Overview of Radiation Modeling in NASA's ESM Project

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- ESM tools for modeling radiation and utilization in mission relevant studies.
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Tech Base Functional Domains

GO Space Transportation	❖ Advanced Propulsion ❖ Nuclear Propulsion	❖ Flight Vehicle Systems (including Ascent Systems) ❖ Cryogenic Fluid Management
LAND Space-to-Surface Access	❖ Deceleration Systems ❖ Guidance & Navigation Systems	❖ Landing Systems & Environments ❖ Entry Modeling & Instrumentation
LIVE Surface Infrastructure and Exploration	❖ Surface Power ❖ In Situ Resource Utilization ❖ Surface Structures & Construction	❖ Environments & Dust Mitigation ❖ Surface Mobility & Transportation ❖ Surface Habitation & Logistics
EXPAND In-Space Infrastructure and Discovery	❖ Observation Systems ❖ In-Space Sustainability	❖ Communications, Position, Navigation & Timing ❖ In-Space Servicing, Assembly & Manufacturing ❖ Small Spacecraft & Distributed Systems
ENABLE Foundational Capabilities	❖ Avionics & Sensors ❖ Autonomous Systems & Robotics	❖ Advanced Materials, Structures & Manufacturing ❖ Advanced Power & Thermal

❖ Capability Area

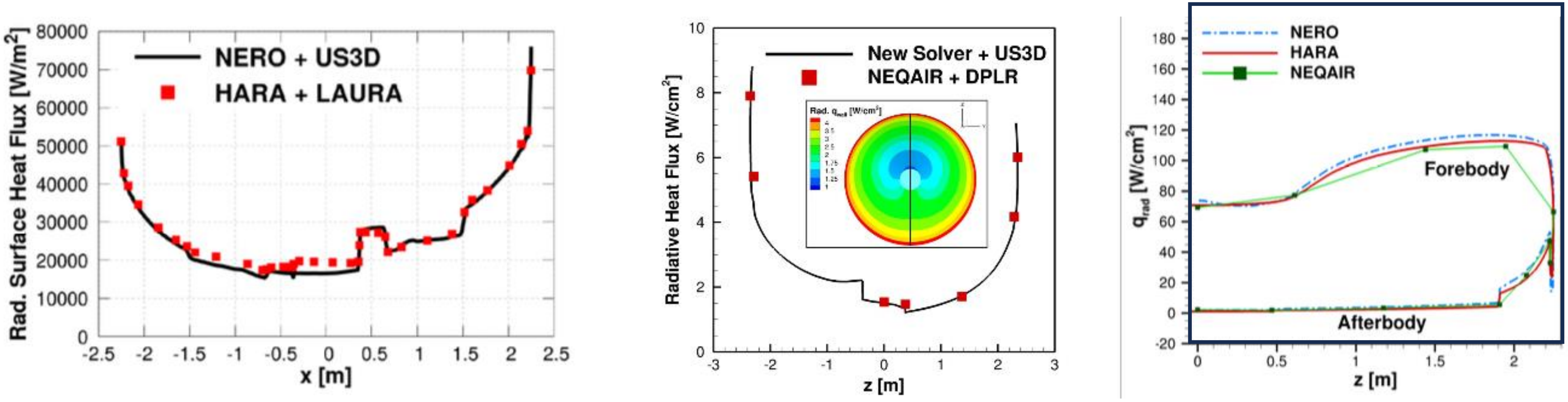
CATALYSTS Innovative Mechanisms				
	• NIAC/CIF/ECI • STRG	• PCC • Tech Transfer	• SBIR/STTR • Flight Opportunities	• TP/ACO • Inclusive Innovation

Efficient Radiation Analysis: NERO

Non-Equilibrium RadiatOn (NERO) accelerates solutions by up to ~1000x compared to NEQAIR and HARA

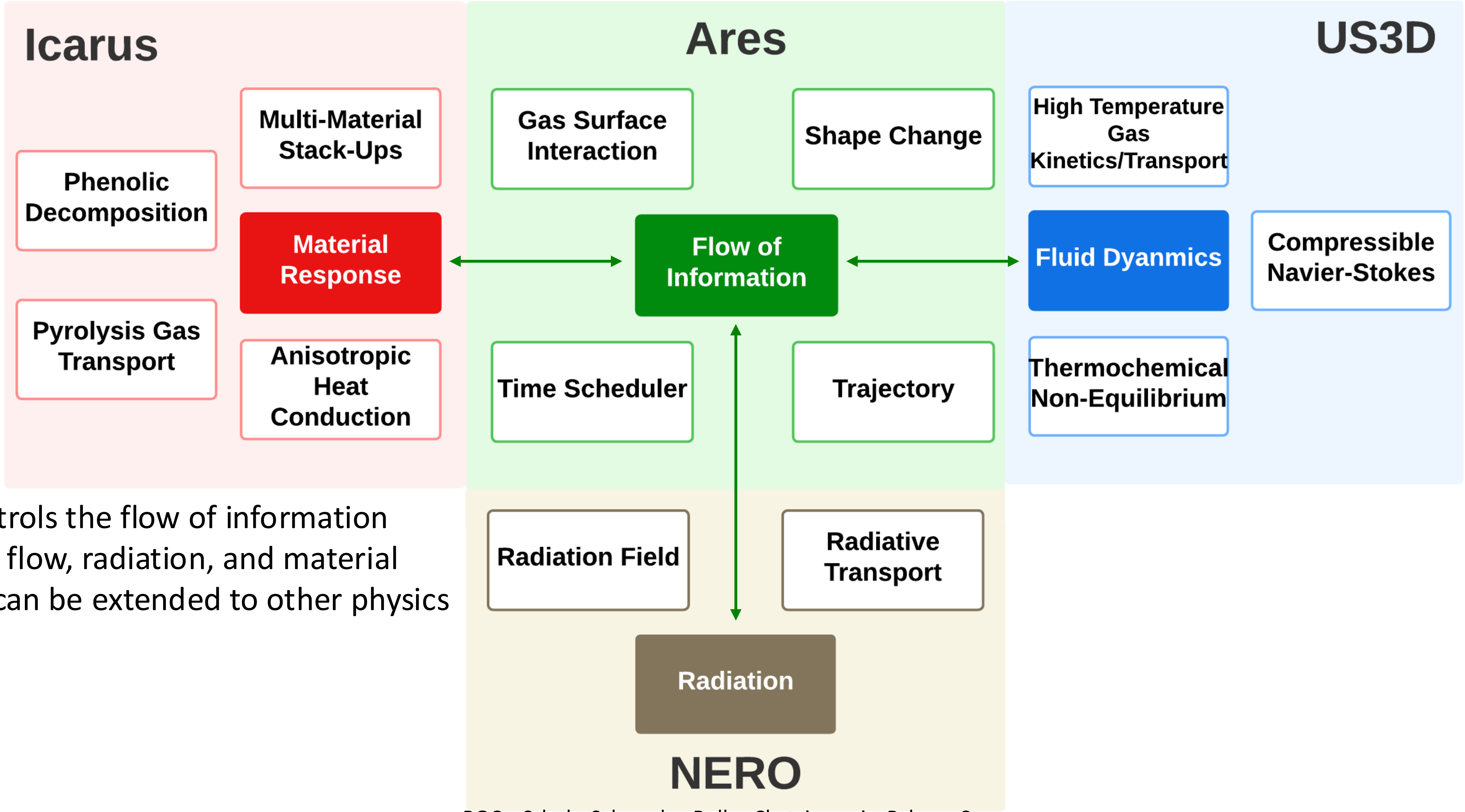
- Finite-volume discretization of radiative transport
- Reduced order spectral models decrease number of spectral evaluations by 3 orders of magnitude
- Leverages solutions from NEQAIR and/or HARA as a basis for developing reduced order spectral models and comparing accuracy
- Integrate into existing aerothermal database workflows and process flow solutions from legacy solvers (DPLR/LAURA).
- Analyze detailed 3D geometries including surface effects such as reflection/absorption.

Comparisons of Accuracy of NERO with NEQAIR and HARA



POCs: Sahai

Ares: Icarus-NERO-US3D



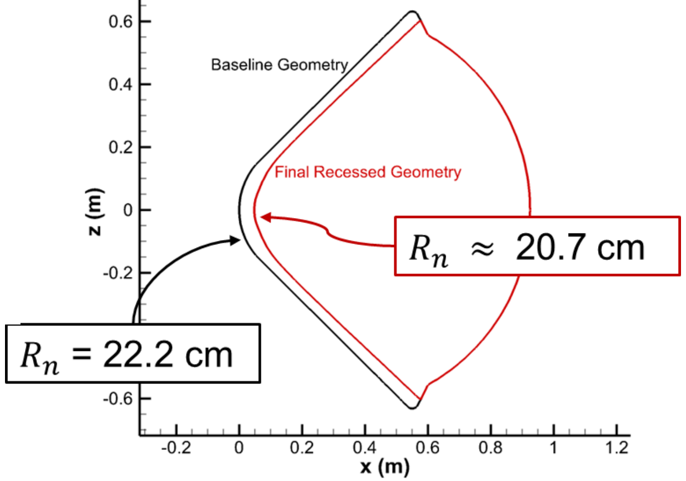
Ares controls the flow of information between flow, radiation, and material solver – can be extended to other physics as well

POCs: Schulz, Schroeder, Bellas Chatzigeorgis, Palmer, Stern

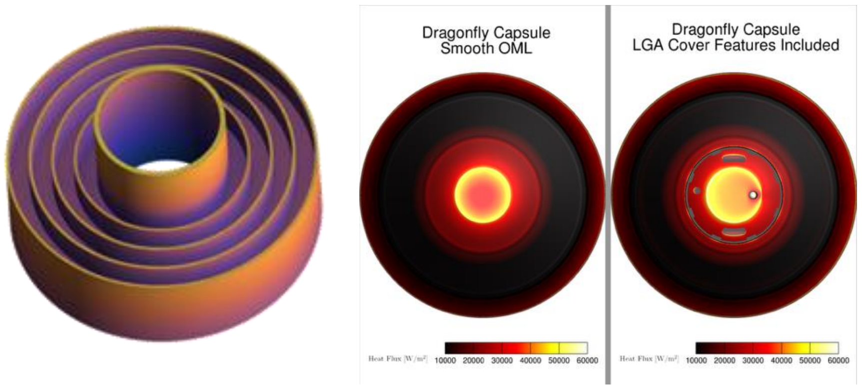
Examples of Mission Relevant Studies

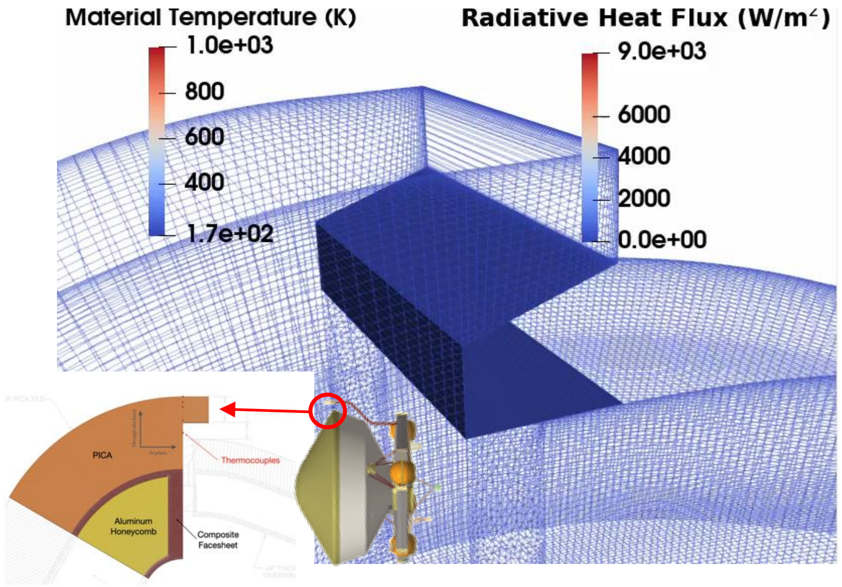
- Galileo Probe Entry Modeling with Coupled Radiation and Ablation [1]
- Modeling of Pioneer probe entry into Venus atmosphere [2]
- Heating predictions of detailed geometries for Dragonfly aeroshells.

Predicted Recession of Galileo Probe Entry into Jupiter



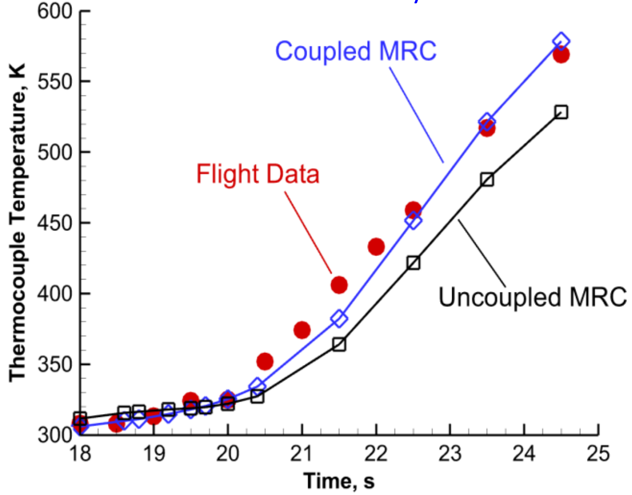
Predicted Heating of Detailed Geometries for Dragonfly Aeroshells with Coupled Radiation, Flow, and Material Response





LGA Impact on Heating of Full Aeroshell
(HyperSolve CFD Solver and NERO)

Coupled Material Response and Nonequilibrium Surface Chemistry for Pioneer Probe Entry into Venus



POCs: Olivia Schroeder, Joey Schulz, Kyle Thompson, Amal Sahai, Prakash Shrestha

[1] Erb et al., Investigation of Galileo probe entry heating with coupled radiation and ablation. *Journal of Spacecraft and Rockets*, 2020
[2] Cabrera, & West, (2024). Assessment of Pioneer Venus Entry Heating With Coupled Radiation and Ablation. In *AIAA AVIATION 2024*.

