ICENES 2011

SAND2011-3355C

Evaluation of Heat Transfer in High-Temperature Refractory Foam Heat Exchangers using Computational Fluid Dynamics

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Albuquerque, NM

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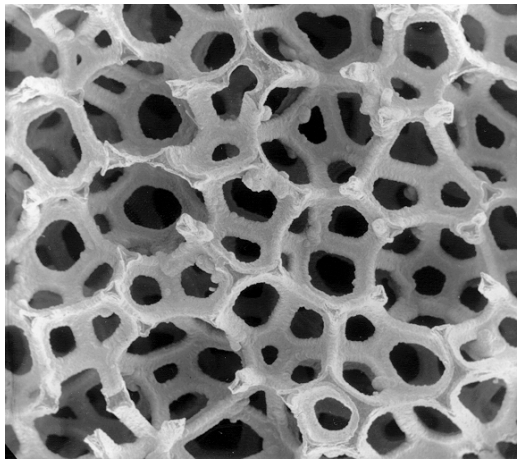
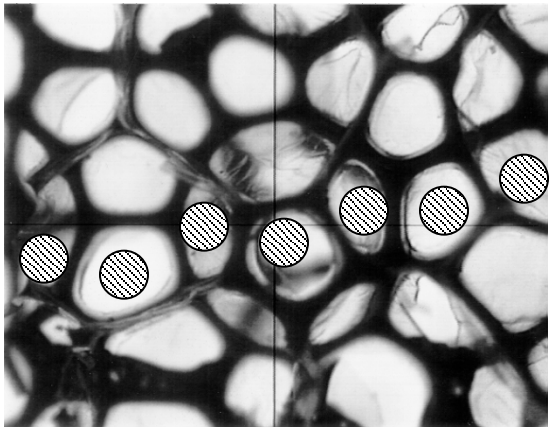
Outline

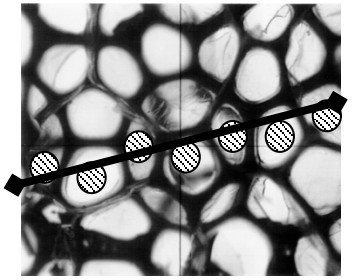
- Porous media - Foam geometry
- Computerized micro-tomography
- Model generation
- Meshing
- Conjugate heat transfer with CFD
- Heat exchanger applications
- Thermal stress analysis

Foam Nomenclature

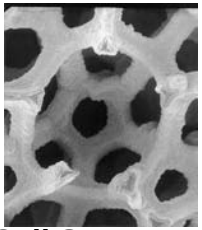




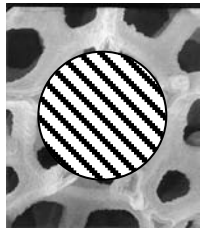
PPI = Pores Per Inch



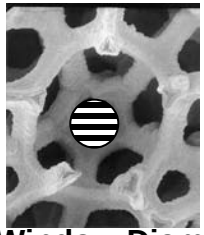
PPI = Pores Per Inch



Cell Structure

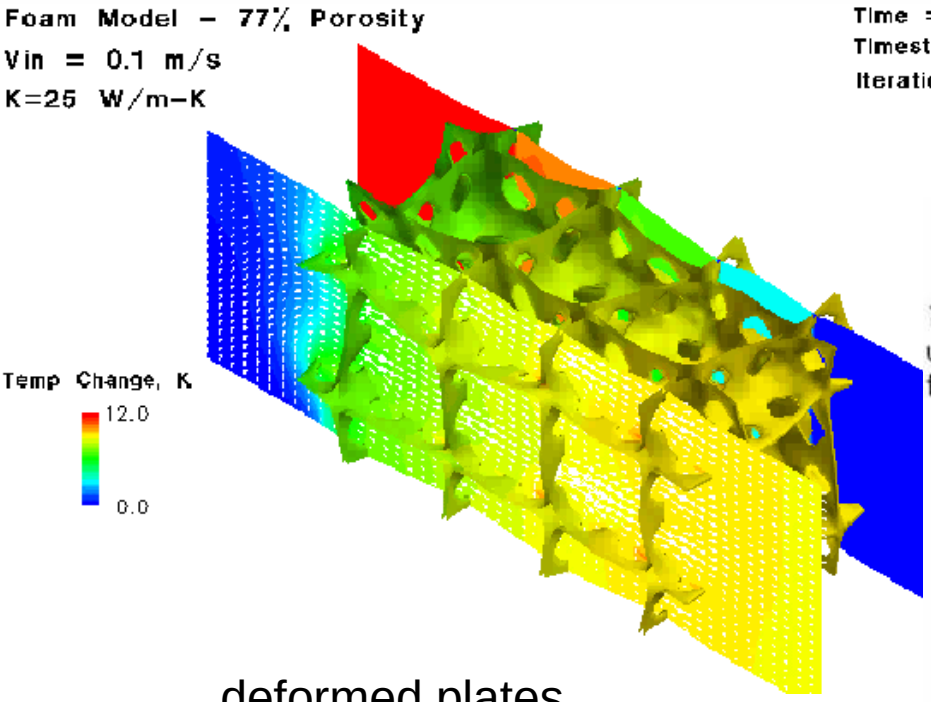


Cell Diameter

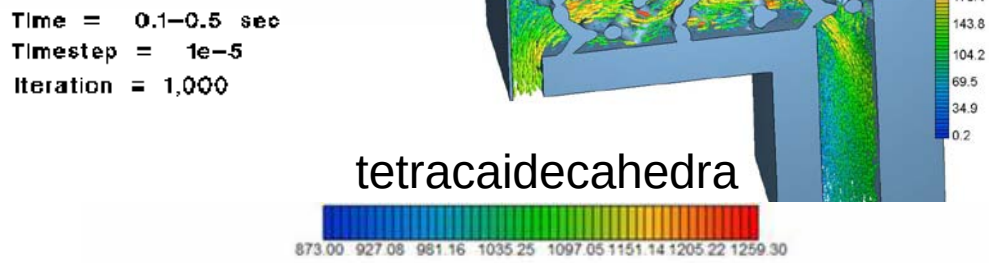


Pore/Window Diameter

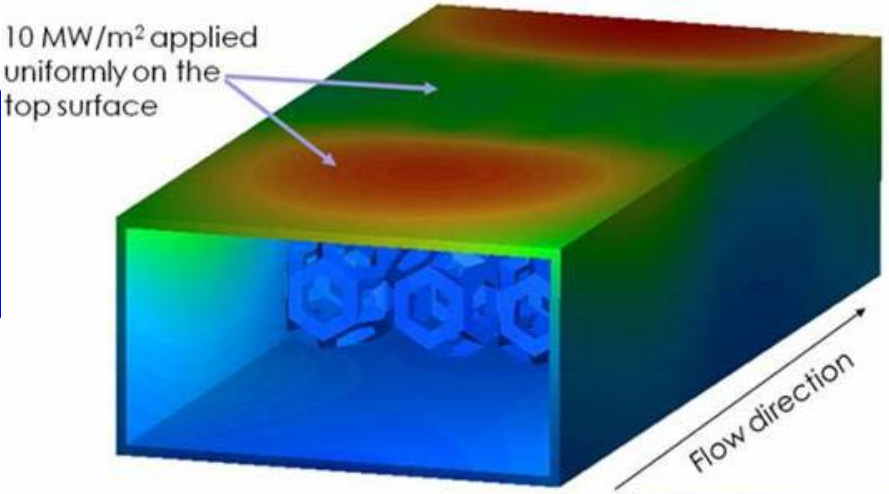
Previous modeling relied on periodic structures.



deformed plates



tetracaidecahedra



All other faces have adiabatic conditions

Front view

Failed to capture the randomness in cell size, window orientation, non-uniform ligaments and other unique characteristics of commercial foams.

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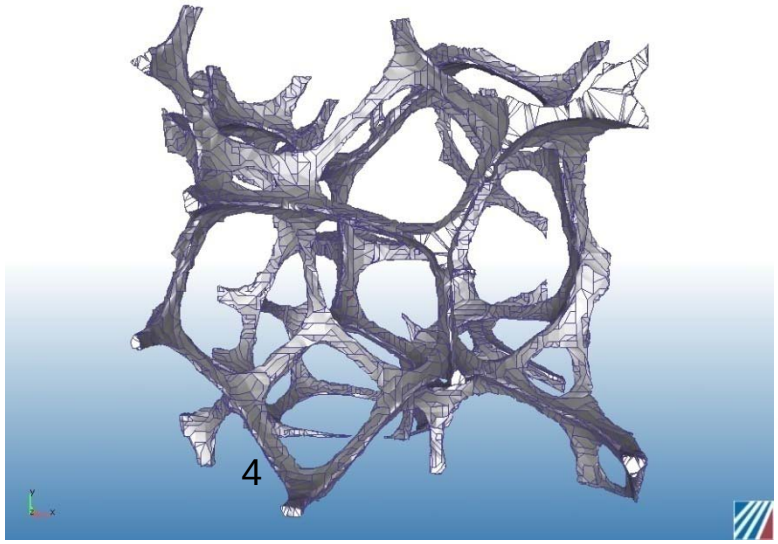
We perform CFD modeling of foam porous media heat transfer on the microscale.

- Computerized X-ray microtomography was completed at Sandia on Ultramet supplied foam samples. The smaller files were translated from stereolithography format to ACIS solid modeling format.
- The solid models of the detailed foam microstructure were meshed and analyzed by commercial computational fluid dynamics (CFD) codes (CFDesign and CCM+) to determine the effective permeability and ligamental heat conduction.
- Foam models derived from computerized x-ray tomography were closed with facesheets of SiC on one side and steel on the other inside CCM+.
- The CCM+ tet mesh was exported to Abaqus for stress analysis.
- Deflections, inelastic strains and stresses were computed in the ligaments and permeation barrier facesheets using Abaqus.

X-ray microtomography file of carbon foam after translation to ACIS solid modeling format.



