



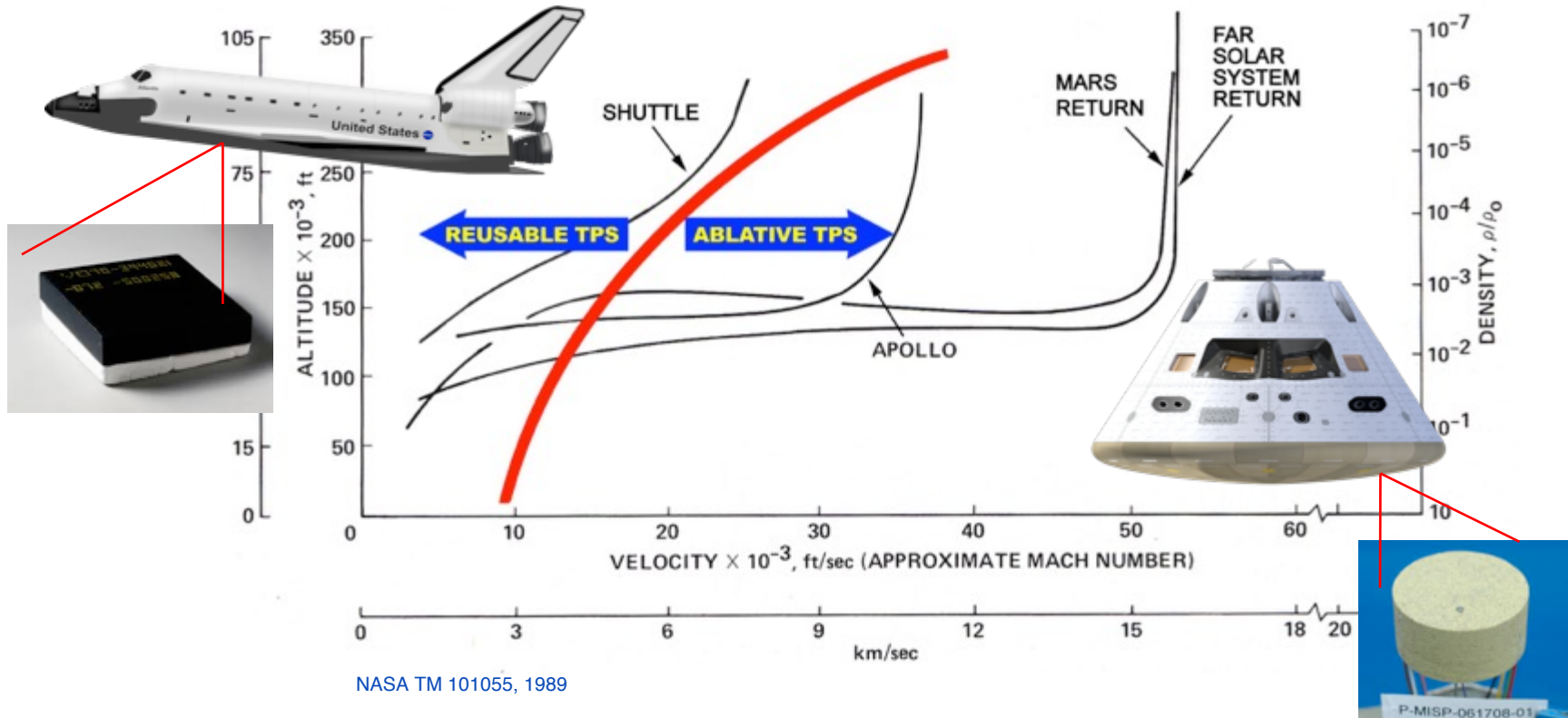
From Tomography to Material Properties of Thermal Protection Systems

Francesco Panerai¹, Nagi Mansour²

¹AMA Inc. at NASA Ames Research Center

²Advanced Supercomputing Division, NASA Ames Research Center

Thermal Protection Systems

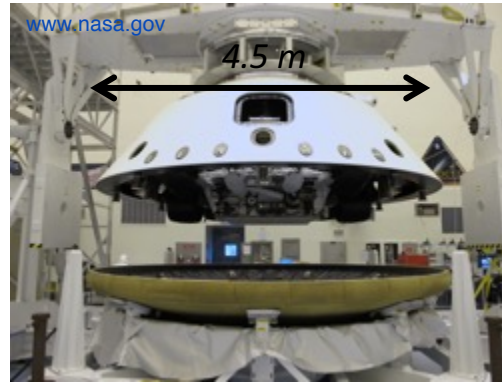


Phenolic Impregnated Carbon Ablator (PICA)

A successful lightweight material for planetary entry



Stardust, NASA

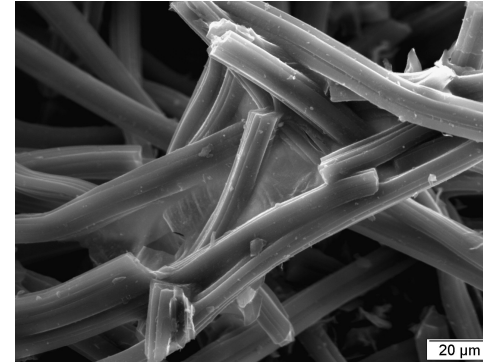
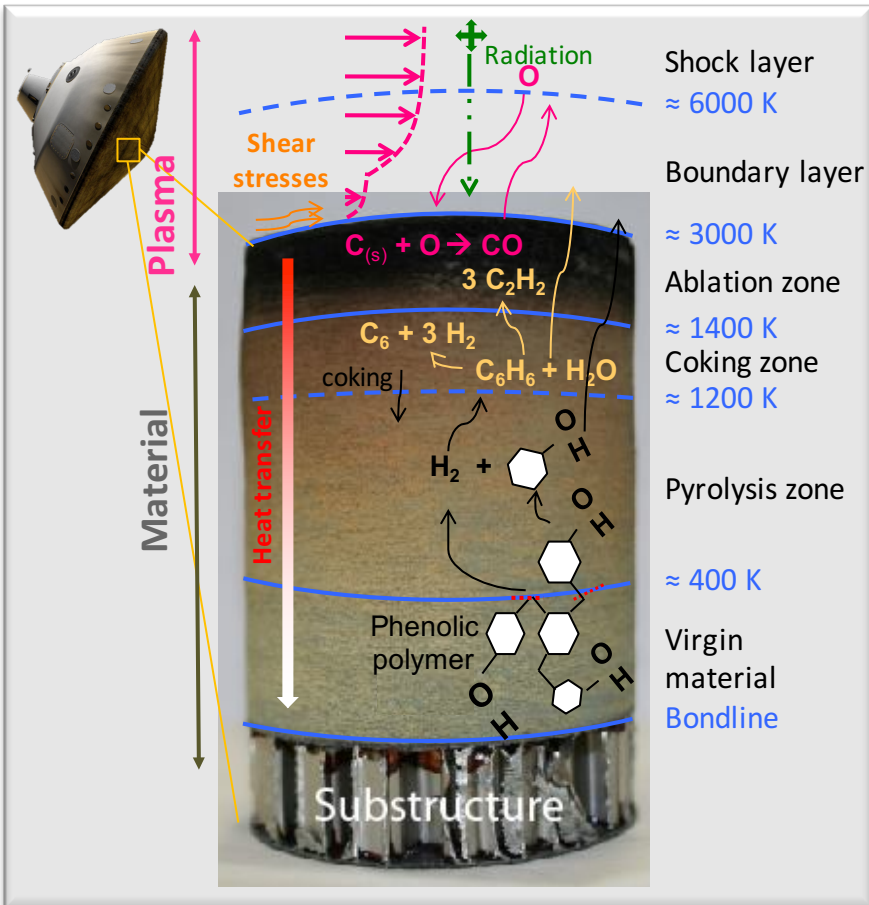


Mars Science Laboratory, NASA



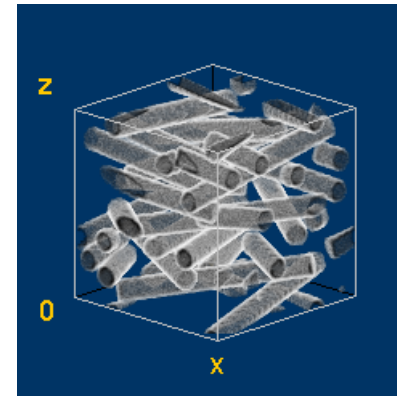
Dragon, SpaceX

Objective: high-fidelity material models



Micrograph of the real material

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



Digital material for simulation

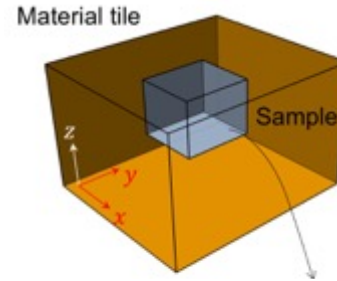
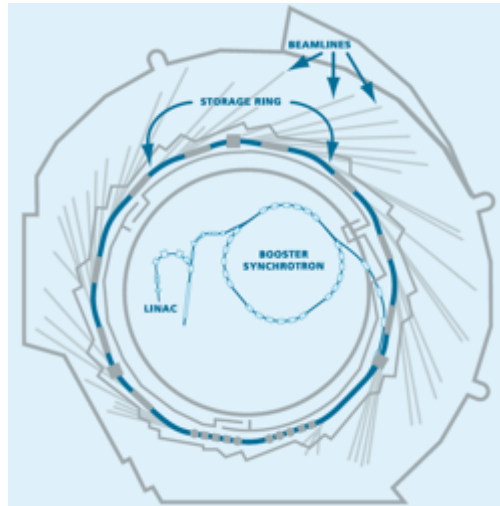
Lachaud and Mansour, *AIAA* 2010-984

A bright source of X-rays

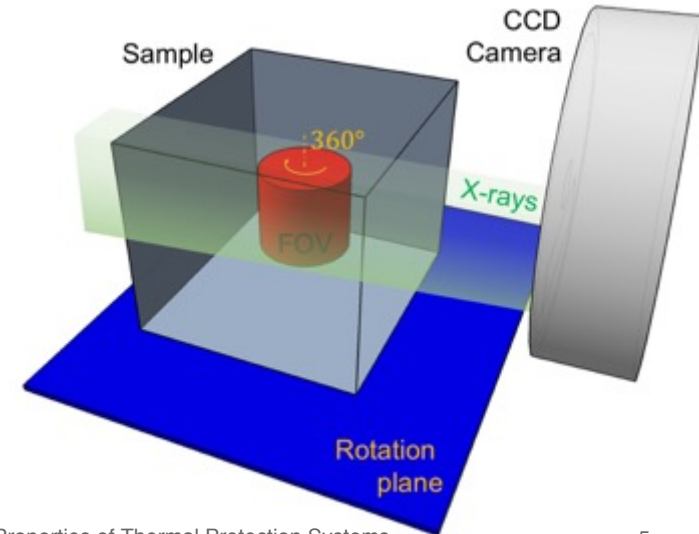


Courtesy of D. Parkinson (ALS)

The synchrotron
Advanced Light
Source (ALS)



Micro-CT
setup



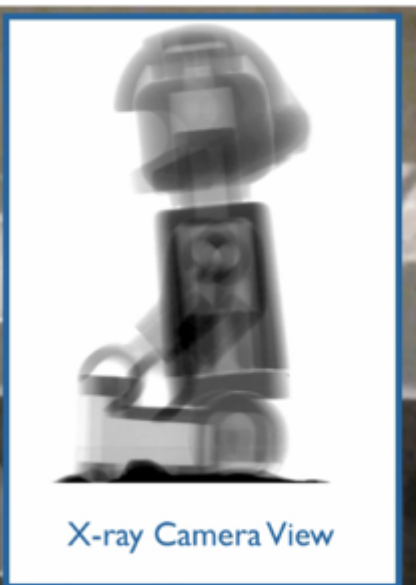
X-ray tomography scan

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

Use this series of images to “reconstruct” the 3D object



Penetrating power



Multiple angles



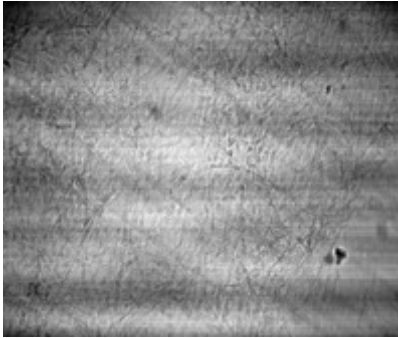
Courtesy of D. Parkinson (ALS)

