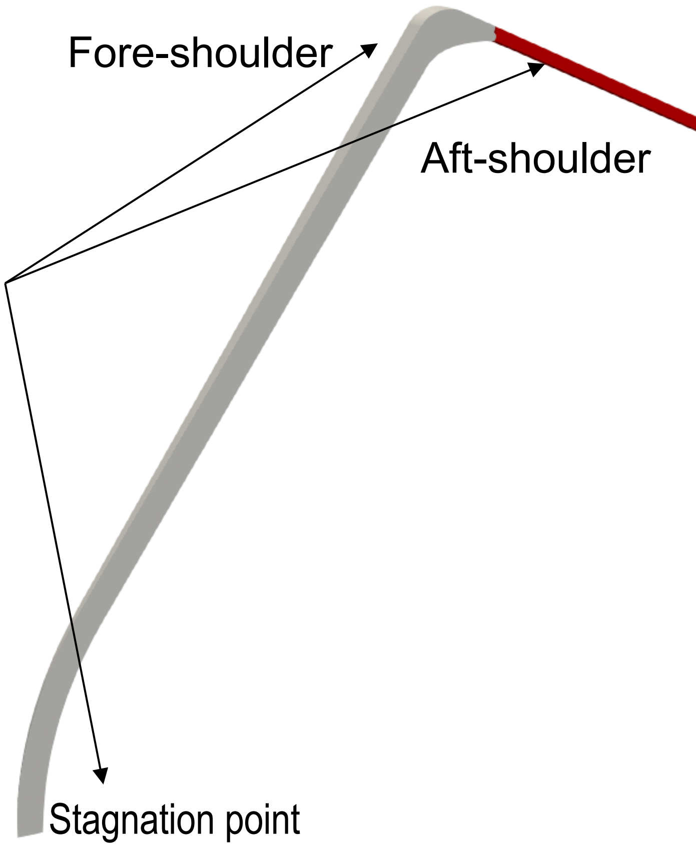
Go see technical talk:

P. Shrestha, C. Johnston, and E. Stern *"Numerical simulations of a conceptual MSR-EES shoulder recession"* **AIAA SciTech 2023**



Example : Dragonfly Capsule / Titan Entry

- Dragonfly mission to Titan
  - Environment : 94.3% Nitrogen + CH_4 + Ar
- Material Stackup



- Boundary conditions – solve the surface mass and energy balance

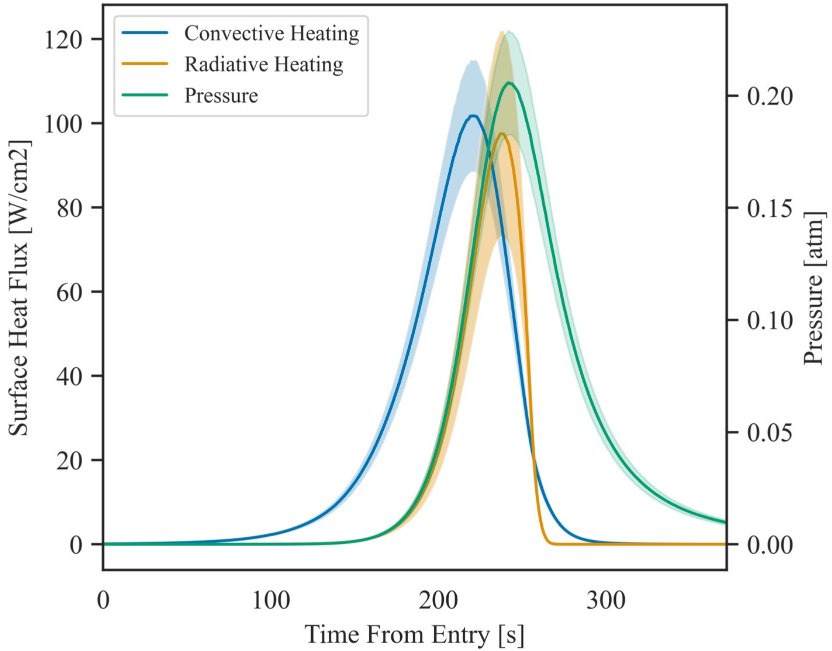
p_s : specified surface pressure

$$T_s : \quad q_s + \alpha q_{rad} - \sigma\epsilon(T^4 - T_\infty^4) - q_{cond} = 0$$

