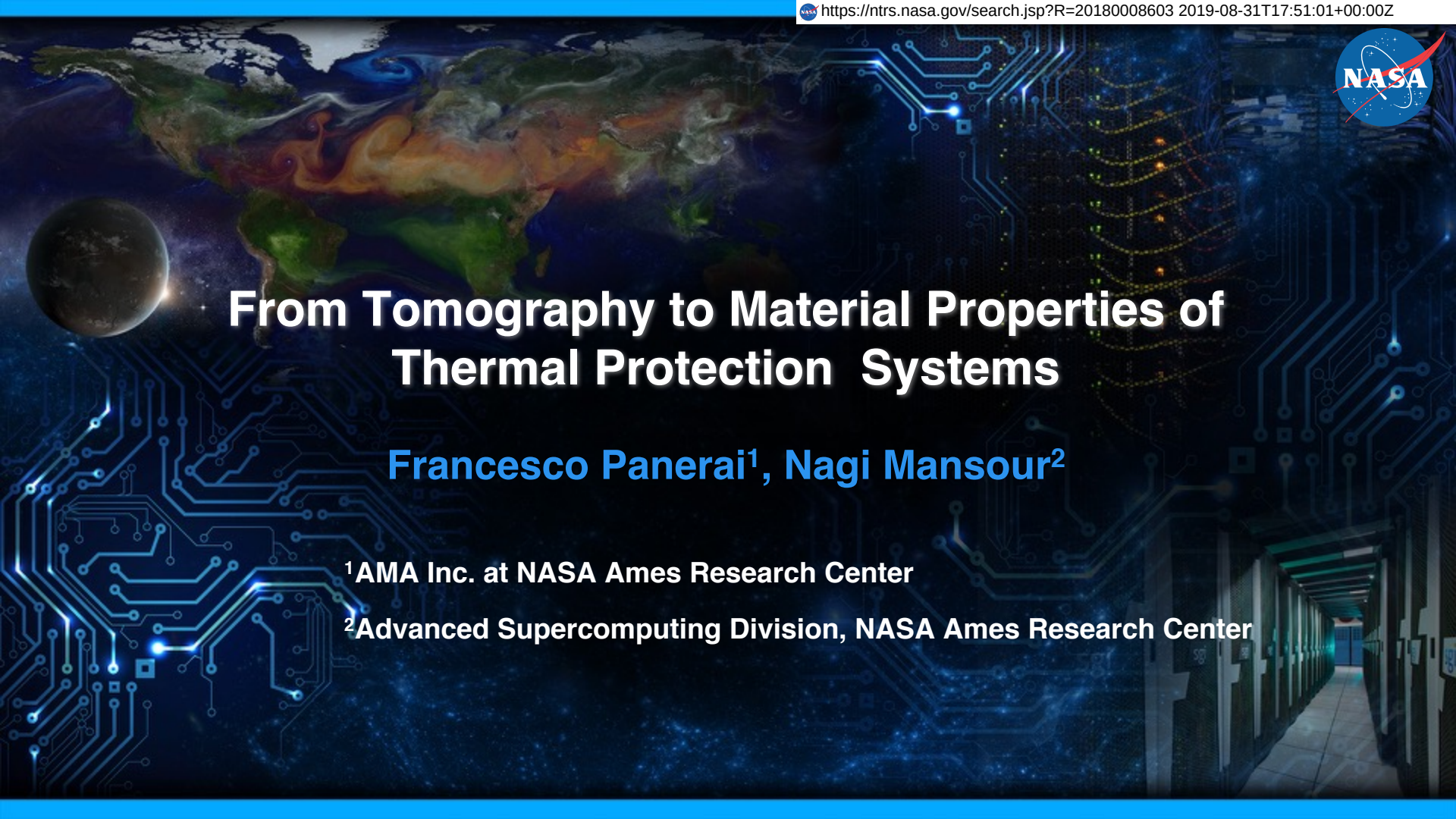


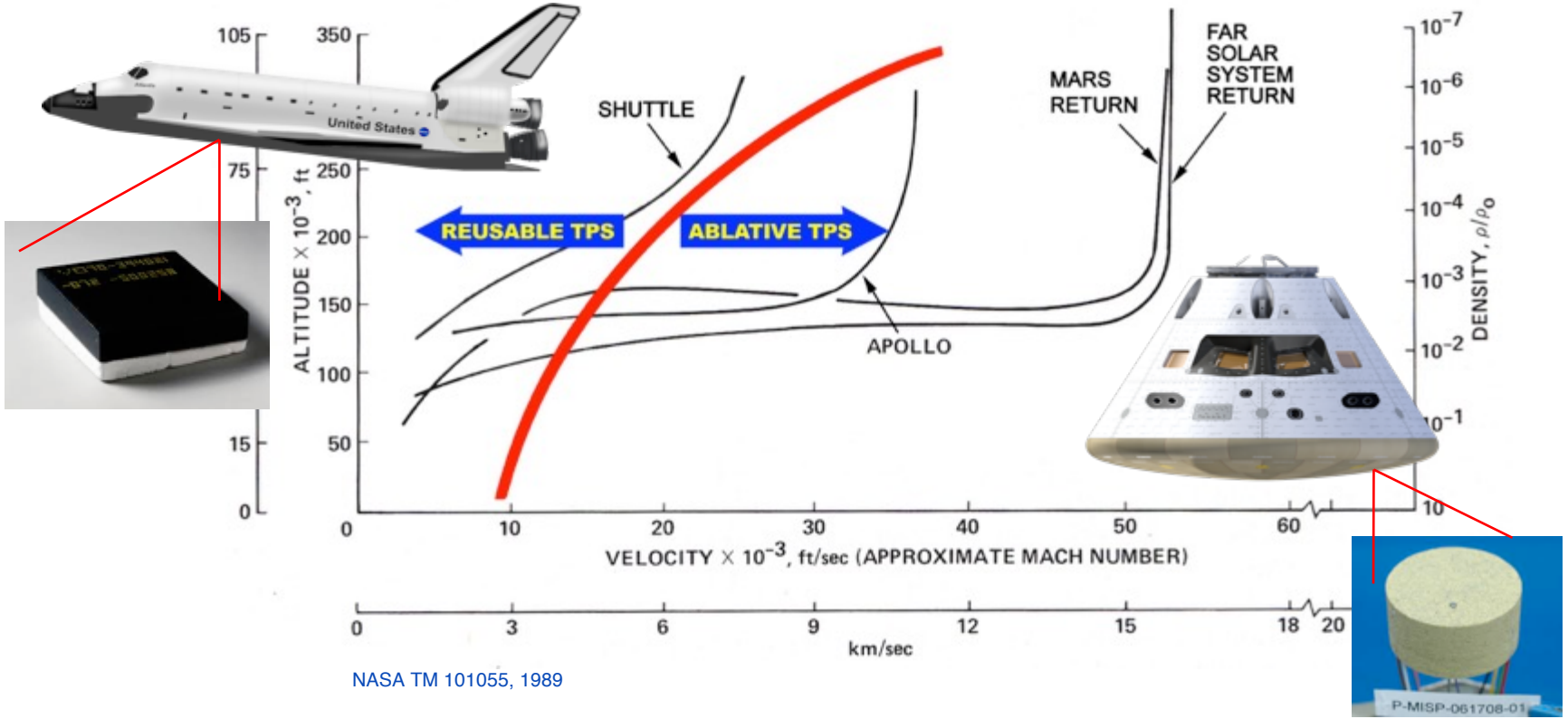
From Tomography to Material Properties of Thermal Protection Systems