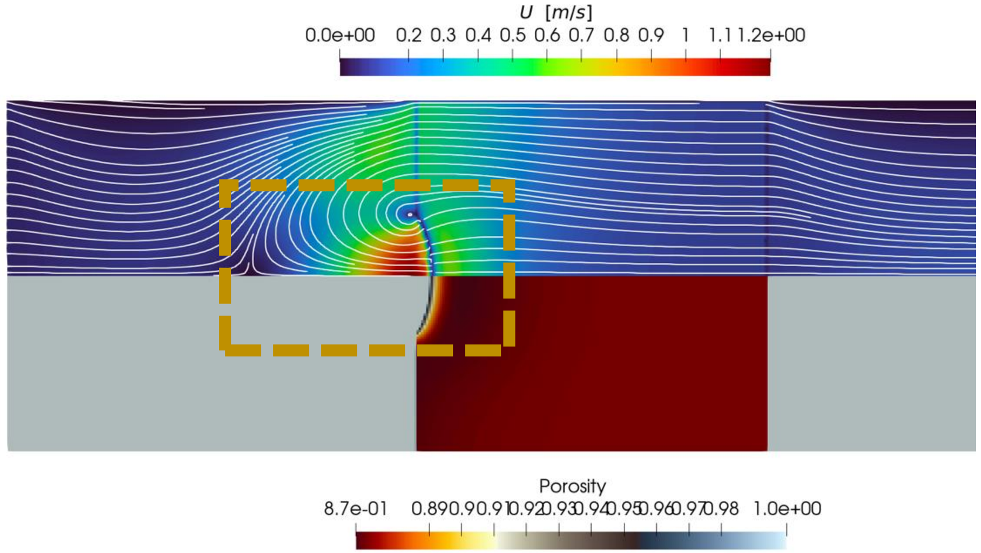
Relevant Project 1

Unified solver with radiation and material recession

POCs: Brandon van Gogh, Bruno Dias, Amal Sahai

Unified Solver with Radiation

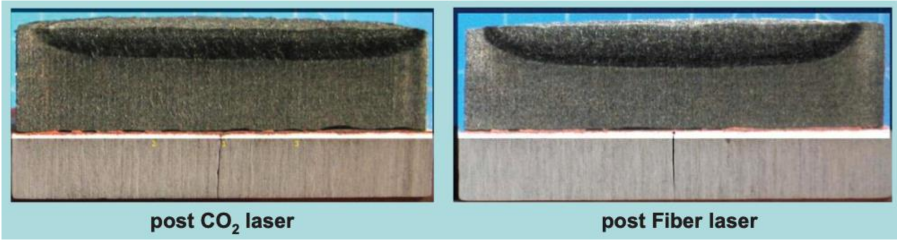
- **Unified solver** (based on PATO)
  - Solves flow + material response in same domain
  - Intrinsic coupling of the material and gas
  - Flexible library for testing radiation solving strategies
  - Simulation setups designed to match LHMEL type experiments



New Unified solver simulation with radiation

Recession and blowing observed where large laser heating is applied

- **LHMEL Tests from TS Division**
  - Laser testing experiments of carbon fiber/felt, glass fiber, and layered TPS materials (White et. al, 2012)
  - Heat flux range of *30-450 W/cm²* for ~30 seconds

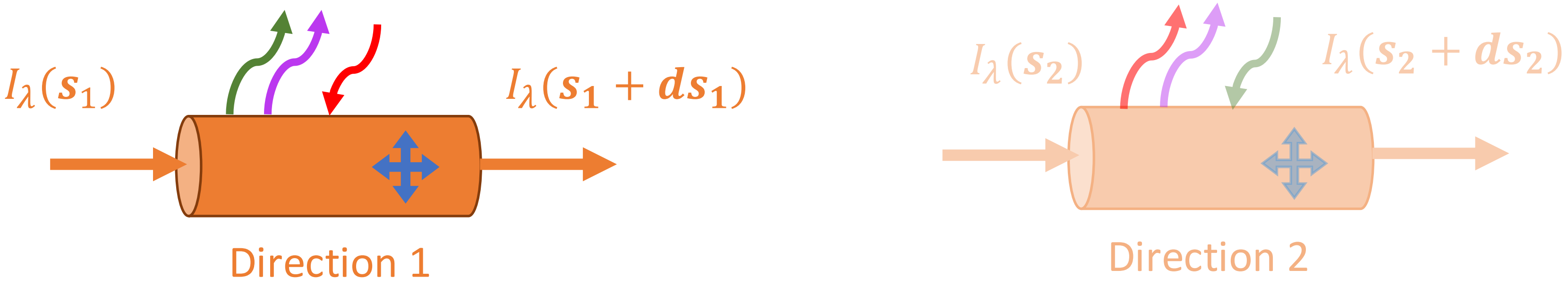


char layer variation due to different wavelengths

LEAF integrator Test, 30kW laser for 12 seconds

Modeling of Radiative Heat Transfer

- **Solving for fully coupled radiation is expensive:**
  - Intensity (I W/m^2/λ/Sr) depends on position (r), wavelength (λ), direction ($\hat{s}$)
- **Radiative Transport Equation (RTE)**
  - Intensity balance involves: Change in intensity along direction = loss from absorbing or scattering + gain from emission + gain from scattering from other directions



- Compute intensity I from RTE → **compute radiative source term** → plug into Total Energy conservation → Iterate

$$-\nabla \cdot \boldsymbol{q}_{rad,eff} = \int_{\lambda=0}^{\infty} \int_0^{4\pi} (\kappa_{\lambda,eff} I_\lambda - J_\lambda)\, d\Omega_i \, d\lambda \quad \rightarrow \quad \frac{dE_{tot}}{dt} = -\nabla \cdot q_{cond} - \nabla \cdot q_{rad} + \cdots$$

*neglecting photochemistry source term in continuity

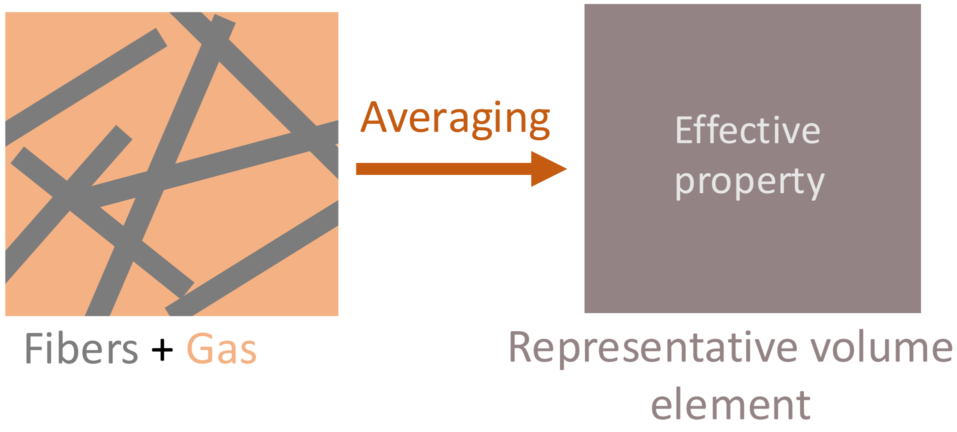
Methods for Solving the Volume Averaged RTE

Rosseland Approximation (trivial expense)

- How : Adding on effective diffusion coefficient, **assumes**
  - large extinction coefficients $\beta_\lambda = \kappa_\lambda + \sigma_\lambda$ and far away from radiating boundaries
  - Near local thermodynamic equilibrium
  - Isotropic intensity (independent of direction)

$$-\nabla \cdot q_{rad,eff} = \sum_i \nabla \cdot \epsilon_i \langle k_R \nabla T \rangle^i \approx \sum_i \left[\nabla \cdot k_{R,i} \epsilon_i \nabla \langle T \rangle^i + \text{surface exchange} \right]$$

Volume Averaging



P1 Approximation (relatively cheap, $O(N_{freq})$ more compute)

- How: Solves additional transport equation for total (direction integrated) intensity
  - P_N - Direction solved with series of spherical harmonics. P_1 includes first two expansion terms.

$$\nabla \cdot (-k_{P1,eff} \nabla G_\lambda) = \kappa_{eff,\lambda}(4\pi I_{b\lambda} - G_\lambda) \longrightarrow -\nabla \cdot \boldsymbol{q}_{eff,rad} = \int_0^\infty \kappa_{eff,\lambda}(G_\lambda - 4\pi I_{b\lambda})\, d\lambda$$

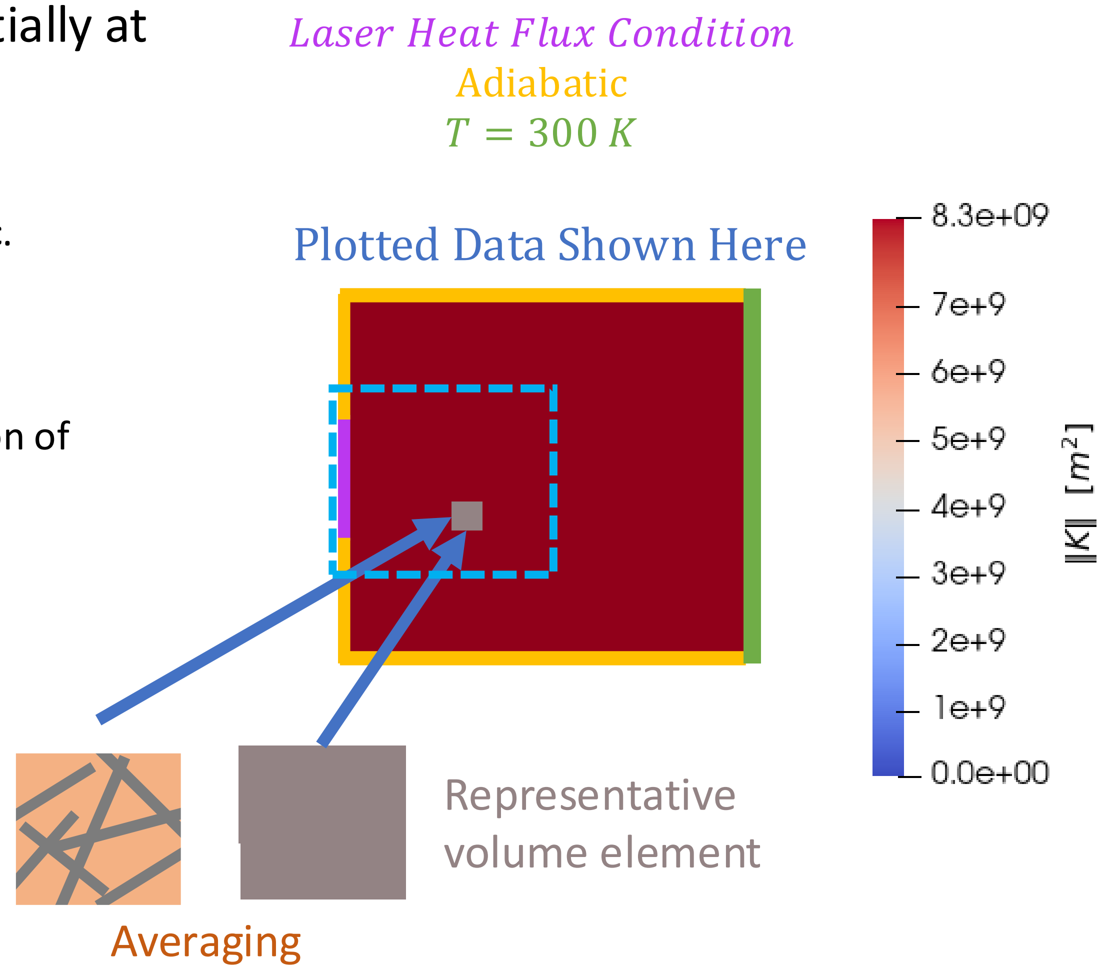
Non-Equilibrium RadiatiOn (NERO) Solver (Very Expensive, $O(N_{freq} \times N_{direction})$ more compute)

- How: Finite volume discretization of RTE, radiative properties for gas radiation + solids accounted for

$$-\nabla \cdot \boldsymbol{q}_{rad,eff} = \int_{\lambda=0}^{\infty} \int_0^{4\pi} (\kappa_{\lambda,eff} I_\lambda - J_\lambda)\, d\Omega_i\, d\lambda$$

Radiation in a Porous Slab

- **Simulation of a porous material in a CO2 environment,** initially at 300 K, laser heat flux for 30 seconds
- **Material Properties:**
  - Fiberform: Characteristic values for density, thermal conductivity, etc.
  - Gas: Mutation++ database
- **Radiative properties:**
  - Generated extinction lookup tables which are interpolated as function of porosity, and temperature
  - Fiberform: Database generated from *Banerjee 2022*
  - Gas: Gaussian band model, *Wei 2018*
- **Assumptions**
  - Carbon based chemistry in porous material
  - Black Body Surface Reradiation
  - Neglect electrons/ionization
  - Neglect photochemistry

