

Boundary-layer flow simulations over ablating woven thermal protection system material

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Motivation

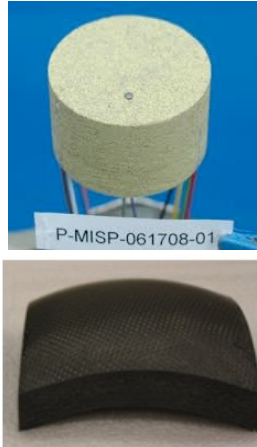
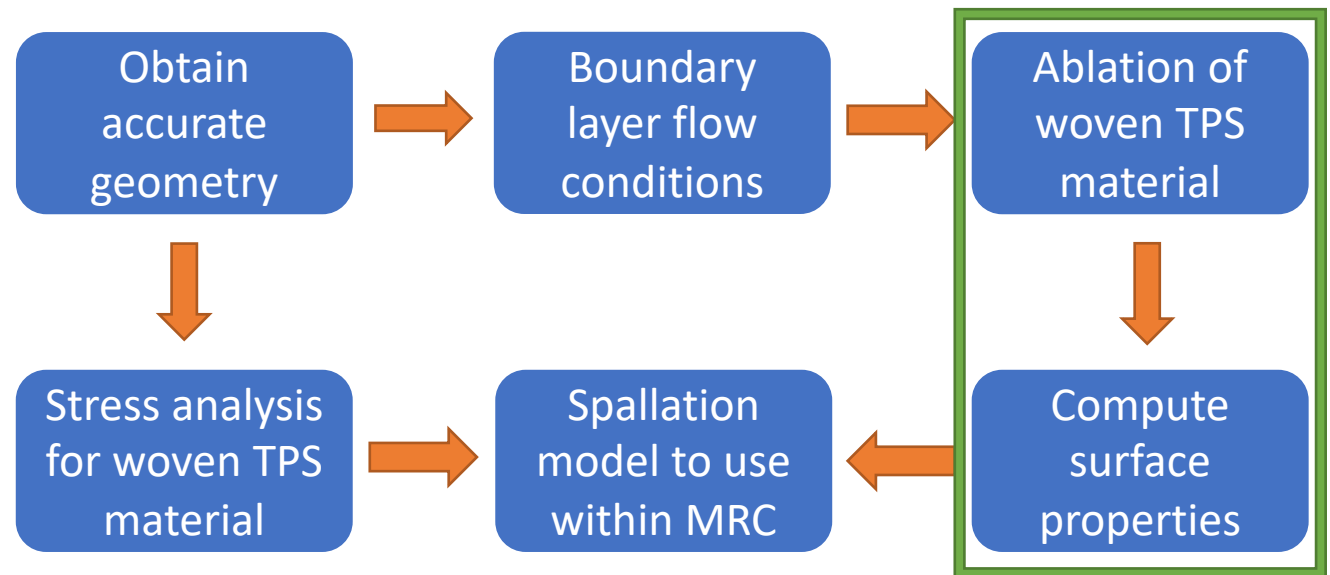


Image credit: NASA

Ablative TPS material considerations:
recession, oxidation, pyrolysis

Overall Objective: Characterize and develop a spallation model for woven TPS material.



Current work objective: Compute surface properties such as heat flux and shear stress for boundary layer flow over woven TPS material.

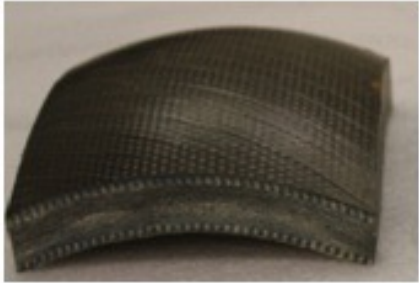
Woven TPS materials



Heat Shield for Extreme Entry Environment Technology (HEEET)

Carbon weave

Phenolic Matrix Resin



+



=



Woven TPS

Image credit: NASA

Woven TPS:

- Woven TPS (WTPS) uses mature weaving technologies to vary material composition and properties while controlling placement of fibers within woven structure.
- The resulting WTPS can be designed and tailored to perform optimally for a wide range of entry environments without substantially changing the manufacturing process.

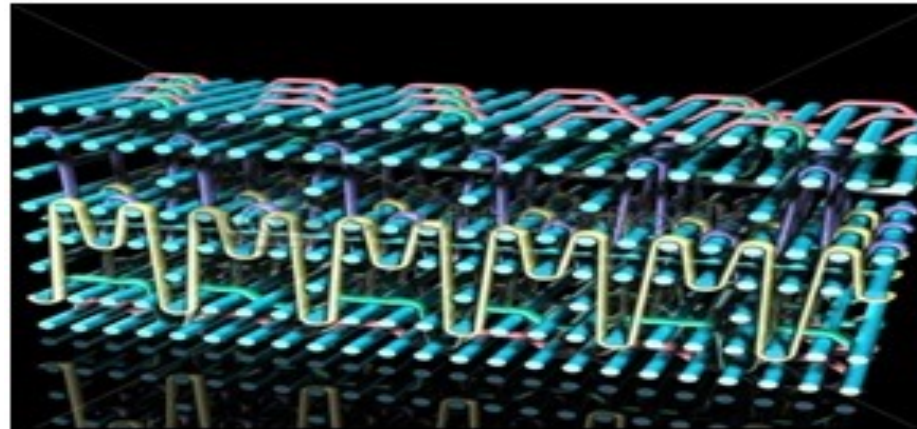
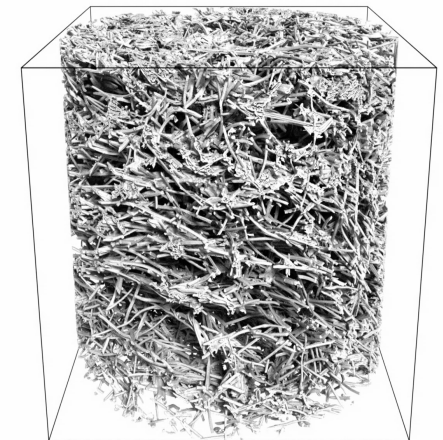
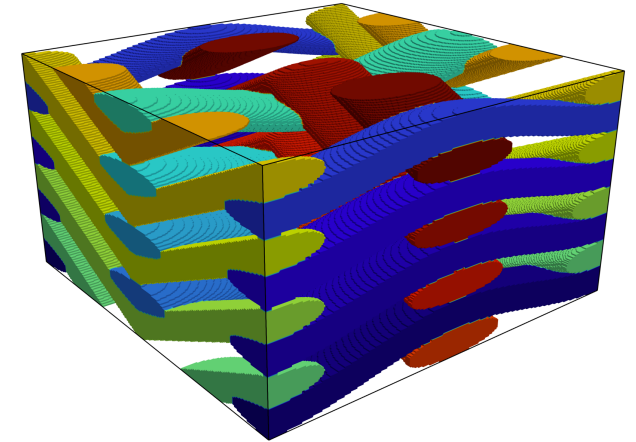
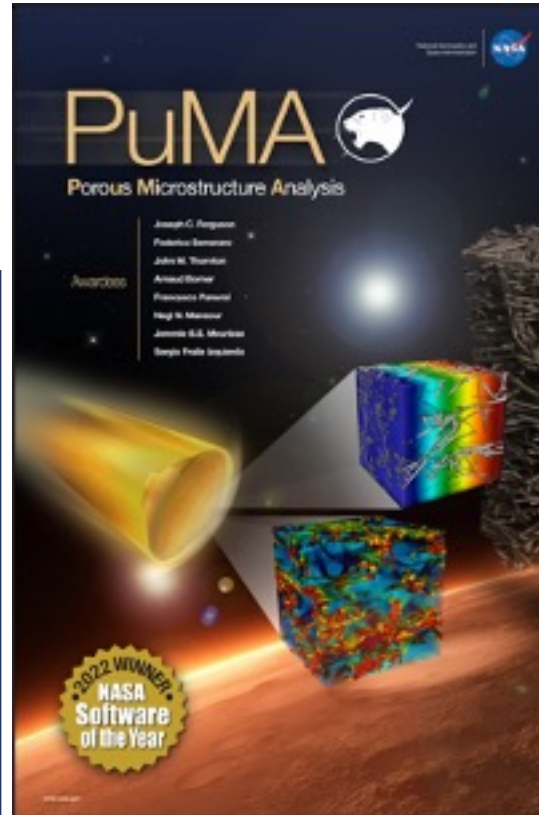
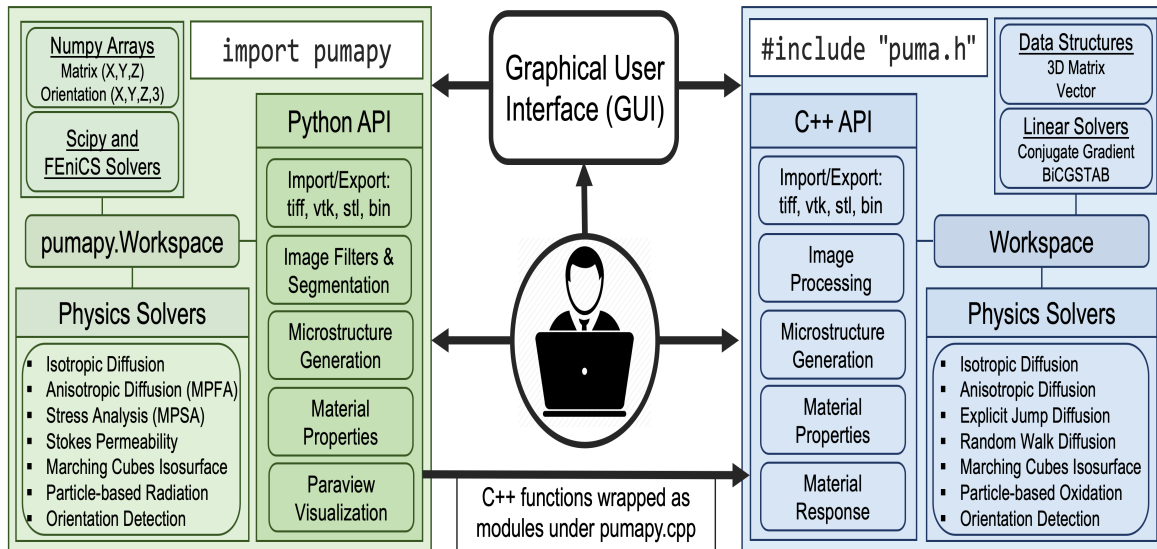


Image credit:
NASA

Porous Microstructure Analysis (PuMA) [1]



- Open source (<https://github.com/nasa/puma>)
- Developed at NASA Ames Research Center
- Python API available through conda-forge
- NASA Software of the year 2022



[1] Ferguson, J. C., Semeraro, F., Thornton, J. M., Panerai, F., Borner, A., & Mansour, N. N. (2021). Update 3.0 to "PuMA: The porous microstructure analysis software", (PII: S2352711018300281). SoftwareX, 15, 100775.