Francesco Panerai[1], Nagi Mansour[2]

[1]AMA Inc. at NASA Ames Research Center

[2]Advanced Supercomputing Division, NASA Ames Research Center

Thermal Protection Systems



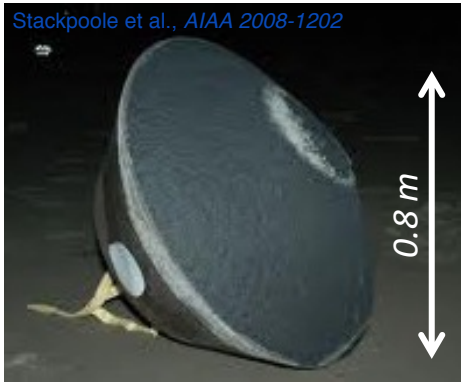
NASA TM 101055, 1989

Phenolic Impregnated Carbon Ablator (PICA)

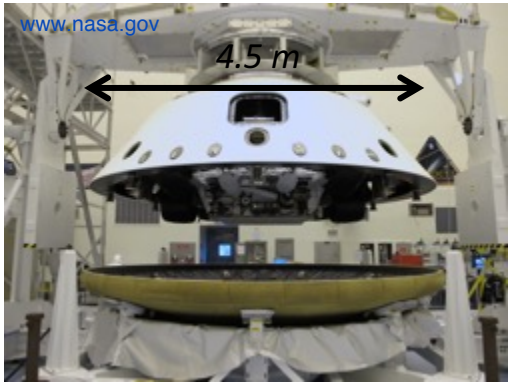
A successful lightweight material for planetary entry

Carbon fibers + Resin = PICA

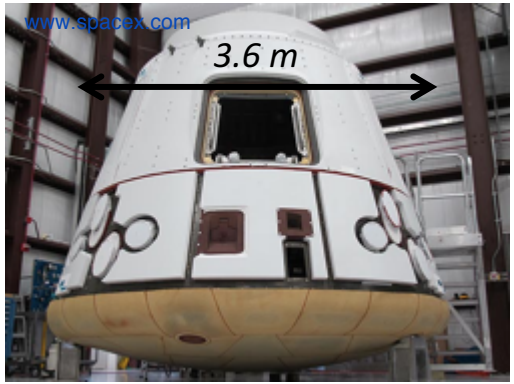
Courtesy of M. Stackpoole (NASA)



Stardust, NASA

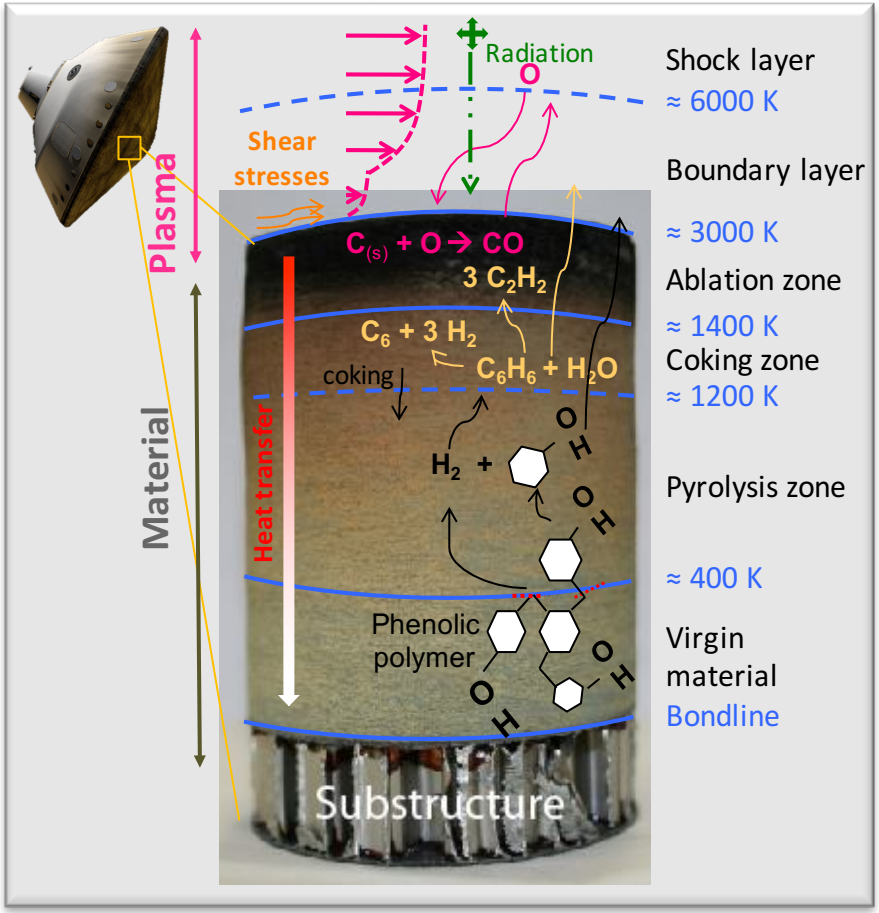


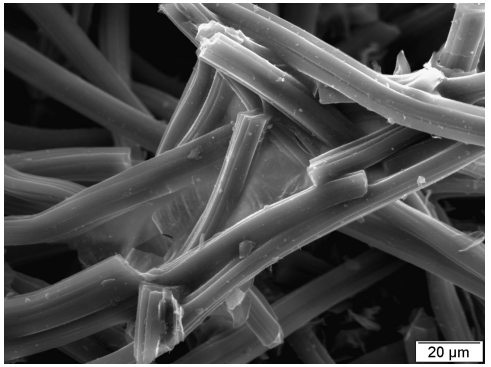
Mars Science Laboratory, NASA



Dragon, SpaceX

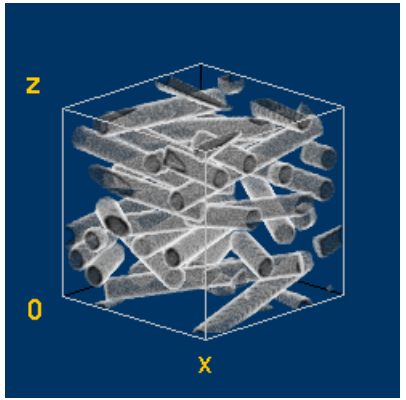
Objective: high-fidelity material models





