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Geometry Design and Transient Simulation of a Heat Pipe Micro Reactor

Dr. Jun Wang

University of Wisconsin - Madison, USA

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Meet the Presenter

Dr. Jun Wang is an associate scientist of Nuclear Engineering and Engineering Physics at the University of Wisconsin-Madison.

His research interests include the advanced numerical analysis of nuclear safety and reliability for various reactor designs. He is leading a few projects on the heat pipe micro reactor, high temperature gas cooled reactor transient analysis, and uncertainty quantification by artificial intelligence.

He is also serving on the ANS thermal hydraulics committee, and the journal Progress in Nuclear Energy, Annals of Energy Research as editorial board.

Dr. Wang earned his Ph.D. from Xi'an Jiaotong University.

Email: jwang564@wisc.edu

Content

- MICRO REACTOR REVIEW
- NUMERICAL TOOL AND BENCHMARK
- STEADY STATE AND SENSITIVITY ANALYSIS
- TRANSIENT SAFETY SIMULATION
- CONCLUSION

Microreactor Development

- Micro-reactors are of interest due to flexible, reliable;
- Small, transportable, on-site installation;
- Support deep space, government off-grid, remote communities, e.g.,

- Designs include heat pipe cooled and gas cooled micro-reactors;
- Research demonstrate designs are safe, and efficient.

Heat Pipe Microreactor Research

Past work for Heat Pipe Micro-Rx's

- Heat pipe cooling technology has been widely applied since 1960s for specialized applications
- Space exploration projects: KRUSTY, HOMER, SAIRS, HP-STMCs, MSR, etc.

*NASA and National Nuclear Security Administration engineers lower the wall of a vacuum chamber around the Kilo power reactor system

Industrial effects

Project	Company	Fuel	Power
		Heat Pipe Cooled Microreactor	
eVinci	Westinghouse	UO_2 or TRISO*	1-5 MWe
Aurora	Oklo	Metallic Uranium-Zirconium	1.5 MWe
		Gas-cooled Microreactor	
Holos Quad	HolosGen	TRISO	3-13 MWe
Micro Modular Reactor	USNC	Fully Ceramic Microencapsulated	5 MWe
Xe-Mobile	X-Energy	TRISO	>1 MWe

*TRISO: Tri-structural ISOtropic particle fuel

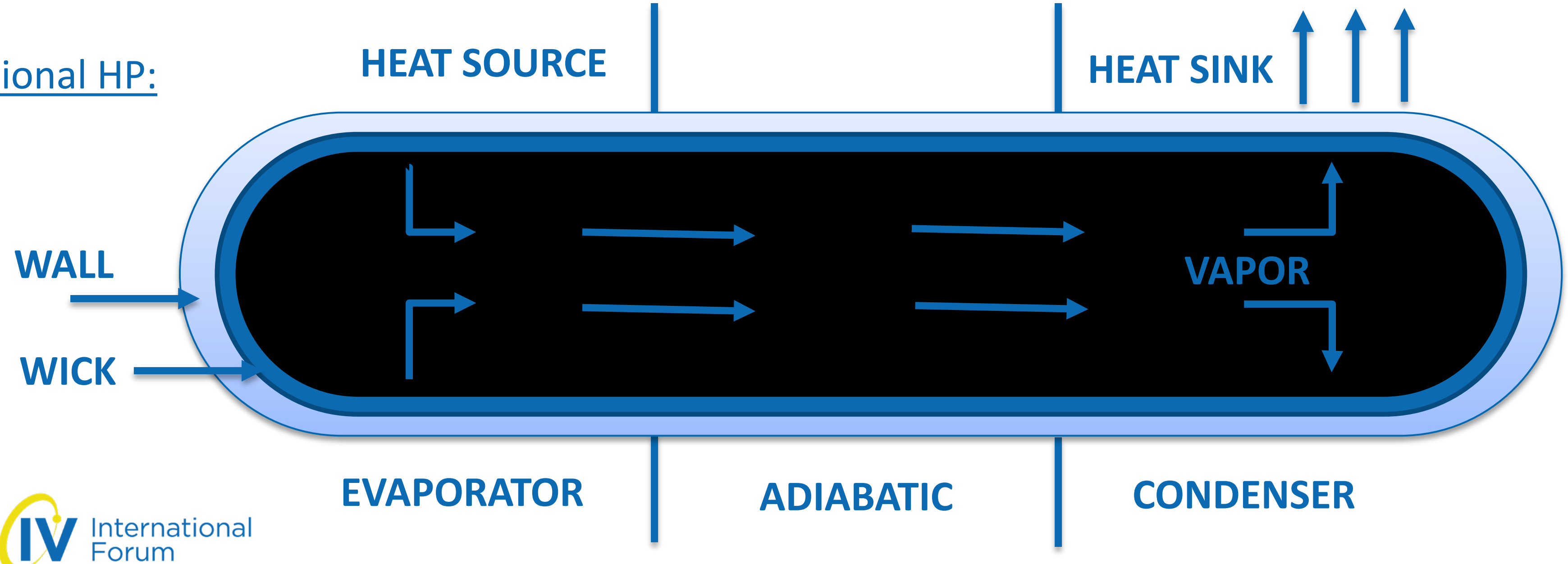
- Westinghouse's eVinci design uses mature heat pipe technology developed by LANL
  - Comprised of solid block with 3 types of channels for fuel rods, moderators, heat pipes
- Oklo's Aurora Powerhouse is inspired by NASA's Kilopower reactor
  - Uses metallic uranium fuel alloy in a solid block with heat pipe cooling technology

Heat Pipe Flowchart

Heat Pipe is made of Wall, Wick, and Coolant

- In the evaporator, liquid coolant turns to vapor
- Vapor coolant goes through adiabatic region
- In the condenser, vapor coolant is cooled back to liquid
- Liquid coolant flows back through Wick

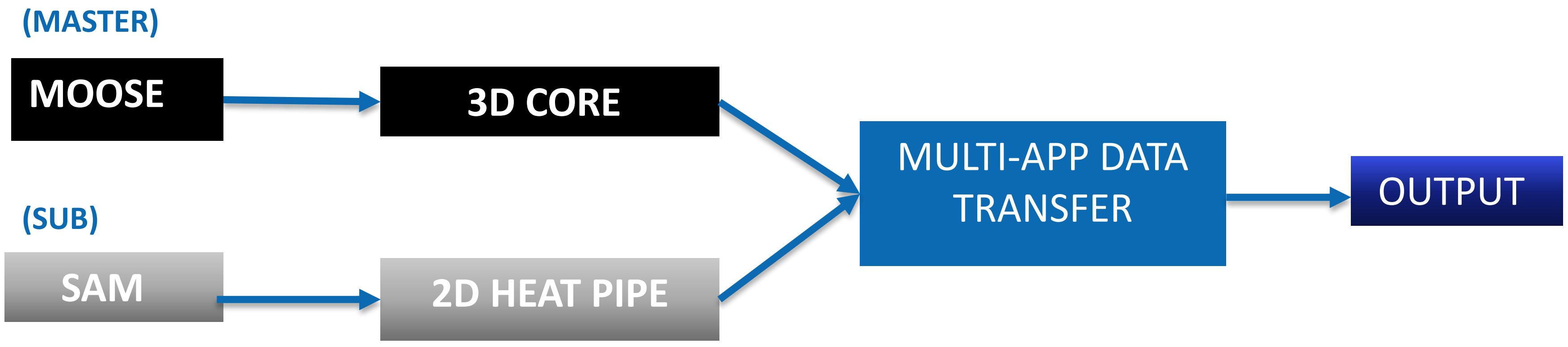
*Conventional HP:



Content

SAM/MOOSE Analysis Approach

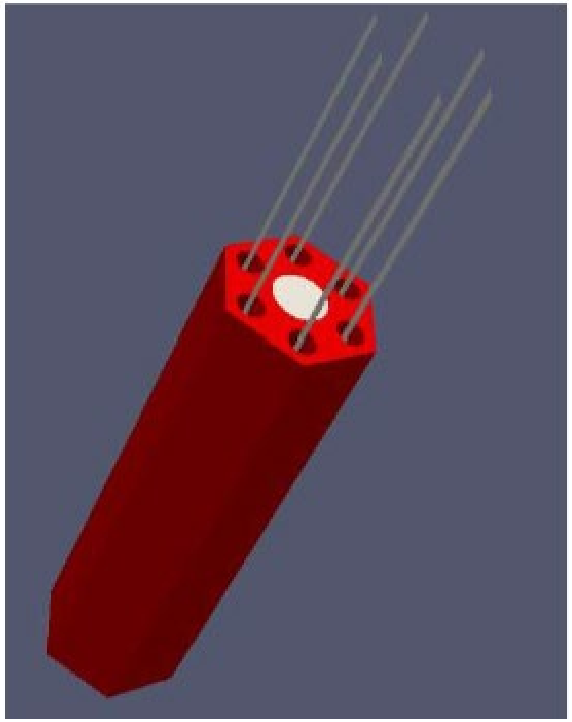
- MOOSE can conduct multi-scale simulation (e.g., heat conduction)
  - Plug-in infrastructure simplifies the definition of key physical processes, material properties, post-processing
- SAM has Heat Pipe model to describe fluid flow and heat transfer behavior; assumes high rate of axial conduction in heat pipe and neglects vapor flow
- Processes considered: Heat conduction, liquid flow/heat transfer, interfacial mass/momentum/energy transfer

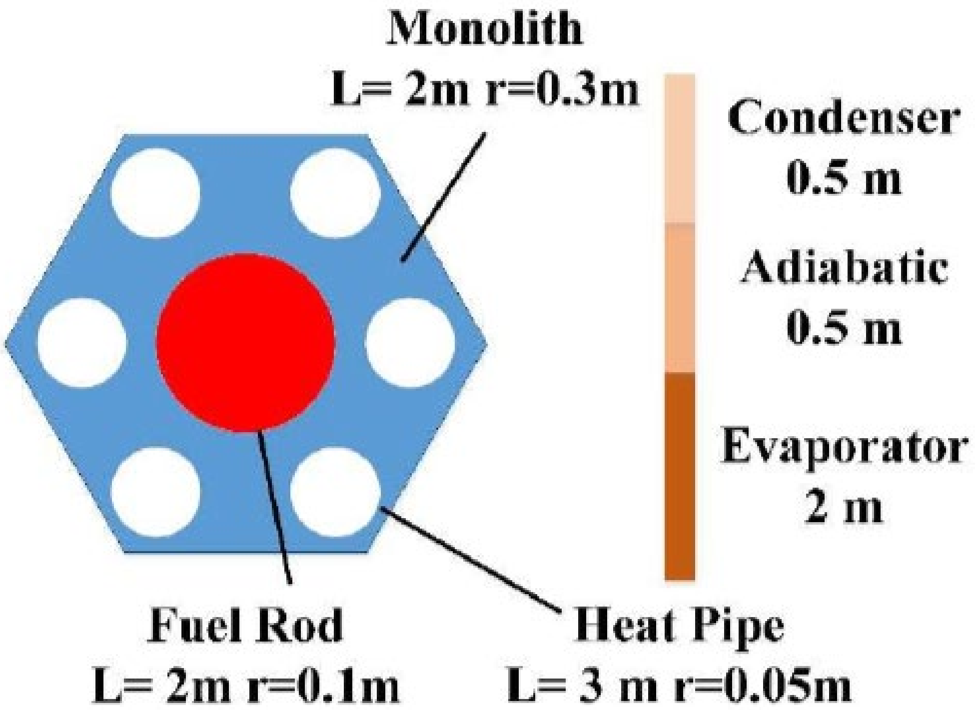


ANL Benchmark Comparison

- To verify SAM/MOOSE coupling, code-to-code comparison is first tested
- Geometry is a solid monolith block; 1 heater rod and 6 heat pipes (Na) – similar to ANL benchmark calculation

Simulation Components:





ANL Benchmark Comparison

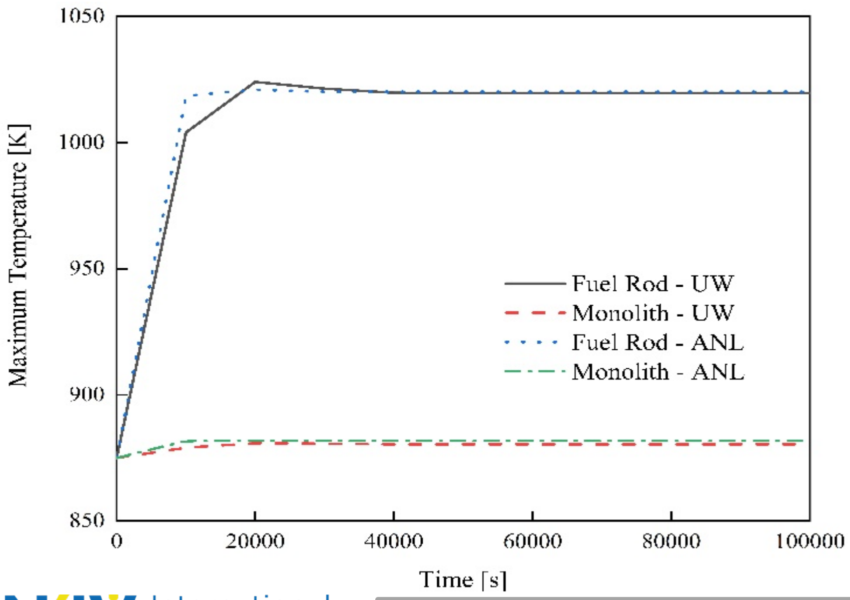
- Time step for both cases is kept the same and results differ early in time
- Initial temperature set at 875K and solid monolith surfaces is adiabatic
- Heat pipe condenser temperature is 750K
- Heat produced in heater rod and removed by heat pipes

Material Properties of HP Micro-reactor

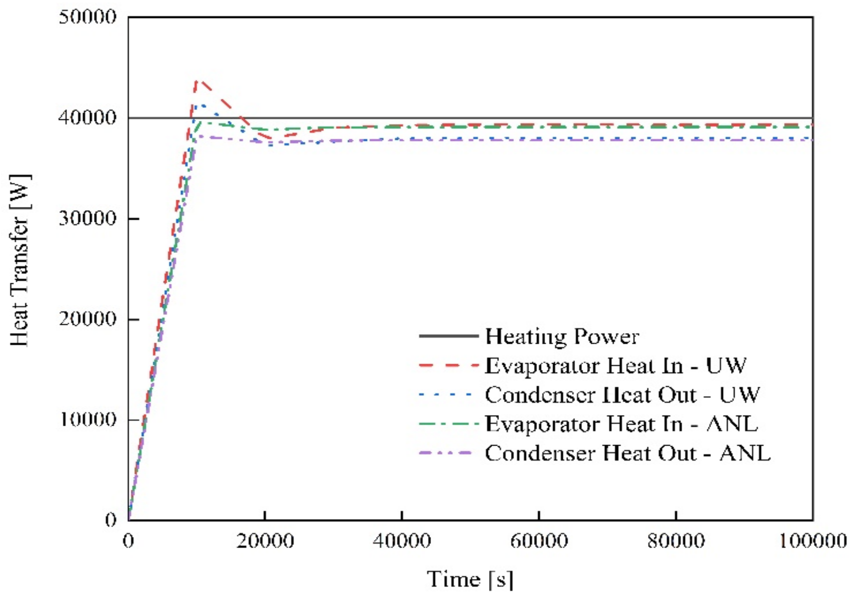
	Monolith	Fuel Rod	Heat Pipe		
			Vapor	Wick	Wall
Density (kg m^3)	1873.9	11,000	1	865	7670
Specific Heat (J/kg)	1603.5	939	10,000	1200	568.7
Thermal Conductivity (W/mK^{-1})	30	18	1E+06	47.4	21.8

ANL Benchmark Comparison

- Small differences at 10000s between ANL & UW analysis
- Both benchmarks use different # of nodes (25459 for ANL, 51573 for our HEX20 elements)
- Results indicate our modeling strategy can be used to couple solid core heat conduction to Heat Pipe cooling. It could potentially be expanded to other research.