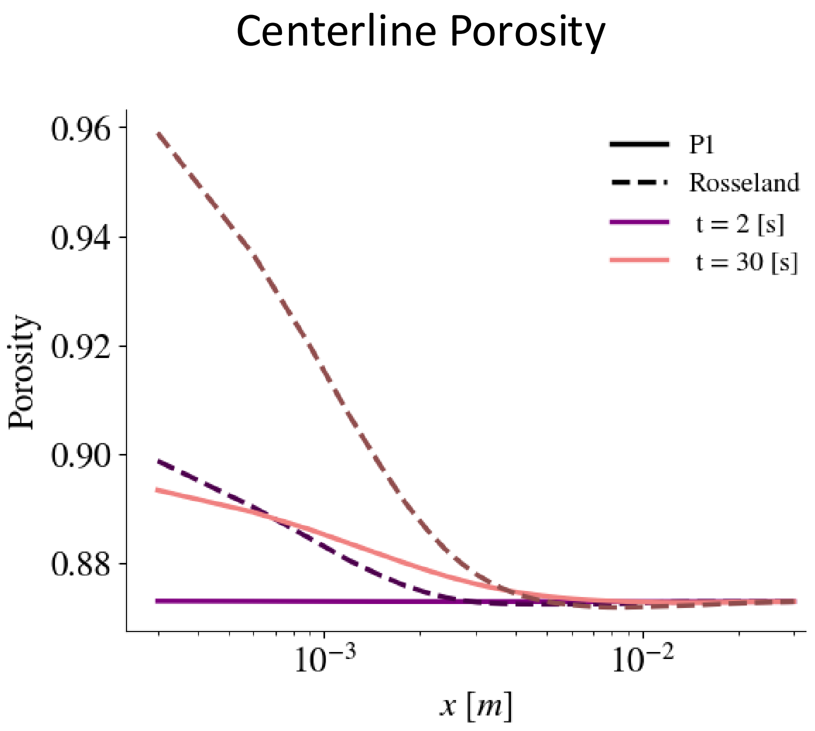


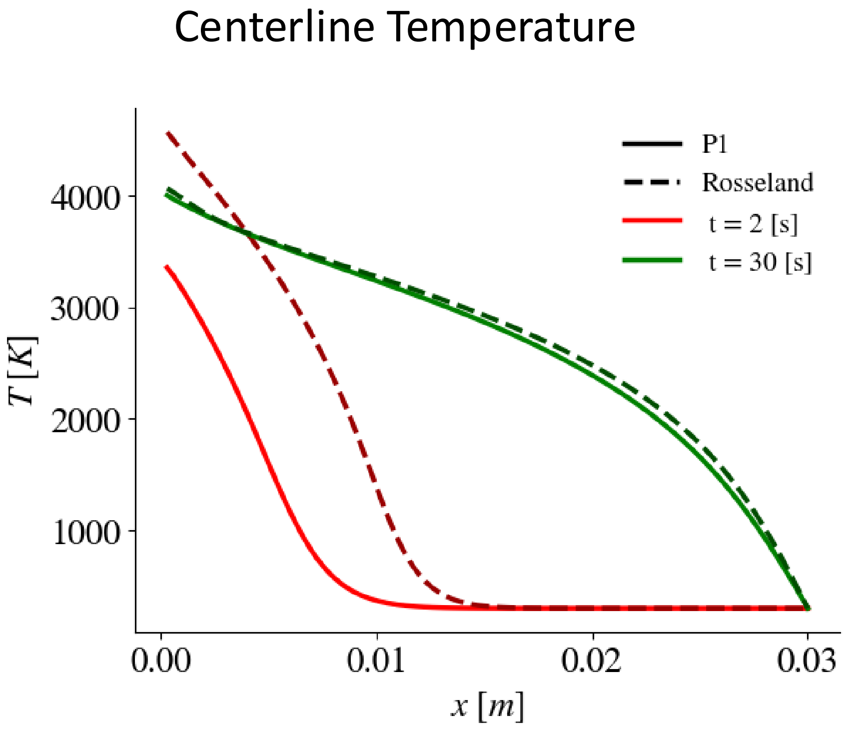
Banerjee, Ayan, et al. "Radiative coefficients and their influence on in-depth heating of porous ablators." *AIAA Journal* 60.12 (2022): 6520-6535.

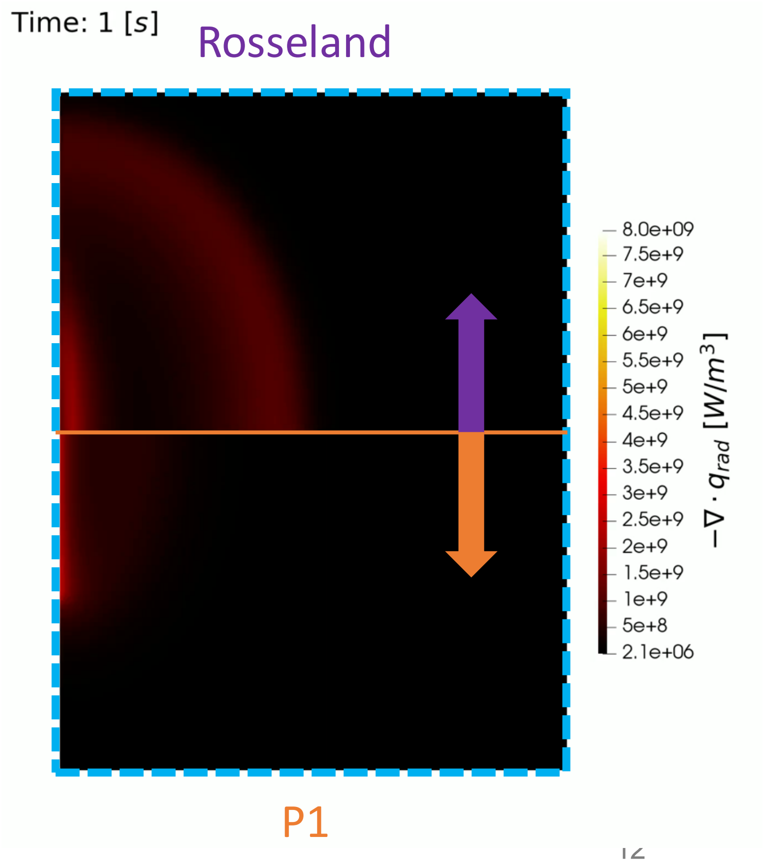
Chu, H., Ren, F. and Wei, Y., 2018. A COMPARISON OF TWO STATISTICAL NARROW BAND MODELS FOR NON-GRAY GAS RADIATION IN PLANAR PLATES. *Thermal Science*, *22*, p.S777.

Porous Slab: P1 vs Rosseland Centerline Comparison

- **P1 Boundary condition for the laser is now applied to intensity rather than diffusion heat flux**
- **Rosseland More responsive:** More recession, faster heating, larger energy transfer







Conclusions and Future Work

Conclusions

- Developed a framework within unified solver to model the material response under radiative environments
- Implemented various radiation solutions within the unified solver.
- Rosseland radiation vs P1 – Rosseland approximation may be over predicting heat transfer rates due to gas radiation

Future

- Implicit coupling of the unified solver with NERO code to fully solve the RTE.
- Refine test cases to validate against LHMEL experiments.
- Simulation of different solid chemistries with semi-transparent radiative properties (AETB, LI-900)

Relevant Project 2

Modeling of radiative conductivity using Monte Carlo Ray Tracing (MCRT)

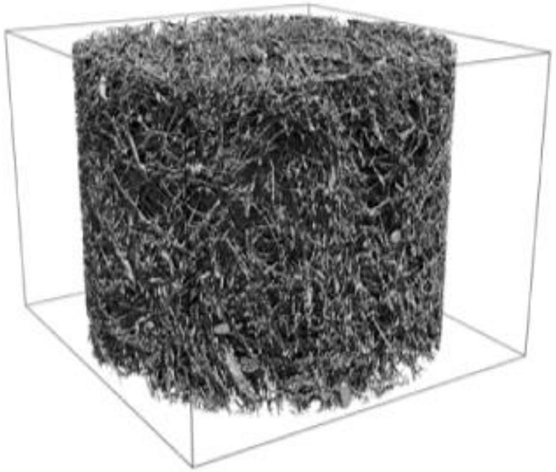
POCs: Krishnan Swaminathan Gopalan, Lauren Abbott

Collaboration with Protect ECI

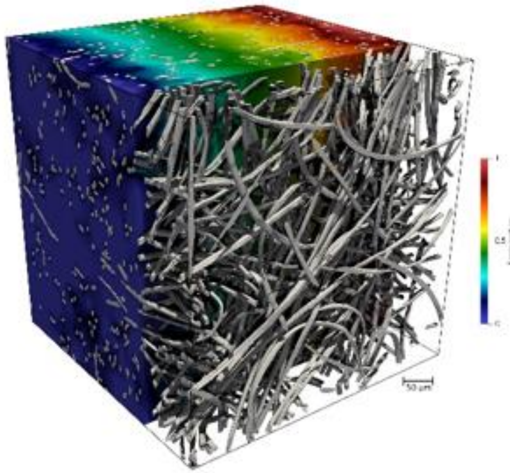
PROTECT: Production and Reuse of Thermally Efficient Ceramic TPS

PROTECT will utilize newly emerging materials characterization methods and advanced computational and predictive tools to aid in the design of new TPS for future NASA and commercial industry space vehicles.

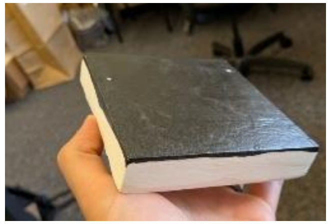
PI: Nathaniel Olson, JSC

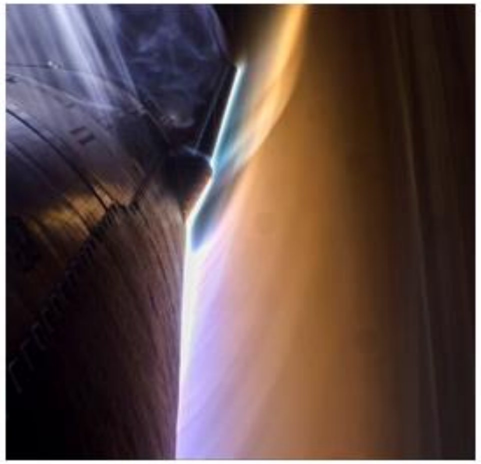


Implement advanced **characterization techniques** to collect novel data on reusable TPS structure and properties.



Develop **predictive capability** to enable improved understanding for materials design.