Panerai et al., *J. Thermophys Heat Transfer* 28 (2014), 181-190

Micrograph of the real material

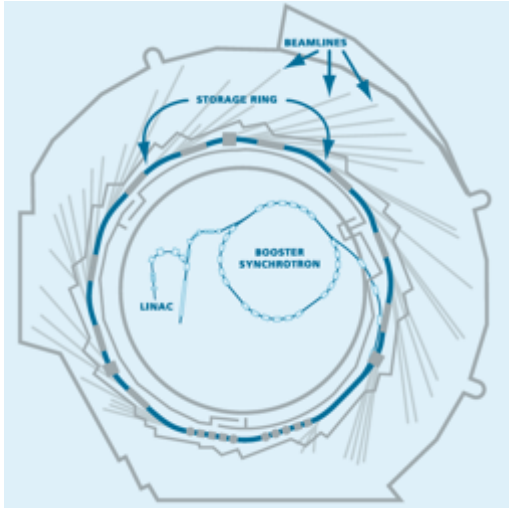


Lachaud and Mansour, *AIAA 2010-984*

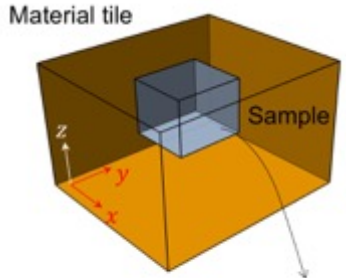
Digital material for simulation

A bright source of X-rays

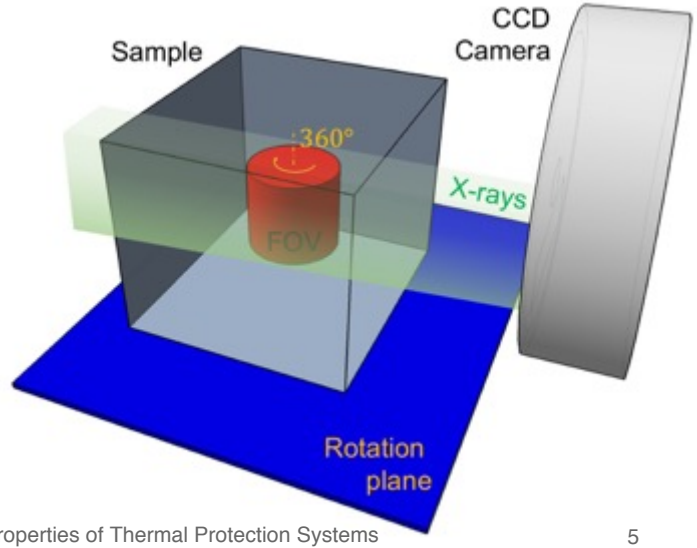
Courtesy of D. Parkinson (ALS)



The synchrotron Advanced Light Source (ALS)

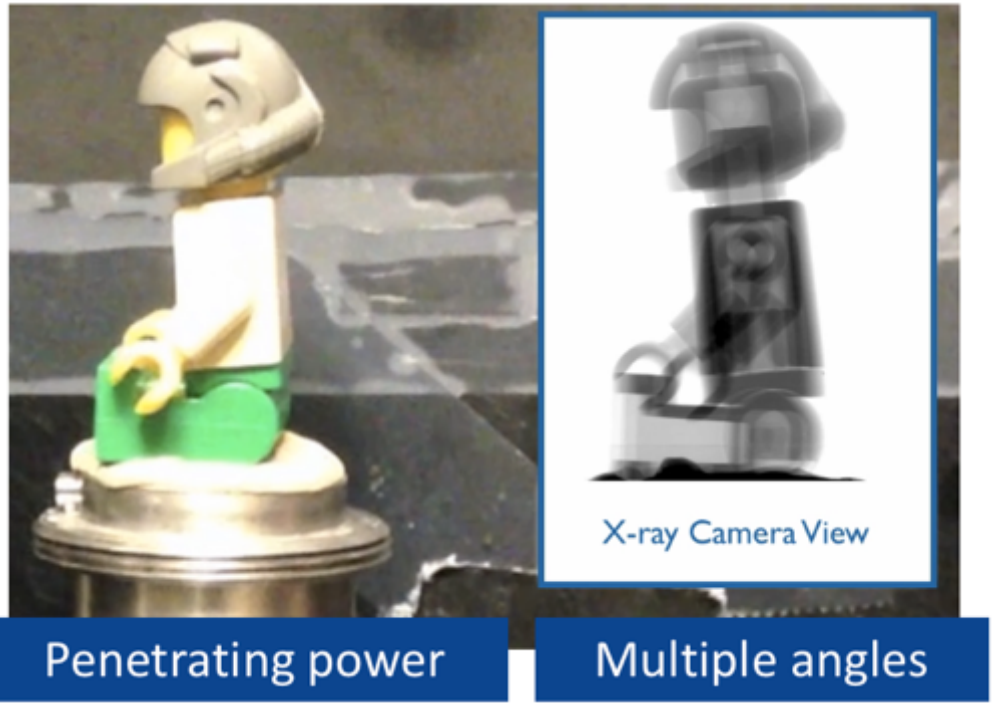


Micro-CT setup



X-ray tomography scan

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



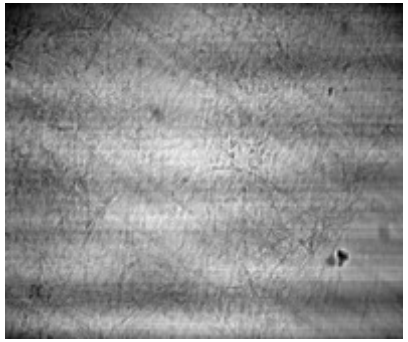
Use this series of images to "reconstruct" the 3D object

Courtesy of D. Parkinson (ALS)

This is a movie. Email: francesco.panerai@nasa.gov for info.

