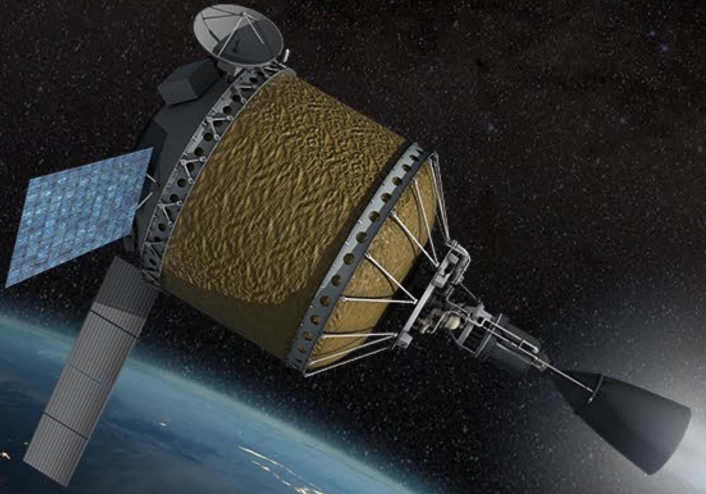
High-Fidelity Modeling Approach for Coupling Thermal, Fluid, and Neutronic Analysis in an NTP Engine



Nuclear and Emerging Technologies for Space Conference

Looking Forward to Future Fission Power Needs

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Introduction

- For modern nuclear thermal propulsion (NTP) designs, modeling and simulation is vital for progressing lower TRL stages of development
  - Analysis of parameter spaces
  - Design tradeoffs
  - Can provide continual support through hardware development and testing

- A complete model of an NTP system must accurately couple thermal and neutronic effects
  - High thermal power density causes rapid changes in core temperature, in turn causing tangible effects on core power distribution
  - Fluid behavior (particularly density) also causes major changes
    - Rapid temperature increase causes density decrease, which reduces moderating power

Motivation

- **Goal: Design an NTP modeling methodology that can accurately couple conduction, thermal-hydraulics, and neutronics**
  - Use open-source software
  - Analyze a steady-state, full-power operational environment
  - Accurately reproduce publicly available test data

- Test data: **XE Prime reactor**, developed under the Nuclear Engine for Rocket Vehicle Application (NERVA) program [1]
  - Only NTP reactor to ever reach a flight configuration test

- Software: Idaho National Laboratory's (INL) **Multiphysics Object-Oriented Simulation Environment (MOOSE)** [2]
  - Including Thermal Hydraulics Module and associated software like Cardinal

[1] Robbins, W. H., and Finger, H. B., "An Historical Perspective of the NERVA Nuclear Rocket Engine Technology Program," *NASA Contractor Report 187154.*, AIAA-91-3451, July 1991.

[2] Harbour, L., et al., "4.0 MOOSE: Enabling massively parallel Multiphysics simulation," *SoftwareX,* vol. 31, pp. 102264, 2025.

Methodology

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Software Tools

- **MOOSE**
  - Conduction kernel for solid temperature calculations [2]
  - Thermal Hydraulics Module for fluid mechanics [3]
  - Multiapp, transfer systems to transfer boundary conditions between solutions [4]

- **OpenMC**
  - Monte Carlo code – calculation of heat source distribution
  - Has been shown to be useful for modeling advanced and experimental reactor designs [5]

- **Cardinal**
  - Generates a mesh mirror used to link geometries across disparate codes [6]
  - Used to link **MOOSE** and **OpenMC**

[2] Harbour, L., et al., "4.0 MOOSE: Enabling massively parallel Multiphysics simulation," *SoftwareX,* vol. 31, pp. 102264, 2025.

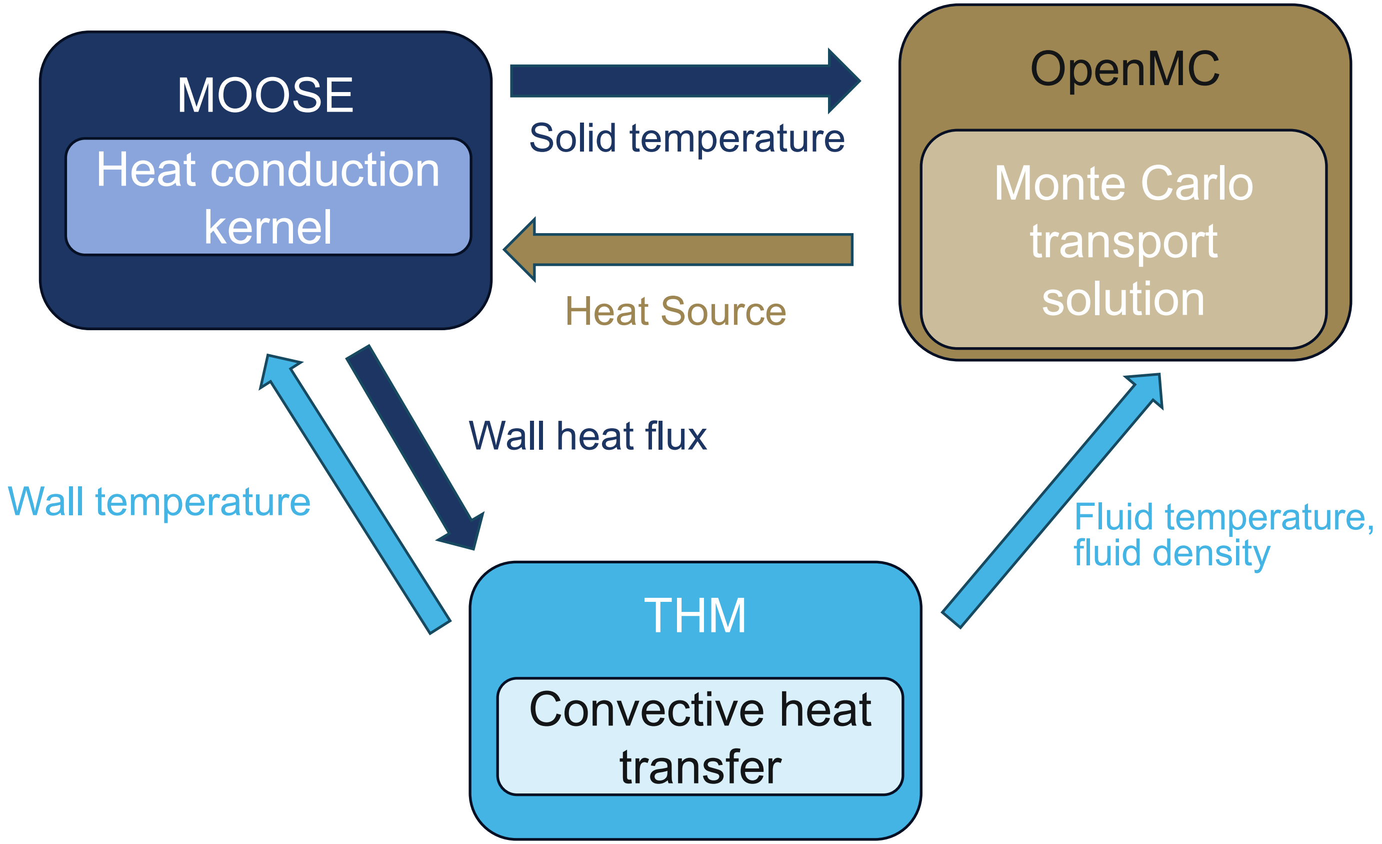
[3] Hansel, J., Andrs, D., Charlot, L., Giudicelli, G., "The MOOSE Thermal Hydraulics Module," Journal of Open Source Software, vol. 9, no. 94, pp. 6164, 2024.

[4] Giudicelli, G., et al. "Data transfers for nuclear reactor multiphysics studies using the MOOSE framework," Frontiers in Nuclear Engineering, vol. 4, 2025.

[5] Nguyen, K. H. N., and DeHart, M. D., "Modeling of the Advanced Test Reactor Using OpenMC, Cubit, and Griffin," Idaho National Laboratory, INL/RPT—23-74489, August 2023.

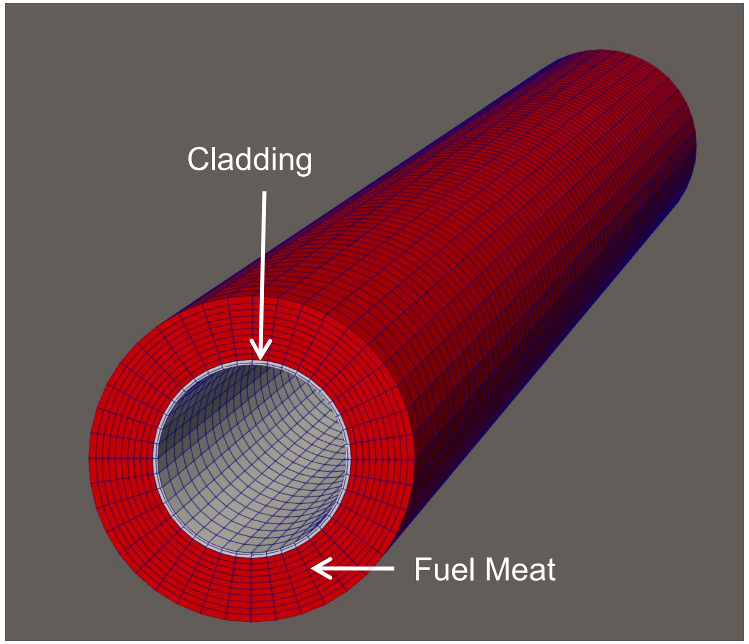
[6] Novak, A. J., "Coupled Monte Carlo and thermal-fluid modeling of high temperature gas reactors using Cardinal," Annals of Nuclear Energy, vol. 177, pp. 109310, 2022.