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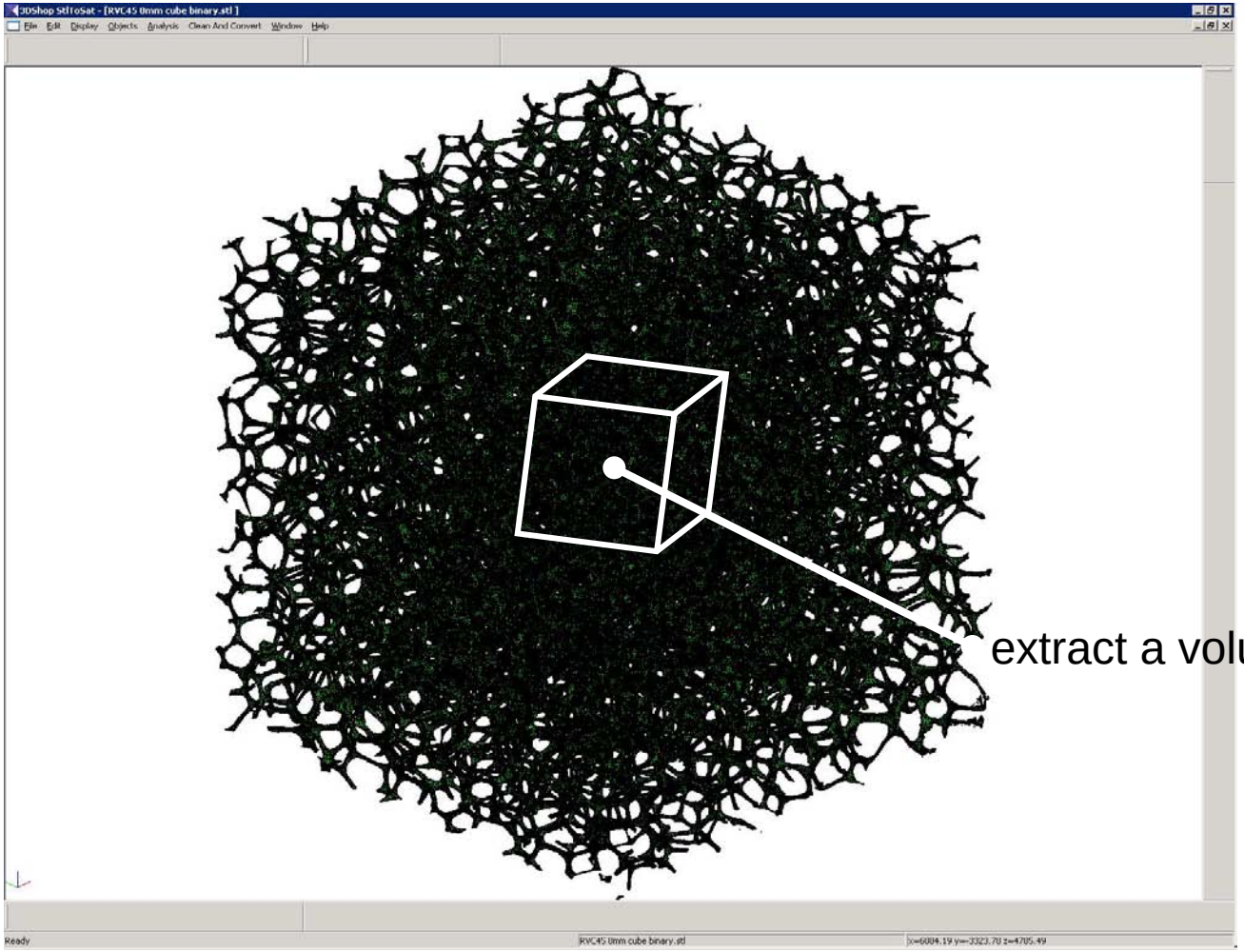
Processing geometry and meshing are greatest challenge.

8 mm x 8 mm x 8 mm 45 ppi RVC skeleton



<u>Tomography</u>

- VGStudio MAX by Volume Graphics

<u>File translation</u>

- 3dShop by C4W
- Rhino 3d
- Cubit
- Star CCM+

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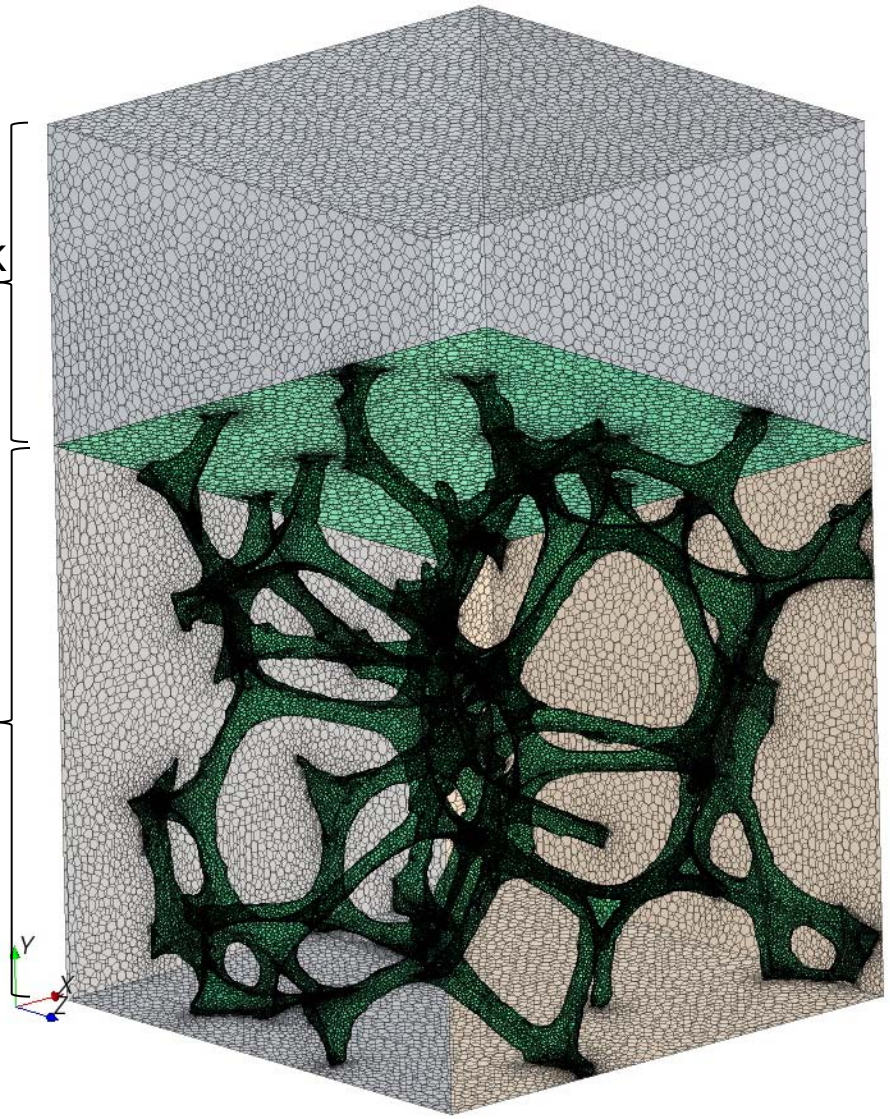
Modeling is computationally expensive.



Commercial CFD Codes

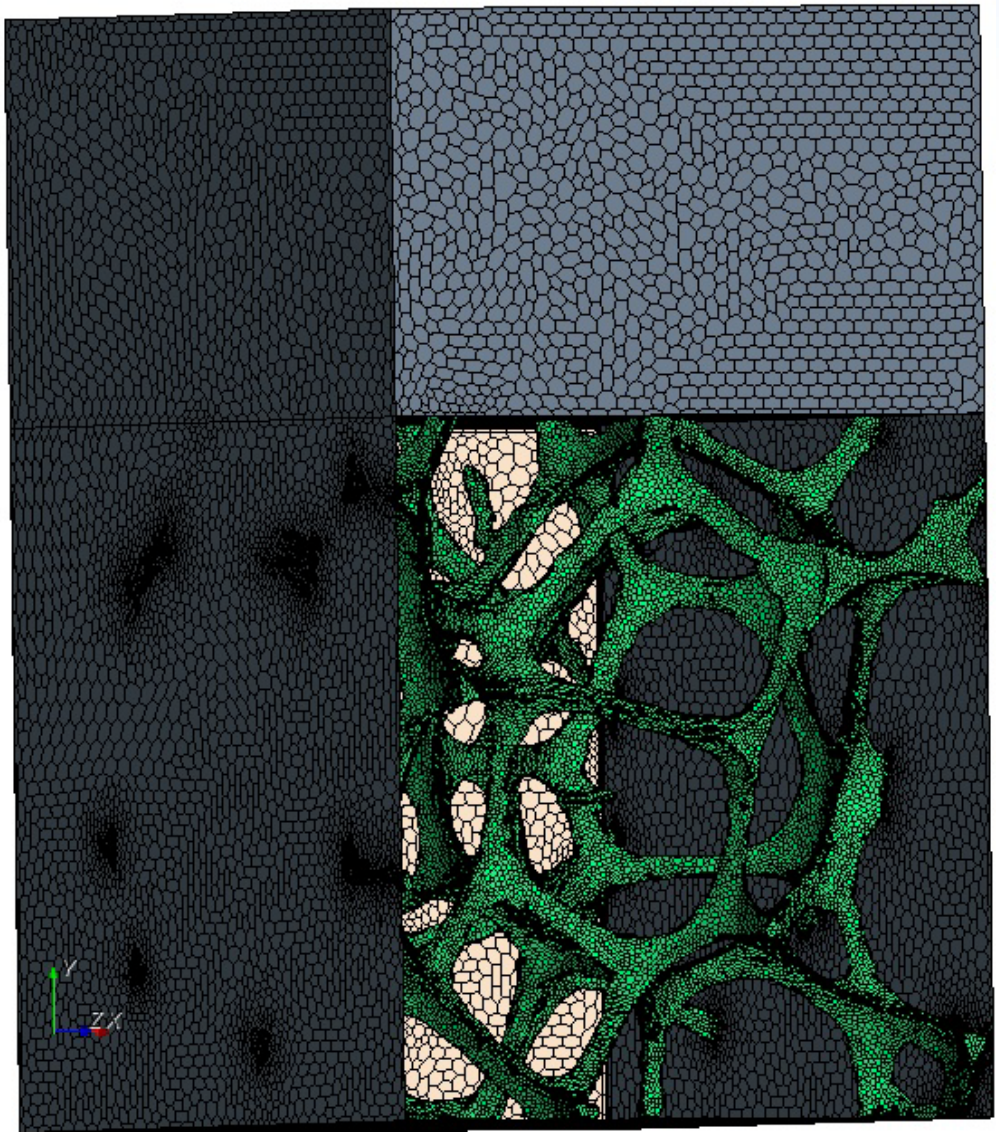
- Star-CCM+ v5.04
- Cfdesign v10

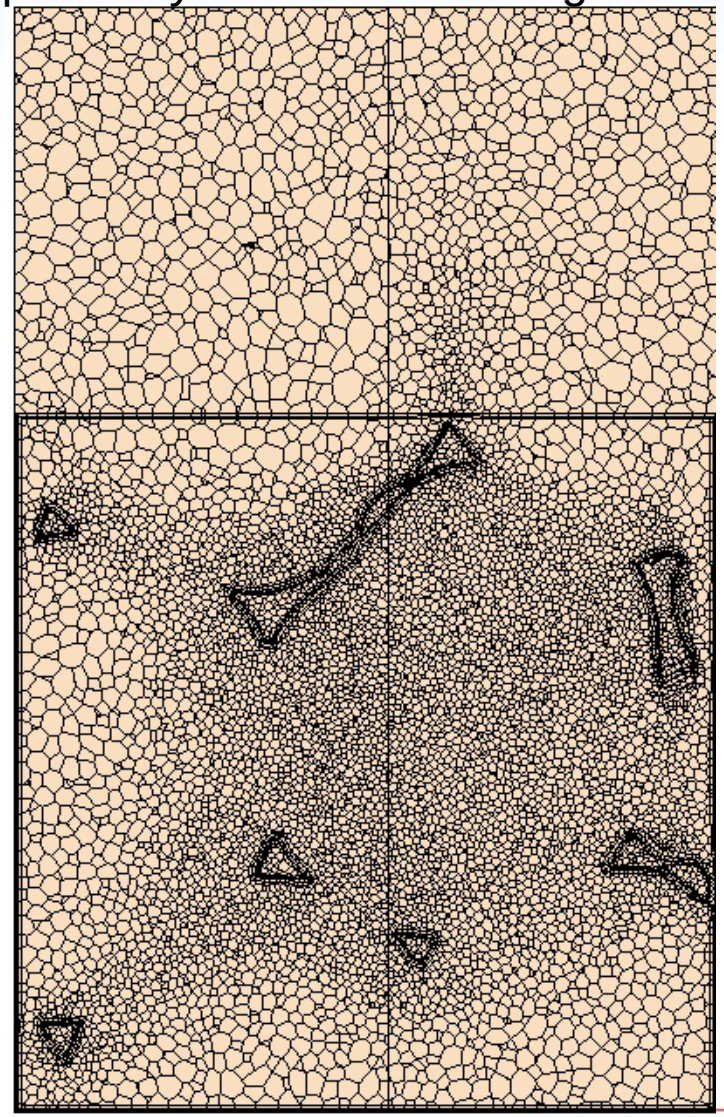
One-million element polyhedral mesh with three prism layers at all solid/gas interfaces.

1.7 mm x 1.7 mm x 2.7 mm high. Arbitrarily chosen volume extracted from 8x8x8 mm^3 volume shown earlier. Wall added in CCM+.

Imprint and merge 3 solids and a fluid

3 prism layers at walls and ligaments





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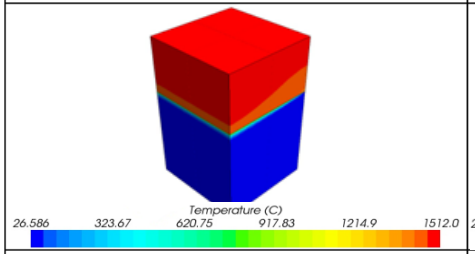
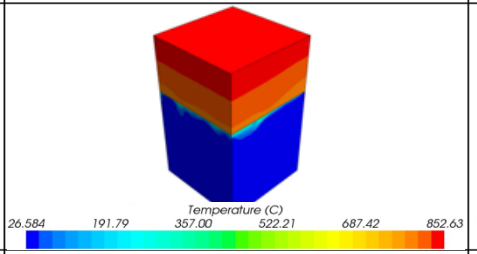
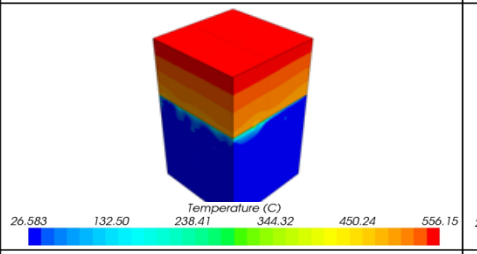
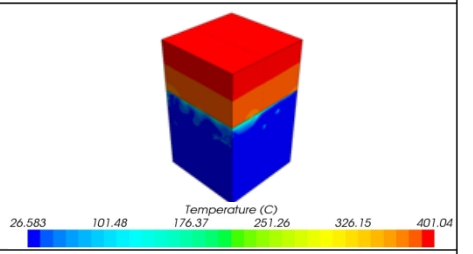
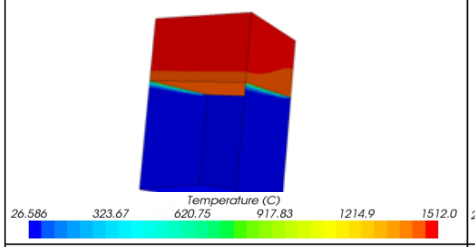
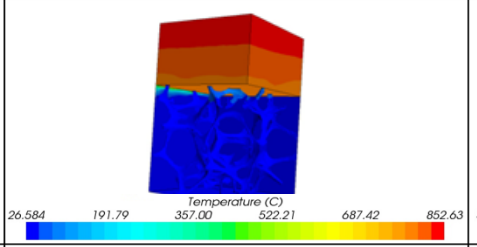
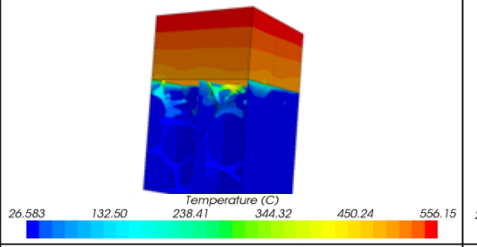
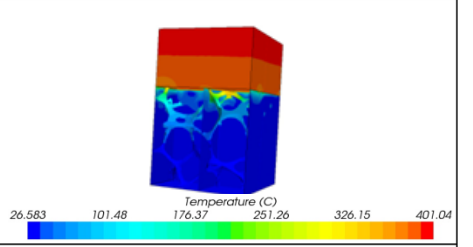
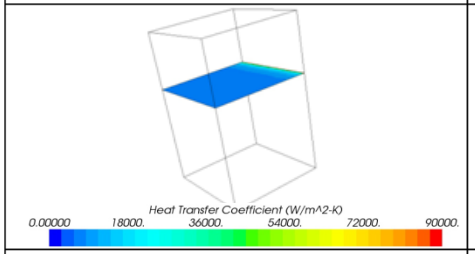
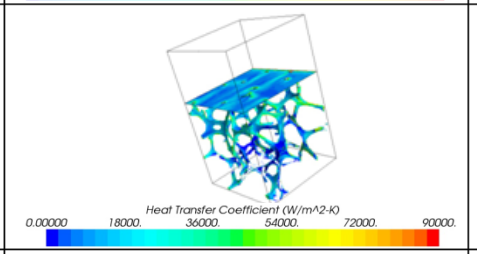
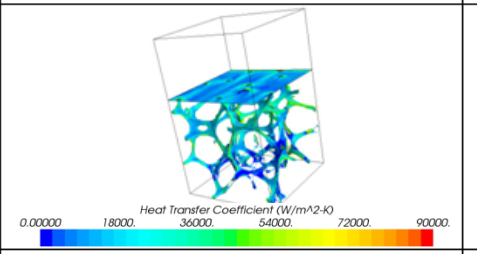
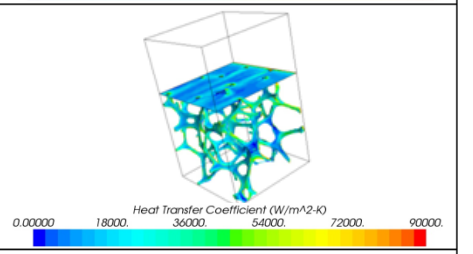
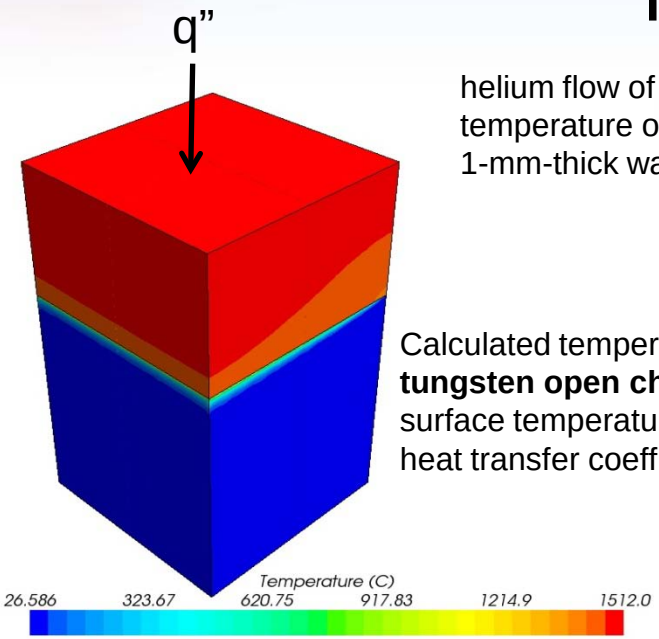
Porous media is effective in enhancing gas cooling.