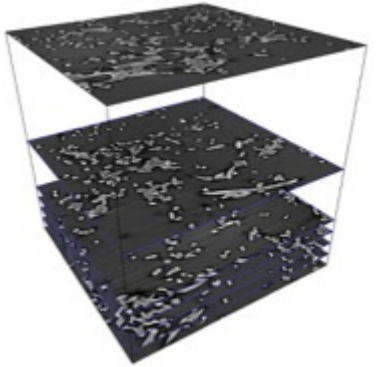
Tomography reconstruction

Material projection

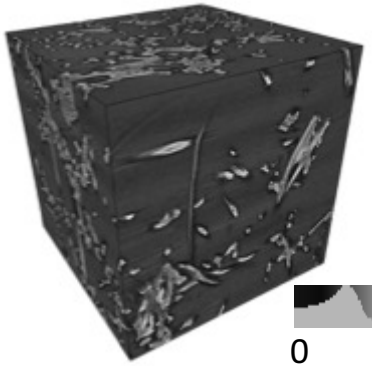


Artifacts removal and reconstruction

Reconstructed stack



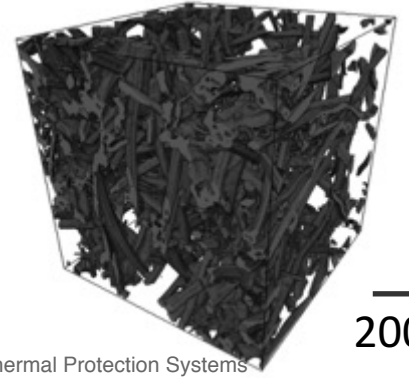
3D gray-value stack



0 255

Segmentation and filtering

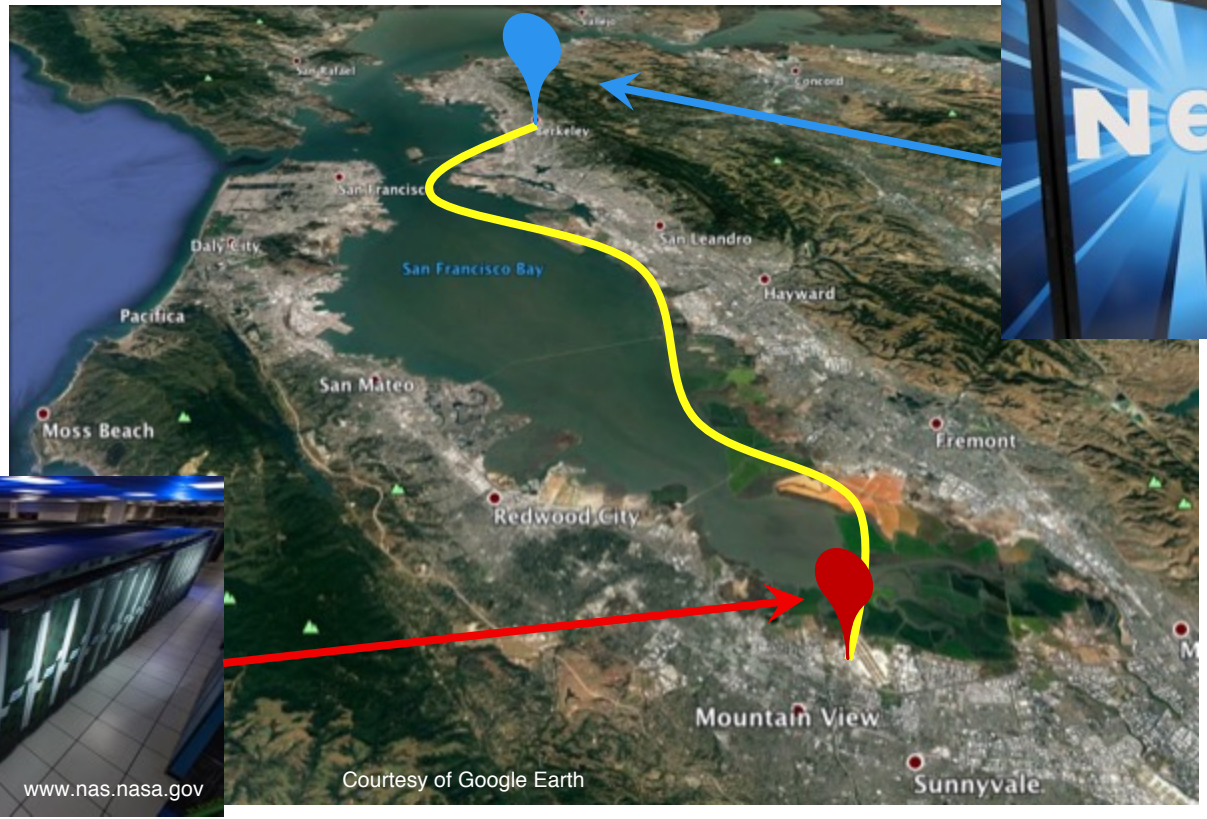
Visualization



200 µm

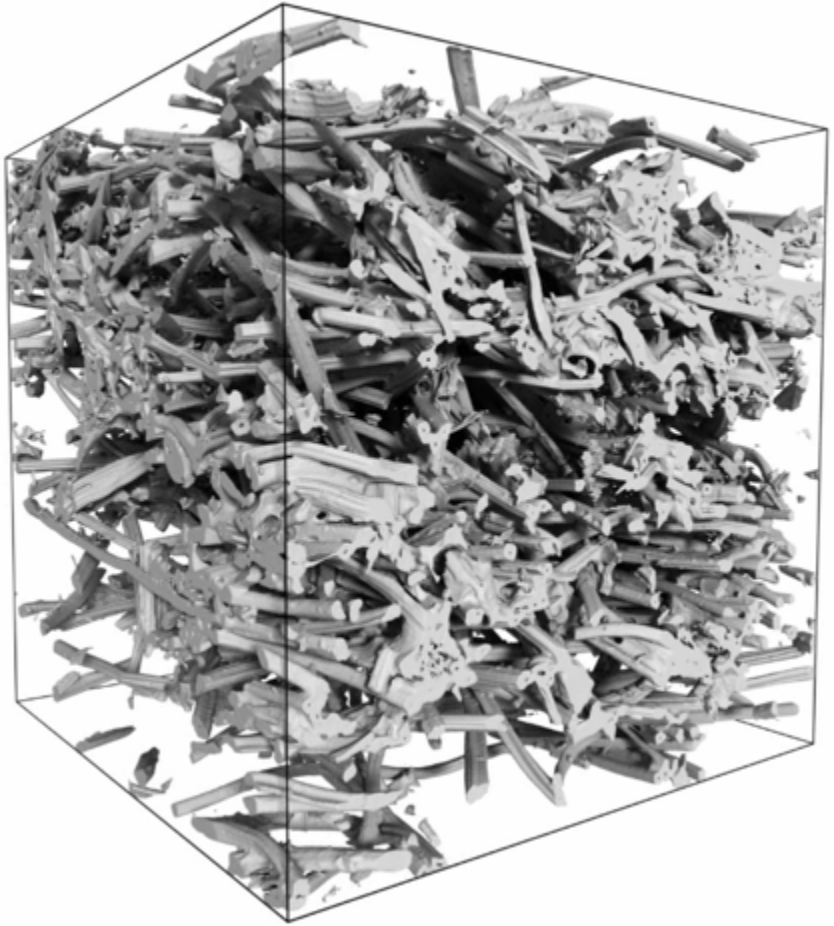
Panerai et al., *Int J Heat Mass Transfer* (2016)

Supercomputing is key



LBNL NERSC

NASA Pleiades



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Panerai et al., *Int J Heat Mass Transfer* (2016)

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Panerai et al., *Int J Heat Mass Transfer* (2016)

Porous Materials Analysis (PuMA)

Domain Generation

- Artificial Material Generator
- Micro-tomography Import, Processing, and Thresholding

