INL/CON-22-66144-Revision-0

[Presentation Slides] Code-to-Code Benchmark Study for Thermal Stress Modeling and Preliminary Analysis of the High-temperature Single Heat-Pipe Experiment

March 2022

Changing the World's Energy Future

Sunming Qin, Minseop Song, Jun Soo Yoo, Piyush Sabharwall, Christian M. Petrie

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Code-to-Code Benchmark Study for Thermal Stress Modeling and Preliminary Analysis of the High-Temperature Single Heat-Pipe Experiment

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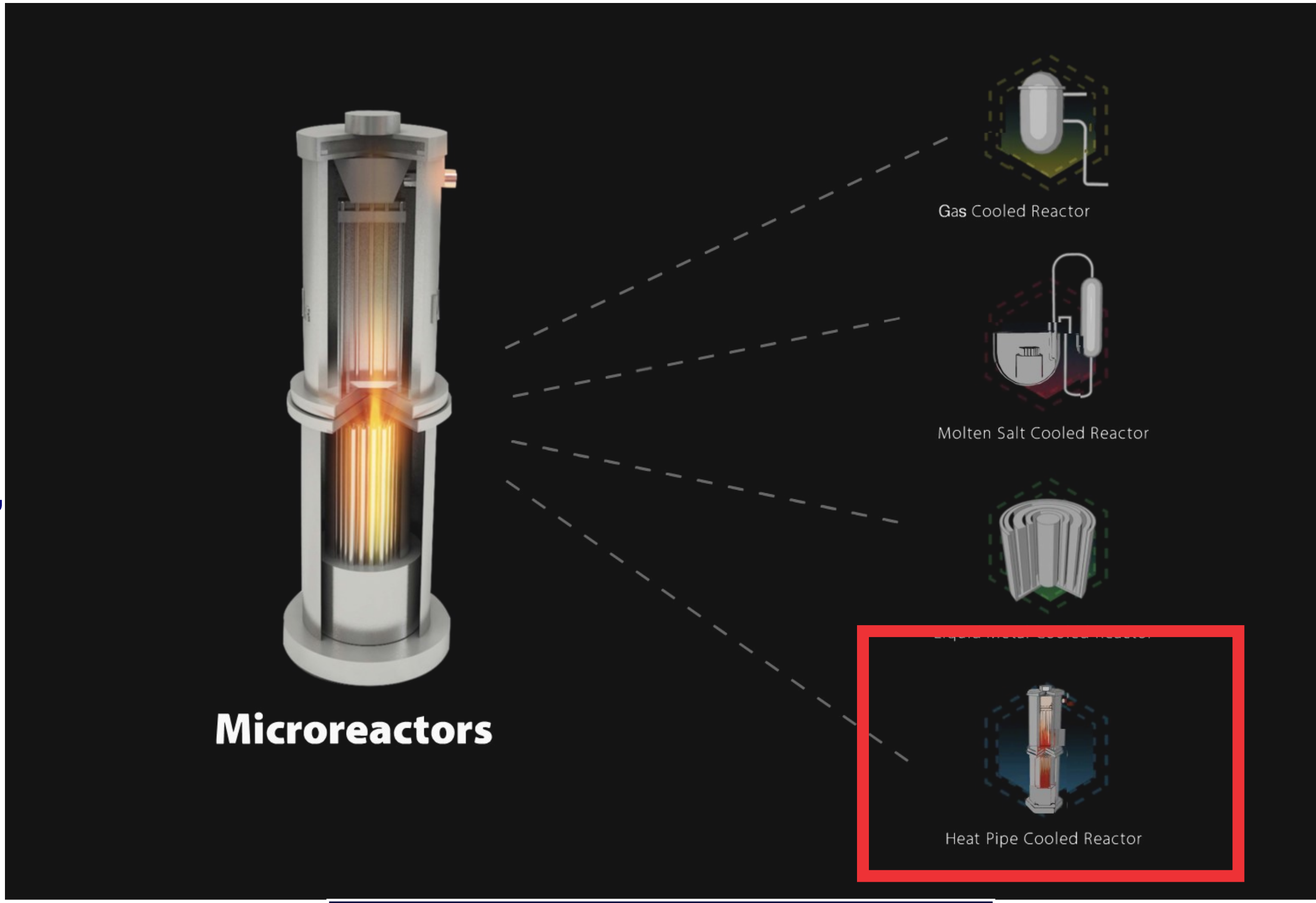
Idaho National Laboratory

MRP Microreactor Program

What are Microreactors?*

- Small size and power level: <1 MW – 20 MW
- Easily transportable to and from site
- Minimum site preparation
- Flexible operation
- High-degree of passive safety
- Operational lifetime: 5 – 20 years
- Technologies evolving from advances in materials, space reactor technologies, advanced nuclear fuels, and modeling & simulation.
- Well suited for remote areas and applications:
  - Remote communities
  - Isolated microgrids
  - Mining sites
  - DOD applications
- Broadly distributed, reliable, and resilient energy sources



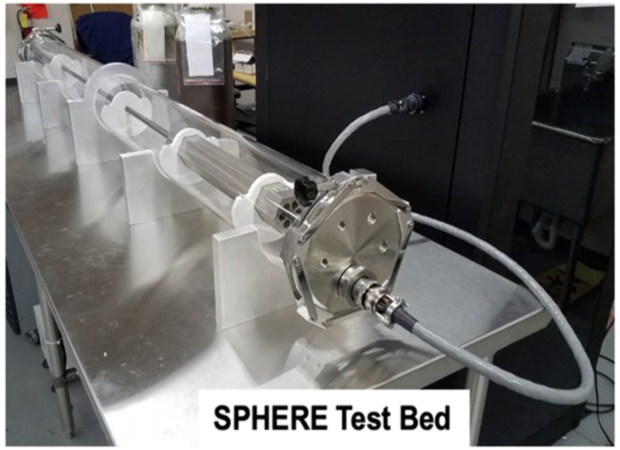
Microreactors are integrated systems that can be based on a range of reactor technologies