Temperature Distributions



Energy Balance

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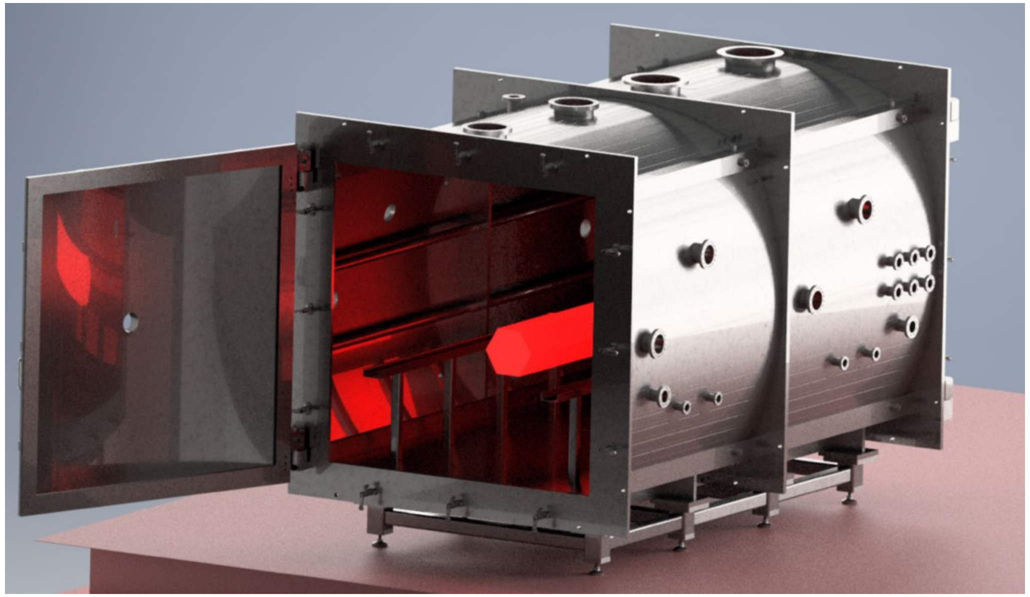
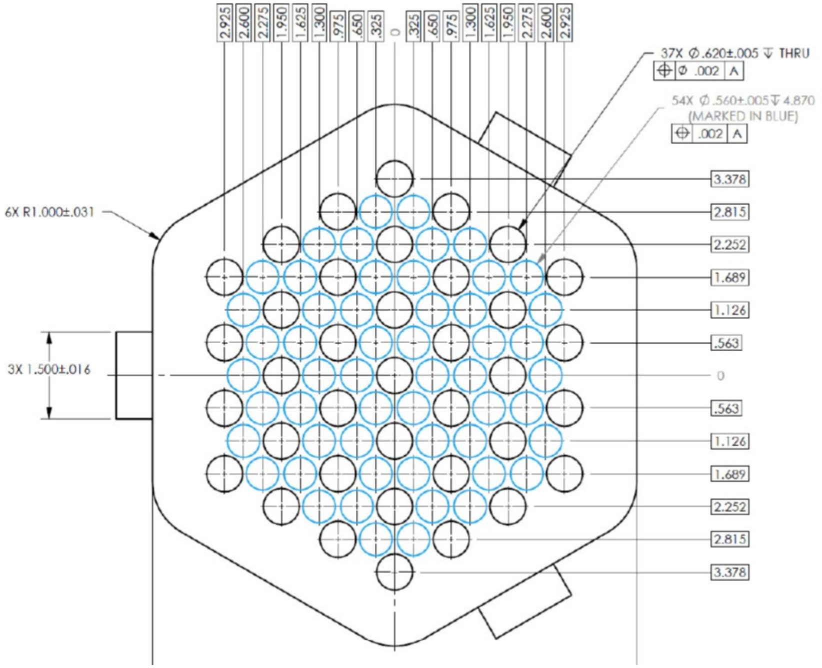
MAGNET Test Facility at INL

- Micro-reactor Agile Non-nuclear Experimental Test-bed (MAGNET) at INL
- Goal is to provide a test bed that is broadly applicable to multiple microreactor concepts (initial HP cooled configuration)



*Vacuum Chamber showing door and test article inside



Solid monolith with 54 fuels and 37 HPs

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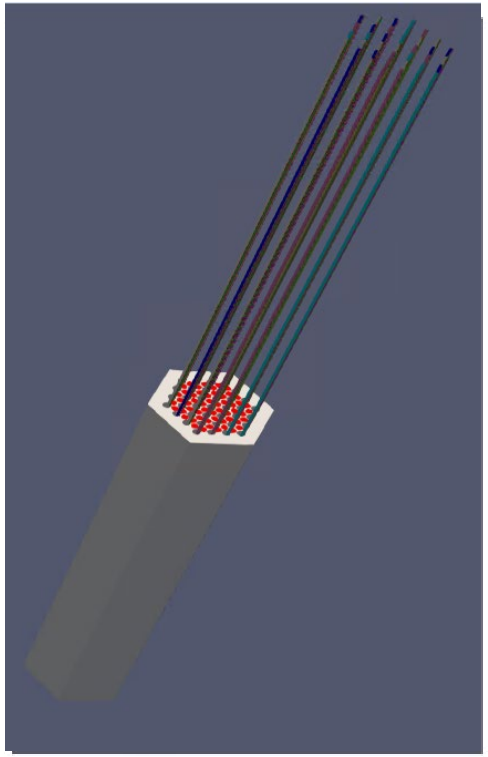
MAGNET Simulation

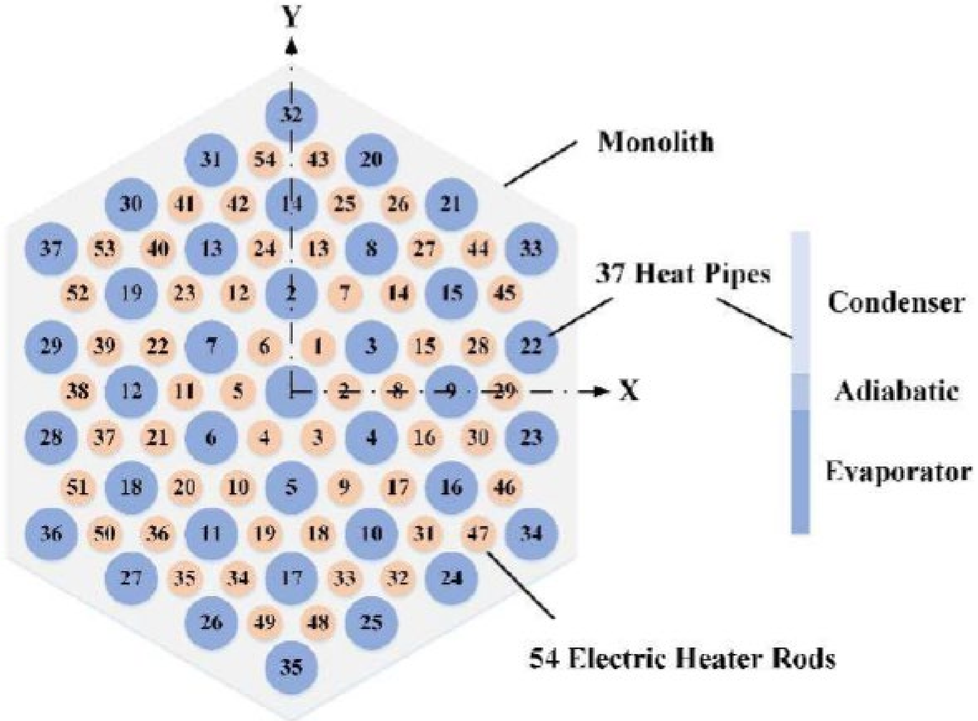
- MAGNET hexagonal solid monolith has: 54 heater rods and 37 heat pipes
- Fission heat is simulated with electric heater rods
- Monolith block and heat rods made up of stainless steel (SS 316L)
- Power distributions of heater rods are not finalized; assumed a **cosine power shape** to approximate actual power profile
- Note: Temp. of monolith heaters (3D) and heat pipes (2D) calculated separately (MOOSE: monolith + rods, SAM: heat pipes)

MAGNET Simulation

- Heat generated transferred from rods to monolith and to embedded heat pipes
- Monolith temperature indicates that heater rods close to center have higher temp than outside edges

MAGNET 37 HP Model Configuration:





MAGNET Heat Pipe Model

Components:

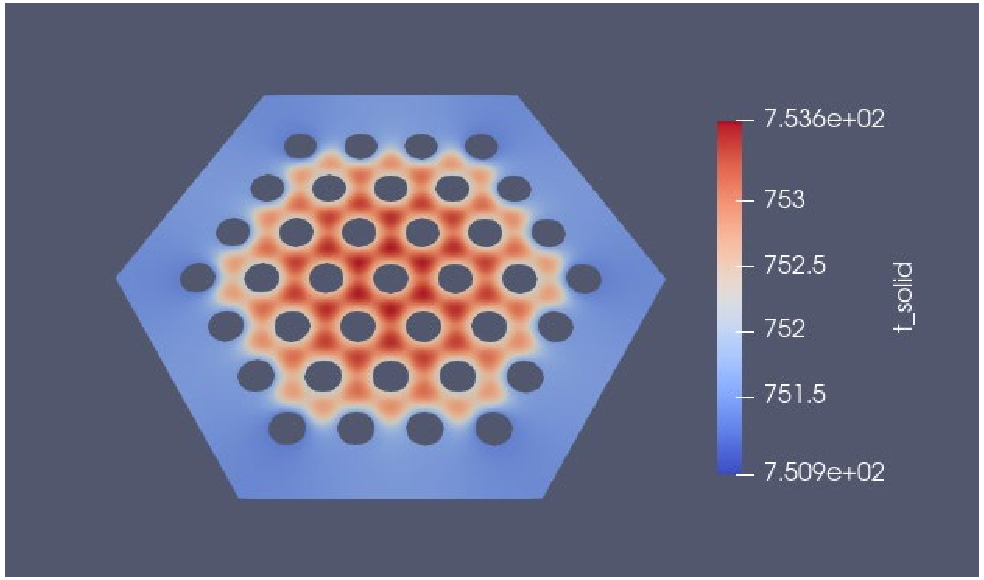
Monolithic Block	
Height:	1 m
Diameter:	0.244 m
Material:	SS 316L
Boundary Condition:	Adiabatic radial & axial
Electric Heaters	
Quantity:	54
Diameter:	0. 014 m
Material:	SS 316L
Total Pwr:	75 kW

Heat Pipe						
Quantity:		37	**Diameter:**		0.0156 m	
Material:	Vapor:	Na	Wick:	SS 316L	Wall:	SS 316L
Outer Radius:	Vapor:	0.0053 m	Wick:	0.0066 m	Wall:	0.0078 m
Length:	Evap:	1 m	Adiab:	0.2 m	Cond.:	0.8 m
Evaporator Wall Interfacial HTC *:		10^5 W/m^2K^{-1}	**Condenser Wall Temperature:**			750 K

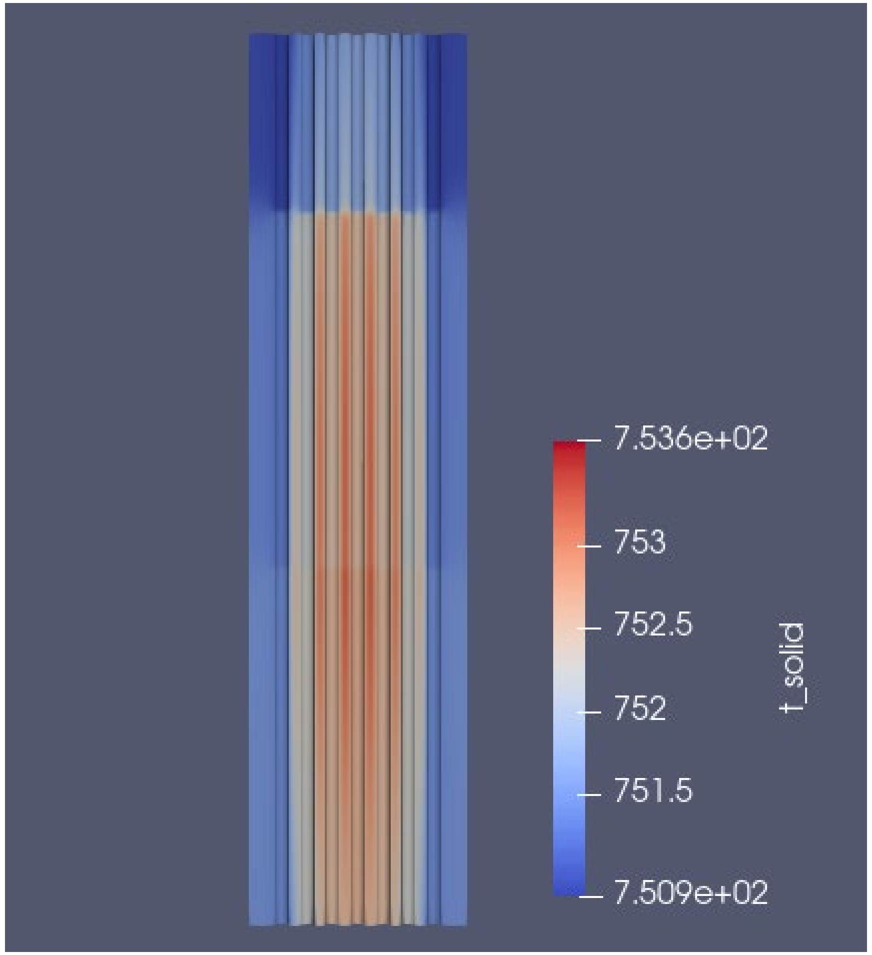
*Assumed gas gap between monolith and HP of ~ 0.5 mm

Steady State Results

Monolith Steady State Temperature:

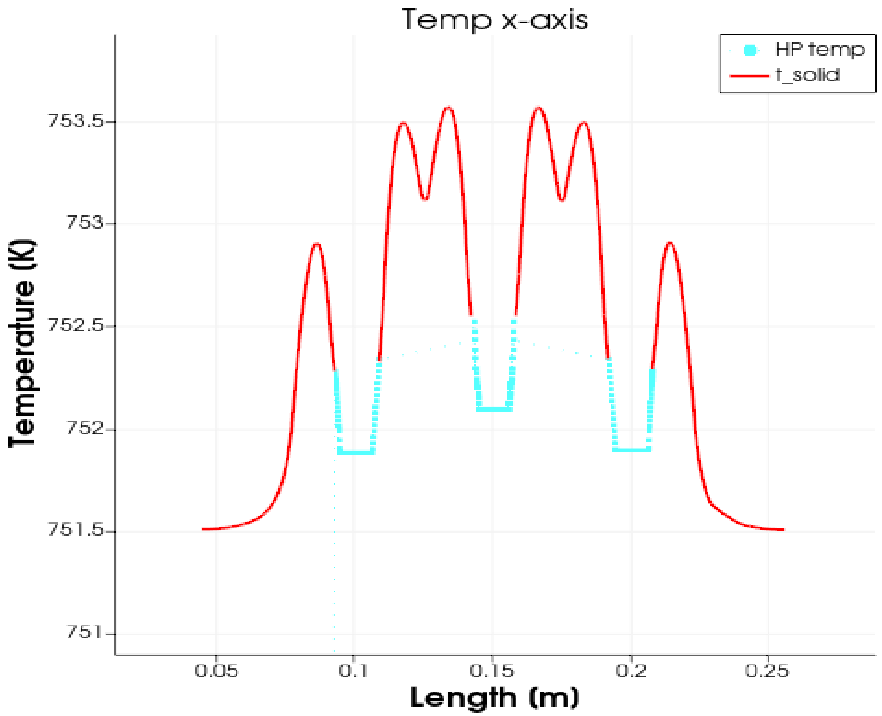


Plane Z = 0

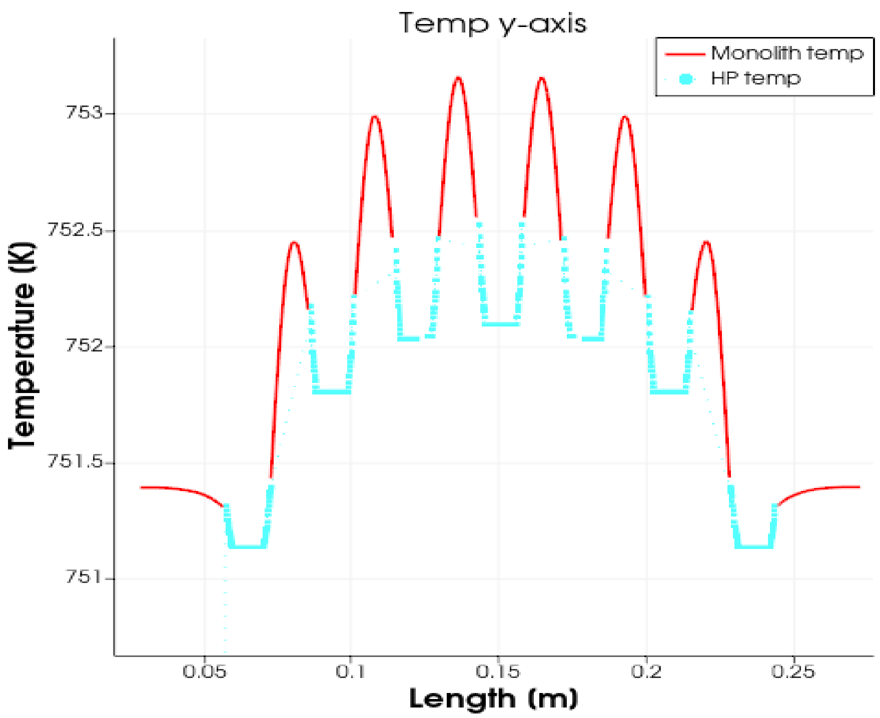


Plane X = 0

Steady State Results

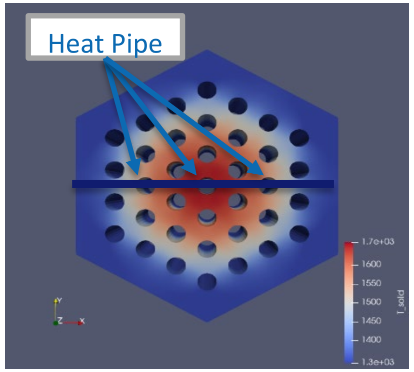


SS temp of monolith along X-axis



SS temp of monolith along Y-axis

*Trends imply temp distributions are symmetrical across monolith



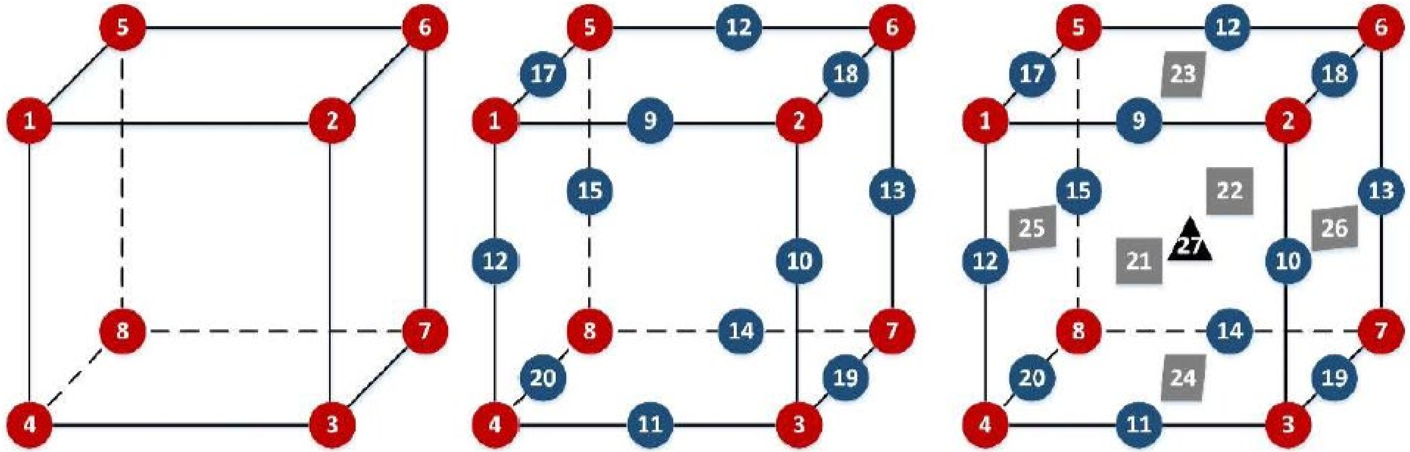
Steady State Analysis

Case	Element Type	Heating Power (kW)	Evaporator Wall HTC (W/m2K-1)	Condenser Wall Boundary Conditions	HP Fail
0	HEX20	75	10^5	750 K	None
1	HEX8	75	10^5	750 K	None
2	HEX27	75	10^5	750 K	None
3	HEX20	100	10^5	750 K	None
4	HEX20	75	10^3	750 K	None
5	HEX20	75	10^7	750 K	None
6	HEX20	75	10^5	730 K	None

*HEX = x-node hexahedral element

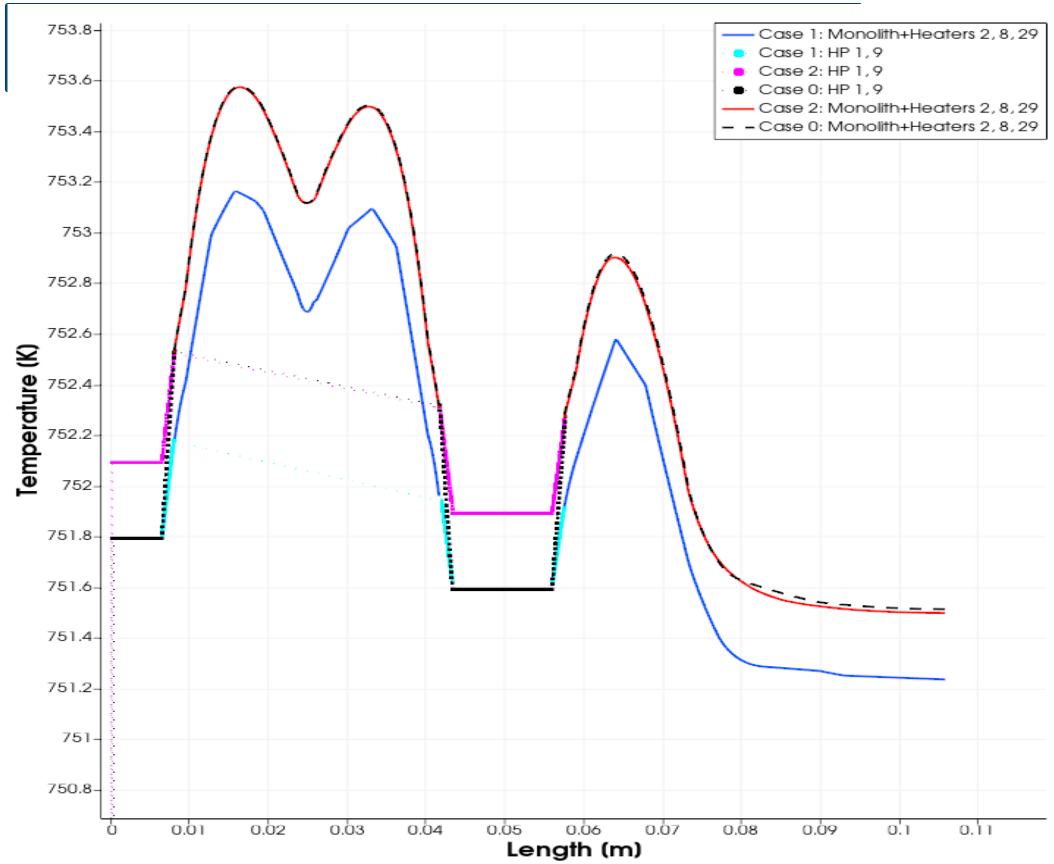
HEX Nodal Background

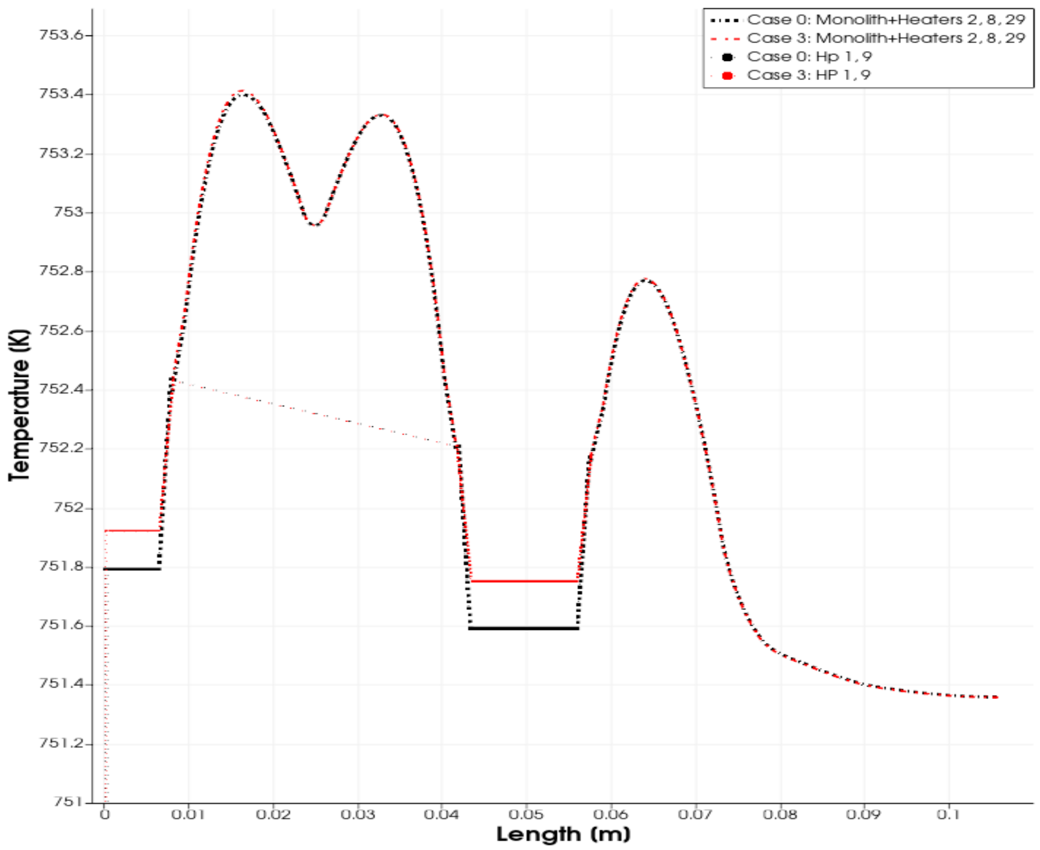
- HEX8 = 8-node trilinear hexahedral element
- HEX20/27 = 20-node and 27-node quadratic hexahedral elements
- More nodes results in higher simulation accuracy but slows computing process
- Increasing # nodes no longer affects accuracy past a certain point
- HEX20 is best option for high-precision simulation



*Node numbering for HEX8, HEX20, HEX27

Steady State Analysis





Cases 0-2

Cases 0, 3

1	**HEX8**	**75**	**10^5**	**750 K**
2	HEX27	75	10^5	750 K
3	HEX20	100	10^5	750 K

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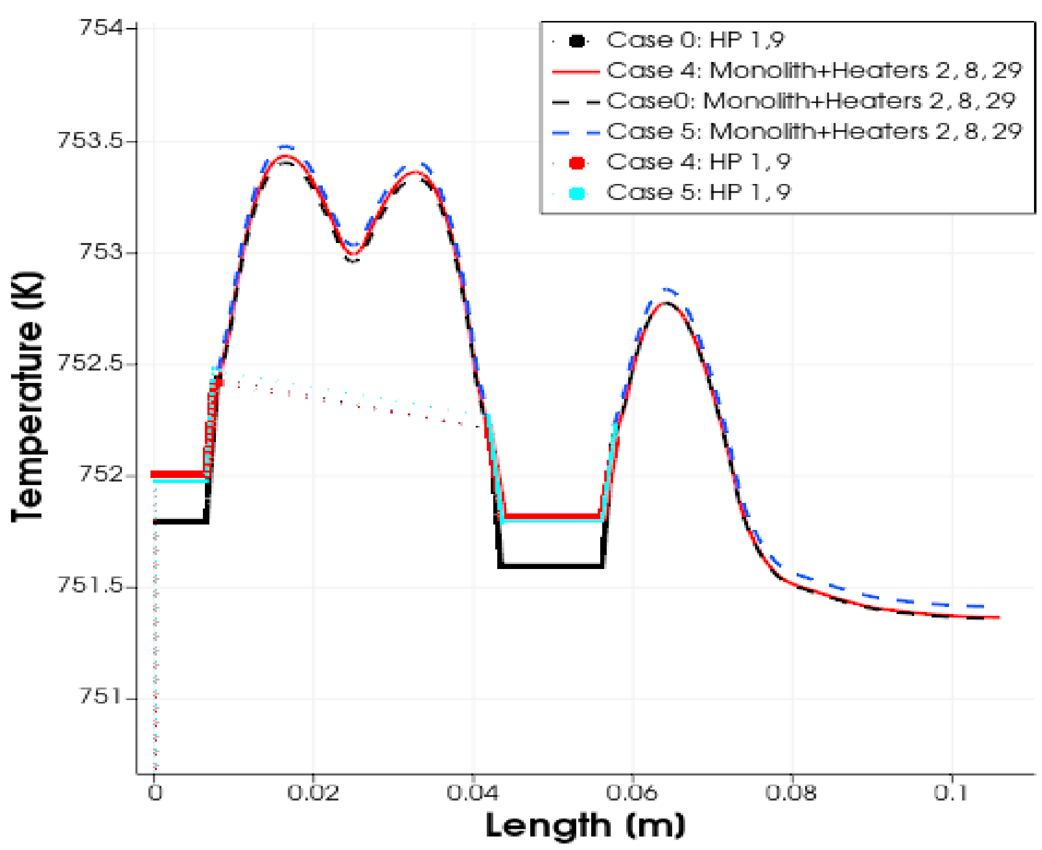
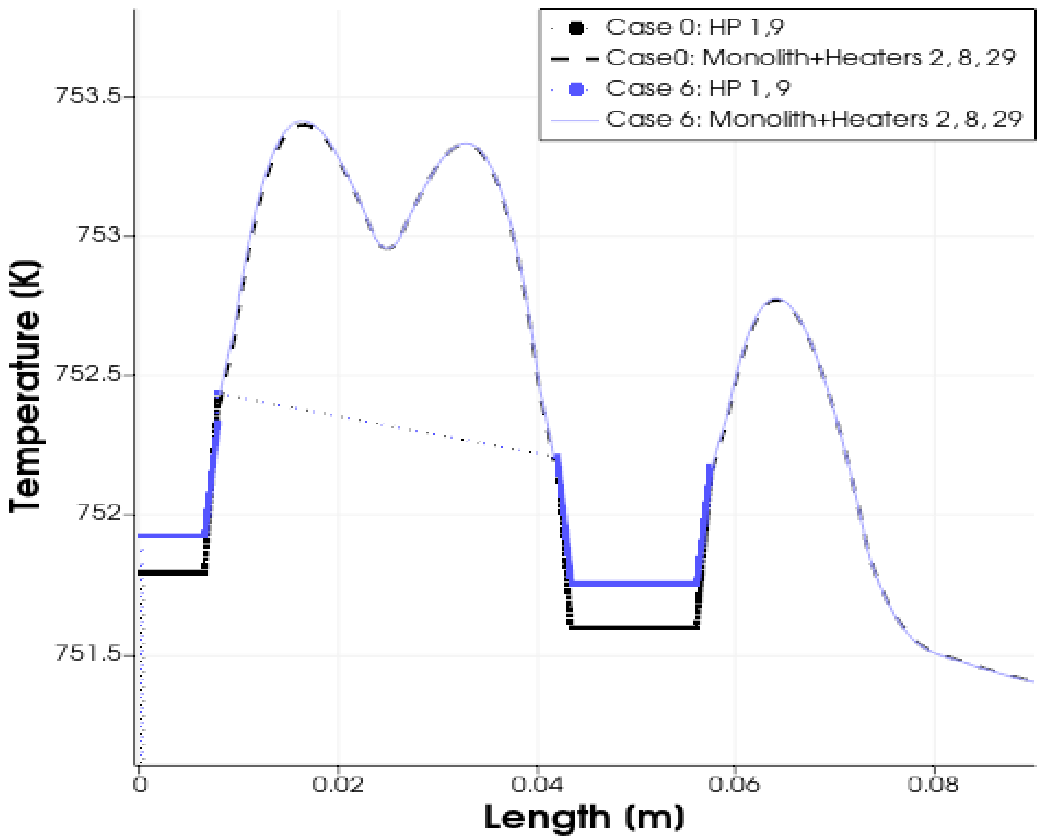
Steady State Analysis