Visualization

- Marching Cubes
- OpenGL Surface Rendering

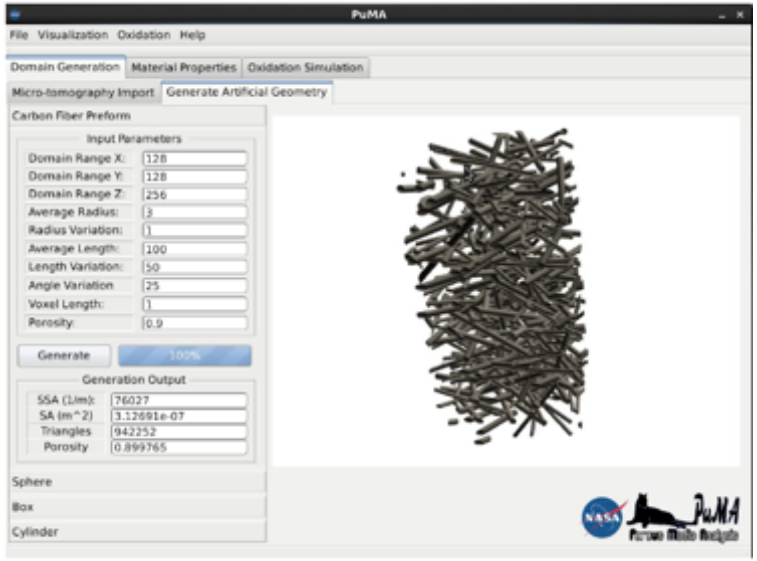
Material Properties

- Porosity
- Specific Surface Area
- Thermal Conductivity
- Tortuosity*

Material Response

- Oxidation Simulation
- Transient Heat Transfer*

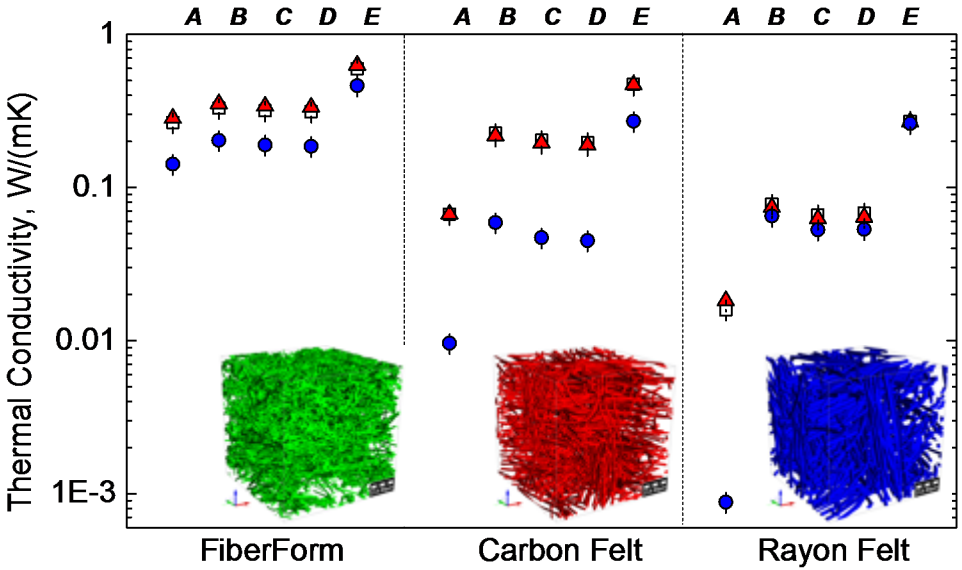
*Under Development



This is a movie. Email: francesco.panerai@nasa.gov for info.

Effective thermal conductivity

- Solve Fourier equation with finite difference method and periodic BCs
- Compute conductivity tensor as a function of constituting phases