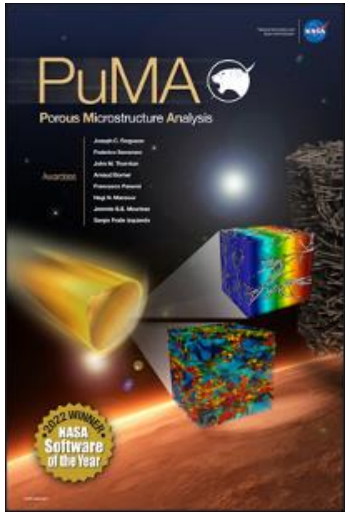


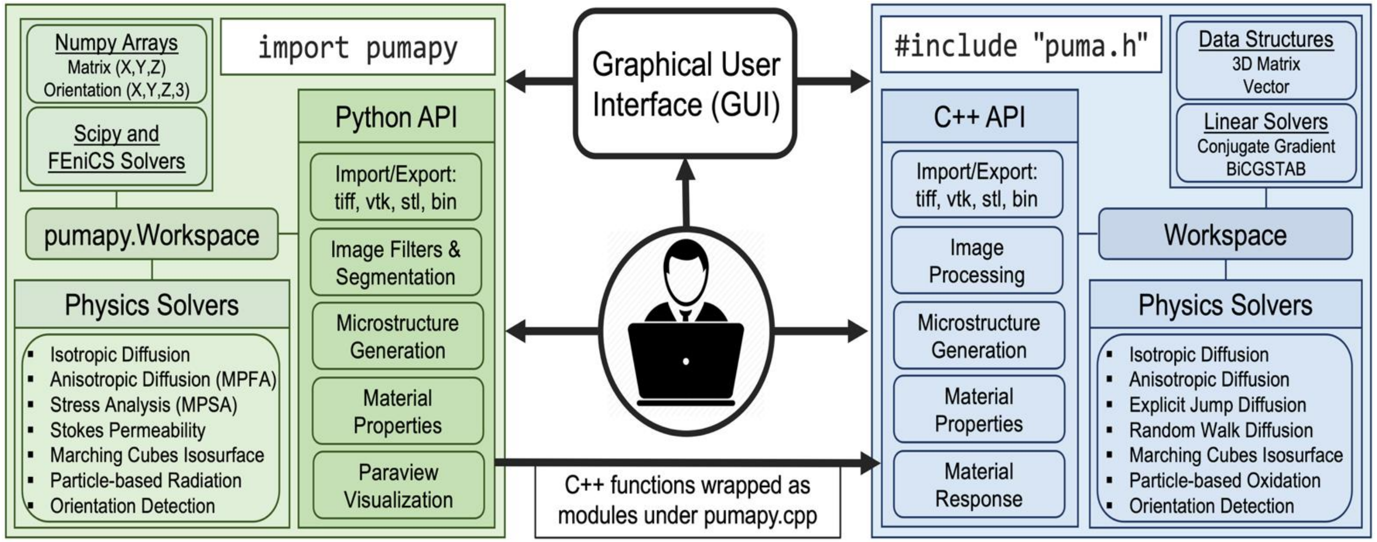


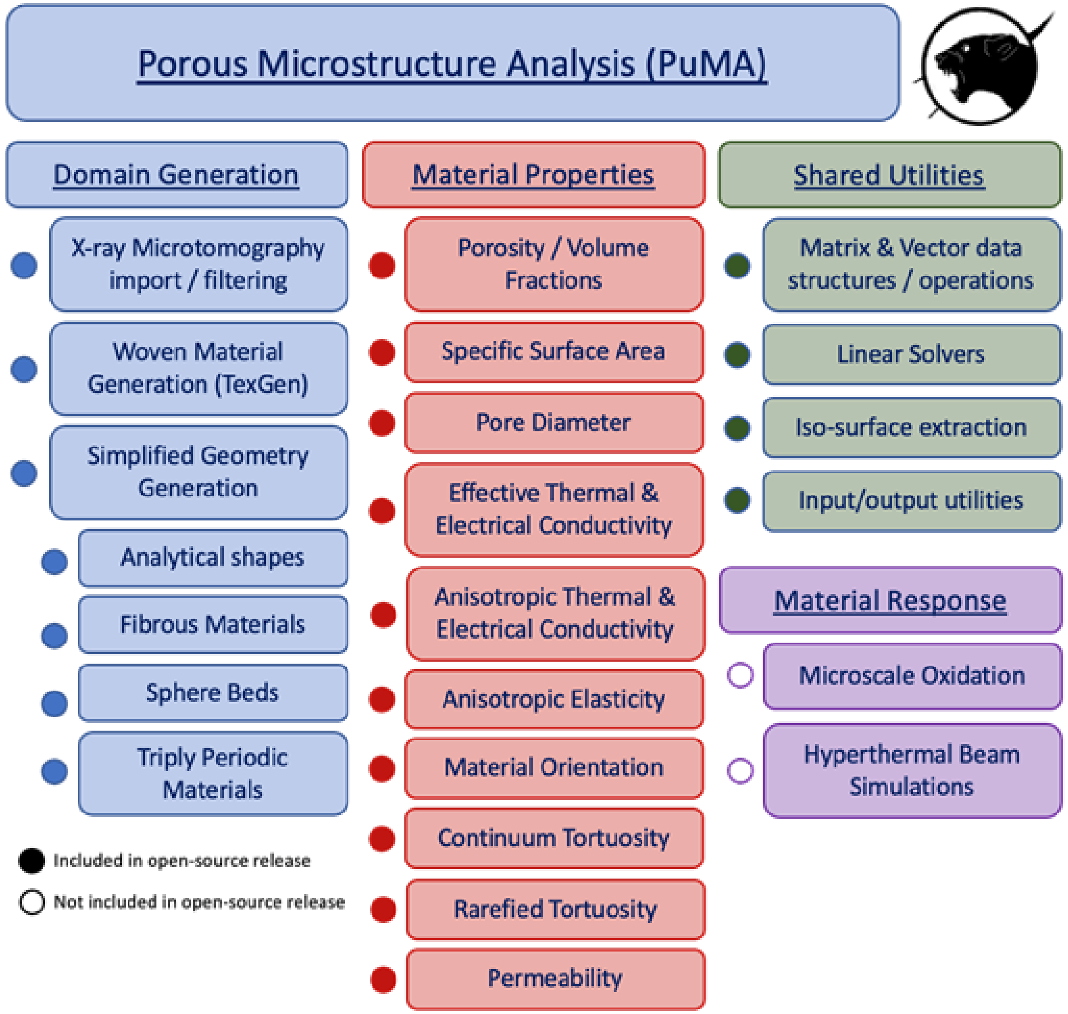
Develop reusable TPS with enhanced performance.
Design, manufacture, and fly our own tile on Starship.

Porous Microstructure Analysis (PuMA)

- Developed at NASA Ames
- Software of the year 2022
- Open source (https://github.com/nasa/puma)
- Installation: conda install -c conda-forge puma

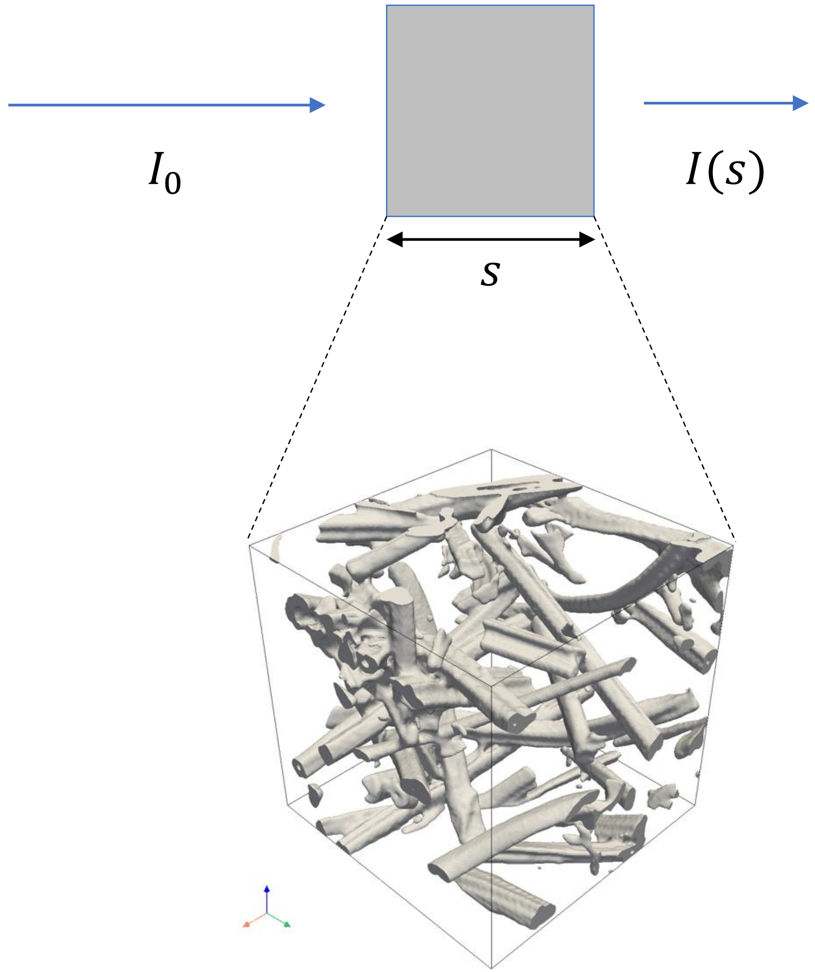






PuMA Radiative conductivity
Monte Carlo Ray Tracing (MCRT)

Effective radiative thermal conductivity in a medium can be computed using Beer Lambert's law [1]



$$\frac{I(s)}{I_o} = \exp(-\beta s)$$

$$k_{rad} = \frac{16\sigma T^3}{3\beta}$$

β is the extinction coefficient
σ is the Stefan-Boltzmann constant

Assumes geometric optical approximation

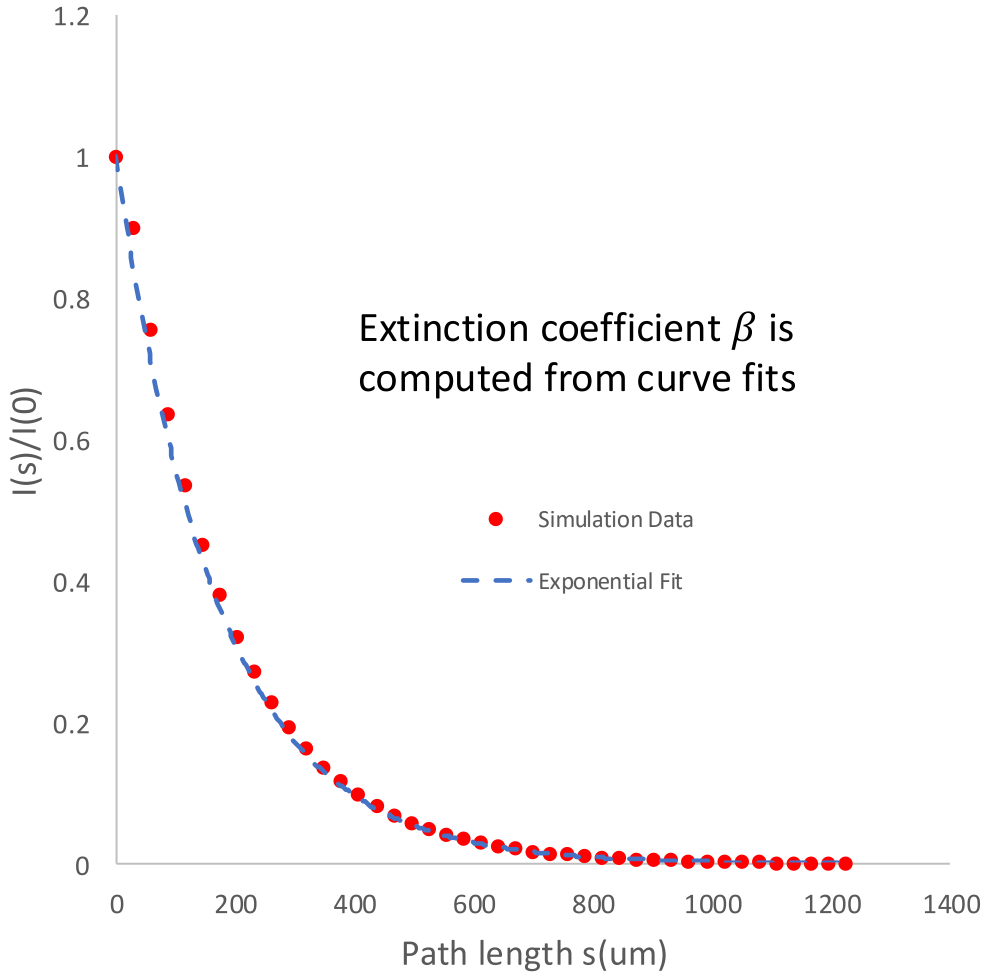
$$D_{particle} \gg \lambda_{light}$$

[1] Horiuchi, Takumi, et al. "Thermal response analysis of porous carbon-based non-ablative heatshield in an arcjet flow condition." *Transactions of the Japan Society for Aeronautical and Space Sciences* 61.5 (2018): 211-218.

PuMA Radiative conductivity Monte Carlo Ray Tracing (MCRT)

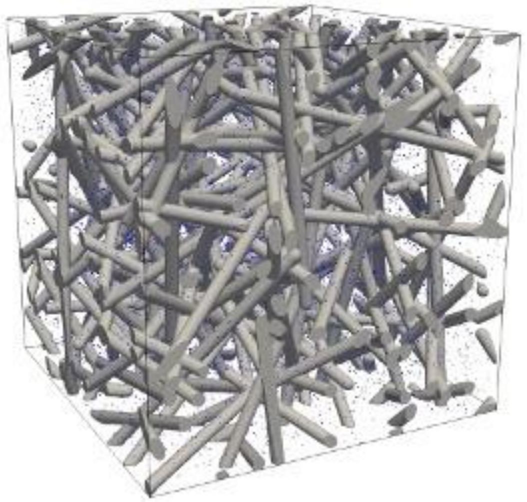
- By binning the distance traveled by each ray, plot the $I(s)/I_0$ as a function of path length s
- Curve fit the data to obtain the extinction coefficient β
- Compute k_{rad} along the direction

$$k_{rad} = \frac{16\sigma T^3}{3\beta}$$



Horiuchi, Takumi, et al. "Thermal response analysis of porous carbon-based non-ablative heatshield in an arcjet flow condition." *Transactions of the Japan Society for Aeronautical and Space Sciences* 61.5 (2018): 211-218.

PuMA Radiative conductivity
Monte Carlo Ray Tracing (MCRT)



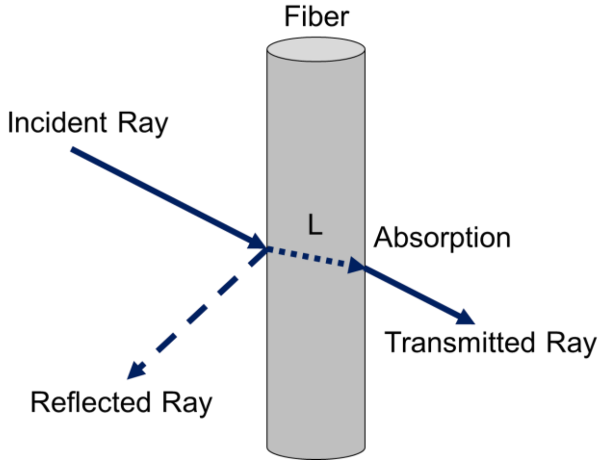
- New feature developed and implemented in PuMA.
- Statistically simulate the motion of light rays through the material microstructure and trace their path.

Initiation

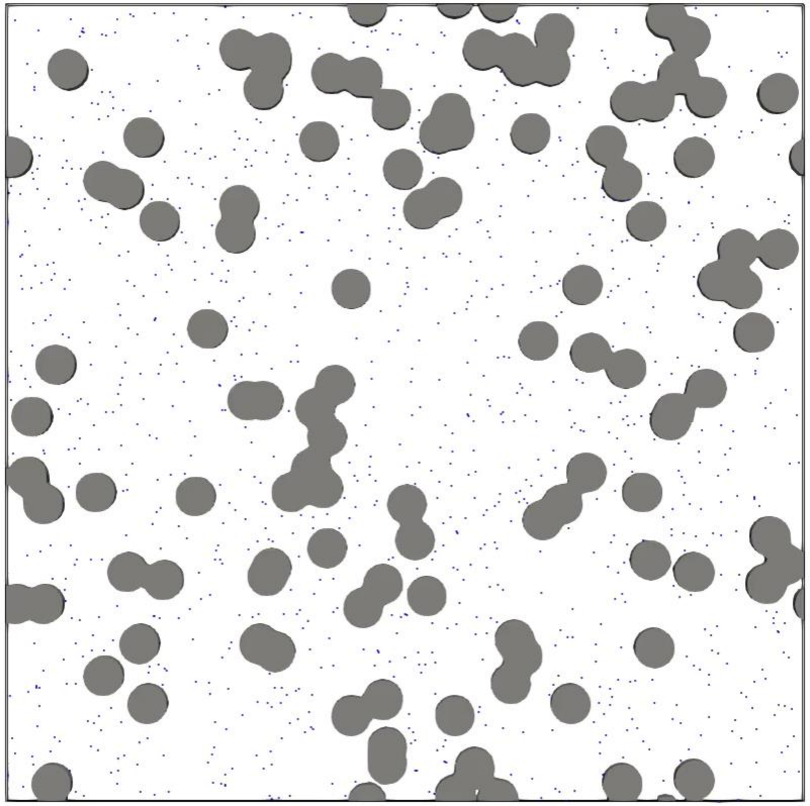
- Randomly select the initial location and direction of each ray in the plane.
- Rays follow a straight-line path until it collides with a surface element.