Cases 0, 4, 5



Cases 0, 6

4	**HEX20**	**75**	**10^3**	**750 K**
5	HEX20	75	10^7	750 K
6	HEX20	75	10^5	730 K

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Case 1-5 Transient Cases

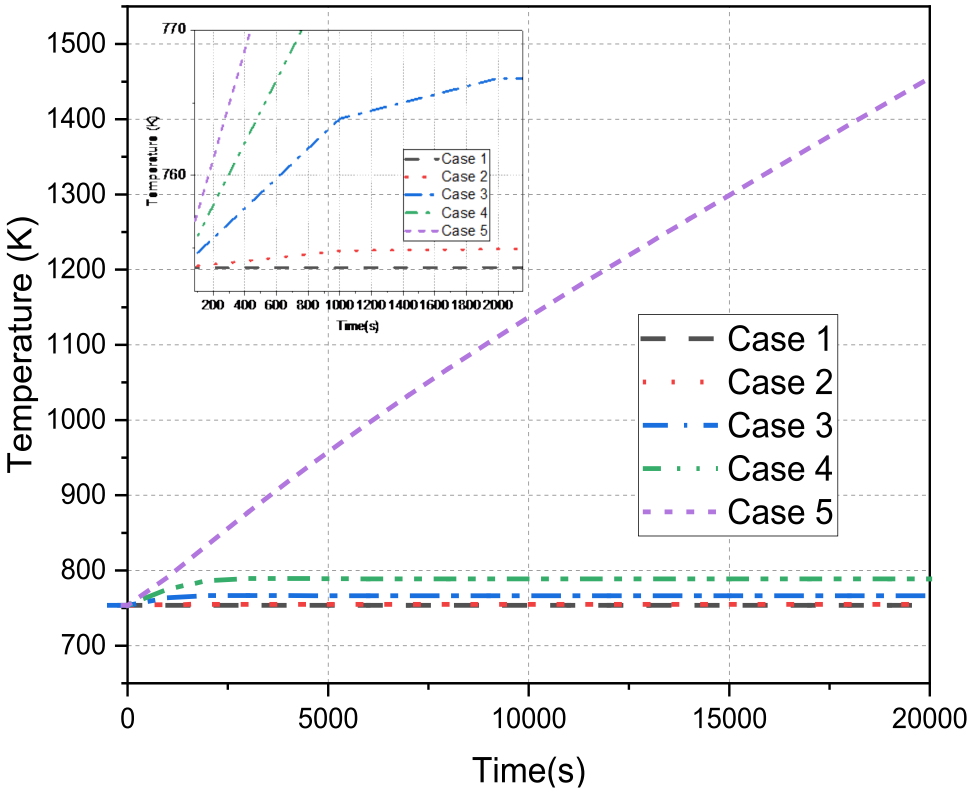
Proposed Cases:

*Assumption: Case fail when T > 1500 K

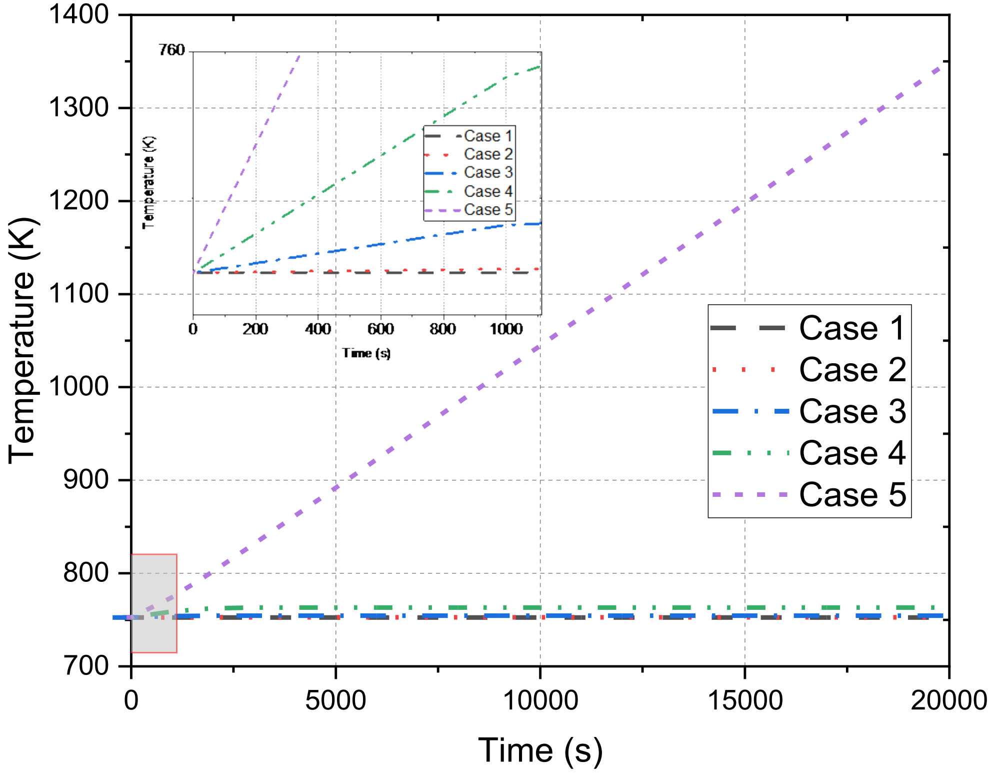
Description HTC (W/m2K-1)		SS Transfer	100s (HP Fail)	20000s
Case 1 *base case	No heat pipe failure	100000	100000	100000
Case 2	HP 1 Failure *center hp	100000	0	0
Case 3	HP 1- 7 Failure *center, first ring	100000	0	0
Case 4	HP 1-19 Failure *center, 2 rings	100000	0	0
Case 5	HP 1-37 Failure *entire monolith	100000	0	0

Fuel Temperature Results

Case 1-5:



Maximum Fuel Temperature

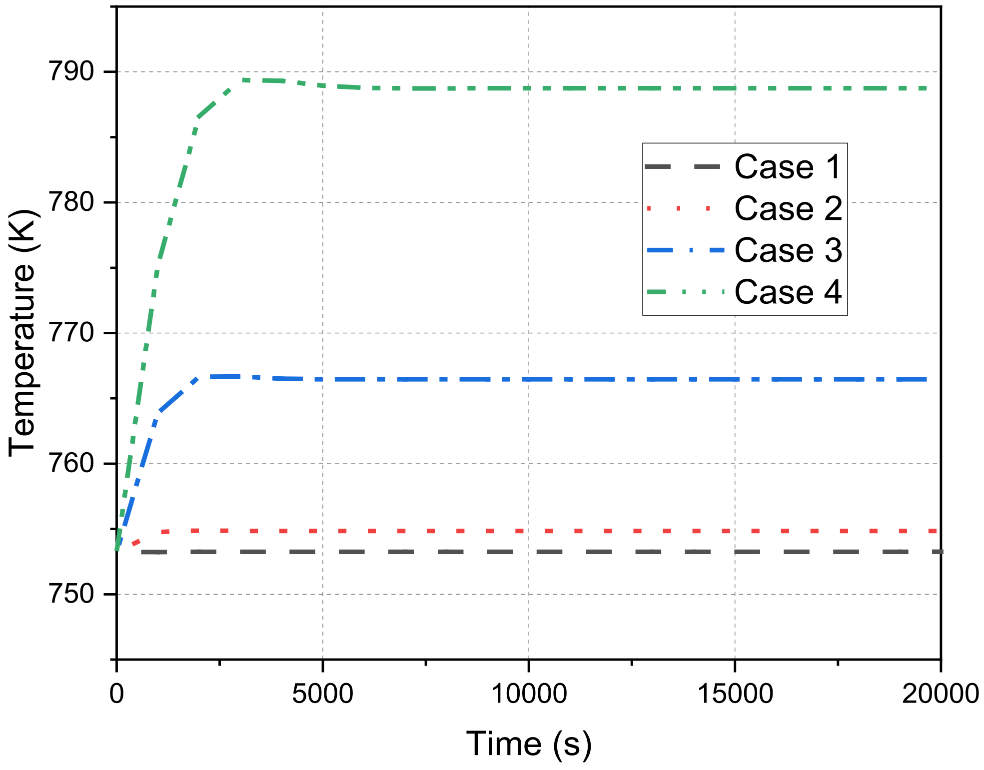


Average Fuel Temperature

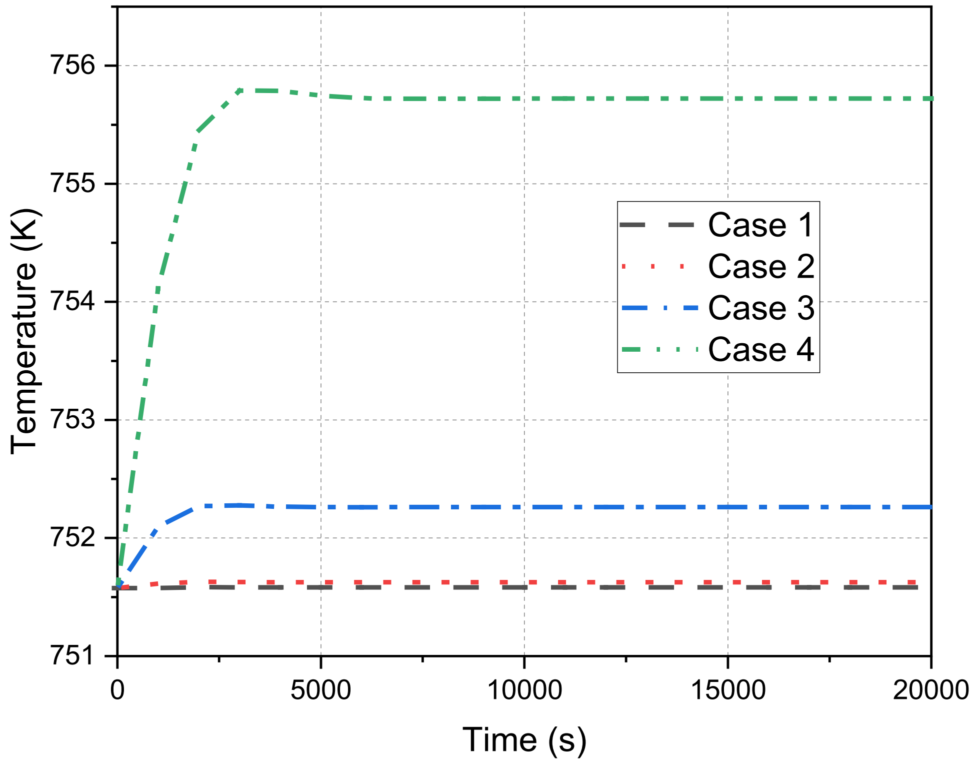
*Trend across average and max fuel temperature are generally similar as expected

Monolith Temperature Results

Case 1-4:



Maximum Monolith Temperature



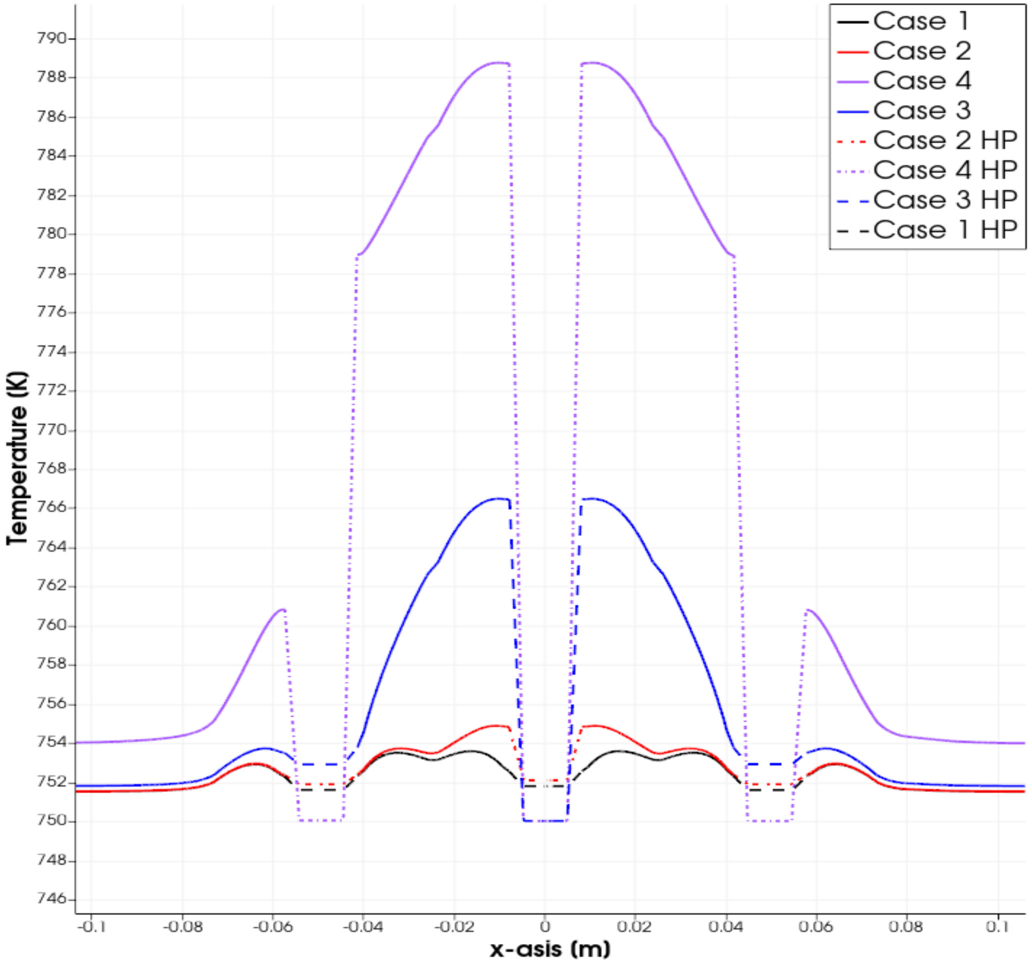
Average Monolith Temperature

*Trend across average and max monolith temperature are generally similar as expected