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

Tomography reconstruction



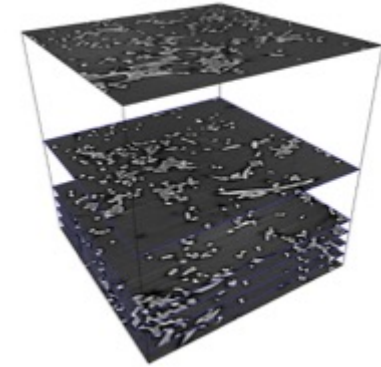
Material projection



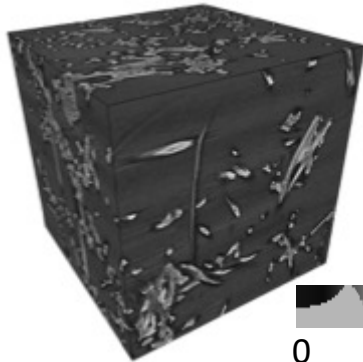
Artifacts removal
and reconstruction



Reconstructed stack



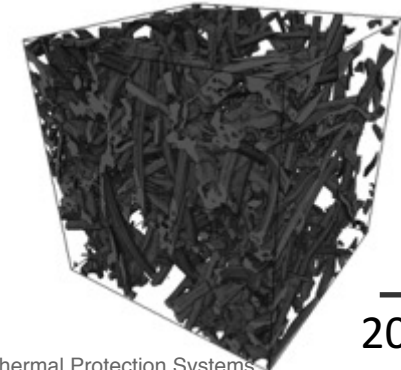
3D gray-value stack



Segmentation
and filtering



Visualization



0

255

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

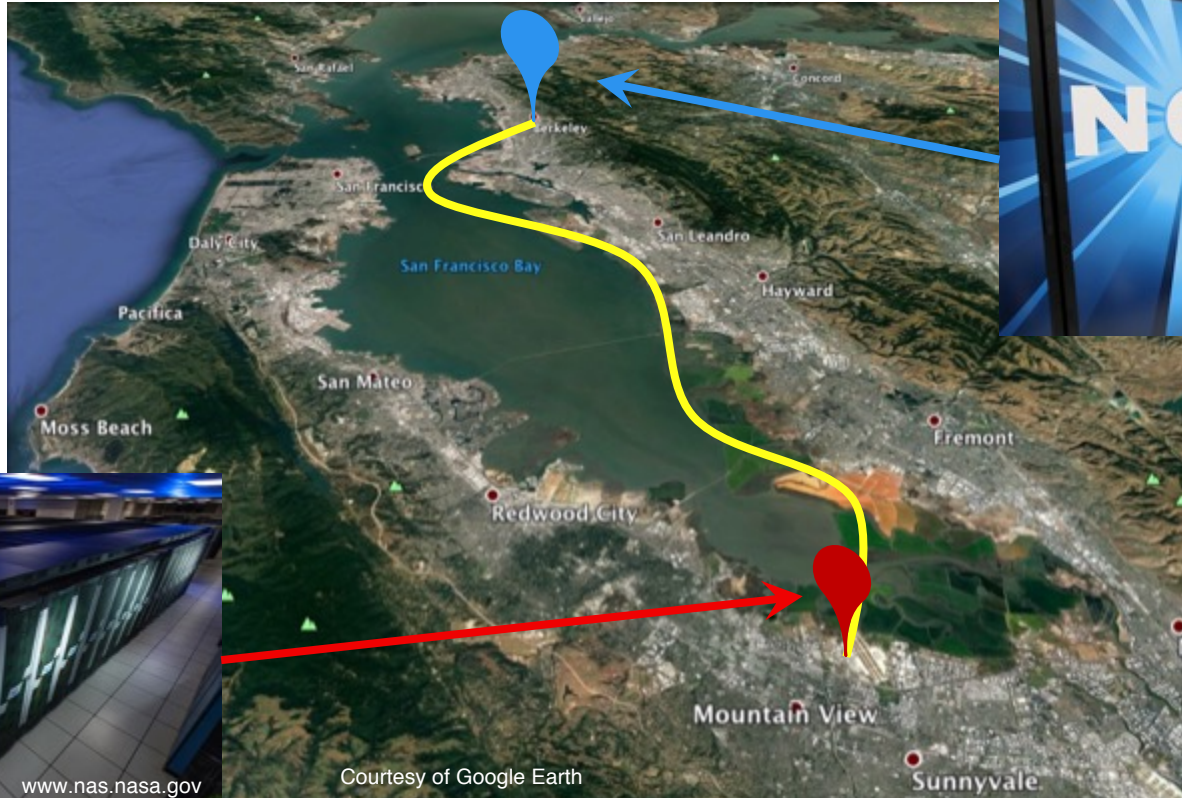
From Tomography to Material Properties of Thermal Protection Systems

200 μm

Supercomputing is key



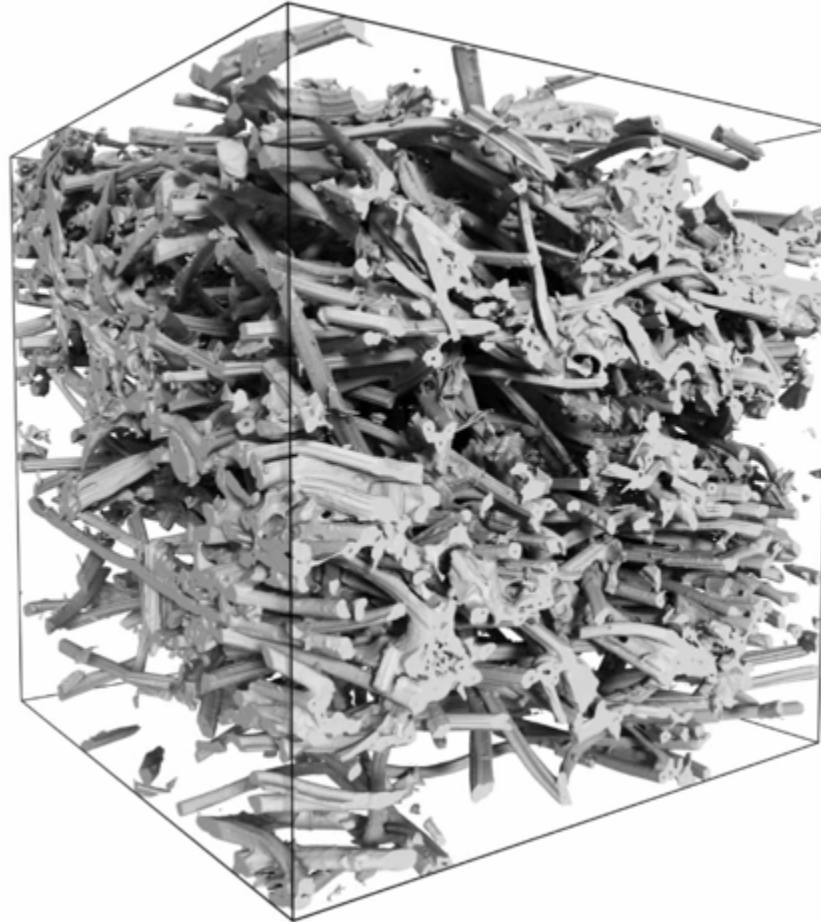
**NASA
Pleiades**



Courtesy of Google Earth



**LBL
NERSC**

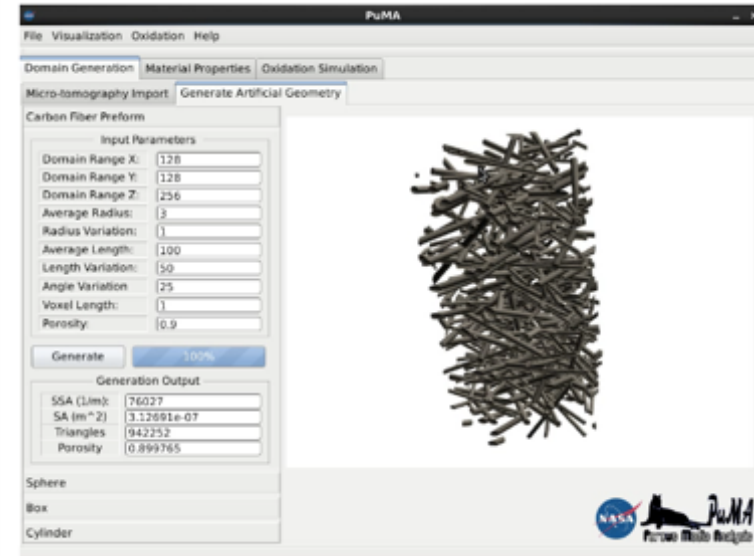
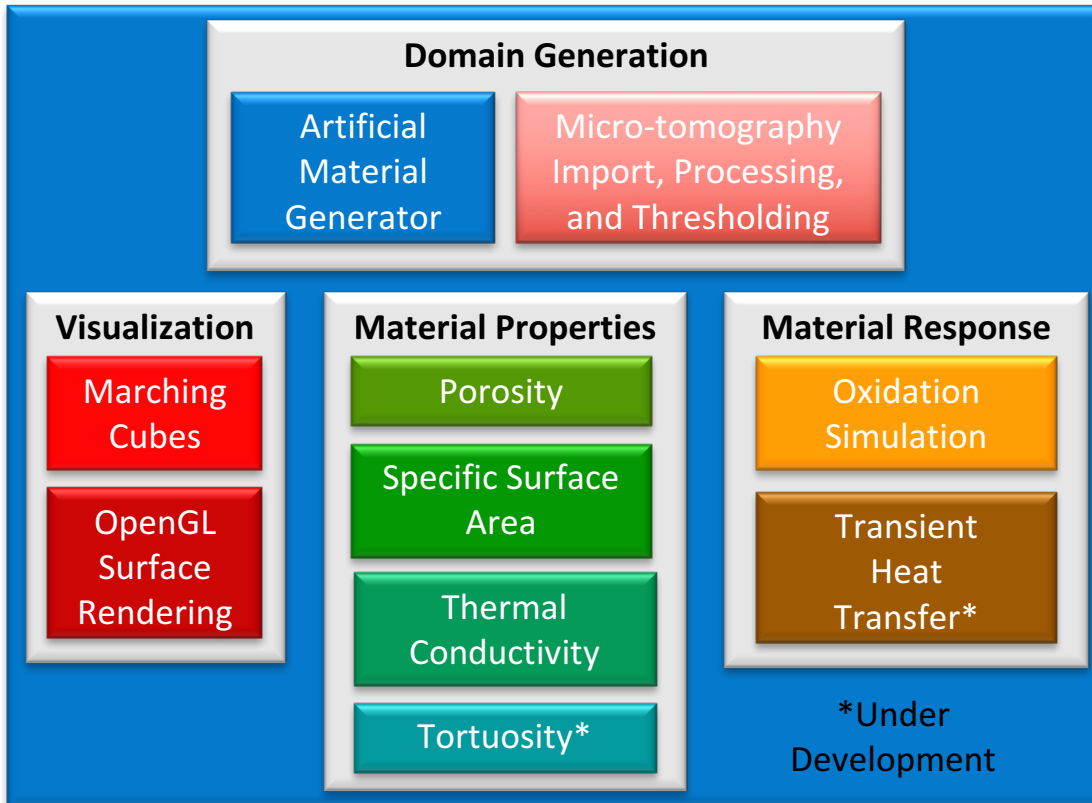


This is a movie.
Email:
francesco.panerai@nasa.gov
for info.



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

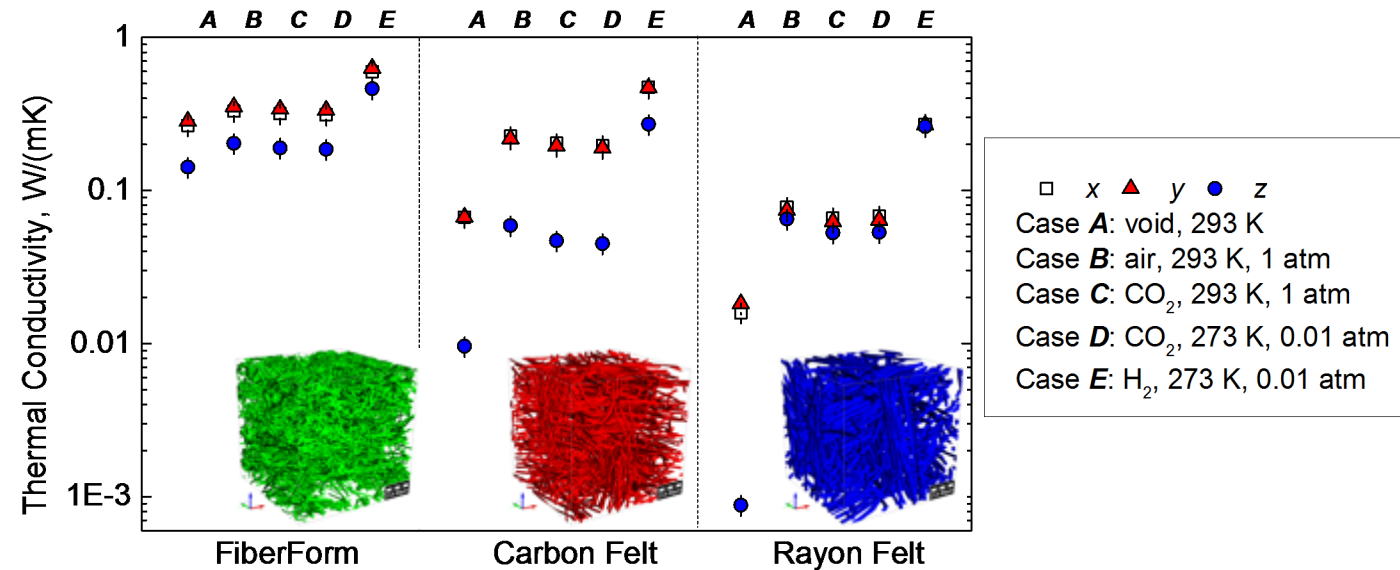
Porous Materials Analysis (PuMA)



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

Effective thermal conductivity

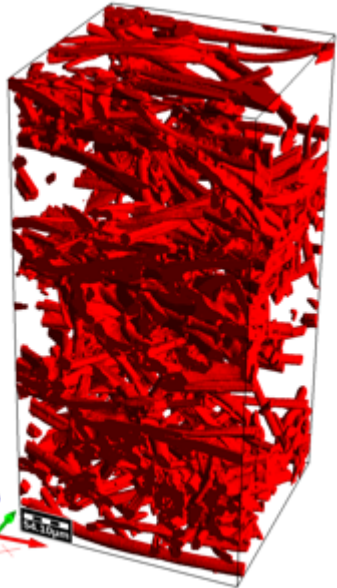
- Solve Fourier equation with finite difference method and periodic BCs
- Compute conductivity tensor as a function of constituting phases



Effect of water on effective conductivity

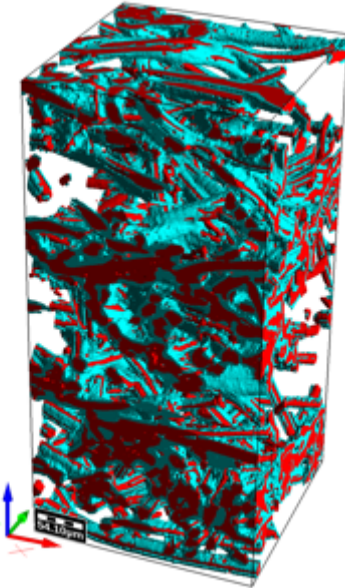


C+CO₂



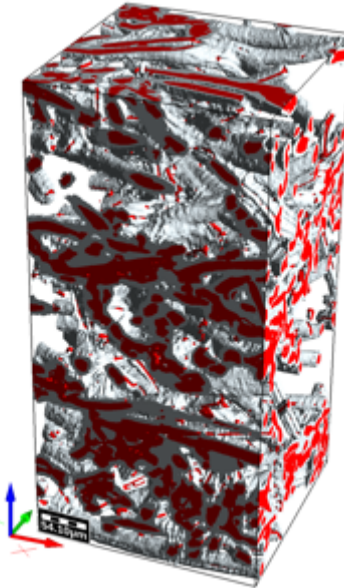
k_{eff}

C+H₂O+CO₂



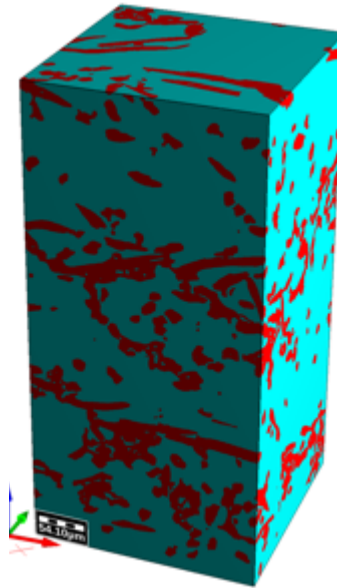
$k_{\text{eff}} \times 1.005$

C+ice+CO₂



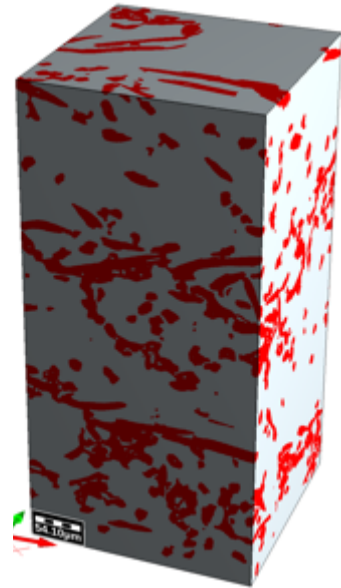
$k_{\text{eff}} \times 1.51$

C+H₂O



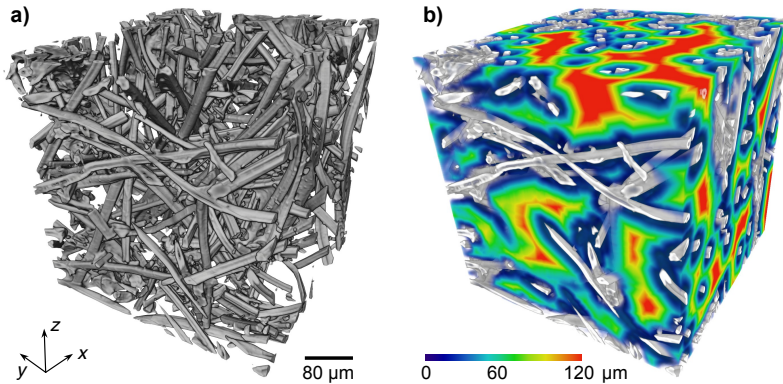
$k_{\text{eff}} \times 3.13$

C+ice



$k_{\text{eff}} \times 8.40$

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)

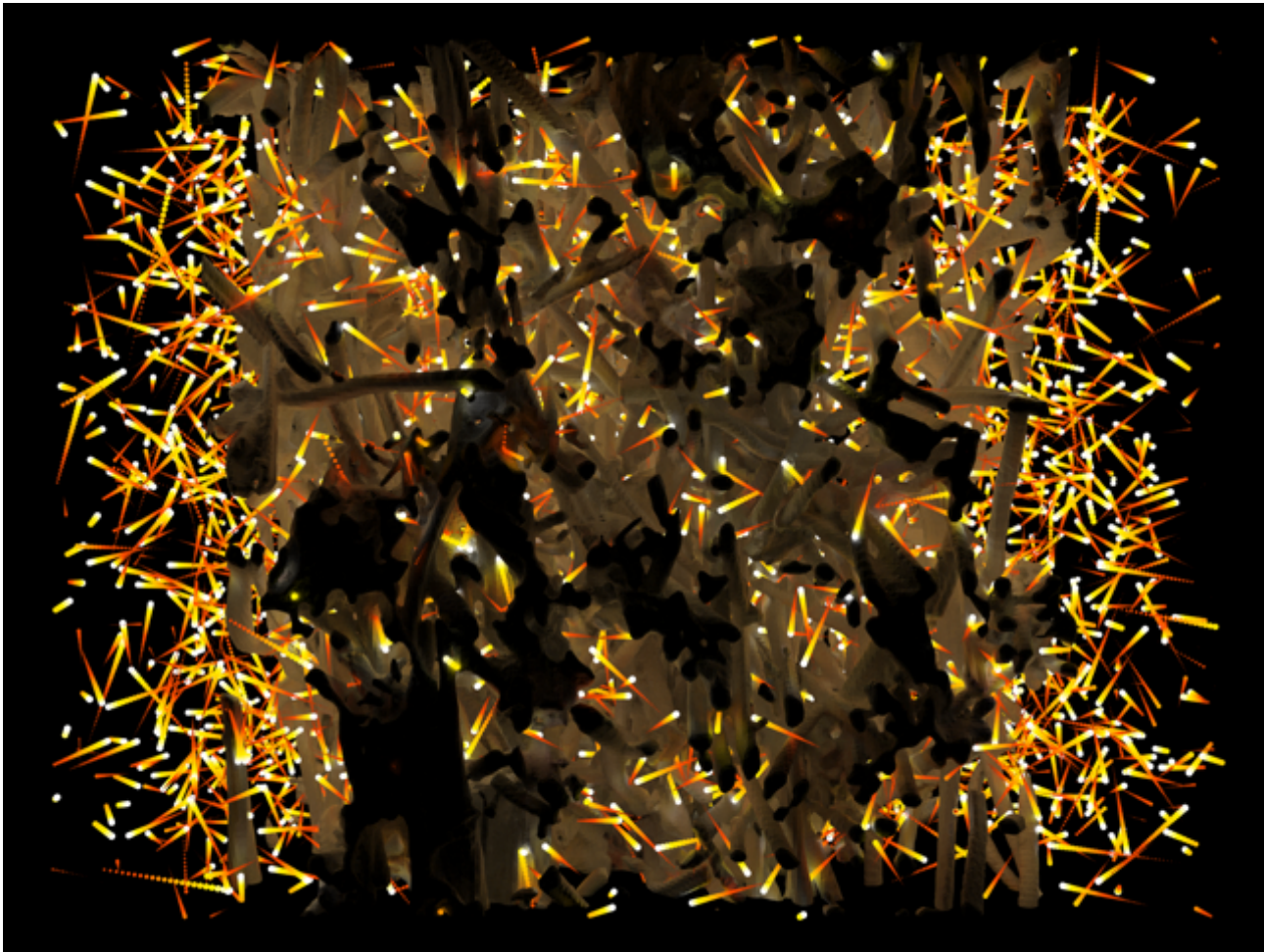
$$Kn = \lambda / d_p$$

1-5 microns (high T, low P)

Kn = Knudsen number

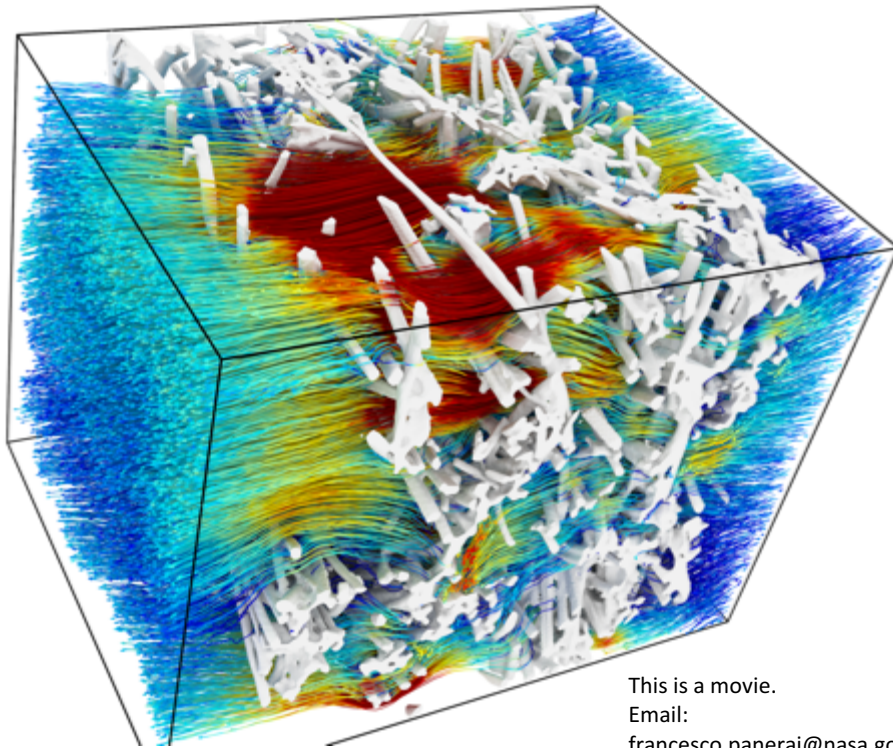
λ = mean free path

d_p = mean pore diameter

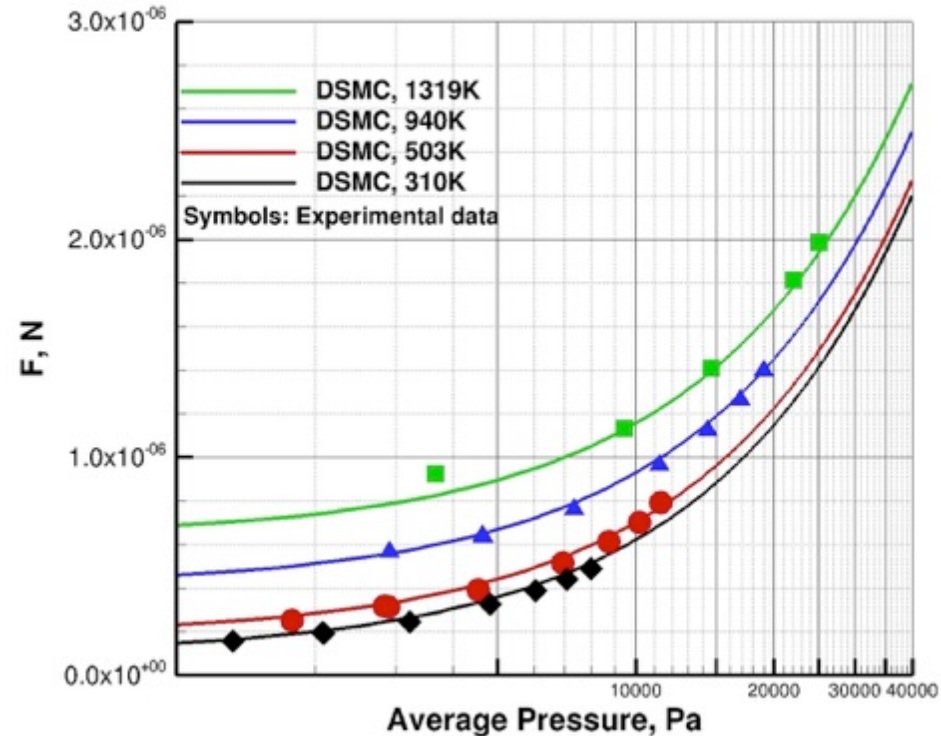


This is a movie.
Email:
francesco.panerai@nasa.gov
for info.

Porous media permeability

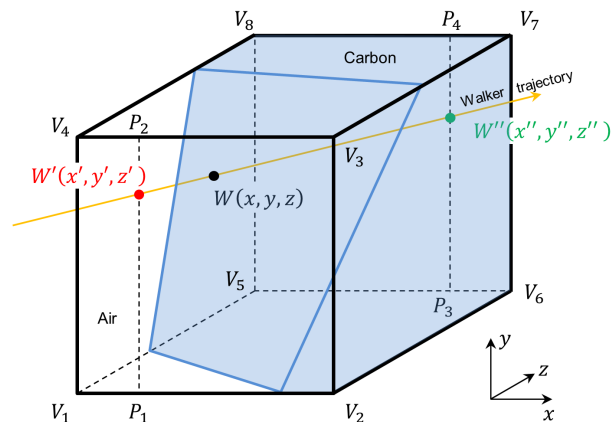
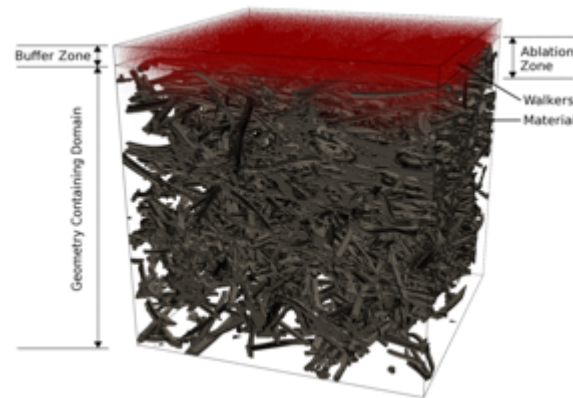


This is a movie.
Email:
francesco.panerai@nasa.gov
for info.