Table 1. Comparison of Foam Effectiveness to Open Channels

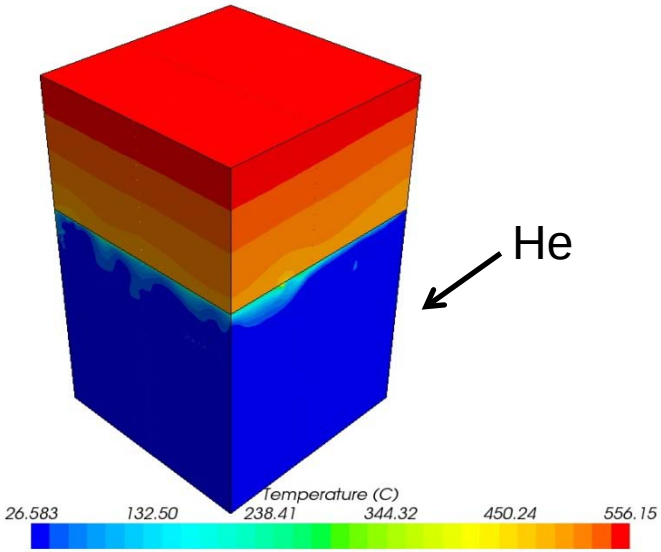
Open Channel	Unconnected 45-ppi W foam	Connected 45-ppi W foam	Connected 45-ppi Cu foam
			
			
			
h=7100 W/m^{2}K	h=13,200 W/m^{2}K	h=21,500 W/m^{2}K	h=28,350 W/m^{2}K

Conductivity of foam can affect performance.



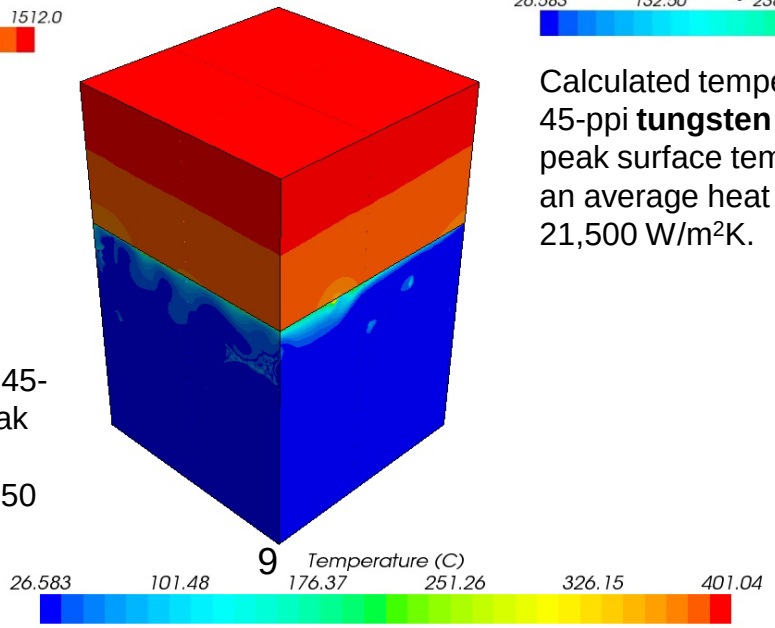
helium flow of 1 g/s at 4 MPa with an inlet temperature of 26.8 ^{o}C. q”=5 MW/m^2 on a 1-mm-thick wall.

Calculated temperature distribution in a **tungsten open channel** duct reveals a peak surface temperature of 1512 ^{o}C with an average heat transfer coefficient of 7100 W/m^{2}K.



Calculated temperature distribution in a 45-ppi **tungsten foam channel** reveals a peak surface temperature of 556 ^{o}C with an average heat transfer coefficient of 21,500 W/m^{2}K.

Calculated temperature distribution in a 45-ppi **copper foam channel** reveals a peak surface temperature of 401 ^{o}C with an average heat transfer coefficient of 28,350 W/m^{2}K.



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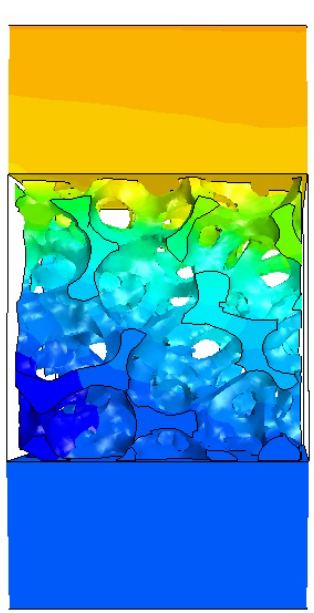
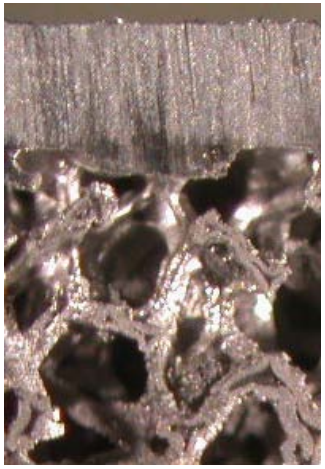
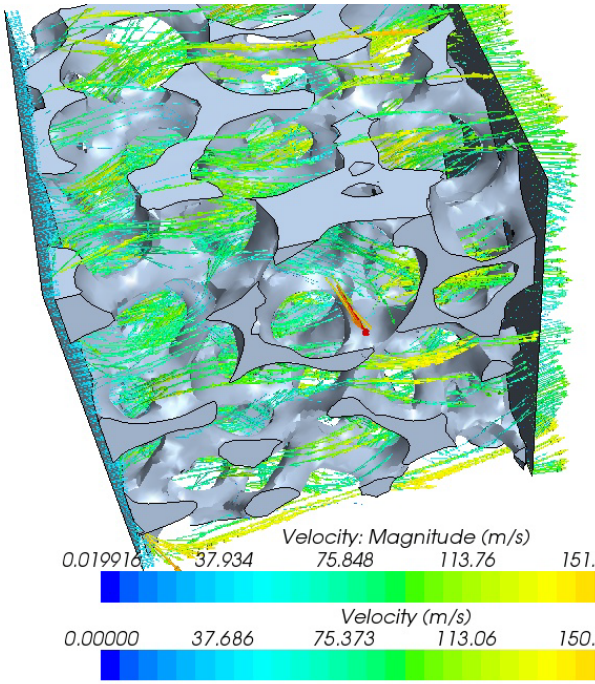
Analysis reveals turbulent mixing and fin effect created by foam.

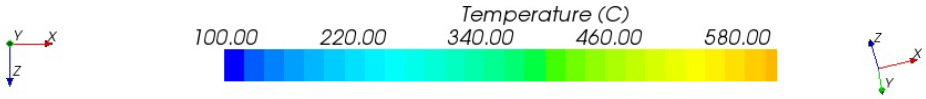
627 C

27 C He









Convection models for 2 mm x 2 mm 65 ppi, 10% dense moly foam attached to 1 mm thick moly walls. Temperature distribution is shown on left with velocity vectors and streamlines through the foam on the right.

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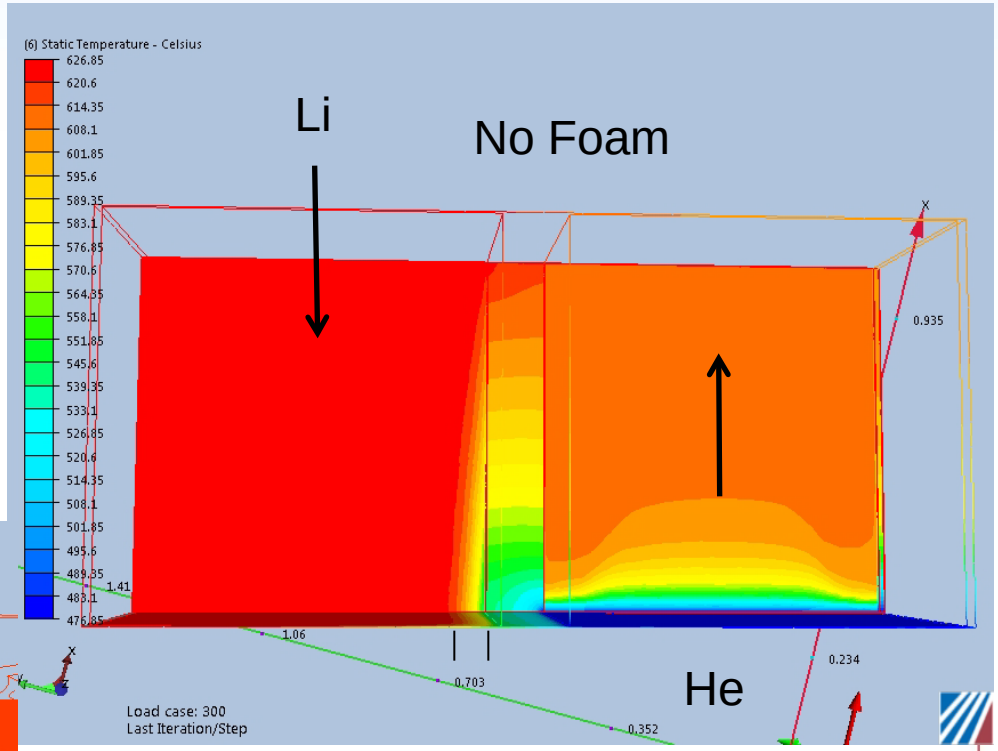
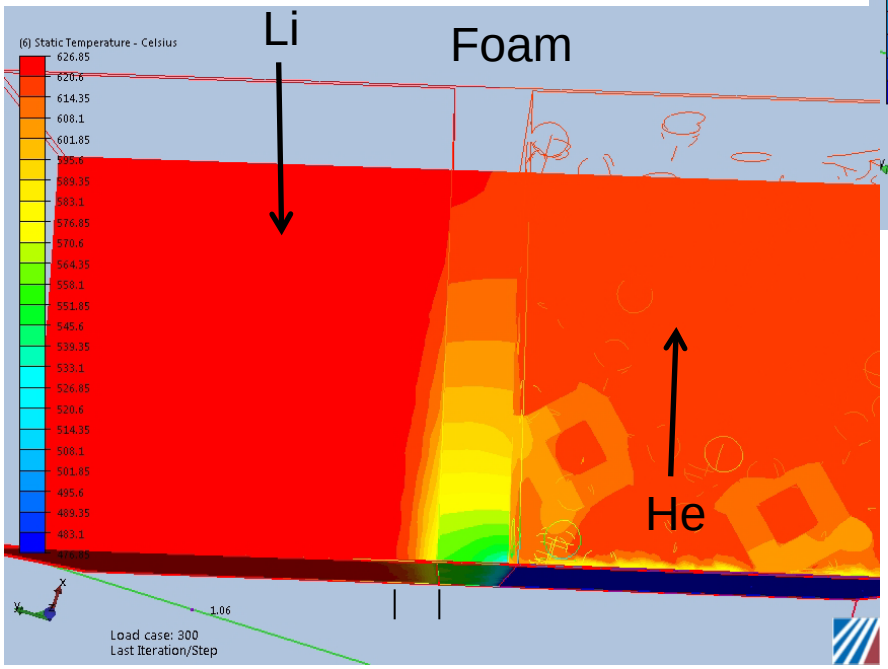
Foams can enhance heat transfer in open channels of dual coolant schemes if the foam is bonded to the intervening wall.