DSMC – SPARTA [2]



Continuum breakdown

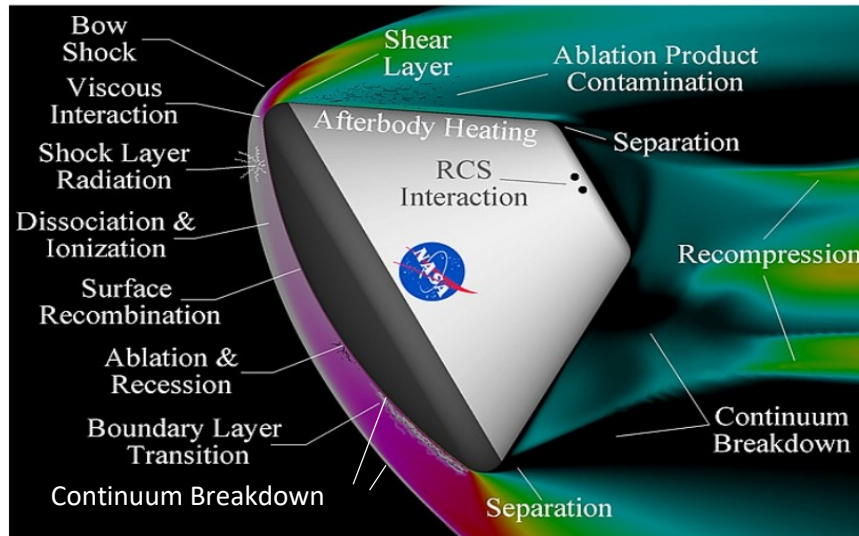


Image Credit: NASA

[2] M. A. Gallis, J. R. Torczynski, S. J. Plimpton, D. J. Rader, T. Koehler, "Direct Simulation Monte Carlo: The Quest for Speed", 29th Intl Symposium on Rarefied Gas Dynamics in Xi'an, China, AIP Conf Proc, 1628, 27 (2014).

DSMC

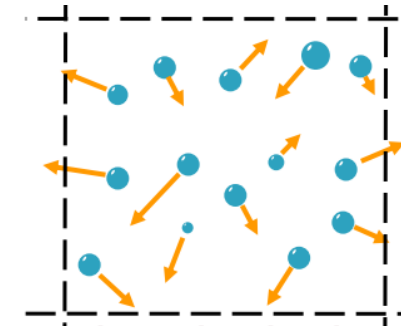
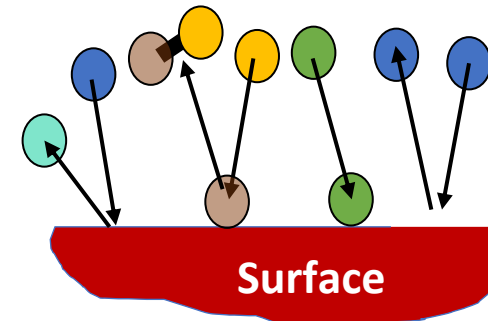
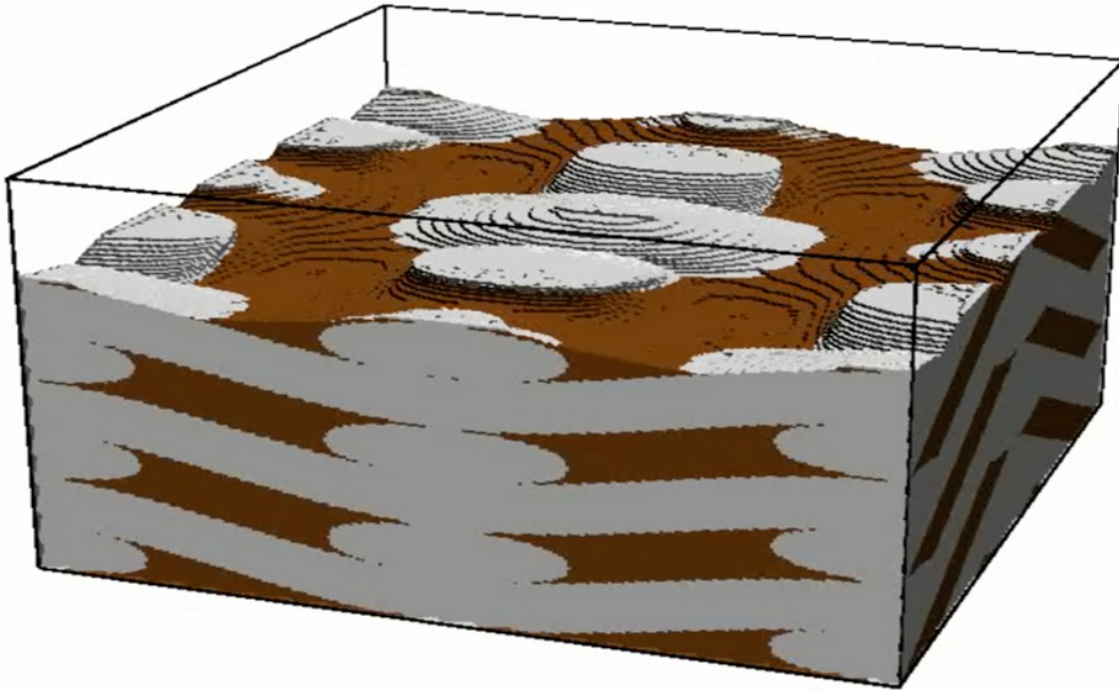


Image courtesy: <https://prateekvjoshi.com/>



- CFD is not valid in regions of continuum breakdown.
- DSMC (direct simulation Monte Carlo) is a stochastic, particle-based method to solve the Boltzmann equation.
- DSMC is valid in all regimes: continuum, rarefied and transition (however computational cost increases with density).