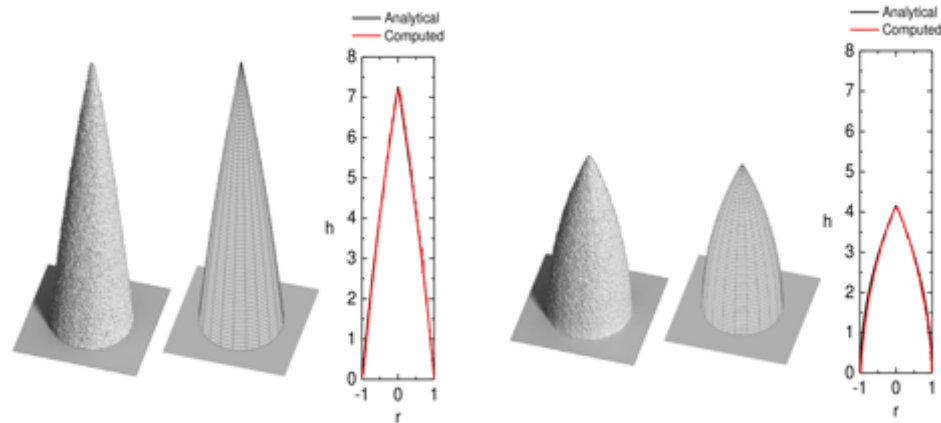


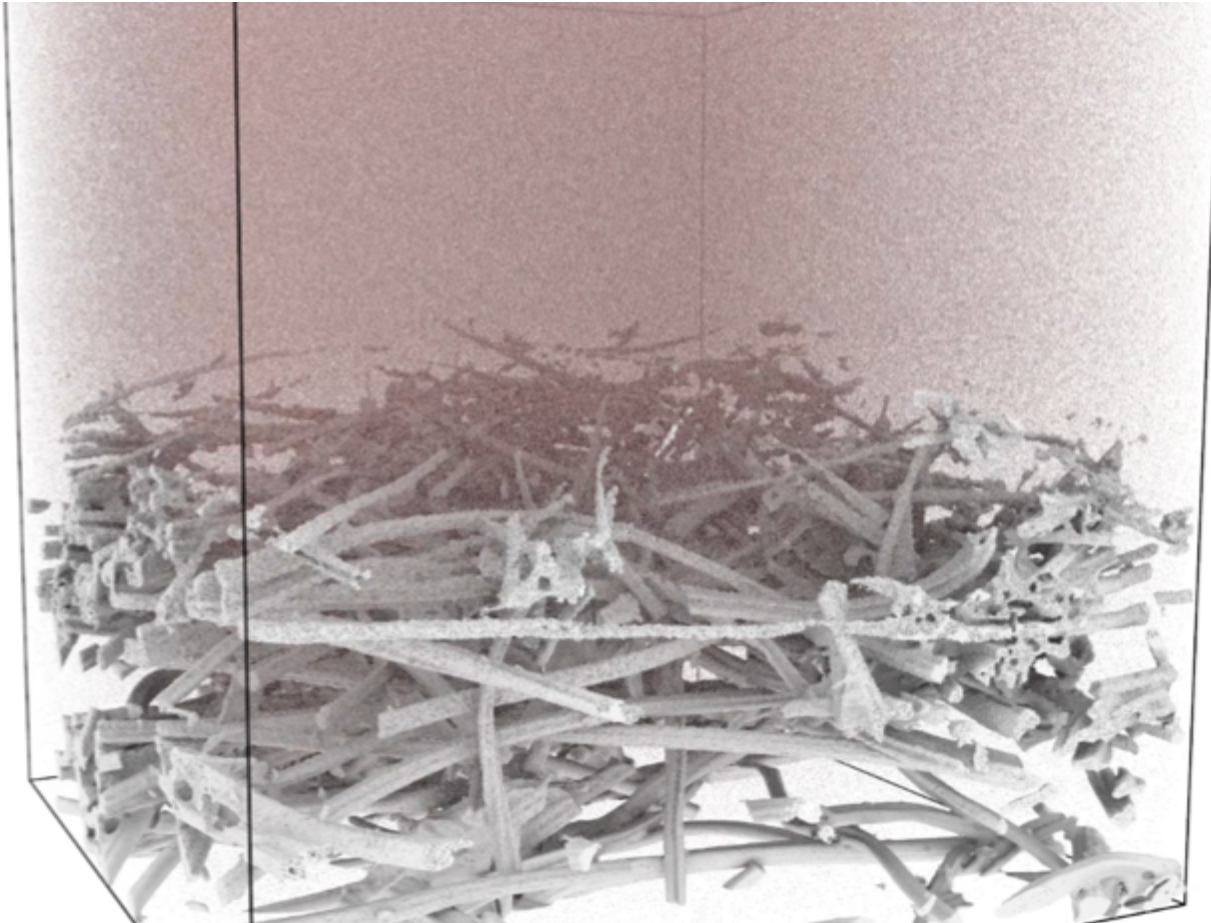
Carbon fibers oxidation simulations

- 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

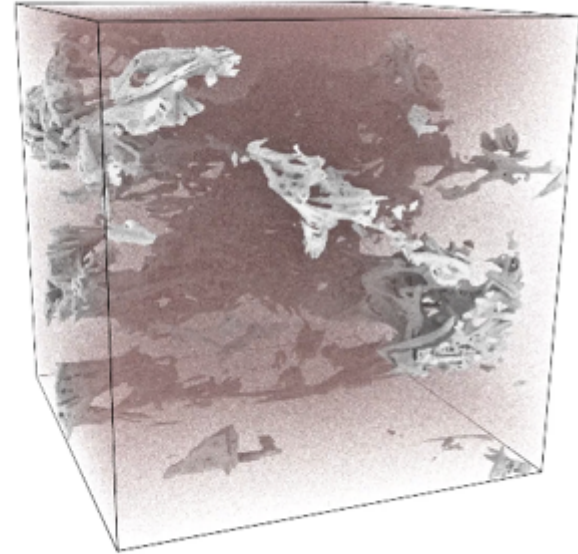
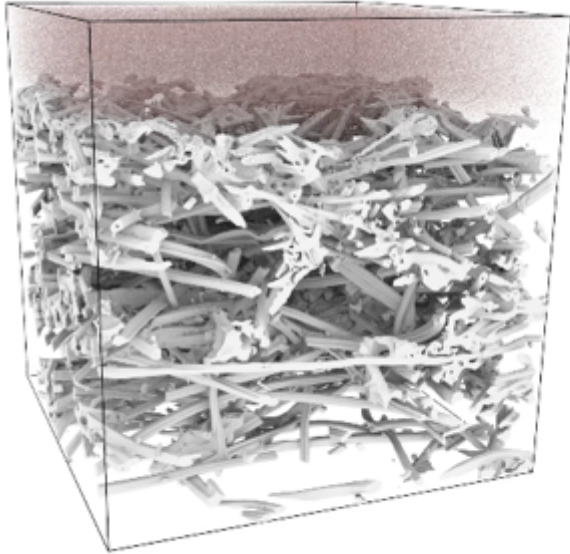


Ferguson et al., *Carbon* 96 (2016), 57-65





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



This is a movie.

Email:

francesco.panerai@nasa.gov

for info.

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:

