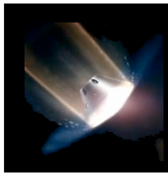

Entry Systems and Technology Division
Ames Research Center

National Aeronautics and
Space Administration

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Multiscale Modeling of Woven Ablative Thermal Protection System Materials

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Accelerating woven TPS certification with improved analysis

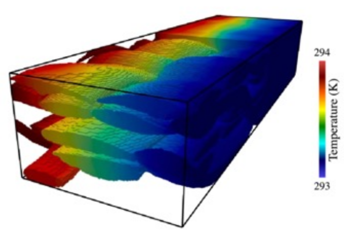
The NASA Entry Systems Modeling (ESM) project seeks to develop and validate new model and tools capabilities to support mission needs

For Mars Sample Return Earth Entry System, focus on woven TPS:

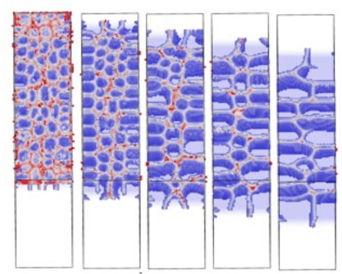
- Characterize uncertainties in material properties – multiscale modeling tools (PuMA/NASMAT)
- Damage response of the material to impact – fracture modeling tools (LAMMPS/HYDRA)
- Modernized heatshield design – multi-dimensional and coupled entry tools (Icarus/Ares)