Coupling Sequence

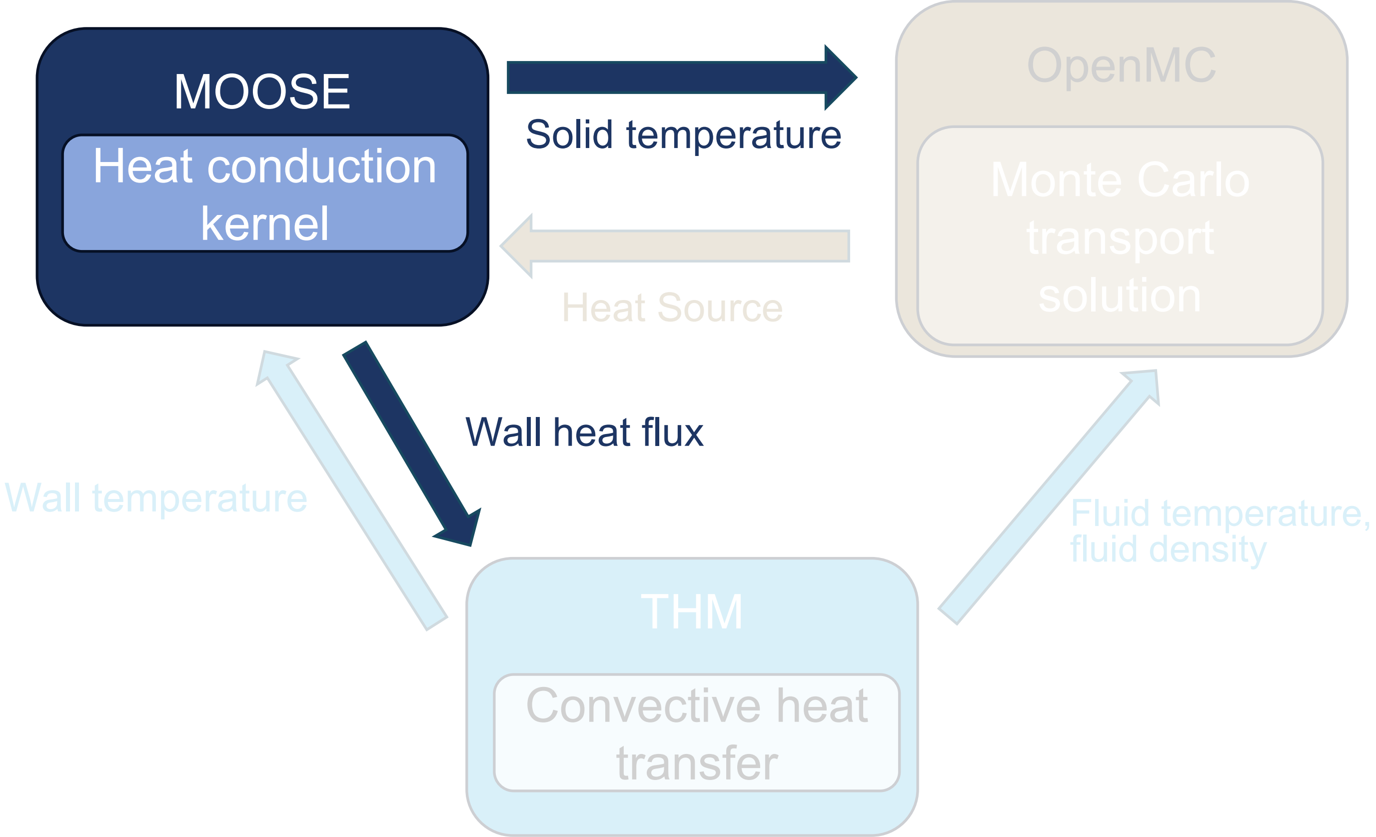


Solid Heat Conduction

- Heat conduction kernel
  - Uses the thermal energy conservation equation [2]



Solid mesh for a single coolant channel

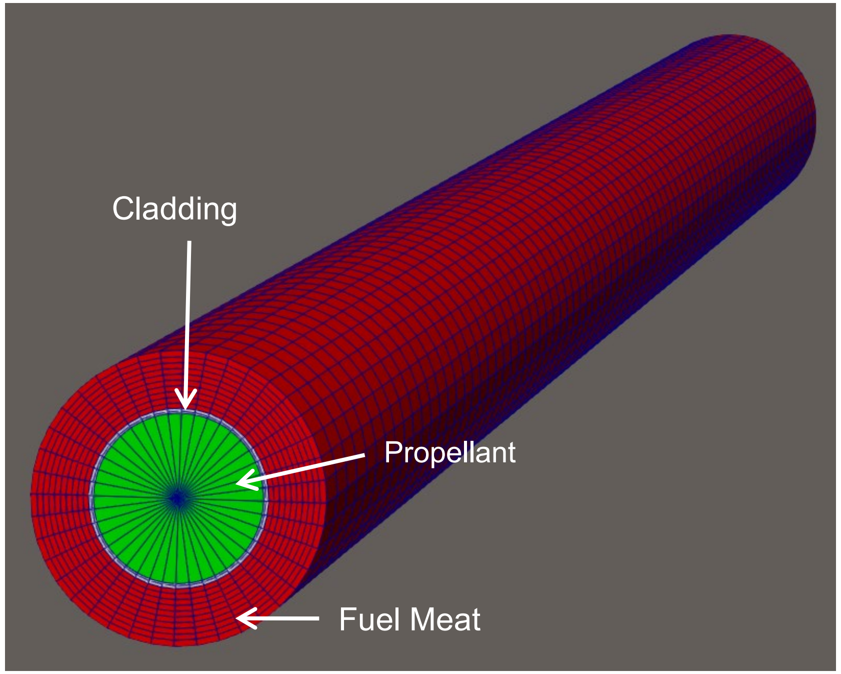


$$-\nabla \cdot (k\nabla T) = 0$$

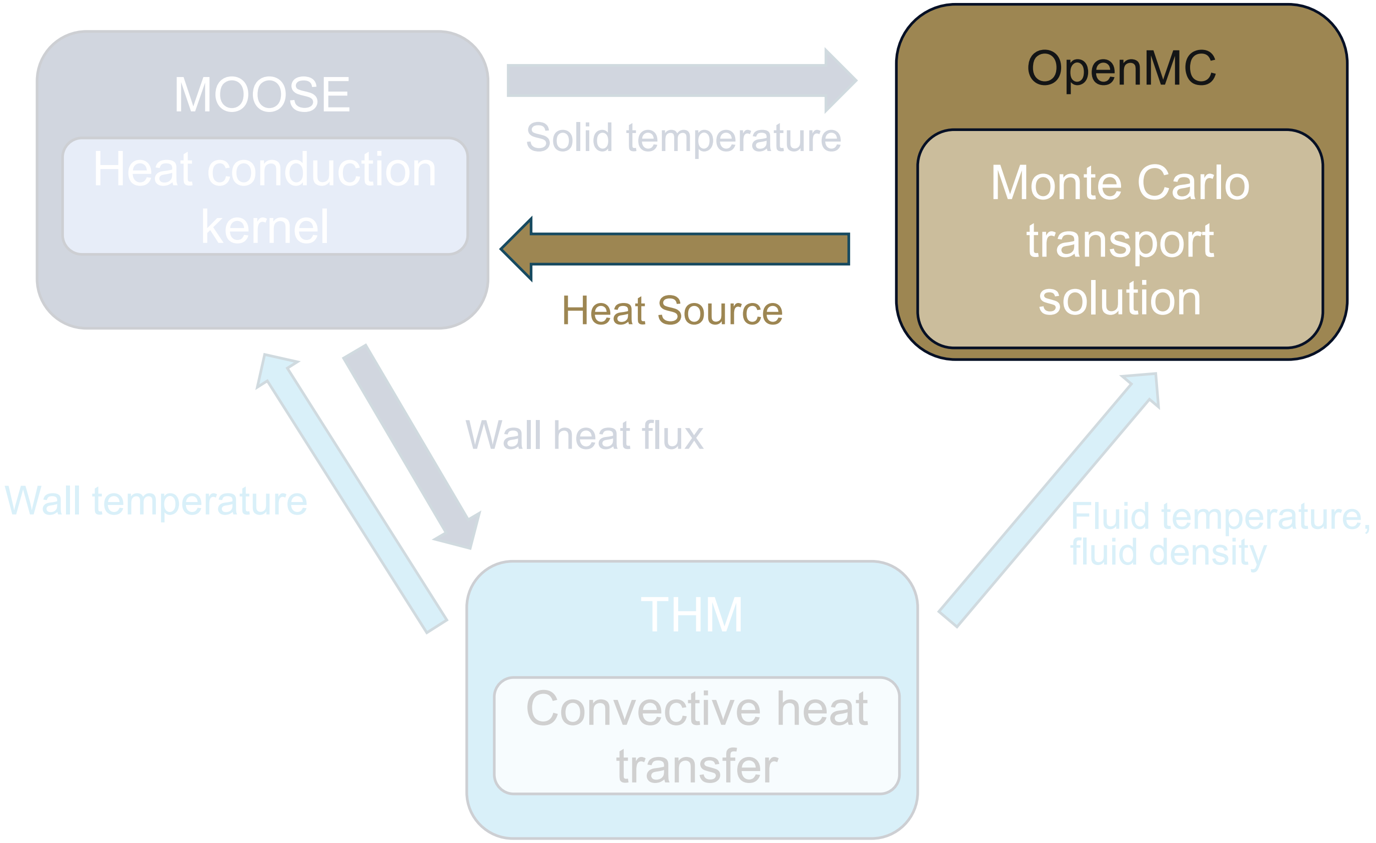
[2] Harbour, L., et al., "4.0 MOOSE: Enabling massively parallel Multiphysics simulation," *SoftwareX,* vol. 31, pp. 102264, 2025.

Neutronics

- Heat source
  - **Nuclear heating** is calculated by OpenMC
  - This becomes a **source term** added to the **thermal energy conservation** equation [2]