□ *x* △ *y* ● *z*

Case ***A***: void, 293 K

Case ***B***: air, 293 K, 1 atm

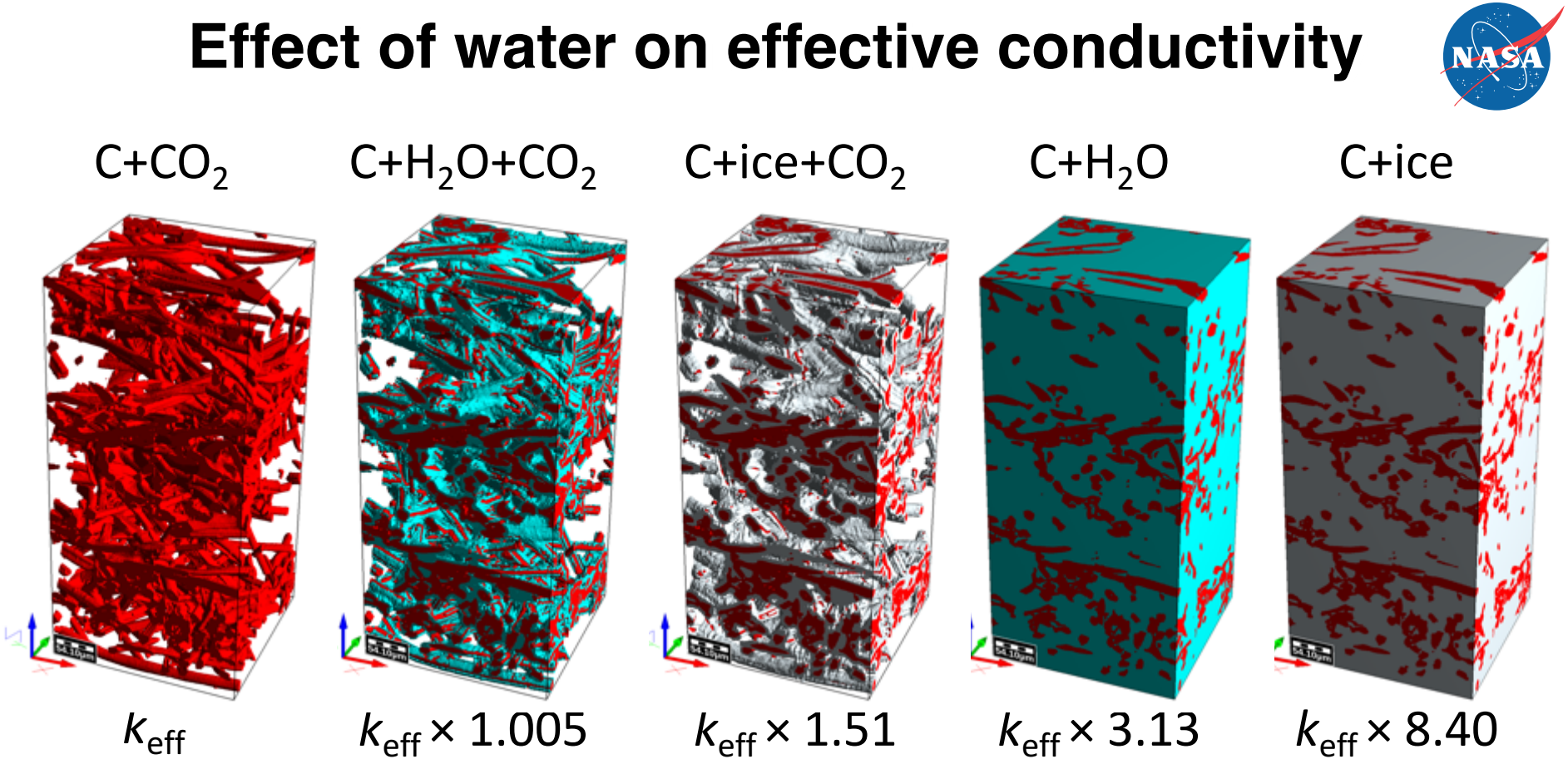
Case ***C***: CO_2, 293 K, 1 atm

Case ***D***: CO_2, 273 K, 0.01 atm

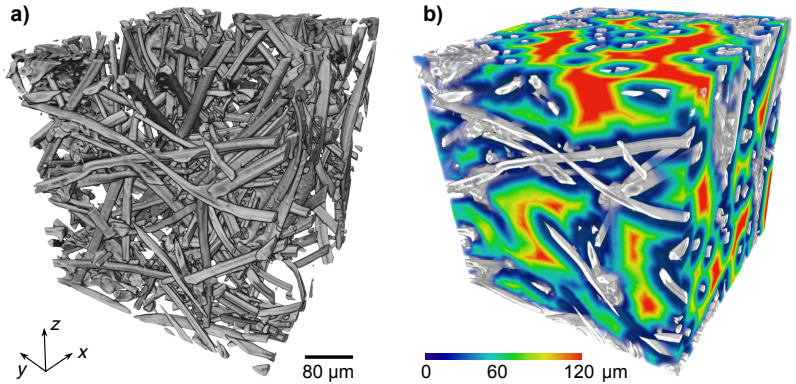
Case ***E***: H_2, 273 K, 0.01 atm

Panerai et al., *International Journal of Heat and Mass Transfer* (2016)

Effect of water on effective conductivity



Direct simulation Monte Carlo



- DSMC: probabilistic simulation method to solve the Boltzmann equation for finite Kn
- Particles motion and collisions are decoupled
- Uses cells and boundaries
- DSMC code: SPARTA (Sandia)

$$\mathrm{Kn} = \lambda / d_p$$

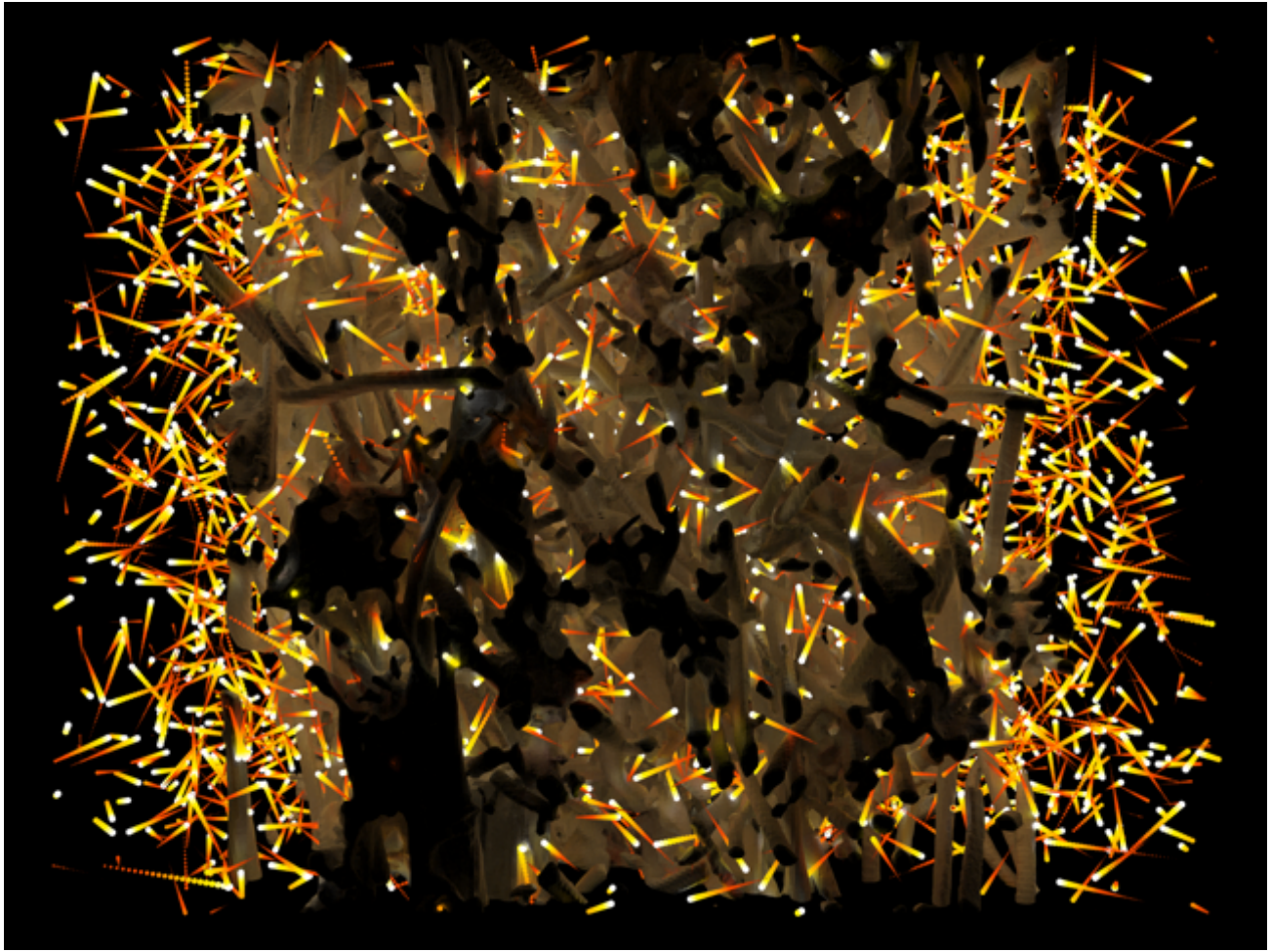
1-5 microns (high T, low P)

