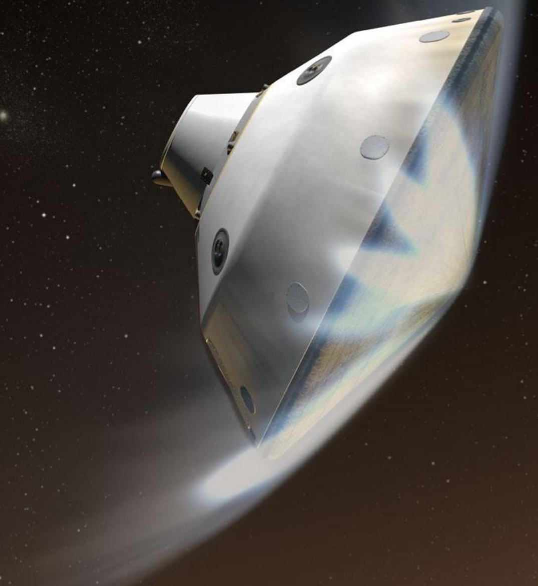
X-ray micro-tomography for advanced material technologies: a NASA perspective



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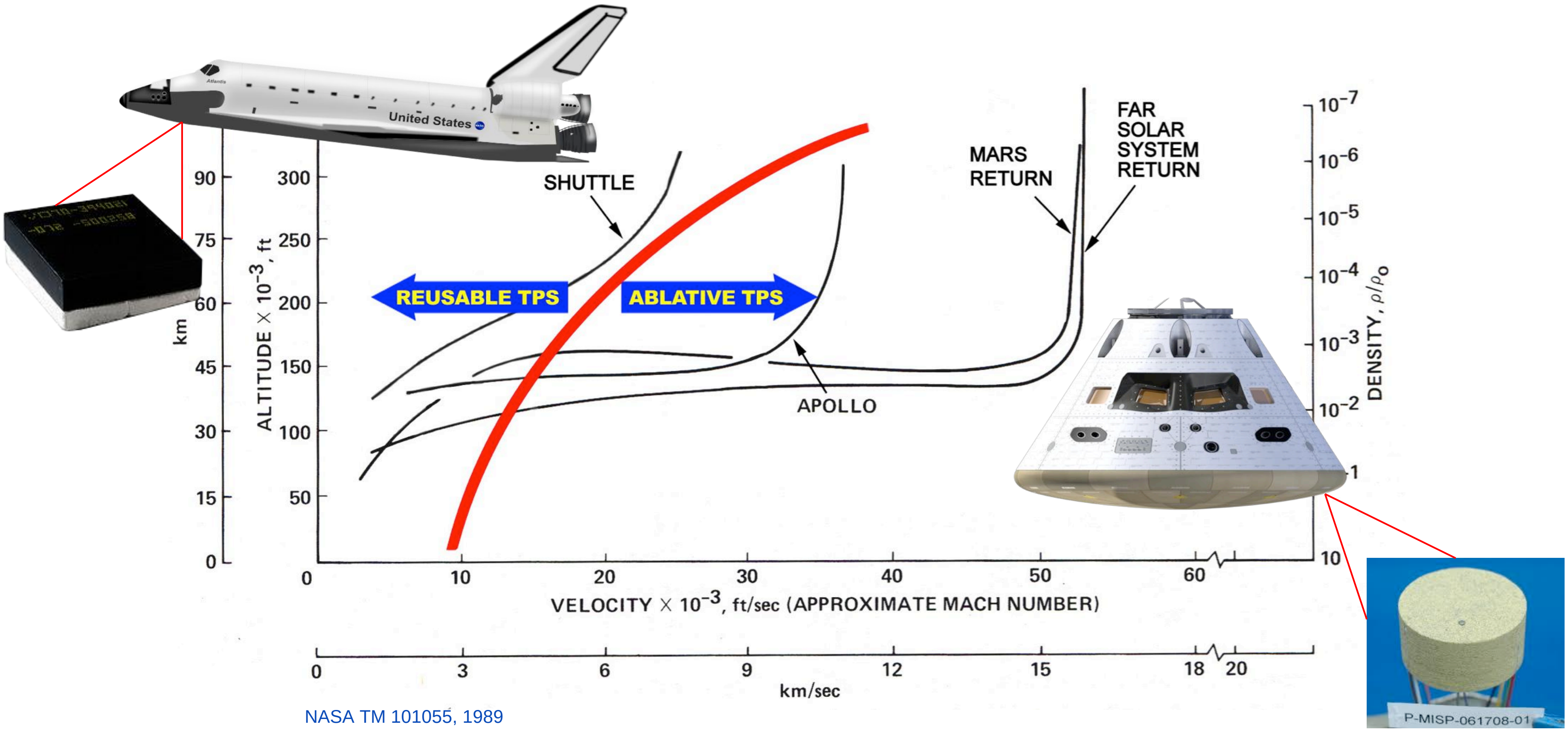
Space Tech Expo, 2017
Pasadena, CA