Solid & fluid mesh for a single coolant channel

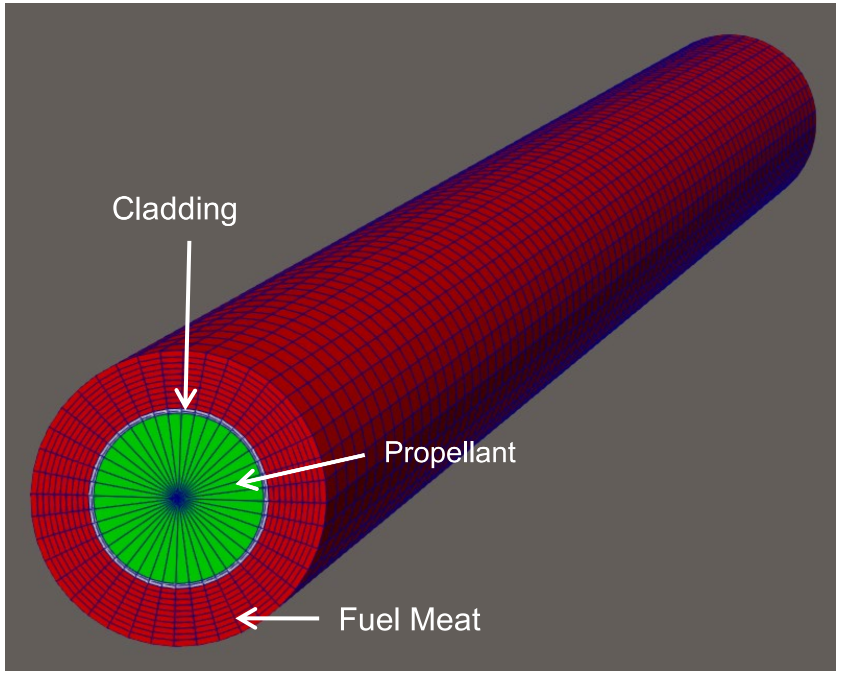


$$-\nabla \cdot (k\nabla T) + Source = 0$$

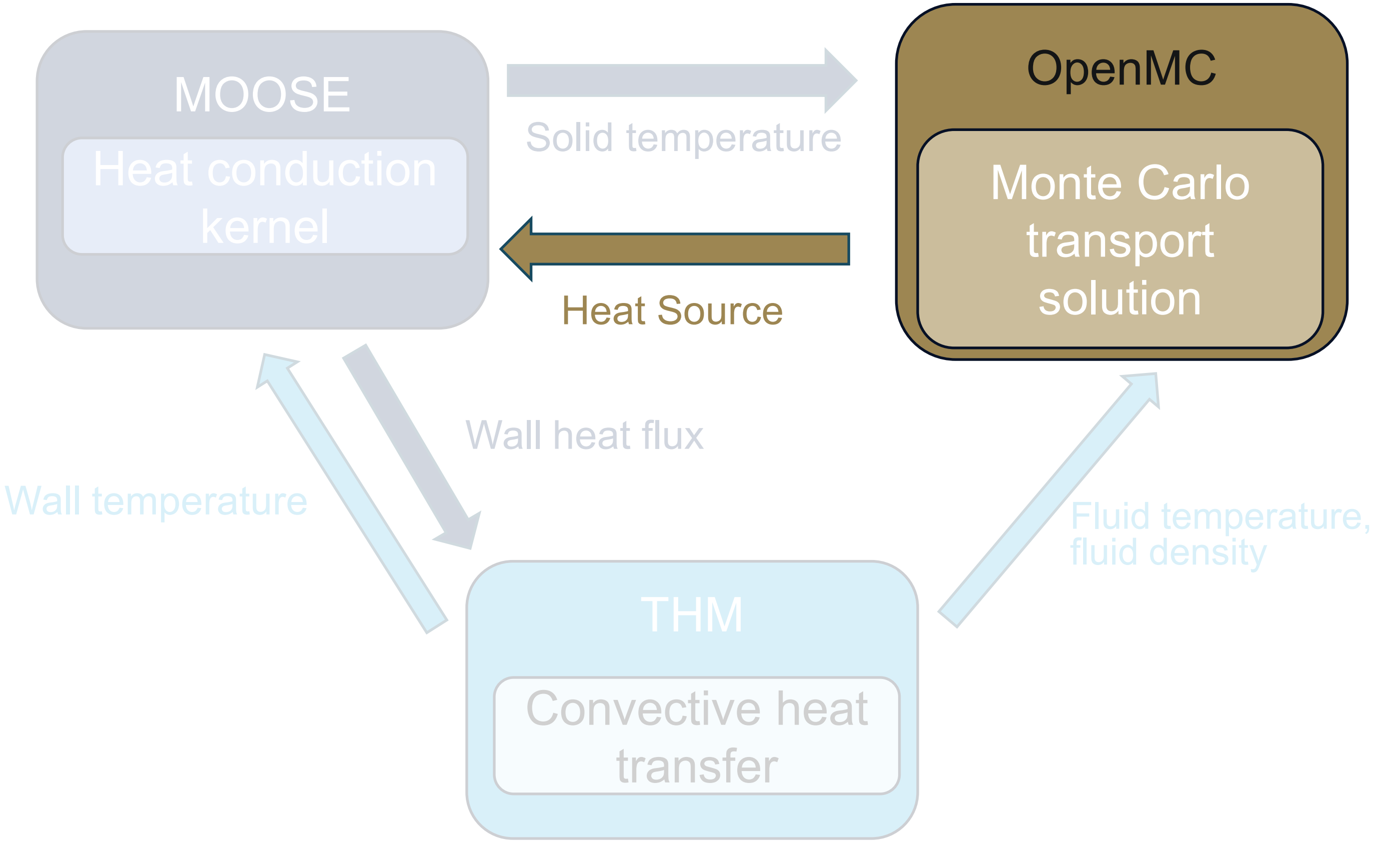
[2] Harbour, L., et al., "4.0 MOOSE: Enabling massively parallel Multiphysics simulation," *SoftwareX,* vol. 31, pp. 102264, 2025.

Neutronics

- **Assumptions
  - Photon heating need not be considered
  - Source is constant in each material region within each axial layer
  - Source only present in fuel



Solid & fluid mesh for a single coolant channel



$$-\nabla \cdot (k\nabla T) + Source = 0$$

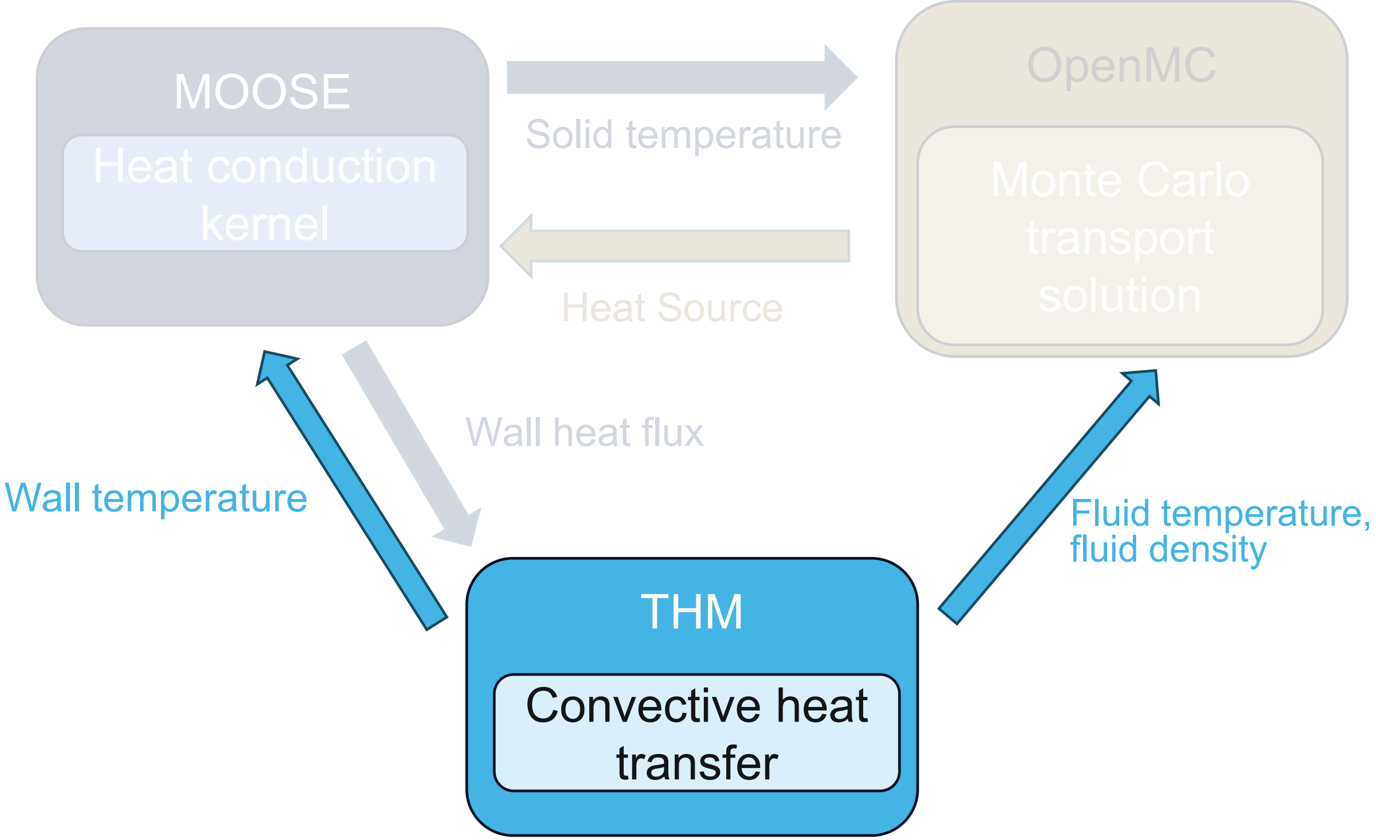
Thermal Hydraulics

- Flow is modeled as 1D, single-phase flow paths
- Split into 100 axial segments of equal length
- Segments are **governed by compressible Euler equations [3]:**

$$\frac{\partial \rho A}{\partial t} + \frac{\partial \rho u A}{\partial x} = 0$$

$$\frac{\partial \rho u A}{\partial t} + \frac{\partial (\rho u^2 + p) A}{\partial x} = p \frac{\partial A}{\partial x} - FA + \rho g_x A$$

$$\frac{\partial \rho E A}{\partial t} + \frac{\partial u(\rho E + p) A}{\partial x} = \rho u g_x A + q''' A$$