X-Axial Monolith Temperature

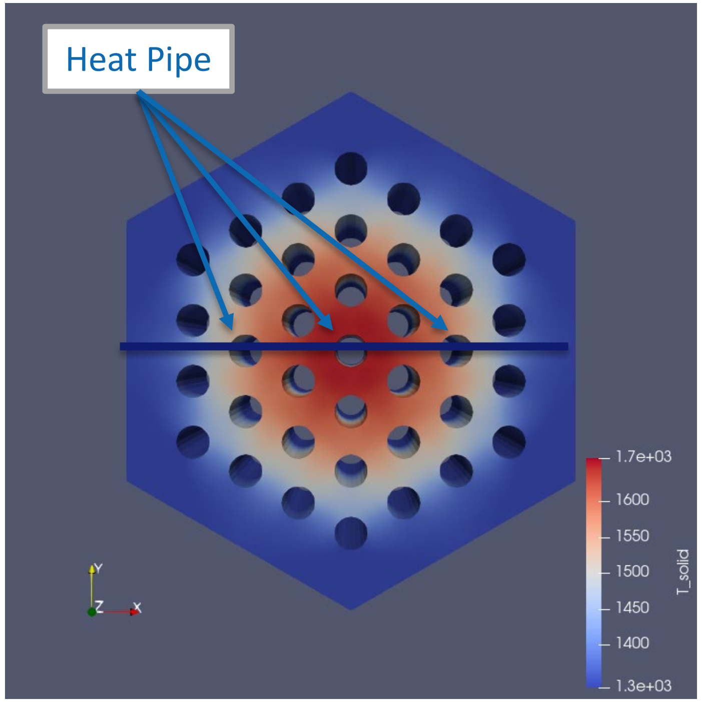
Case 1-4:

T_Solid Temp



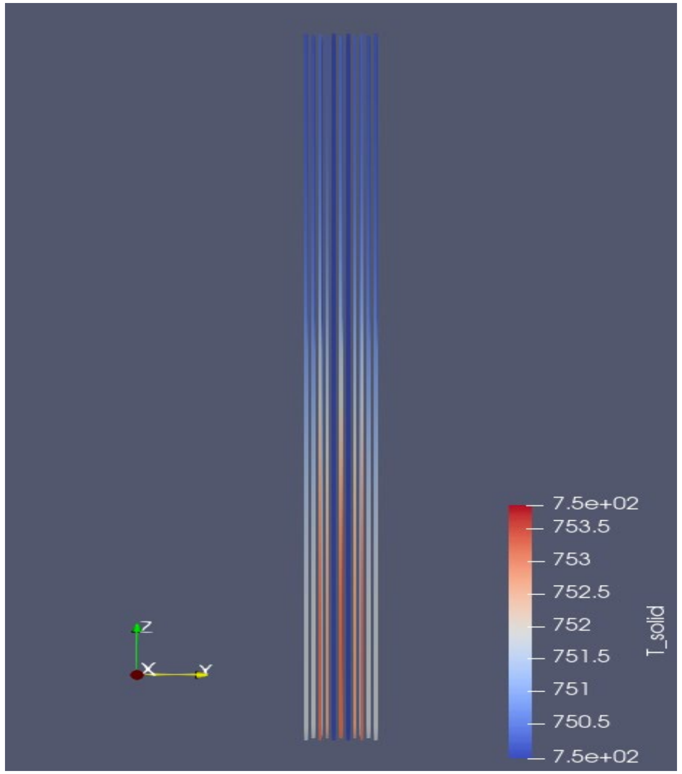
*X-Axial data plot line runs along the x axis through monolith center

✓ Example:

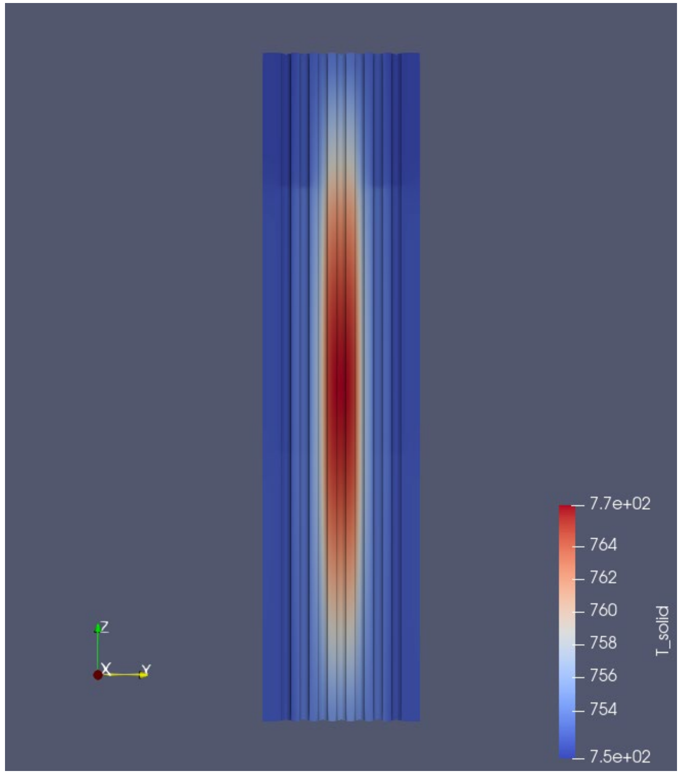


Case 3 Temperature Distributions

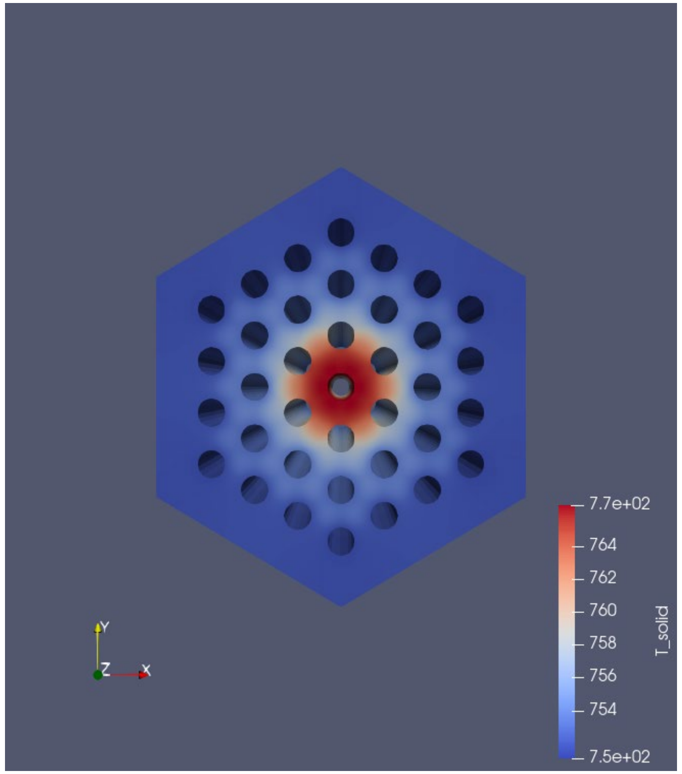
*Take note of temperature scales, vary significantly between cases



*Heat Pipe Temperature cut along the y plane



*Monolith Temperature cut along the y plane

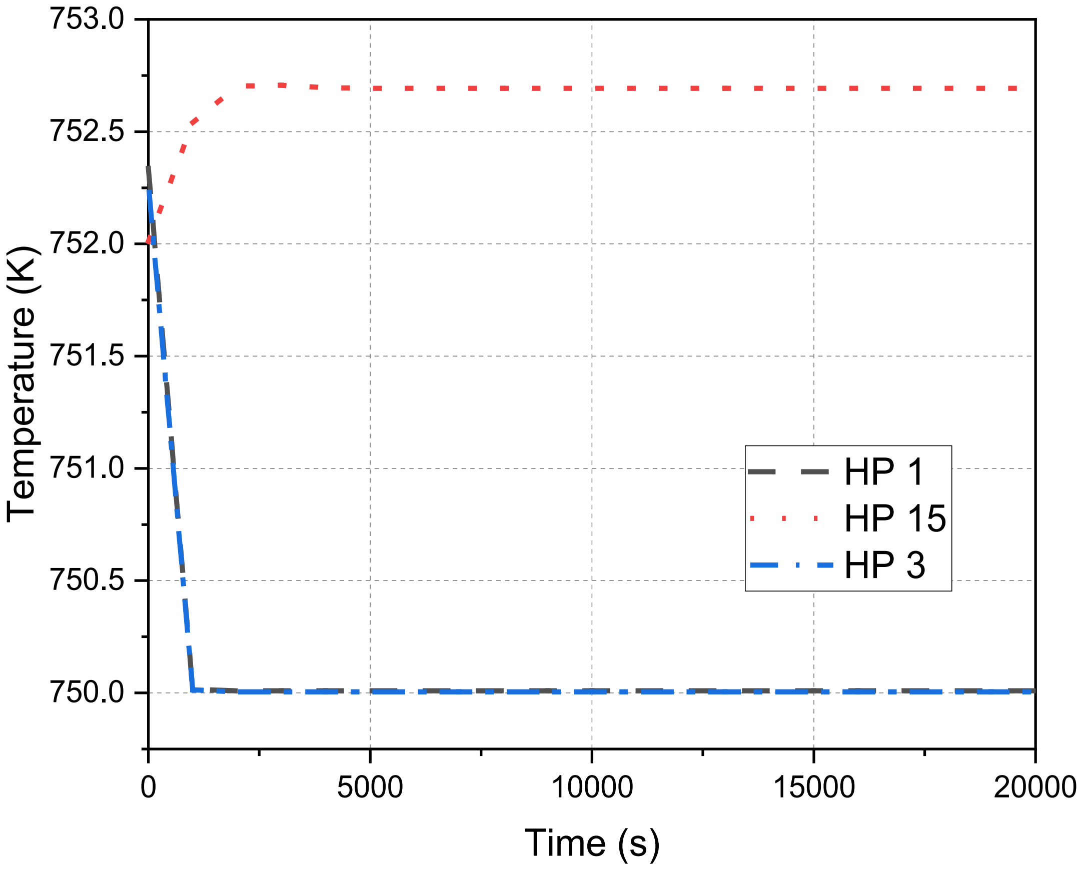


*Monolith Temperature cut along the x plane

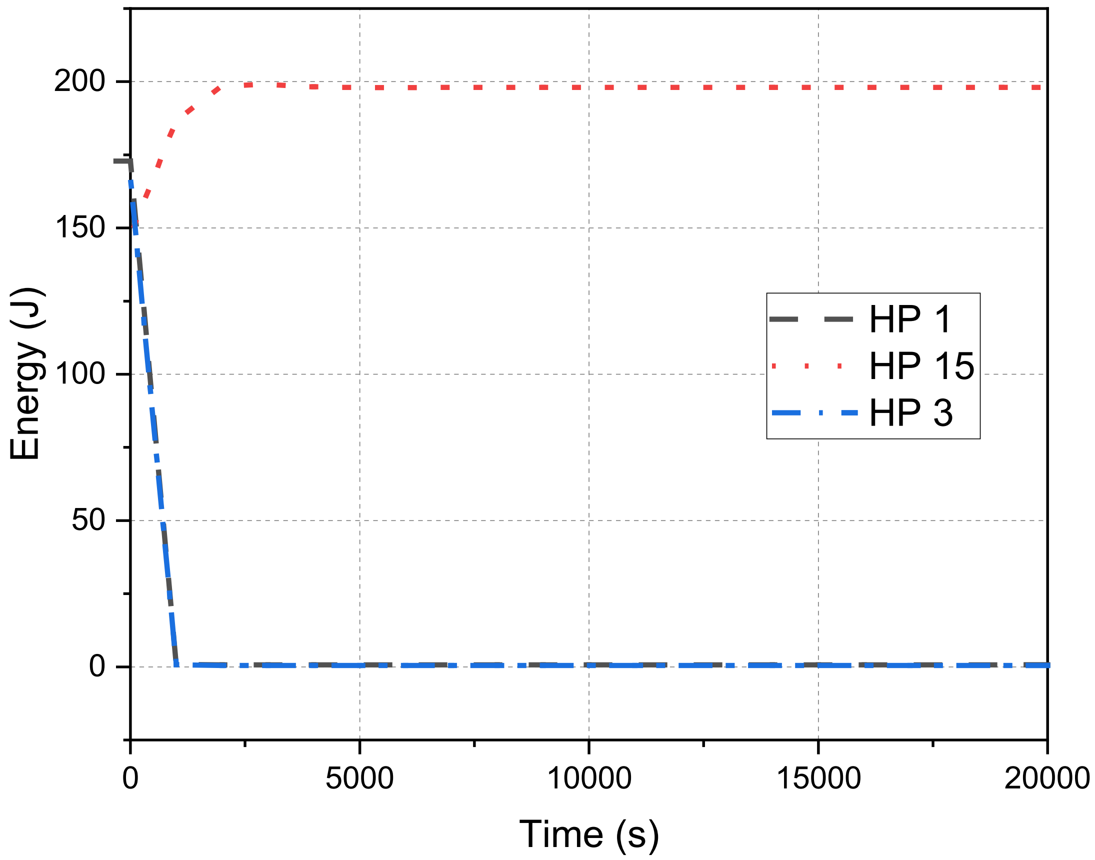
*Visuals constructed using Paraview

Case 3 Calculation Results

Average Temp of First 3 HP

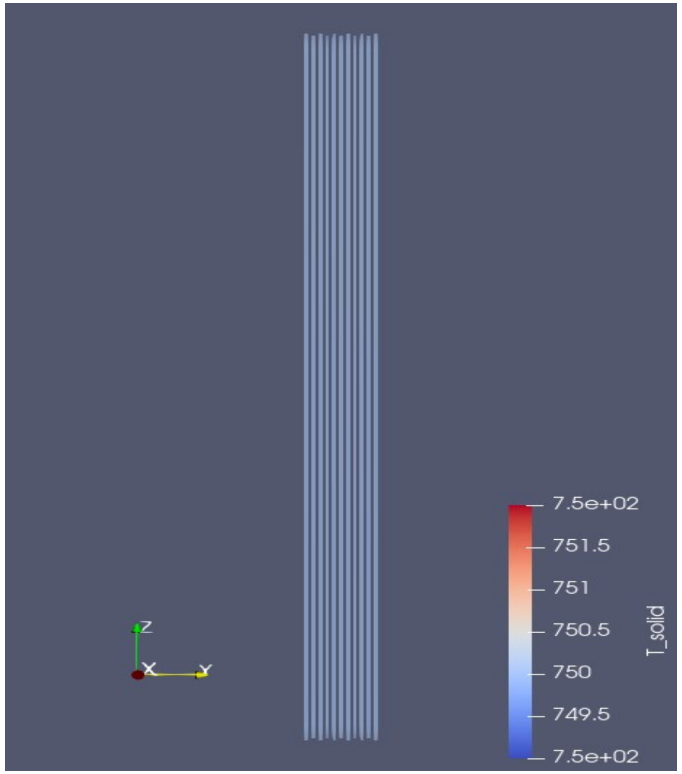


Energy Transfer of First 3 HP

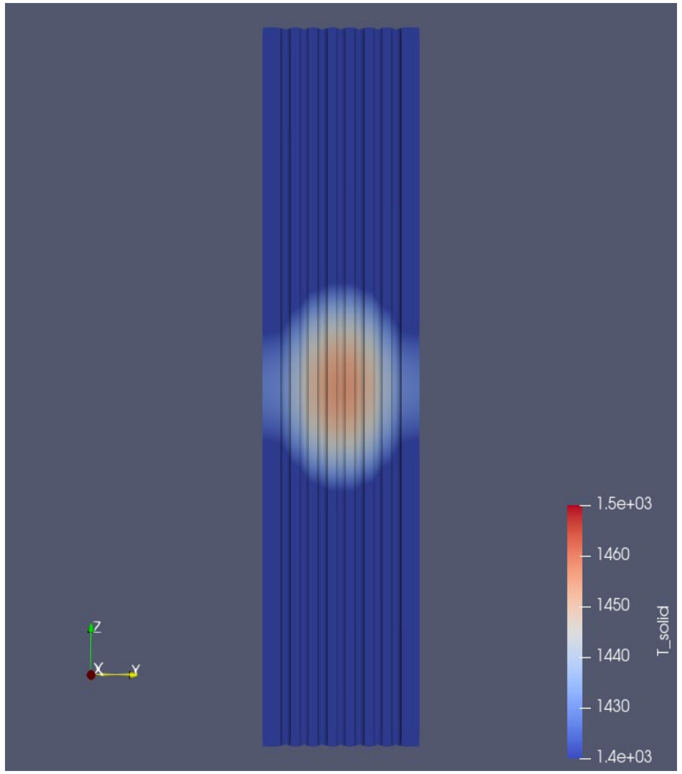


Case 5 Temperature Distributions

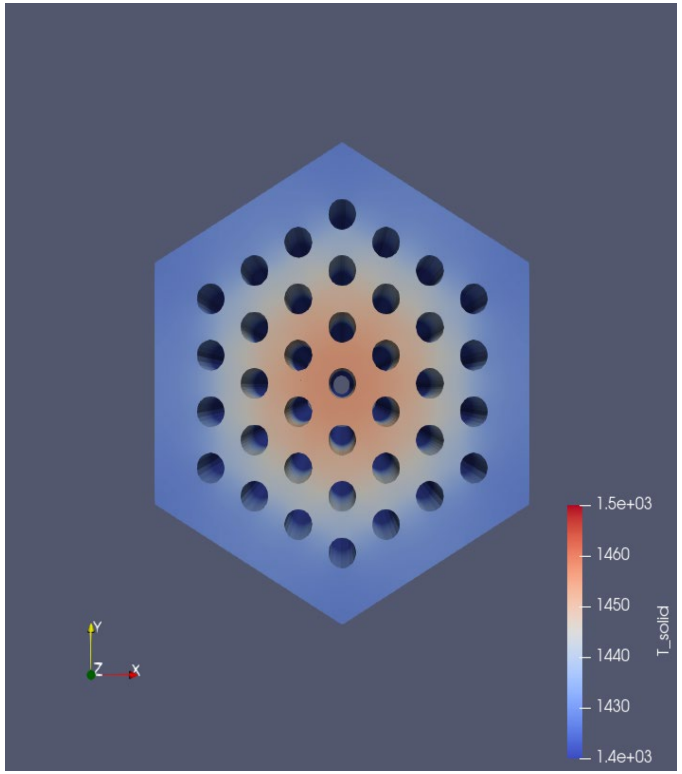
*Take note of temperature scales, vary significantly between cases



*Heat Pipe Temperature cut along the y plane



*Monolith Temperature cut along the y plane

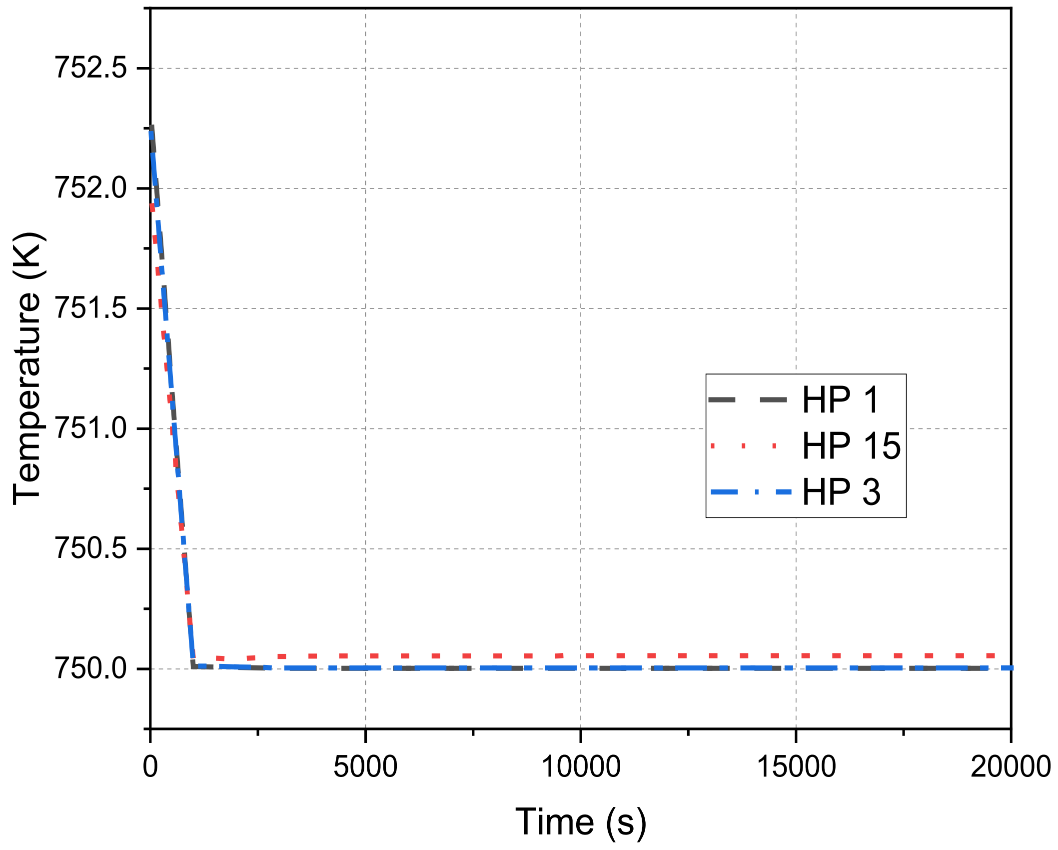


*Monolith Temperature cut along the x plane

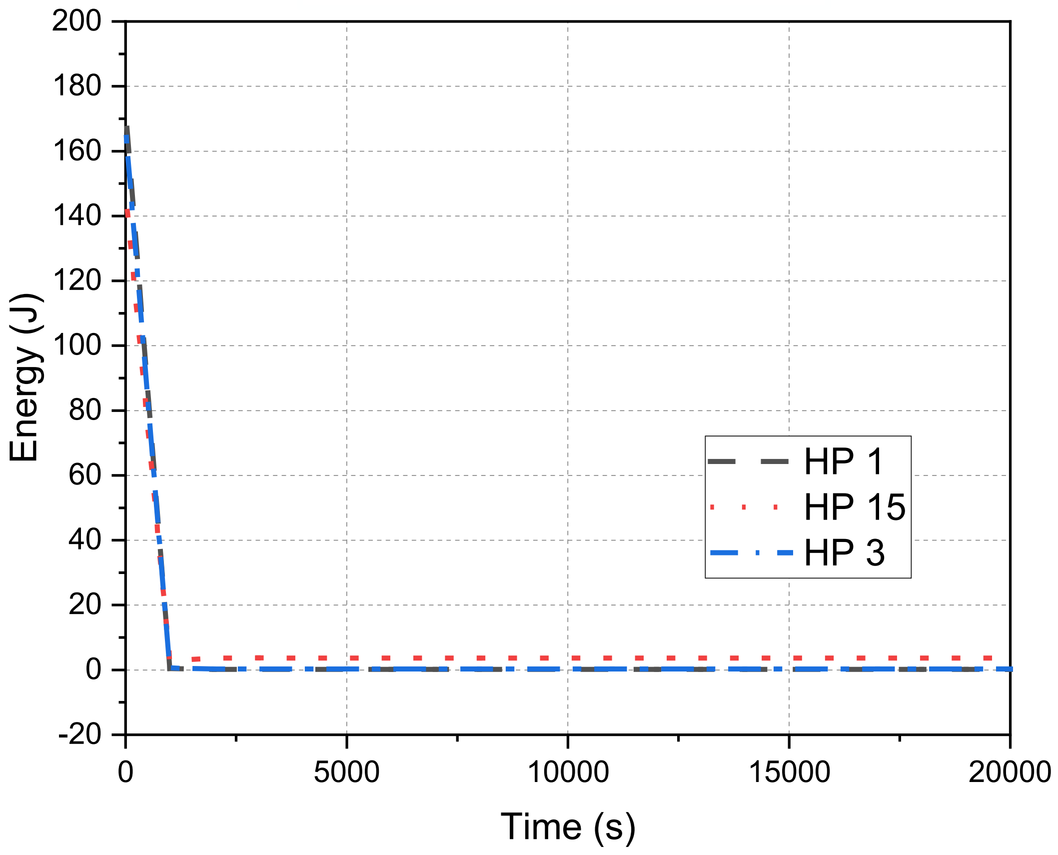
*Visuals constructed using Paraview

Case 5 Calculation Results

Average Temp of First 3 HP



Energy Transfer of First 3 HP



Case 1, 3, 6-8 Overview

Proposed Cases:

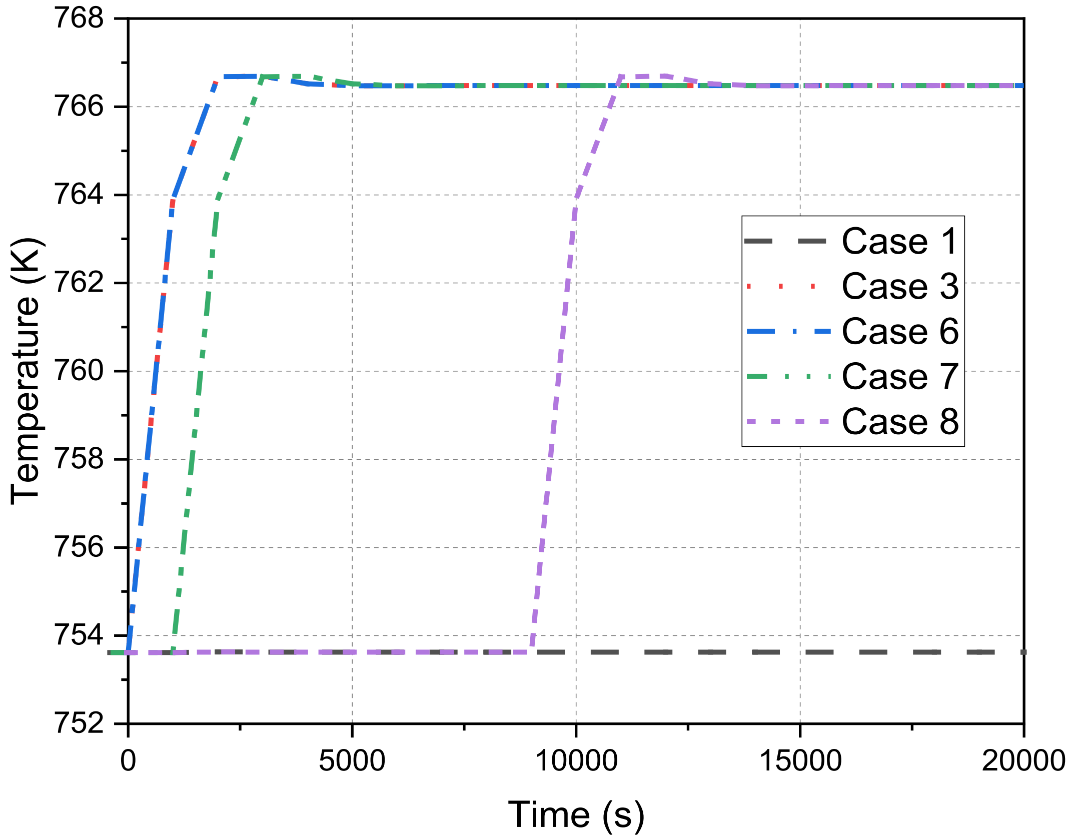
➢ Assumption: Case fail when T > 1500 K

Description HTC (W/m2K-1)		Starting Time (s)	Ending Time (s) *Fail time
Case 1	No heat pipe failure	N/A	N/A
Case 3 *base case	Base Case	0	N/A
Case 6	***	400	500
Case 7	***	1900	2000
Case 8	***	9900	10000

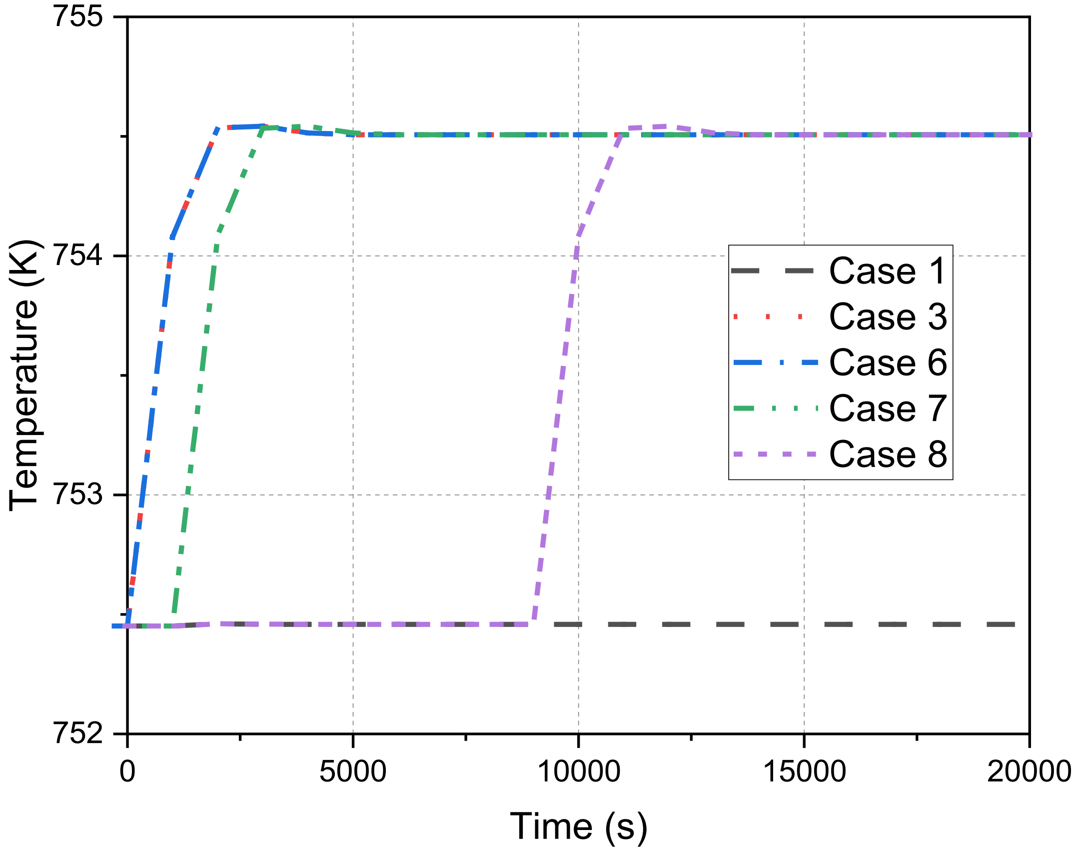
***same as case 3 with different failure times

Fuel Temperature Results

Case 1, 3, 6-8:



Maximum Fuel Temperature

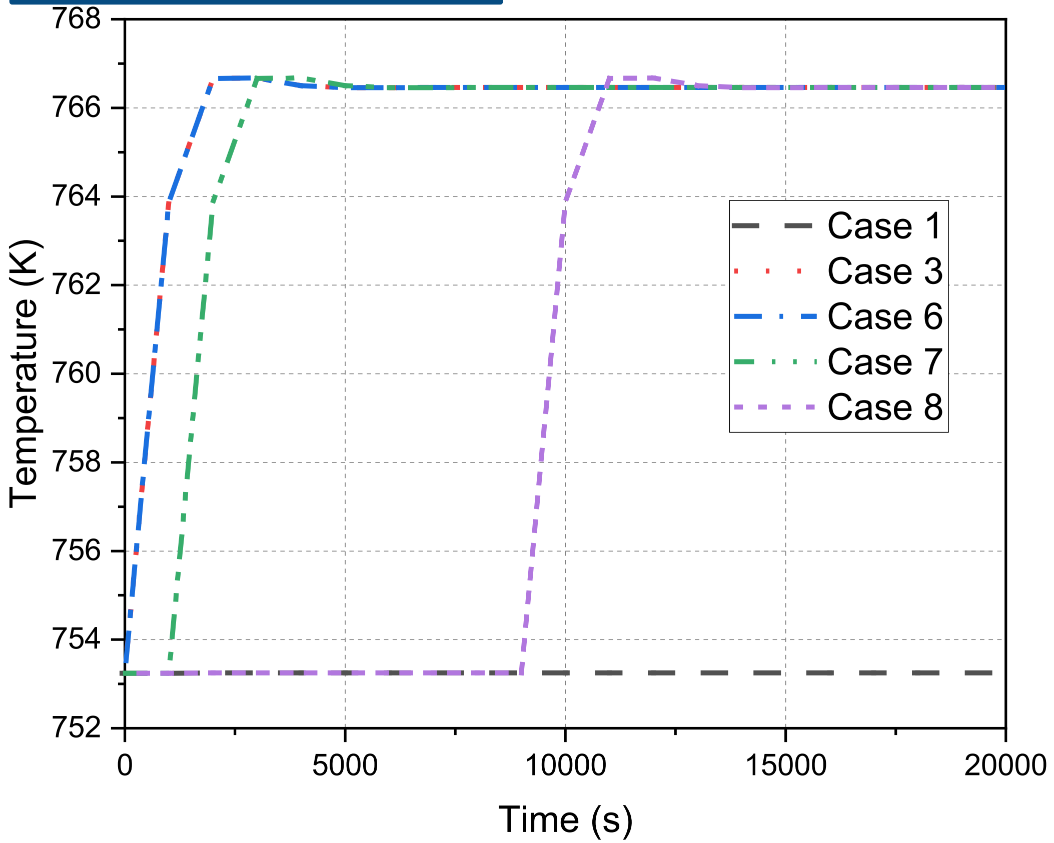


Average Fuel Temperature

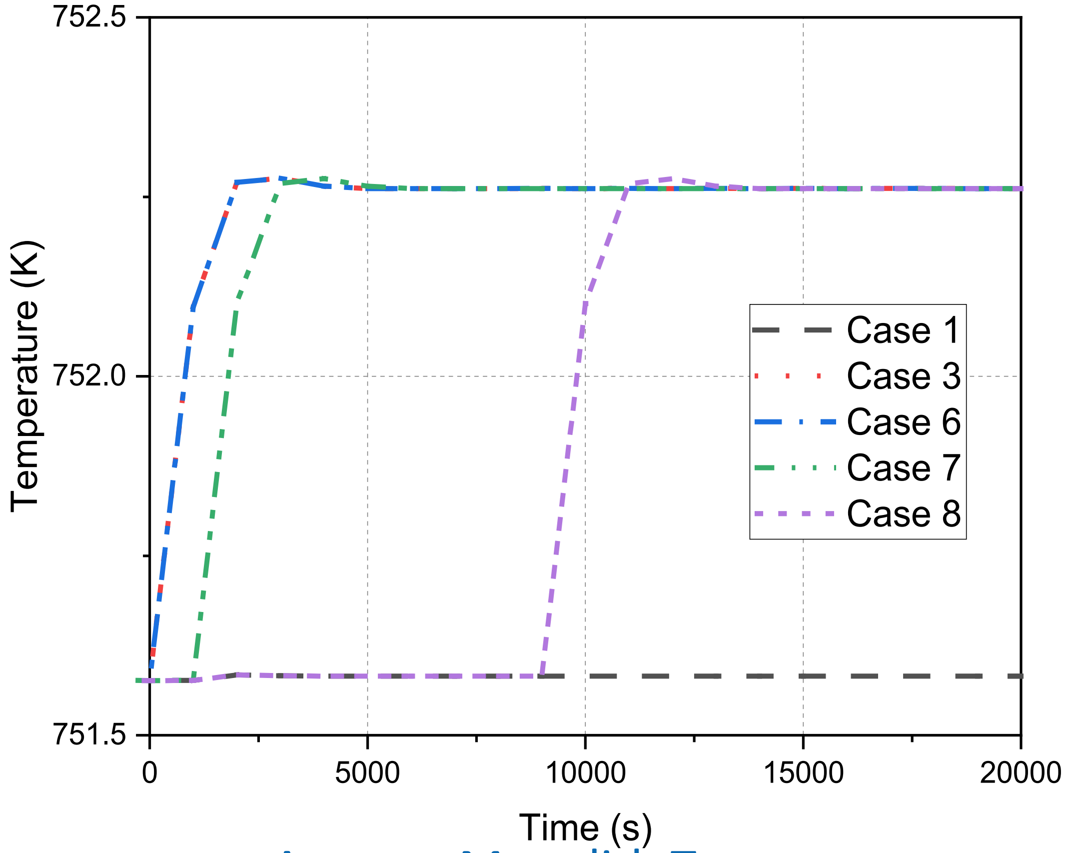
*Trend across average and max fuel temperature are generally similar as expected

Monolith Temperature Results

Case 1, 3, 6-8 :



Maximum Monolith Temperature

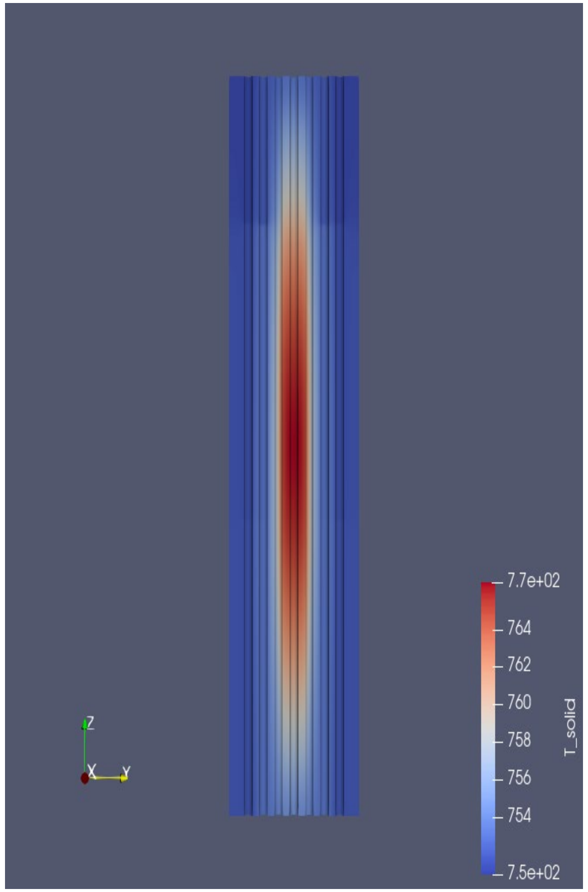


Average Monolith Temperature

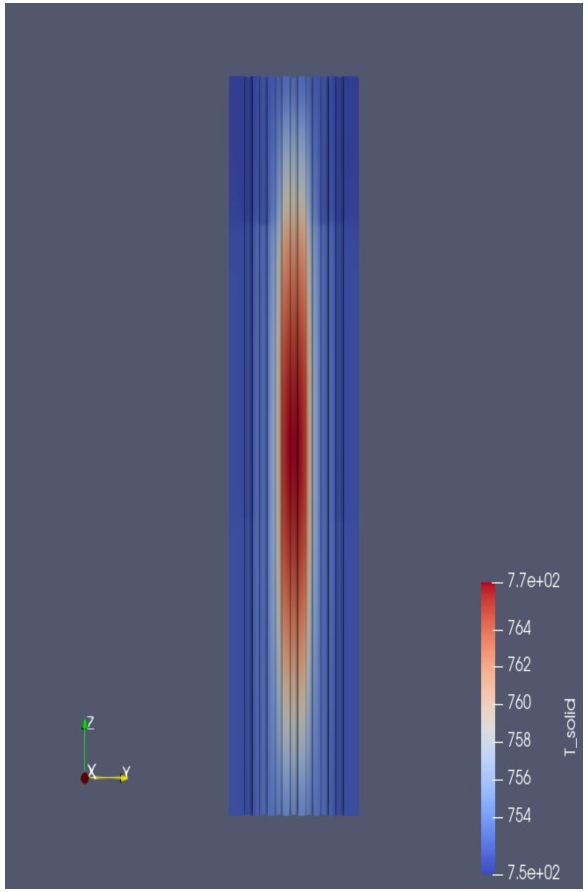
*Trend across average and max monolith temperature are generally similar as expected

Case 3, 6, 7, 8 Comparison

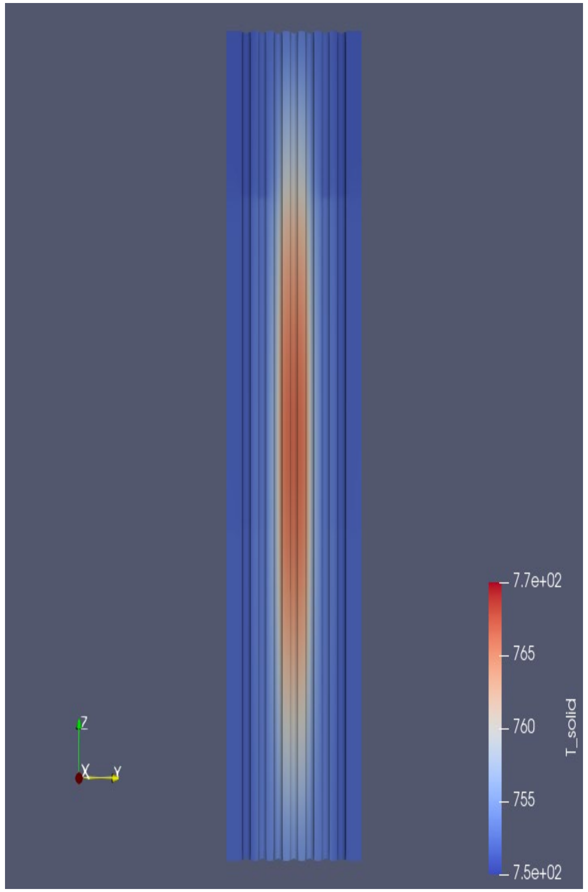
AT 5000s:



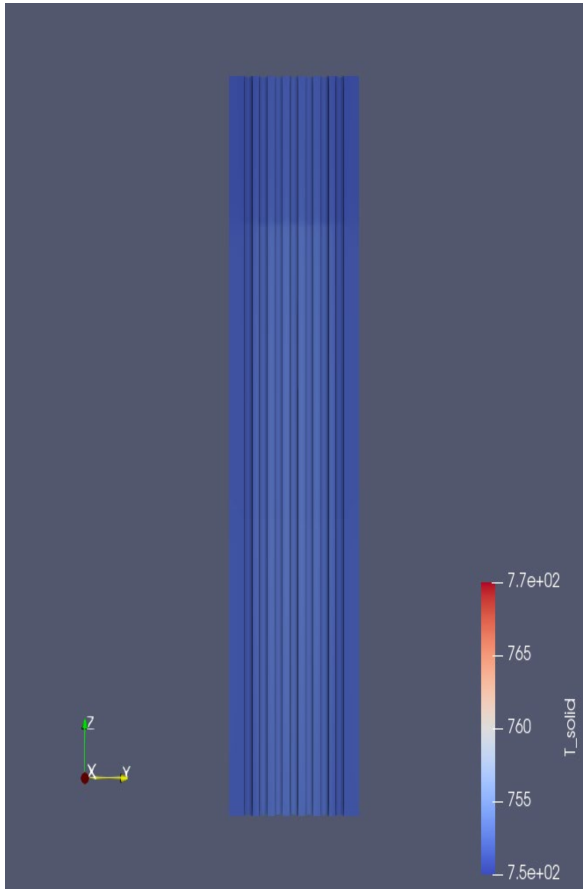
Case 3



Case 6



Case 7

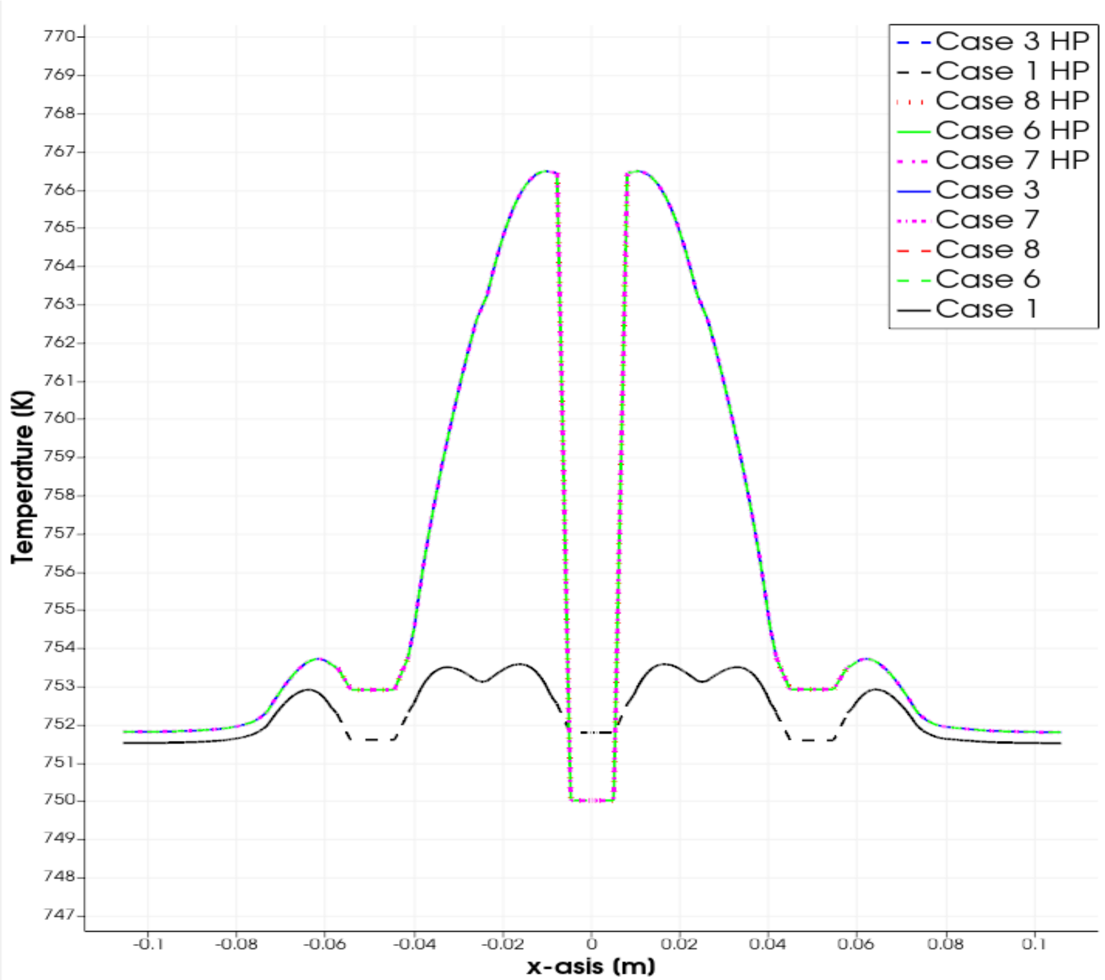


Case 8

X-Axial Monolith Temperature

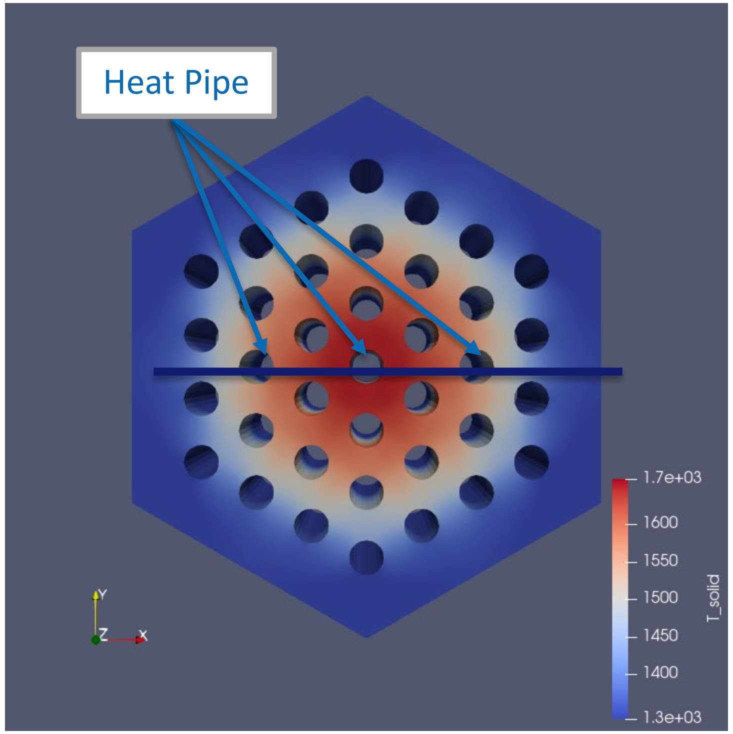
Case 1, 3, 6-8 :

T_Solid Temp



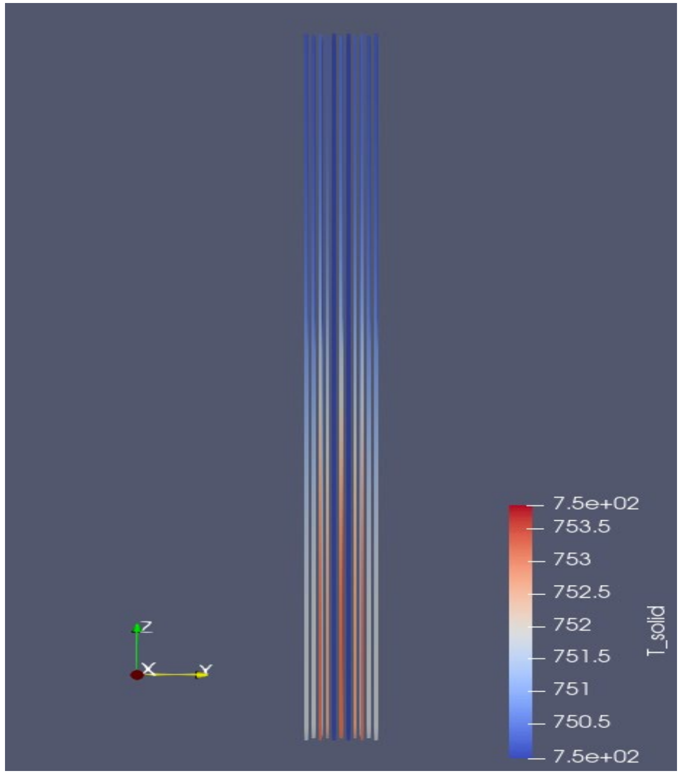
*X-Axial data plot line runs along the x axis through monolith center

✓ Example:

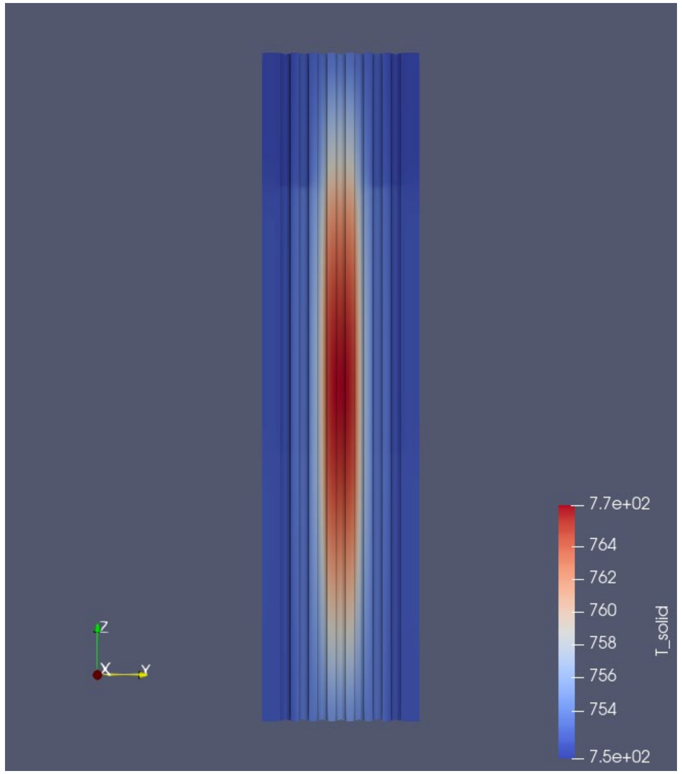


Case 8 Temperature Distributions

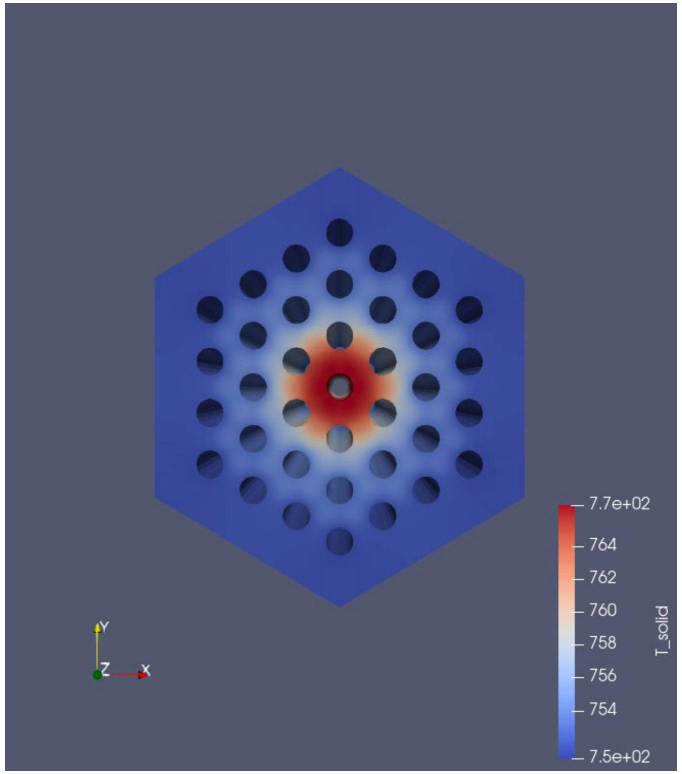
*Take note of temperature scales, vary significantly between cases



*Heat Pipe Temperature cut along the y plane



*Monolith Temperature cut along the y plane



*Monolith Temperature cut along the x plane

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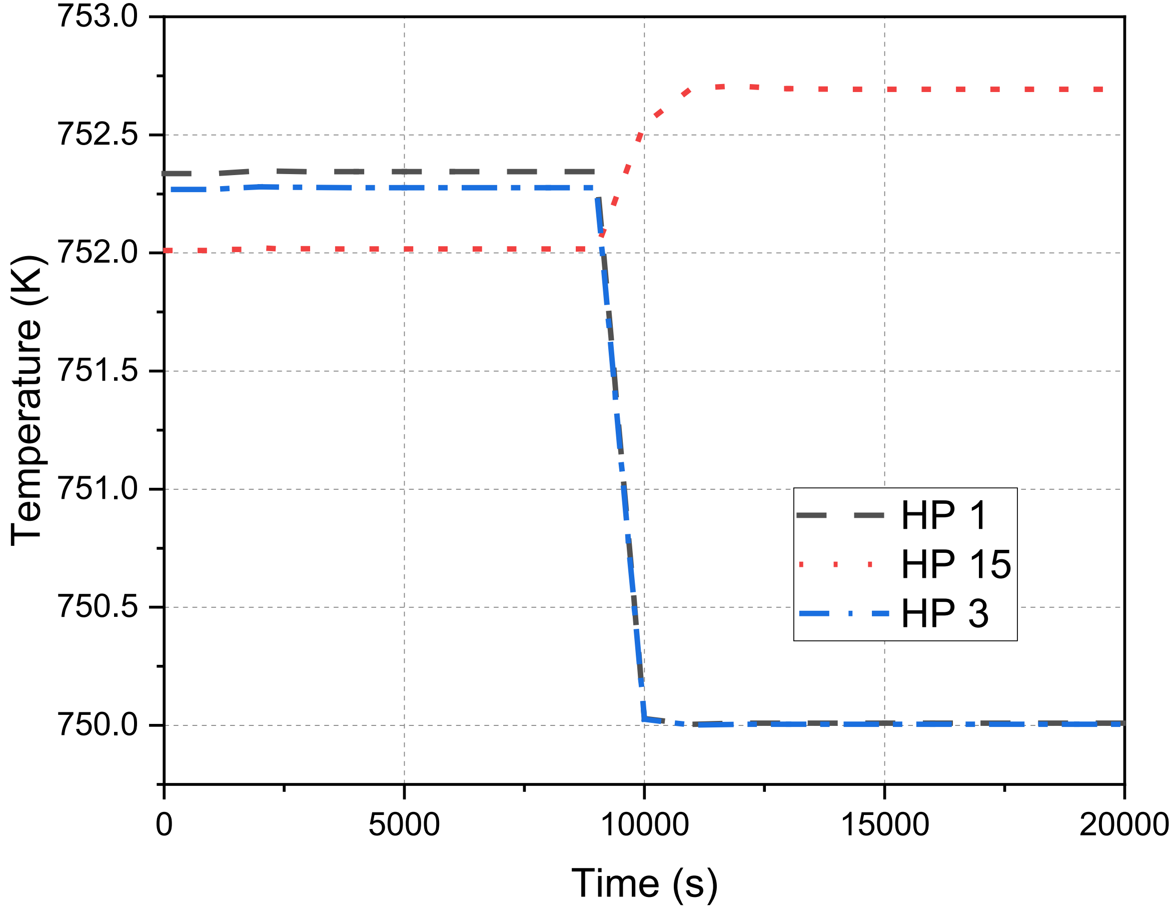
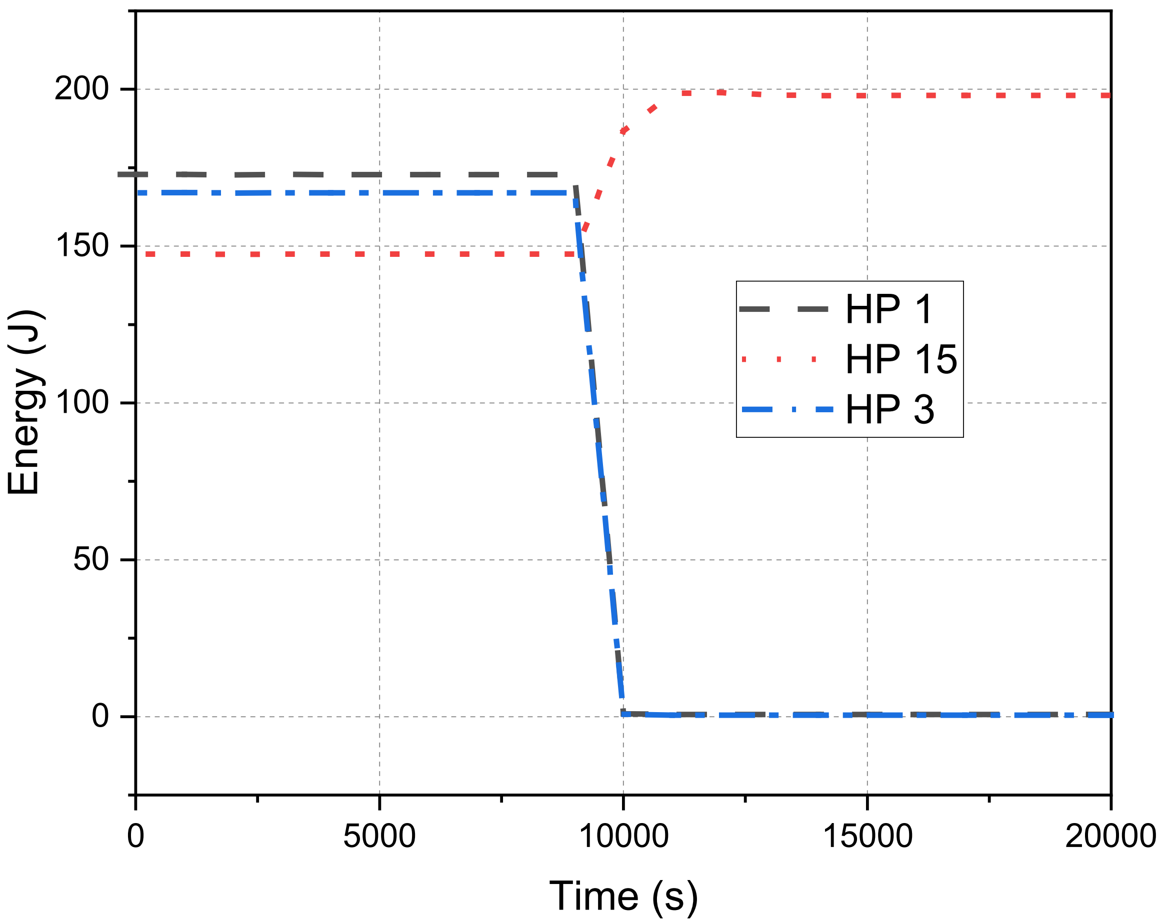
*Visuals constructed using Paraview

Case 8 Calculation Results

Average Temp of First 3 HP



Energy Transfer of First 3 HP



Content

- MICRO REACTOR REVIEW
- NUMERICAL TOOL AND BENCHMARK
- STEADY STATE AND SENSITIVITY ANALYSIS
- TRANSIENT SAFETY SIMULATION
- CONCLUSION

General Conclusions/Observations

- SAM/MOOSE coupling successfully applied to the heat pipe microreactor;
- Heat pipes transfer the energy from core to secondary side well;
- Sensitivity analysis test a few critical thermal hydraulic parameters;
- Heat pipe failures can challenge the monolith integrity.

Summary

- Current contribution:
  - Heat Pipe model using SAM/MOOSE coupling
  - MAGNET - Steady state and transient results

- Future projects:
  - Couple HP to heat exchanger with secondary loop
  - Develop more detailed heat pipe model
  - Couple to neutronics and thermal hydraulics

Acknowledgement

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- Consultation in using SAM for analysis - Argonne National Lab – Drs. R. Hu and G.J.Hu

Upcoming Webinars

Date	Title	Presenter
15 December 2021	Development of an Austenitic/Martensitic Gradient Steel by Additive Manufacturing	Dr. Flore Villaret, EDF, France Winner of the Pitch Your PhD Contest
27 January 2022	ESFR SMART a European Sodium Fast Reactor Concept including the European Feedback Experience and the New Safety Commitments following Fukushima Accident	Mr. Joel Guidez, CEA, France
24 February 2022	Artificial Intelligence in Support of Nuclear Energy Sector	Prof. Prinja Nawal, Jacobs, UK