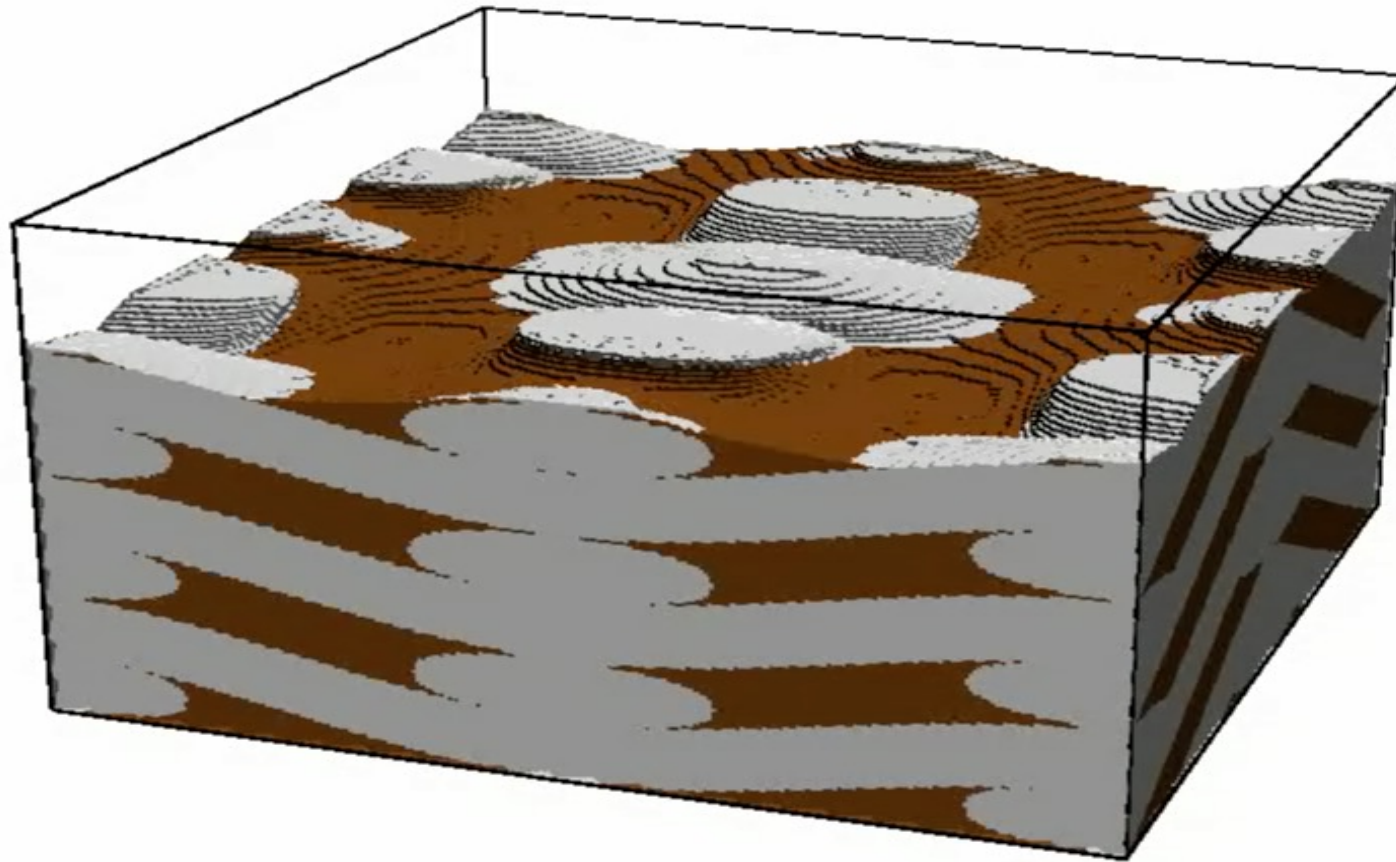
PuMA oxidation simulation



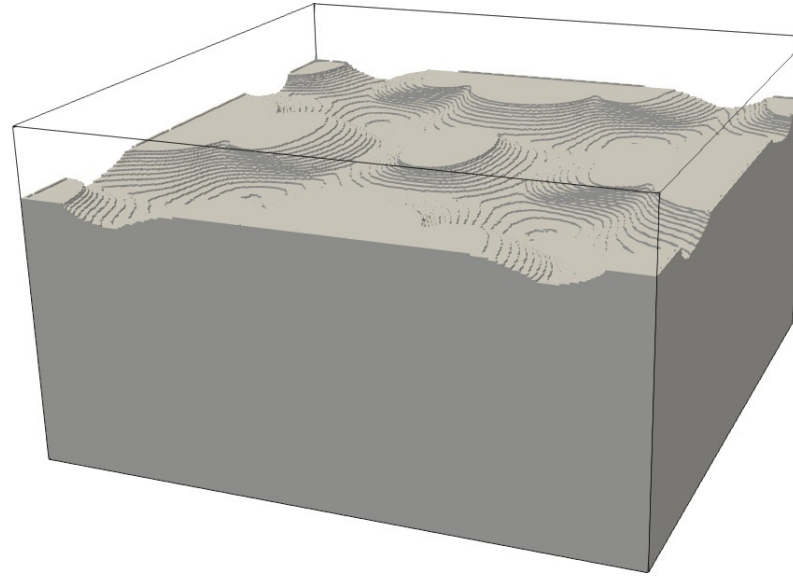
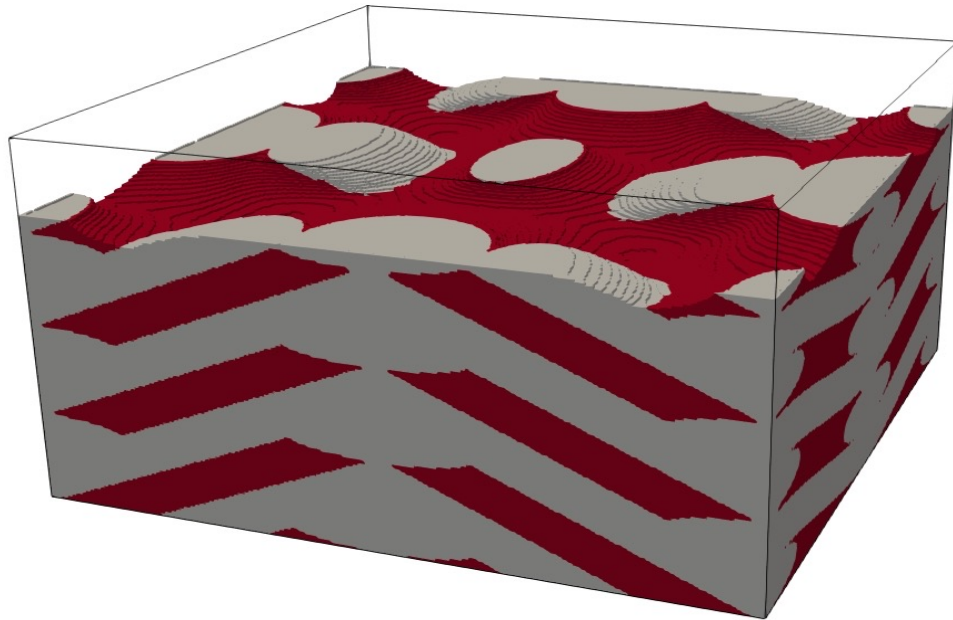
- We use a surrogate geometry similar to the MSR-EEV weave architecture
- Earth re-entry velocity = 10.3 km/s
- $T_{\text{gas}} = 4000 \text{ K}$, $P = 75 \text{ kPa}$.
- Fully dissociated air - O(21%), N(79%)
- Only O is reactive
- Oxidation rate from Park [3]
 $k = 0.63 \exp(-1160/T)$
- Resin (brown) is assumed to be 5 times more reactive and 10 times less dense than fibers (grey)

[3] Park, C. (1976). Effects of atomic oxygen on graphite ablation. *AIAA journal*, 14(11), 1640-1642.