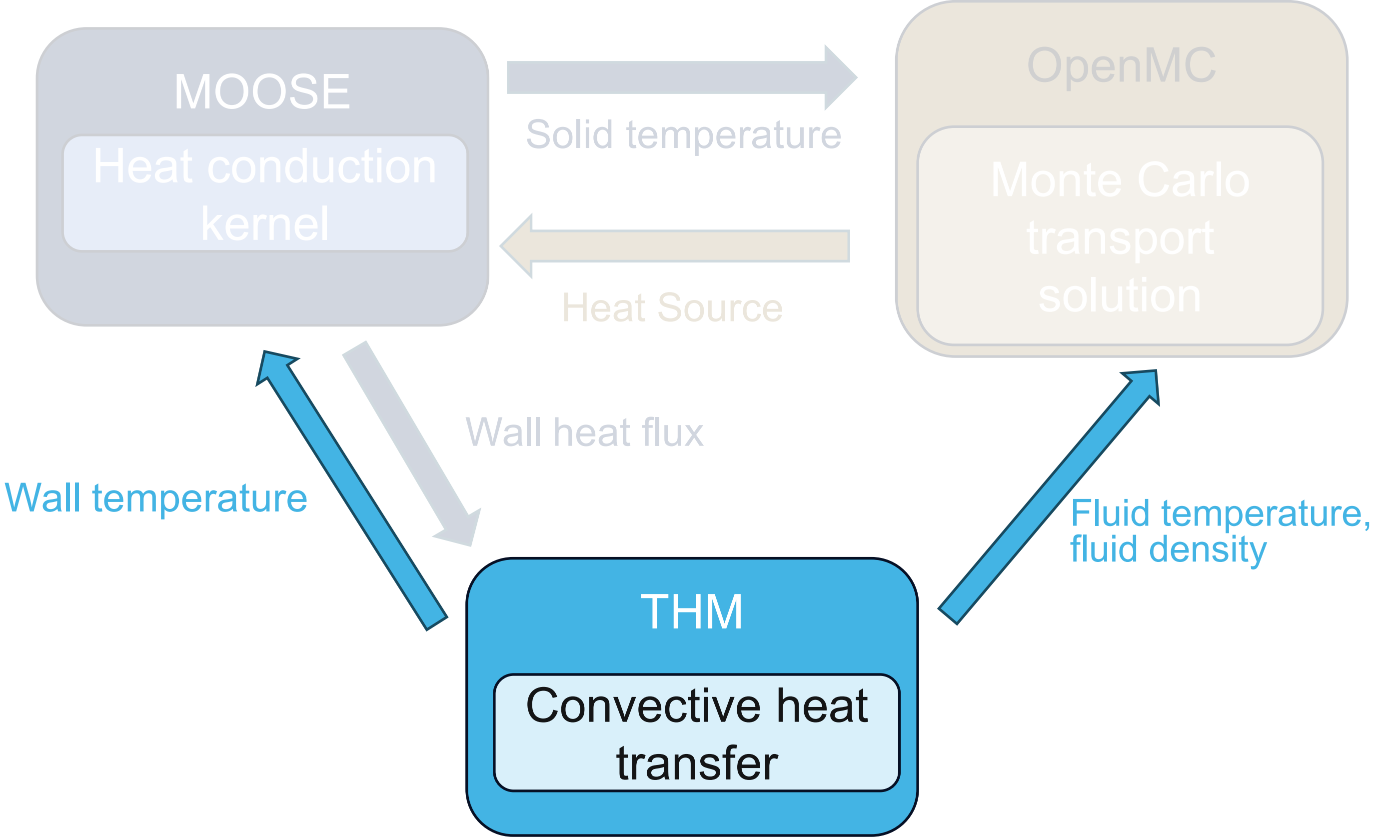
[3] Hansel, J., Andrs, D., Charlot, L., Giudicelli, G., "The MOOSE Thermal Hydraulics Module," Journal of Open Source Software, vol. 9, no. 94, pp. 6164, 2024.

Thermal Hydraulics

- Reynolds and Prandtl numbers solved using **hydrogen fluid properties** [7]
  - Used to calculate Nusselt number with a **Dittus-Boelter correlation** [8]

$$Nu = 0.023Re^{0.8}Pr^{0.4}$$

  - **Assumptions
    - Hydrogen behaves as an ideal gas
    - Dittus-Boelter correlation is adequate
    - Wall temperature and wall heat flux are channel-averaged for each axial layer



[7] Giudicelli, G., et al., "The MOOSE fluid properties module," Computer Physics Communications, vol. 307, pp. 109407, 2025.

[8] Winterton, R. H. S., "Where did the Dittus and Boelter Equation come from?" International Journal of Heat and Mass Transfer, vol. 41, no. 4, pp. 809-810. January 1998.

Thermal Hydraulics

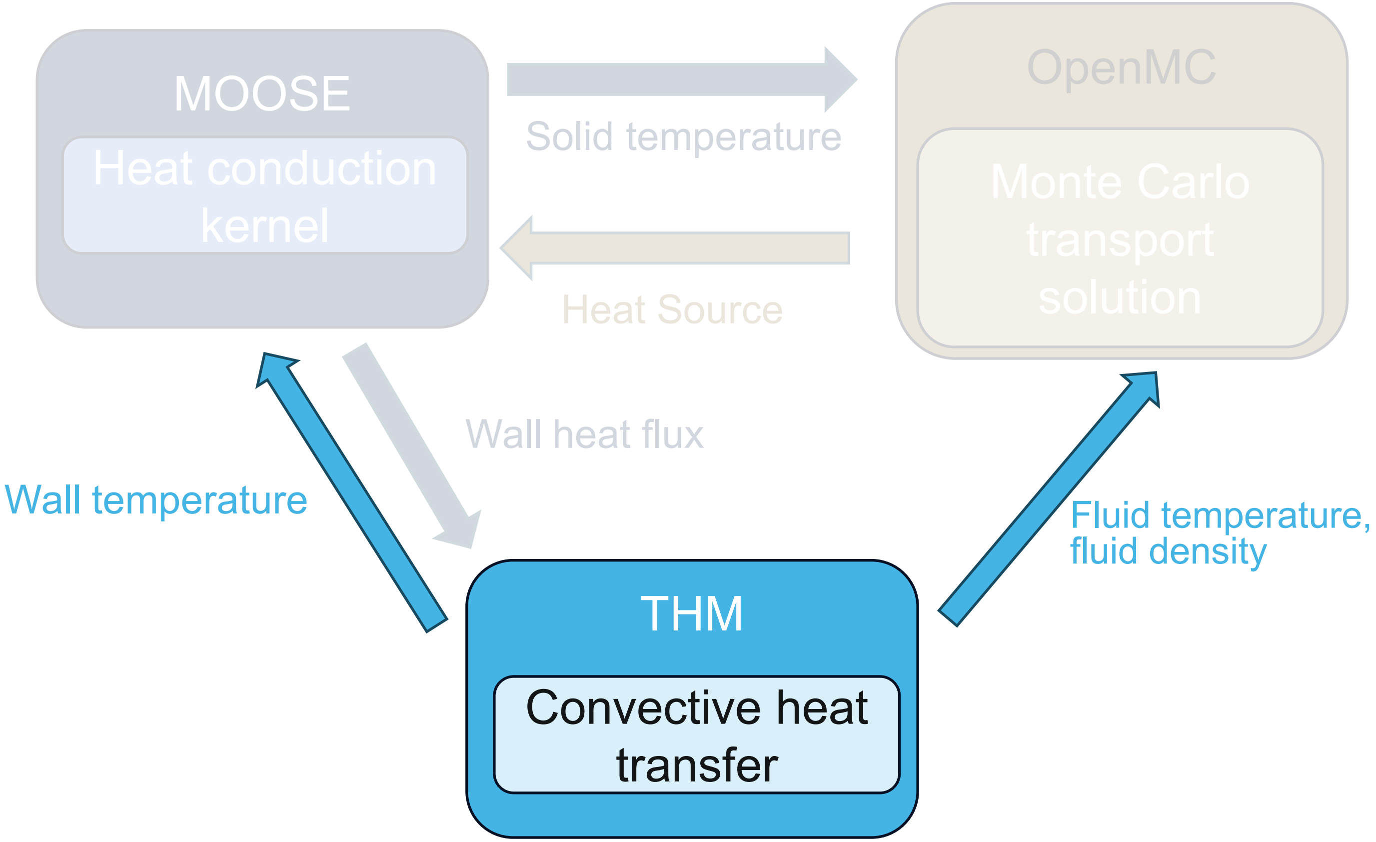
- **Reynolds and Prandtl numbers solved using hydrogen fluid properties**
  - Used to calculate Darcy friction factor with a **Churchill correlation [3]**

$$F = \frac{f \rho u |u| A}{2D_h}$$

$$f = 8\left[\left(\frac{8}{Re}\right)^{12} + \frac{1}{(A+B)^{1.5}}\right]^{\frac{1}{12}}$$

$$A = \left[2.457 ln\left(\frac{1}{\left(\frac{7}{Re}\right)^{0.9} + 0.27\frac{\epsilon}{D_h}}\right)\right]^{16}$$

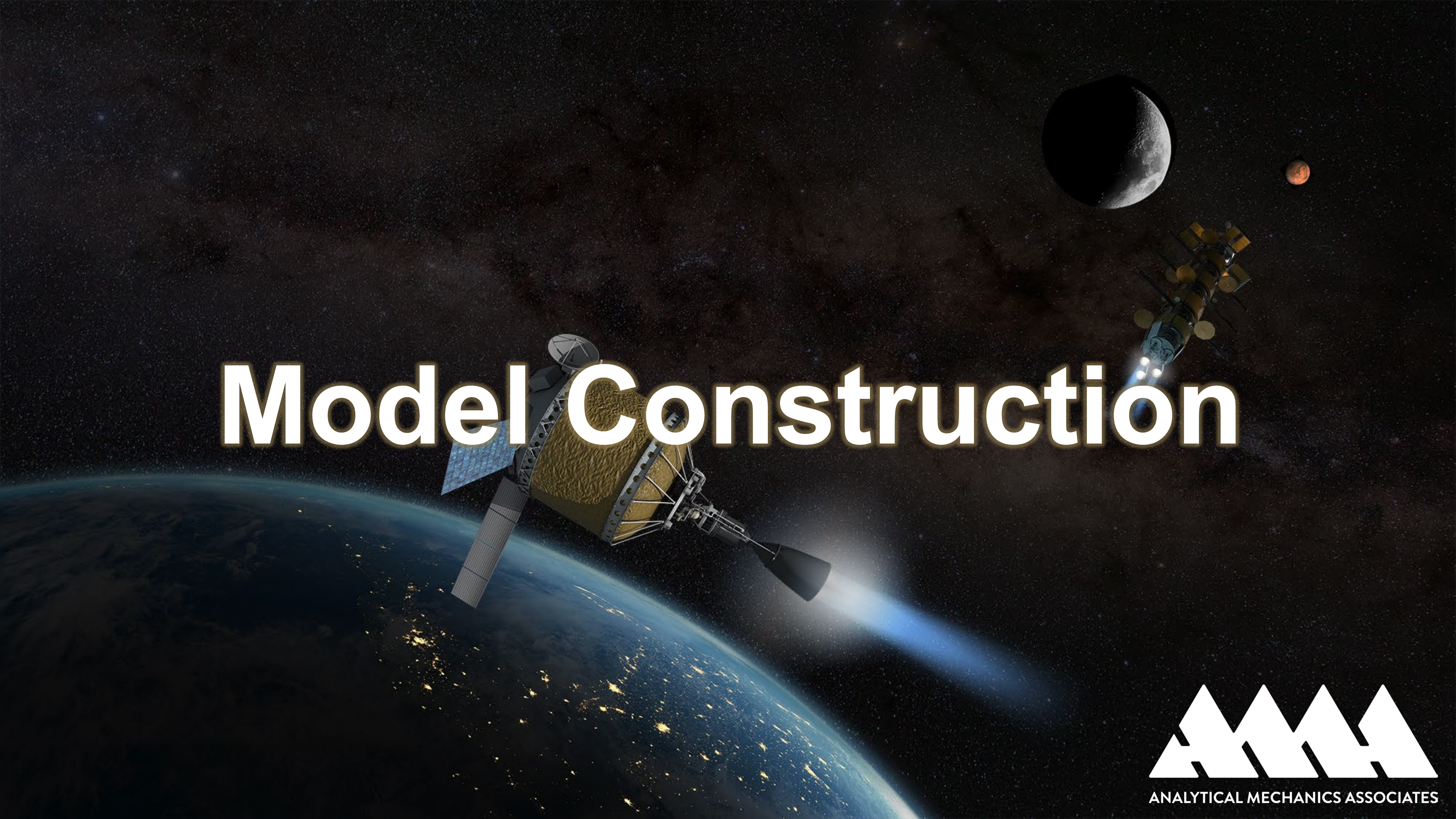
$$B = \left(\frac{37530}{Re}\right)^{16}$$



**Assumption: Channel roughness is constant

[3] Hansel, J., Andrs, D., Charlot, L., Giudicelli, G., "The MOOSE Thermal Hydraulics Module," Journal of Open Source Software, vol. 9, no. 94, pp. 6164, 2024.