1-D Uncertainty Quantification

- Uniform sampling between the nominal and margined environments (left)
  - CFD computed inputs to the surface boundary conditions
- PICA property uncertainties (below)

Name	Distribution	Parameters
$\rho_v = \rho_c$	Uniform$(L/\mu, U/\mu)$	1 ± 0.018
$C_{v,v} = C_{v,c}$	Normal$(2\sigma/\mu)$	0.05
$\epsilon_{v,v} = \epsilon_{v,c}$	Normal$(2\sigma/\mu)$	0.03
k_v	Normal$(2\sigma/\mu)$	0.12
k_c	Correlated	$(15/12)k_v$



[H. Alpert et al. AIAA Paper 2022-0550]

Python Wrapper (icarusPy)

```python
stackup = [
    ('PICA', 1.44),
    ('HT-424', 0.015),
    ('M55J-composite', 0.04),
    ('Al-hc-4.3-2.5in', 1.25),
    ('M55J-composite', 0.04),
]

case = Stackup(stackup, pyrolysis_gas_mixture='51sp-pica-pyro')
```

```
stackup-montecarlo
    case_00000000
    case_list.xlsx
    input.yml
    lhs_sample.py
    montecarlo.py
```

Create case directories

Define uncertain variables

Sample generation

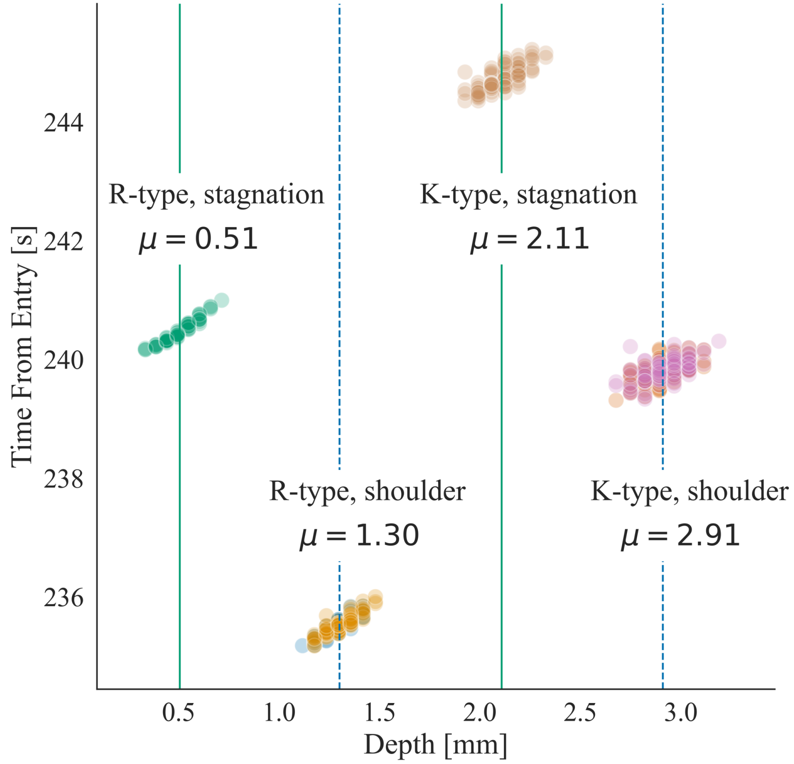
UQ runner

```python
case.set_boundary_conditions(
    bc_type = 'dragonfly',
    permeable = True,
    file_name = 'stag_point.dat',
    file_type = 'time',
    pressure = 1.0,
    temperature = 223.150,
    T_infinity = 70.0,
)

case.set_environment_parameters(
    T_infinity = 200.0,
    convective_cooling = {
        'background_temperature' : (200.0, 150.0, 70.0),
        'convective_cooling_coefficient' : (5.0, 5.0, 5.0),
        'time' : (1500.0, 6000.0)
    }
)

mc = MonteCarloManager(
    case,
    database_path=Path('../properties'),
    environment_path=Path('../bcs/dac1'),
)
mc.run()
```

Results



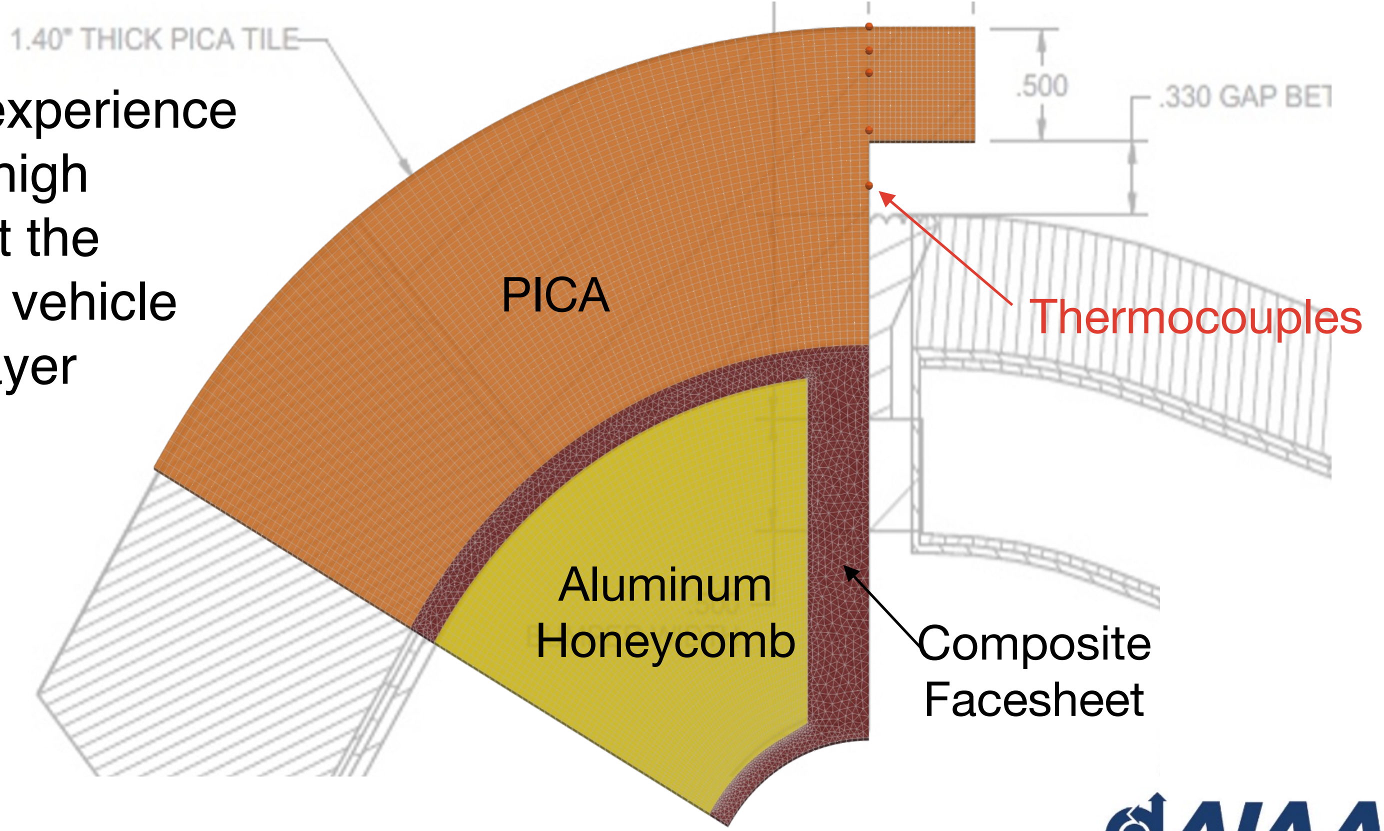
- Ensure operational integrity of embedded thermocouples (TC)
  - R-type : 1750 K
  - K-type : 1530 K

- Determine the distance in-depth at which the maximum temperature is exceeded

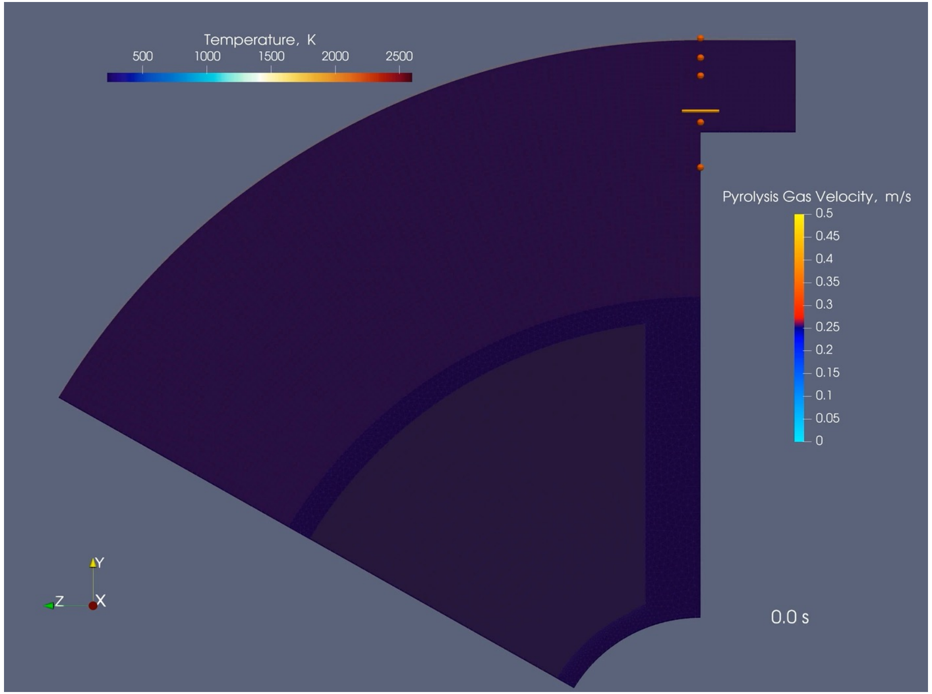
- At the shoulder region, convective heating is higher

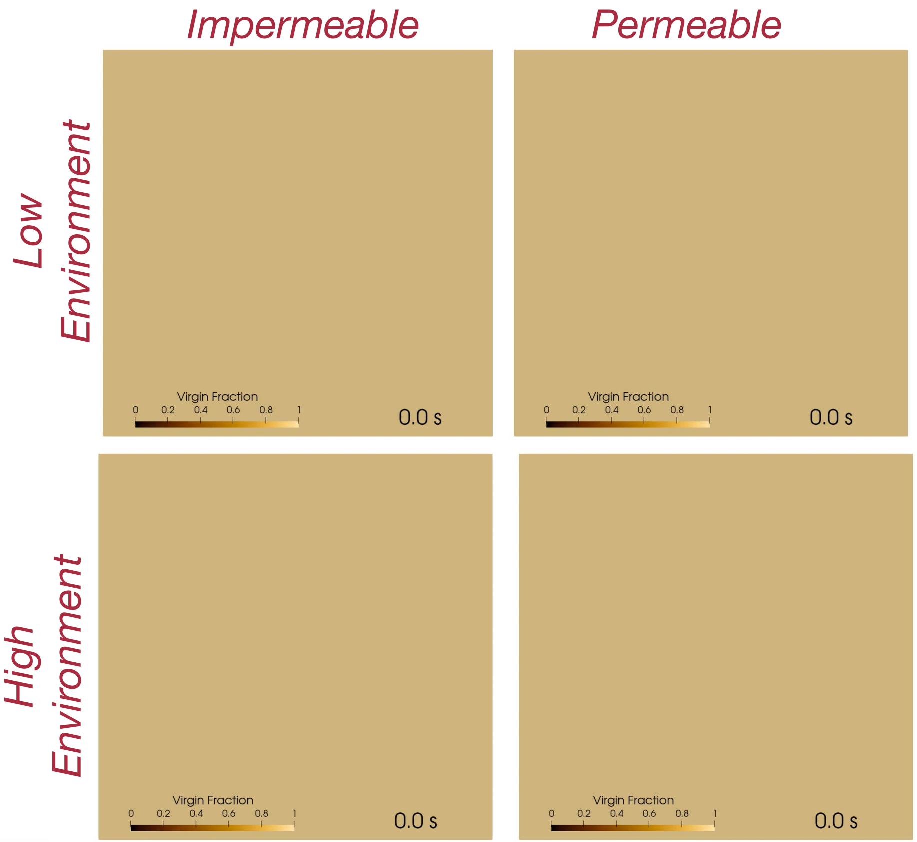
Application: Dragonfly Main Seal

- Dragonfly will experience comparatively high heating rates at the shoulder of the vehicle due to shock layer radiation