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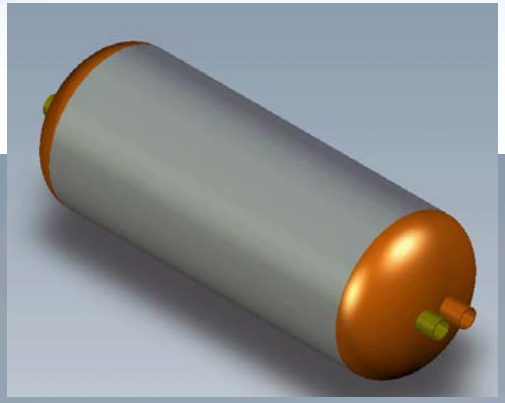
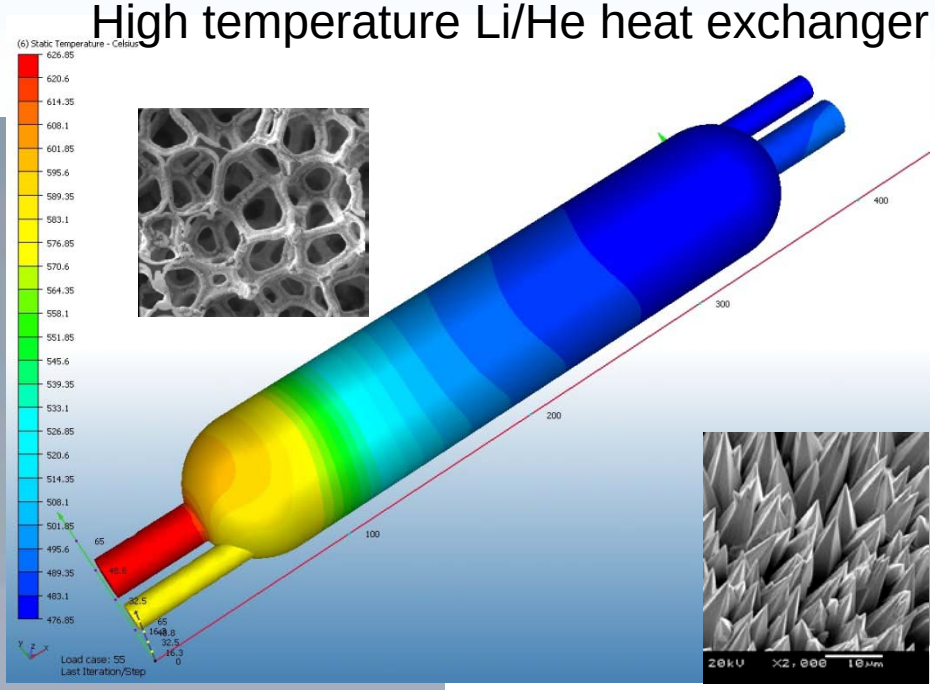
Refractory heat exchangers are under fabrication.

All Mo



High temperature Li/He heat exchanger



ε_{hx} = (T_c, He out - T_c, He in) /(T_h, Li in - T_c, He in)

$\varepsilon_{hx}=h_L A_L/(\text{m-dot}_L C_{p(L)})/[1+h_H A_H/(\text{m-dot}_H C_{p(H)})]$

HX effectiveness

High temperature He/He regenerator

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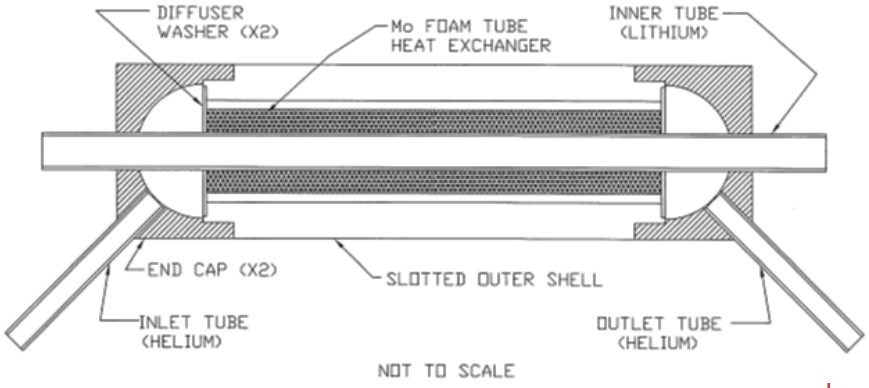
Li/He design concept

- The classic counterflow flat plate heat exchanger can have high specific area, on the order of 3000 m^2/m^3. This design can be improved if refractory foam is added to the gas channels. Molybdenum foam on the order of 65 ppi and 20% dense can have a specific surface area as high as 7000 m^2/m^3 exposed to helium.
- The dendritic molybdenum coating can increase the lithium-exposed area by a factor of two to three depending on dendrite size (shape and height). This new configuration more than doubles the convective heat transfer area between lithium and helium.
- Since the dendrites and foam are integrally bonded to the wall, conduction through the thermal boundary layer is enhanced from the lithium into the bulk helium gas stream, improving the heat transfer by an additional 10%.
- The foam on the helium side promotes turbulence and mixing, resulting in a very low temperature difference between the inlet lithium and exit helium (several degrees). The dendrites aid wetting of the molybdenum wall by lithium, yet do not represent a restriction or increase the pressure drop by reducing the channel size to the point where surface tension and capillary forces dominate.

LiHe HX Prototype

Views showing Mo Inner Tube + Mo foam fully slid into the ID of Mo

Mo foam heat exchanger slid over Mo inner Tube with dendritic internal coating



Fully-Assembled Prototype (before brazing)