Model Construction



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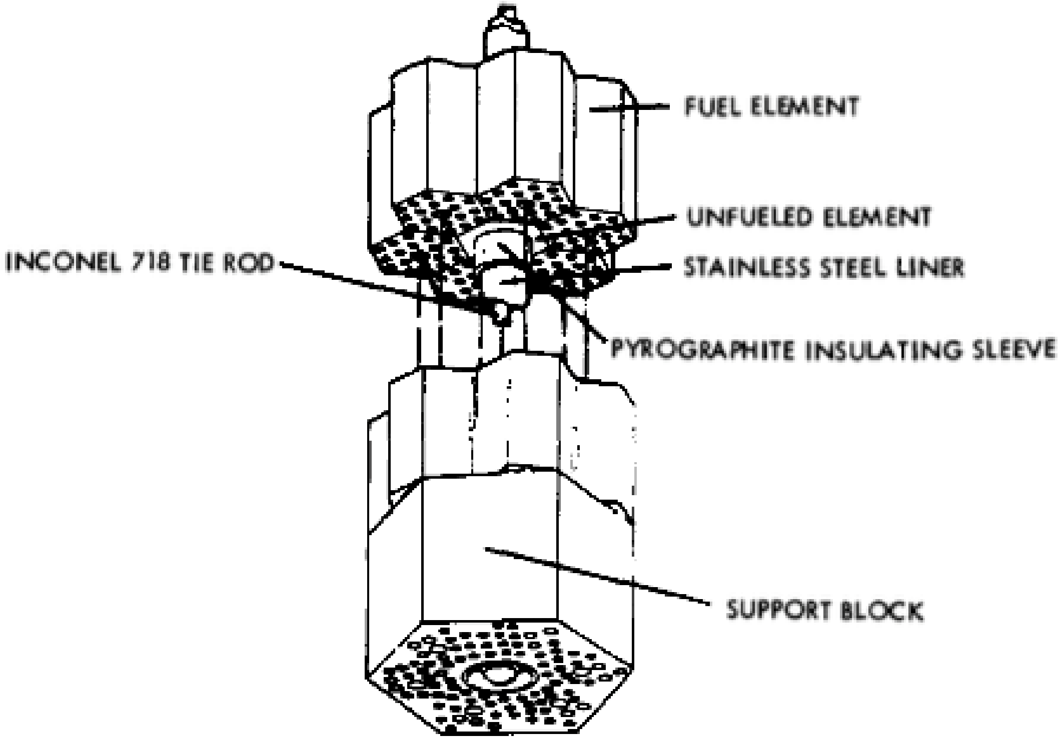
Regular cluster

- XE Prime reactor – active core comprises 199 “regular clusters”
  - Single unfueled element surrounded on all sides by fueled elements
  - Elements are hexagonal



XE Prime regular cluster [9]

[9] Reese, J. C., “WANL-XE-1 Nuclear Subsystem Design Data Book,” *Westinghouse Astronuclear Laboratory*, WANL-TME-1565, September 1973.

Fueled Element

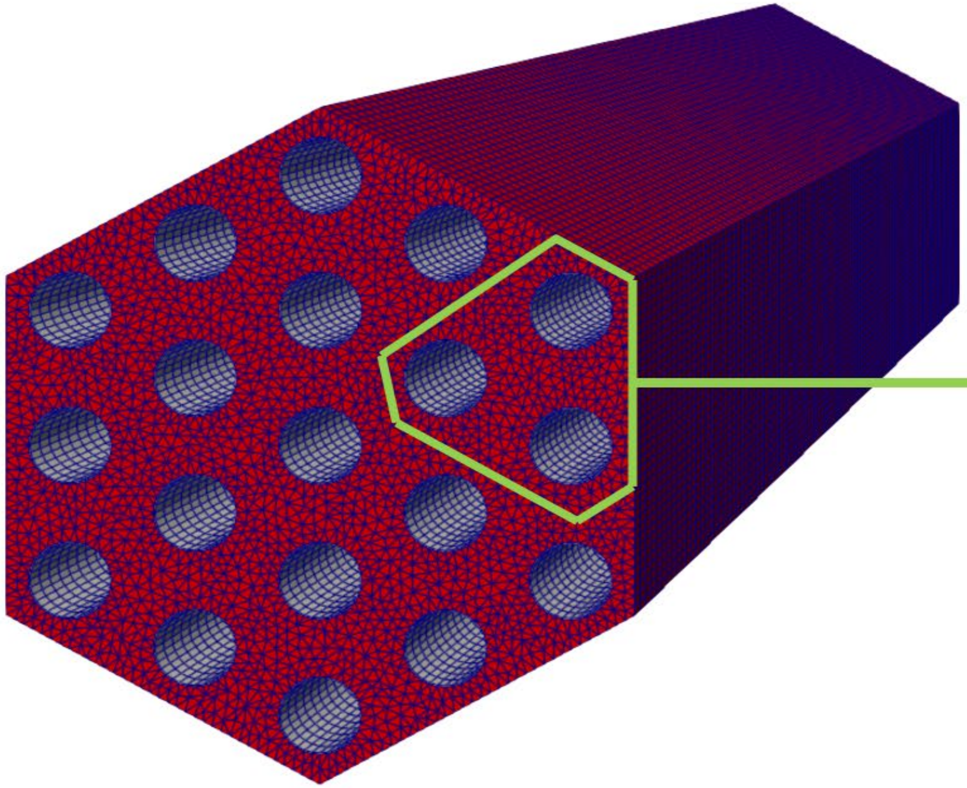
- Graphite matrix loaded with UC fuel pellets [9]
  - Pellets enriched to 93.15 wt%
  - 19 equally spaced coolant channels coated in NbC
  - 52 inches long, with one inch of bottom tip unfueled
    - Only fueled portion is modeled
  - Densities calculated from XE Prime as-built data
  - Material properties based on Aerojet databooks for the NERVA program

Fueled element model dimensions

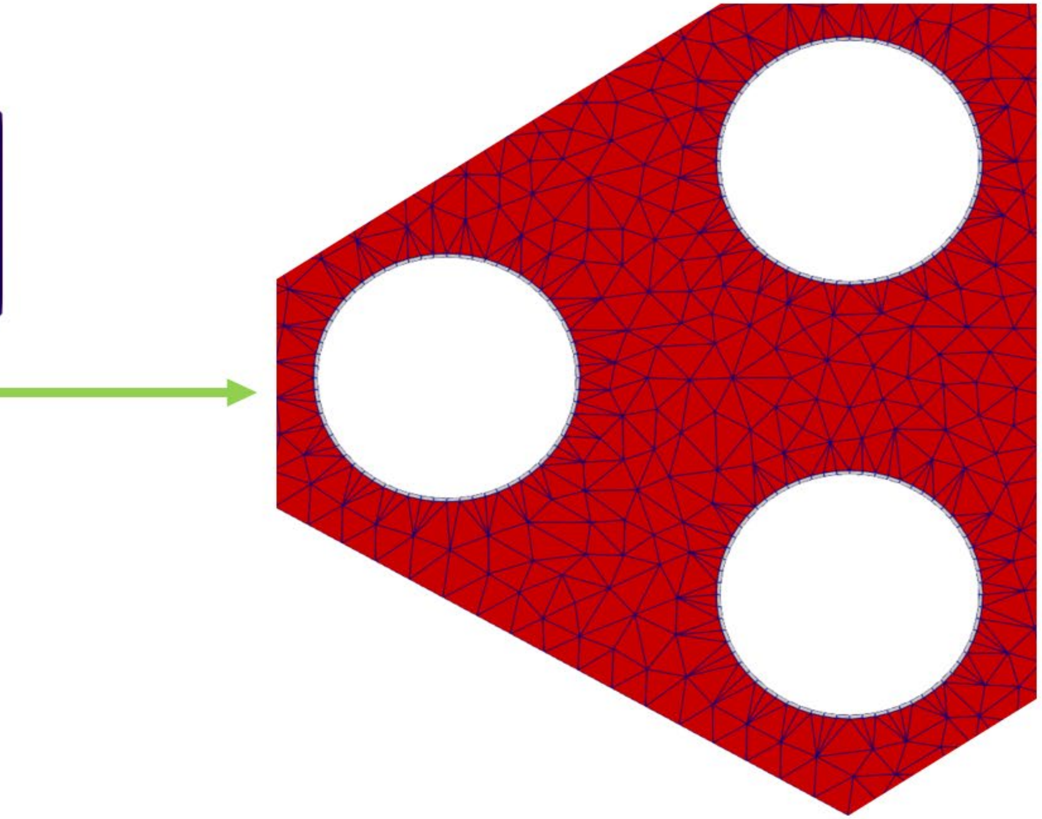
Parameter [units]	Value
Element pitch [cm]	1.91262
Reamed channel radius [cm]	0.12573
Coated channel radius [cm]	0.1215644
Fueled length [cm]	1.2954
Channel pitch [cm]	0.43942
Fueled matrix density [g/cc]	2.217

[9] Reese, J. C., “WANL-XE-1 Nuclear Subsystem Design Data Book,” *Westinghouse Astronuclear Laboratory*, WANL-TME-1565, September 1973.

Fueled Element



Fueled element mesh



Slice view of three channels

Unfueled Element

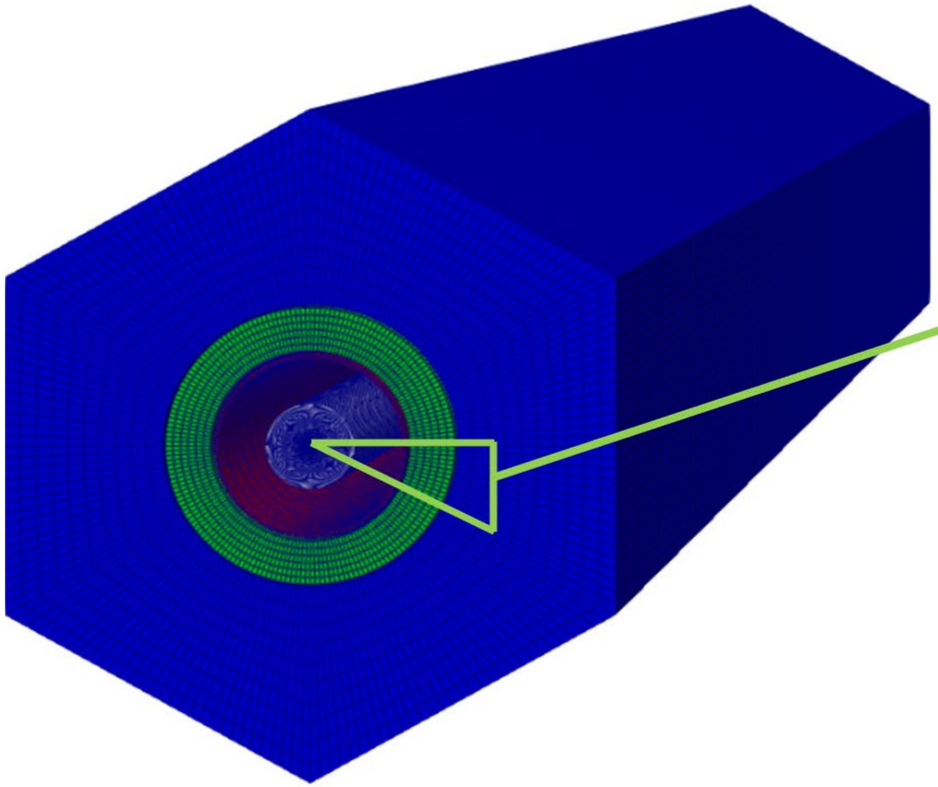
- Single, annular coolant channel [9]
  - Inner wall is a structural tie rod made of Inconel-718
  - Outer wall is stainless steel liner
  - Liner is wrapped in insulation layer of pyrolytic graphite
  - Channel is inserted into hexagon with single, large hole
    - Made of unfueled matrix material
  - Only first 51 inches are modeled to match length with fueled element
  - As-built data used again for density
  - Aeroject databook used again for material properties
    - Pyrographite has two given conductivities (in-plane vs. through-plane)
      - Through-plane is used for entire mesh

Unfueled element model dimensions

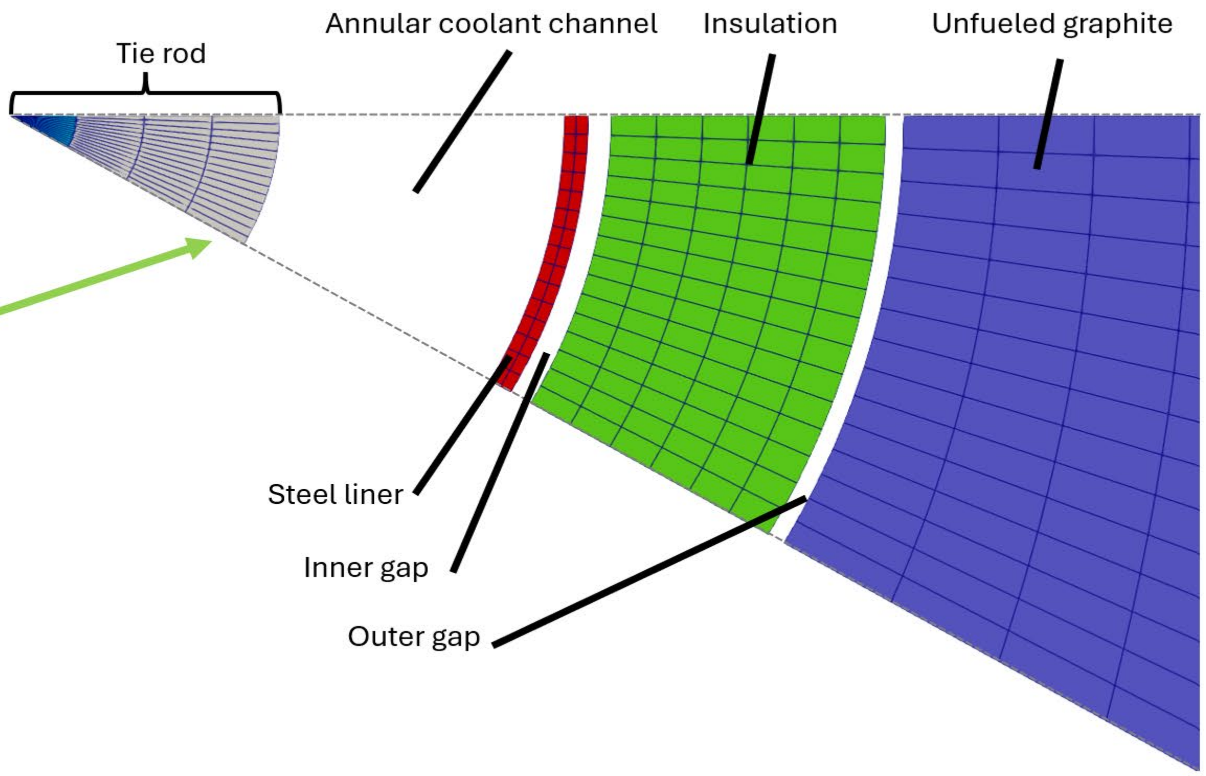
Parameter [units]	Value
Element pitch [cm]	1.91262
Tie rod radius [cm]	0.140335
Coolant channel outer radius [cm]	0.28702
Steel liner outer radius [cm]	0.29972
Insulation inner radius [cm]	0.31115
Insulation outer radius [cm]	0.45339
Unfueled graphite inner radius [cm]	0.46228
Element length [cm]	1.2954

[9] Reese, J. C., "WANL-XE-1 Nuclear Subsystem Design Data Book," *Westinghouse Astronuclear Laboratory*, WANL-TME-1565, September 1973.

Unfueled Element



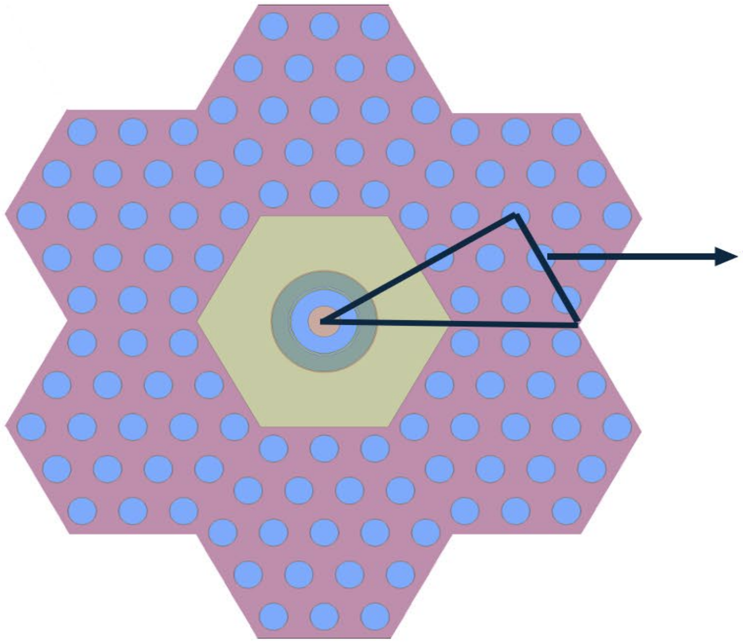
Unfueled element mesh



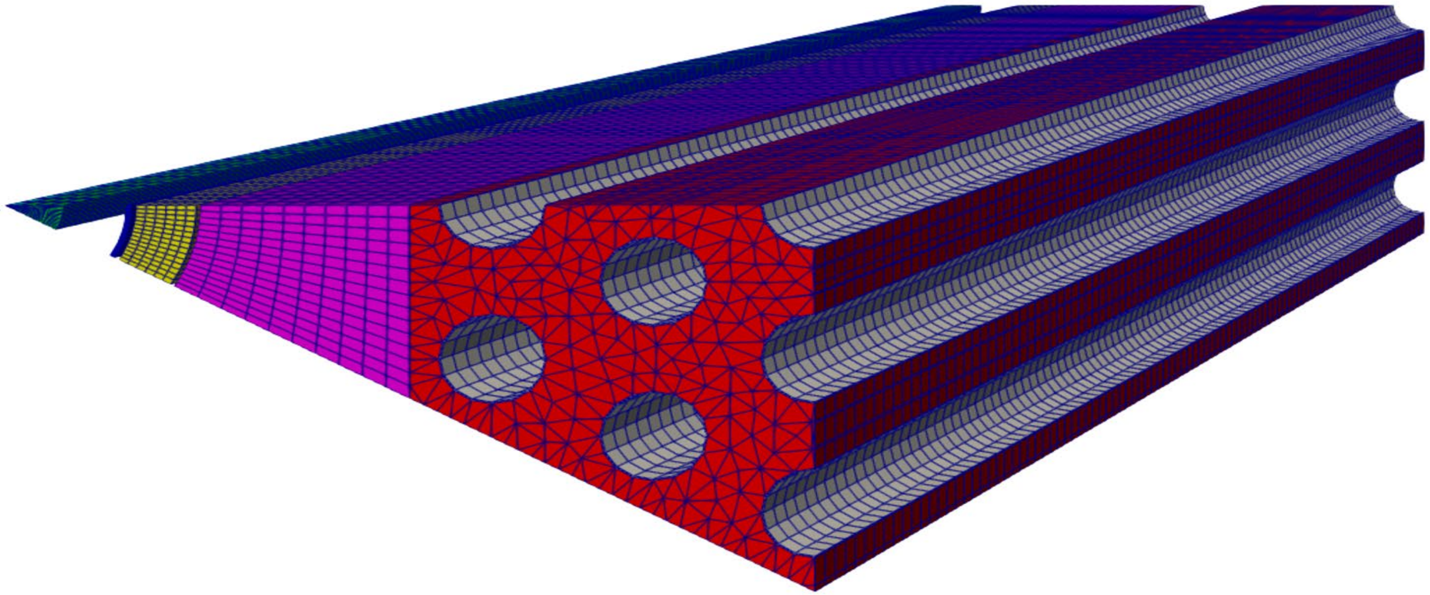
Annular channel slice view

Cluster Slice

- Rather than simulate an entire regular cluster, a 30º slice was made based on three axes of symmetry
  - Each is modeled thermally as an adiabatic wall and neutronically as a perfectly reflective surface



Regular cluster (top-down)



Regular cluster slice mesh

Results

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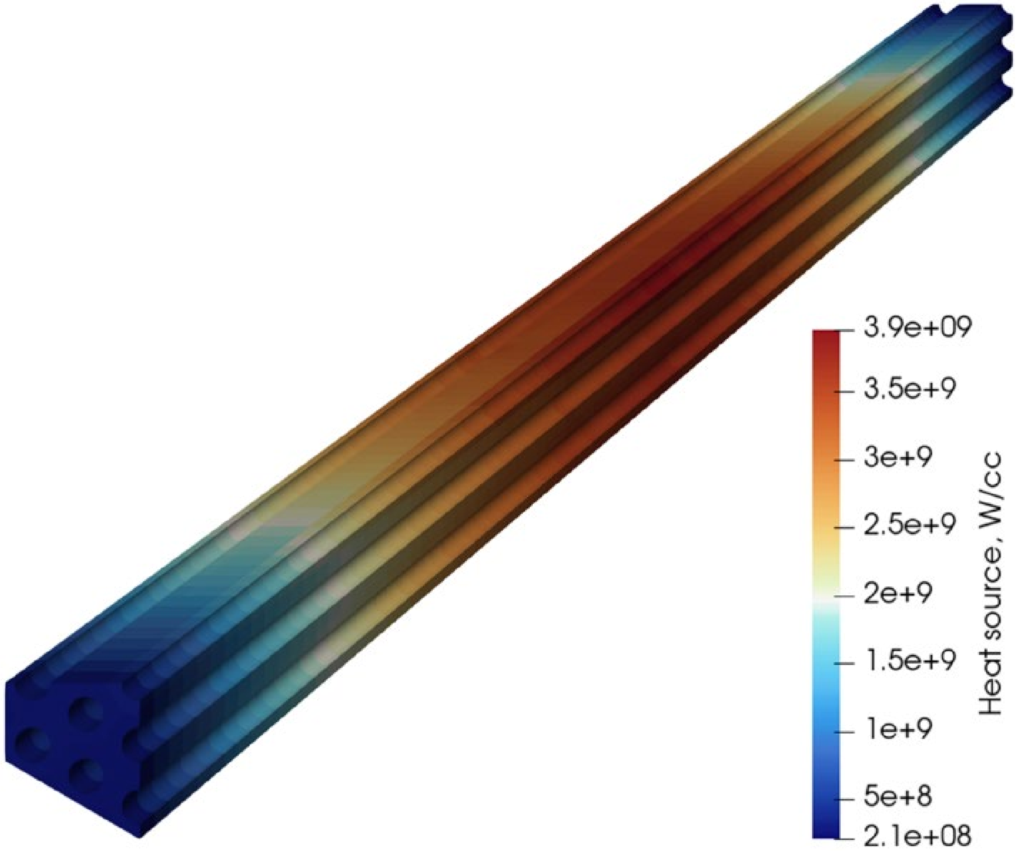
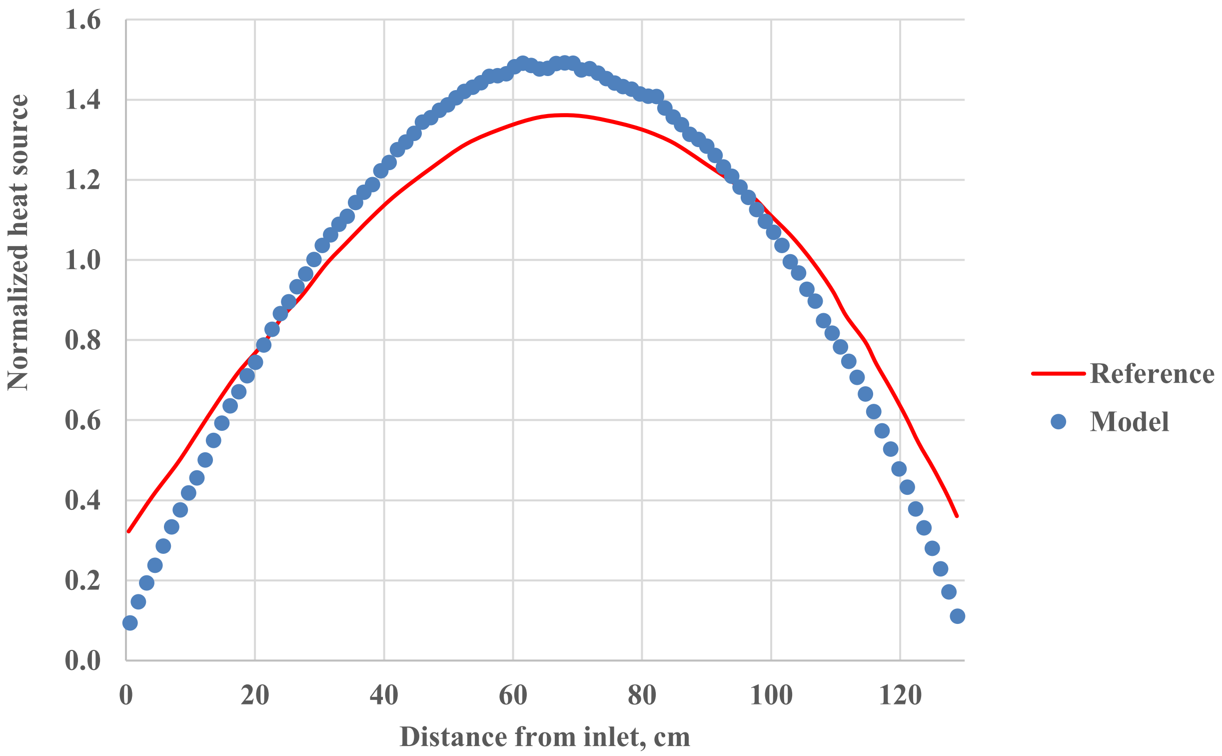
Power Shape



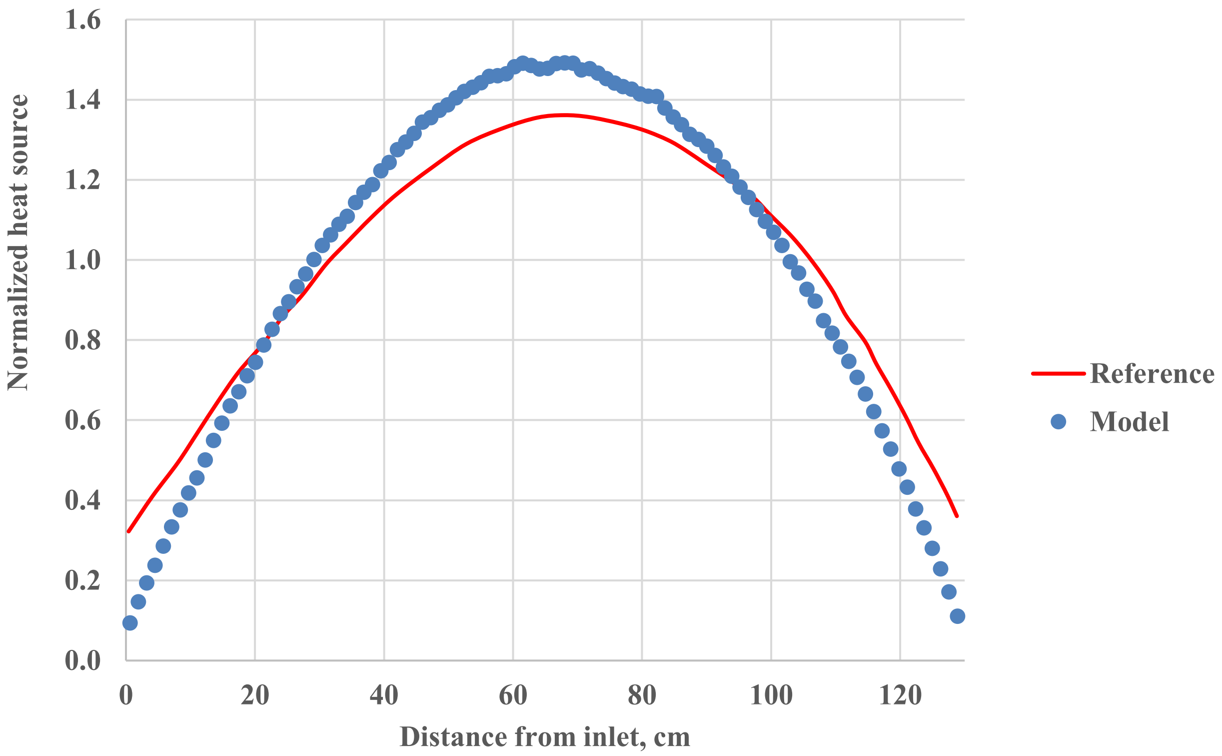
Volumetric heat source distribution



Axial heat source distribution

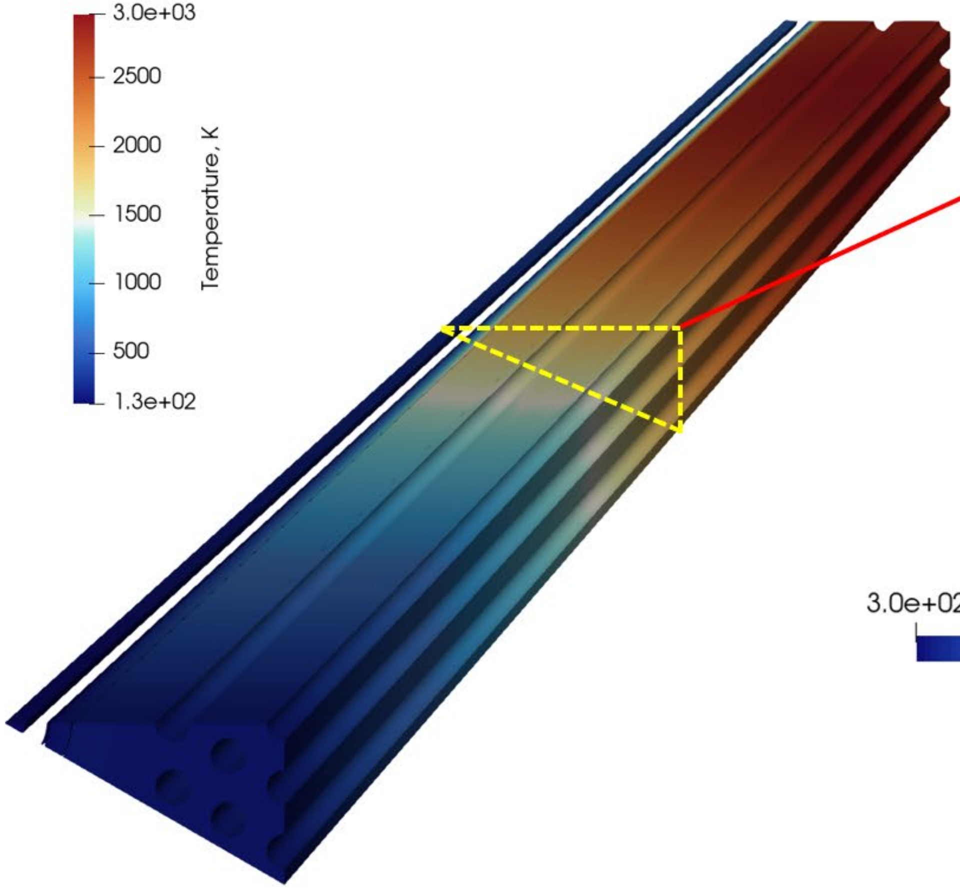
Power Shape

- Model peaks far more sharply than the reference
  - Lack of dome-side axial reflection and shielding
  - Lack of aft-side unfueled-tip
  - Slice model does not account for irregular cluster arrangements in active core periphery, nor any radial reflection