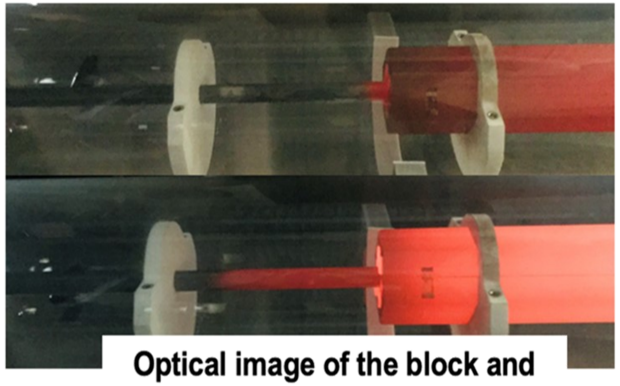
*https://gain.inl.gov/SitePages/MicroreactorProgram.aspx

Single **P**rimary **H**eat **E**xtraction and **R**emoval **E**mulator **(SPHERE)**

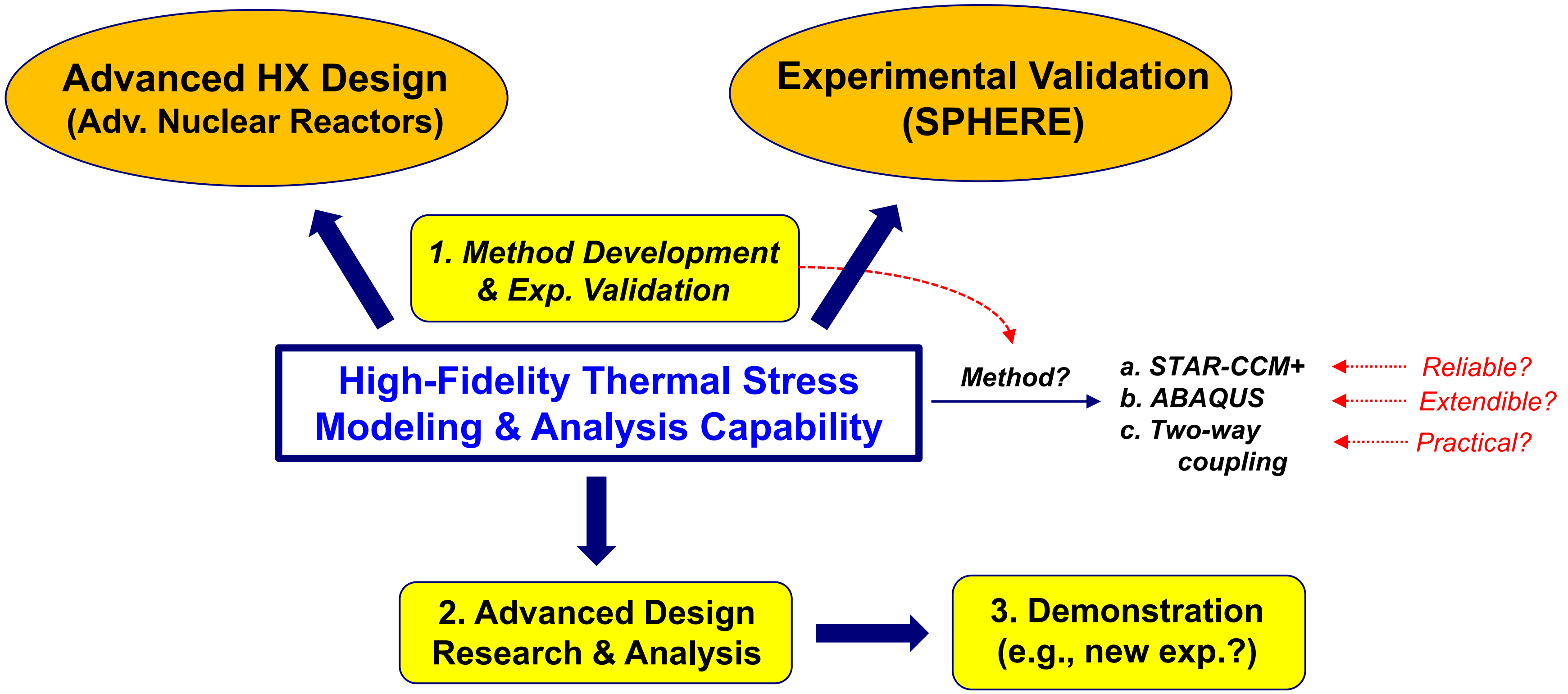
- Provide capabilities to perform steady-state and transient testing of heat pipes and heat transfer:
  - Wide range of heating values and operating temperatures.
  - Observe **heat pipe startup and transient operation.**
- **Develop** effective thermal coupling methods between the heat pipe outer surface and core structures.
- **Measure** heat pipe axial temperature and thermal-induced stress profiles during **startup, steady-state, and transient operation** using thermal imaging and surface measurements.

Parameter	Value
Length	243 cm
Diameter	15 cm
Tube material	Quartz
Connections	Flanged for gas flow and instrumentation feed through
Maximum power	20 kW
Max Temperature	750 C
Heat Removal	Passive radiation or water-cooled gas gap calorimeter


SPHERE Test Bed


Optical image of the block and heat pipe operation

Research Goal with Code-to-Code Benchmark Study



1. Identify the potential & limitations of methods a, b, and c.
2. Find the best way of thermal stress analysis through (i) benchmark study, and (ii) experimental validation (will be problem-dependent).
3. Guide the experimental matrix and propose the optimized facility design.

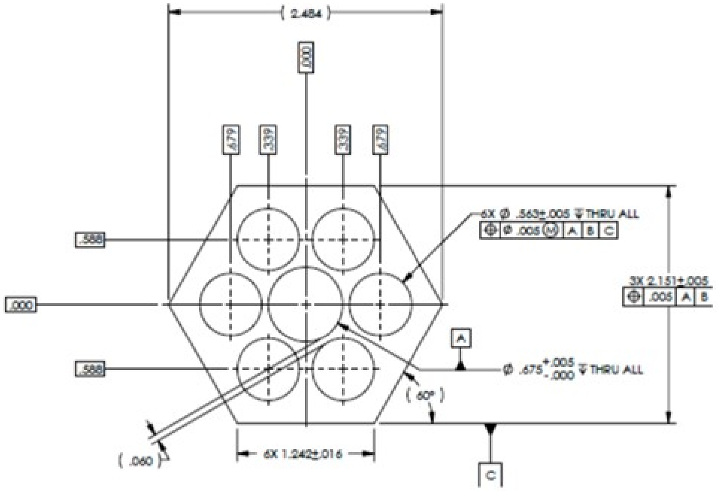
Modeling Method – Geometry and Material Properties

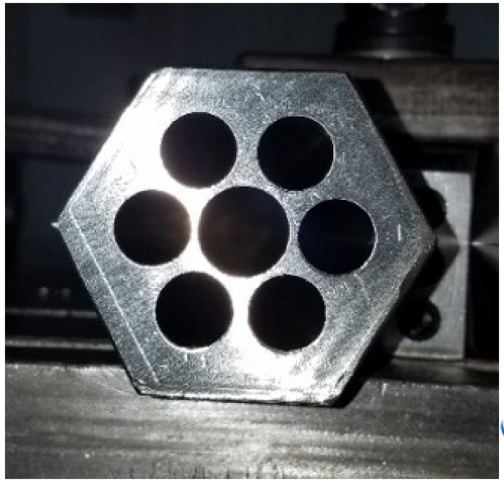
- Length of hex block and six cartridge heaters (CHs) = 152.4 mm (6”)
- Center hex block hole diameter: 17.15 mm (0.675”);
- HP: 15.88 mm (0.625”) outer diameter (OD) × 14.45 mm (0.569”) inner diameter (ID);
- Diameter of 6 holes containing CHs: 14.30 mm (0.563”);
- CH OD: 12.70 mm (0.500”).

➢ The CHs were modelled as monolithic 304 stainless steel (SS304) with uniform volumetric heating.

➢ The hex block and the HP’s sheath were modeled using the material properties of SS304.

➢ The CH-to-hex block gaps and the hex block-to-HP gap were assumed to be filled by boron nitride (BN) paste. The BN paste was not included in this preliminary structural analysis.

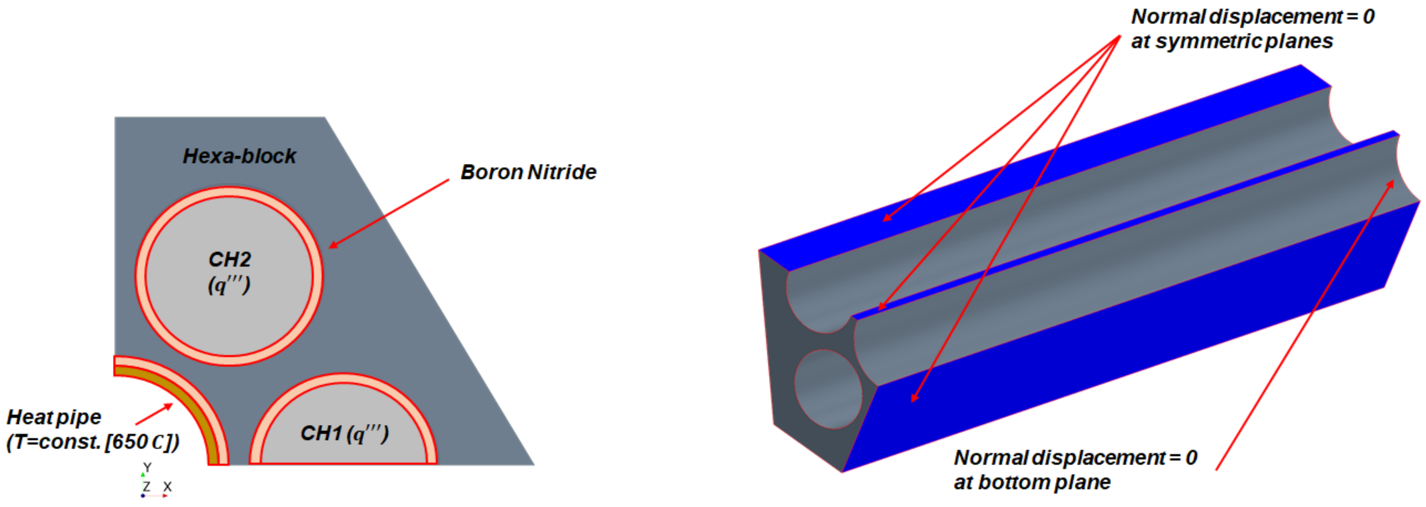




Modeling Method – Assumptions and Boundary Conditions

- Quarter symmetry is assumed.
- Radial heat losses to the surrounding and axial heat losses besides heat transferred to the HP were not included.
- The structural simulations only included elastic deformation, with no consideration of creep or plasticity in the model.

- The whole model is assumed to have an initial temperature of 20°C (293.15K).
- Interfaces between CH-BN, HP-BN, and BN-Hexblock are set to be tie constraint.
- The bottom of the model is set to be fixed (constrained not to move axially).
- The plane symmetry is applied to the two side surfaces for the quarter model.
- The inner surface of the HP was fixed at a constant temperature of 650C (923.15K).



(a) Boundary condition for Thermal Analysis (b) Boundary condition for Stress Analysis

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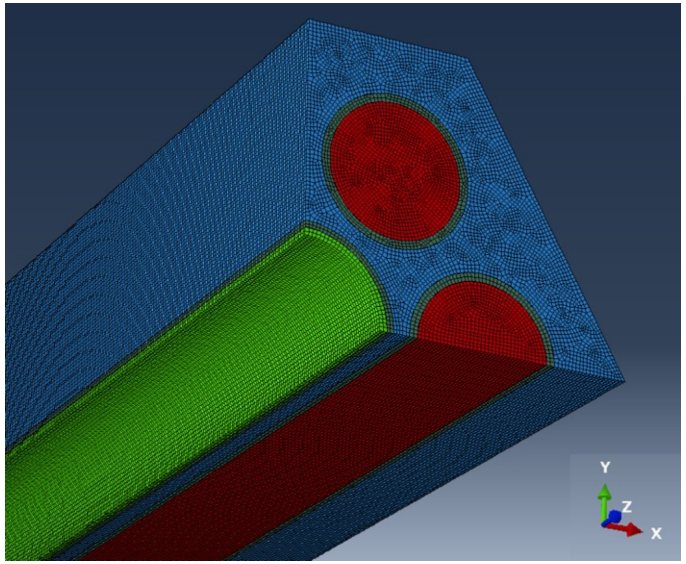
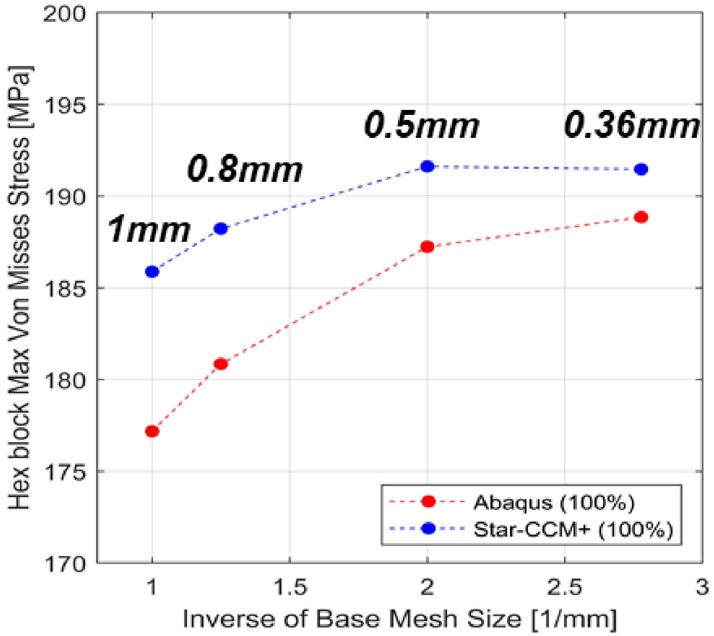
Modeling Method – Mesh Sensitivity Study

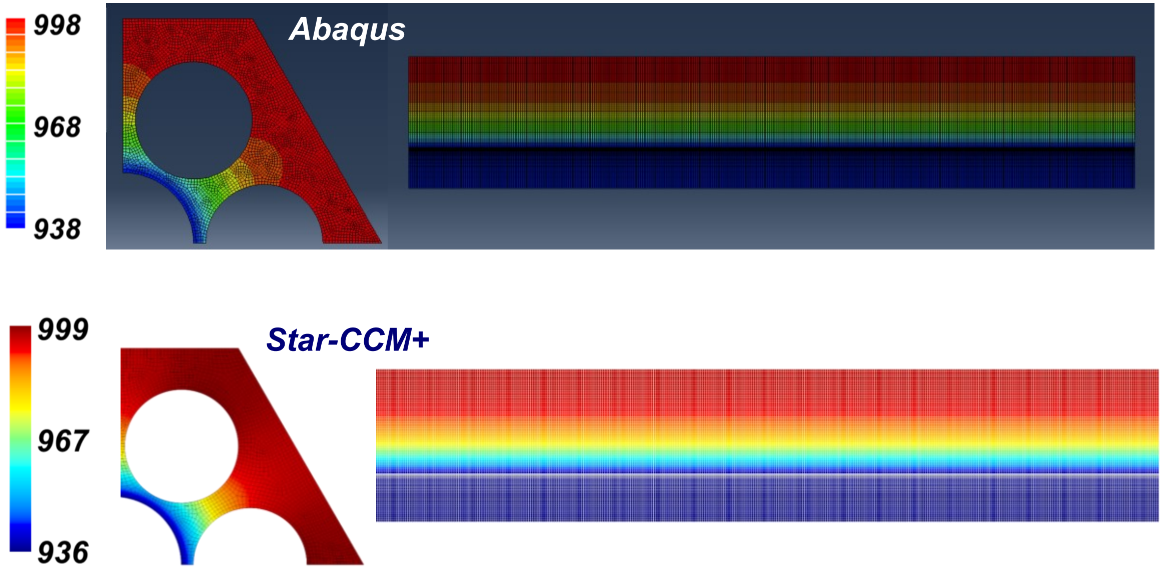
- The accuracy of stress analysis is inversely proportional to mesh size.
  - Smaller mesh resolve the temperature variation, therefore, affecting the stress calculations.
    - $\frac{F}{A} = E\alpha dT$
- The mesh sensitivity for Abaqus and Star-CCM+ shows similar trend on the Von Misses stress.
  - Difference between Star-CCM+ and Abaqus: **1.3% (0.36mm)**.
- Uniform 0.36-mm hexahedral mesh base size was chosen and applied to the temperature and stress analysis with both Star-CCM+ and Abaqus.



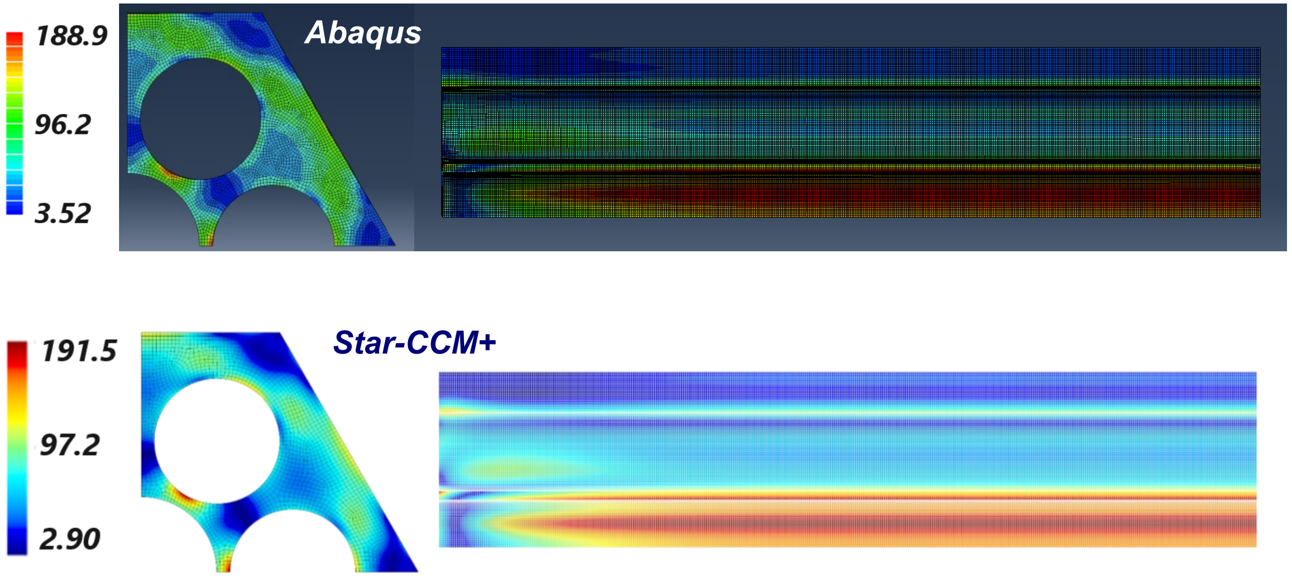


Results – Temperature and Stress Distribution

(a) Temperature [K]



(b) Von Mises Stress [MPa]

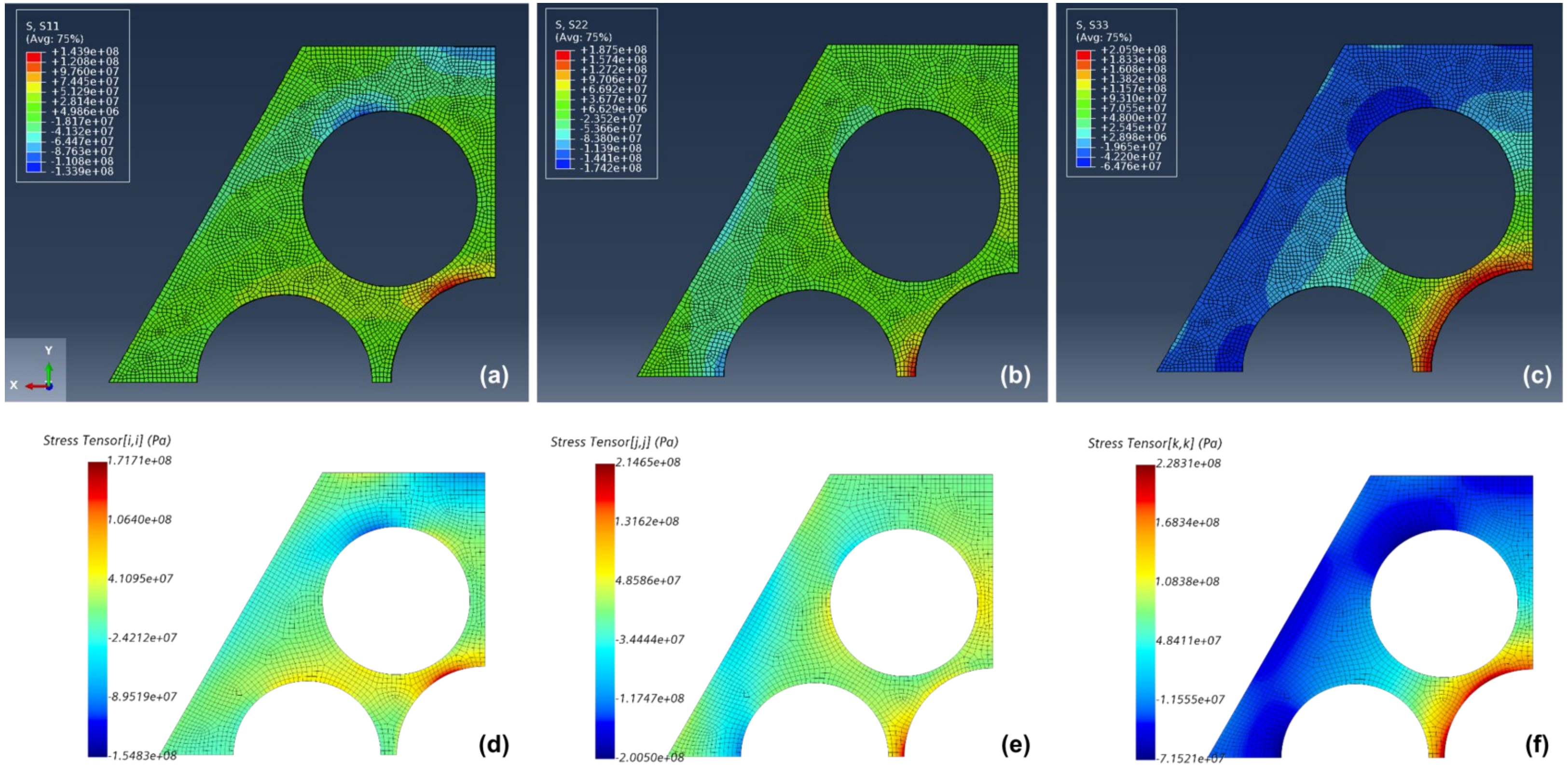


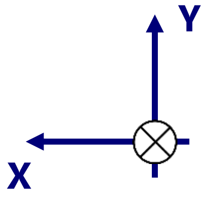
- A heat conduction simulation was conducted for whole geometry including heat pipe, BN gap, cartridge heater, and hex-block, and a thermal stress analysis was conducted only for hex-block.
- For the test section having uniform hex mesh size of 0.36mm, figures shows that both the temperature and stresses profiles have quite similar distributions.
- The Von Mises stress shows the maximum value at the interface between heat pipe and hex-block.

Results – Stress Component Comparison

Abaqus

Star-CCM+





*Z into the screen

- The stress components at the bottom of the hex-block, where zero-displacement constraint was applied, was investigated for the comparison.
- The distribution of stress component is almost identical for both cases, but the absolute magnitude is higher in the Star-CCM+ case, which result in higher Von Mises stresses.
- The reason of stresses differences between codes should be verified and validated.

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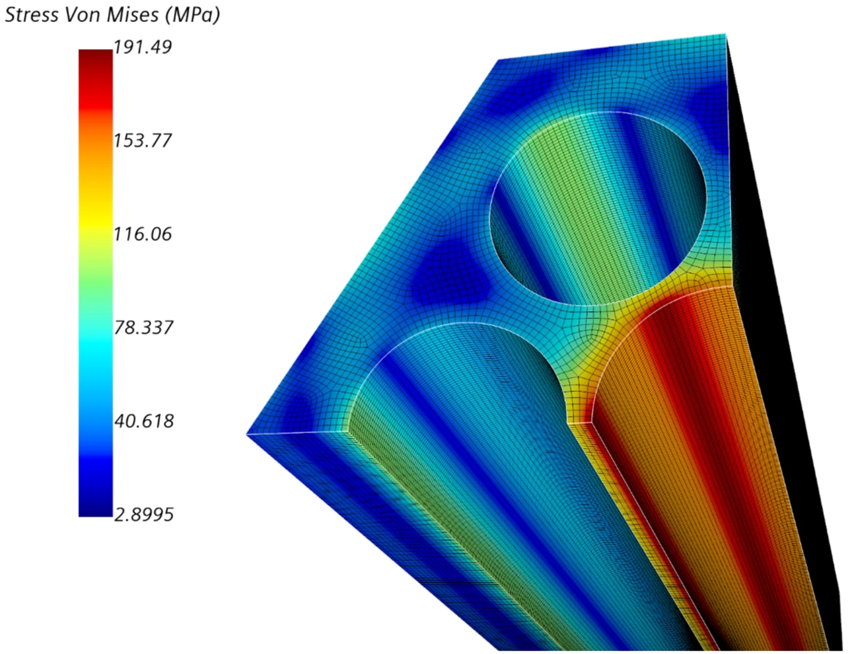
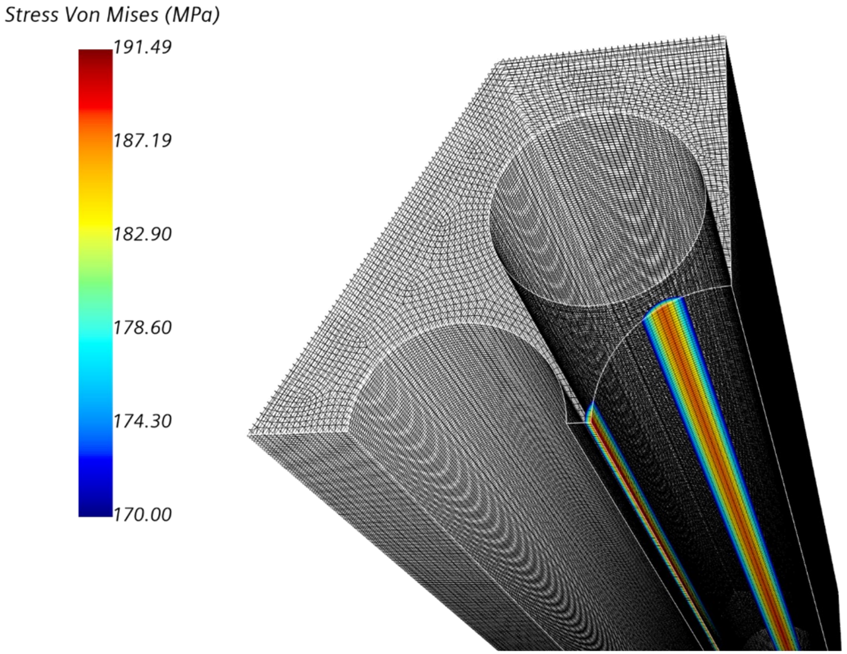
Results – Thermal Stress Field



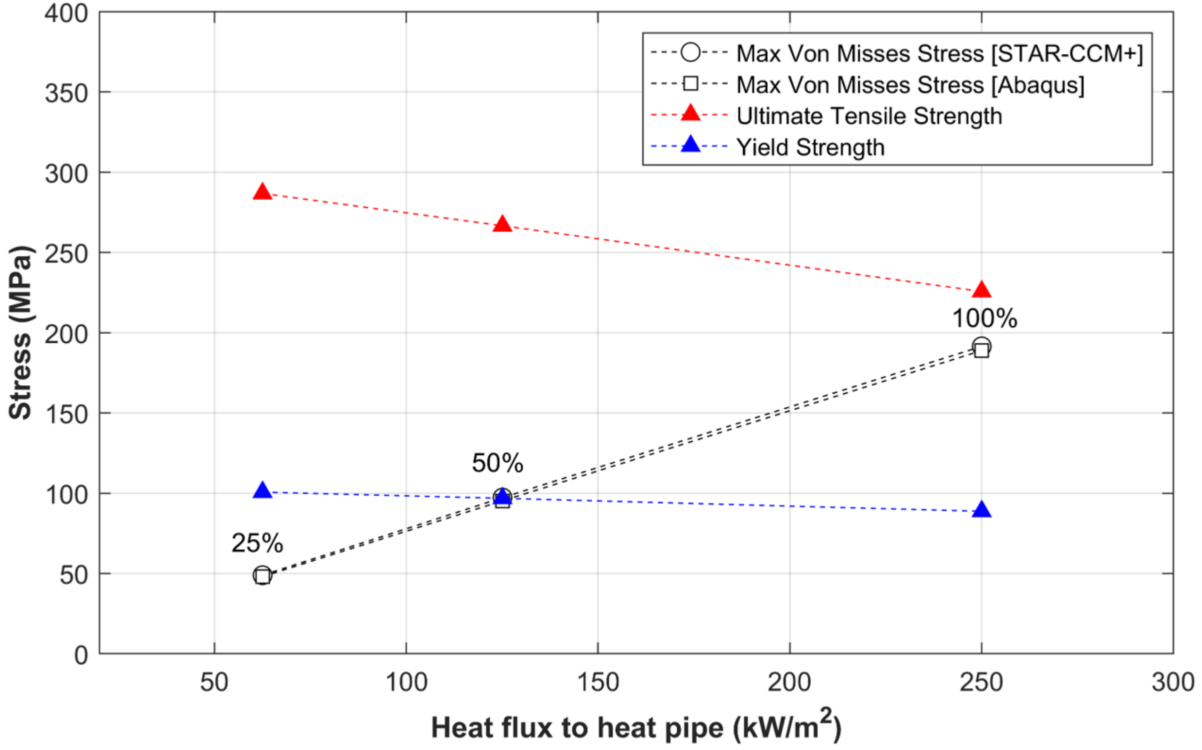
(a) Distribution of Von Mises Stress



(b) Location of Maximum Von mises Stress

- The maximum Von Mises stress is located along the center lines between heat pipe and holes.
- The thinnest part of the hex-block between CH-HP holes has the larger temperature differences, resulting in a larger Von Mises stresses.
- Therefore, the parametric study for the web thickness between the HP and CH is needed in the future study to find the best value for relief of the thermal-induced stresses.

Results – Parametric Study for Heating Power



Power Level	% difference in Temperature		% difference in Stresses	
	Min.	Max.	Min.	Max.
25%	-0.060	0.018	-17.86	1.79
50%	-0.117	0.035	-17.84	2.08
100%	-0.231	**-0.066**	-17.71	**1.38**

*Abaqus results used as reference to calculate the percentage error.

- A parametric study for the power level of cartridge heater was conducted with a max. of 1,902 W (317W per CH).
- The range of temperature from both tools is almost same for a percentage error within 0.25%.
- The range of max. Von Mises stress from Star-CCM+ is slightly larger than the ABAQUS.
- Therma stress results suggest to avoid using heating power level above 50% (i.e., 158.5 W per CH).

Summary and Conclusions

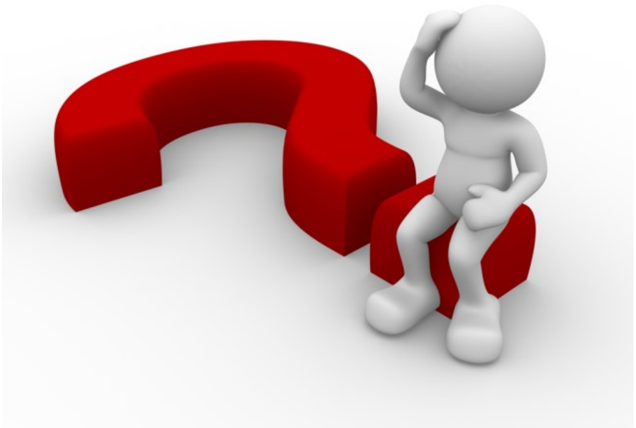
- The profiles of temperature and Von Mises stresses computed by Abaqus and Star-CCM+ have been observed to agree well with each other, especially the locations where the maximum temperature and stresses happened in the geometry.
- The modest deviations probably come from the different built-in mesh engines in these two commercial codes.
- With various heating power levels, the computed maximum Von Mises stresses using Abaqus and Star-CCM+ are plotted and compared with the UTS and YS of SS304.
- The maximum Von Mises stress values computed from both codes yet indicates that the hexblock could experience plastic deformations with a heating power larger than 158.5 W per CH (951W total). If this persists, the hexblock could potentially fail and break in long-term steady-state heating operations.

Ongoing and Future Work

- Further investigation into the potential cause of the difference in the stress analysis results between Abaqus and STAR-CCM+ (e.g., mesh engine, temperature difference caused by material properties).
- Creep or plasticity models in both packages will be included in future analyses to investigate the potential failure of structural material for high-temperature operation ranges.
- The constraints of the stress modeling on the test section will be changed to be consistent with the actual experimental constraints. The changes will include simulation on whole geometry with BN paste, central heat pipe and the fixing of the hex block.
- The parametric study for web thickness between CH and HP holes is needed to optimize design parameters considering manufacturing tolerance of holes and thermal-induced stresses at the gap.

Thanks for your attention!

Questions?



Backup Slides

NURETH-19 Virtual Conference

March 7, 2022

DOE Microreactor Program

Dr. John Jackson (INL), National Technical Director, Diana Li (DOE-NE), Federal Program Manager

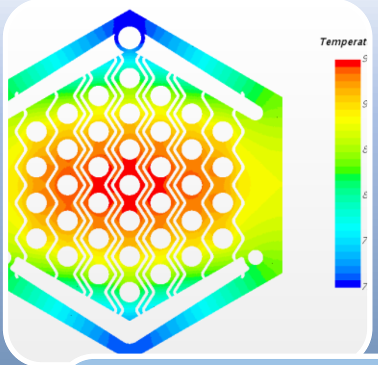
Program Vision

Through cross-cutting research and development and technology demonstration support, by 2025 the Microreactor Program will:

- Achieve technological breakthroughs for key features of microreactors
- Empower initial demonstration of the next advanced reactor in the US
- Enable successful demonstrations of multiple domestic commercial microreactors.

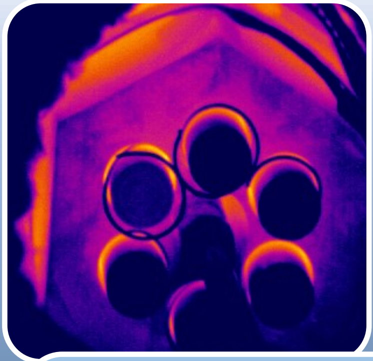
Program Objectives

- Address critical cross cutting R&D needs that require unique laboratory/university capability or expertise
- Develop R&D infrastructure to support design, demonstration, regulatory issue resolution, and M&S code validation
- Develop advanced technologies that enable improvements in microreactor viability



System Integration & Analyses

- Economics & Market Analysis
- Integrated Systems Analysis
- Applications of NEAMS computational Tools
- Technoeconomic Analyses
- Regulatory Development



Technology Maturation

- Advanced Heat Pipes
- Advanced Moderators
- Heat Exchangers
- Instrumentation & Sensors
- Advanced Materials and Material Code cases

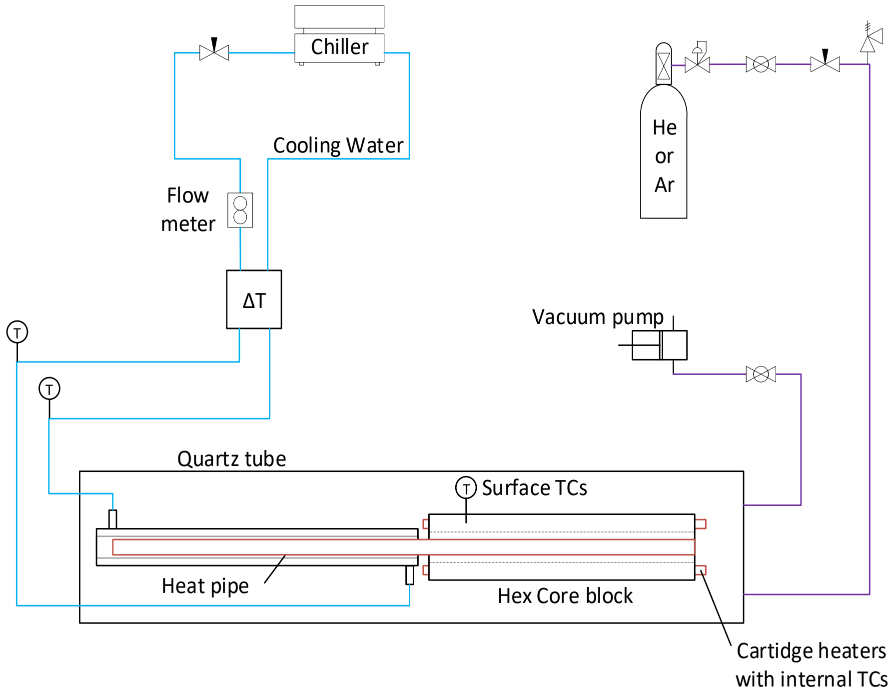
Demonstration Support Capabilities

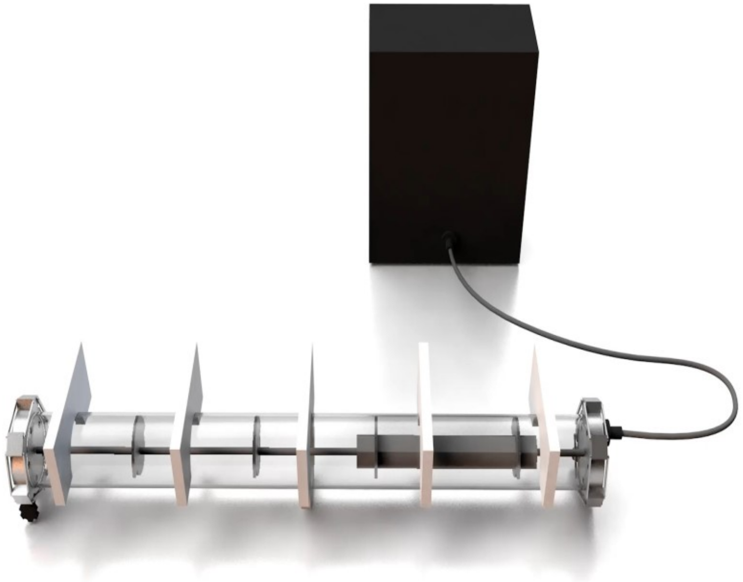
- Non-nuclear thermal and integration testing
- Microreactor Agile Non-nuclear Experimental Tesbed (MAGNET)
- Microreactor Applications Research, Validation and Evaluation (MARVEL)

Microreactor Demonstrations & Applications

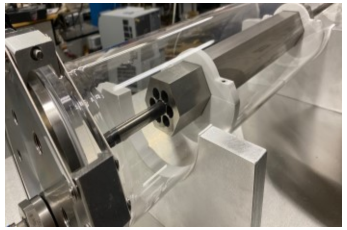
- Reactor Demonstrations
- Remote heat & power
- Hydrogen co-generation
- District heating
- Desalination

Single Heat Pipe Test Stand – Process Flow Diagram





- Quartz tube enclosure will be charged with inert gas
- Vacuum pump supports successive dilution for air removal
- Turbine flow meter and △T meter allow for determination of heat removal rate to the cooling water; comparison to total heater power at steady-state
- Cooling water is recirculated with heat rejection to a 2.5 kW circulating chiller



Quartz tube allows testing in vacuum or inert gas environments

Process flow diagram for single heat pipe (7-hole hex block) experiments

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Single Heat-pipe Shakedown Test

Views showing end flanges, 7-hole core block, Major supports, and ACT heat pipe installed in quartz tube

Initial testing performed under vacuum with the heat pipe evaporator radiating to the surroundings at low power