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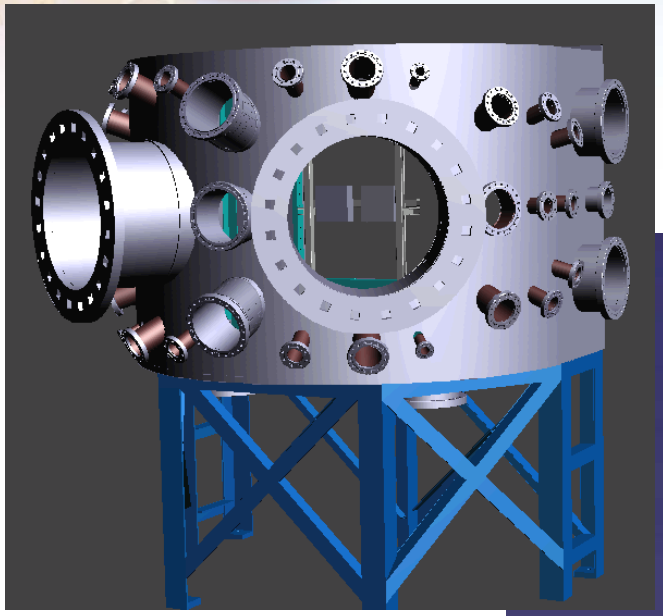
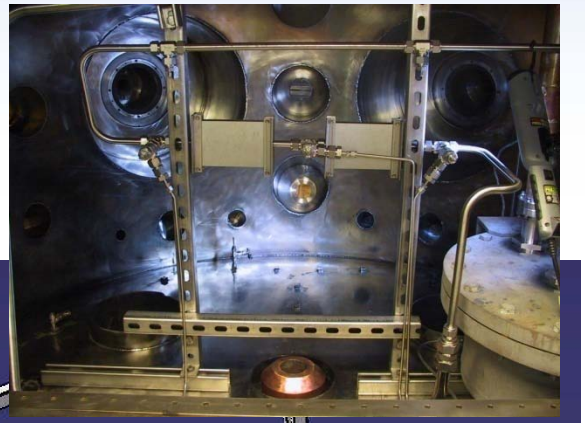
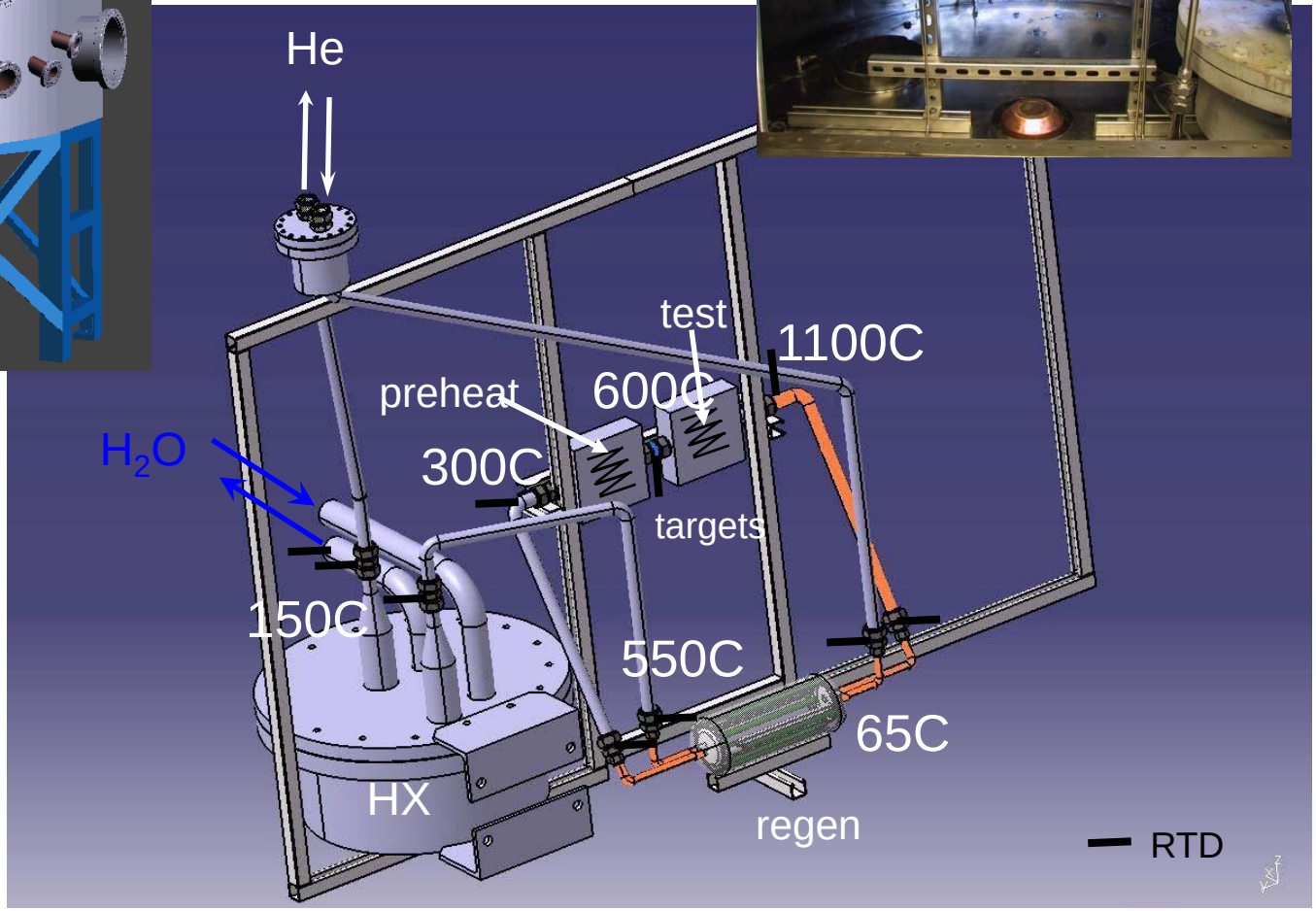
HHF testing of helium-cooled panels underway at PMTF.





- Short hi-temp runs (Mo)
- In-vacuo
- Experimental
- Low cost
- Small impact on HeFL loop



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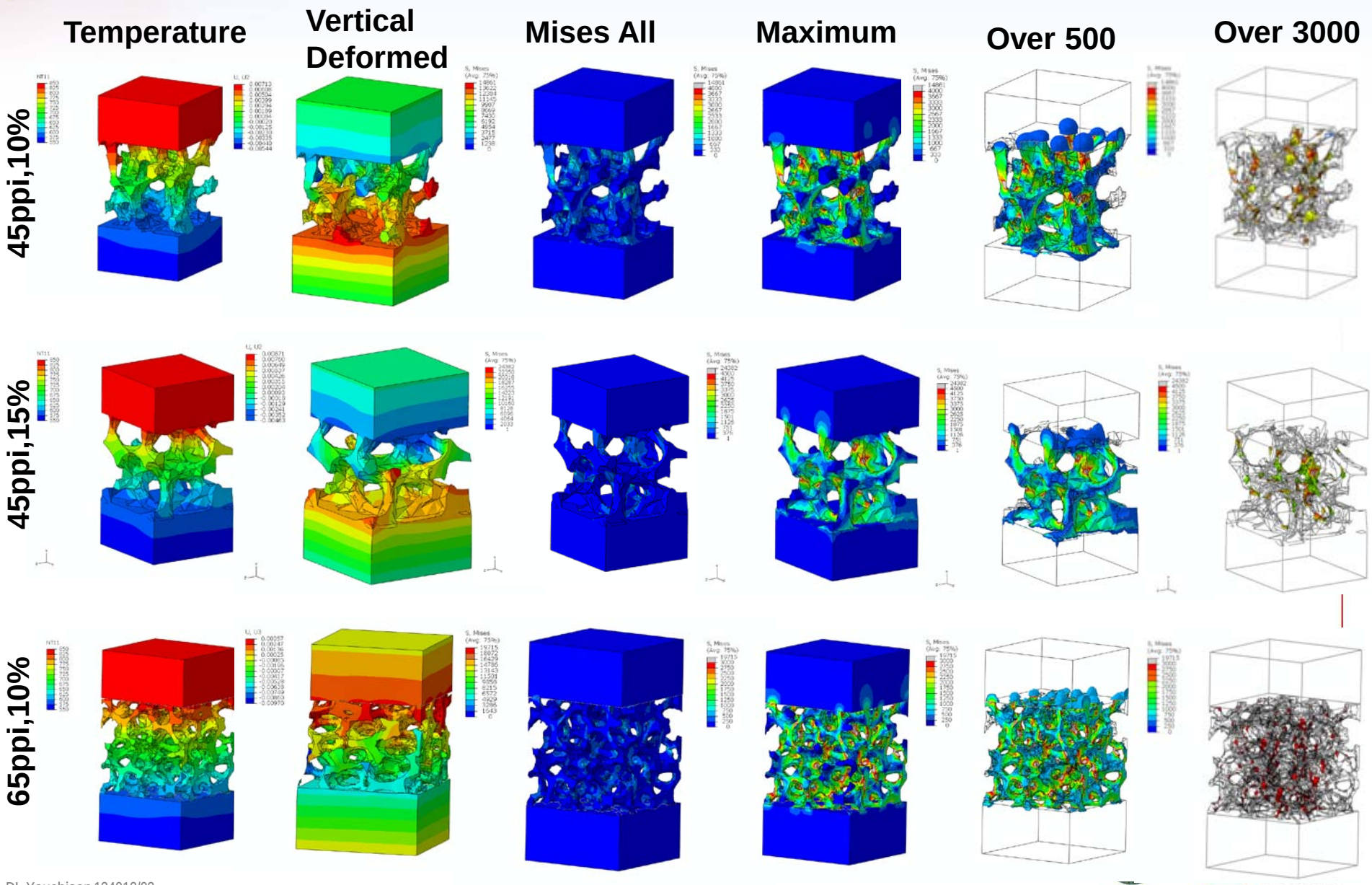
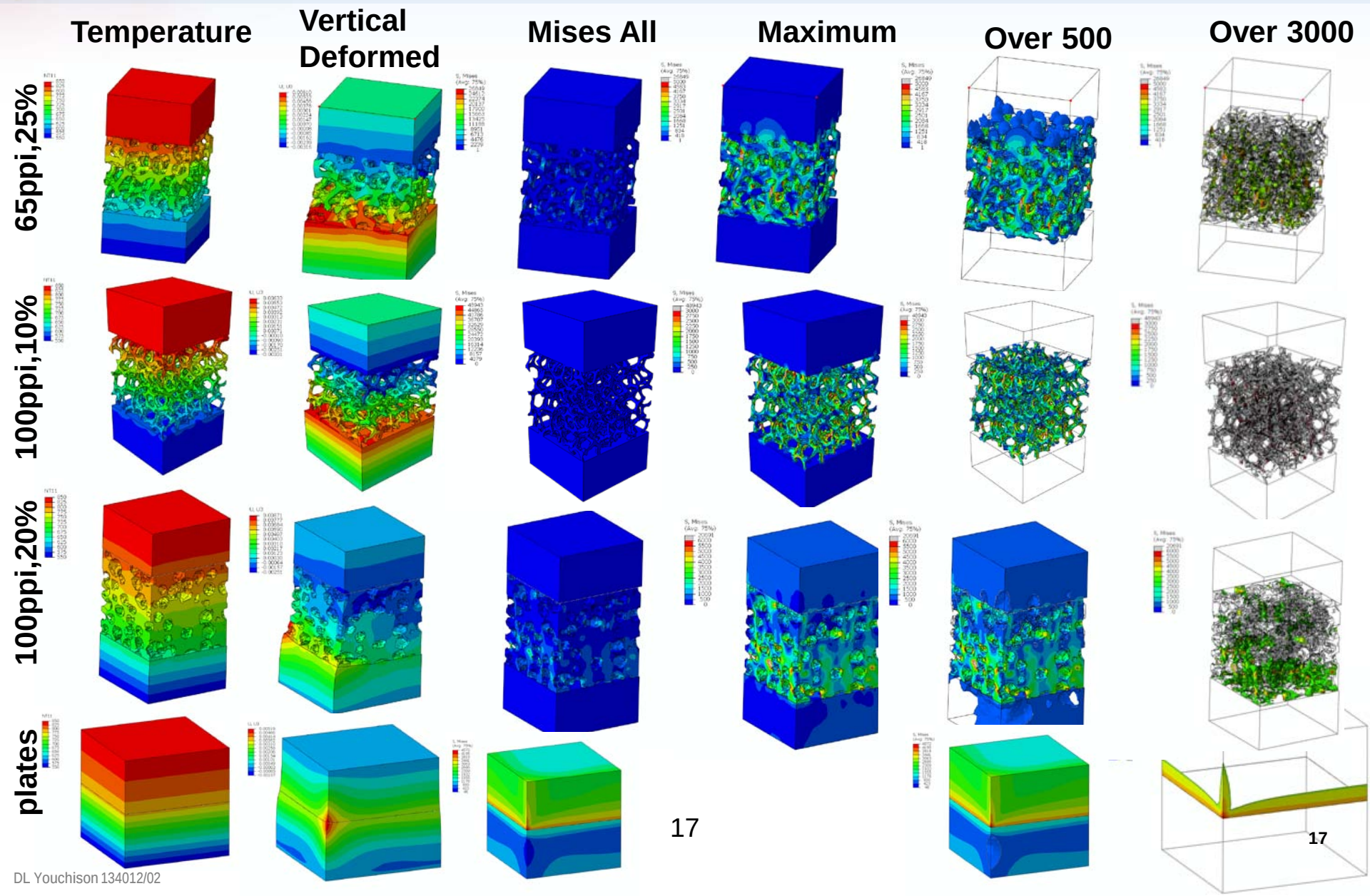
Modeling of SiC Foam