Surface Interaction

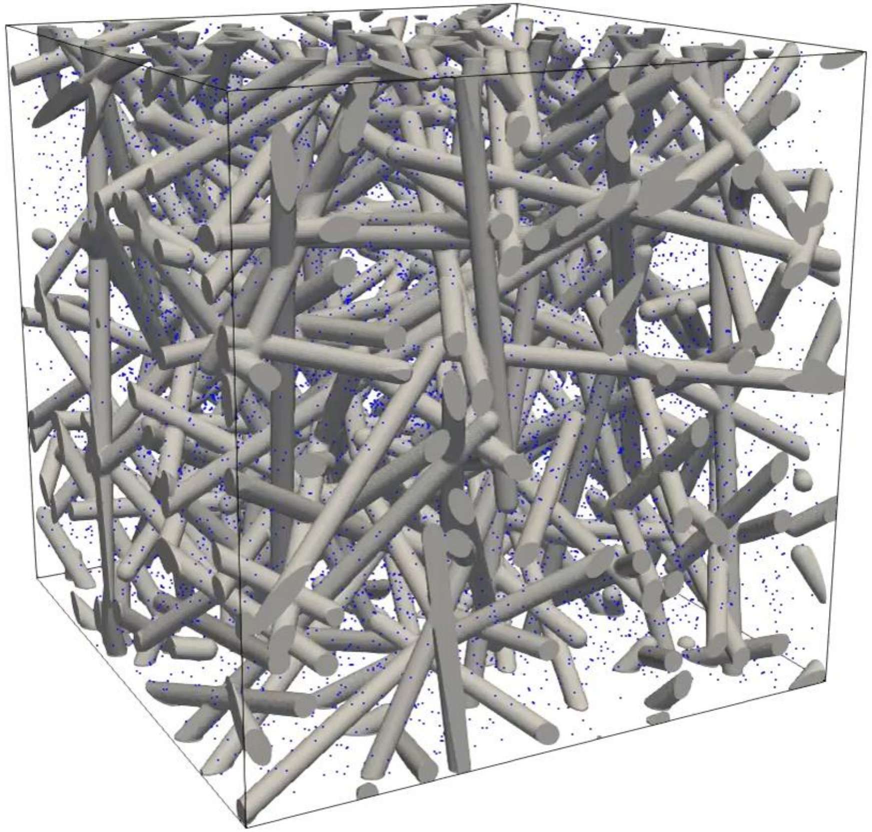
- The ray can be reflected, transmitted or absorbed based on reflectivity (ρ) and absorptivity index α (required as input)
- Reflection: New direction from the reflection model (specular, diffuse)
- Absorption: The ray is terminated and total distance travelled is noted.
- Transmission: New direction from Snell's law.



PuMA Radiative conductivity Monte Carlo Ray Tracing (MCRT)



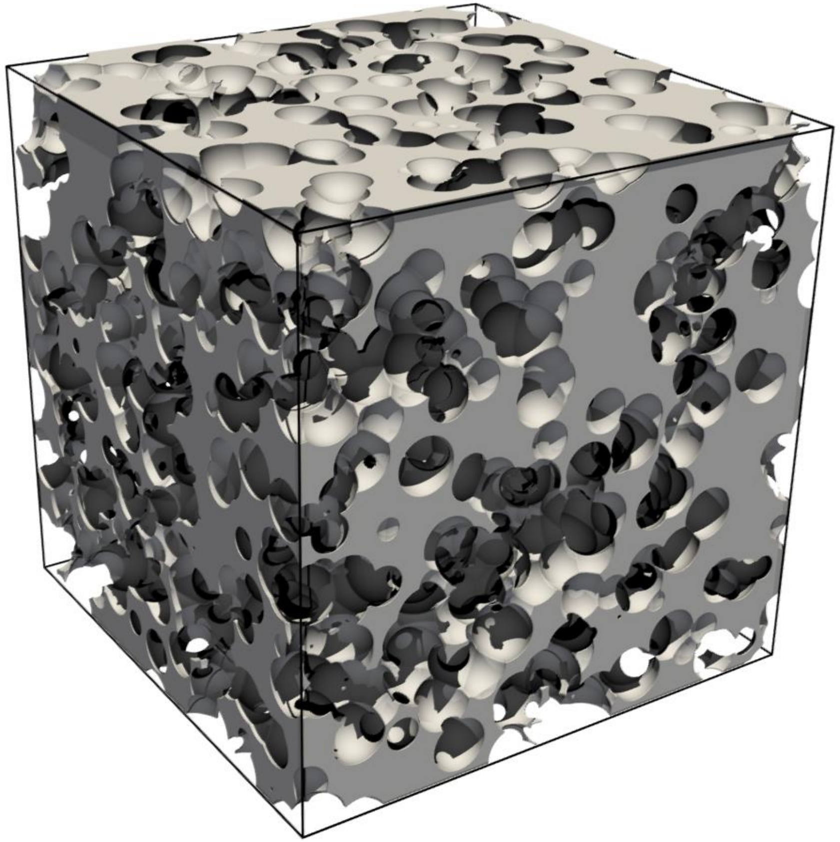
2D visualization of PuMA radiative conductivity solver. 1000 rays are randomly cast until they intersect with a solid. The ray distances are used to calculate the extinction coefficient.

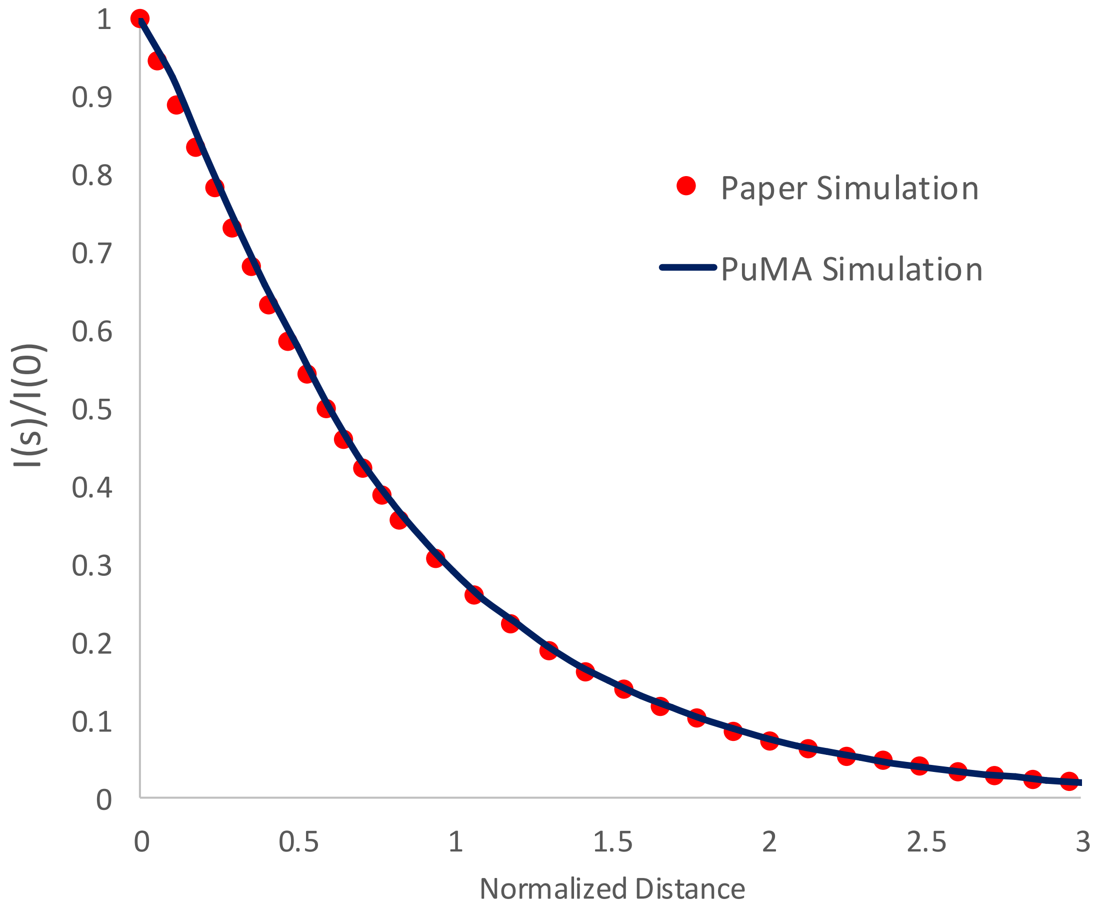


3D visualization of PuMA radiative conductivity solver. 1000 rays are randomly cast until they intersect with a solid. The ray distances are used to calculate the extinction coefficient.

Validation of PuMA MCRT

Identical overlapping transparent spheres (IOTS case from Petrasch et al)



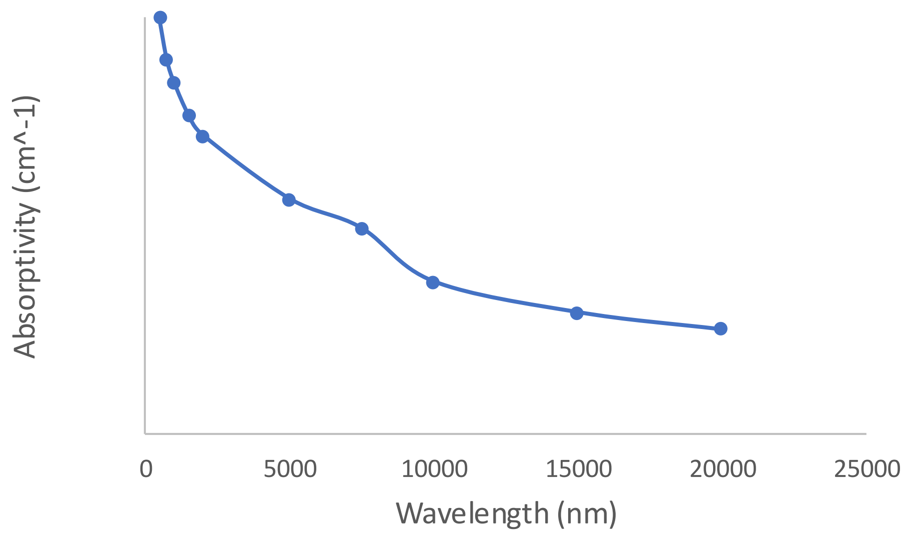


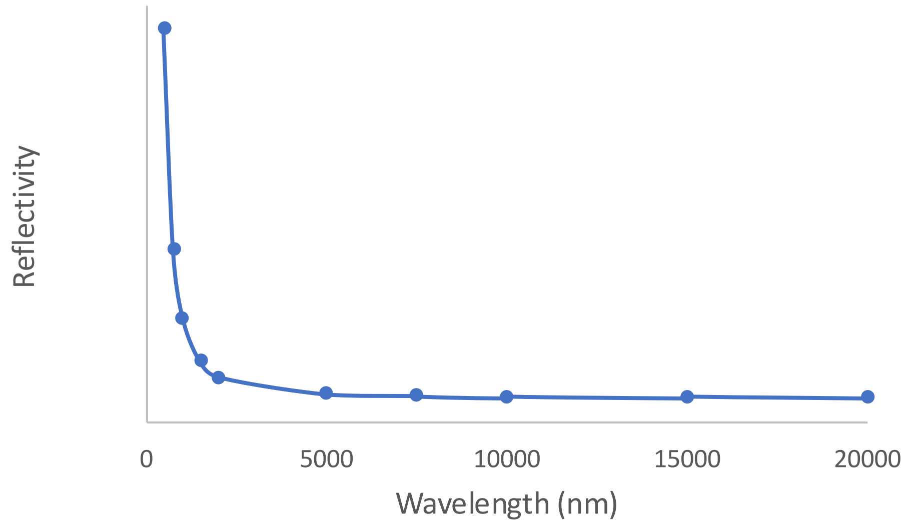
Petrasch, J., Wyss, P., & Steinfeld, A. (2007). Tomography-based Monte Carlo determination of radiative properties of reticulate porous ceramics. *Journal of Quantitative Spectroscopy and Radiative Transfer*, *105*(2), 180-197.