Application : Dragonfly Main Seal





Multi-dimensional Simulations

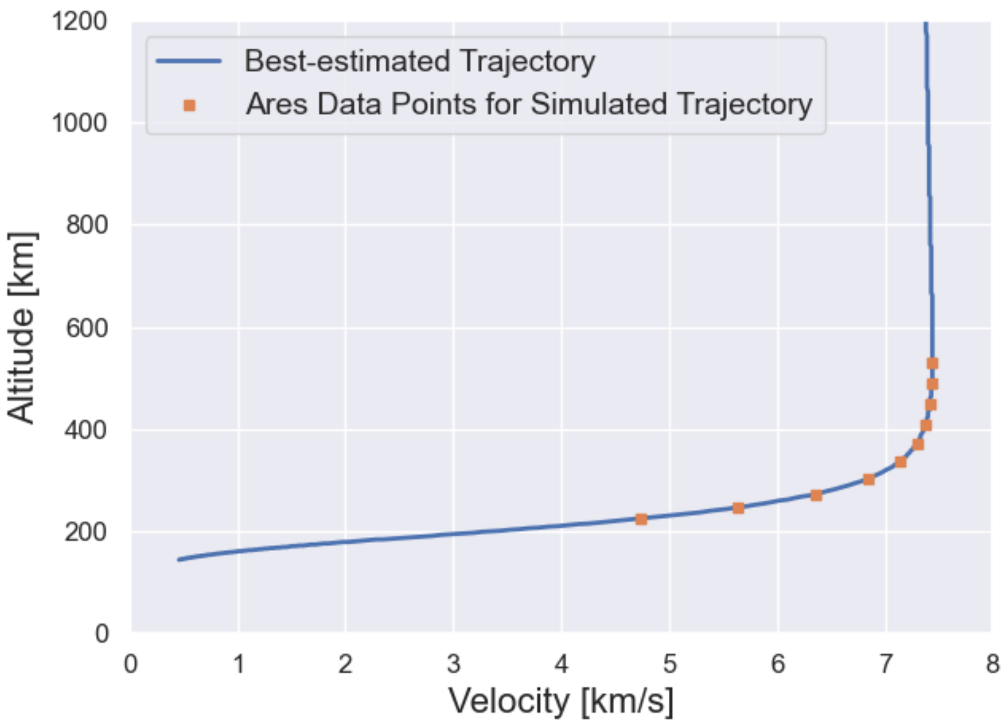
- Two approaches:
  1. Construct a database of flow / radiation solutions of the best-estimated trajectory and interpolate to spatial and time-varying profiles

$$q_s^{DPLR}(x,t) + \alpha q_R^{NEQAIR}(x,t) - \sigma\epsilon(T^4 - T_\infty^4) - q_{cond} = 0$$

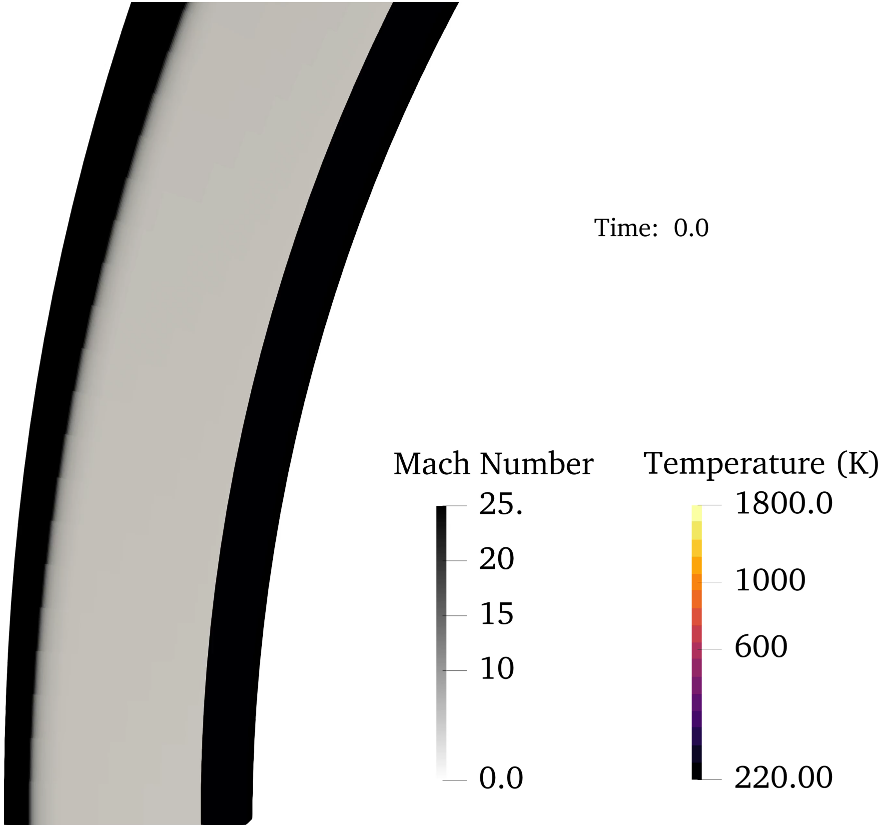
  2. Multi-physics coupling of the material (Icarus) and flow simulations (US3D)
     - Inputs are freestream conditions of the trajectory
     - Physics at material / fluid interface is consistent!

