Investigating Heat Transfer In Horizontal Micro-HTGRs Under Normal and PCC Conditions

PI- Hitesh Bindra

Collaborators: Masahiro Kawaji (CCNY), Richard Schultz (ISU), Don McElligott, Piyush Sabharwall (INL)

Students/Associates: T-Ying Lin (Purdue), Molly Ross (Purdue) Ketan Ajay (Purdue), Dinesh Kalaga (CCNY), El Mokhtar Mojdoub (CCNY), Ahmed Solman (CCNY)

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    - Experimental Setup
  - Boundary Conditions
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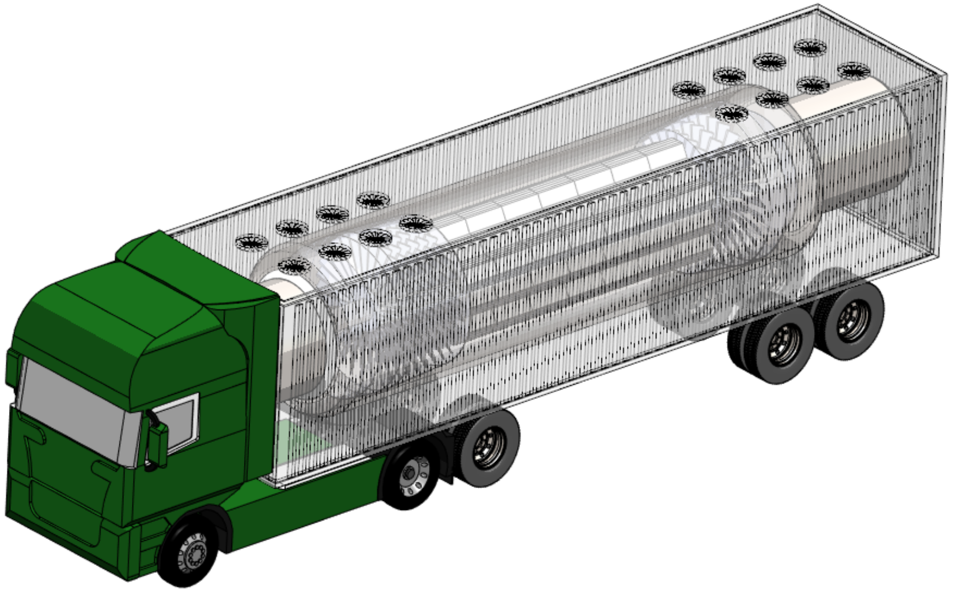
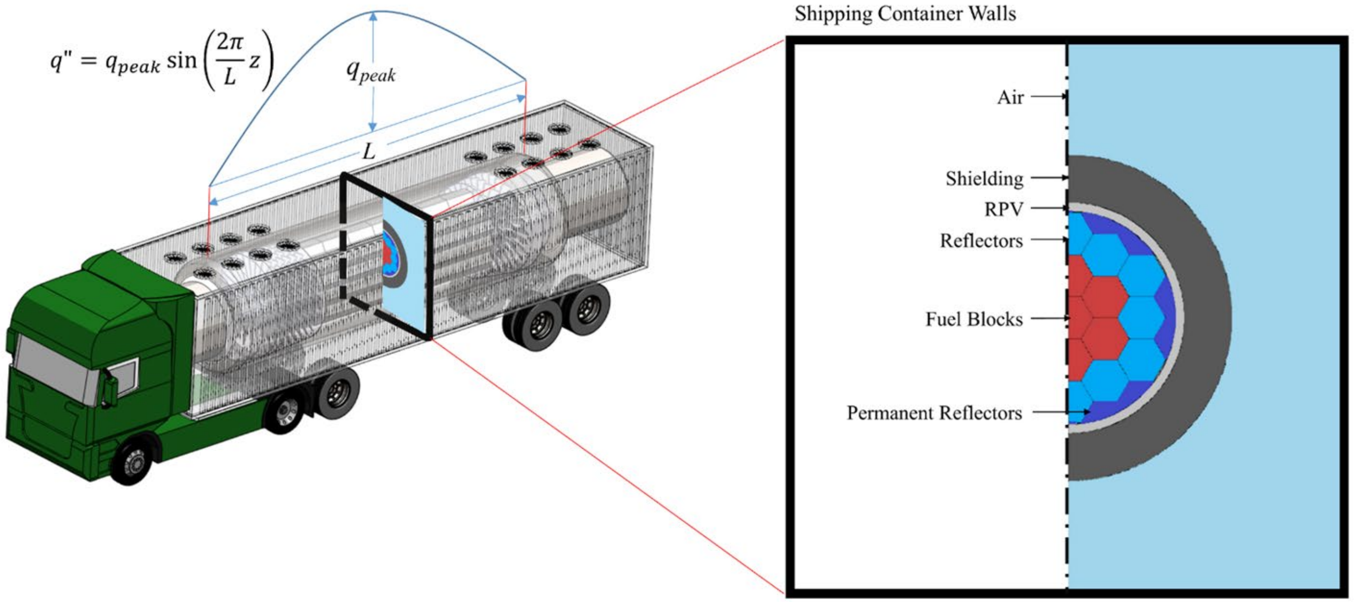
  - Model Validation
  - Case Studies and design implications
  - Results
- Coupled model- Combined Internal/External heat transfer resistances
  - Case Studies and design implications
  - Results

Motivation



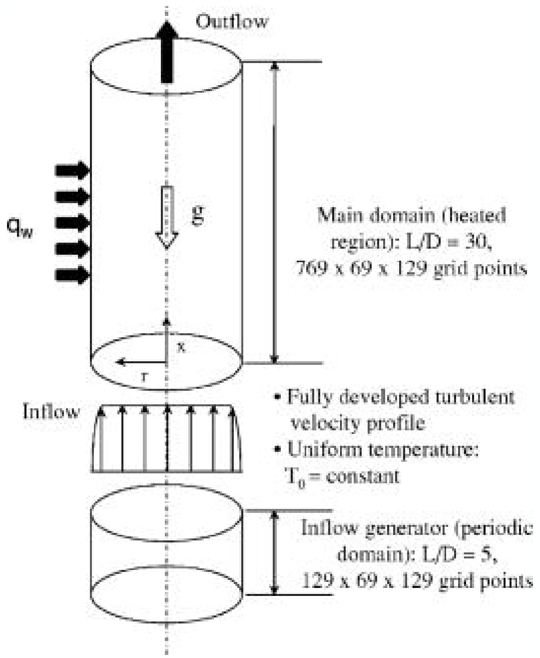
- Microreactors are nuclear reactors that must be factory fabricated, transportable, and self-adjusting with a maximum power of 20 MW.
- Micro-reactor research is vital for the future:
  - Provide options for decarbonization and decentralization efforts
  - Create an easily transportable form of energy for remote communities, military forces, or natural disasters
- Optimized transport involves standardized designs which can be transported using a shipping container

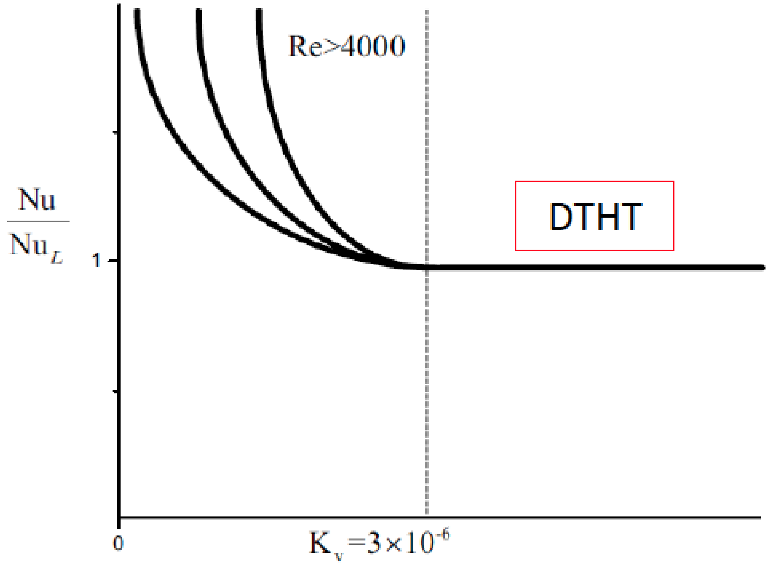
Mobile Microreactor Transport



- Mobile Microreactors must be able to dispel decay heat after shutdown to be transported to its new location
- Title 49 of CFR 173.442 states that the external, accessible surface of a package of class 7 radioactive material must not exceed 85°C [1]
- This work examines:
  - TCC between prismatic blocks impact on temperatures during PCC
  - Natural convection cooling impact on external temperature
- All following cases use ANSYS and the micro-HTGR design is based off of that of the MHTGR-350

Normal Operation-Flow Laminarization



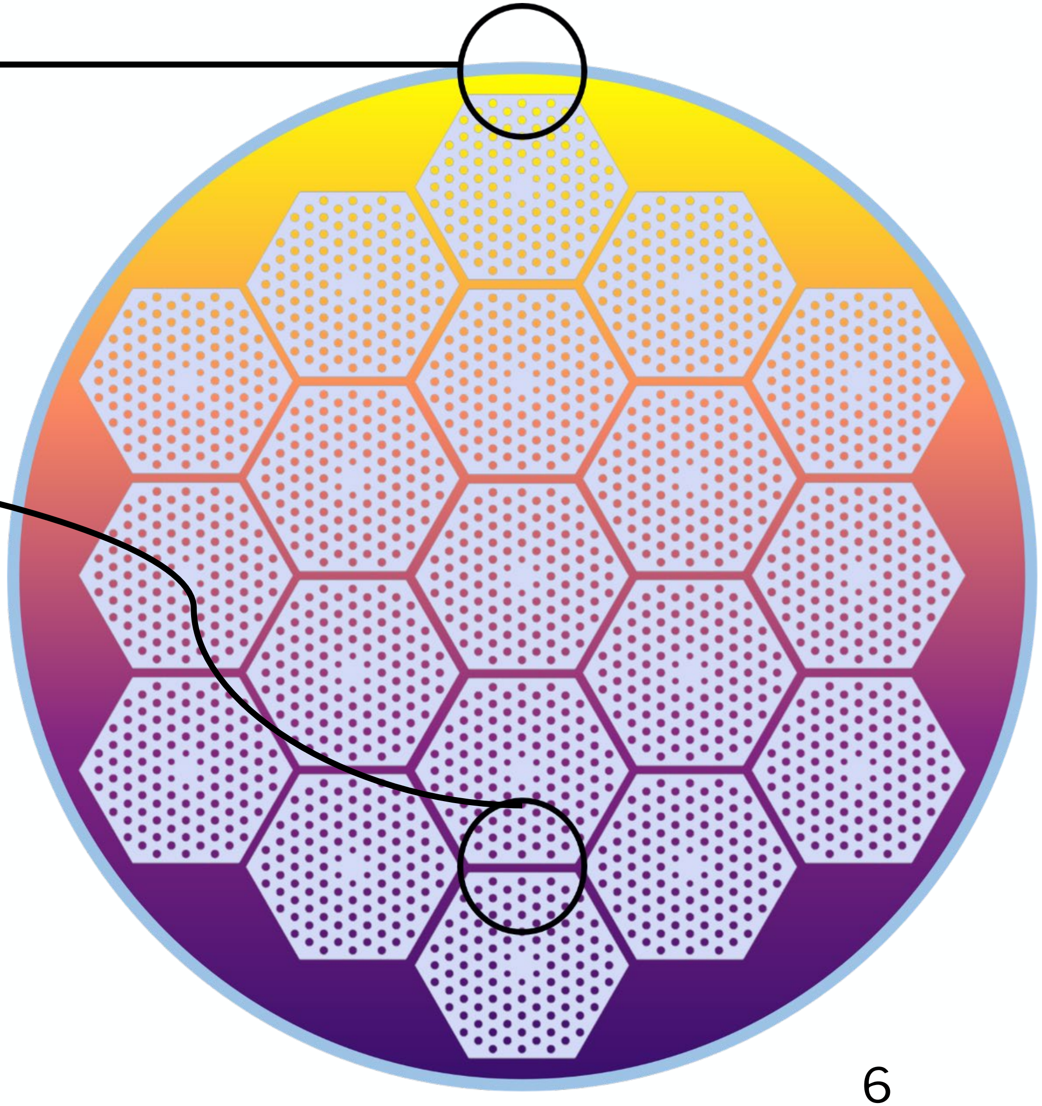


- Laminarization effects induce reduced heat transfer from the core
- Deteriorated heat transfer occurs at acceleration parameter K_v = 3E6

$$K_v = \frac{\nu}{V^2}\frac{dV}{dx}$$

- Traditional HTGRs utilize a downward flow through the core to counteract laminarization effects
  - Buoyancy produces an upwards force countering the downward acceleration, encouraging heat transfer
- Microreactors with their horizontal orientation will lose this verticality and countering effect

Core Heat Transfer Changes



Helium Stratification

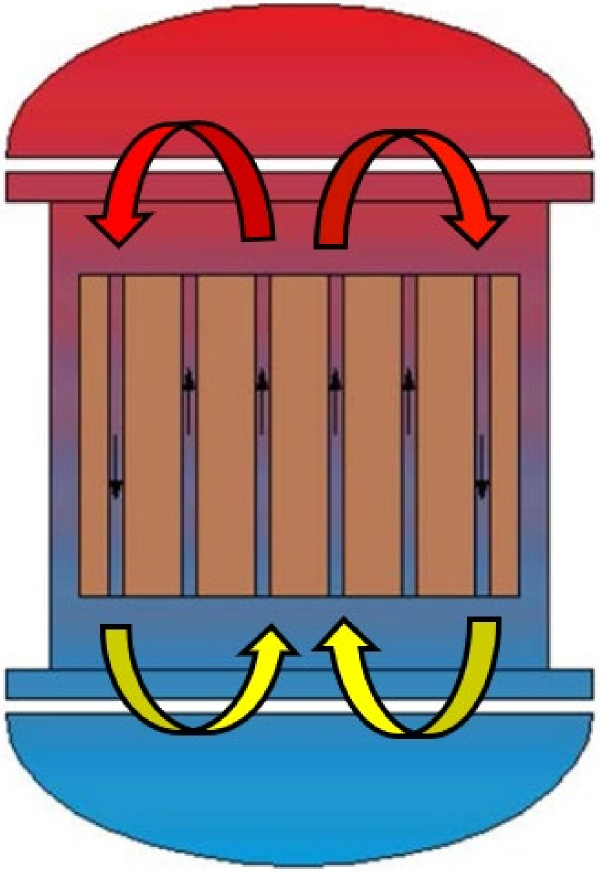
- Higher temperature helium will stratify to the top within the core RPV
- Heat distribution will vary significantly throughout the microreactor core

TCC Changes

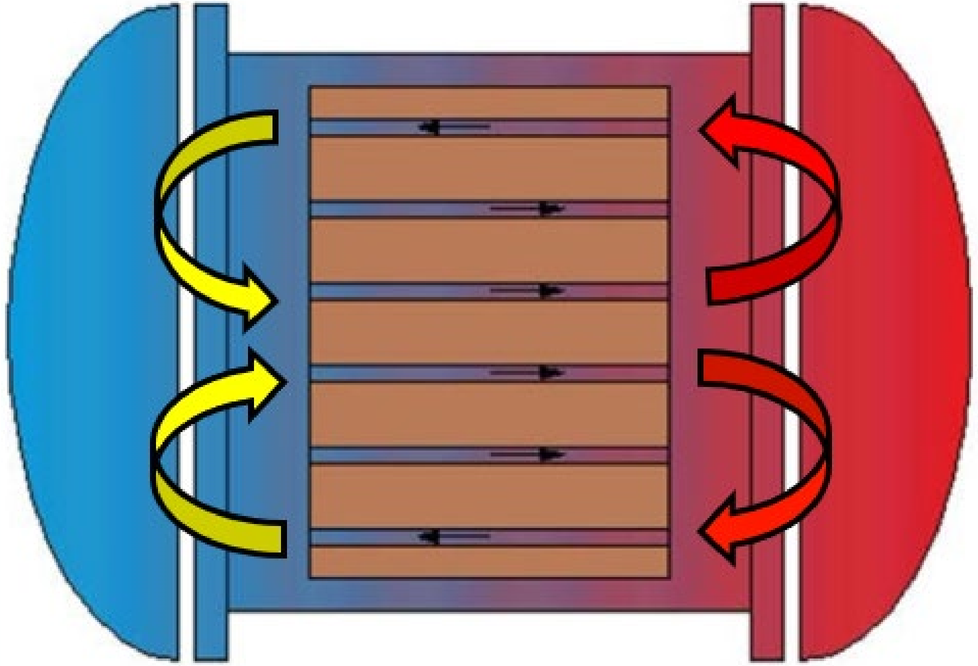
- Without extensive experimentation, predicting TCC is quite difficult
  - TCC can vary with many different factors
- Horizontal orientation can change typical gap widths as well as contact pressure due to the weight of the prismatic blocks above
  - TCC will decrease near the upper sections of the microreactor core

Loss of Gravitational Head

- Flipping the reactor horizontal reduces the gravitational head
  - Natural convection effects within the core are expected to significantly diminished



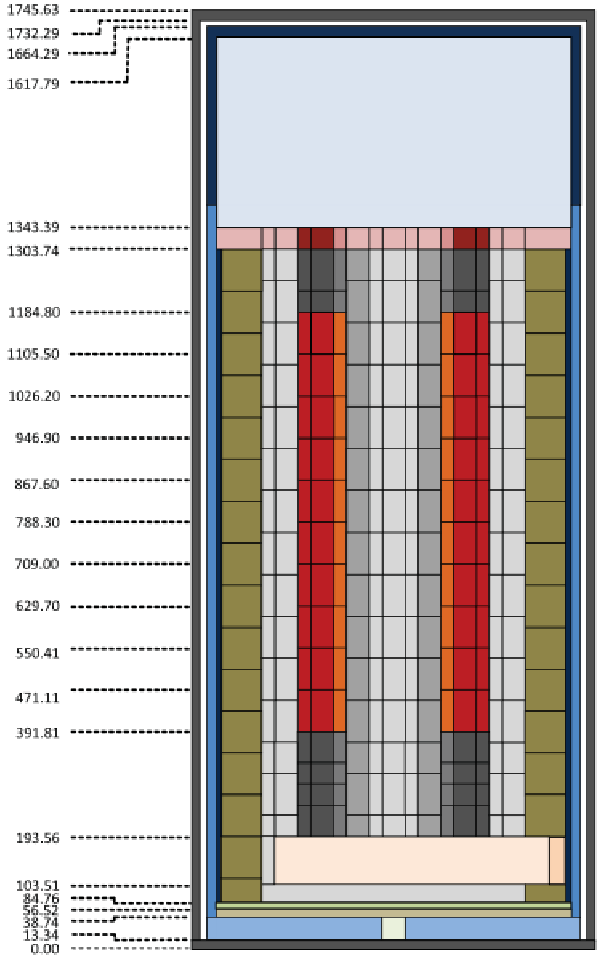
Natural Circulation in a vertical HTGR

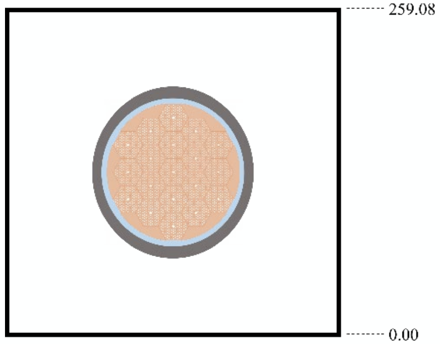


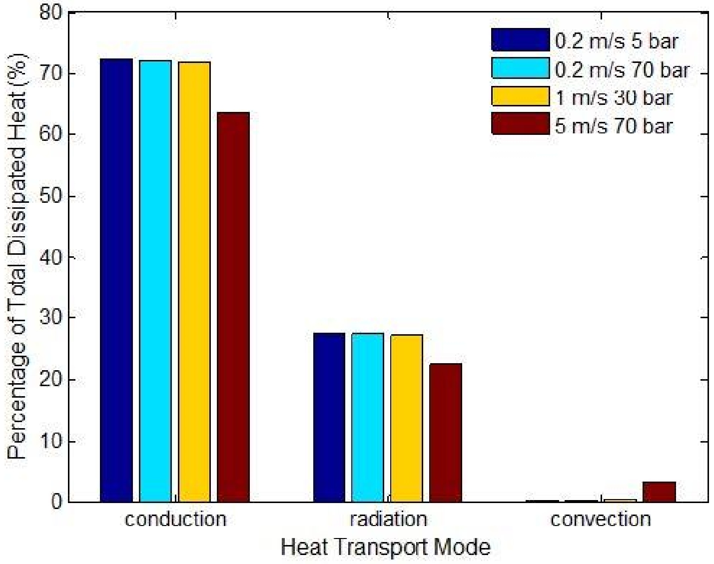
Natural Circulation possible in a horizontal micro- HTGR?

Loss of Gravitational Head

- Flipping the reactor horizontal reduces the gravitational head
  - Natural convection effects within the core are expected to significantly diminished



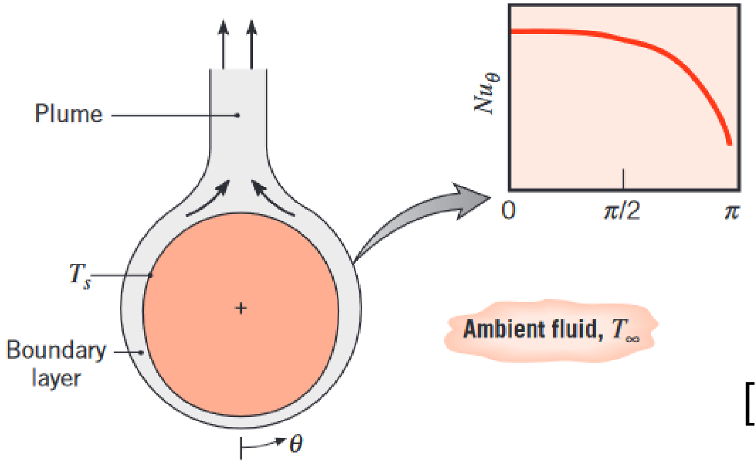




Natural Convection External to the Microreactor

Azimuthal Variation

- Given cylindrical geometry, boundary layer separation and developing plume will cause variations for the Nusselt number
- Lower heat transfer coefficients near the top further exacerbates



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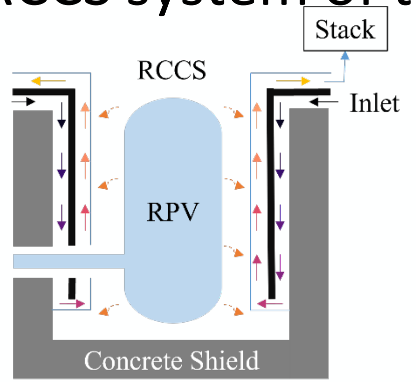
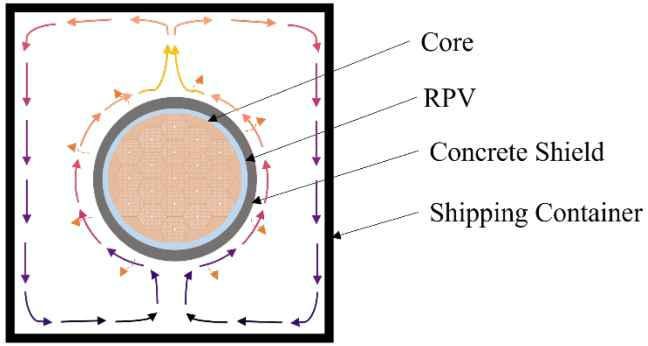
Natural Convection within the Shipping Container

- Worst case scenarios would limit heat transfer methods to natural convection within the confines of the shipping container
- The microreactor should be able to remove heat passively similar to the RCCS system of the HTGR

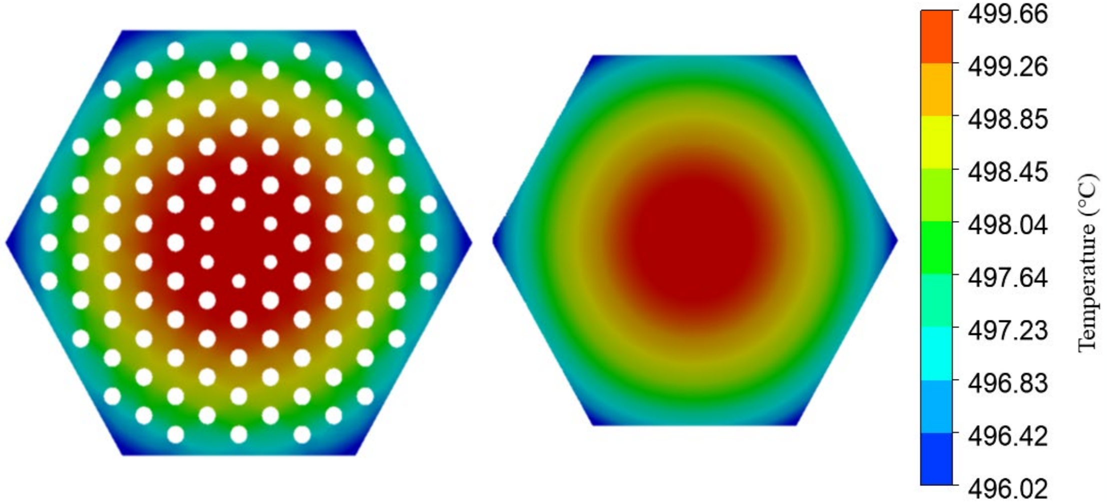




Thermal Contact Conductance Modeling Motivation

- After operation, the microreactor will undergo PCC for 3 days before being transported to its next destination
- During PCC, internal temperatures must remain under a certain threshold to ensure microreactor safety
- Because of the limited data on microreactor designs and their response, predictions of resulting TCC values in between prismatic blocks are limited especially given the differences in heat transfer phenomena
- Predictions of resultant temperature can be accomplished based on the geometric connectivity instead of surface contact knowledge

Prismatic Block Comparison



(Left): Prismatic blocks modeled with coolant channels. (Right): Prismatic blocks modeled without coolant channels

- To reduce experimental/computational costs, prismatic blocks were modeled without the coolant channels that would be present in a full scale model
- Blocks would be replaced with solid hexes of the same mass
- Temperatures over the course of 300 seconds were modeled with a standard initial temperature and consistent convective heat flux at the exterior
    - Temperatures were within 1% of one another with a similar temperature gradient

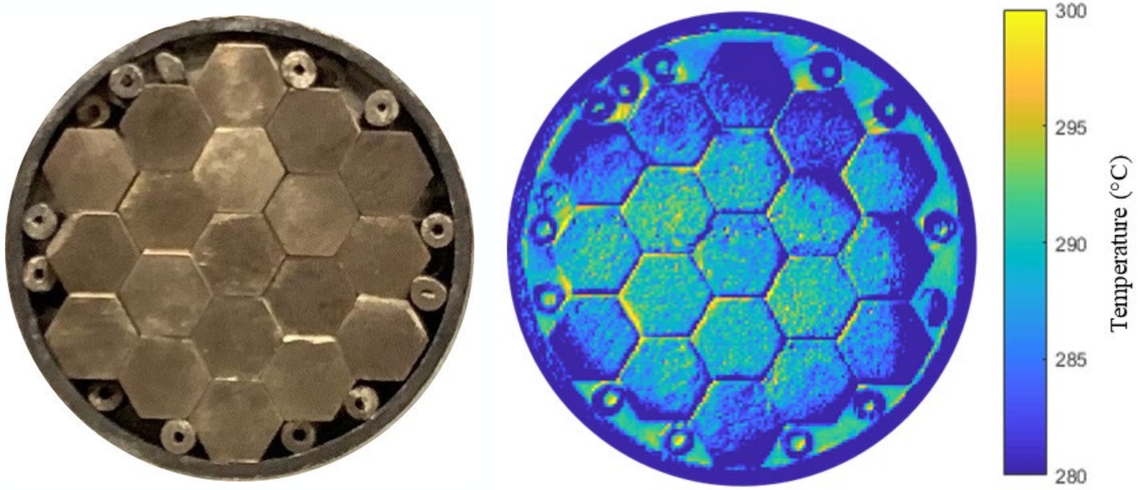
Experimental Parameters

	Model	MHTGR-350
Operating Temperature [°C]	300	650
Material	303 Stainless Steel	H-451 Graphite
Effective Length [cm]	0.793735	14.172
Thermal Conductivity [W/m K]	16.2	30 (Irradiated)
Density [kg/m^3]	8000	1740
Specific Heat [J/kg K]	500	1400
Thermal Diffusivity [m^2/s]	4.05E-6	4.8E-6

- Experimental setup validates the numerical simulation using the time scale
  - Given the difference in length scale, 15 minutes for the experiment corresponds to 80 hrs
  - Approximately 3 days after shutdown

$$t_m = \frac{\alpha_r L_m^2 t_r}{\alpha_m L_r^2}$$

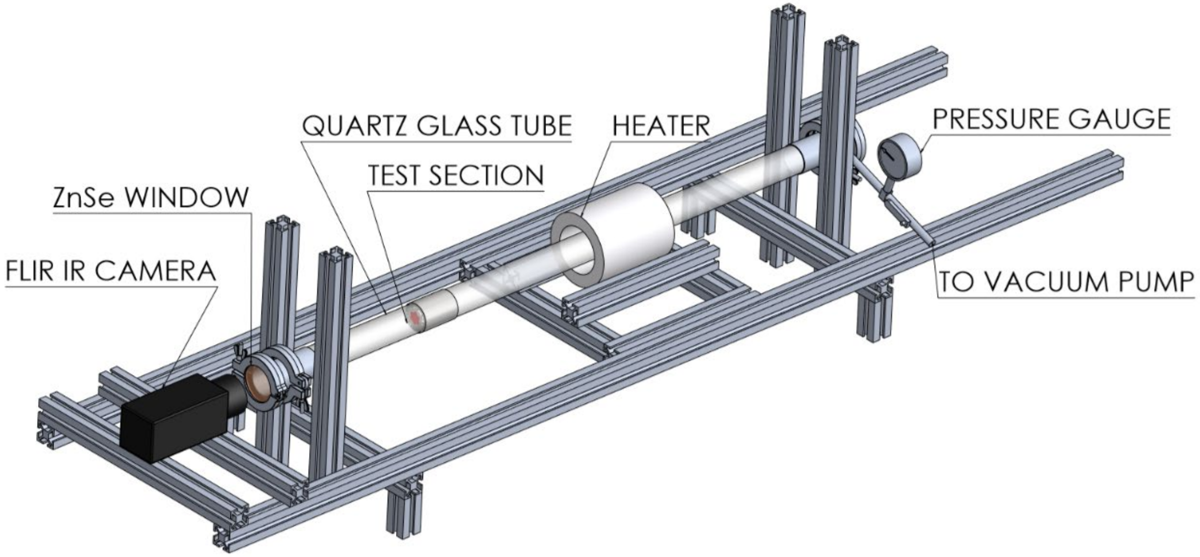
Experimental Setup



- Hexes are arranged to resemble the core of the micro-HTGR
- Steel tubes were used to keep the hexagonal blocks in close contact
- An IR camera was used to record temperature differences within the test section
- Imperfections around the edges of the blocks cause inaccurate temperature readings and were omitted from average block temperature values.

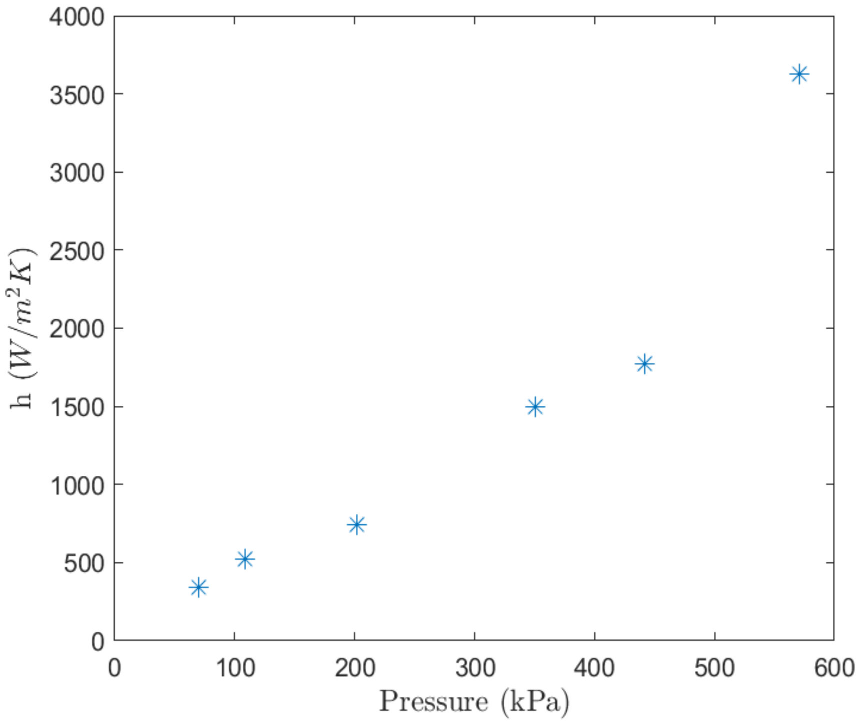
Experimental Setup

Procedure



1. Core geometry loaded 25 cm away from the end of the quartz tube with the ZnSe window
2. IR camera mounted 8 cm from the face of the ZnSe window
3. Vacuum was pulled until -1 atm was reached
4. The tube furnace was placed over the test section and heated until the test section had reached steady state 300°C
5. After reaching steady state, the heater was moved away from the test section and turned off
6. The IR camera began recording for the next 15 minutes at a rate of 2 Hz

TCC Measurements

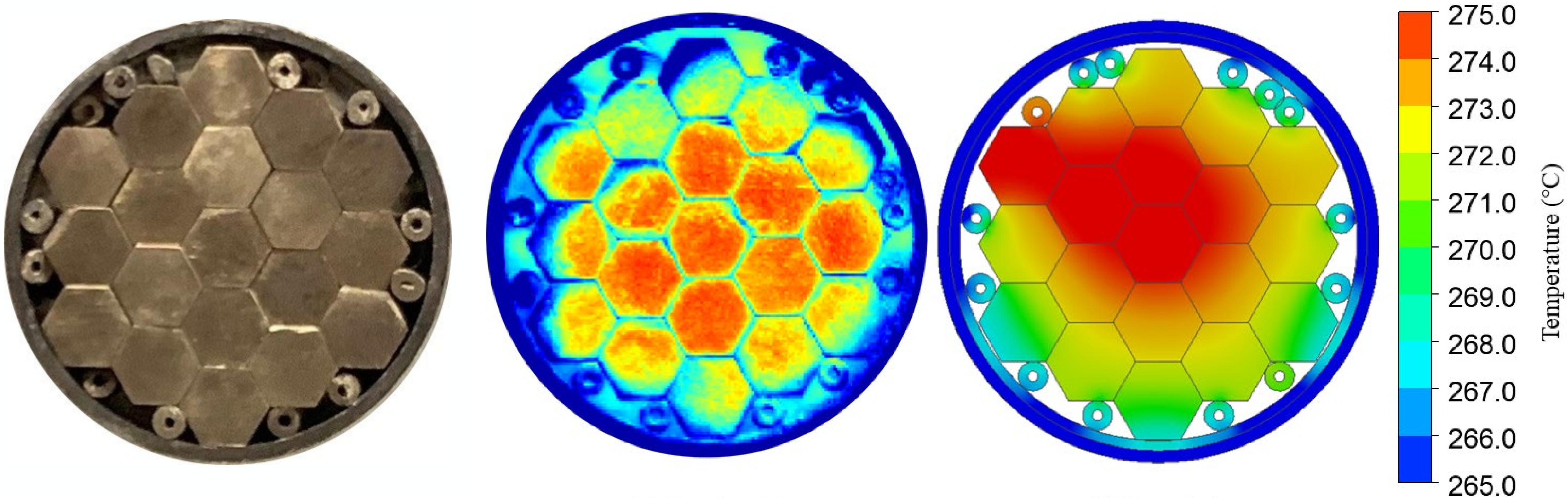


- 10 measurements were taken using a profilometer from several sides of the steel blocks used within the experimental setup to calculate root mean squared surface roughness
- Mean R_q: 1.505 µm
- Standard Deviation R_q: 0.397 µm

$$R_q = \frac{1}{N}\sum_{n=1}^{N} z_n^2$$

- Depending on contact pressure and angle, the TCC value could vary anywhere from 300 – 3800 W/m^{2}K [2,3]

Numerical Simulation Validation

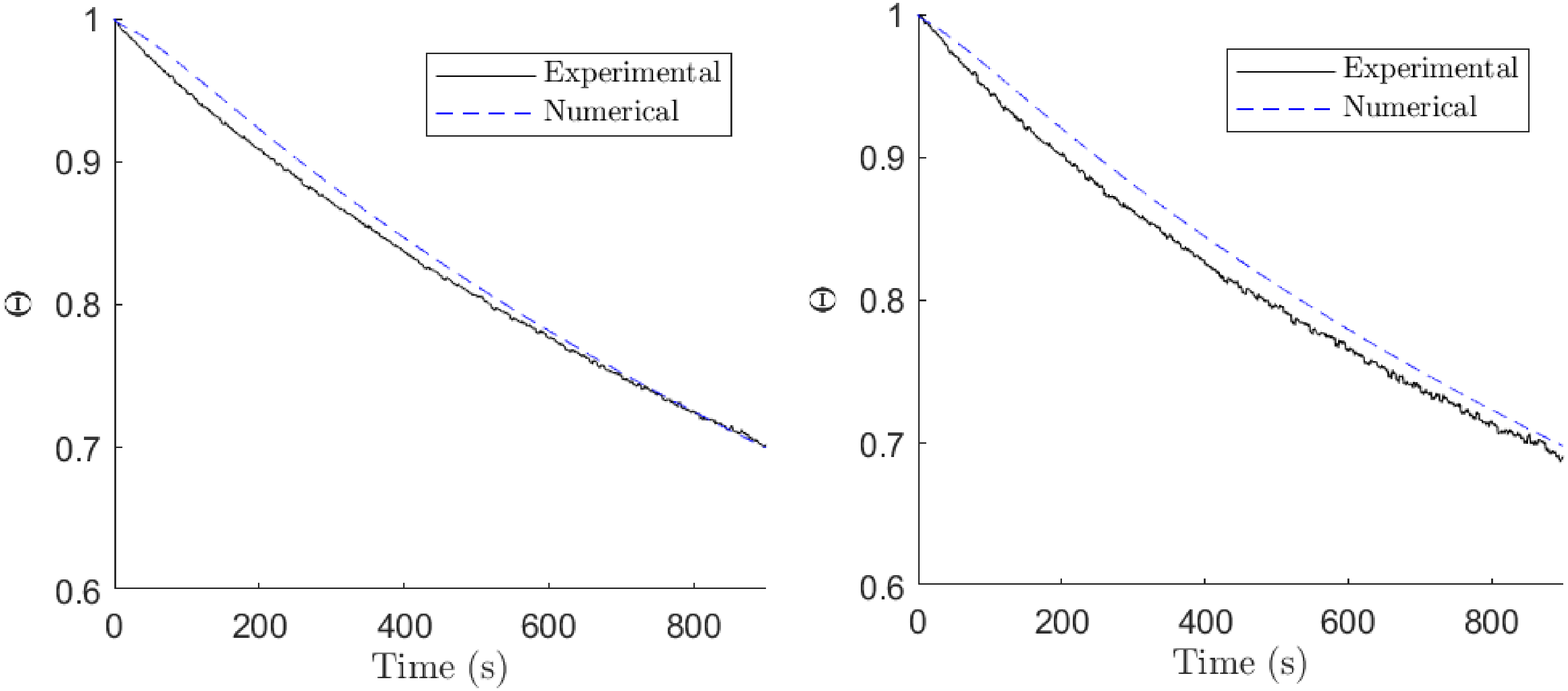


(a) Experimental

(b) Numerical

At t = 300 s

Numerical Simulation Validation



Non dimensional temperature comparisons between numerical and experimental values for the (Left): center active block and the (Right): outer reflector block.

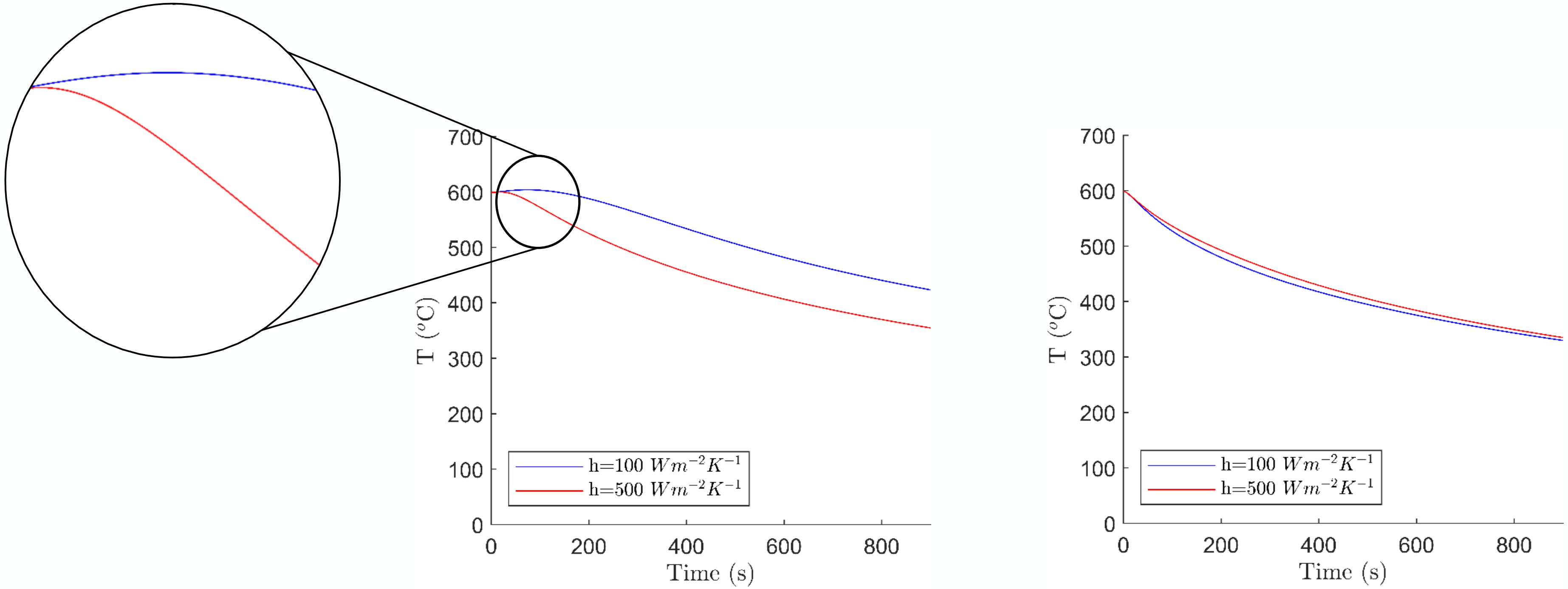
- Overall relative RMS error was 3.23%
  - Innermost blocks had the best agreement with an average relative RMS of 1.19%.
  - The outer blocks had a higher relative RMS error of 4.52%

$$\theta = \frac{T - T_i}{T_\infty - T_i}$$

Micro-HTGR Boundary Conditions

- Boundary conditions selected to mimic hypothetical micro-HTGR PCC
- Initial Temperature: 600 °C
- Internal Heat Generation: 20 kW/m^2
  - Corresponds to 2% of an operational heat generation of 1 MW/m^2
- TCC Values: 100 and 500 W/m^{2}K
  - Selected as conservative estimates of micro-HTGR TCC

Micro-HTGR



Temperature comparisons between numerical simulations with heat generation for low TCC for the (Left): center active block and the (Right): outer reflector block.

External Cooling through Natural Convection

External Microreactor Cooling

- Given CFR guidelines limiting accessible surfaces to <85°C, knowledge of microreactor temperature profiles is vital
- External cooling methods will predominantly drive the external temperature profile, should mechanical failure cause active cooling methods to shut down, microreactors should be able to remain under safety guidelines using only passive systems
- Worst case scenarios would thus involve natural convection systems

Natural Convection Validation

$$T^* = \frac{T - T_c}{T_h - T_c}$$

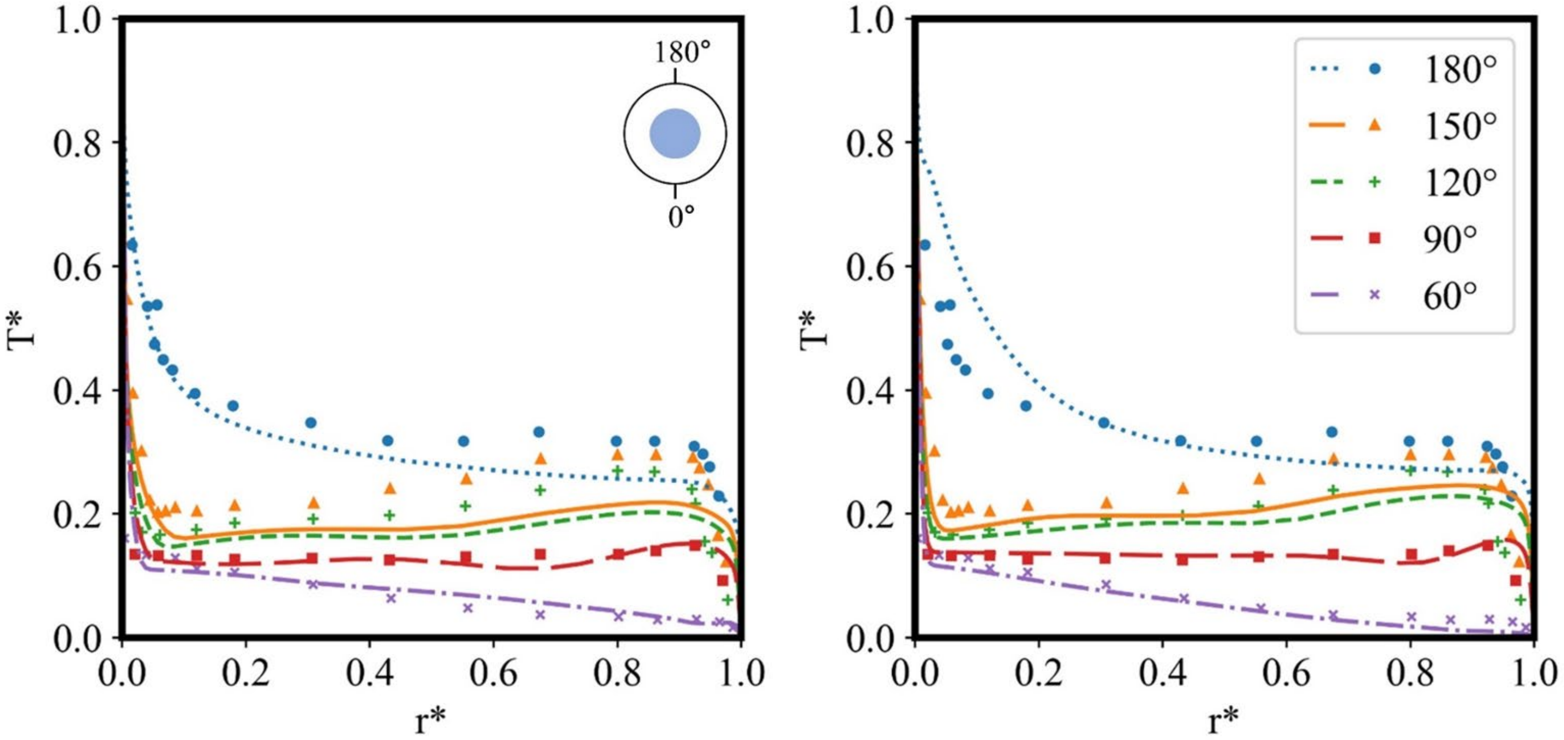
- Validation was accomplished using experimental data from McLeod et al. on the turbulent natural convection of horizontal, cylindrical annuli [4].
- Comparisons were made for k-ε and k-ω models to find the best fit for the resultant temperature profiles
- Natural convection of various volumes within an enclosure have demonstrated that the shape of the enclosure does not significantly impact the average Nu around the circumference of the internal structure [4]

Natural Convection Validation

- Additional validation of the model was completed when compared to Warrington and Powe's correlation for a cylinder within a cube annulus:

$$Nu_L = 0.288(Ra\frac{L_c}{r_i})^{0.261}$$

- And model values fell within the validations accepted average percent deviations

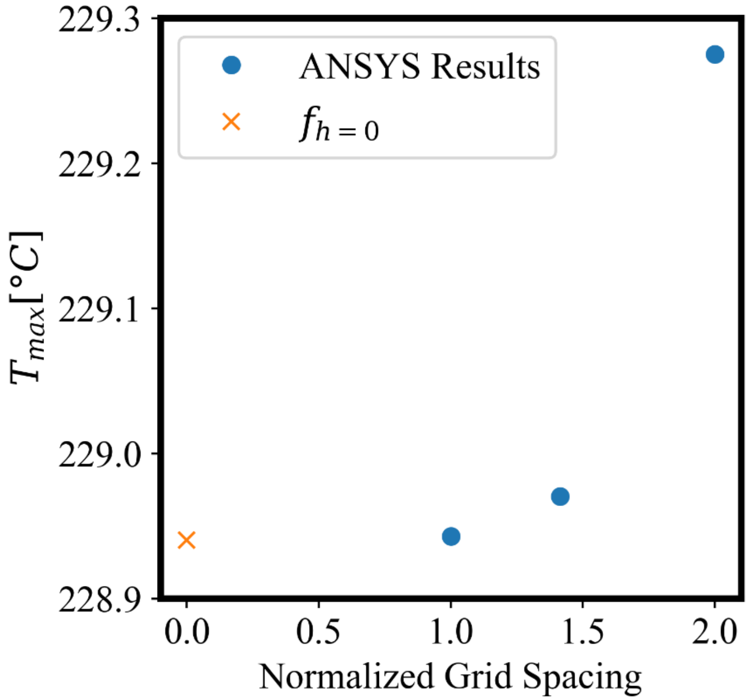


Temperature comparisons between numerical simulations and experimental data using the (Left): k-ω and the (Right): k-ε turbulence models.

Model	This Work's k_{eq}	Benchmark's k_{eq}	Error [%]
k-ω SST	33.12	34.6	4.28
k-ε Real.	47.44	34.6	37.11

$$k_{eq} = \frac{Q ln(\frac{D_o}{D_i})}{2\pi L_c \Delta T k}$$

Mesh Verification



- Meshes with node quantities ranging from 3000-6000 were tested and their maximum temperatures recorded
- The Richardson extrapolation is used to solve for the continuum value should the spacing equal 0 ($f_{h=0}$)
- Afterwards the grid convergence index can be calculated to ensure the simulation is within the asymptotic range of convergence

$$GCI = \frac{F_s|\varepsilon|r^p}{r^p - 1}$$

F_s: Safety factor = 1.25
ε: Relative error as compared to $f_{h=0}$
r: Refinement ratio
p: Order of convergence

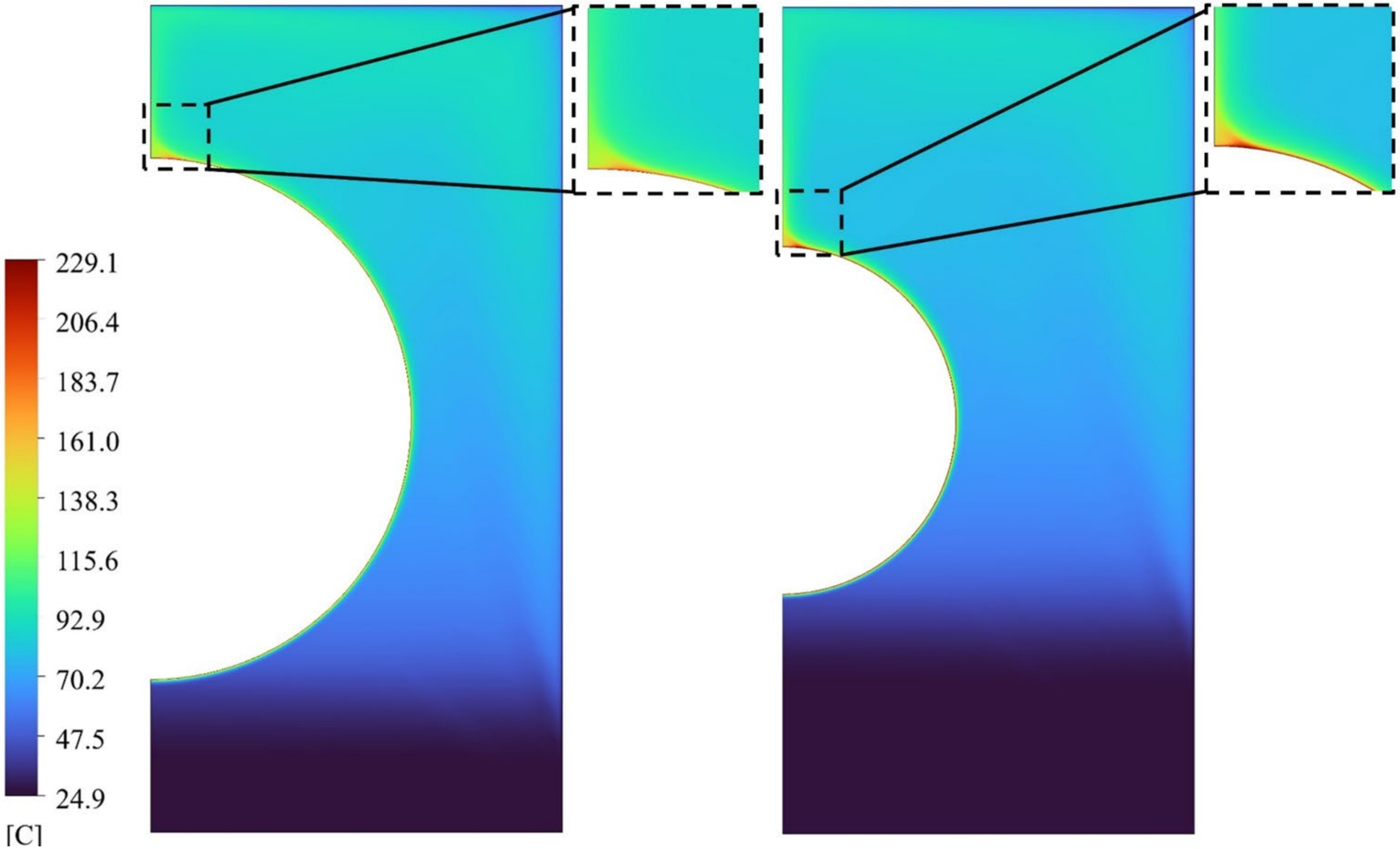
Boundary Conditions

Case	Power Rating (MWe)	r_i (m)	Shielding
1	5	0.743	No
2	5	0.496	No
3	1	0.743	No
4	1	0.496	No
5	1	0.496	Yes
6	2	0.496	Yes

- 33% efficiency
- 10 m long microreactor
- Transportation - 7 days after shutdown
  - Decay heat: 0.5% full power
- Modeled at the axial center of the microreactor to simulate maximum temperatures achieved
- Shipping container walls set to 25°C
- Cases selected to examines temperature profile differences that result from:
  - Size
  - Power level
  - Inclusion of shielding

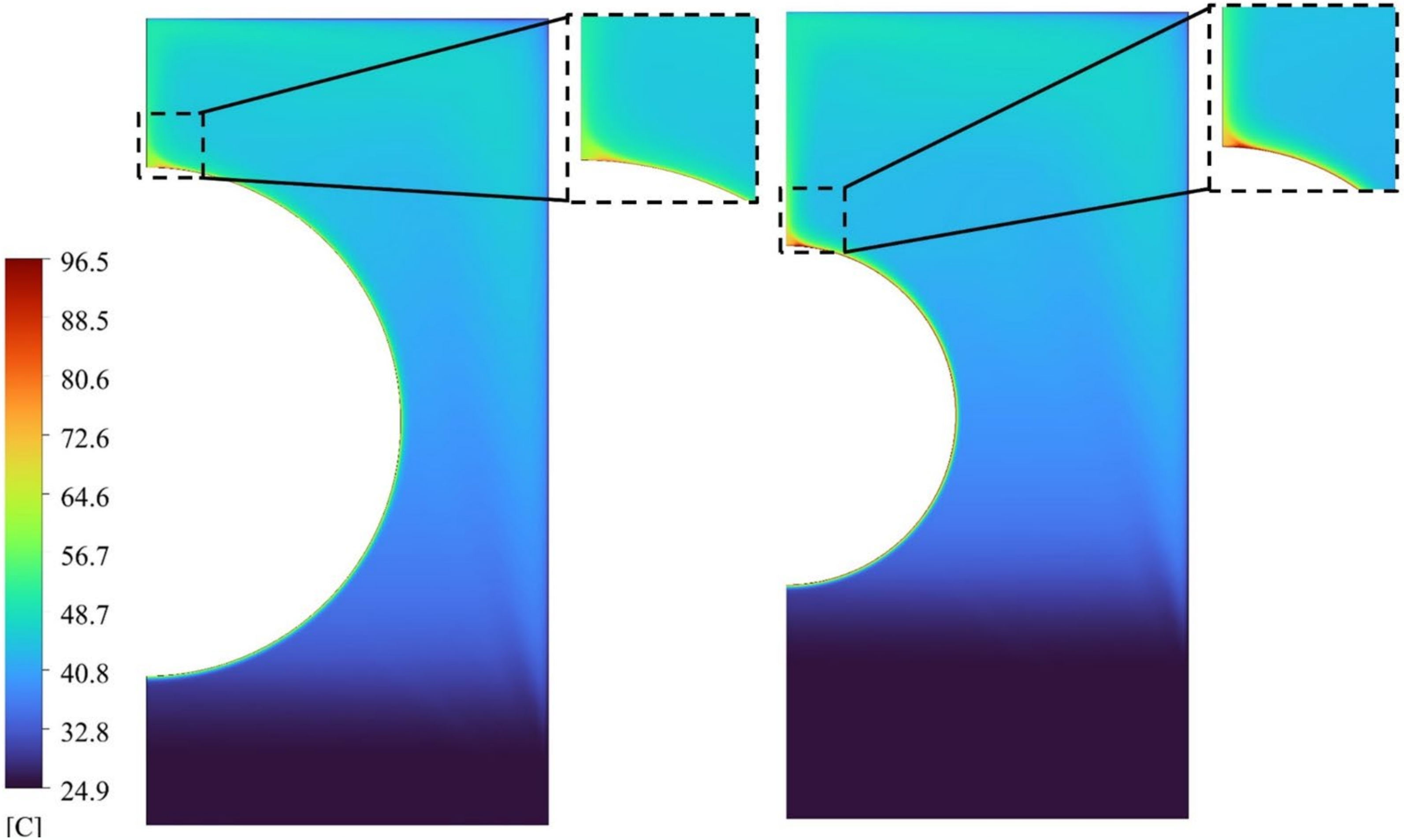
5 MWe Size Comparison

- Case 1 Maximum Temperature: 191°C
- Case 2 Maximum Temperature: 229°C
- Well above CFR limitations, 5 MWe microreactors will require additional cooling methods to stay consistently under limits
- The increase in surface area allows for lower temperatures, but given limited space, such tactics are also limited



1 MWe Size Comparison

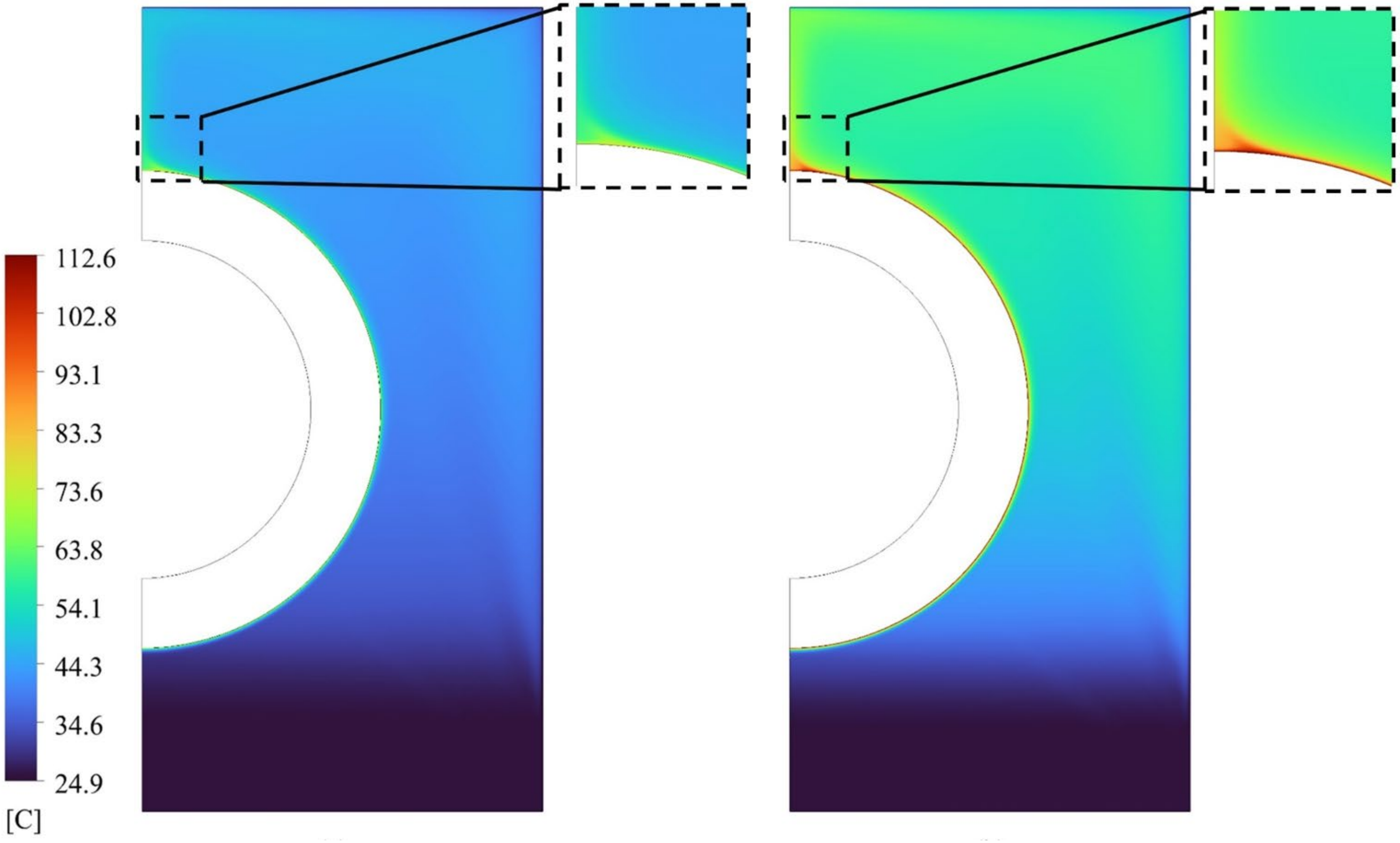
- Case 3 Maximum Temperature: 79°C
- Case 4 Maximum Temperature: 96°C
- The lower end of the power range for mobile microreactors keeps within CFR limits indefinitely



1 – 2 MWe Shielded Comparison

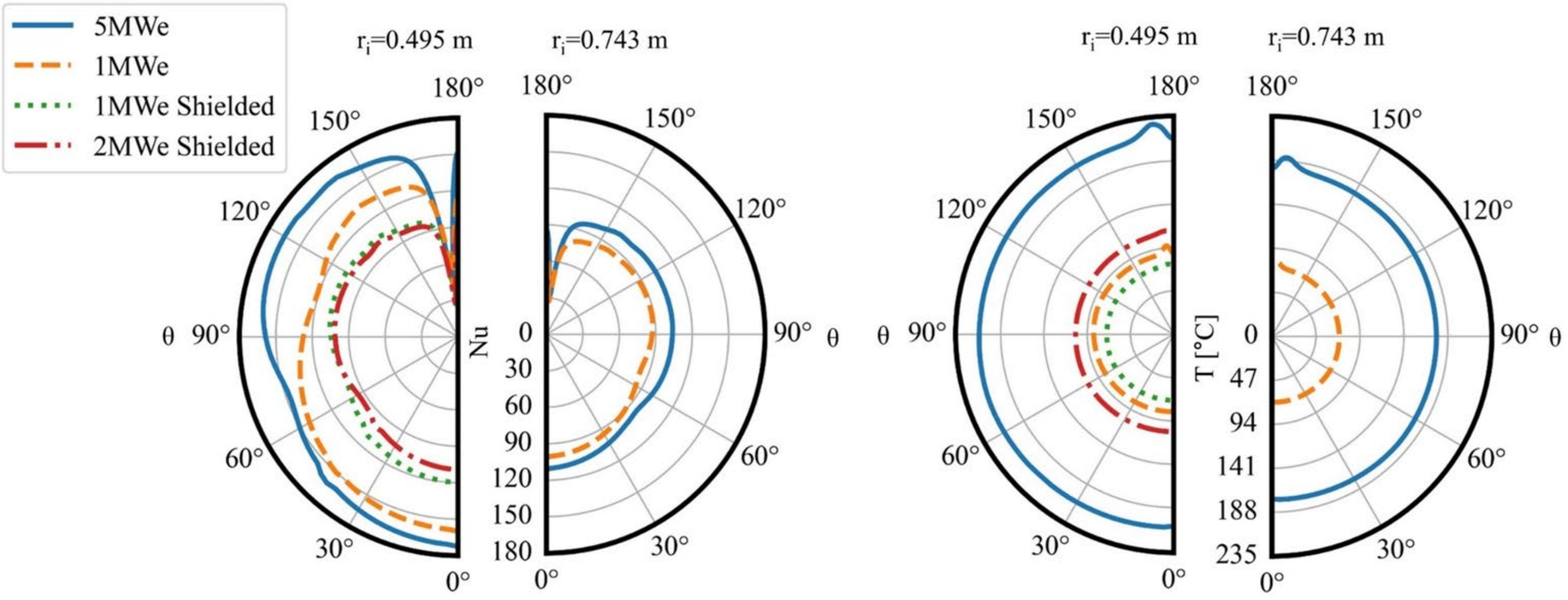
- Thermal properties of shielding concrete with an inacreased portion of crushed barite was used [5]
- Case 5 Maximum Temperature: 75°C
- Case 6 Maximum Te 11

Variable	Value
k	1.21 W/m K
ρ	3329 kg/m^3
c_p	511 J/kg K



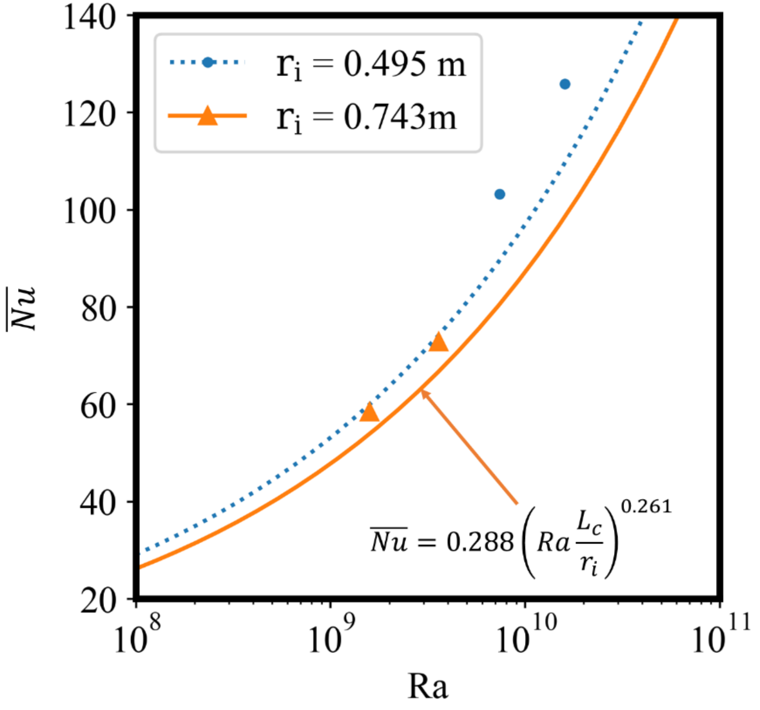
Overall Comparisons

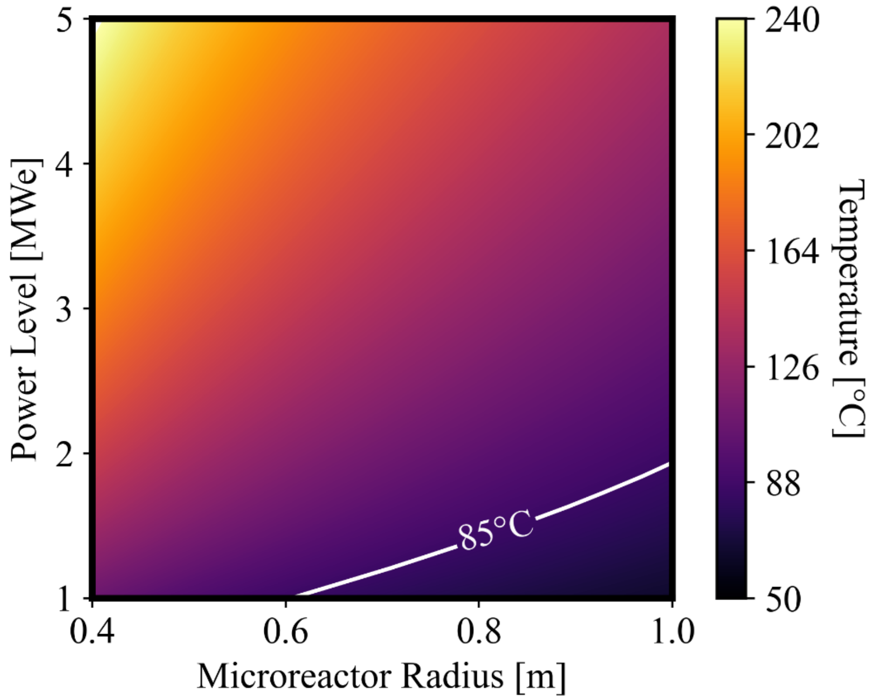
Case	Convective Heat Flux (%)
1	20.99
2	20.61
3	24.52
4	26.21
5	24.33
6	23.04



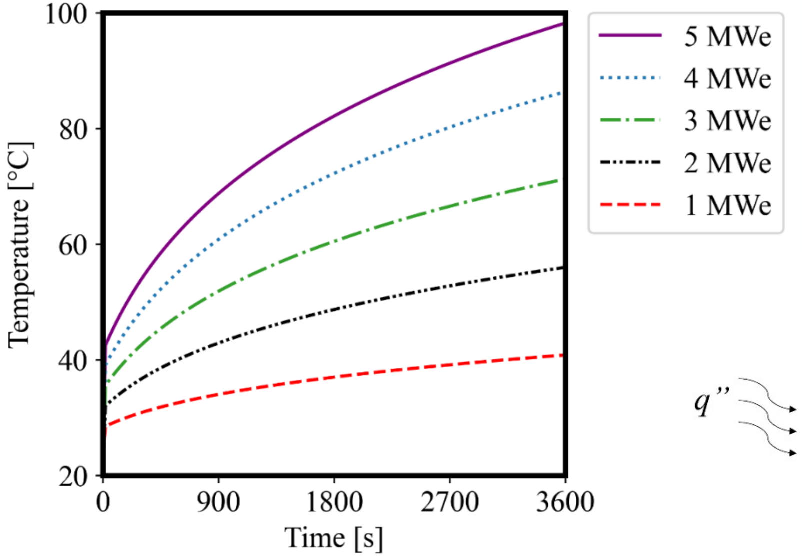
Design Implications

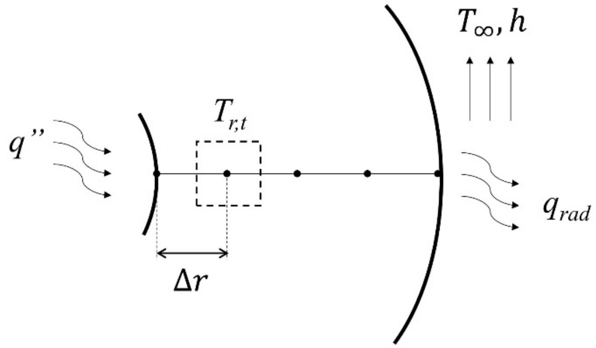
- A correlation from Warrington and Powe for natural convection around a horizontally oriented cylindrical body was used [6]
- Initial analysis of the correlation implies that microreactors are limited to 1 MWe when using only natural convection
- This serves as a highly conservative study lacking fan cooling or ventilation





Transient Analysis- Forced Cooling of container stops





- Initial temperatures established using:

$$T(r,0) = -\frac{q''r_i}{k}\ln\left(\frac{r}{r_o}\right) + T_0$$

- Supposing loss of forced surface cooling, over the course of one hour, a heat transfer coefficient of 1.99 W/m^{2}K was assumed.
- Power levels 1-3 MWe stay well below 85 °C, allowing for extended transport using only natural convection
- 4 MWe design reaches 85 °C under natural cooling after 1 hour.
- 5 MWe design reaches 85 °C under natural cooling after 34 minutes.

Coupled Model

Coupled Model Motivations

- After performing the separate heat transfer models, a coupled model demonstrating both mechanisms is necessary
- The validations performed for the TCC case and the natural convection cases are used to ensure temperature profile accuracy
    - While a scaled down experimental model could be used for the coupled case, the geometry is complex and the turbulent phenomena difficult to mimic with the smaller experimental sizes
    - Without a coupled model validation for the unique geometry being studied, chances for inaccuracies exist in the boundary between the prismatic blocks and the innermost walls of the shielding
- The impact that the inner and outer thermodynamic phenomena have on one another must be observed to determine whether the coupled model is necessary

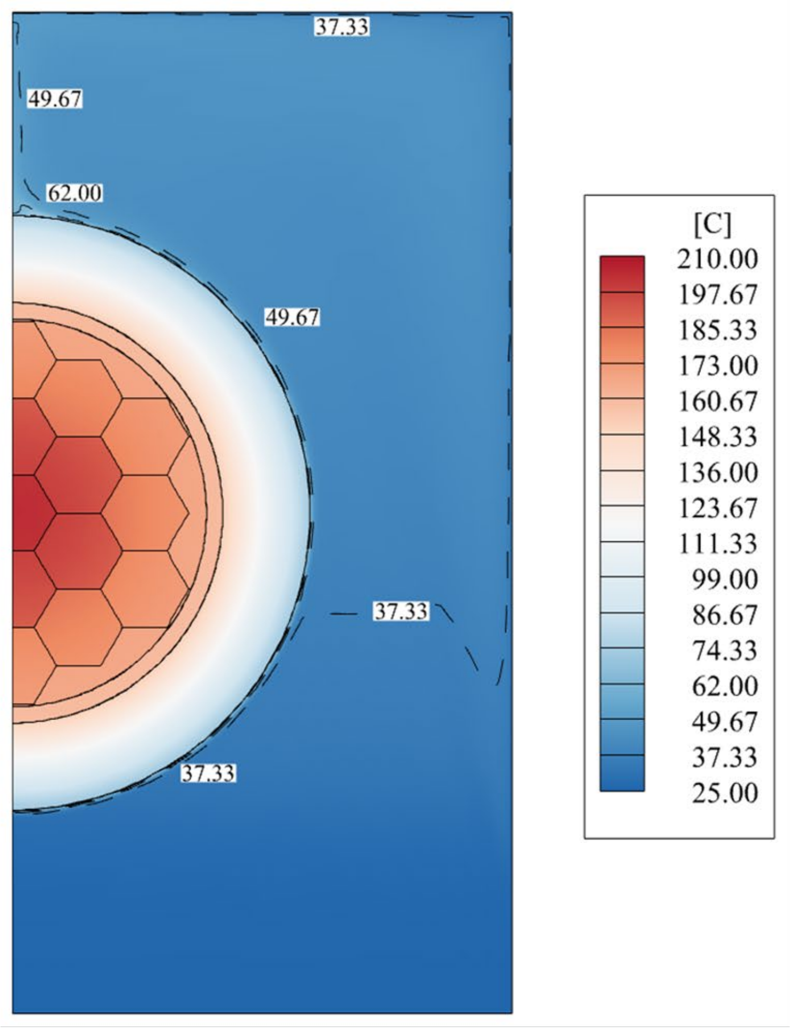
Cases

- 20 cm thick layer of shielding using the same thermal properties of the shielding concrete mentioned previously
- The first 2 cases mimic the conditions from cases 5 and 6 from the external cooling section
- The latter 3 cases examine the worst-case scenario for 3 different power levels
  - TCC: 100 W/m^2K
  - Shipping container temperature determined using a model representing ambient air surroundings to determine maximum temperature for the shipping container walls

Case	Power Rating (MWe)	Volumetric Heat Generation (W/m^3)	TCC ($W/m^2 K$)	Shipping Container Wall Temperature (°C)
1	1	9129.55	100	25
2	2	18259.10	100	25
3	1	9129.55	100	47
4	2	18259.10	100	65
5	5	45647.75	100	103

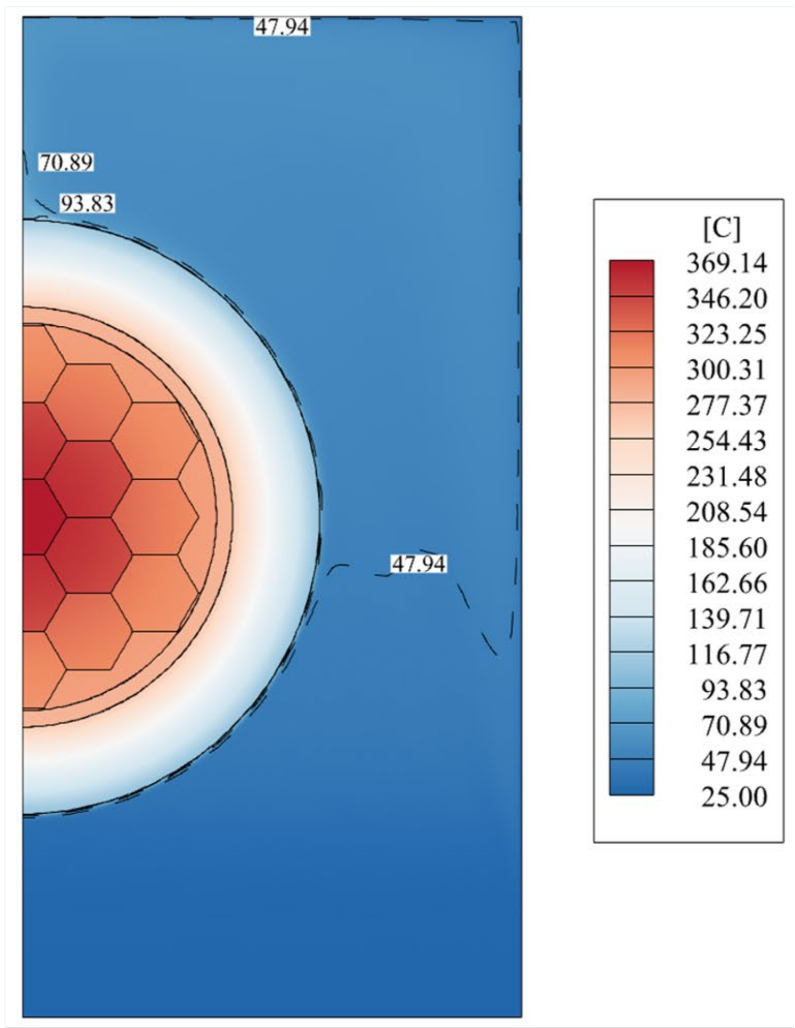
Comparison to Natural Convection Cases

Case 1



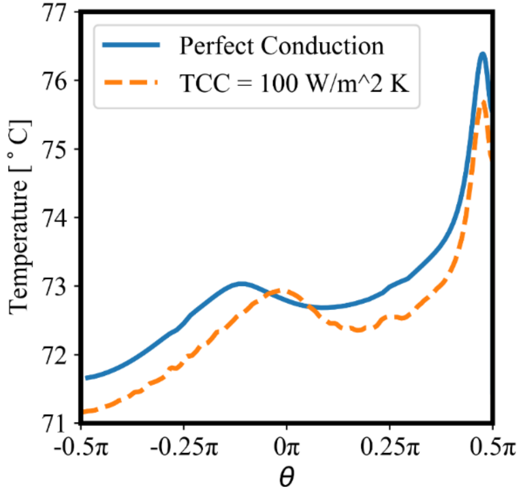
(a)

Case 2

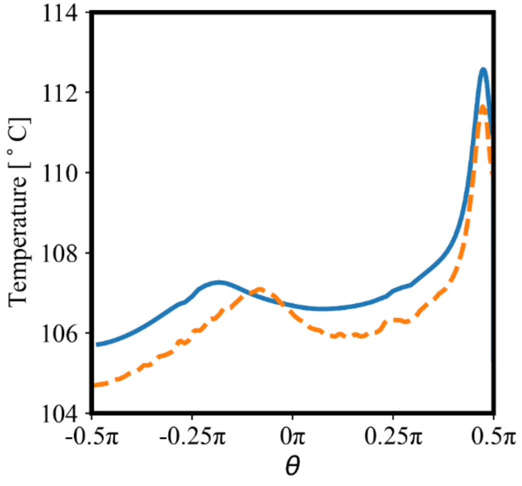


(b)

Case 1

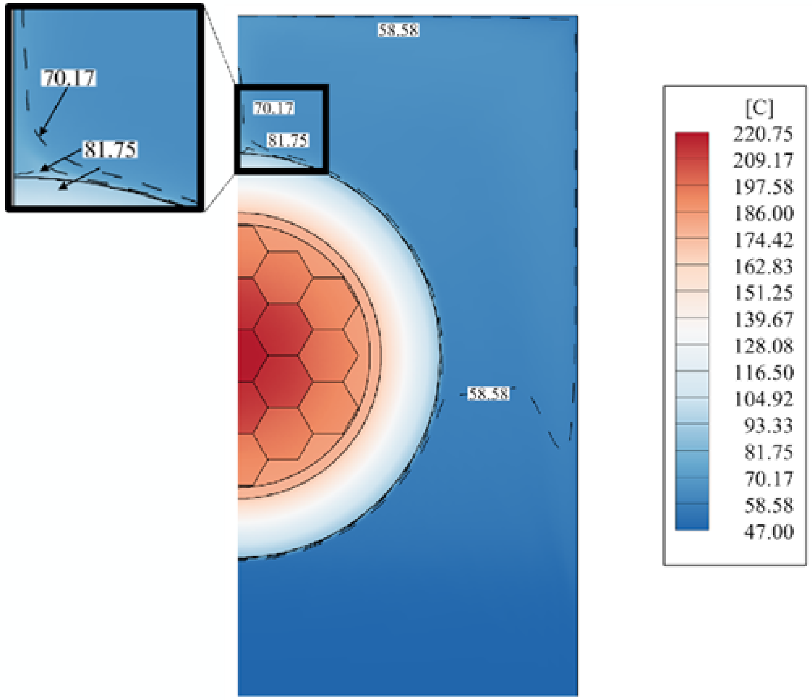


Case 2



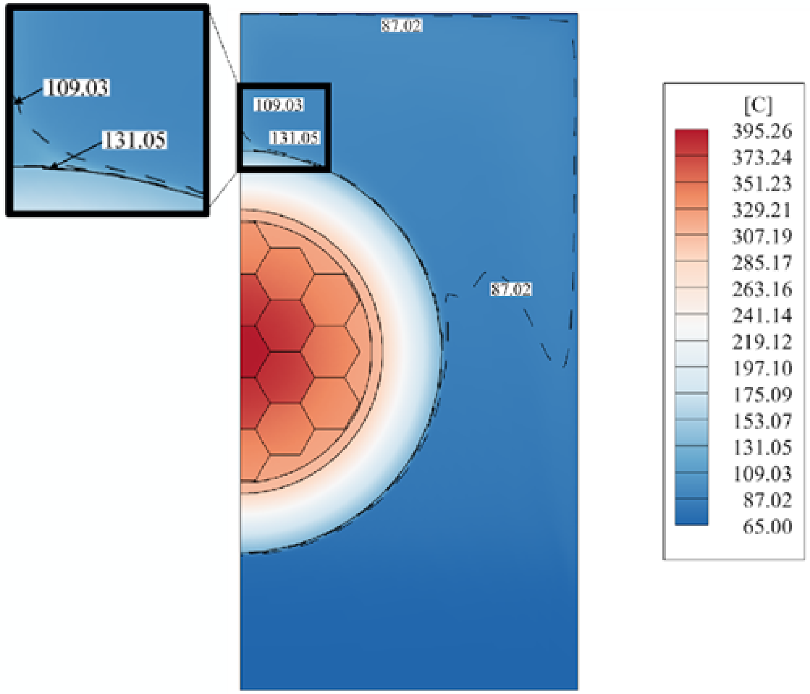
Worst Case Scenario Cases

Case 3



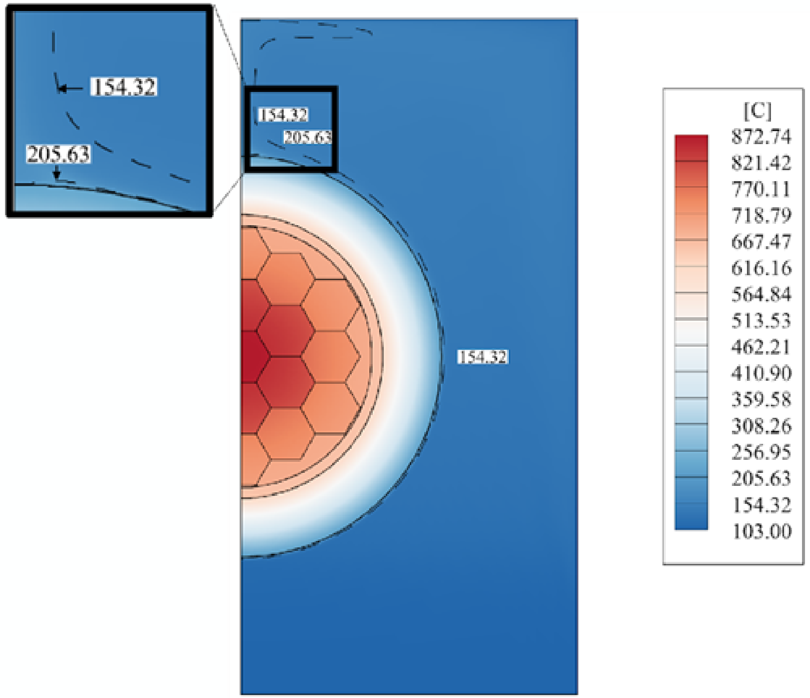
(a)

Case 4



(b)

Case 5



(c)

Conclusions

- Maintaining surface temperatures below current CFR guidelines proved much more difficult
  - 1 MWe microreactors would be able to indefinitely remain below CFR guidelines
- Assuming natural convection is only required for brief periods of time when active methods encounter mechanical failure, even higher level microreactors can be transported safely
  - 4 MWe microreactors can last a full hour without access to active cooling while remaining under the 85 °C limit.
  - 5 MWe microreactors can last 34 minutes using only natural convection to stay under the 85 °C limit.
- When coupling the models, while internal changes to TCC had a very minimal effect on external temperature, changes to the microreactor surroundings significantly changed the internal maximum temperatures
  - Given the worst case scenarios, the 1 MWe reached 220.75 °C , the 2 MWe case reached 395.26 °C , and the 5 MWe case reached 872.74 °C.
- Coupled models will prove necessary to ensure internal core temperatures do not exceed material limits

Publications and other output from this work

- Lin, T-Ying, Ketan Ajay, and Hitesh Bindra. "Numerical Simulations of Passive Heat Removal from Mobile Microreactors." *Nuclear Science and Engineering* (2024): 1-15.
- Ross, M., Lin, T. Y., Wicoff, I., Sieh, B., Sabharwall, P., McEligot, D. E., & Bindra, H. (2023). Passive heat removal in horizontally oriented micro-HTGRs. *Progress in Nuclear Energy*, *156*, 104530.
- Ross, M., Lin, T. Y., Gould, D., Das, S., & Bindra, H. (2022). Projecting the Thermal Response in a HTGR-Type System during Conduction Cooldown Using Graph-Laplacian Based Machine Learning. *Energies*, *15*(11), 3895.
- List of several conference publications (Can be provided)
- Molly Ross (PhD graduate)- Working at ORNL
- T-Ying Lin (MS graduate)- Working at Westinghouse eVinci Microreactor program

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Questions?