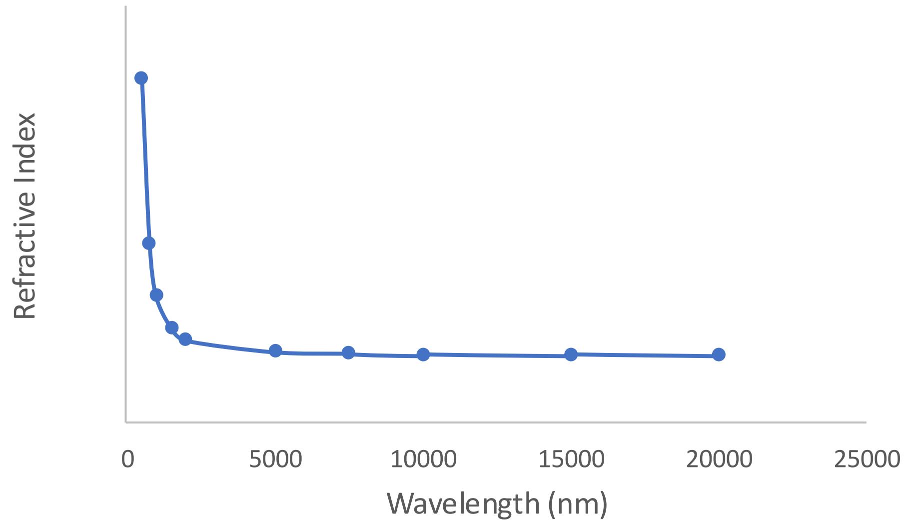
Radiative Conductivity Calculations

Inputs

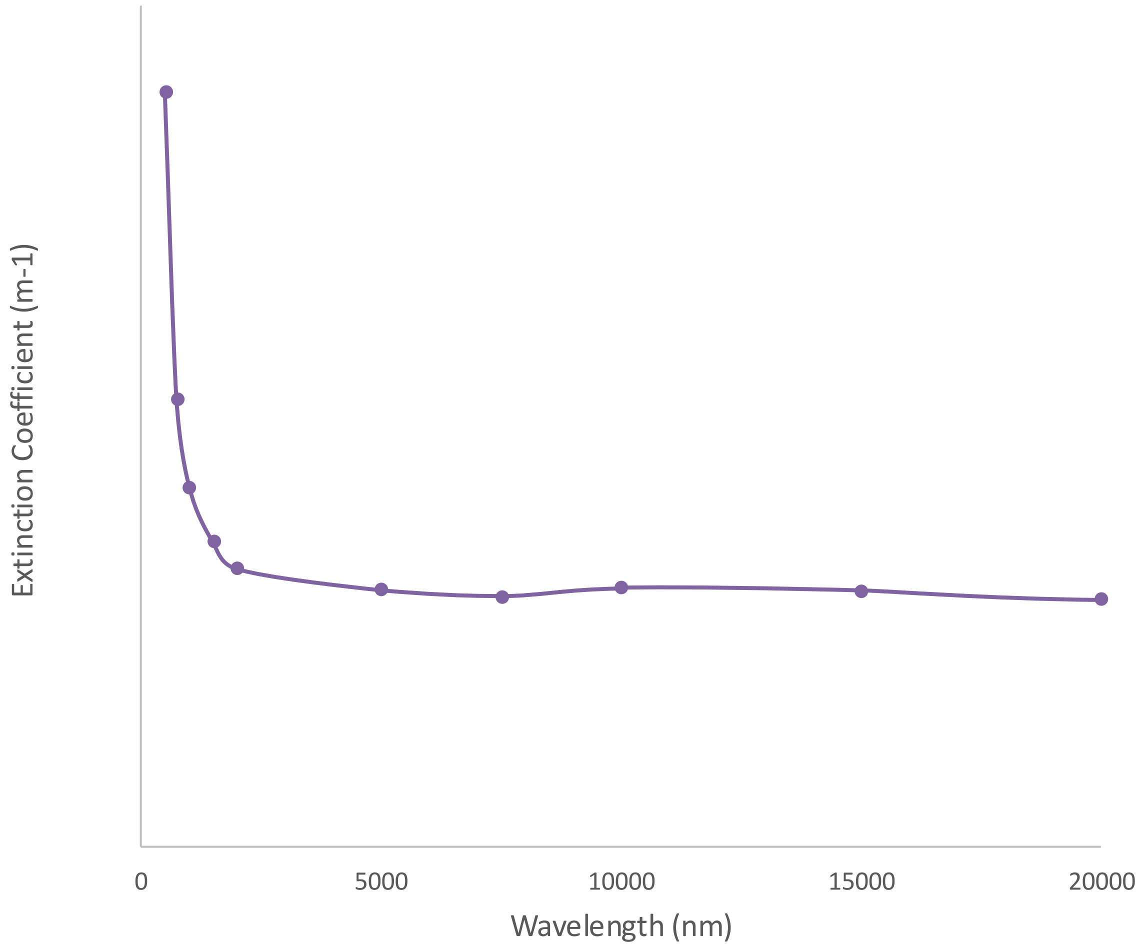
- Segmented and labeled microstructure.
- For each constituent phase
  - ➢ Reflectivity
  - ➢ Reflection model – specular, diffuse
  - ➢ Absorptivity
  - ➢ Refractive index







AETB-8 CT scan – radiative conductivity



- The effective extinction coefficient is computed at each temperature using the Planck's distribution.

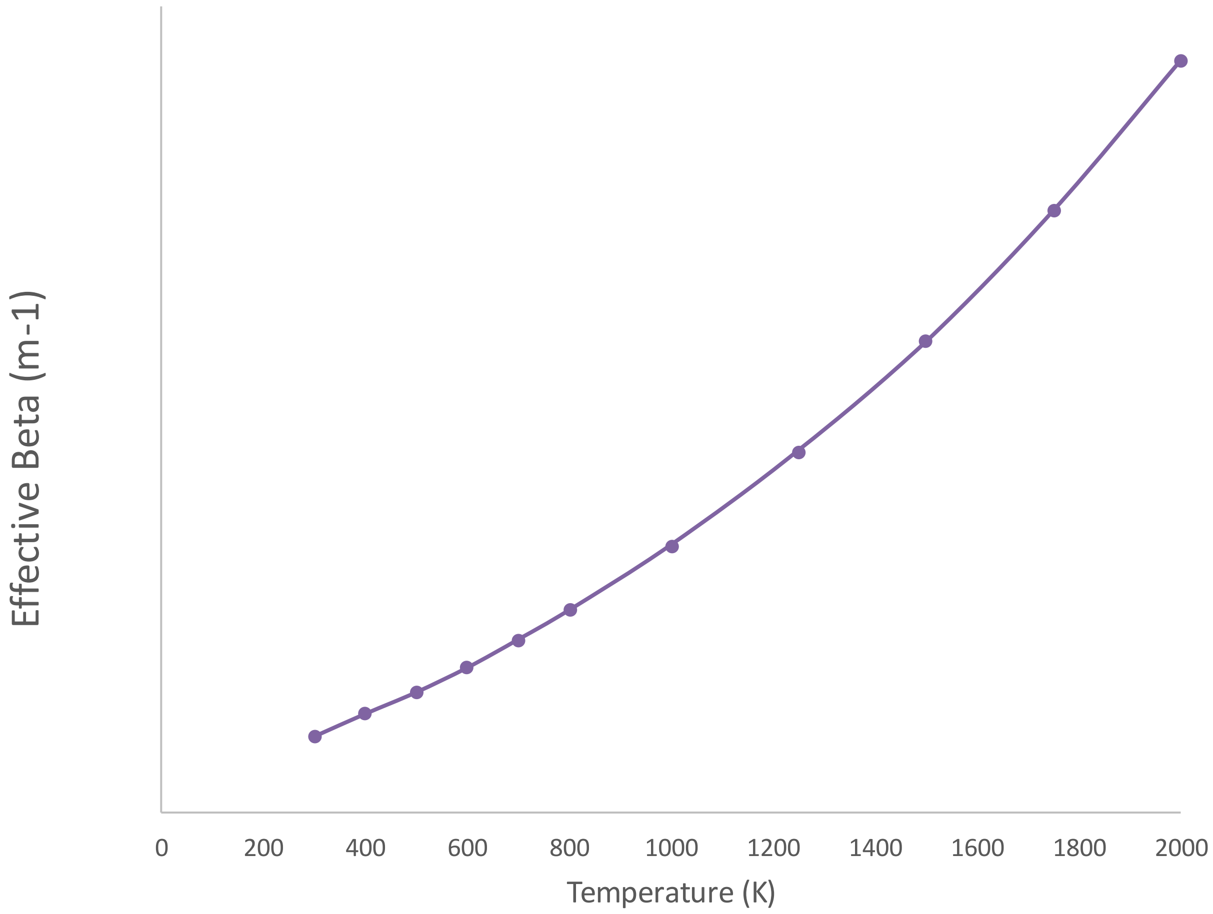
$$f(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1}$$

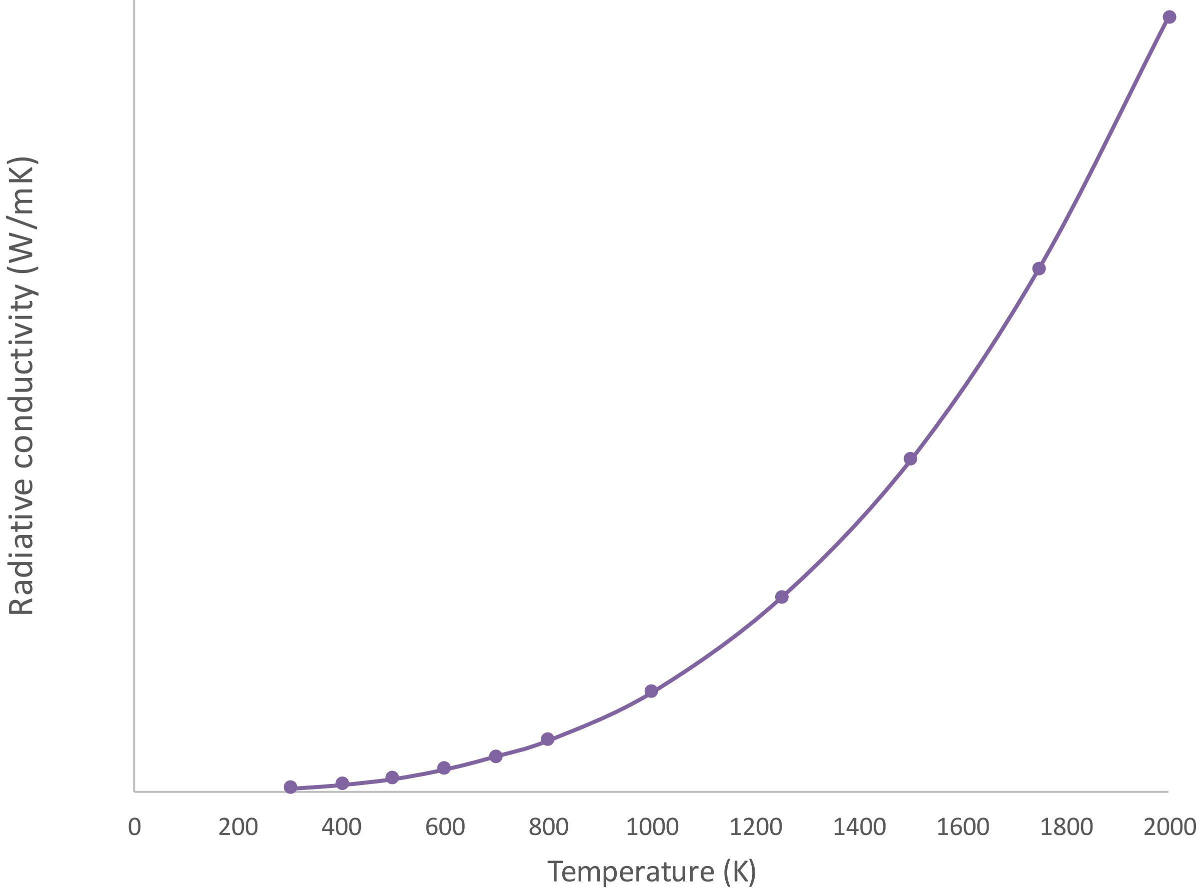
- The radiative conductivity at each temperature is computed using the effective extinction coefficient.

$$k_{rad} = \frac{16\sigma T^3}{3\beta_{eff}(T)}$$

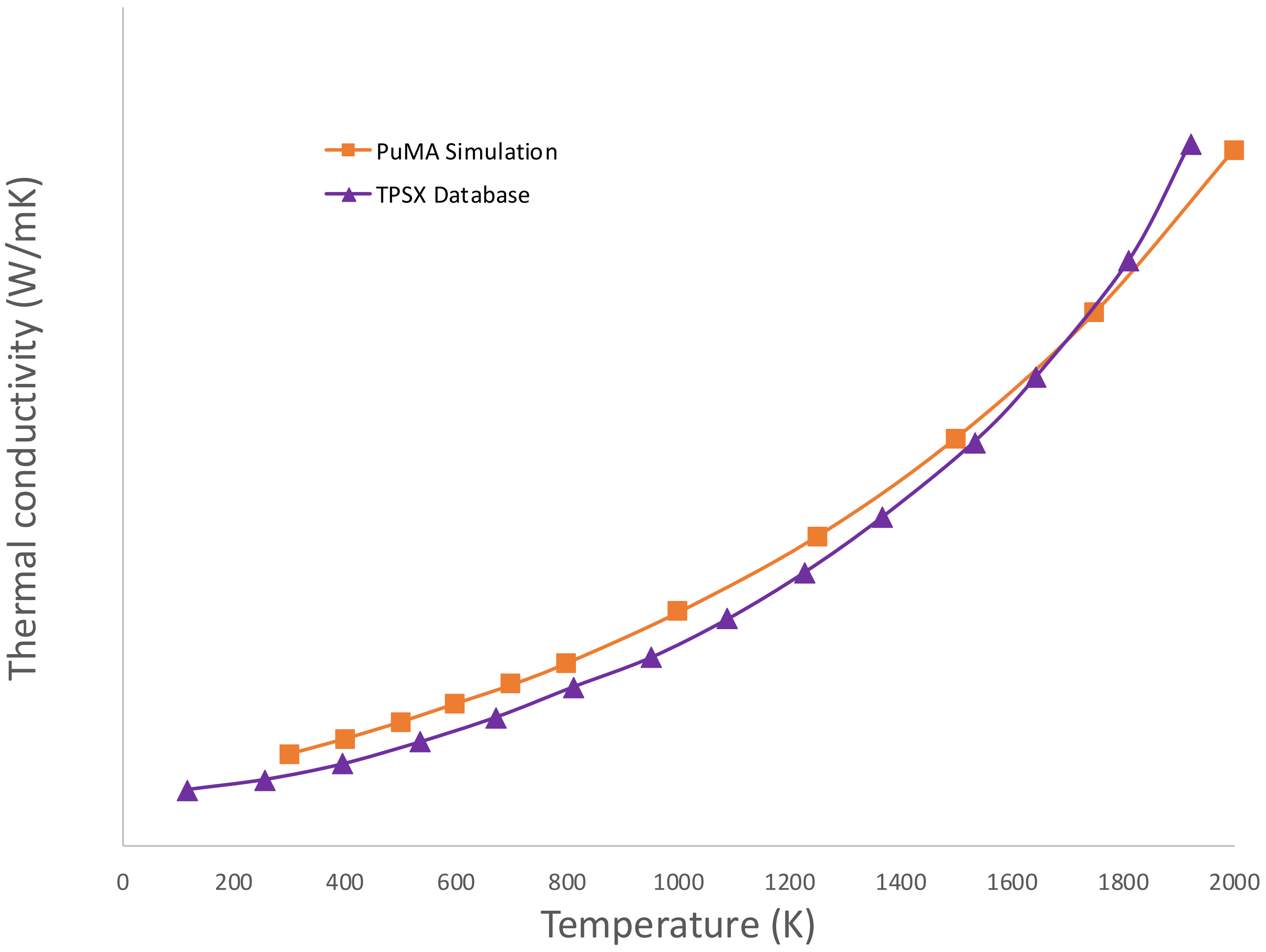
- The radiative conductivity scales with temperature due to the third power.
- In the current model, the radiative conductivity is not a function of pressure.