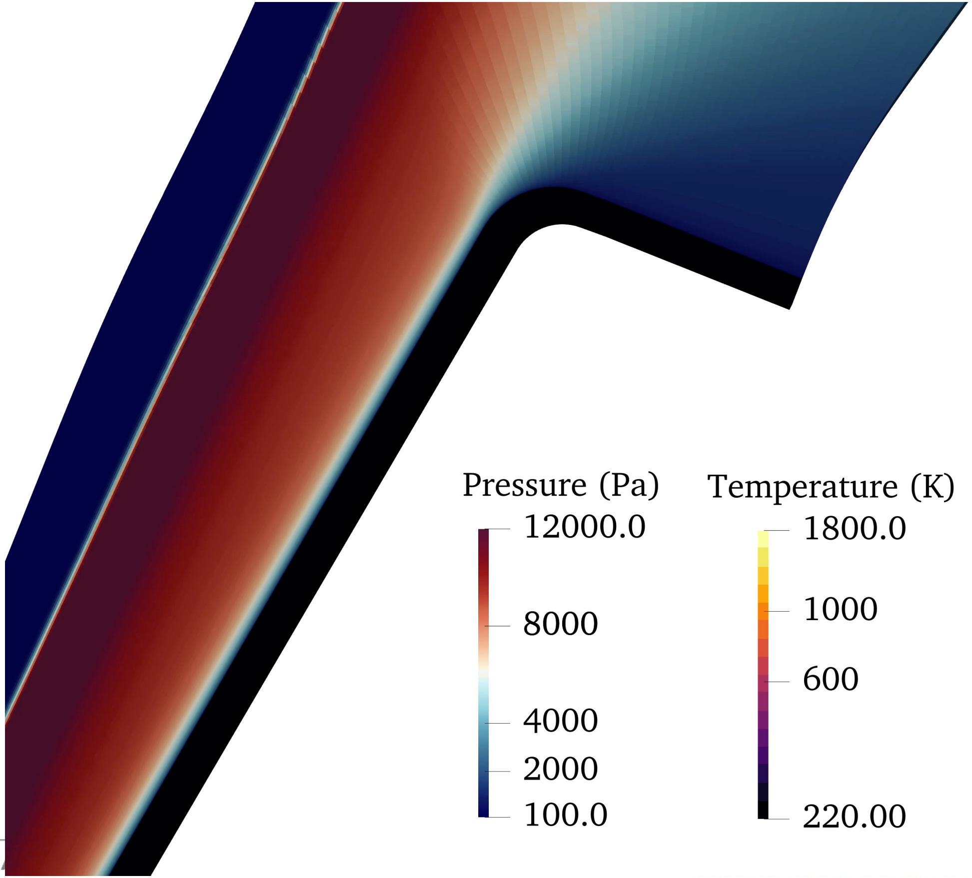
Multi-physics coupling with Ares

- Simulate 50 seconds of entry
- Multi-physics coupling
  - ”Tight-coupling” first 5 seconds, then every 1000 fluid iterations, solid updated for 0.25 seconds
- US3D solution
  - Mesh tailored for peak heating
  - No mesh adaption during transient
  - Pyrolysis gases neglected in the flow simulation



Results


Time: 0.0
Mach Number
25.
20
15
10
0.0
Temperature (K)
1800.0
1000
600
220.00


Pressure (Pa)
12000.0
8000
4000
2000
100.0
Temperature (K)
1800.0
1000
600
220.00

Conclusions

- Icarus is a multi-dimensional, unstructured material response solver
  - Design applications: heatshield sizing, uncertainty quantification
  - Material model validated against experimental data
- Actively maintained and is being used as a part of several NASA missions
  - Dragonfly, Mars Sample Return, etc.
- Current / Future development timeline
  - Validation (always on-going) and Software Refinement / Profiling
  - Additional physics as requested by users
  - Multi-physics coupling (Flow + Radiation + Particles + Material)

Thank You!

Questions?

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