Thermal Protection Systems



NASA TM 101055, 1989

Ablative Thermal Protection Systems

Carbon fibers

+

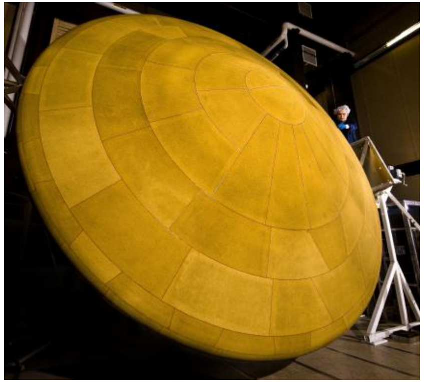
Resin

=

PICA

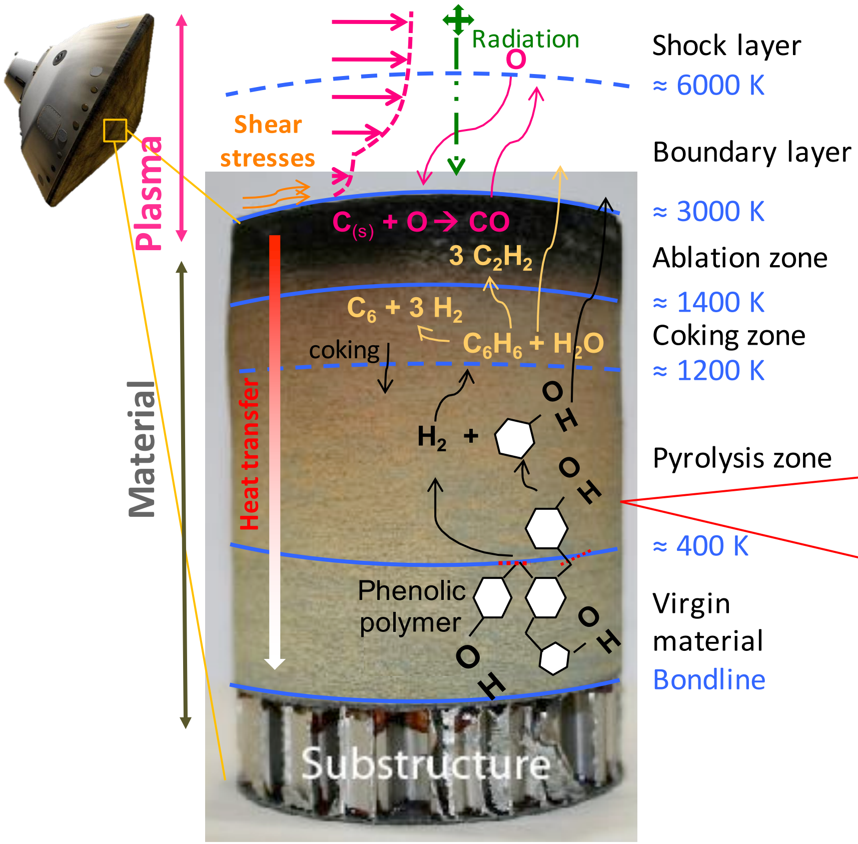
Stardust Capsule

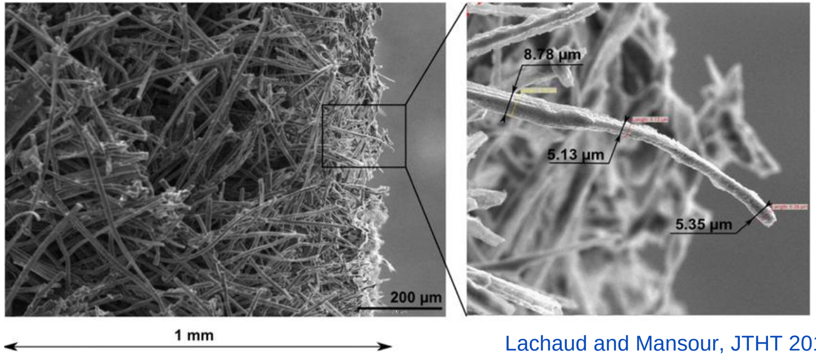
Dragon V1 & V2



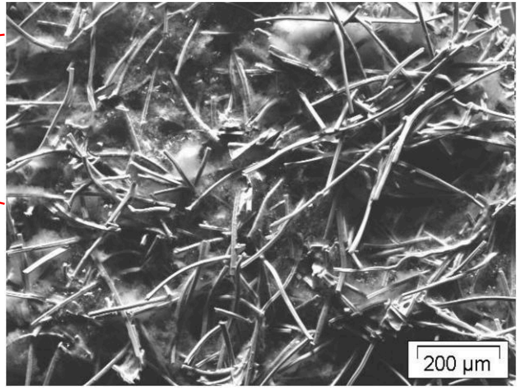
Mars Science Laboratory

Material Design and Modeling



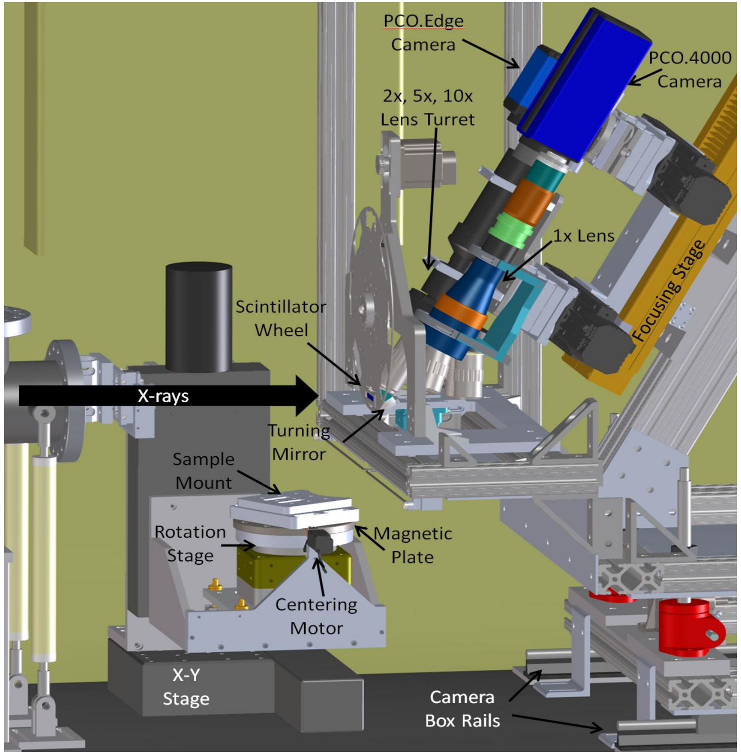


Lachaud and Mansour, JTHT 2013



Lawson et. al. 2010

X-ray micro-tomography

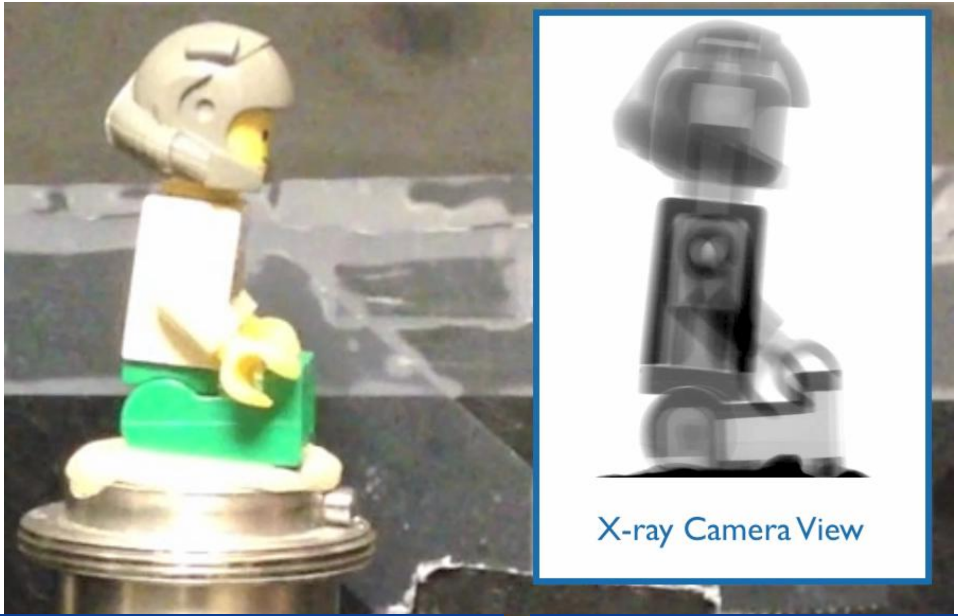


http://www2.lbl.gov/MicroWorlds/ALSTool