AETB-8 CT scan – radiative conductivity





Comparison with experiments



- Good agreement with experimental data for total thermal conductivity.
- Additional radiation-specific experimental data are needed for more accurate model validation

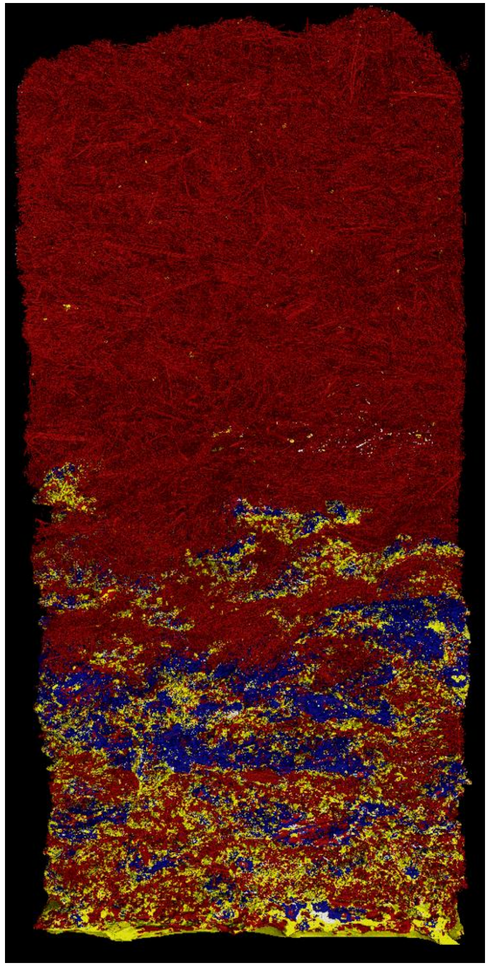
Parametric studies

- Conduct parametric studies to investigate the effect of various microstructure characteristics on the thermal properties.
- Each characteristic was investigated independently; all other parameters were kept constant.
- The effect of density, composition, fiber diameter and length on the thermal properties are shown below:

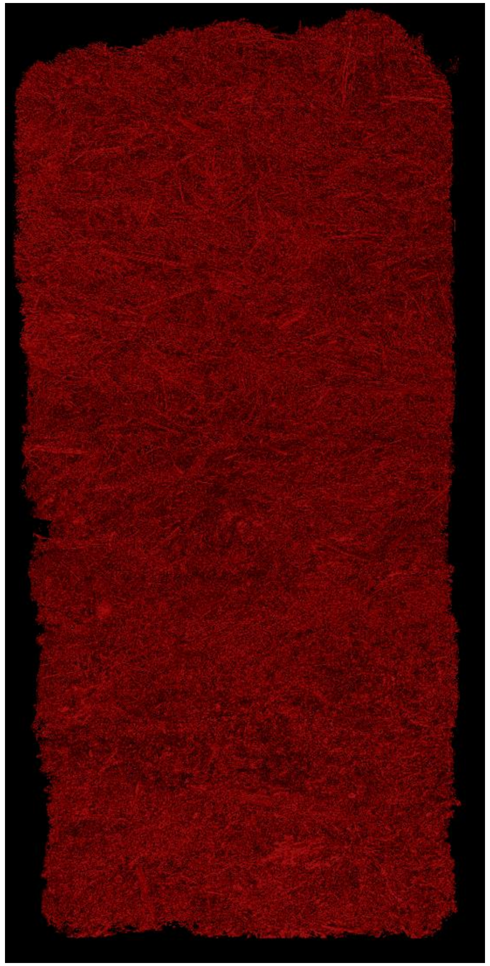
Effect	Material conductivity	Radiative conductivity
Porosity/density	Major	Major
Composition	Minor	Minor
Fiber diameter	Minor	Major
Fiber length	Significant at lower pressures	None

Segmentation of AETB + coatings

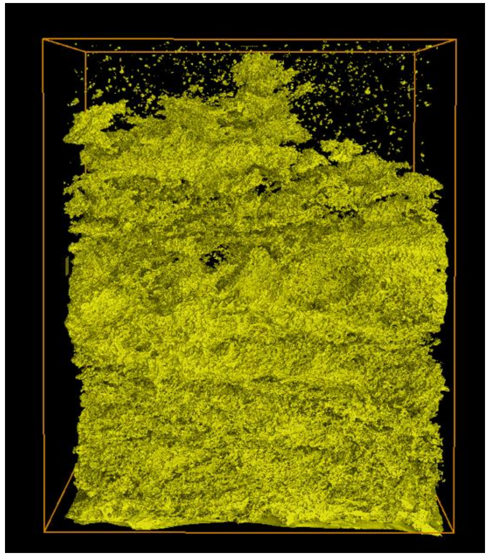
- Fibers
- RCG + Rest of TUFI
- Emissivity agent



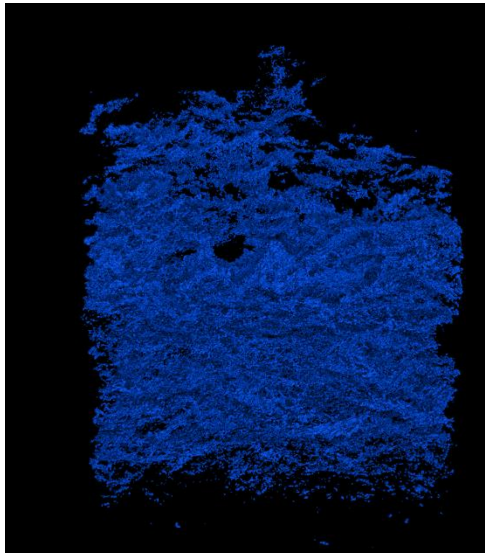
AETB-12 with TUFI/RCG



Fibers



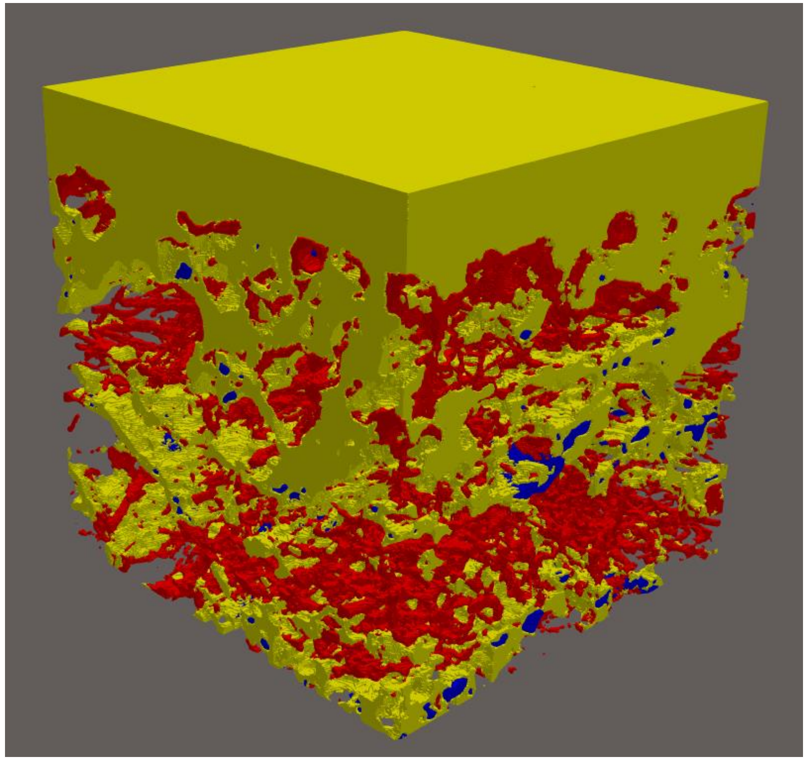
RCG + Rest of TUFI



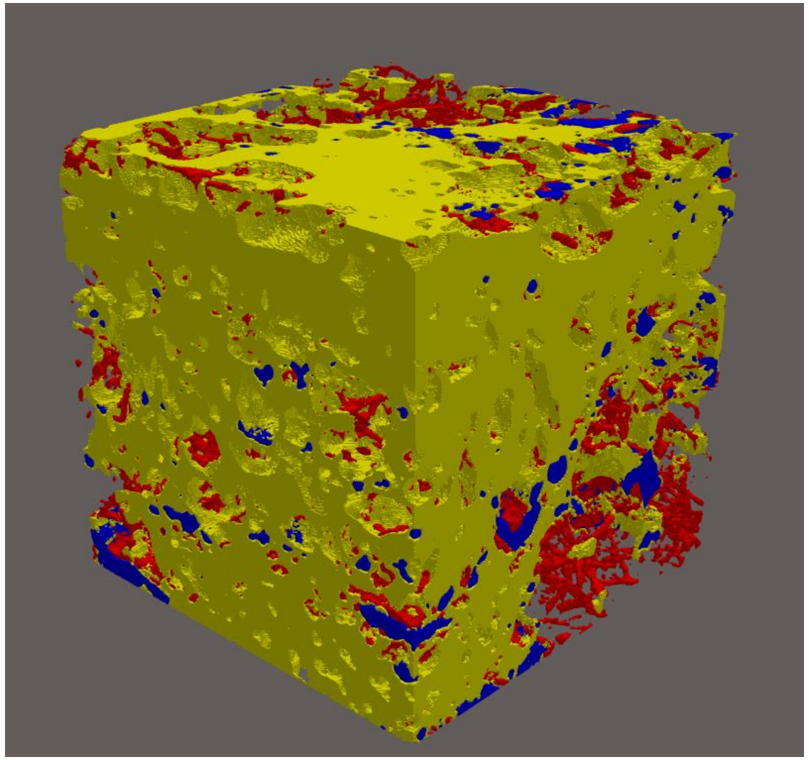
Emissivity agent

CT scan of AETB + coatings

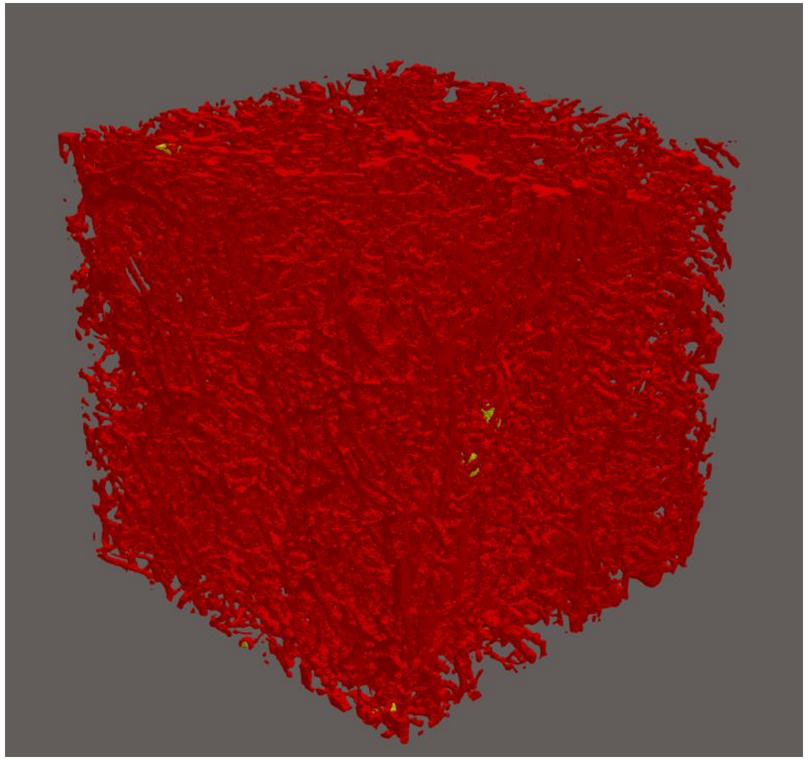
RCG-region
Surface
0.0-0.7 mm



TUFI-region
Middle
1.4-2.1 mm

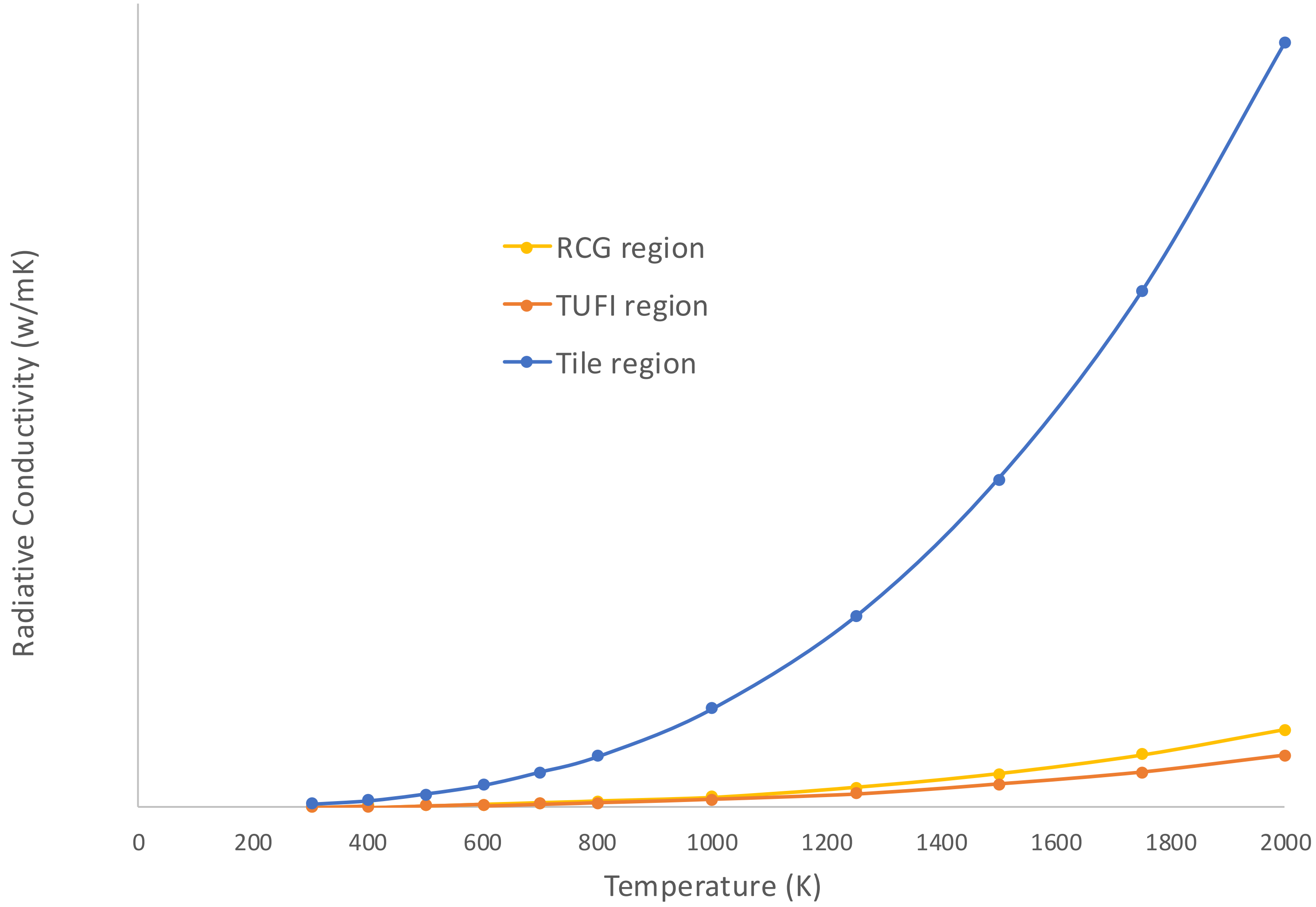


Tile-region
Interior
5.0-5.7 mm



- Fibers
- RCG + Rest of TUFI
- Emissivity agent

Radiative Conductivity of AETB-12 + coatings



- The radiative conductivity of interior is similar to AETB-12.
- Both surf and middle sub-structures have lower porosity compared to interior, and therefore lower radiative conductivity.
- The middle has the lowest porosity and highest amount of $MoSi_2$ leading to very low radiative conductivity

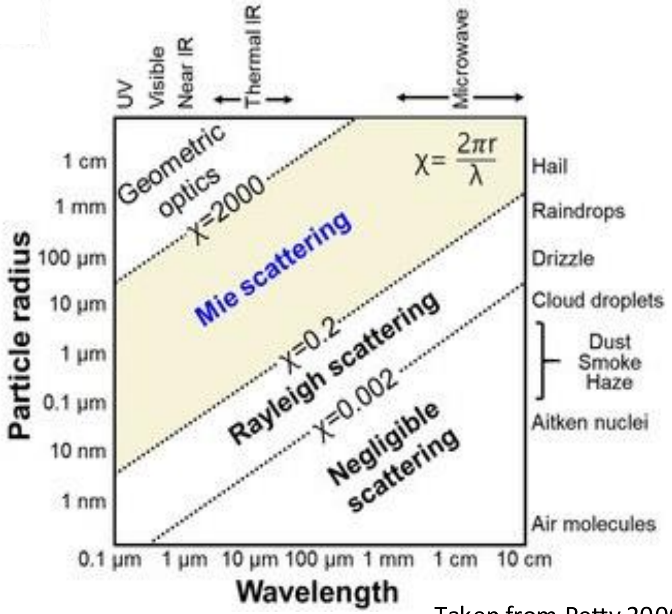
Conclusions and Future Work

Conclusions

- Developed a MCRT framework within PuMA to compute the radiative conductivity using geometric optical approximation.
- Validated the framework with analytical solutions and comparison to experimental data.
- Conducted parametric studies to analyze the effect of fiber density, composition, diameter, and length, on the radiative properties.
- Studied the effect of different coatings on the radiative properties.

Future Work

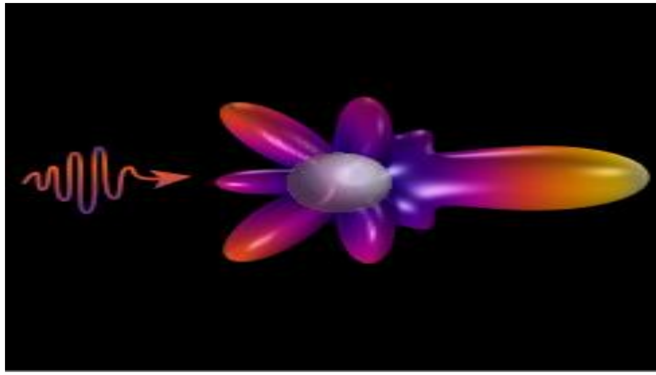
- Implement Mie scattering within PuMA MCRT with different scattering phase functions.
- Solve the full Radiative Transport Equation (RTE) to model the flow of heat through the material.
- Develop a mesoscale RTE solver for coarse-grained modeling of heat transfer through the TPS material at tile-scale.



Taken from Petty 2006

Petty, G. W., *A First Course in Atmospheric Radiation*, 2nd ed., 2006

Mie scattering



Taken from Wikipedia

ESM

ENTRY SYSTEMS MODELING

Backup Slides

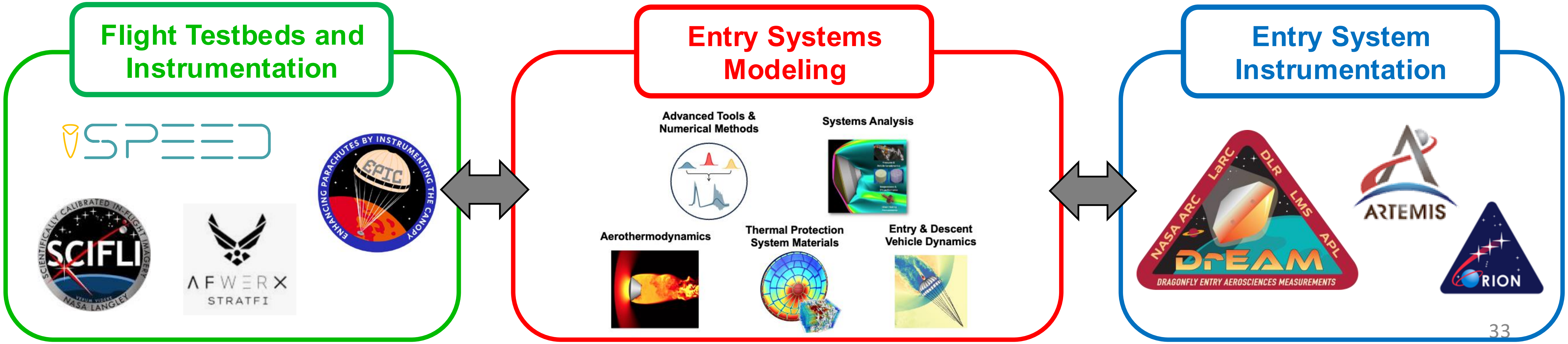
EM&I Technical Content

EM&I develops validated models and simulation tools to assess reliability and improve design of entry systems for missions to destinations across Solar System

EM&I technical content is composed of three major elements:

- Entry Systems Modeling (ESM) – improved EDL models and simulation tools (M&S) and validating ground tests
- Entry System Instrumentation – instrumentation of agency missions for EDL reconstruction and M&S validation
- Flight Testbeds and Instrumentation – platforms to improve scope, quality, and availability of flight data for M&S validation

Entry Modeling and Instrumentation Portfolio Elements

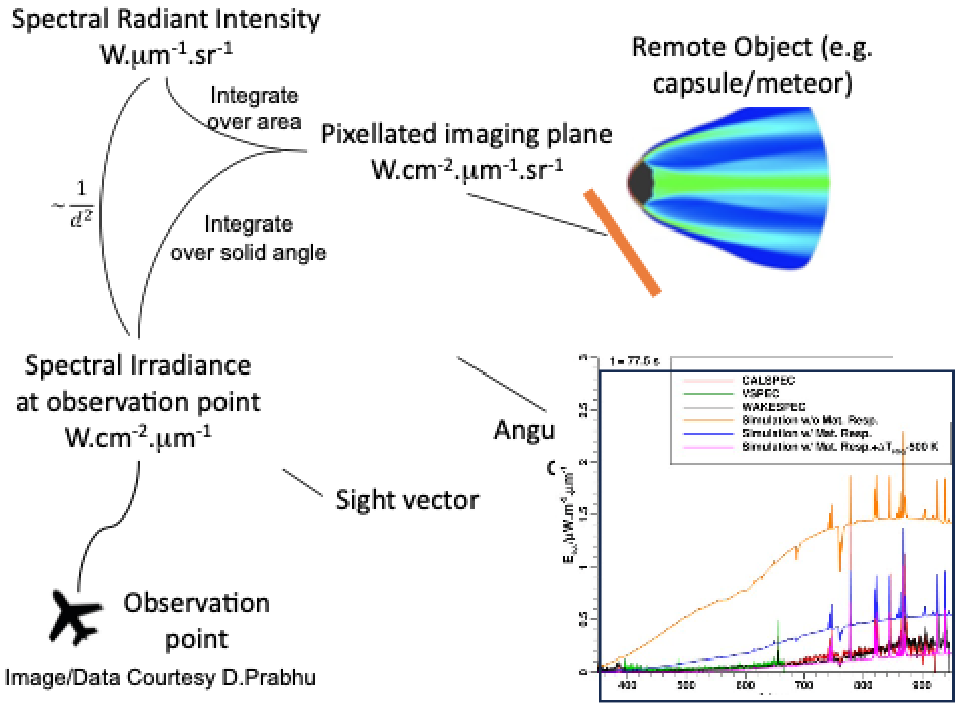


Radiation Toolsets: NEQAIR and HARA

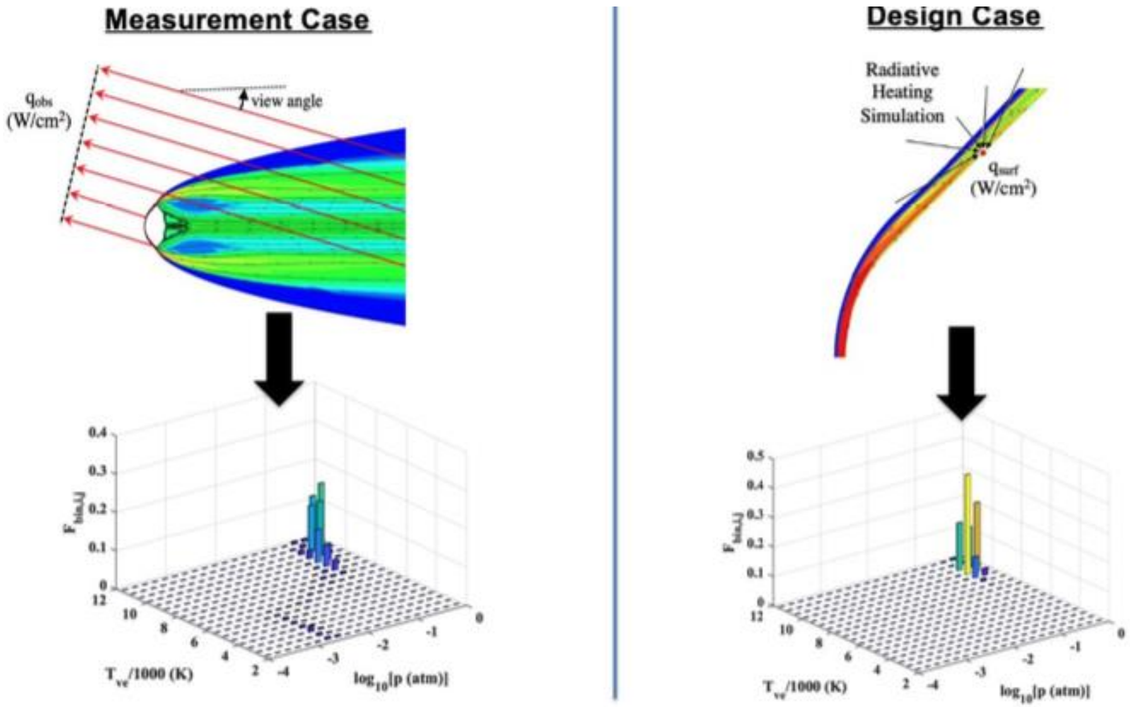
ESM maintains the Agency's tools to assess radiative heating: Non-Equilibrium Air Radiation (NEQAIR) and High-temperature Aerothermodynamic RAdiation (HARA)

- Model incident radiation from shock layer using relaxation of atomic/molecular species and ray tracing
- Recent updates: adaptive 3D radiation, built-in remote observation (NEQAIR)
- Recent update: UQ automatic uncertainty/margin assessment using a variety of methods (HARA)

NEQAIR



HARA



POCs: Cruden and Johnston