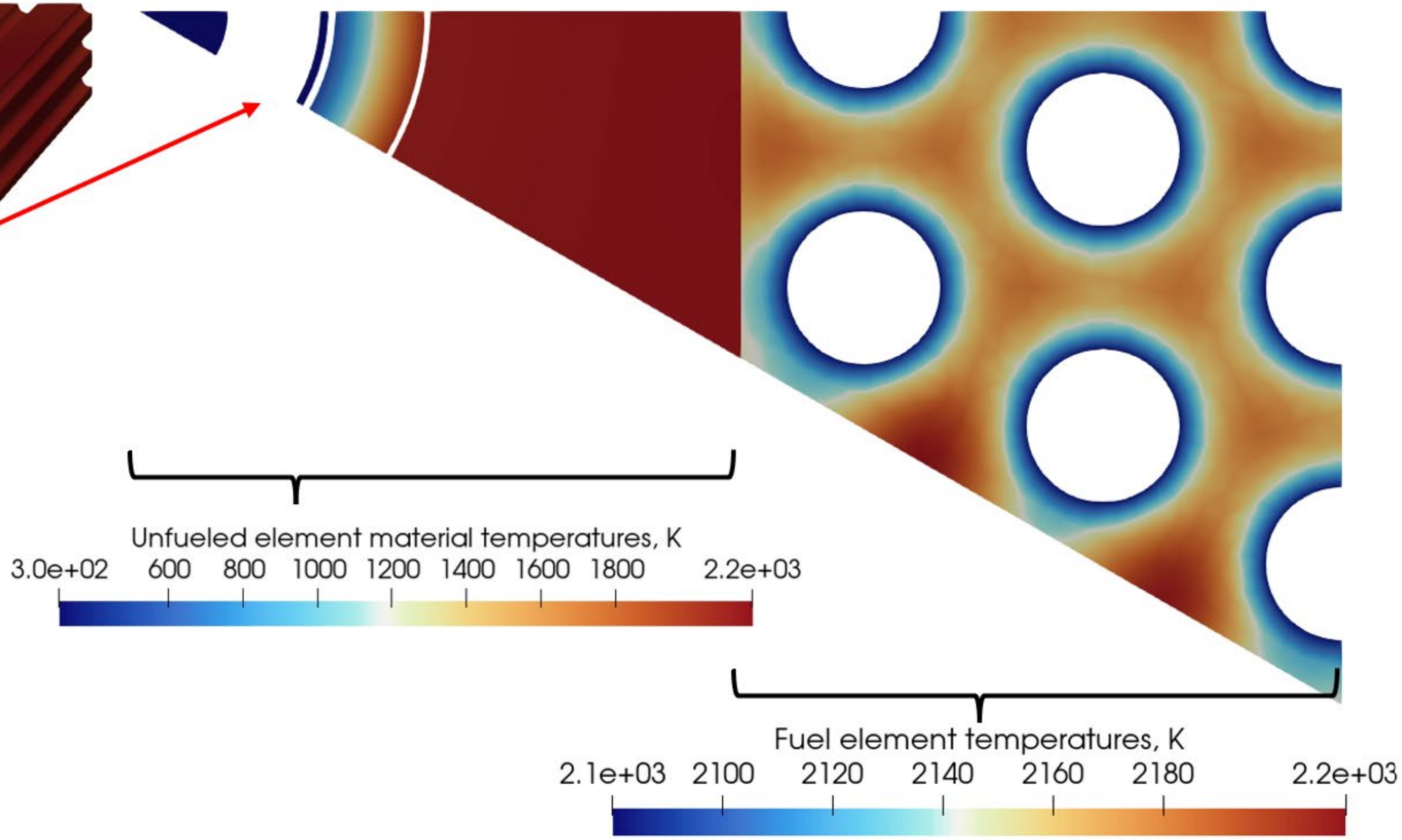


Axial heat source distribution

Solid Temperature



Solid temperature distribution



Mid-plane radial temperature distribution

Solid Temperature

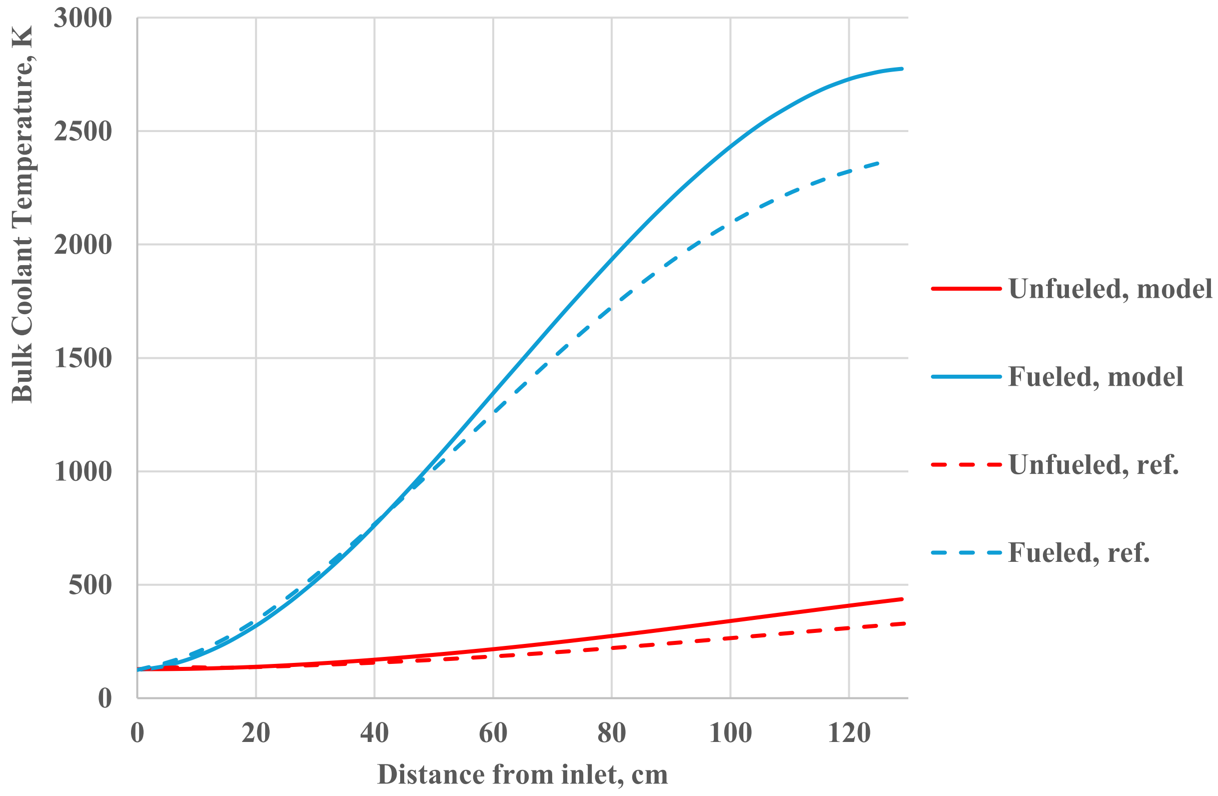
Max temperature of each mesh region

Region	Max temperature, reference [K]	Max temperature, model [K]	Error [%]
Fueled matrix	2473	2959	19.7
Channel coating	2392	2923	22.1
Unfueled matrix	2464	2932	19.0
Pyrolitic graphite	2368	2811	18.7
Steel liner	411.2	537.2	30.6
Tie rod	348.3	524.9	50.7

- All temperatures are way too high
  - Can be reduced by substituting Dittus-Boelter with Wolf-McCarthy [10]
  - Ideal gas hydrogen needs to be substituted with parahydrogen
  - Other minor issues
    - False axis of symmetry
    - Gap relationships use constant emissivity and default conductivity

[10] Nikitaeva, D., Smith, C., Palomares, K., "Comparison of Convective Heat Transfer Correlations and Their Application to Nuclear Thermal Propulsion Reactors," *Analytical Mechanics Associates*, April 2020.

Bulk Coolant Temperature



Bulk temperature axial distribution

- Temperatures are too high again, likely for similar reasons as with the solid temperatures
  - Dittus-Boelter needs to be substituted with Wolf-McCarthy
  - Ideal gas hydrogen needs to be substituted with parahydrogen

Conclusions

Conclusions

- Major refinements to this model are needed
  - Nusselt number correlation
  - Fluid properties
  - Hydrogen gaps
  - Axial reflectors, unfueled tip, support block
- However, the approach still has merit
  - Successful coupling of three key physical behaviors
  - Can be expanded across multiple time steps

Next Steps

- Refine model
- Expand model to full core
  - Include irregular clusters on periphery, radial reflectors, control drums, etc.
- Expand methodology for transient analysis
  - Link PRK solver into solution sequence
    - Include reactivity effects of temperature changes, propellant density changes, control drum movements
- Link methodology to system-level analysis
  - Engine cycle model can dynamically update inlet/outlet conditions as time steps progress

Acknowledgements

- This work was supported by NASA's Space Technology Mission Directorate (STMD) through the Space Nuclear Propulsion (SNP) project.
- This work was funded under Contract No. 80LARC23DA003.