PuMA oxidation simulation



Resin vs No resin

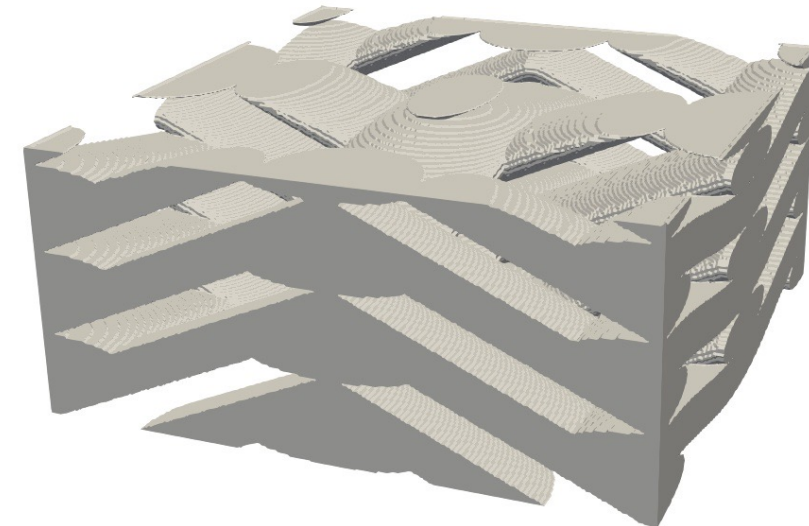


With Resin

- Resin is treated same as the carbon weaves.
- **Diffusion limited regime**

Without Resin

- Resin is completely removed from the top layers
- **Reaction limited regime**

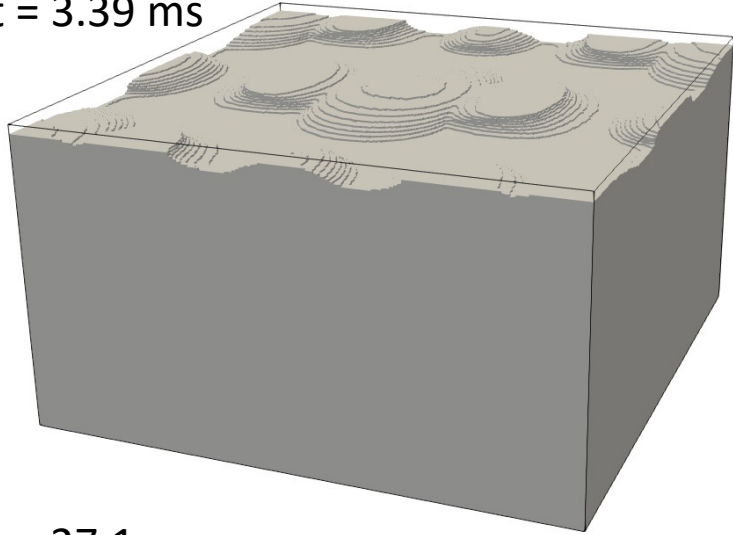


Geometry from PuMA simulation

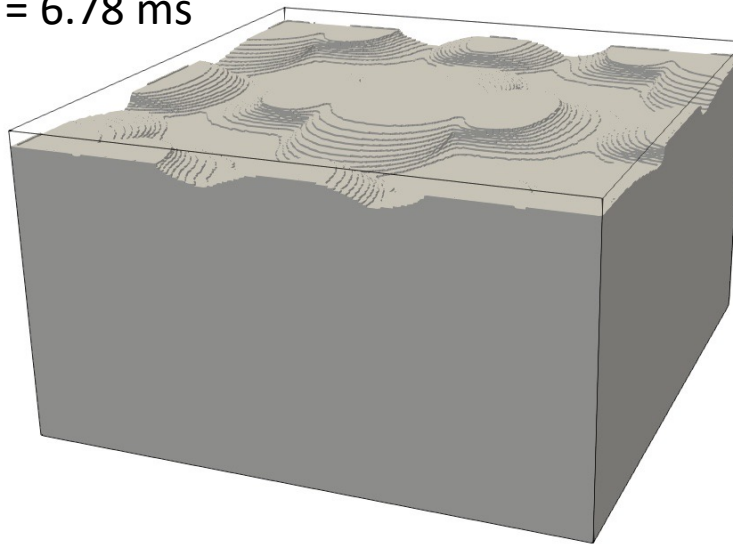
With Resin – Diffusion limited regime



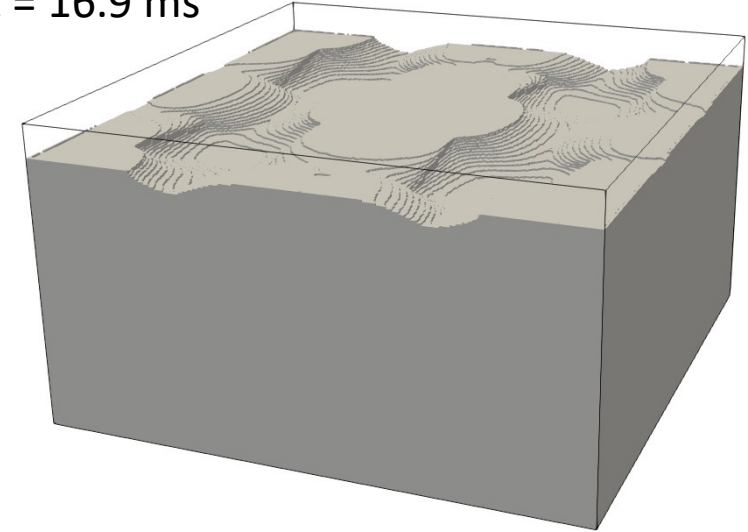
$t = 3.39 \text{ ms}$



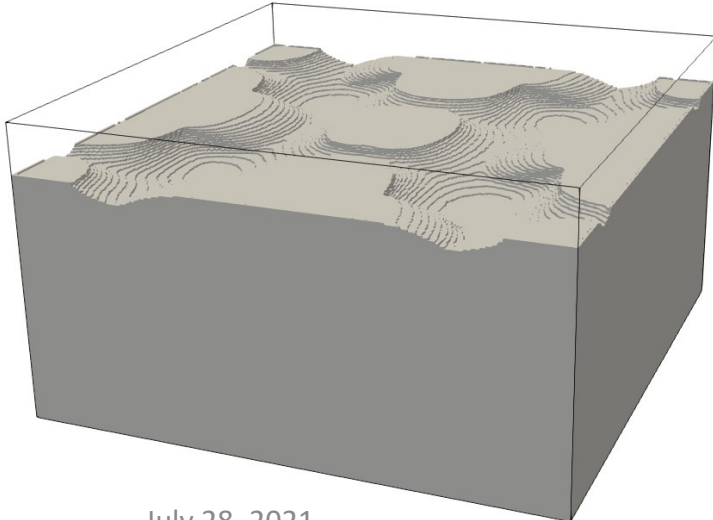
$t = 6.78 \text{ ms}$



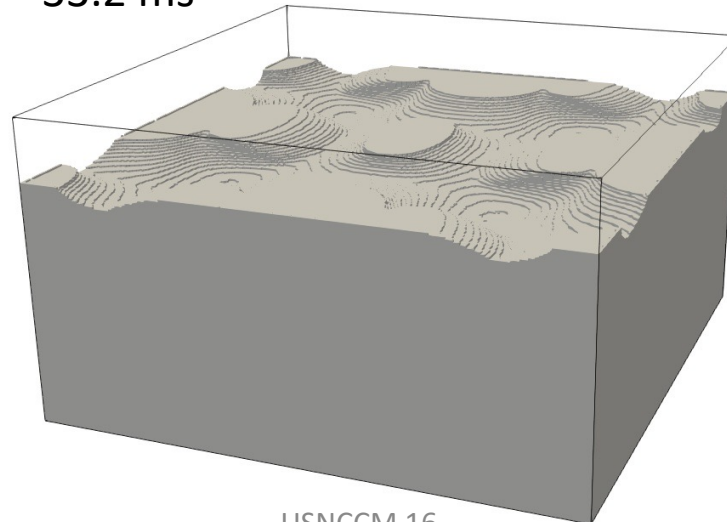
$t = 16.9 \text{ ms}$



$t = 27.1 \text{ ms}$



$t = 33.2 \text{ ms}$

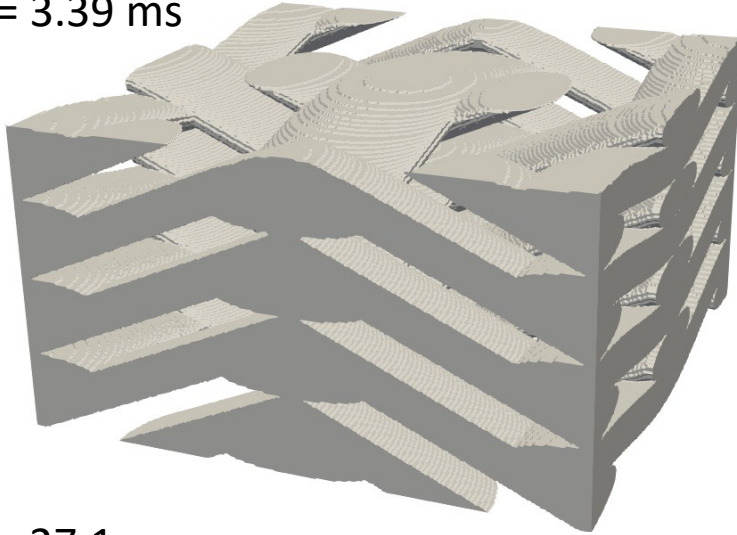


Woven TPS geometries with resin at various stages of oxidation

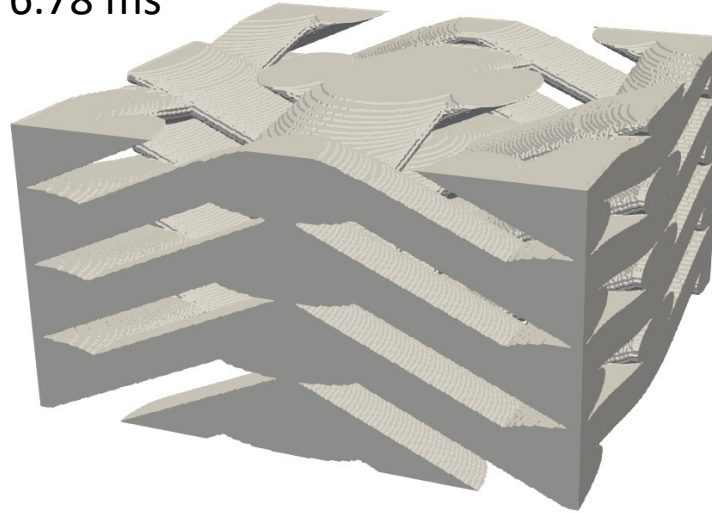
Without Resin – Reaction limited regime



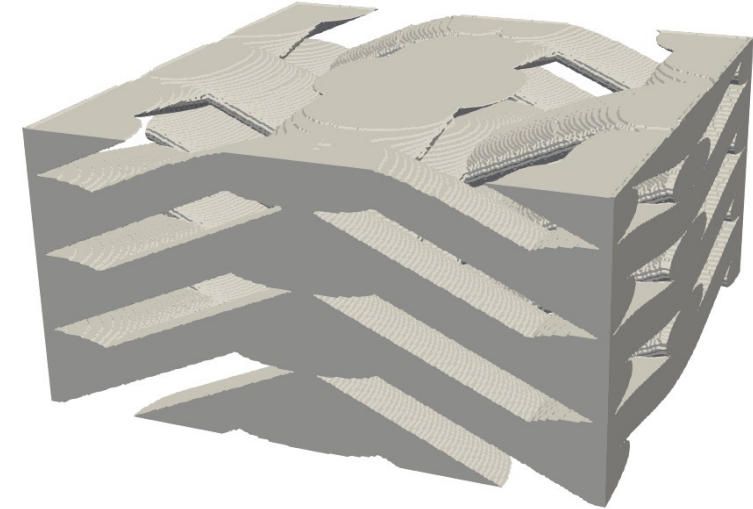
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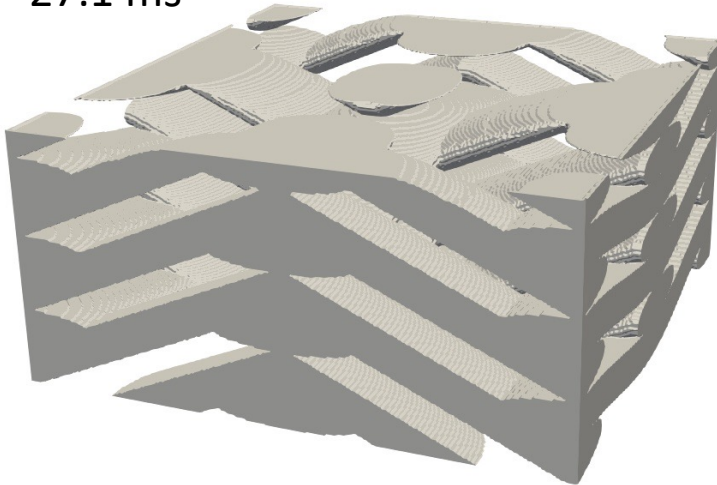
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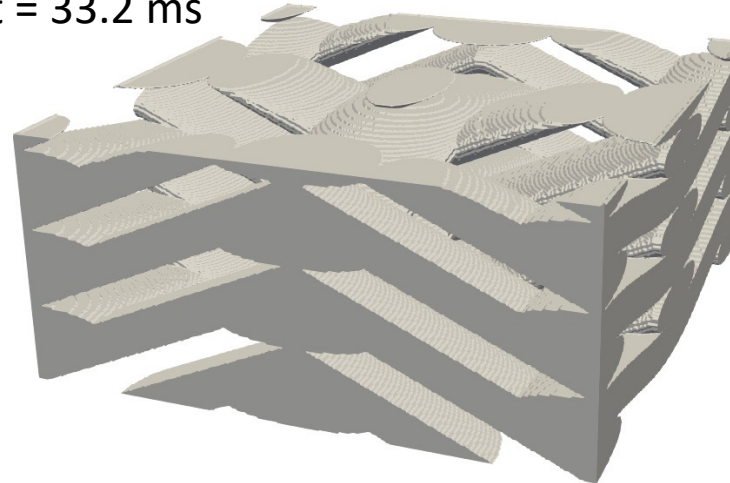
$t = 16.9 \text{ ms}$



$t = 27.1 \text{ ms}$

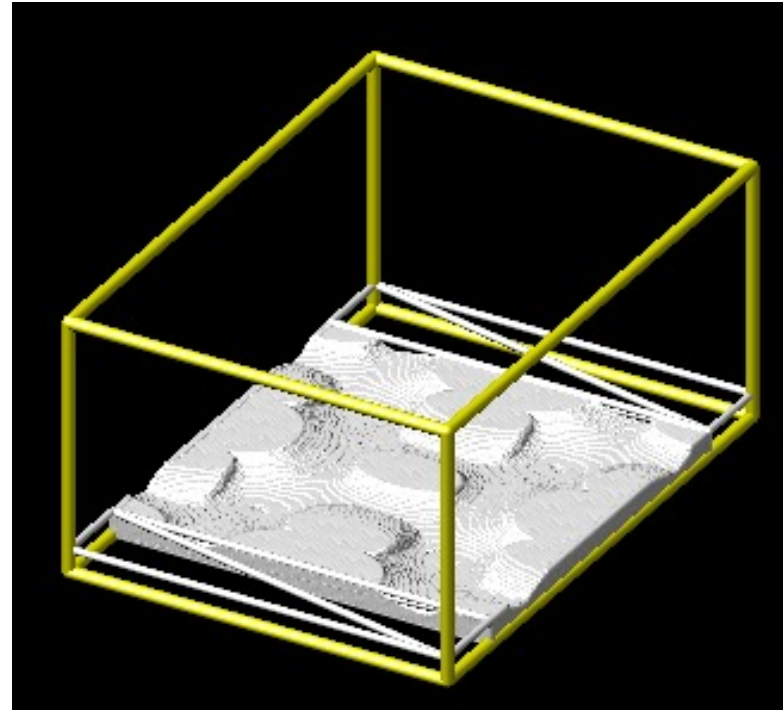
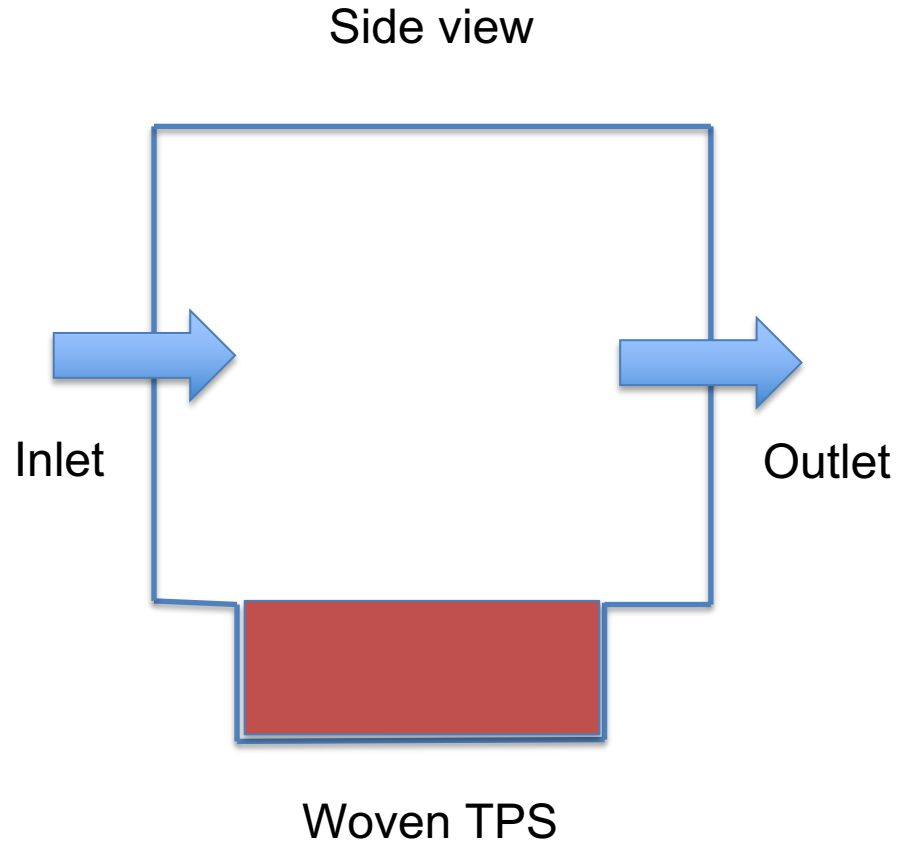


$t = 33.2 \text{ ms}$



Woven TPS geometries without resin at various stages of oxidation

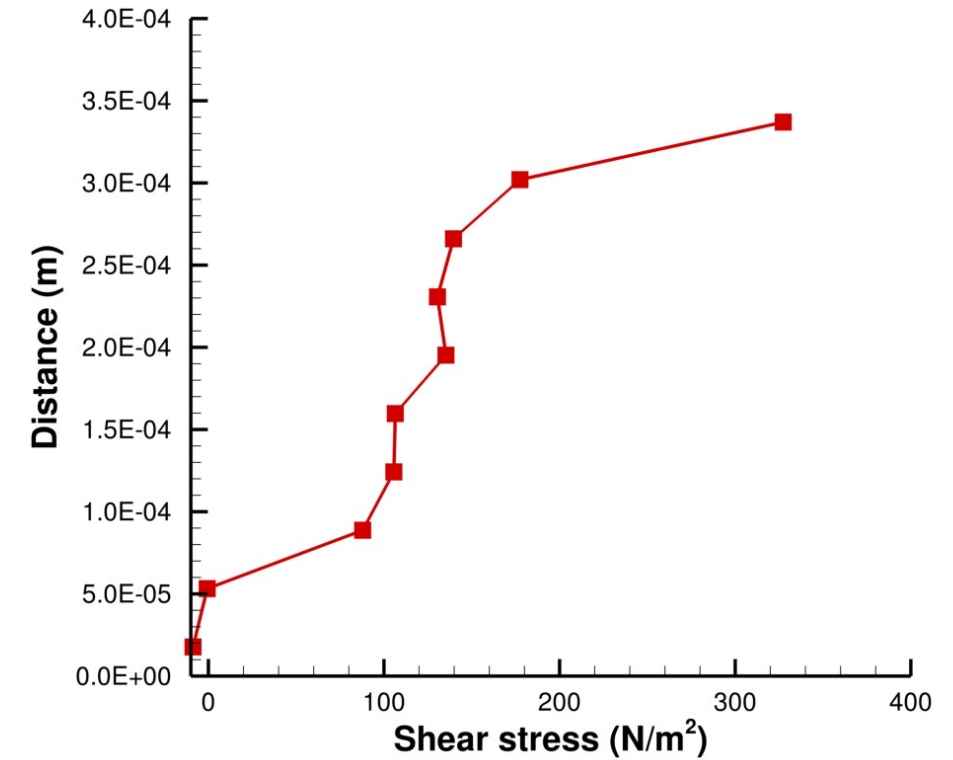
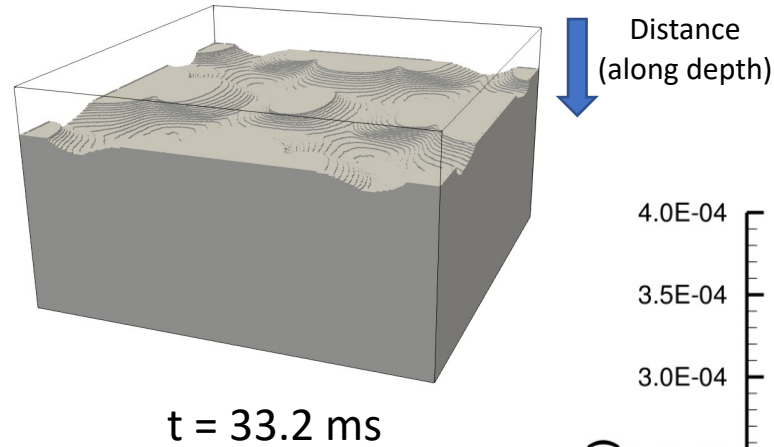
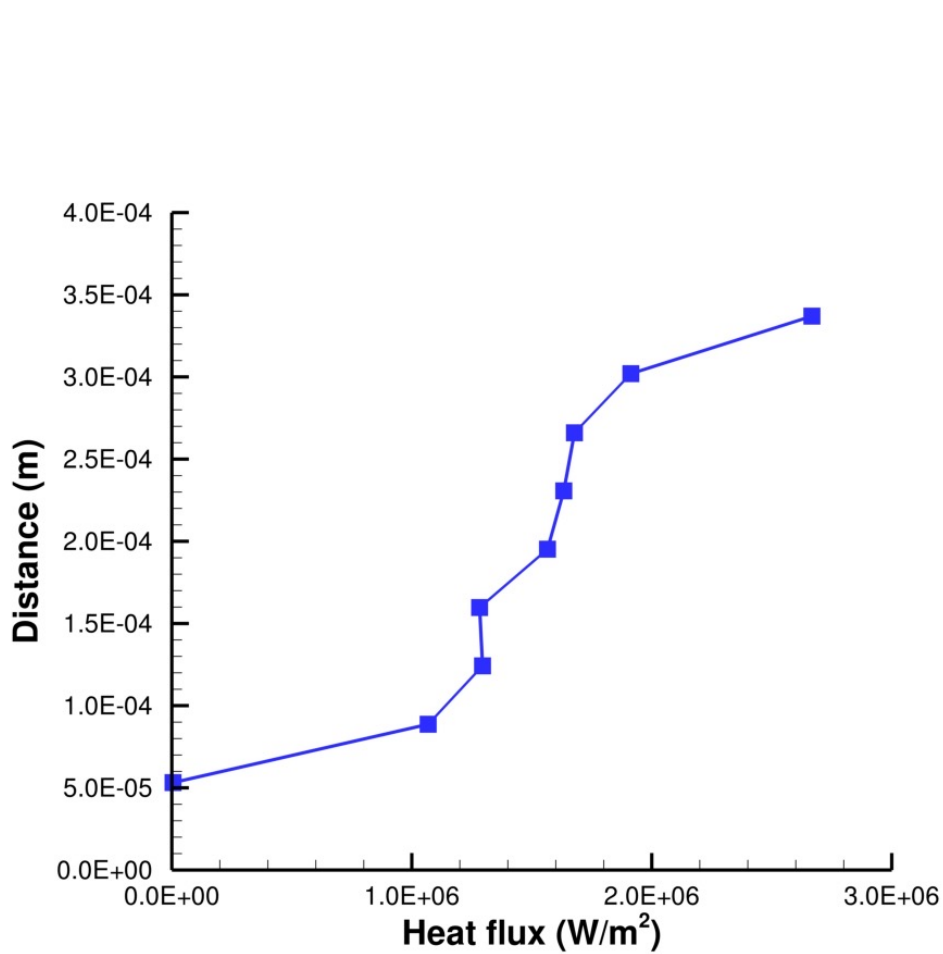
SPARTA DSMC simulation domain



- Fully dissociated gas - O(21%), N(79%)
- $T_{\text{gas}} = 4000\text{K}$ $T_{\text{surf}} = 3250\text{K}$
- Fully diffuse scattering
- ~ 13 million particles in the domain
- After steady state is reached, the final data is averaged over 100,000 timesteps

With Resin – Diffusion limited regime

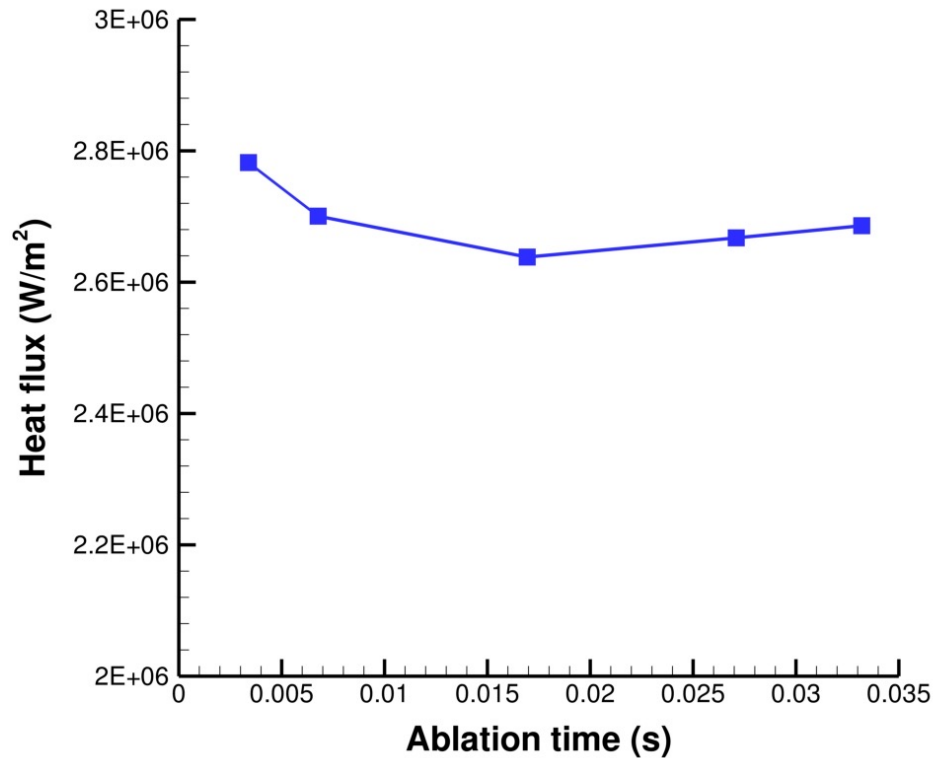
$t=33.2$ ms geometry



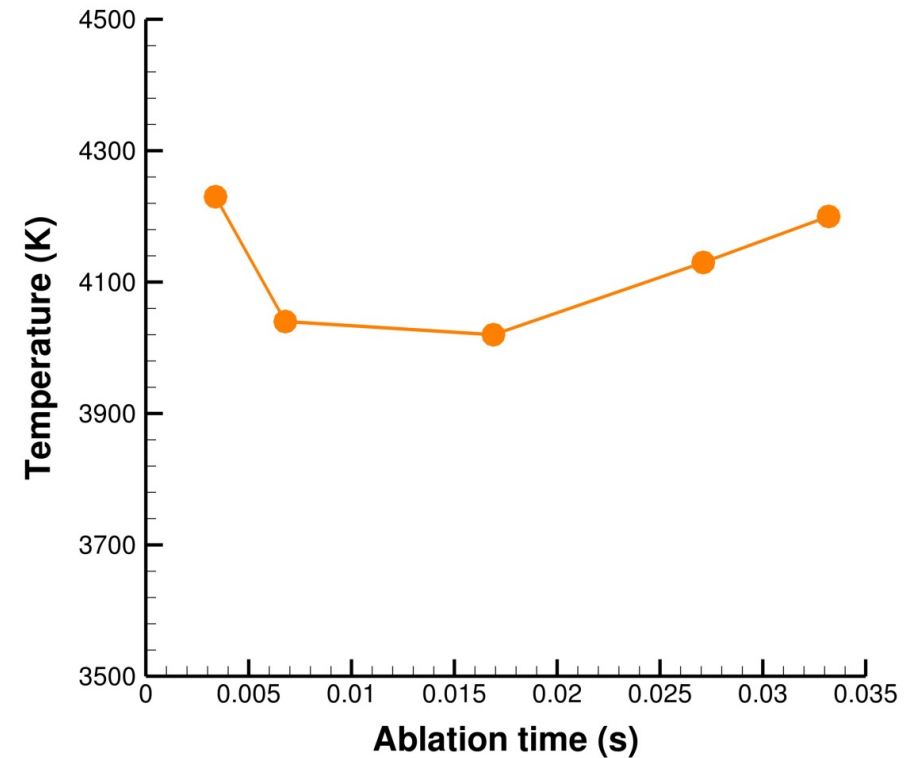
With Resin – Diffusion limited regime Variation with different geometries



Maximum heat flux from all geometries



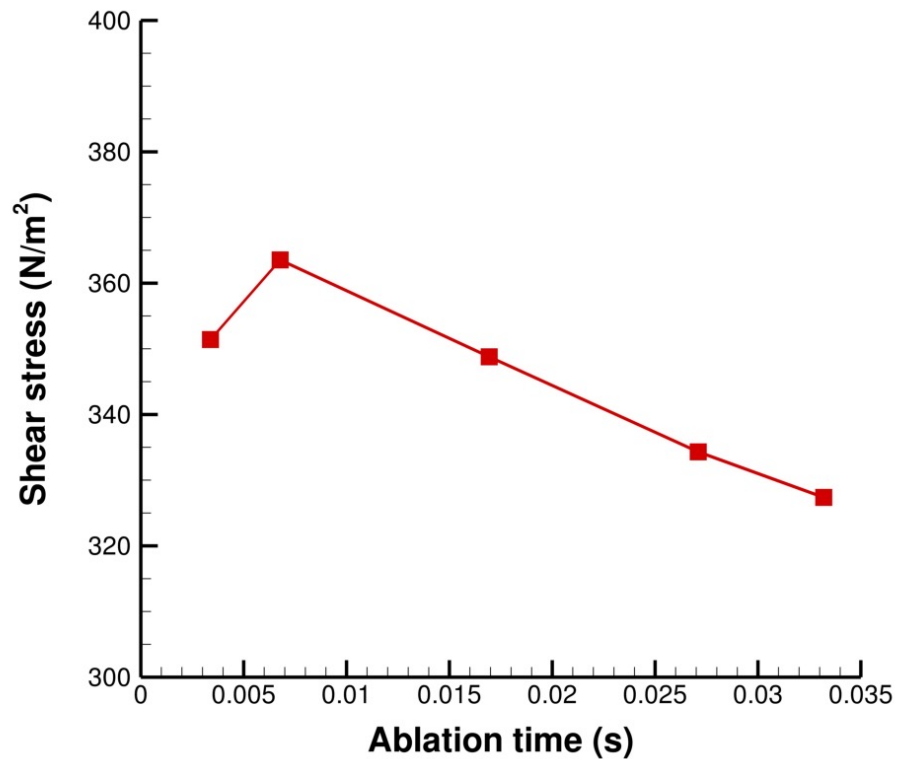
Average temperature next to the surface



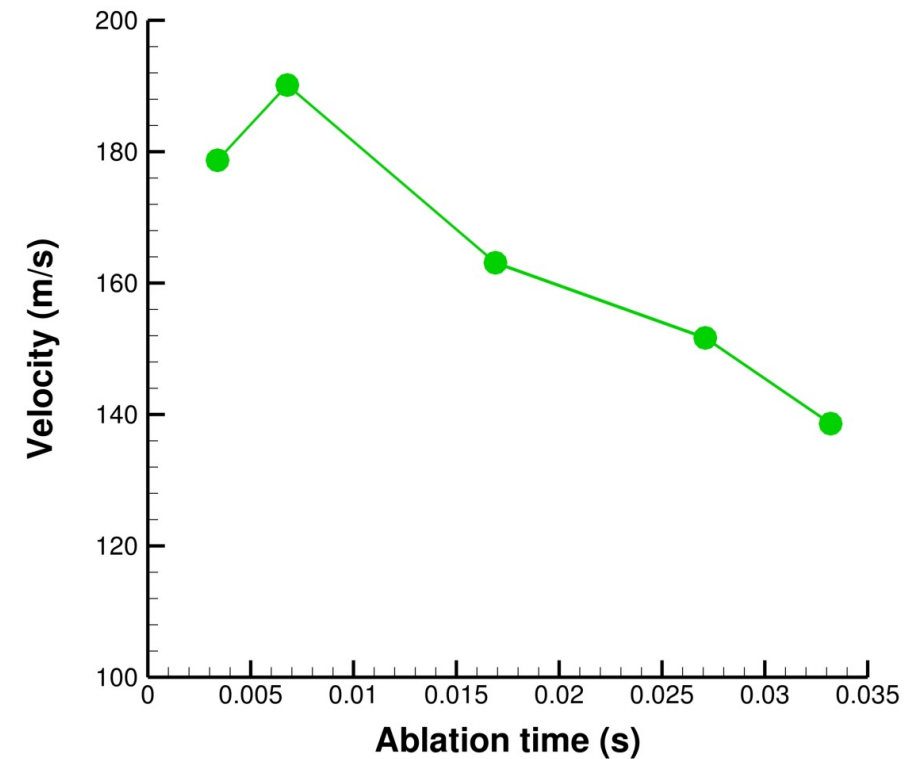
With Resin – Diffusion limited regime Variation with different geometries



Maximum shear stress from all geometries

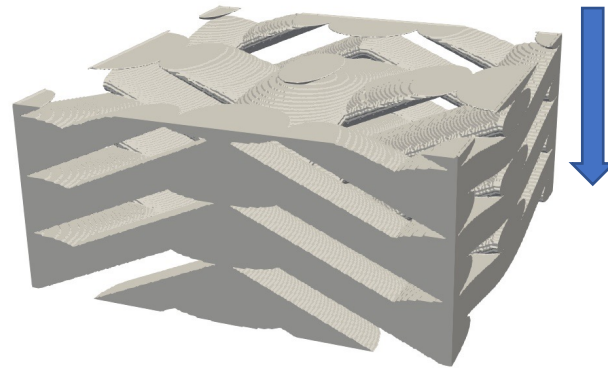
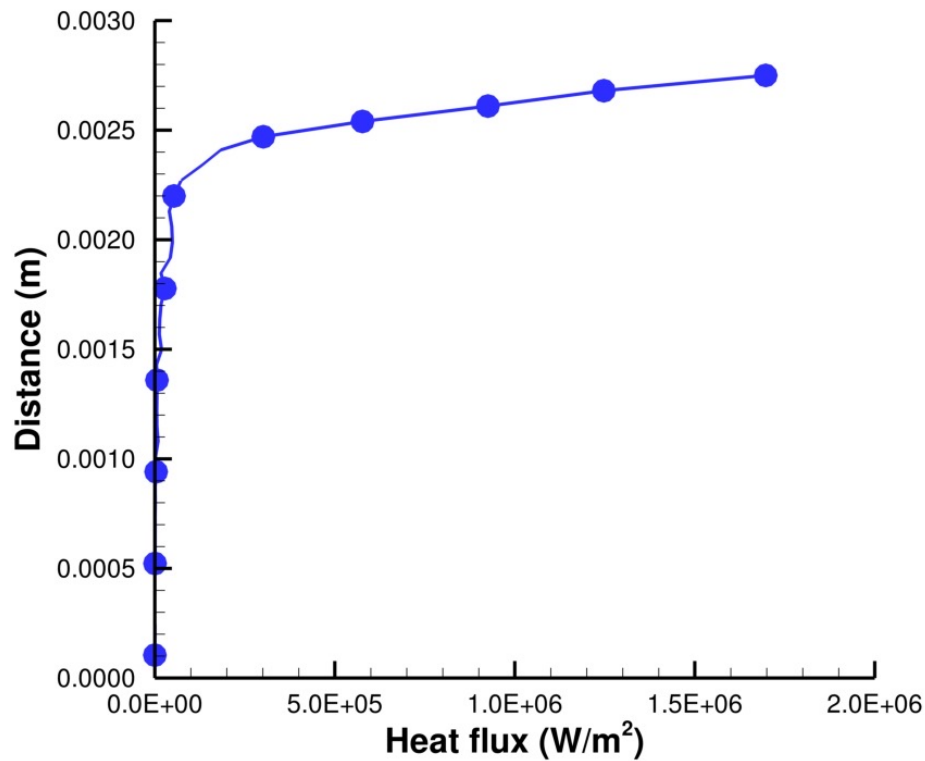


Average velocity next to the surface



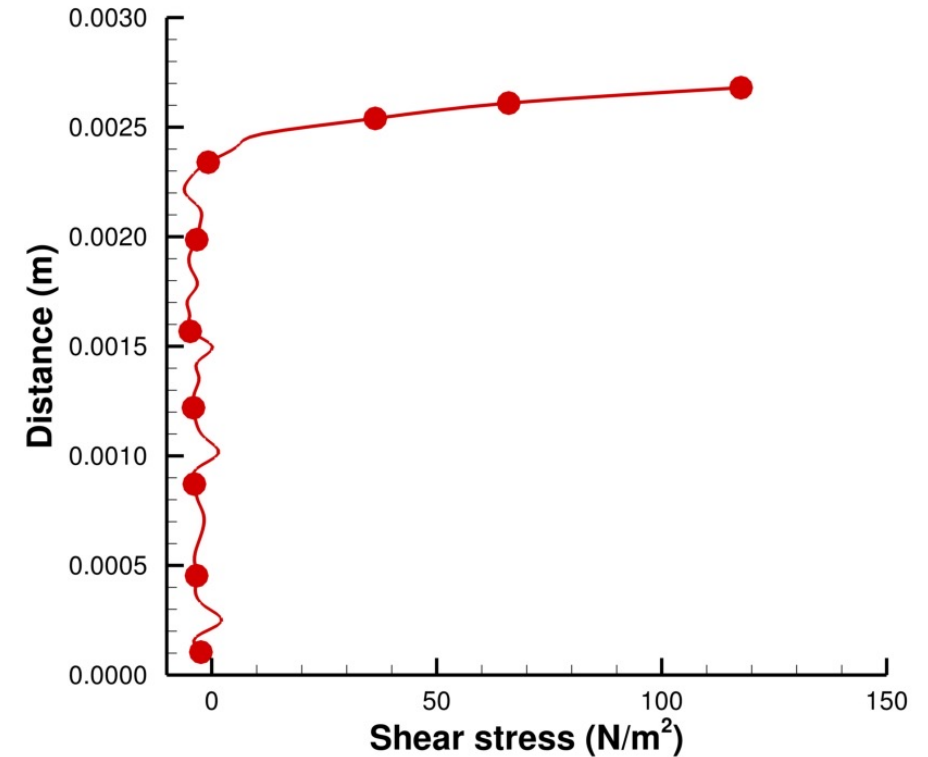
Without Resin - Reaction limited regime

$t=33.2$ ms geometry



$t = 33.2$ ms

Distance
(along depth)

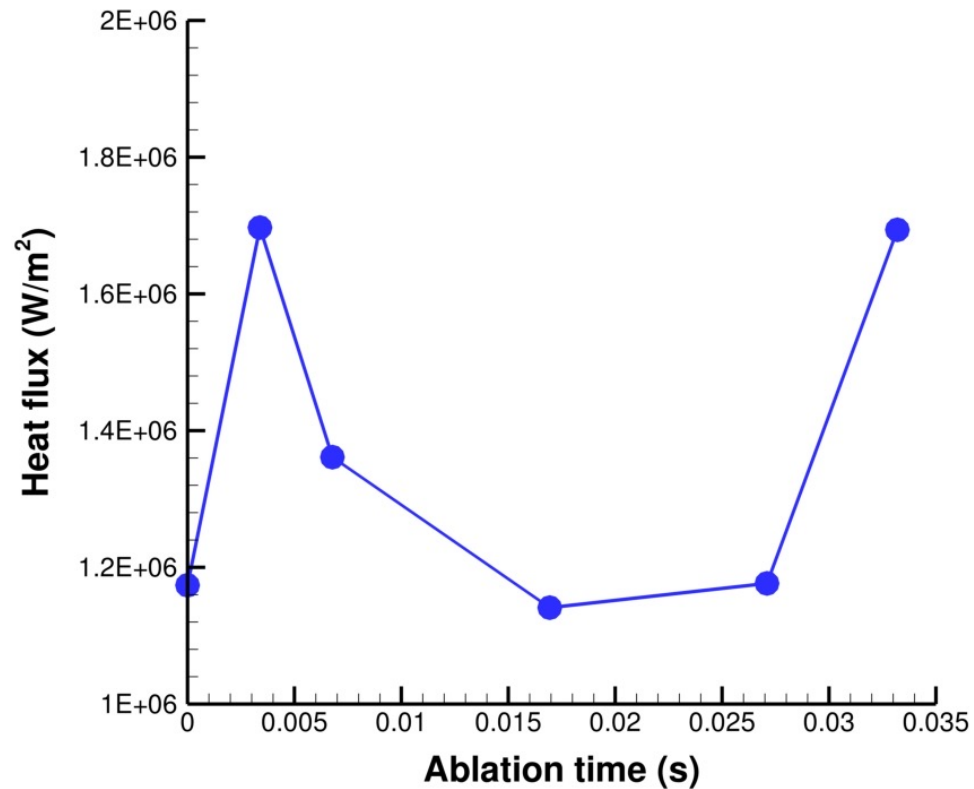


Without Resin - Reaction limited regime

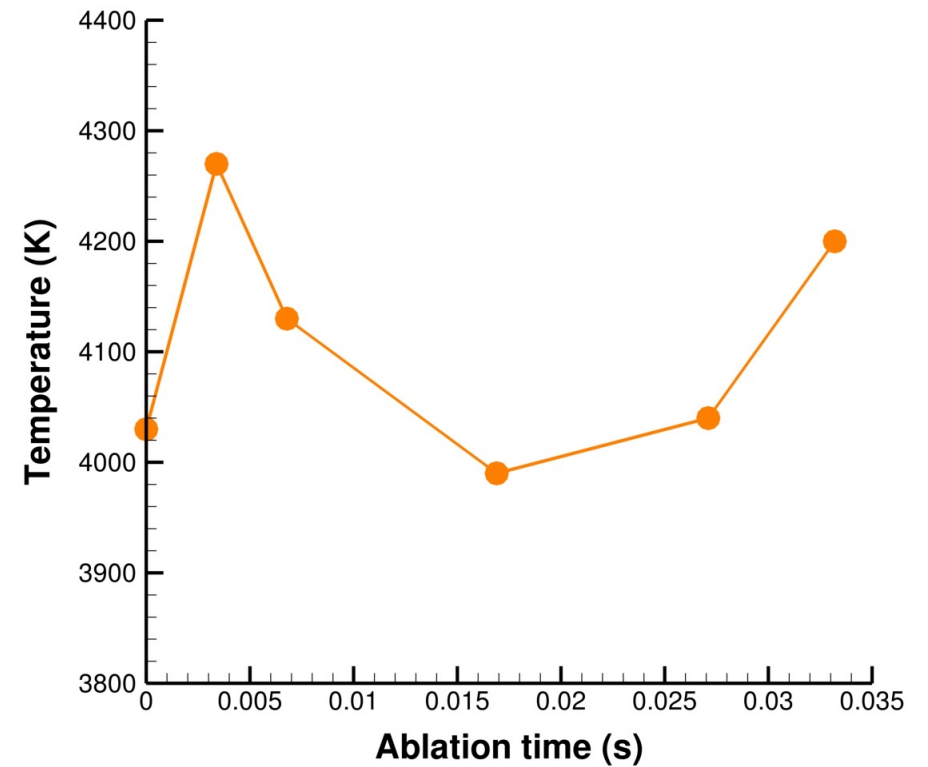
Variation with different geometries



Maximum heat flux from all geometries



Average temperature next to the surface

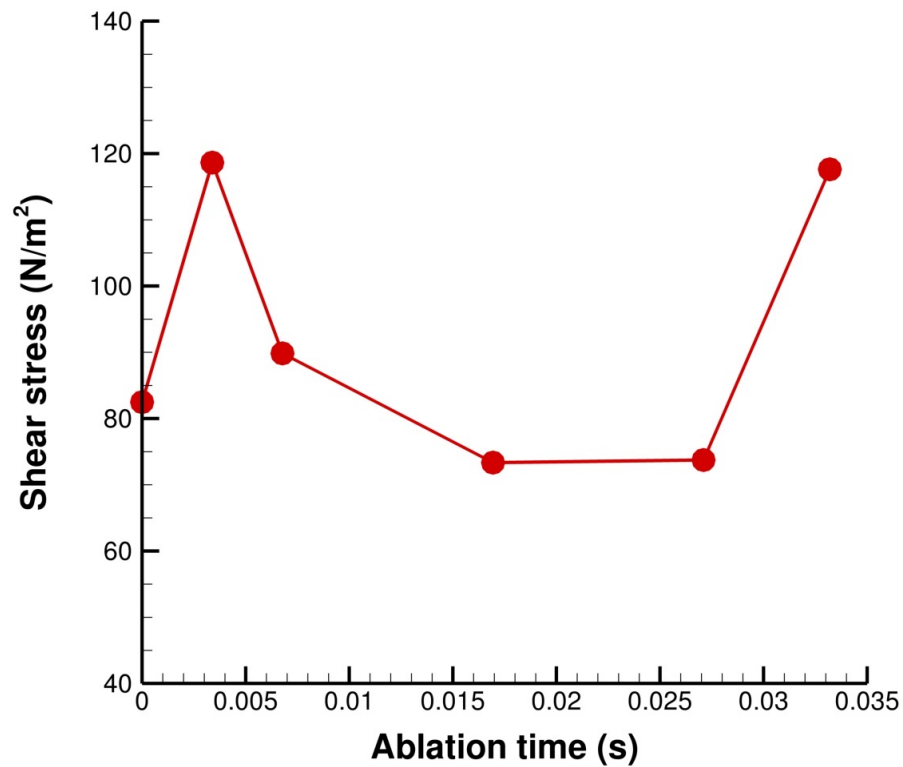


Without Resin - Reaction limited regime

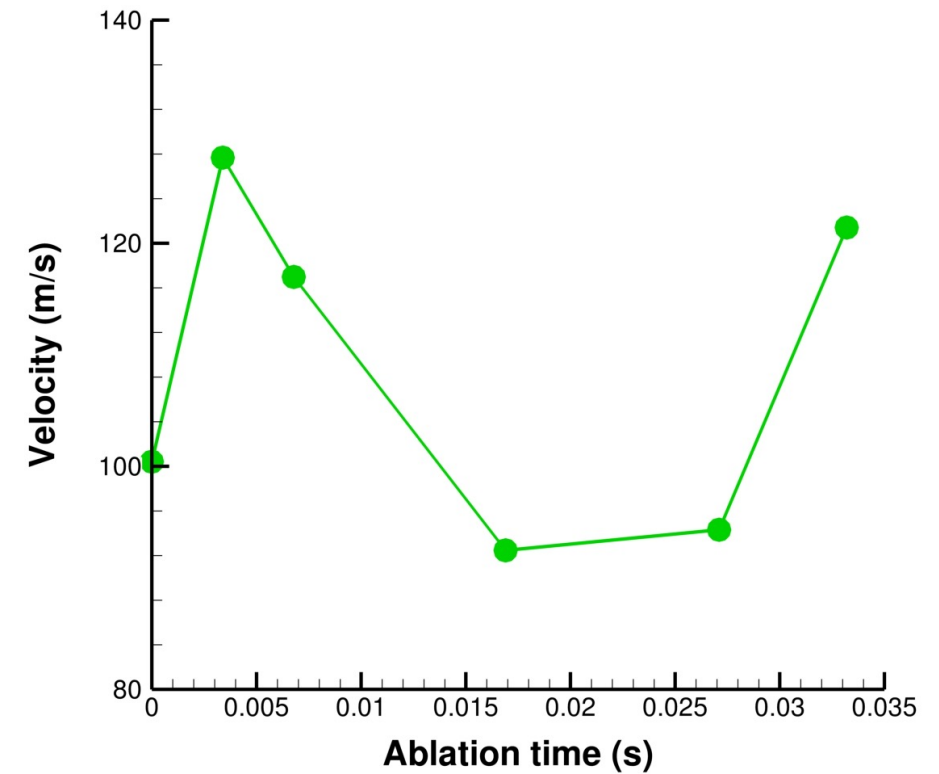
Variation with different geometries



Maximum shear stress from all geometries



Average velocity next to the surface



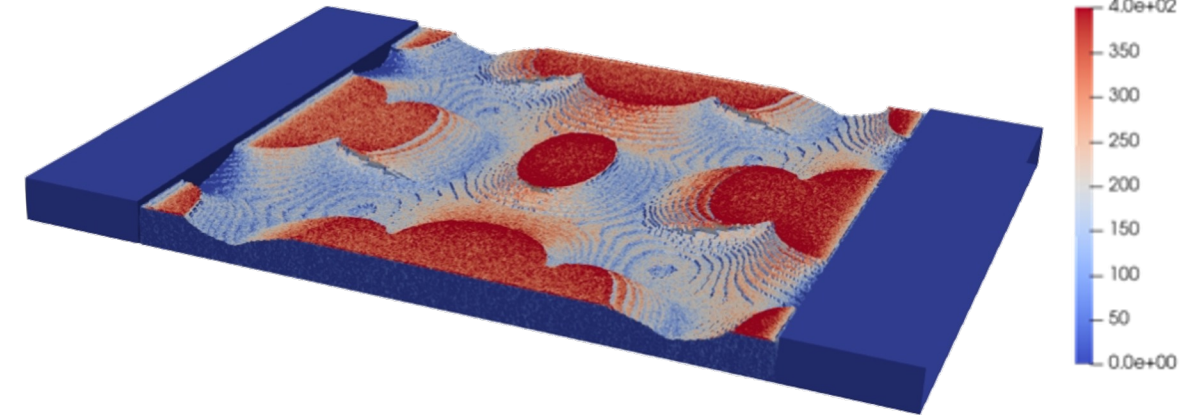
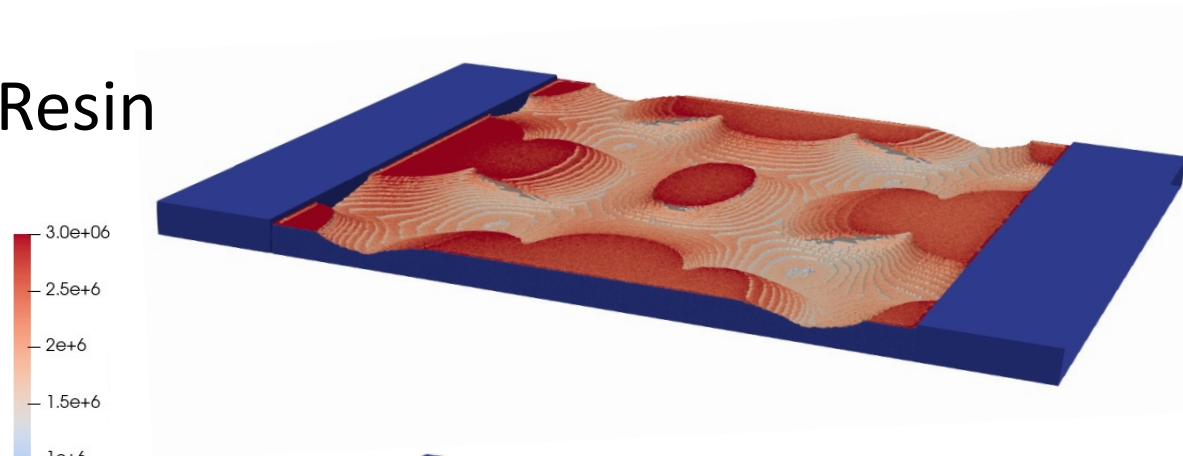
Comparison of with and without resin



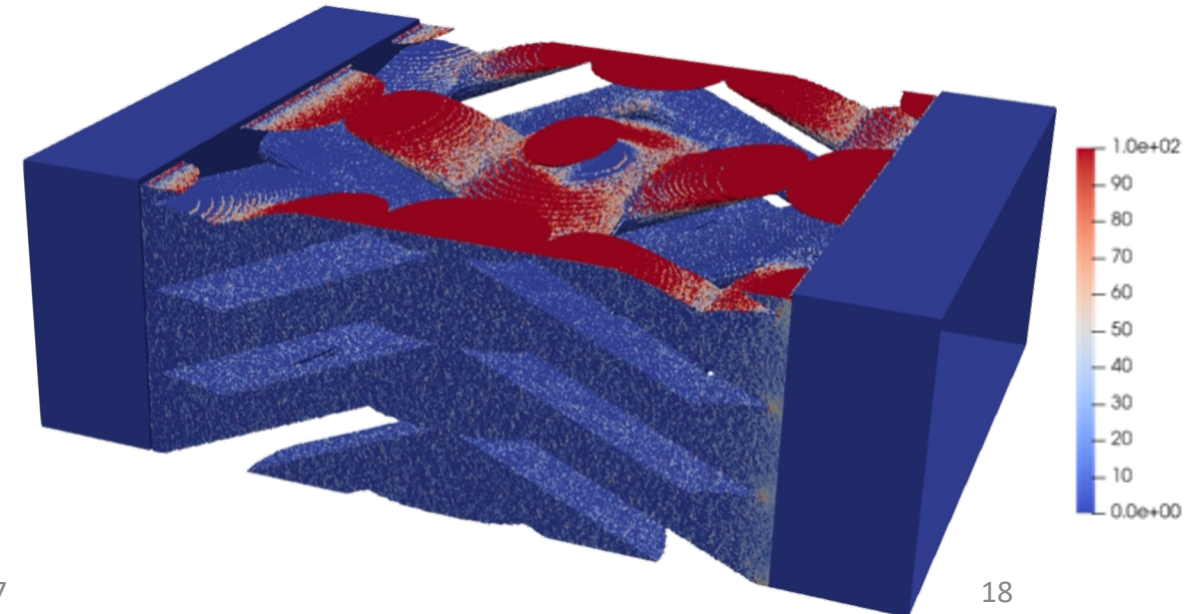
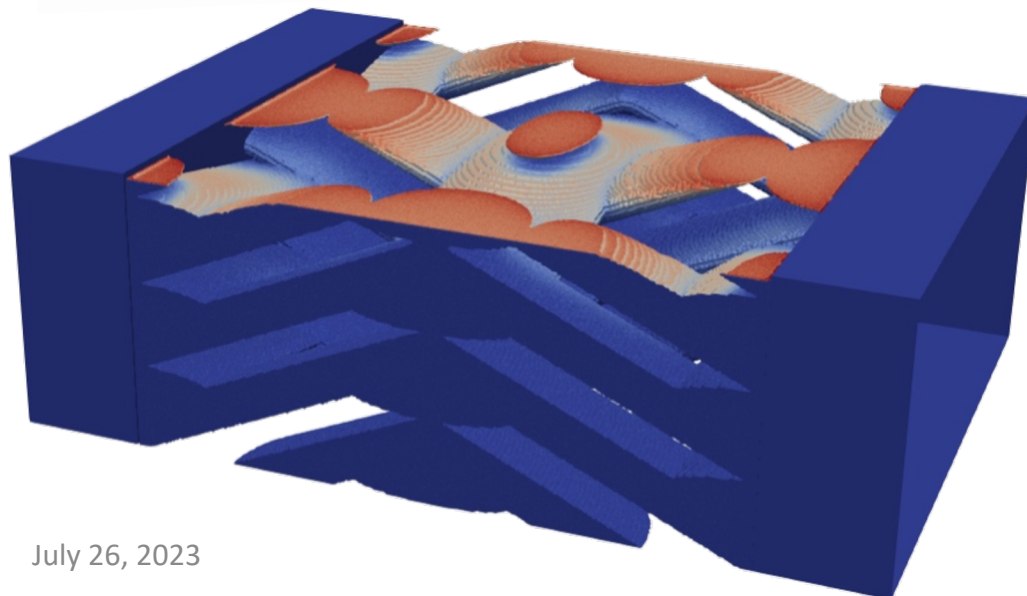
Heat flux (W/m^2)

Shear stress (N/m^2)

Resin



No
Resin



Summary and Future Work

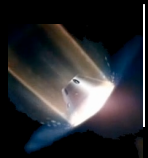


Summary

- Oxidation simulations of woven TPS material were performed in PuMA, and the micro-structure of the material at various stages of chemical degradation were obtained.
- Boundary layer flow simulations were carried out in SPARTA with these geometries: both the extreme limits – diffusion (with resin) and reaction (without resin) limited regimes were considered.
- Various surface properties such as heat flux and shear stress were computed and analyzed for all the geometries.
- Consistent trends were observed between the variation in the surface and flow properties.
- The case with resin had greater heat flux (1.5x) and shear stress (4x) compared to the case without resin and therefore more susceptible to mass loss due to spallation.

Future Work

- Use this information to develop a Spallation model for woven TPS material.



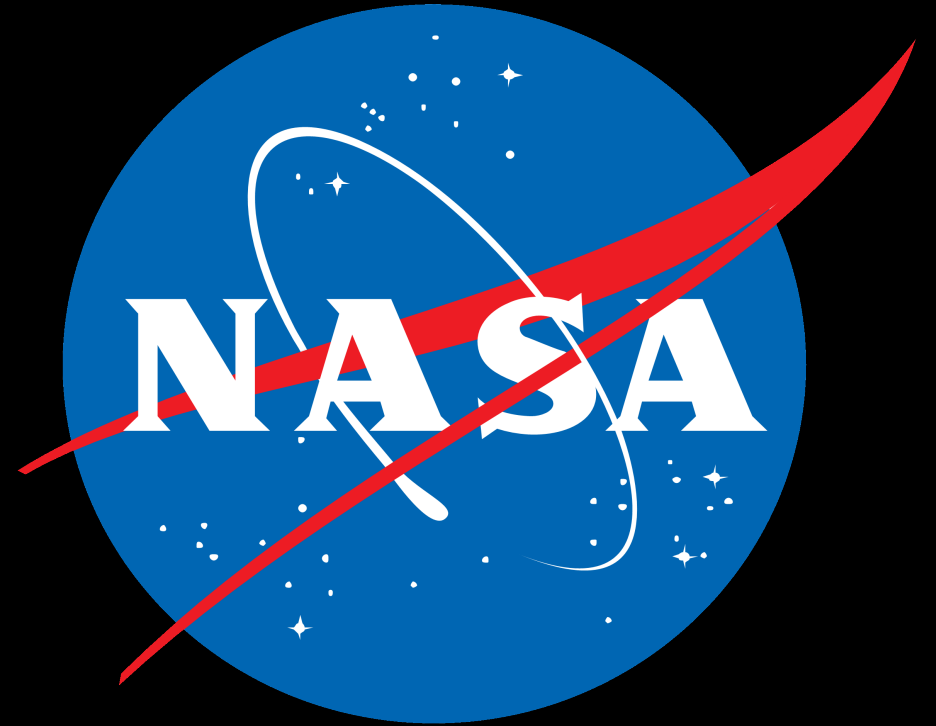
Questions?

Backup – Re-entry flow conditions



V (m/s)	Density (kg/m3)	T (K)	Altitude (km)	Mach #	Dynamic Press (kPa)
10256.0	1.427E-03	263.9	48.1	31.44	75.06

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