Kn = Knudsen number

λ = mean free path

d_p = mean pore diameter

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



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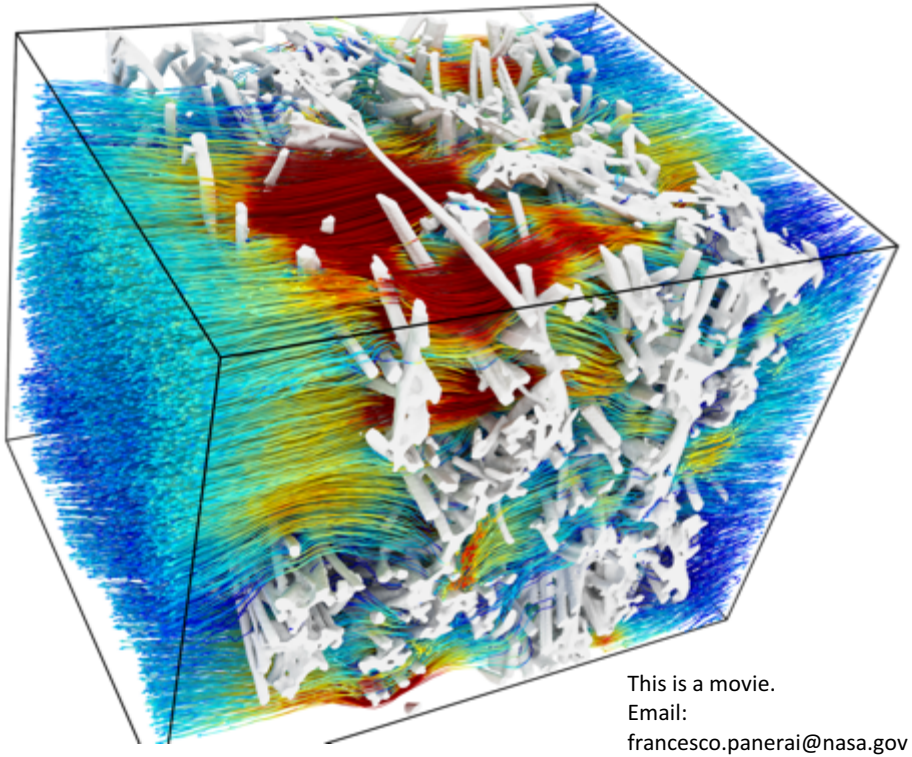
Porous media permeability



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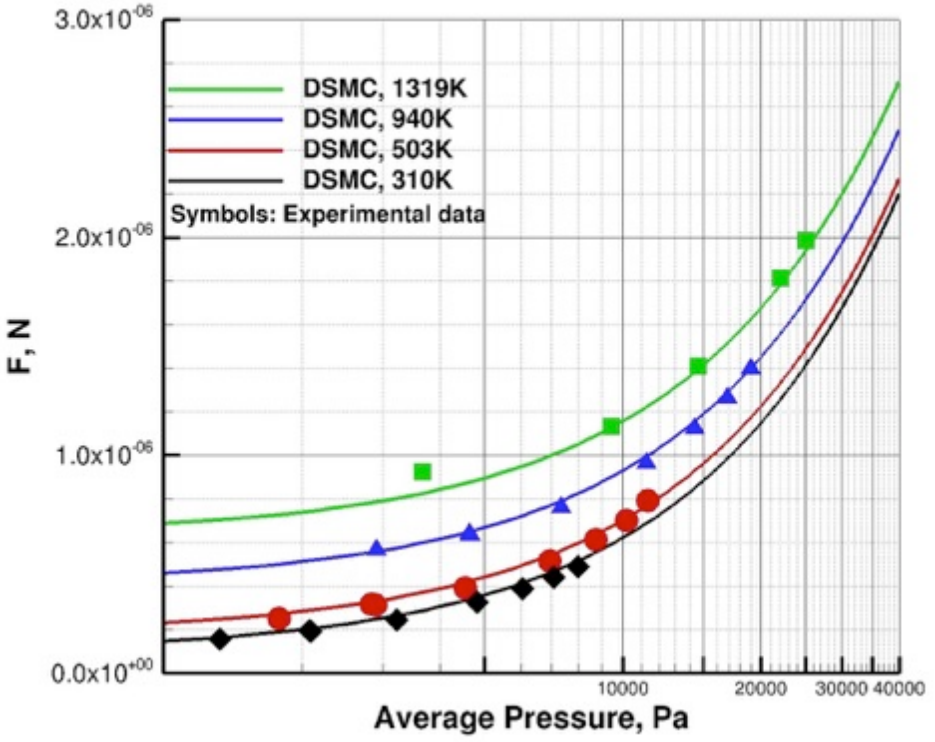
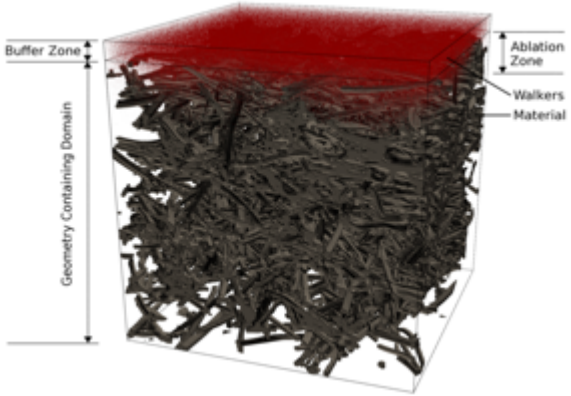
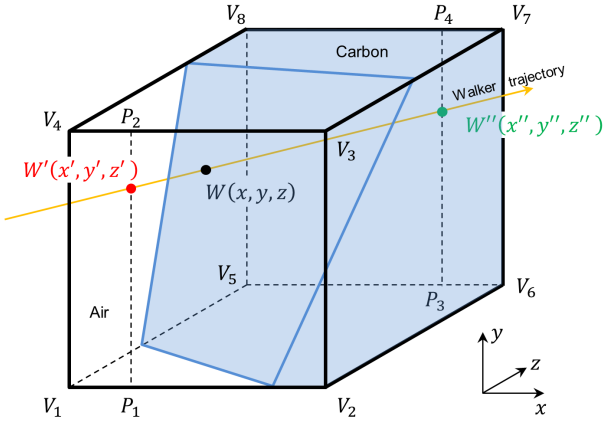


Panerai et al., *Int J Heat Mass Transfer* 101 (2016) 267–273
Borner et al., *Int J Heat Mass Transfer* (2016), in press