- Advanced Light Source (ALS) at the Lawrence Berkeley Natl. Laboratory
- Synchrotron electron accelerator used to produce 14Kev X-rays
- Used for many research areas, including optics, chemical reaction dynamics, biological imaging, and **X-ray micro-tomography**.

X-ray micro-tomography

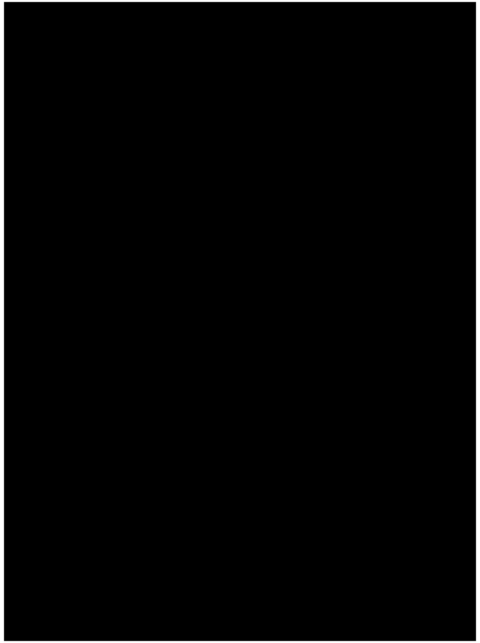
Collect X-ray images of the sample as you rotate it through 180°



Penetrating power

Multiple angles

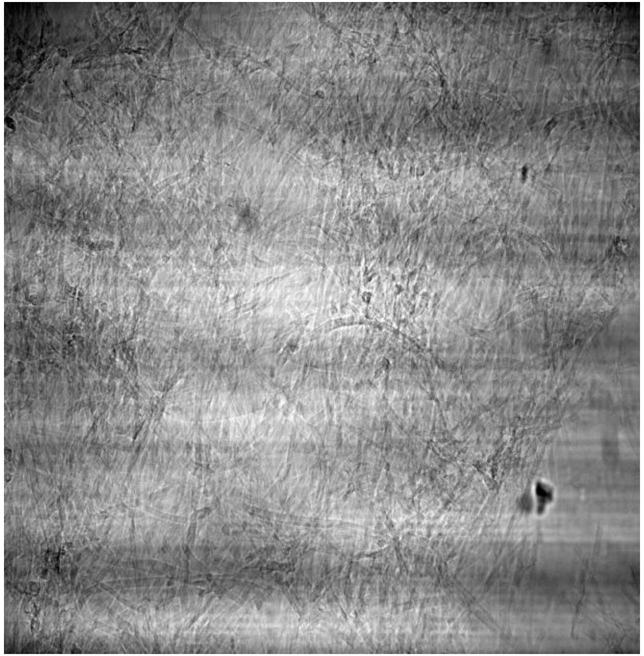
Use this series of images to "reconstruct" the 3D object



Courtesy of D. Parkinson (ALS)

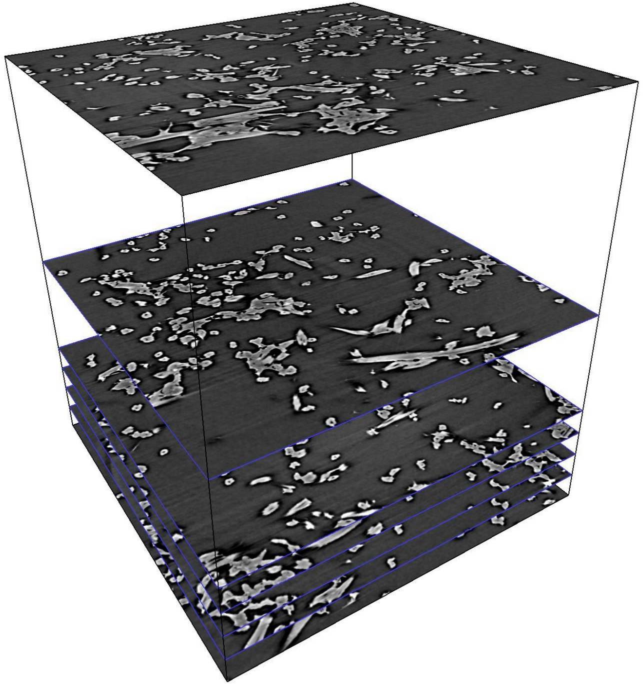
X-ray micro-tomography

X – Ray Projections



Reconstruction
Software

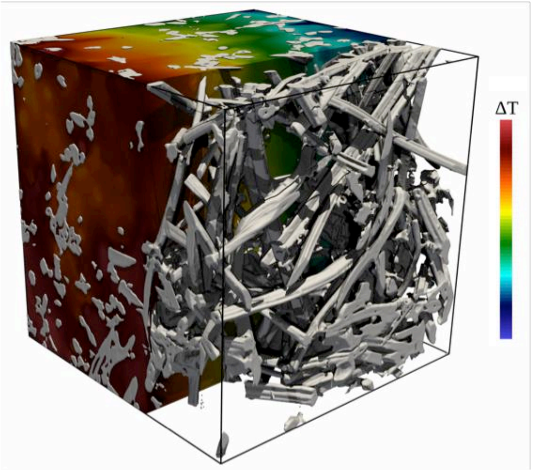
Reconstructed Image Stack



Characterize material micro-structure

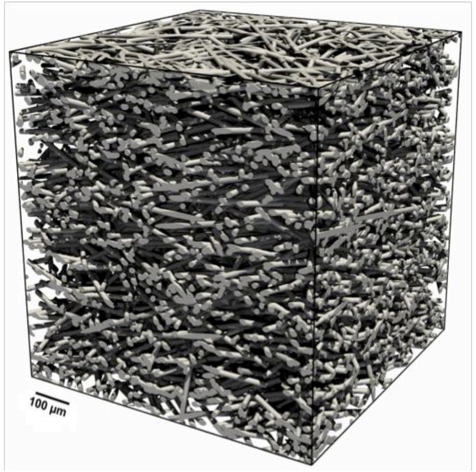
- Use of x-ray micro-tomography to characterize material micro-structure
- Determination of physical properties such as pore size, fiber diameter

Determine effective material properties and response



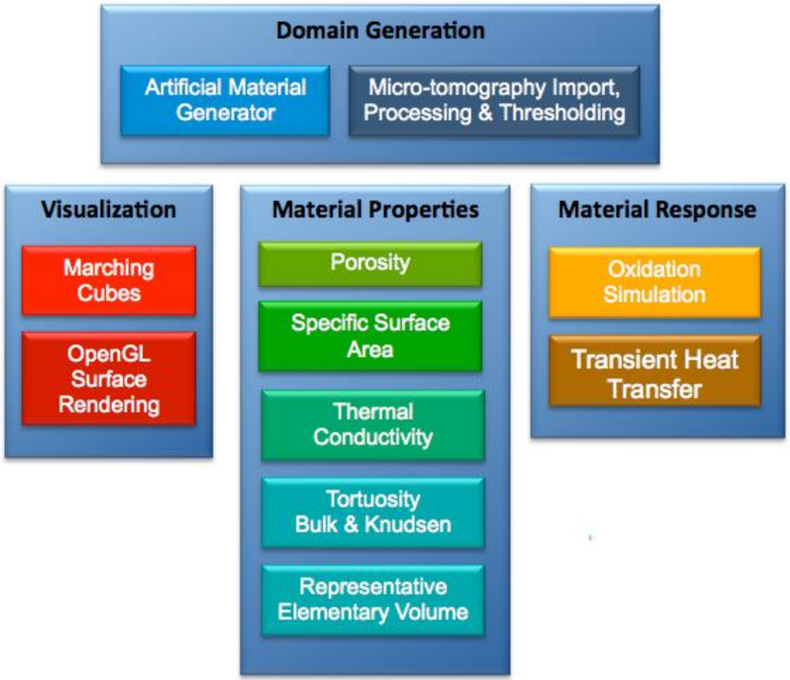
- Determination of material properties and response based on micro-structure
- Porosity, specific surface area, thermal conductivity, permeability, tortuosity

Material design from micro-structure



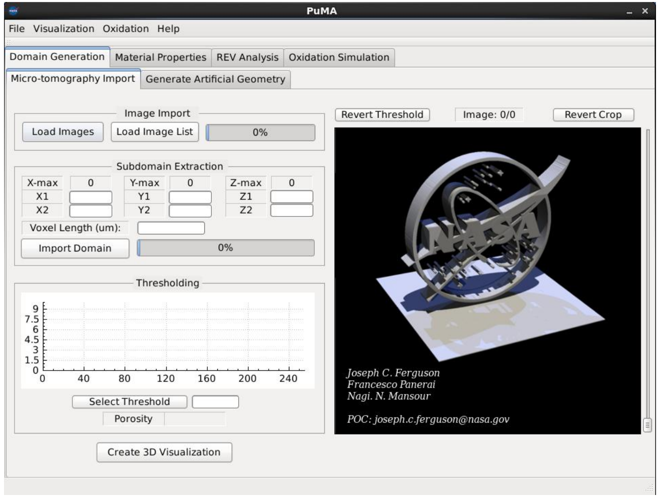
- Generation of artificial micro-structures
- Goal of fine-tuning material characteristics to meet design requirements

Porous Materials Analysis (PuMA)



Technical Specifications

- Written in C++
- GUI built on QT
- Visualization module based on OpenGL
- Parallelized using OpenMP for shared memory systems



Effective Material Properties

Porosity

- Based on the grayscale threshold
- Sum of all void voxels over the total volume

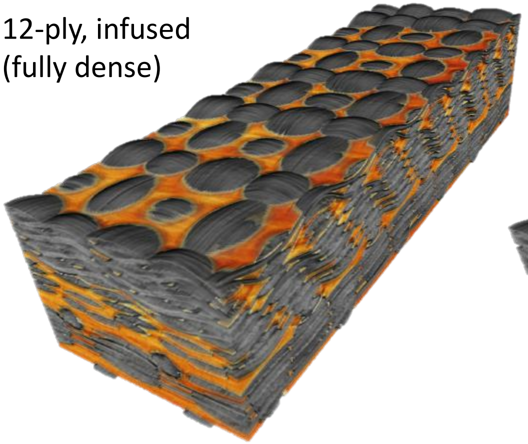
Specific Surface Area

- Based on the Marching Cubes algorithm
- Overall surface area computed as a sum of individual triangle areas

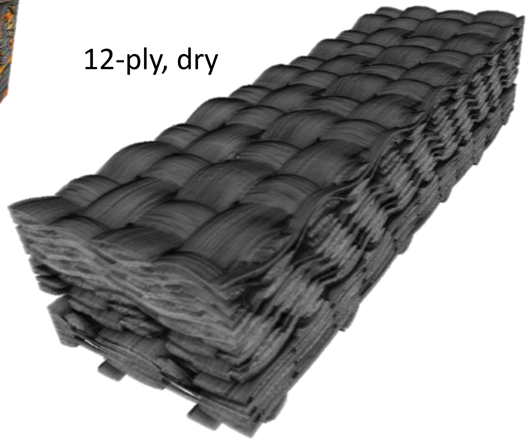
Effective Thermal Conducitivity

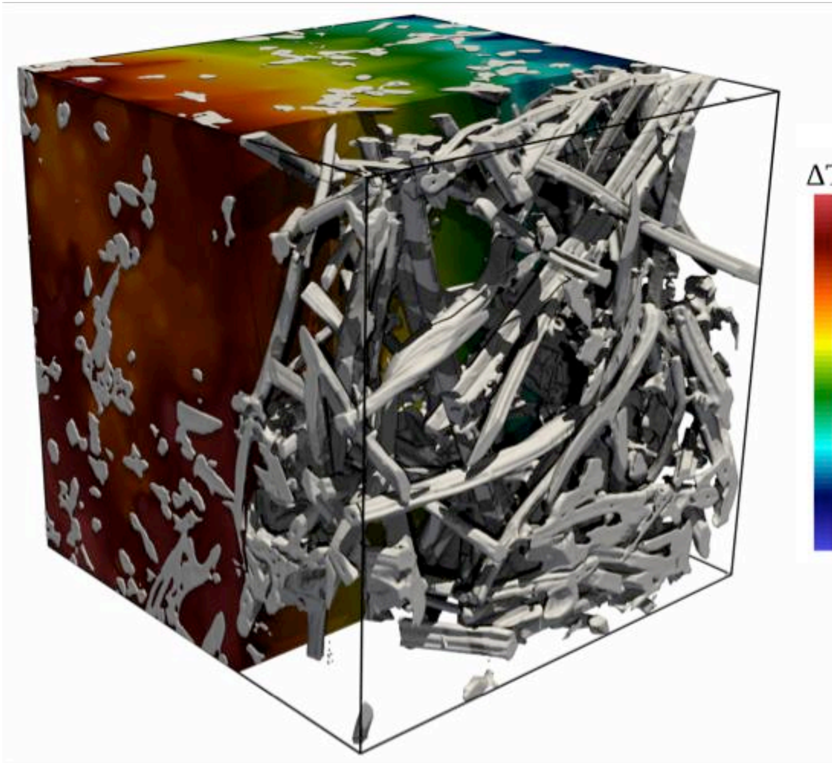
- Computes effective thermal conductivity using a finite difference method [Weigmann, 2006]
- BicGStab iterative method and FFTW used to solve linear system of equations [Sleijpen, 1993]
- Parallelized based on OpenMP
- Verified against complex analytical solutions

12-ply, infused (fully dense)



12-ply, dry





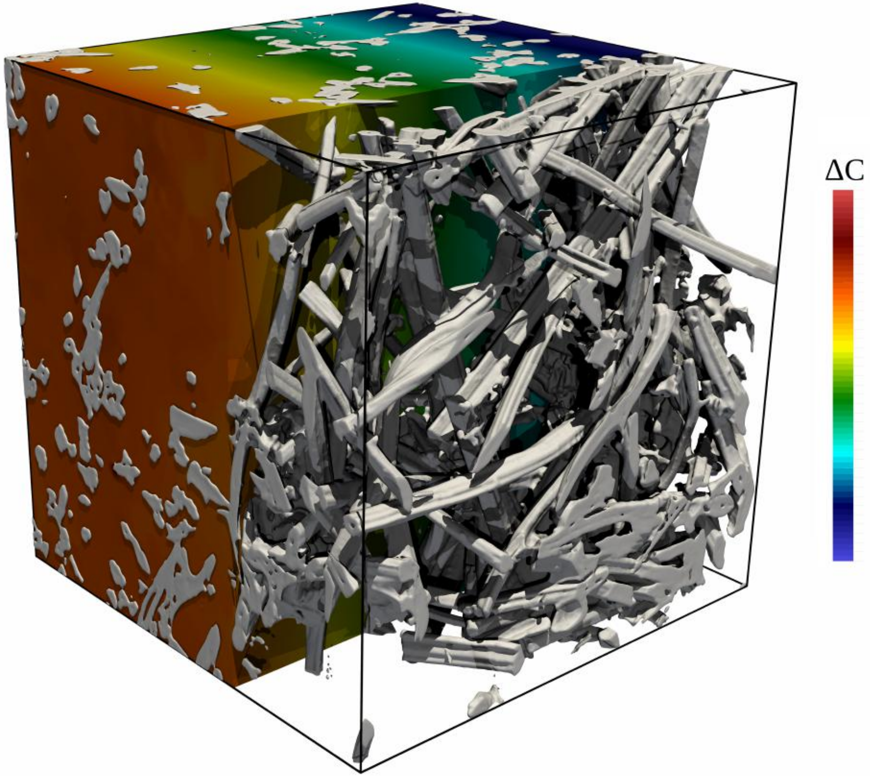
Diffusivity / Tortuoosity

Continuum

- Solves for effective diffusivity using a finite difference method

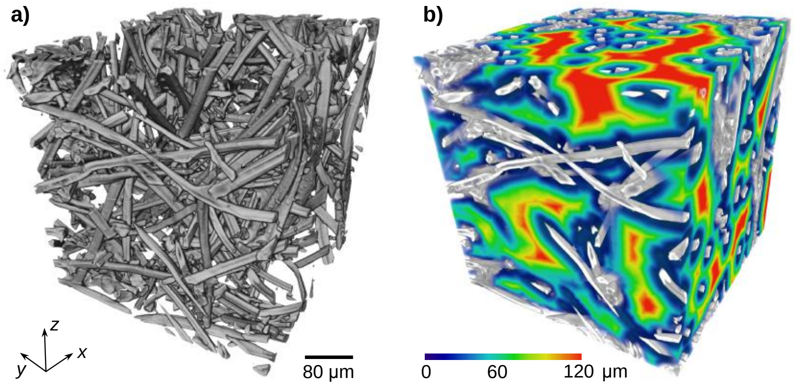
Transitional/Rarified

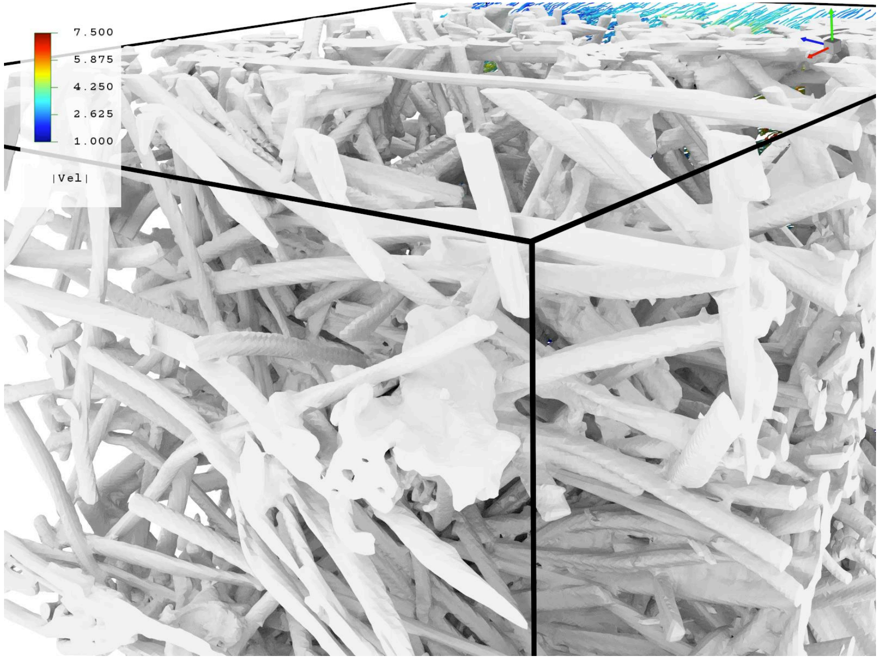
- Solves effective diffusivity through a random walk method
- Knudsen number is varied by changing molecular mean free path



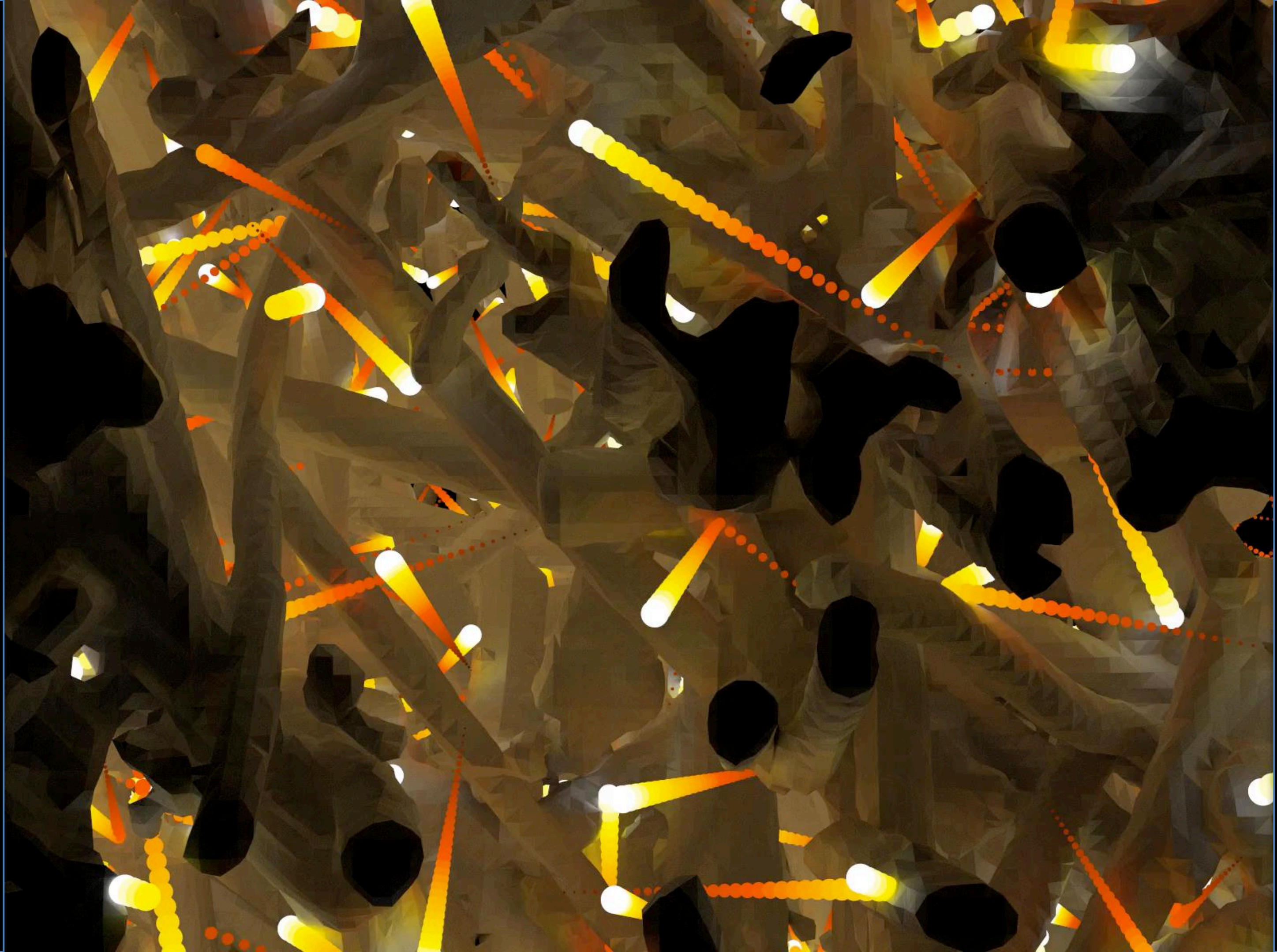
Permeability using DSMC

- Direct Simulation Monte Carlo (DSMC): probabilistic simulation method to solve the Boltzmann equation for finite Kn
- Simulates fluid flow using a particle-based approach with particle-particle and particle-surface interactions
- Ability to solve chemically reacting flows at high Knudsen numbers (where typical CFD is no longer valid)
- DSMC code: SPARTA (Sandia)



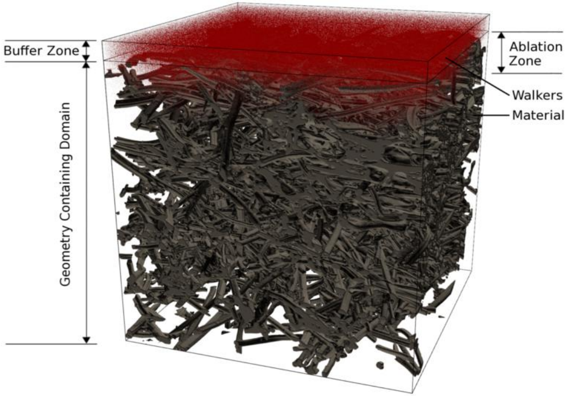


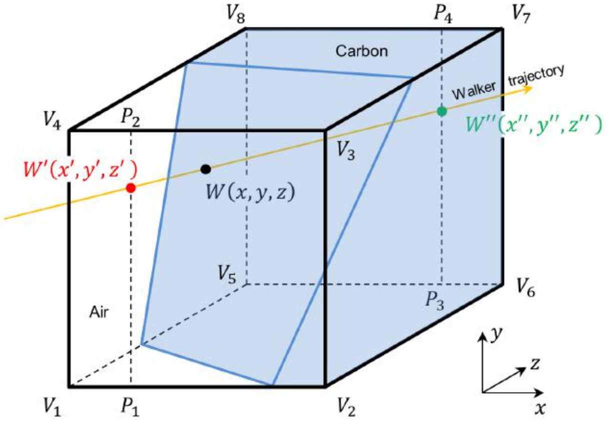
Borner et al., *Int J Heat Mass Transfer* (2016), in press



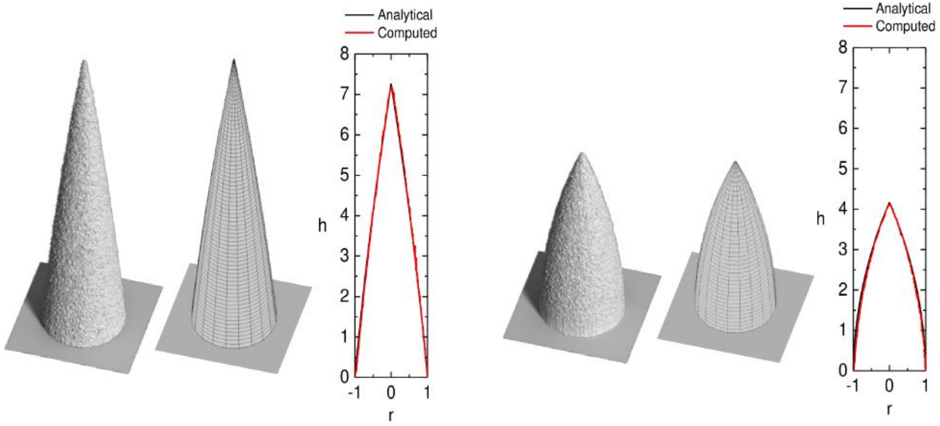
Micro-Scale Oxidation Simulations

- Particle-based oxidation method
- Diffusion simulated through random walks
- Collision detection with linear interpolation method
- Sticking probability method for material recession
- Verified against analytical solutions for single fiber

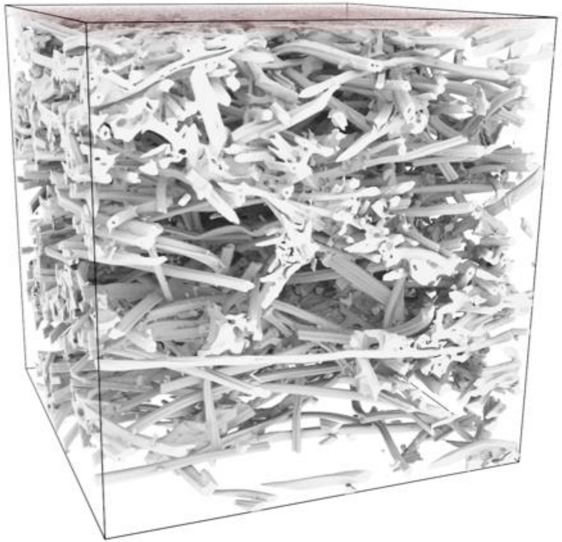


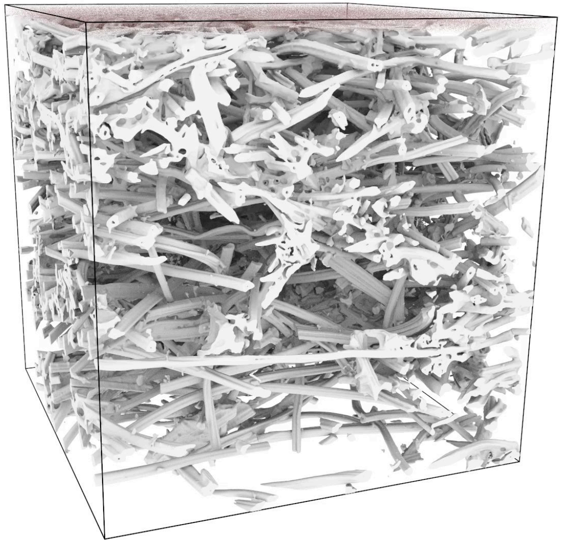


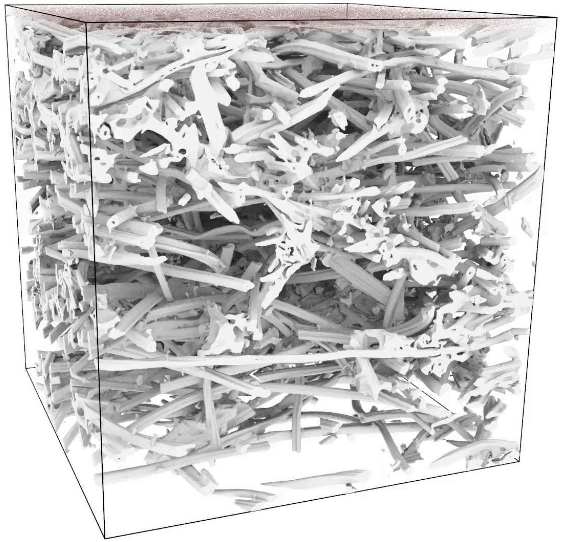
Ferguson et al., *Carbon* 96 (2016), 57-65



Micro-Scale Oxidation Simulations



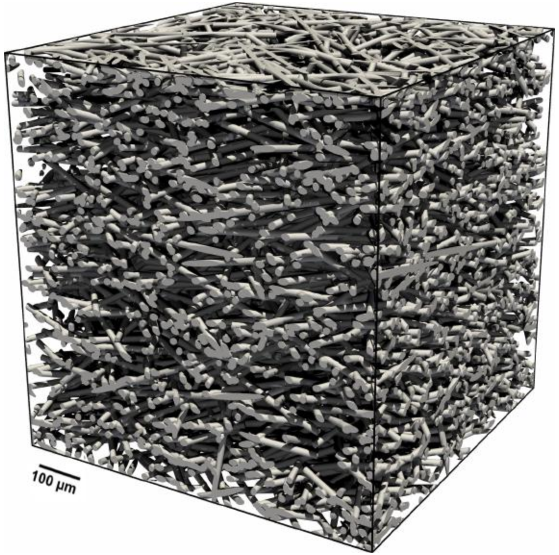




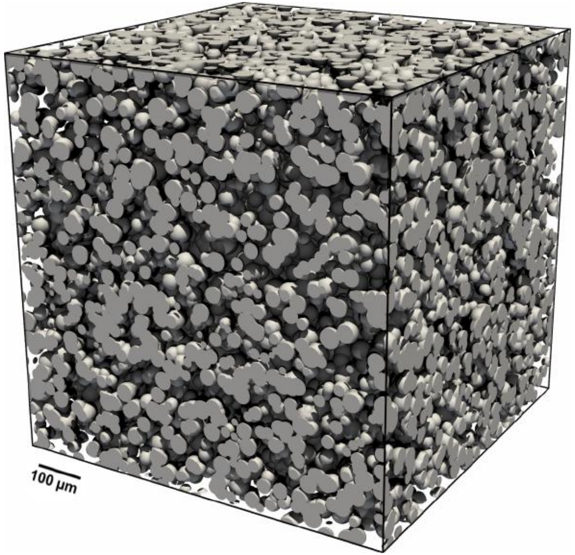
Ferguson et al., *Carbon* 96 (2016), 57-65

Material Generation

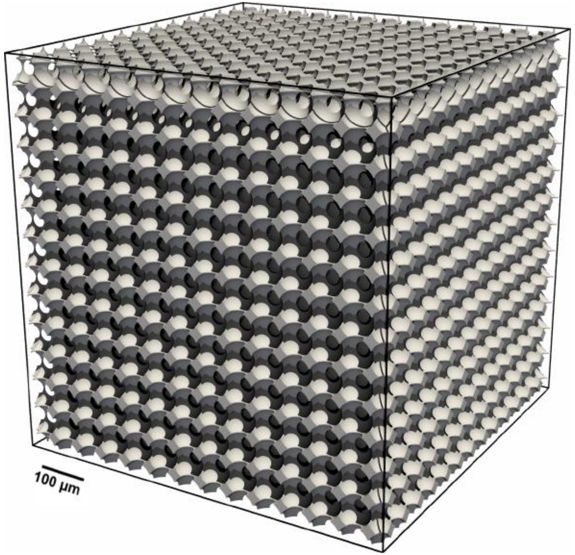
Random Fiber Structures



Packed Sphere Beds

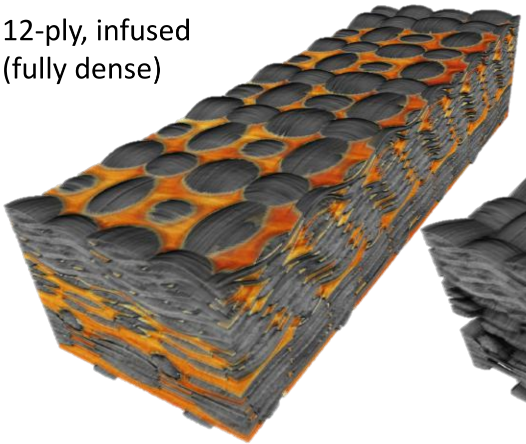


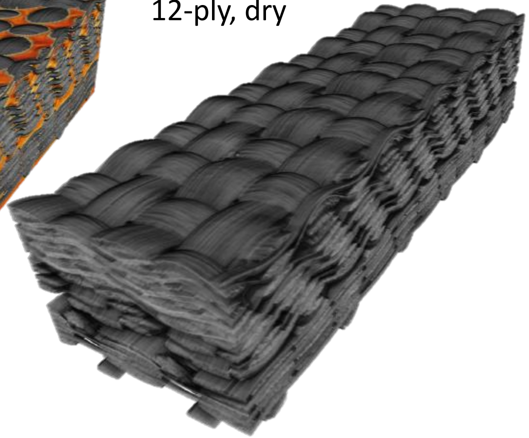
Periodic Foams

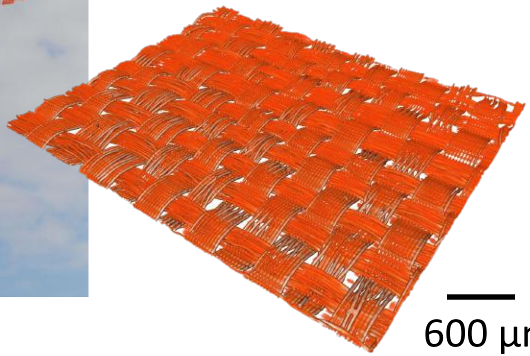


Conclusion and Outlook

- **Micro-tomography and simulations**
  - Help us developing TPS response modes
  - Enable predictive materials modeling
  - Support cheaper and faster material development
  - Impact not only Entry Descent Landing, but also other NASA’s grand challenges:







Acknowledgements

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