ENTRY SYSTEMS MODELING

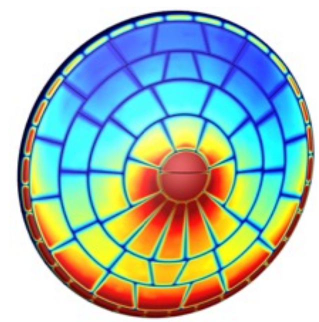
Property and Structure Variability



Material Damage



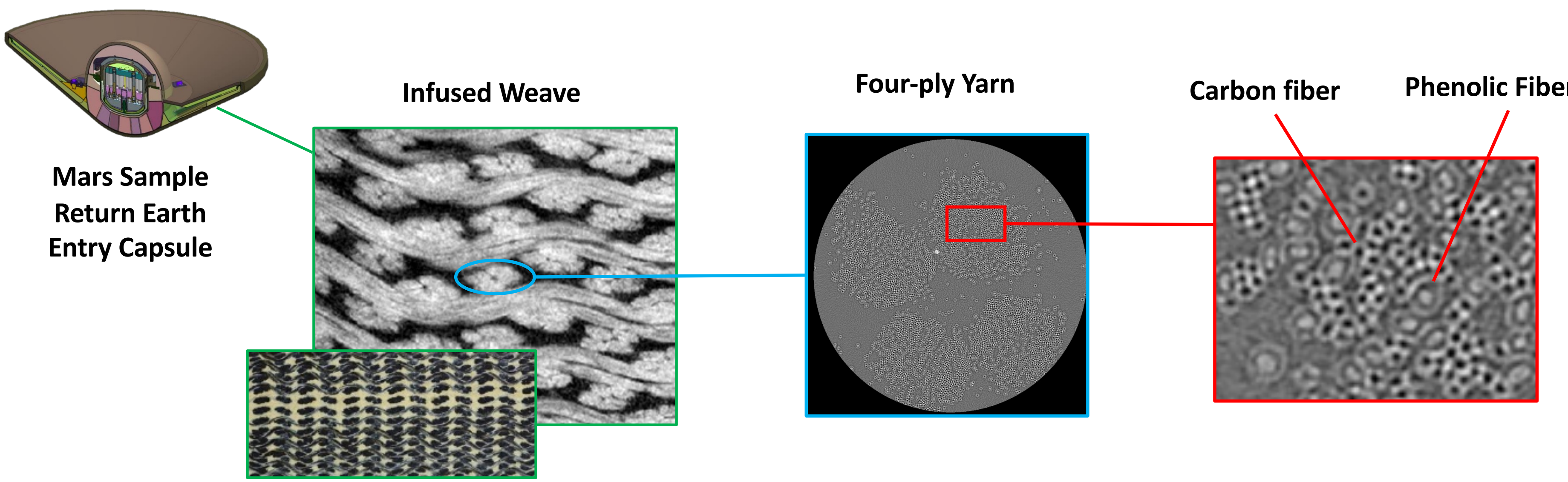
Heatshield Design



MSR-EES woven TPS structure composition and structure

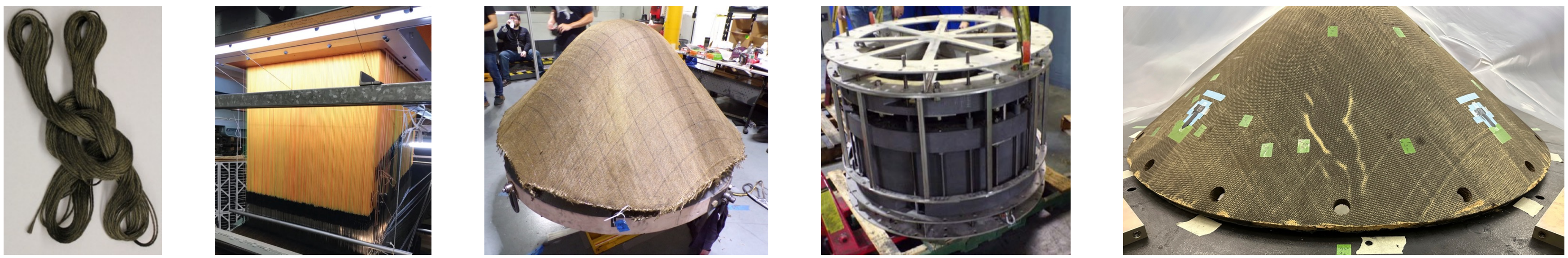
3D Woven Mid-Density Carbon Phenolic (3MDCP) material, a derivative of the insulation layer of the Heatshield for Extreme Entry Environment Technology (HEEET IL)

- Complex structure: 3D weave pattern, stretch broken four-ply yarns, and two types of fibers
- Variability from manufacturing, processing, and integration of interest



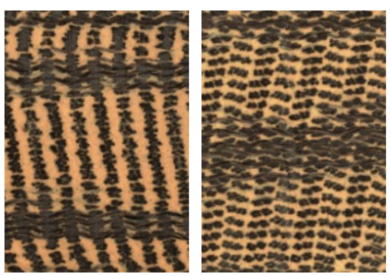
Ellerby et al., MS&T (2019)

Variability from manufacturing, processing, integration

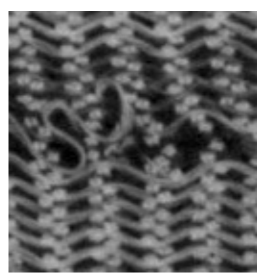


- Twisted and stretch-broken yarn
- 3D woven preform
- Formed and trimmed sphere-cone preform
- Infused heatshield
- Machined heatshield
- Integrated on substructure

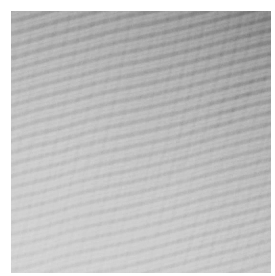
Constituent variability



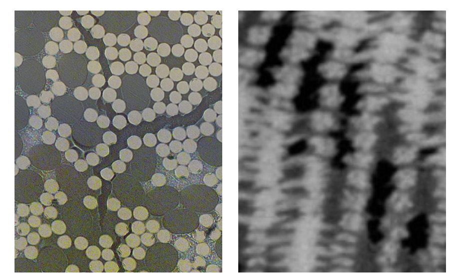
Variability in yarn stacking during weaving process



Weaving defects



Weave scissoring during forming



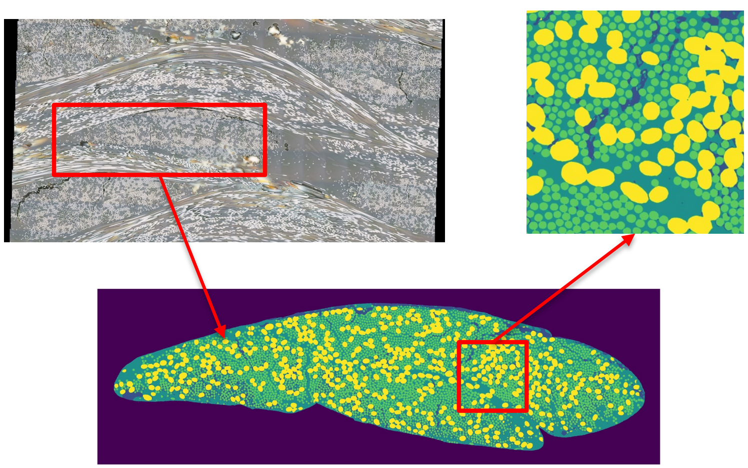
Infusion cracks and voids

Computational approach to modeling weave properties

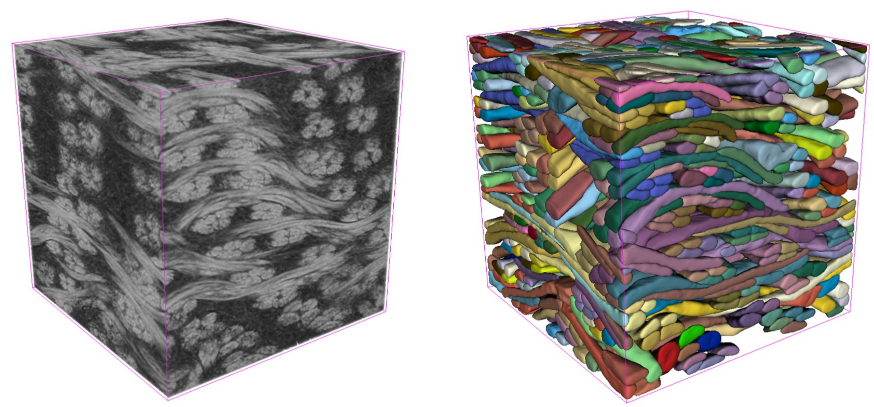
Computational evaluation of structure-property relationships accelerate certification by informing weave pattern and variability influence on properties

- Optical or tomographic data analyzed to provide metrics on yarn/weave variability
- Weave models developed from metrics or direct imaging to compute properties

Yarns: HEEET IL
Optical Microscopy



Weave: S-DEV PC-1
Microtomography

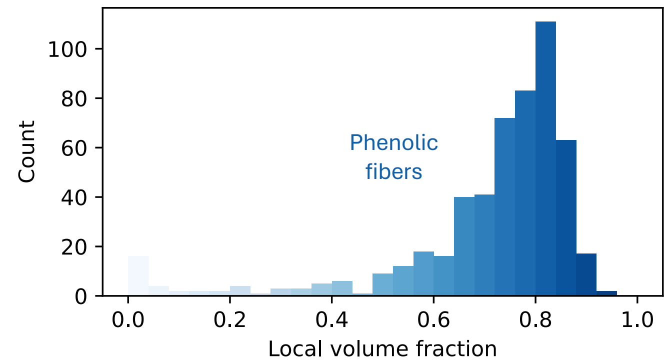


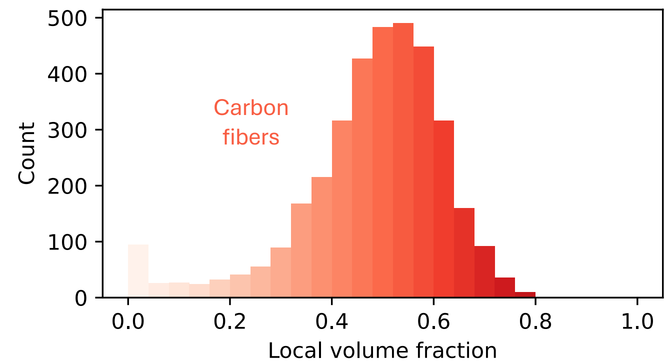
Characterization of yarn/fiber structure

Yarn-fiber metrics populated as a first step in constructing effective yarn models for property generation

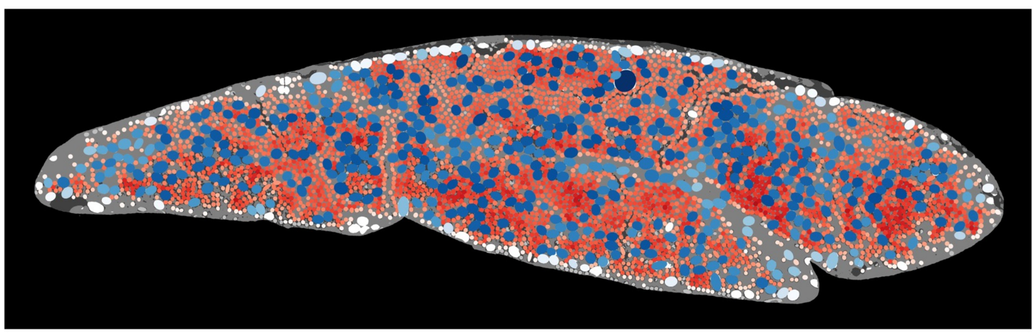
- Fibers count, diameter, and local volume fraction determined
- Machine learning segmentation and Voronoi tessellation leveraged
- Metrics used to determine average fiber properties

Fiber Packing Metrics





Segmented Yarn Image

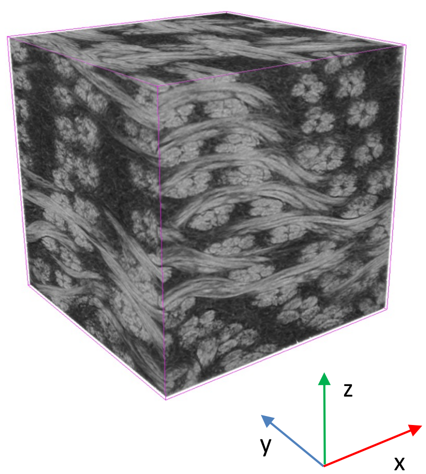


Types of weave variability

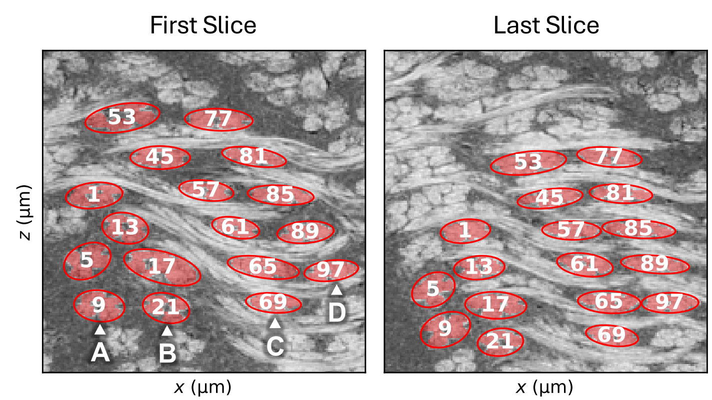
Various forms of variability noted from X-ray computed tomography of HEEET IL

- Yarn column tilting – monotonic lateral shifting in centerlines along the thickness (z)
- Yarn column oscillation – periodic lateral shifts in centerlines along the thickness (z)

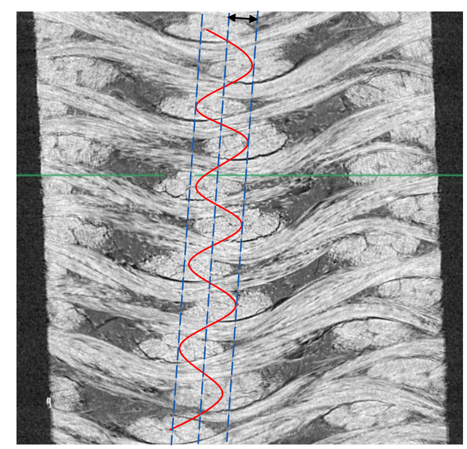
Volumetric CT HEEET IL



Yarn Colum Tilting



Yarn Column Oscillation

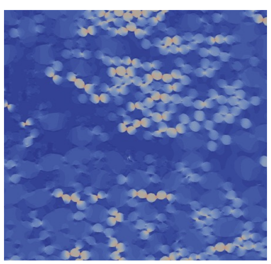


Influence of weave pattern and oscillation on properties

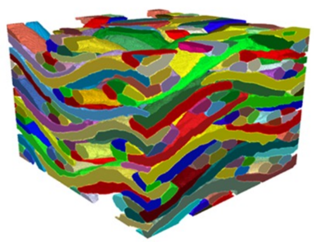
Weave patterns with oscillation were examined to understand influence on properties

- Use of CT vs ideal structure has up to 35% influence on thermal conductivity (through thickness)
- Oscillation in ideal structures induces up to 20% change in thermal conductivity (in plane)

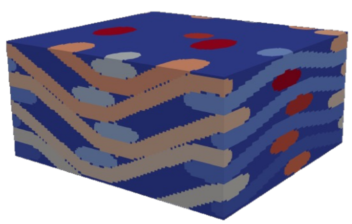
Yarn Properties

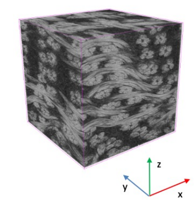


CT HEEET-IL



Ideal HEEET-IL





Computed Thermal Conductivity

Weave	Oscillation	κ_{xx} (W/mK)	κ_{yy} (W/mK)	κ_{zz} (W/mK)
HEEET-IL (CT)	yes	0.548	0.542	0.178
HEEET-IL (Ideal)	yes	0.511	0.499	0.132

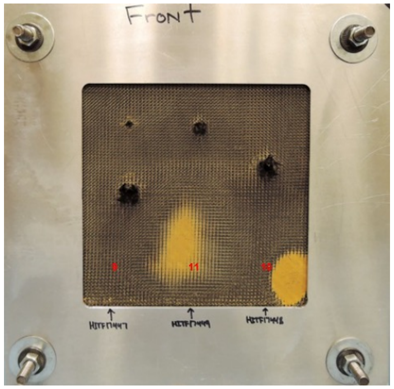
Simulations performed with the Porous Microstructure Analysis (PuMA) and NASMAT tools

MMOD Impact Testing and Modeling

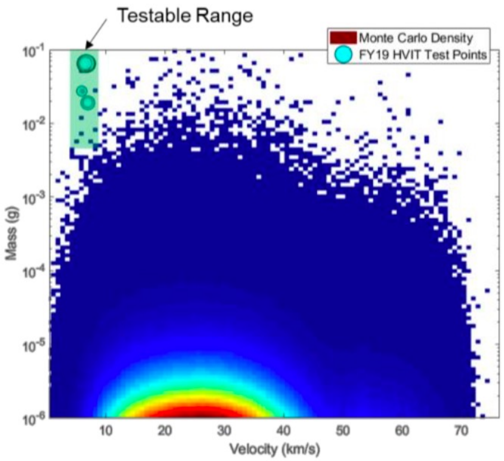
MMOD impact simulation capabilities needed to bridge ground-to-flight conditions

- Ground impact testing on woven TPS performed at the White Sands Remote Hypervelocity Impact Testing (RHIT) facility: ~5mm impactors and 7 km/s
- Ground testing limited to impacts that are higher mass and lower velocity than typical MMOD

Weave Impacted at RHIT



MMOD mass-velocity heat map



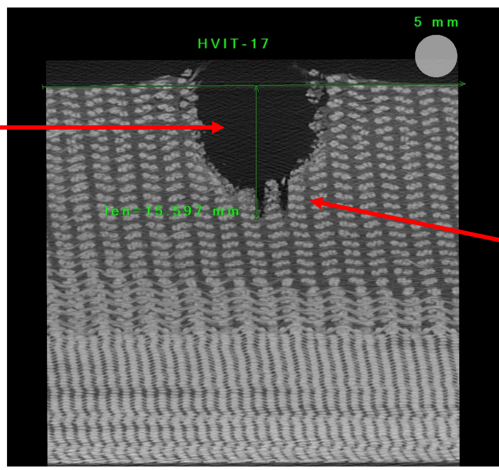
Libben, et al., First Int'l Orbital Debris Conf. (2019); Mars Sample Return Earth Entry System

Ballistic impact test results

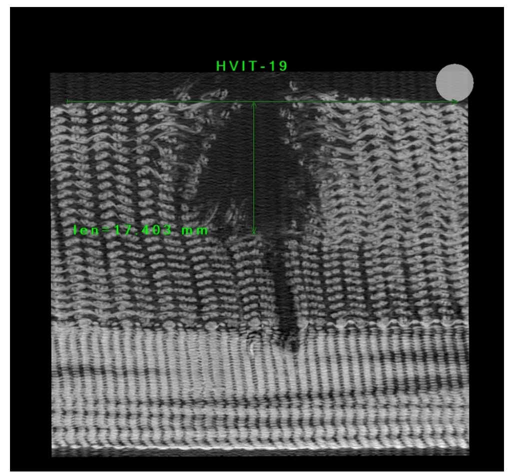
Infused and uninfused woven TPS targets impacted with nylon spheres and imaged with X-ray CT to characterize damage

- Both samples exhibit *cratering* – formation of ellipsoidal cavity from impact vaporization
- Both samples exhibit *crack propagation* – fracture emanating radially from the *crater*

nylon impactor; 7 km/s; infused HEEET IL



nylon impactor; 7 km/s; uninfused HEEET IL



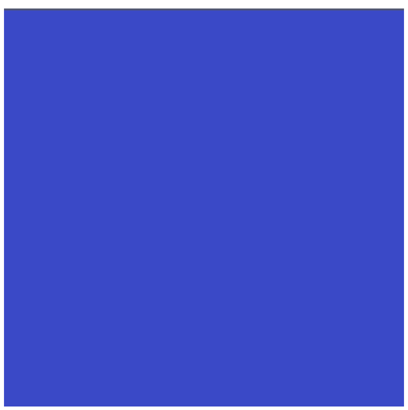
Libben, et al., First Int'l Orbital Debris Conf. (2019); Mars Sample Return Earth Entry System

Ballistic impact and damage modeling

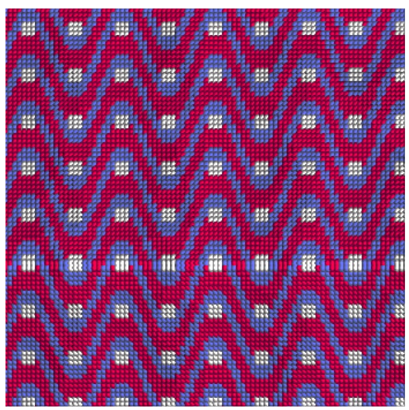
Impact simulations conducted on model weave targets at ground impact test conditions to examine cratering and secondary damage effects

- Weave models with varying structural detail leveraged as impact targets
- Peridynamics – mesh-free approach developed specifically for fracture – used to simulate

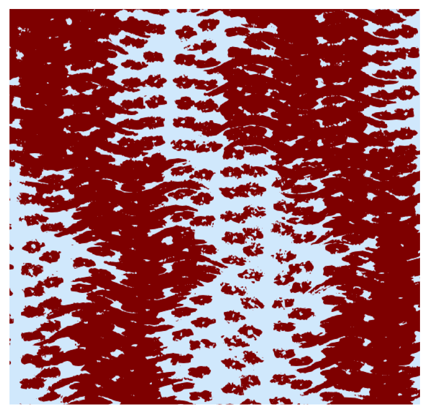
Homogeneous Model



Ideal Weave Model



As Manufactured Weave Model



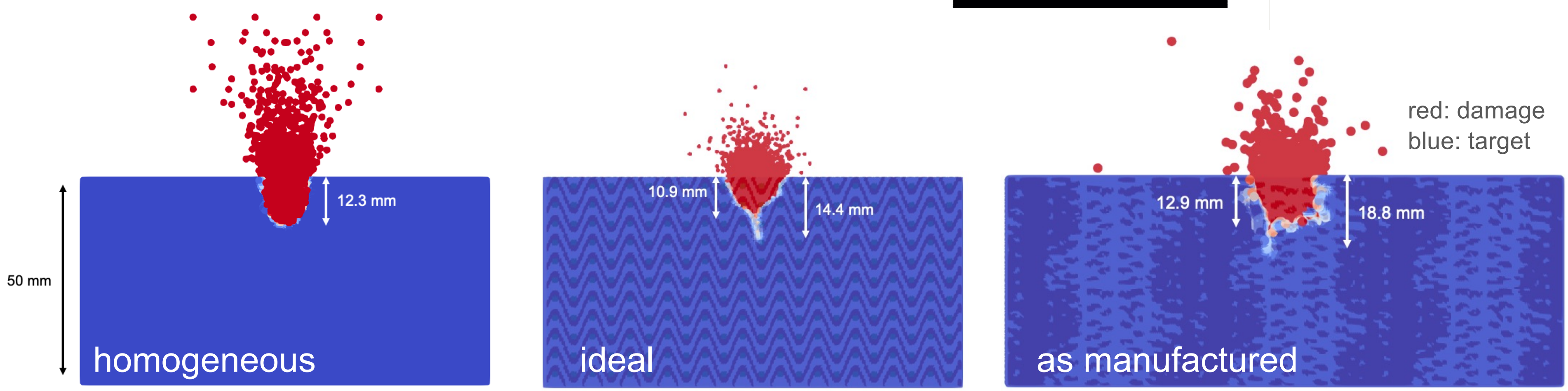
- Targets are 100-150 x 100 mm^2 and thickness is 50 mm^3 (~5M particles)
- Large-scale Atomic Molecular Massively Parallel Simulator (LAMMPS) used
- Ideal and as-manufactured weaves akin to IL-HEEET weave
- 5mm and 4-7 km/s impactor

Generation of yarn-level models: segmented weaves (hand)

Woven TPS weave pattern influences ballistic impact damage response

- Cratering volume is similar across all three models
- Secondary cracks require heterogeneity in mechanical properties from weave pattern

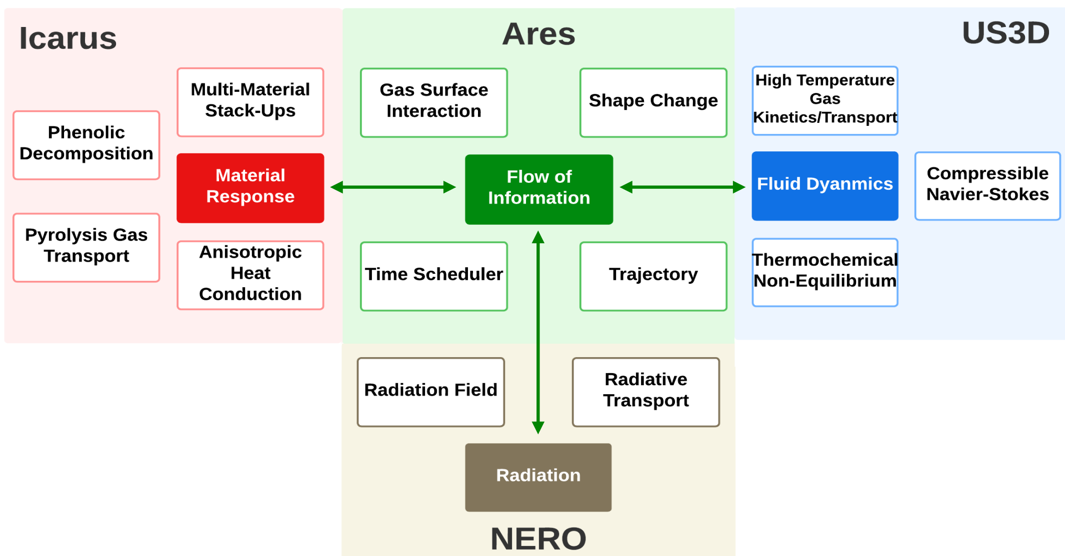
Evaluation of Secondary Damage Modes during Impact



Multi-dimensional heatshield design tools

Multi-dimensional and coupled analysis capabilities streamline TPS mission design and improve fidelity of performance estimates

- NASA ESM implemented baseline coupled capabilities in the Ares/Icarus framework
- Ares closely integrates material (Icarus), radiation (NERO), and flow (US3D) solves

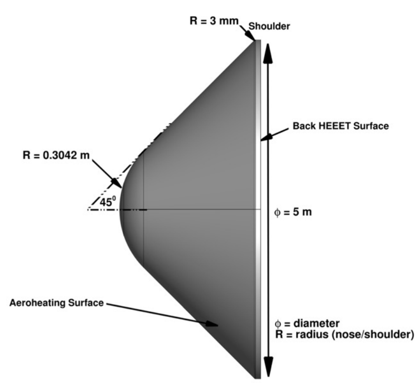


Application to the MSR-EES heatshield

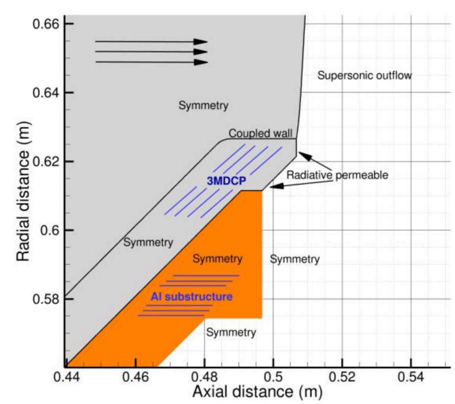
Multi-dimensional approaches Uncoupled and coupled approaches applied to the response of the MSR-EES heatshield to characterize recession

- Allows detailed evaluation of heat fluxes, pyrolysis gas generation, and temperature across heatshield – some differences in surface properties noted

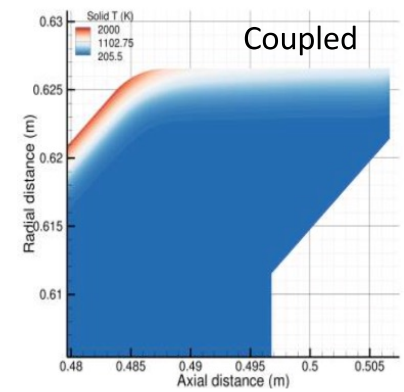
MSR-EES Heatshield

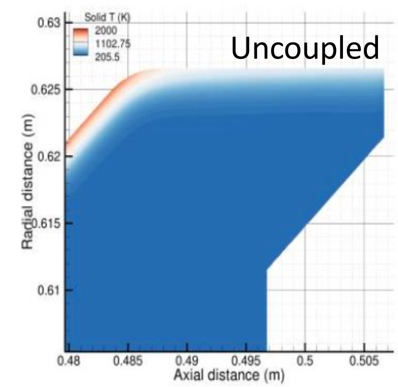


Simulation Setup



Temperature





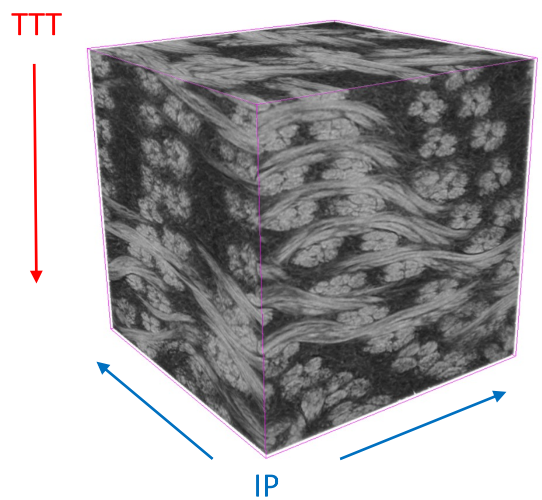
Shrestha et al., AIAA SciTech (2024)

Application to MSR-EES TPS material orientation

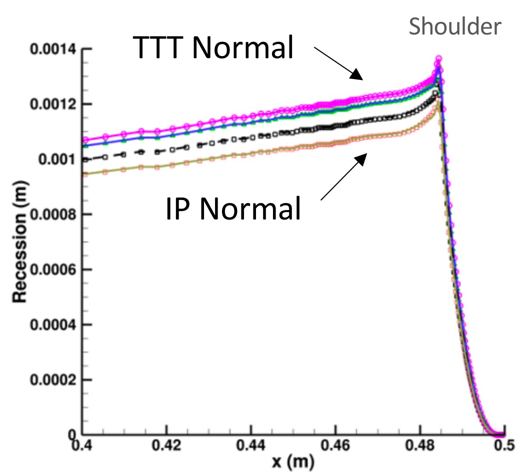
Orientation of through-the-thickness (TTT) and in-plane (IP) directions influence recession

- TTT normal to the flow leads to maximal recession (0 degrees), while recession decreases with other orientations
- Recession correlates with conductivity, which is lowest TTT and leads to more charring and ab

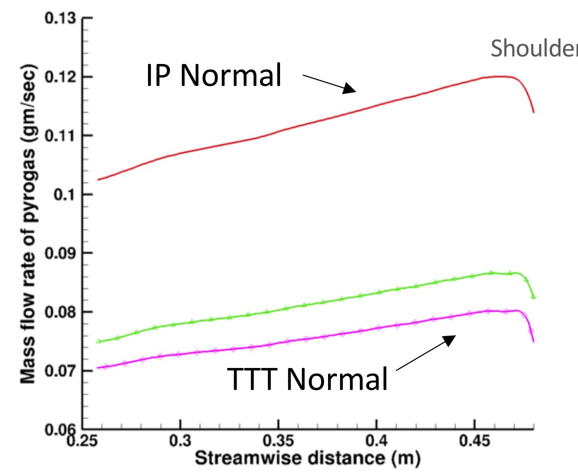
Weave Shoulder Orientation



Recession



Pyrolysis Gas Outflow



Shrestha et al., AIAA SciTech (2023)

Summary

- Capabilities developed by the Entry Systems Modeling project to improve description of woven TPS performance for current and future NASA missions

- Multiscale techniques developed to address various challenge problems
  - Material structure and property variability
  - Material damage response to impact
  - Design and multi-dimensional response during entry

- Toolsets applicable to other ablative TPS as well as dense composites and distributed through the NASA Software Catalogue

Tools and Questions?

Tools Available on the NASA Software Catalogue: https://software.nasa.gov/

Icarus	Material Response	Limited Release
PATO	Material Response	Open Source
PuMA	Micro-Material Response	Open Source
NASMAT	Multiscale Properties	Limited Release

Questions?

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