Modeling of SiC Foam



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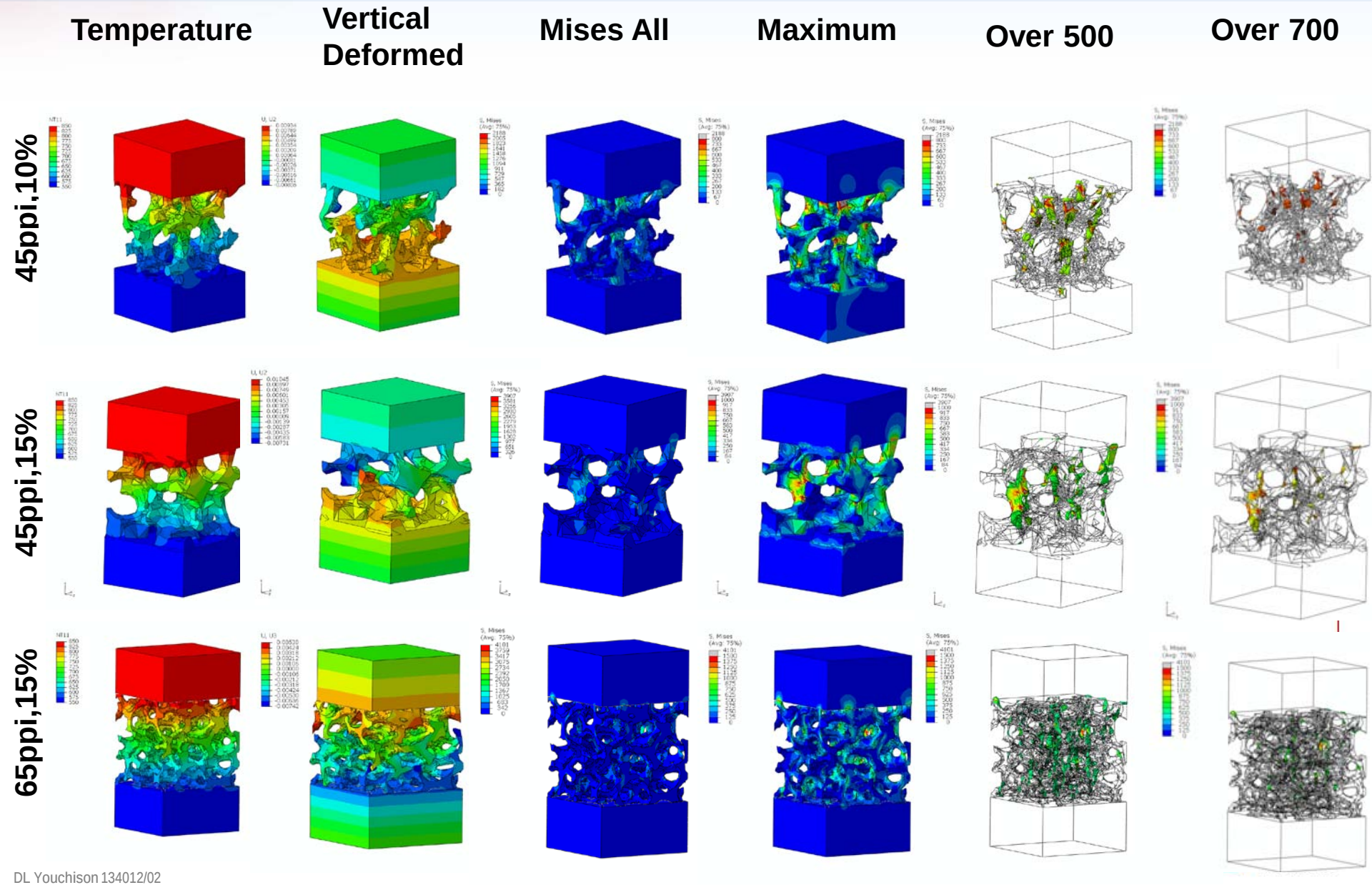
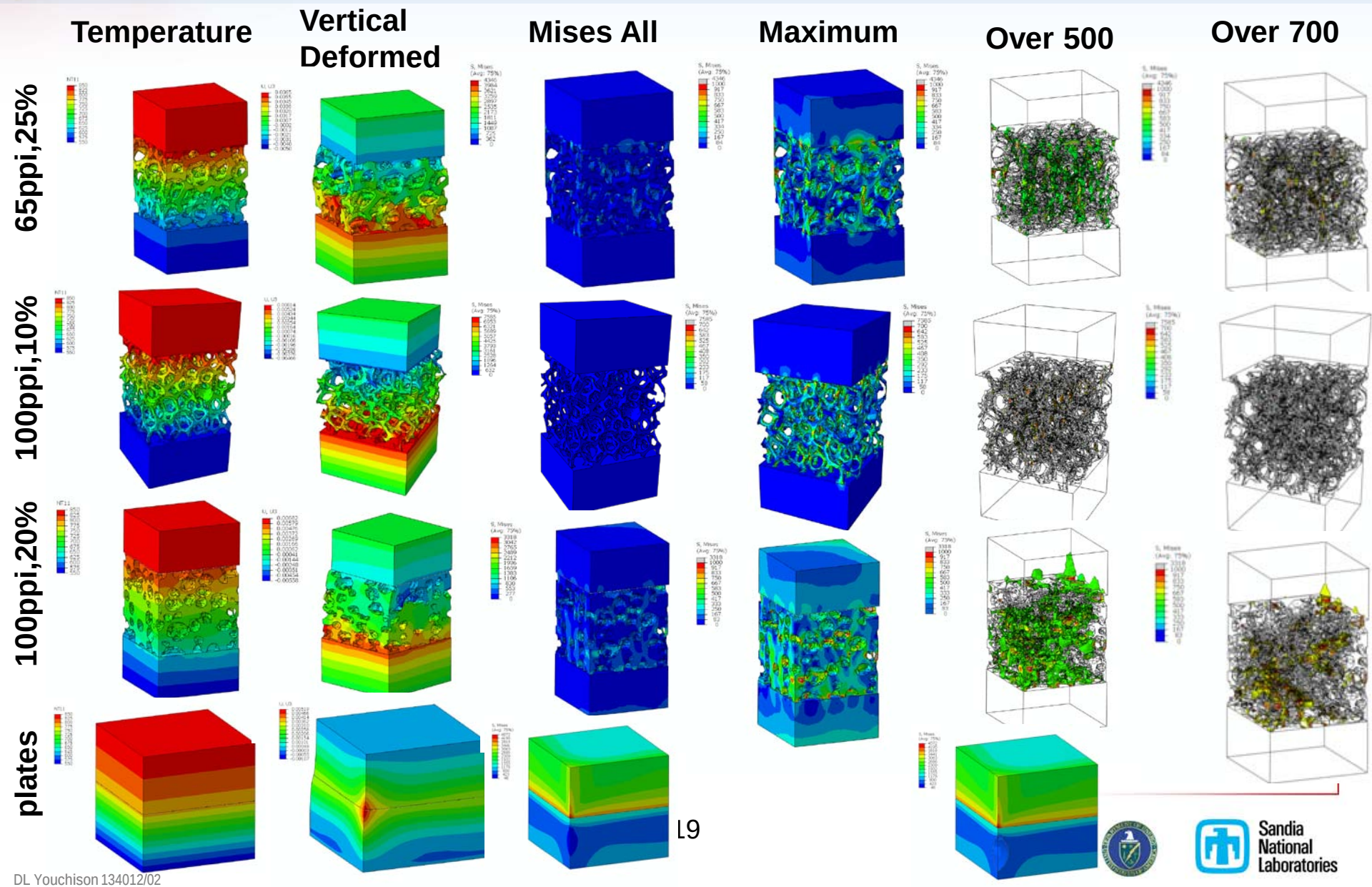
Modeling of Nb Foam



Modeling of Nb Foam



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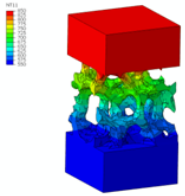
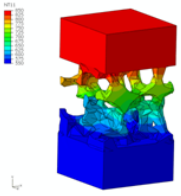
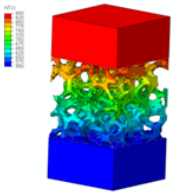
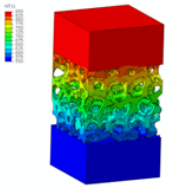
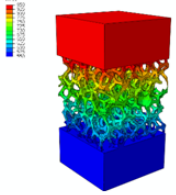
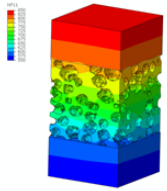
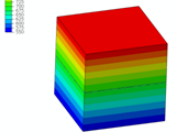
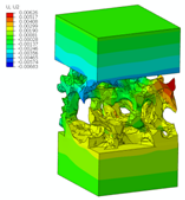
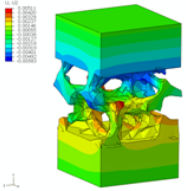
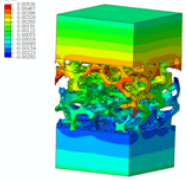
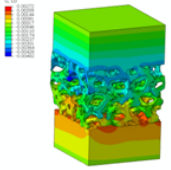
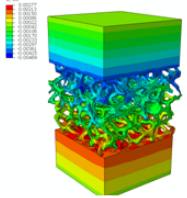
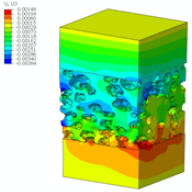
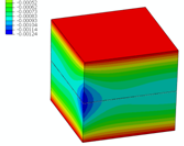
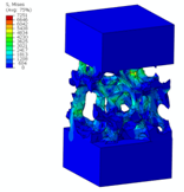
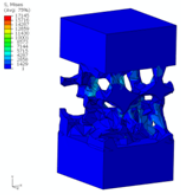
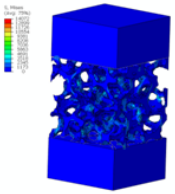
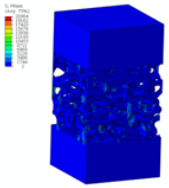
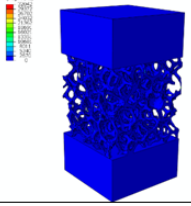
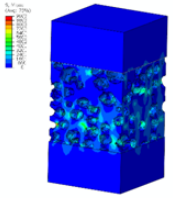
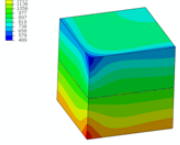
Modeling of Mo Foam

	Mo-Mo-Mo 45 ppi/10%	Mo-Mo-Mo 45 ppi/15%	Mo-Mo-Mo 65 ppi/10%	Mo-Mo-Mo 65 ppi/25%	Mo-Mo-Mo 100 ppi/10%	Mo-Mo-Mo 100 ppi/20%	Plates
Temp							
Vertical def.							
Mises All							

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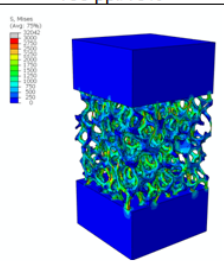
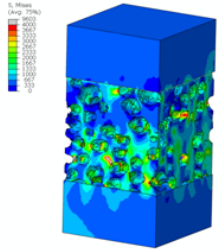
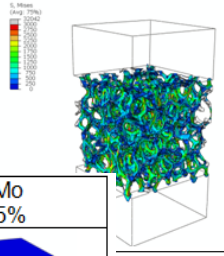
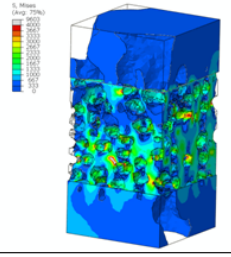
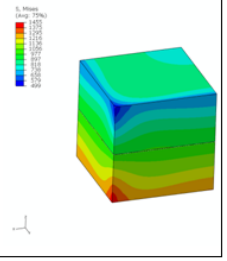
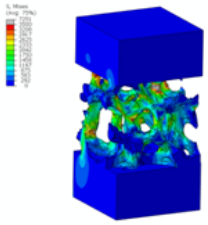
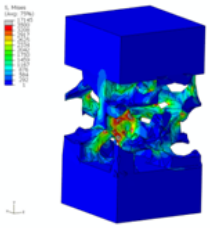
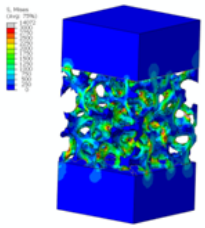
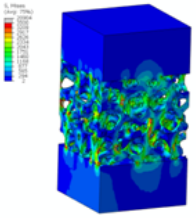
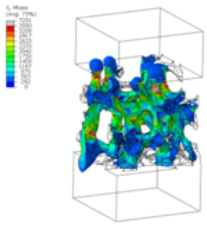
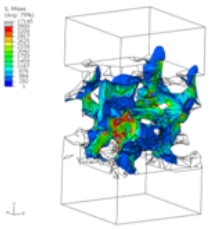
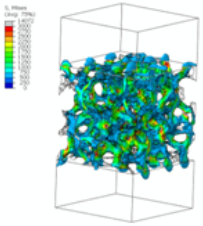
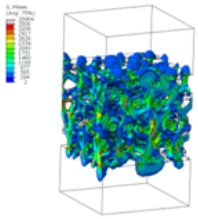
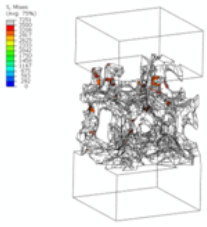
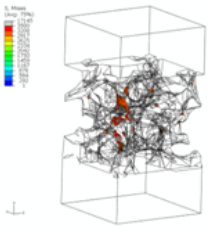
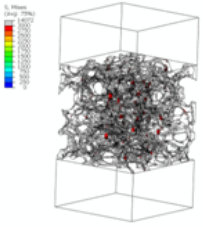
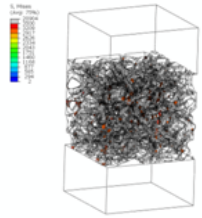
Modeling of Mo Foam

	Mo-Mo-Mo 100 ppi/10%	Mo-Mo-Mo 100 ppi/20%	Plates
Max			
>500			

	Mo-Mo-Mo 45 ppi/10%	Mo-Mo-Mo 45 ppi/15%	Mo-Mo-Mo 65 ppi/10%	Mo-Mo-Mo 65 ppi/25%
Max				
>500				
>3000				

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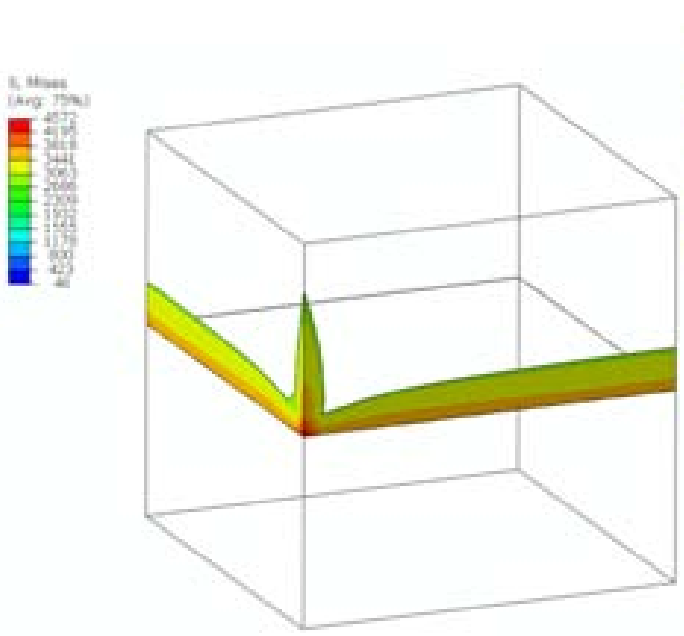
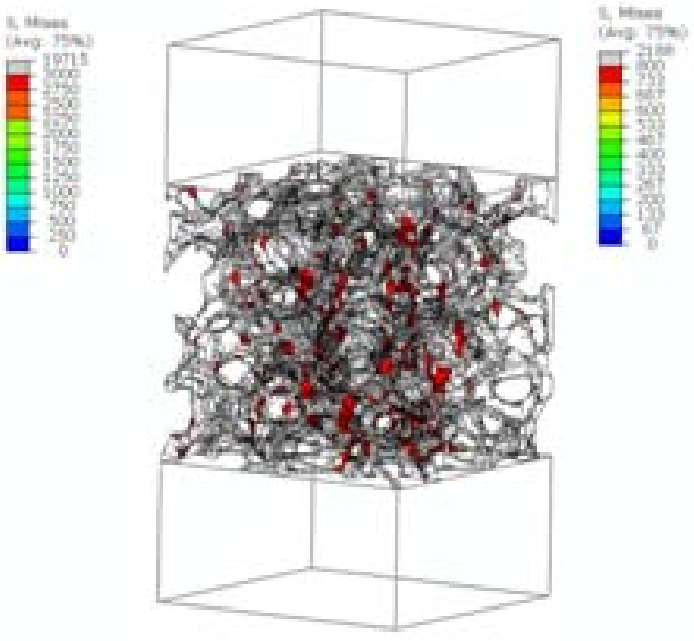
Thermal stress summary

- Nb foam with 45ppi 10% dense has the lowest thermal stress of all, followed by Mo and SiC (roughly x3 and x4 higher)
- The SiC foam with 65 ppi 10% density has the lowest stress for the SiC foams. The 100 ppi cases were higher.
- Stresses increased with density. Effect of ppi not as clear.
- In all cases the foam reduces the stress in the faceplates as expected, the Nb foam by an order of magnitude.
- The SiC foam was not as effective because of higher stresses in the ligaments, but stresses in the faceplates were still very low.

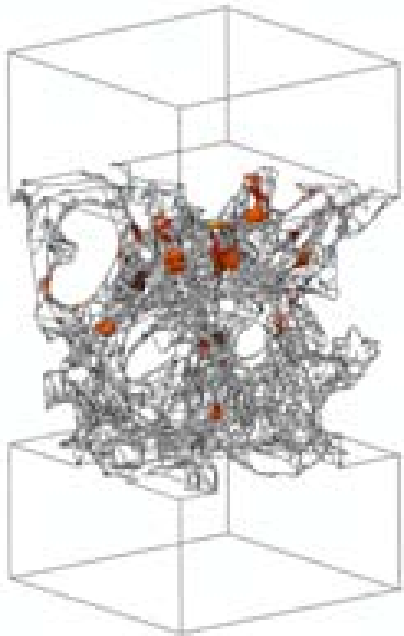
Plates (over 3000)



65ppi, 10% SiC foam (over 3000)



45ppi, 10% Nb foam (over 700)



Concluding remarks

- modeling of porous media on micro-scale now possible
- 64-bit, 4 to 16-node MPI computations, 98 GB ram
- tomography useful for reverse engineering
- improvements in file translation and meshing, but still challenging
- Investigated effectiveness of foams to improve heat transfer
- CFD and thermal stress analysis of porous media
- refractory high temperature foams for Brayton applications
- applications to various gas/gas heat exchangers, recuperators, regenerators, LM/gas heat exchangers
- modeling of foams for thermal stress reduction and insulation