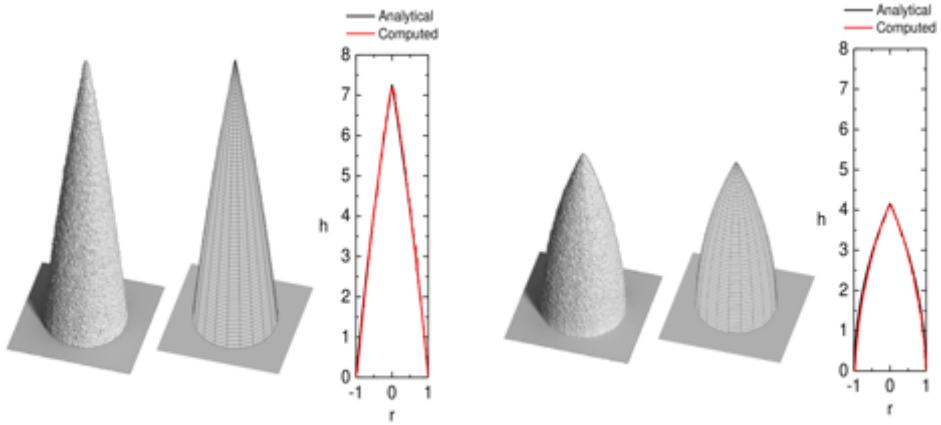
Carbon fibers oxidation simulations

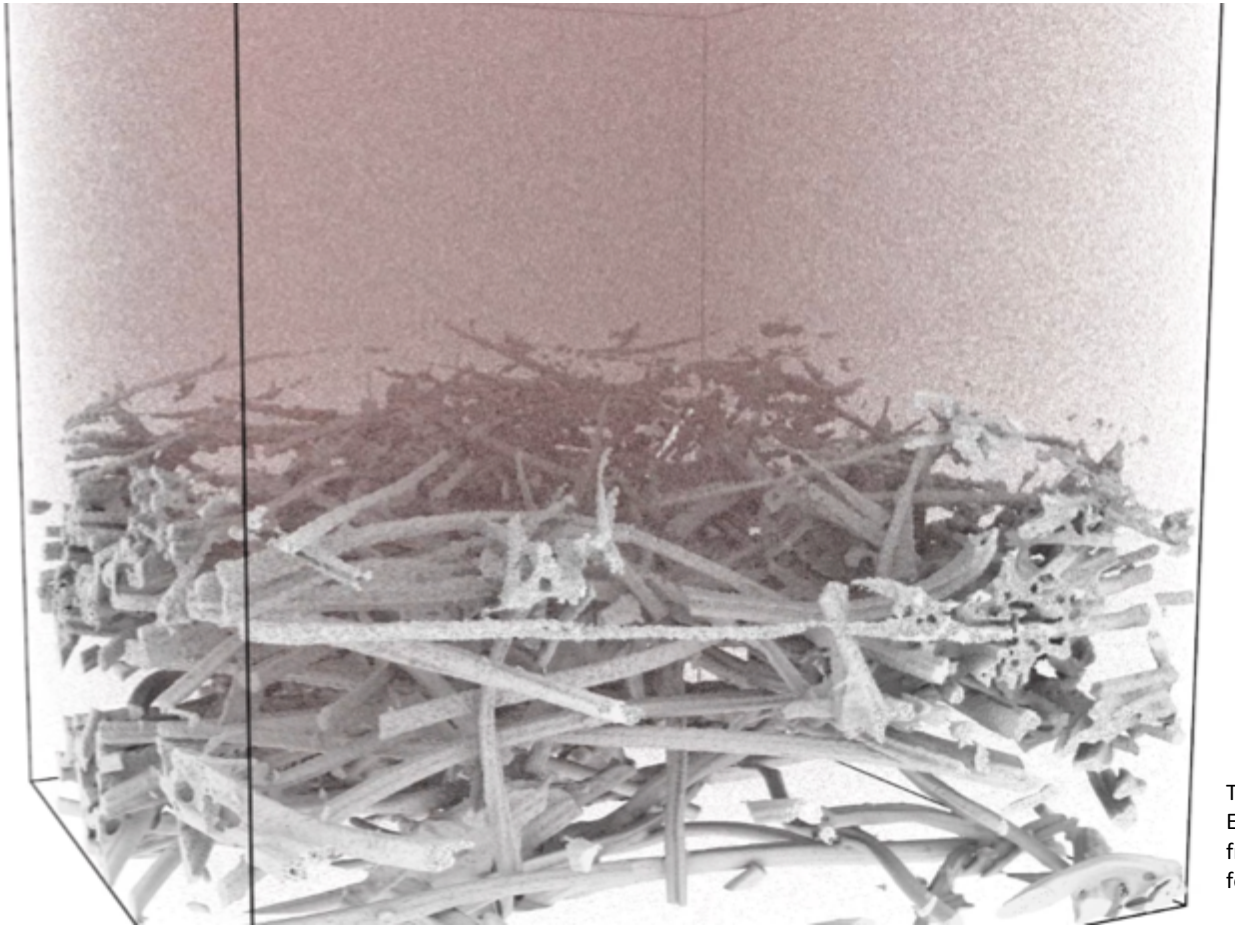
- Particle-based oxidation method
- Diffusion simulated through random walks
- Collision detection with linear interpolation method
- Sticking probability method for material recession
- Verified against analytical solutions for single fiber





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





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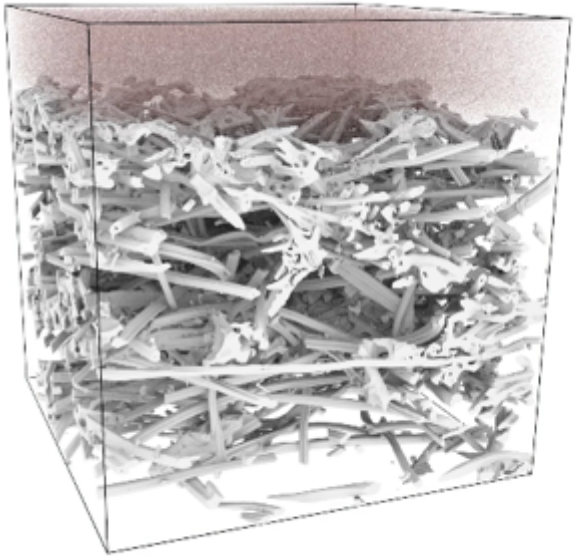
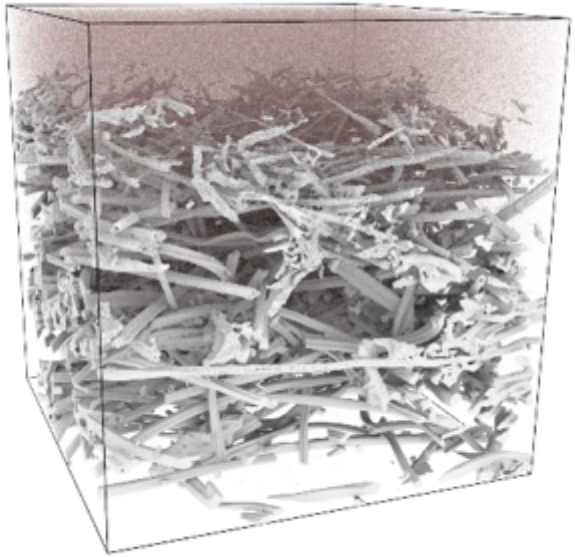
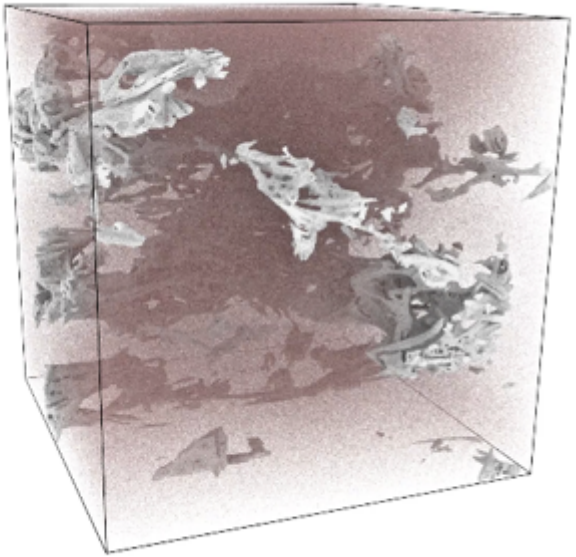
Ferguson et al., *Carbon* 96 (2016), 57-65







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

Concluding remarks

- **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: