INL/CON-23-75691-Revision-0

RELAP5-3D Modeling in the OECD-NEA HTTF Benchmark

December 2023

Changing the World's Energy Future

Robert Forrester Kile

Idaho National Laboratory

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2023 International RELAP5-3D User Group Meeting
Idaho Falls, ID
December 7-8, 2023

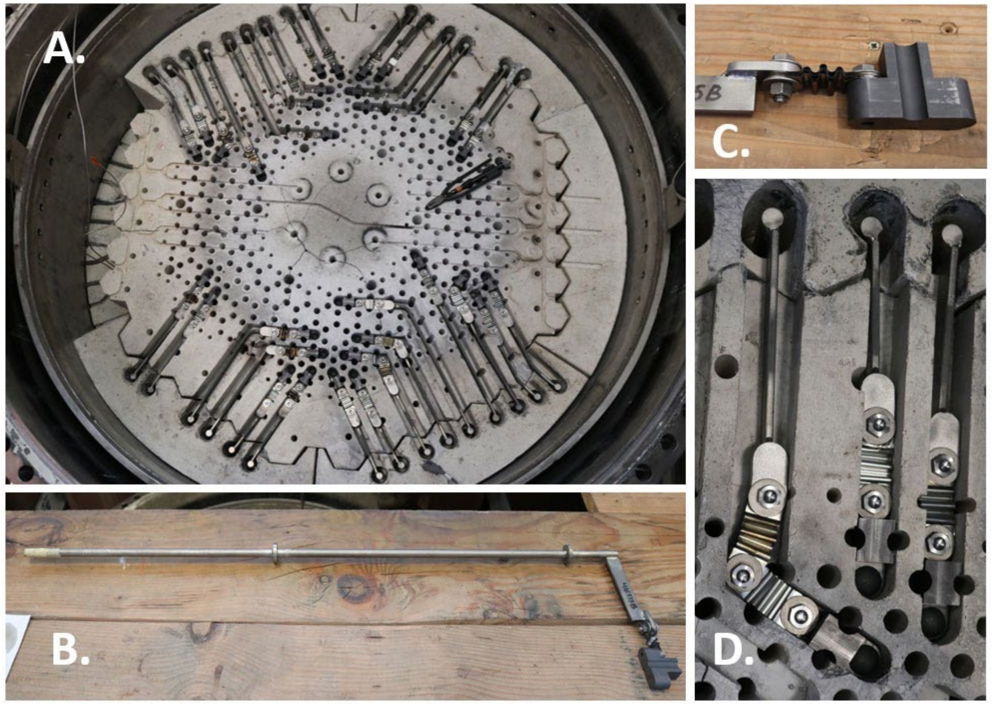
ART Advanced Reactor Technologies
GAS-COOLED REACTORS

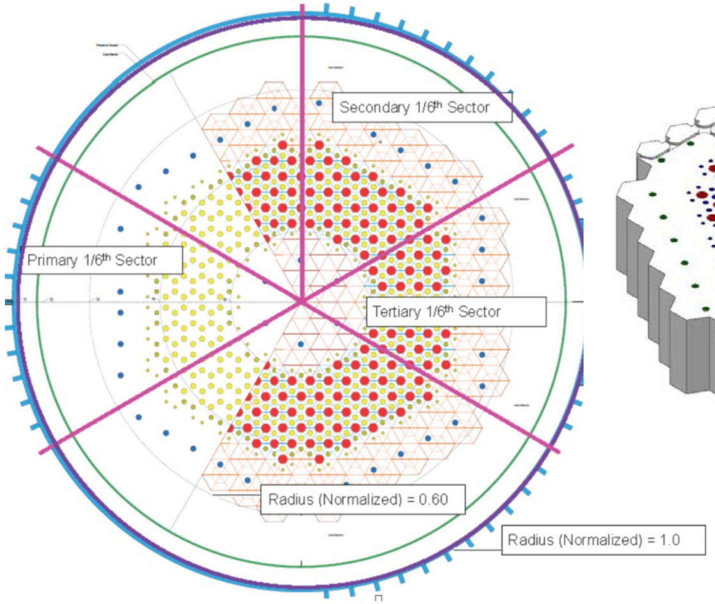
Introduction

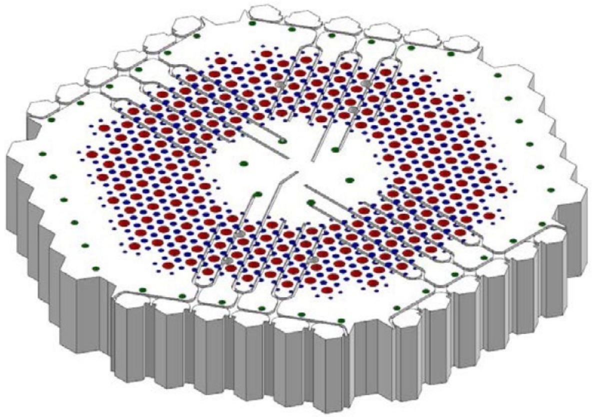
- Prismatic HTGRs are a concept approaching deployment
  - USNC: Micro Modular Reactor
  - BWXT: BWXT Advanced Nuclear Reactor
  - Radiant Nuclear: Kaleidos
- Deploying these reactors requires modeling and simulation tools that have been validated for these systems, but most thermal hydraulics modeling and simulation tools were developed and validated for LWRs
  - Objective in this work is to validate RELAP5-3D for prismatic HTGR modeling based on HTTF data
- To provide a set of verification and validation problems, we have been spearheading the development of an HTGR thermal hydraulics benchmark based on the High Temperature Test Facility (HTTF)
  - In collaboration with Argonne National Lab/NEAMS Program, Oregon State University, Canadian Nuclear Labs, NRG

The High Temperature Test Facility

- HTTF is an integral-effects thermal hydraulics test facility for prismatic HTGRs built at Oregon State University (OSU)
- Non-nuclear facility heated by graphite resistive heater rods
- Facility contains > 500 instruments capable of providing high-quality time-dependent data about the state of the facility







Gutowska, I. and Woods, B., "OSU High Temperature Test Facility Design Technical Report," OSU-HTTF-ADMIN-005-R2, Oregon State University, Corvallis, OR, 2019.

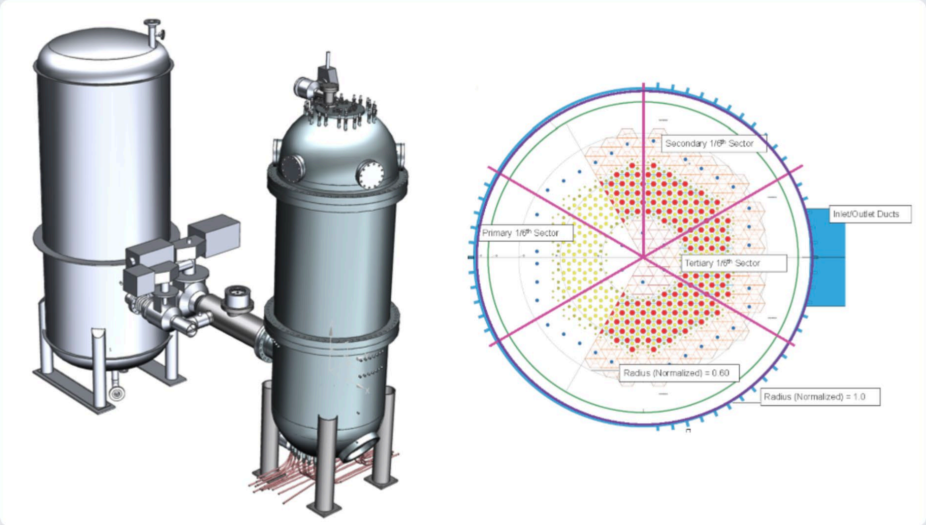
OECD-NEA High Temperature Gas-Cooled Reactor Thermal Hydraulics Code Validation Benchmark

- Benchmark is being spearheaded by ART-GCR
  - Input from INL, ANL, OSU, CNL and NRG
- Benchmark includes problems for lower plenum mixing, depressurized conduction cooldown (DCC), and pressurized conduction cooldown (PCC)
- Benchmark problems include exercises for code-to-code comparison, best-estimate modeling, and error scaling
- Benchmark has interest from participants in Belgium, Canada, Italy, Korea, Poland, UK, US, and more

Thermal hydraulic code validation benchmark for high temperature gas-cooled reactors using HTTF data (HTGR T/H)

Ongoing

Benchmark | Reactor physics | Thermal hydraulics | ...



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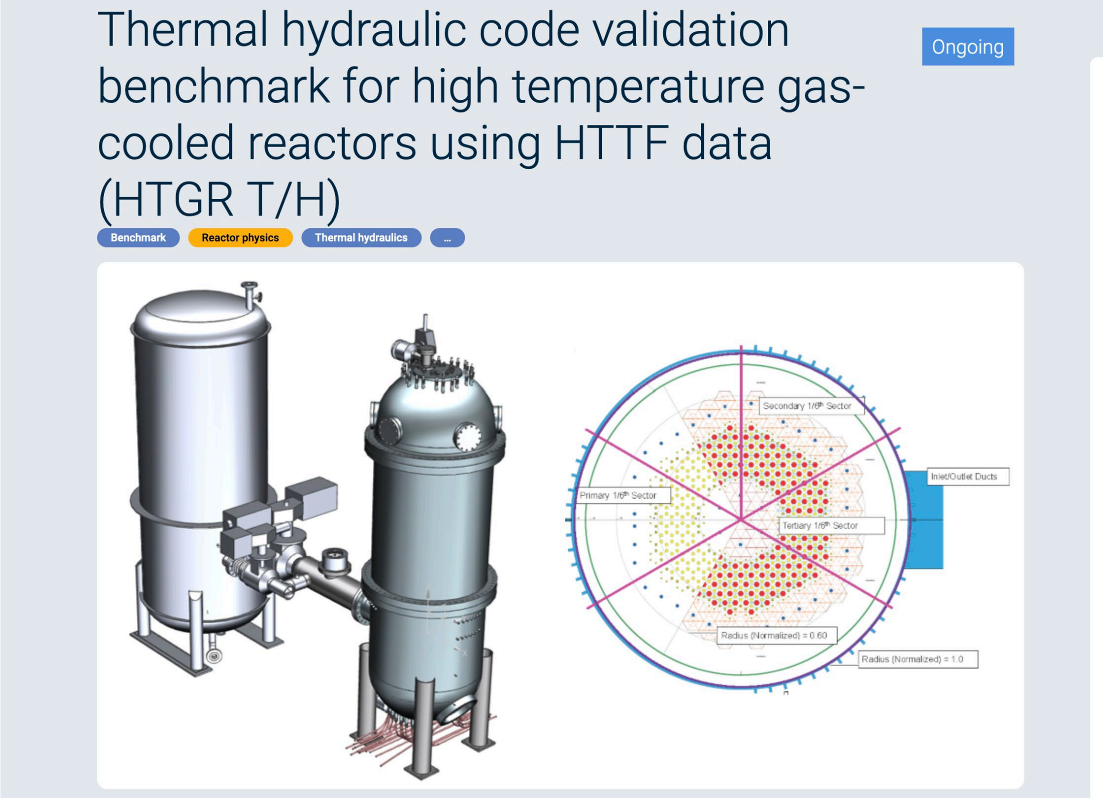


Problem	Experiment	Exercise 1	Exercise 2	Exercise 3
1 – Lower Plenum Mixing	PG-28	CFD/COU	CFD/COU	N/A
2 – DCC	PG-29	SYS/COU	SYS/COU	SYS
3 - PCC	PG-27	SYS/COU	SYS/COU	SYS

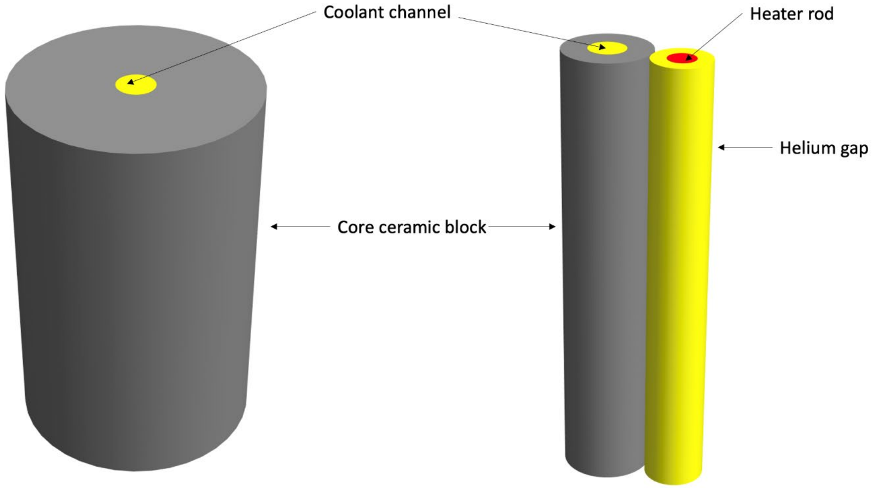
Benchmark Problems and Exercises

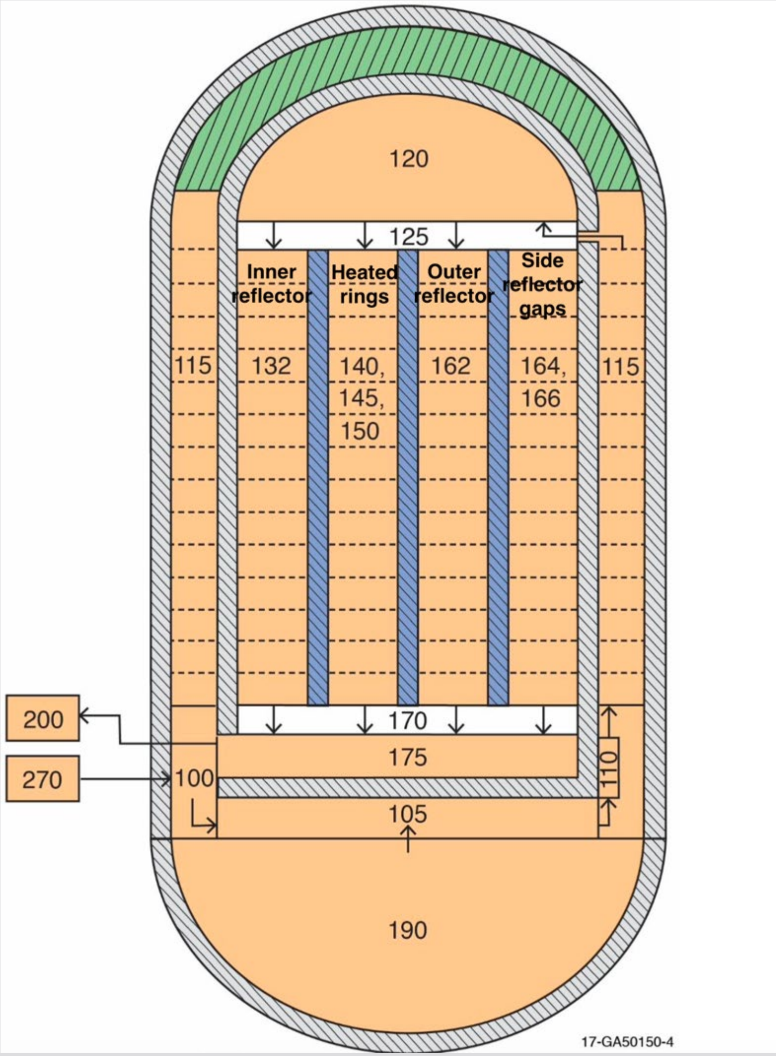
- Benchmark is broken down into 3 problems representing different physical phenomena
- Problems are broken down further into exercises, which represent different modeling approaches
  - Exercise 1: Code-to-Code comparison, fixed boundary conditions
  - Exercise 2: Code-to-Data comparison, open boundary conditions, validation
  - Exercise 3: Error scaling, quantifying how well codes validated based on HTTF provide insight into MHTGR
- Problems and exercises are intended for computational fluid dynamics (CFD), Systems codes (SYS), or coupled systems code/CFD models (COU)
- Focus of this talk will be on Problem 3: Exercise 2

Problem	Experiment	Exercise 1	Exercise 2	Exercise 3
1 – Lower Plenum Mixing	PG-28	CFD/COU	CFD/COU	N/A
2 – DCC	PG-29	SYS/COU	SYS/COU	SYS
3 - PCC	PG-27	SYS/COU	SYS/COU	SYS

RELAP5-3D Model of HTTF

- Descends from the INL model published in 2018
- Core is modeled as a set of nested heat structures
  - 3 represent inner reflector
  - 3 represent area containing heater rods
  - 3 represent outer reflector
  - Permanent side reflector is modeled as a single piece
- Core divided into 14 axial levels
  - 2 upper reflector
  - 10 active core blocks
  - 2 lower reflector
- Heater rods communicate with core blocks through radiation heat transfer only
- Heat structures containing coolant channels have to be modeled with unit cell approach

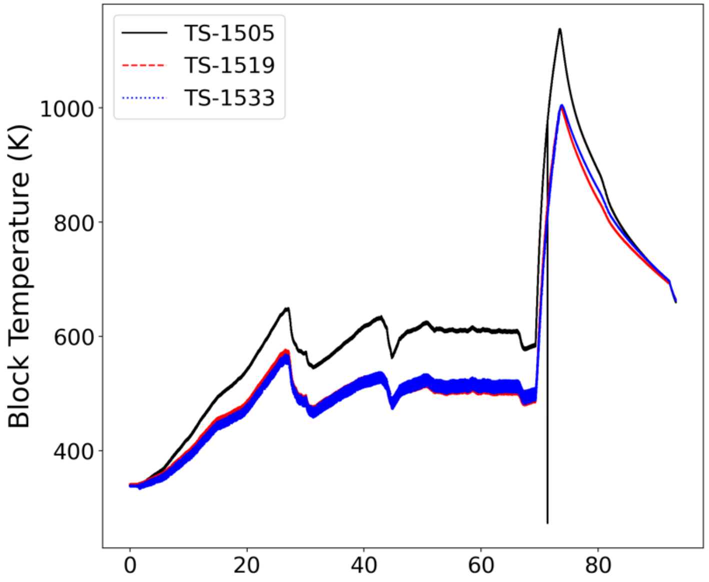


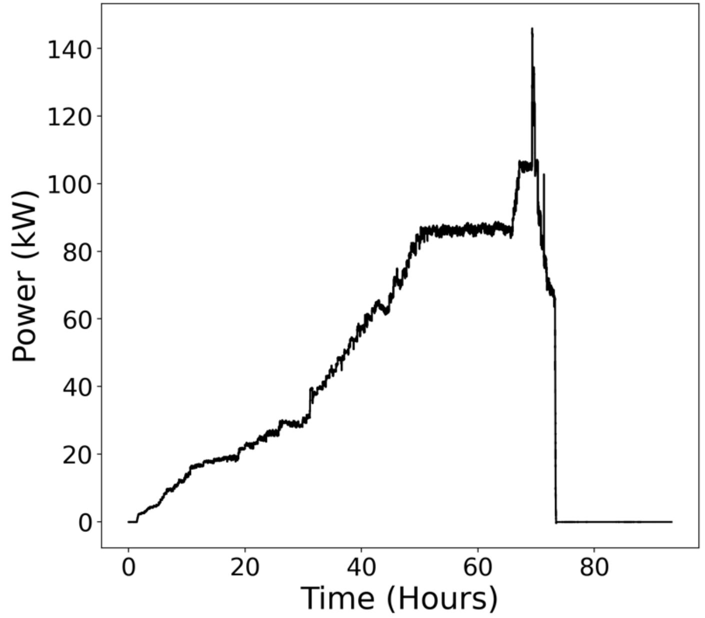


RELAP5-3D model description can be found in: Bayless, P., "RELAP5-3D Input Model for the High Temperature Test Facility," Idaho National Laboratory, Idaho Falls, ID, INL/EXT-18-45579, 2018.

Validation studies with RELAP5-3D start with PG-27

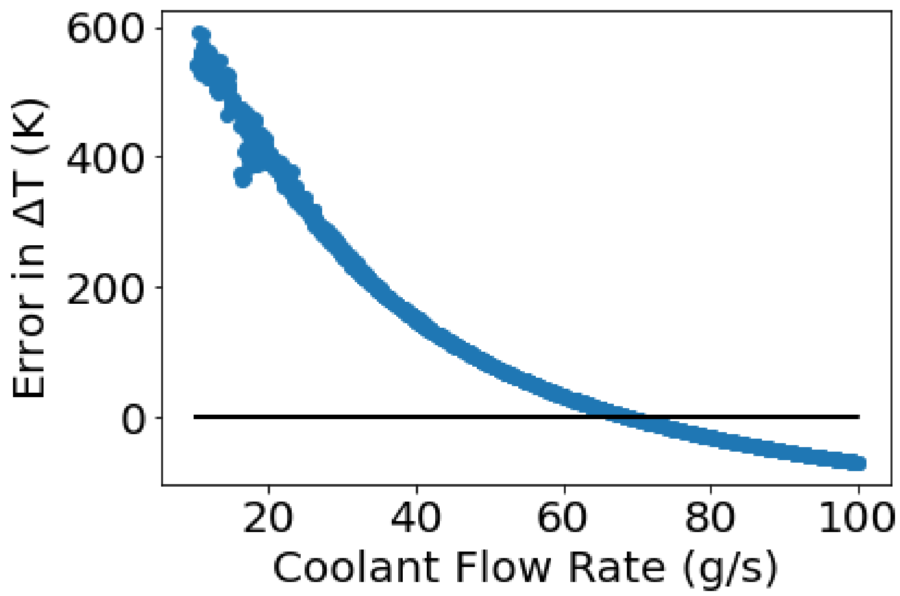
- PG-27 is an experiment representing the pressurized conduction cooldown (PCC)
- Extended steady state from 50-65 hours provides an opportunity to do a steady-state calibrate then test the calibration against transient behavior
- PCC initiated at a time of 69 hours
- Heaters shut off at 73 hours
- Primary focus is block temperatures in the region containing heater rods
- 25 of 27 block TCs were working, so there is plenty of data here
  - Even more TCs available once we start looking at reflector temperatures





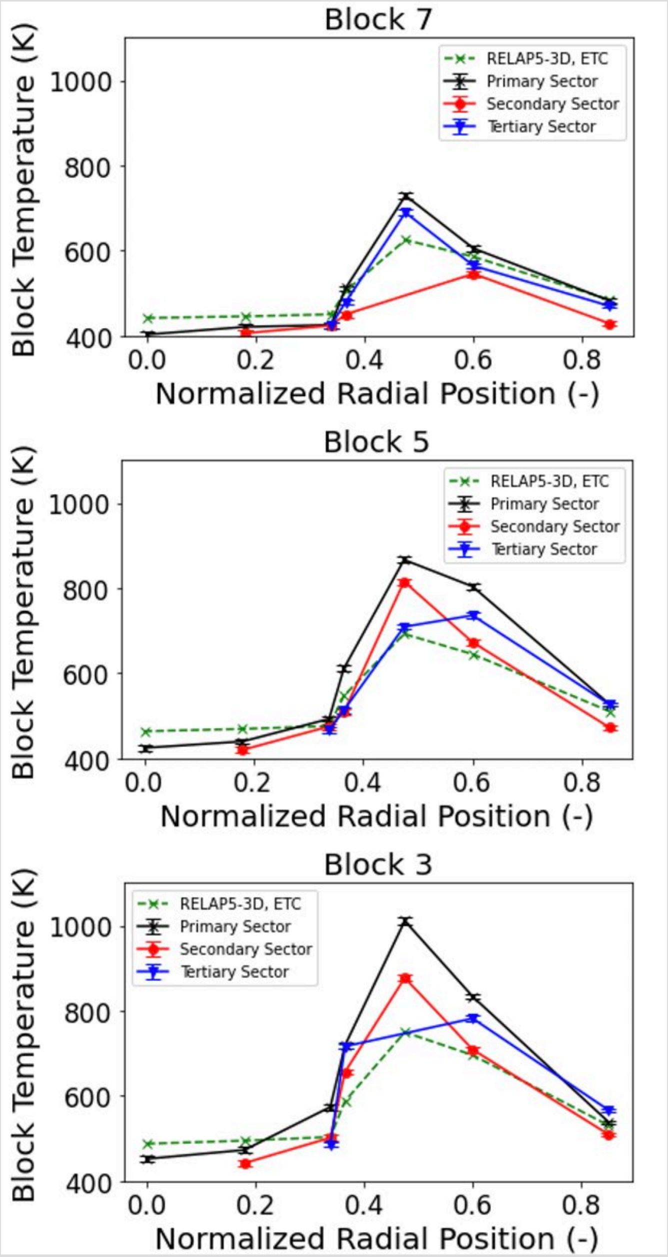
Helium flow rate provides the first-order effect on temperatures

- Calibrated helium flow rate based on the difference between measured and RELAP5-3D temperature rise at a time of 62 hours
- RELAP5-3D estimates the flow rate at 62 hours to be 69 g/s
- Hand calculation based on conditions at 60 hours suggests flow rate of 72 g/s
- We chose to model a flow rate of 69 g/s from 60-69 hours, at which point the PCC is initiated and inlet flow is set to 0 over 0.5 seconds



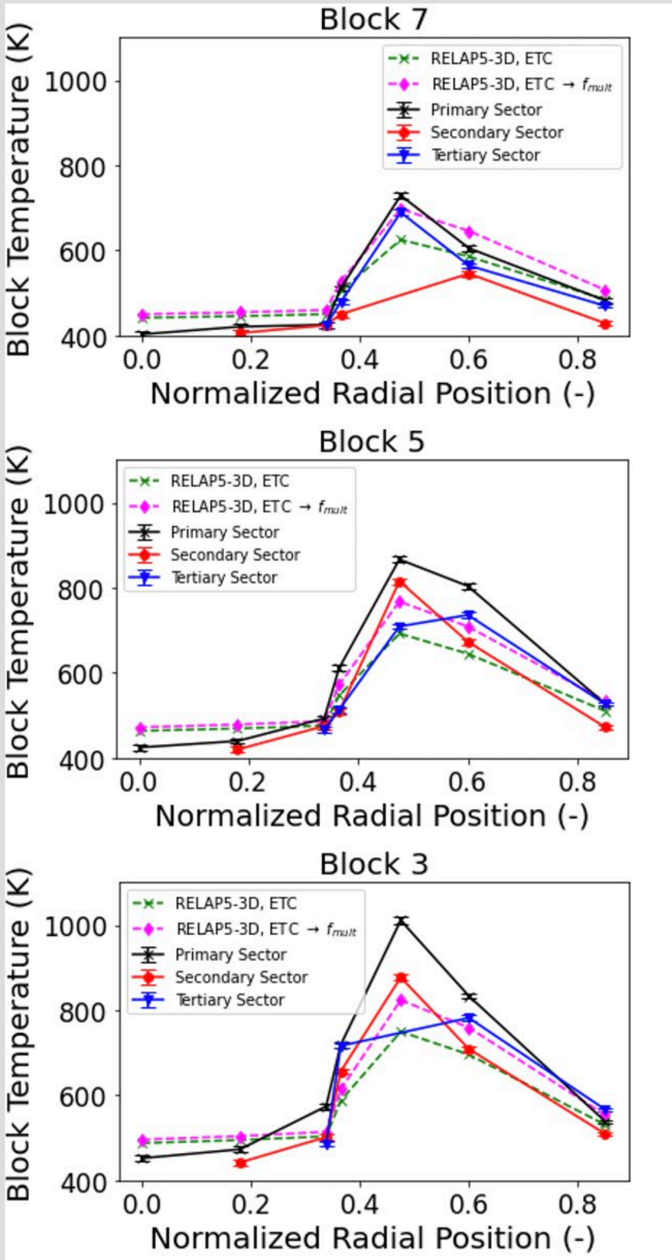
Calibrated block thermal conductivities

- Heat generation is primarily in the outer portion of the active core, near normalized radius of 0.475
- Applied a thermal conductivity multiplier of 0.36, comparable to the 0.34 ANL identified for SAM
  - This was done to improve prediction of block temperatures
- Block temperatures are generally well-predicted in the inner and middle rings of the core
- Inner reflector temperatures are overpredicted
- Inner ring well-predicted at blocks 3 and 5
- Middle ring well-predicted at blocks 5 and 7
- Outer ring temperatures are underpredicted
  - Is this because the flow distribution is wrong or because of something else?
- Outer reflector is well-predicted at blocks 3 and 7
- Permanent side reflector well-predicted everywhere



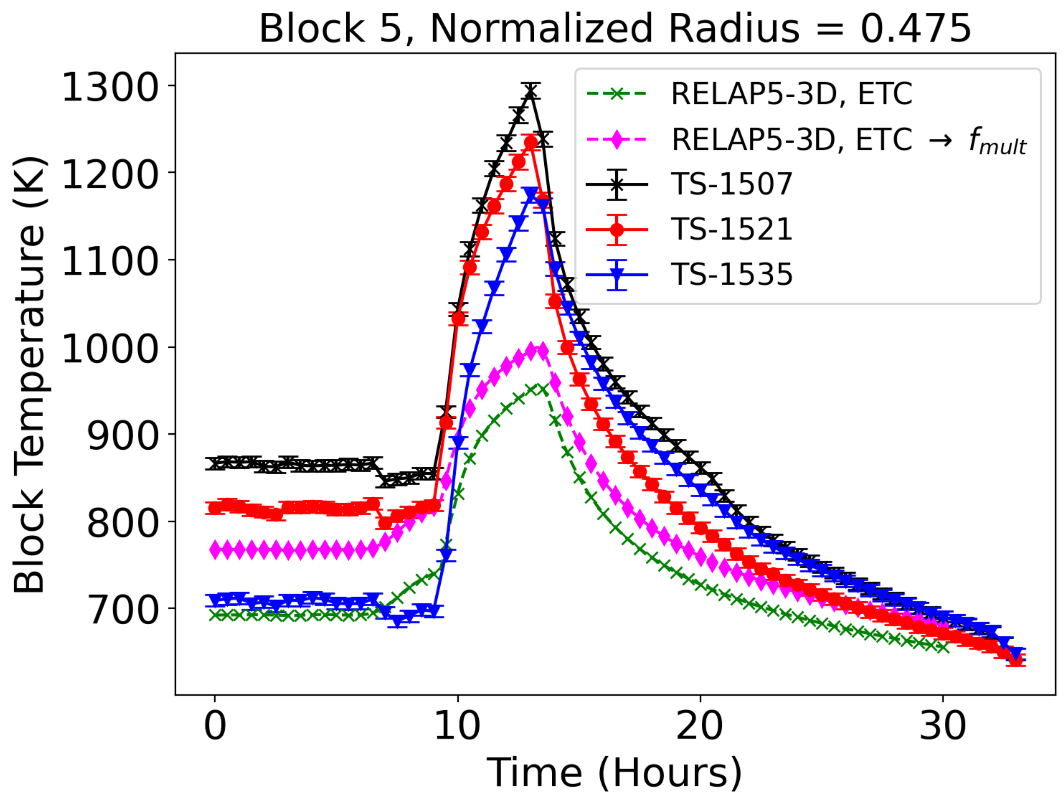
Increased friction to improve outer ring temperatures

- Inner reflector temperatures are worse, not better
- Inner ring is not improved
- Middle ring no longer well-predicted at block 7. Now well-predicted only at block 5
- Outer ring temperatures were always better with the increased friction, but block 3 still too low
- Outer reflector now worse at block 7 but well-predicted at block 3
- Permanent side reflector only well-predicted at block 3
- **Conclusion:** Increasing friction improved some things, particularly in the region with the greatest heat generation, but it made things worse in some regions with no heat generation
- **Question:** Have we improved the model or just cancelled out some error?



PG-27 transient modeling

- Used conditions at 60 hours as t=0
- Transient temperature rise is always under-predicted
  - Under-predicted by 28-48%
- Peak temperatures are too low, even in locations where initial temperatures were too high
- Uncertainty in the heat capacity of the blocks is relatively low, so heat capacity is not the driving factor
- Temperature drop from 5-10 hours is likely due to increase in coolant flow rate in that time period. We do not model that flow increase

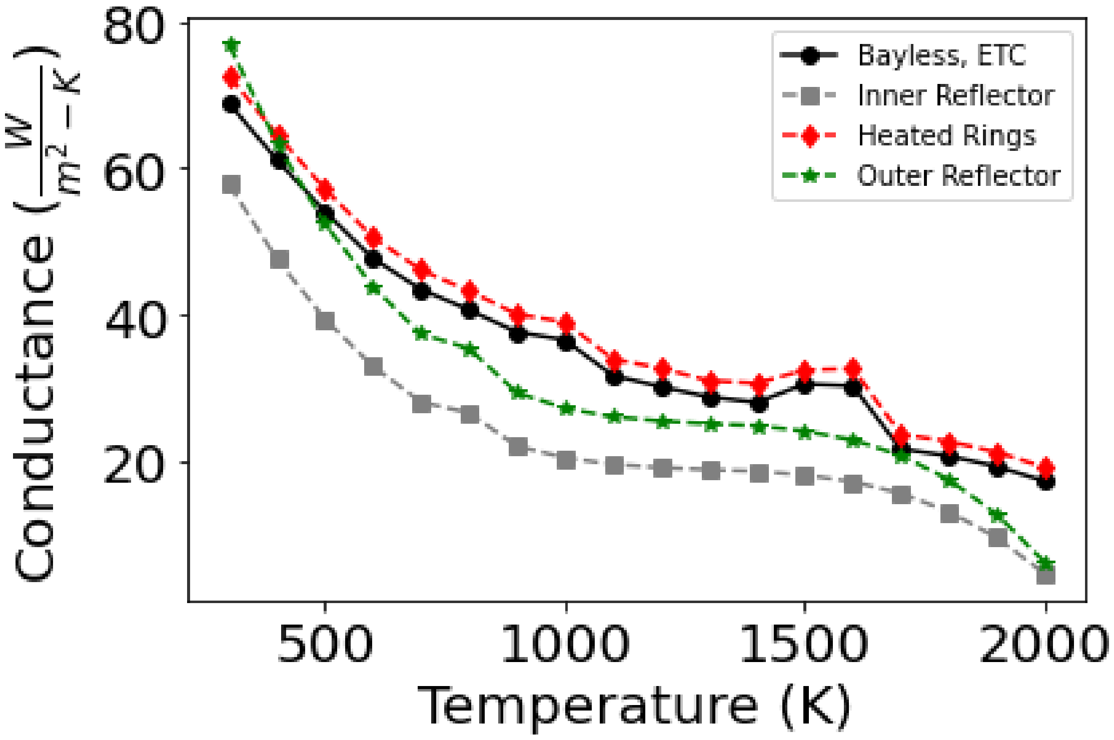


Measured|Standalone ETC|ETC + friction calibration temperature rise

	Inner Ring	Middle Ring	Outer Ring
Block 7	480|305|327	552|324|232	505|300|272
Block 5	487|297|317	504|306|317	453|263|232
Block 3	424|284|304	426|286|295	322|232|202

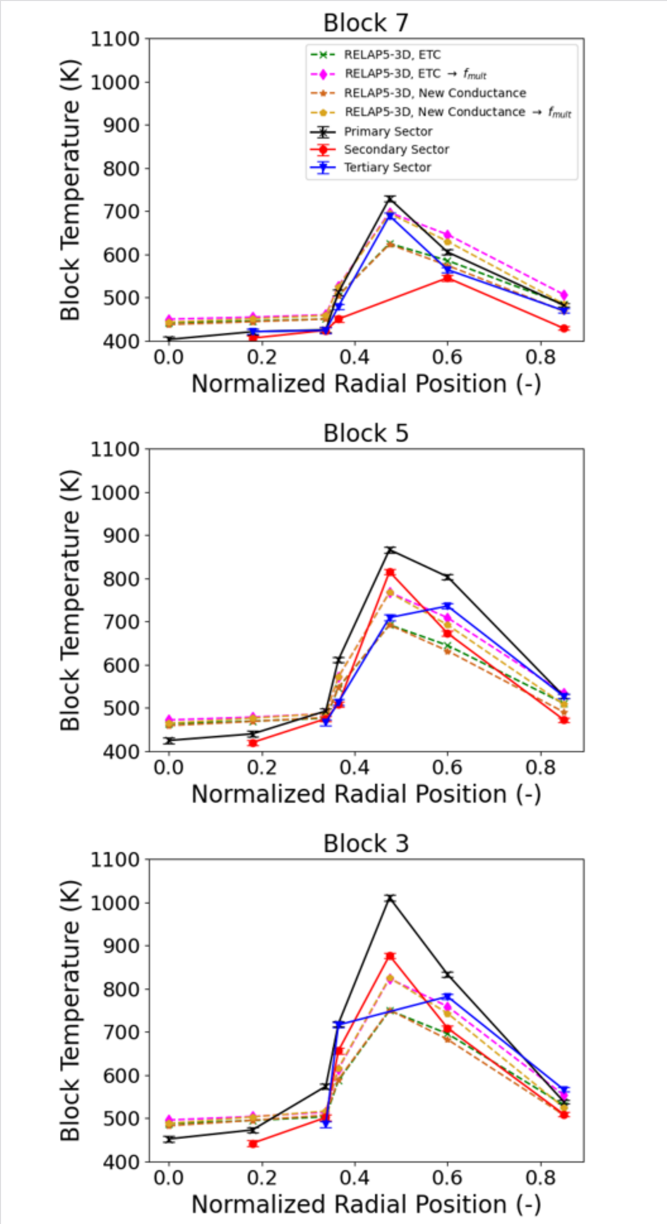
Revisited the conduction enclosures

- Original model used 3 conduction enclosures but 1 temperature-dependent conductance table
  - Table used the conductance in the core region
  - Conductance in reflectors was implemented by scaling conduction area factors according to the conductance ratio between reflectors and core at 900 K
- We developed new conductance tables for each enclosure based on the calibrated ETC and applied those to the enclosures



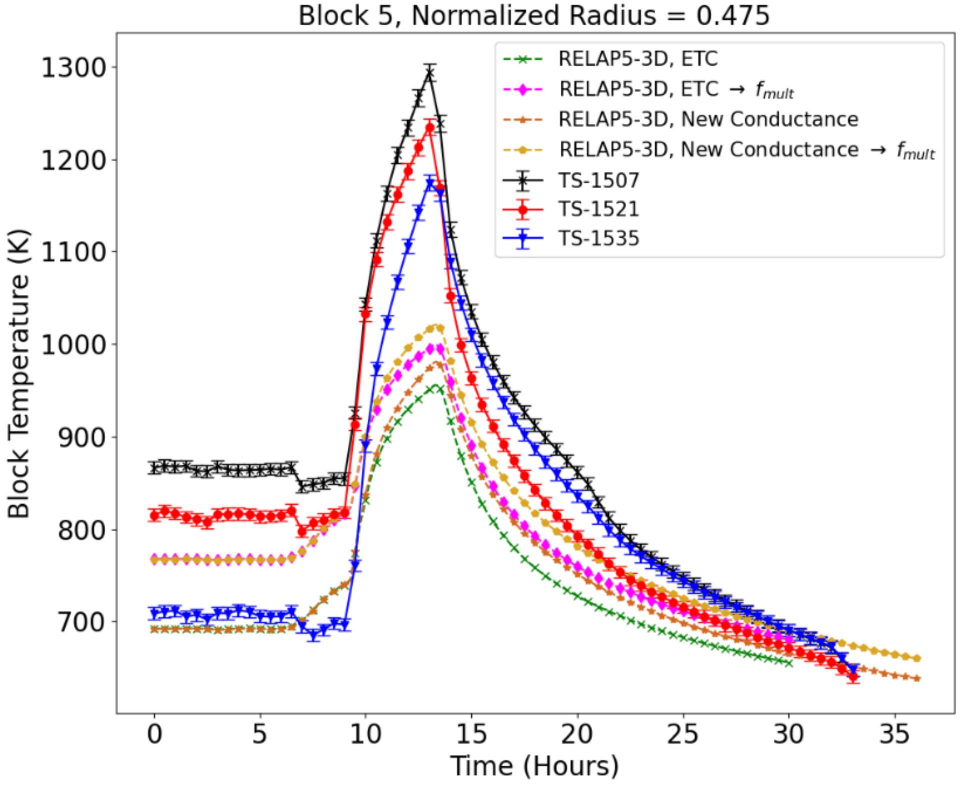
New radial conduction showed comparable steady-state results

- Developed new radial conduction models that removed some of the simplifying assumptions made in the original model
- New conductance was slightly higher in heated rings but lower in reflectors
- Nothing that was well-predicted with the old conductance model is now poorly predicted
- Temperature in the permanent side reflector at blocks 5 and 7 went from over-predicted to well-predicted
- Inner reflector temperatures are still too high
- New conductance models only have small impact on temperatures in steady-state



PG-27 transient with new conduction

- Steady-state temperatures were comparable, and transient temperature rise is better
- Even though it is better, the temperature rise is still far too low
  - 11-38% underprediction
- There is still something being misrepresented by the RELAP5-3D models
- **Is this driven by RELAP5-3D, or by the model itself?**

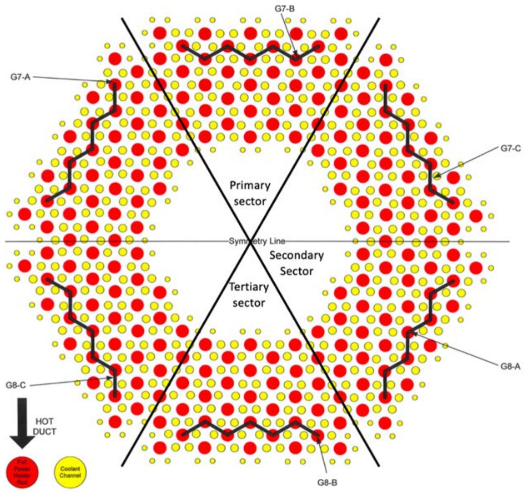


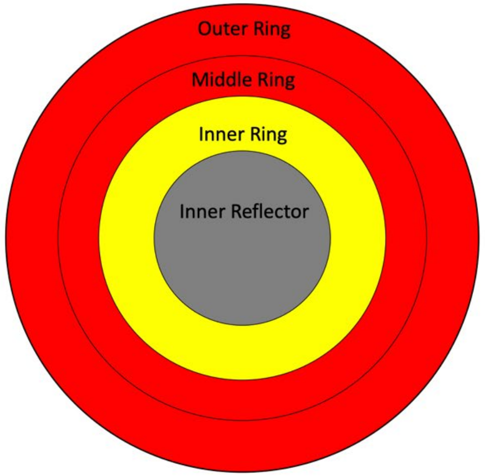
Measured|Standalone ETC|ETC + friction calibration temperature rise

	Inner Ring	Middle Ring	Outer Ring
Block 7	480|336|358	552|349|363	505|345|294
Block 5	487|326|347	504|330|341	453|315|254
Block 3	424|311|331	426|308|317	322|285|222

Power density differences likely drive model problems

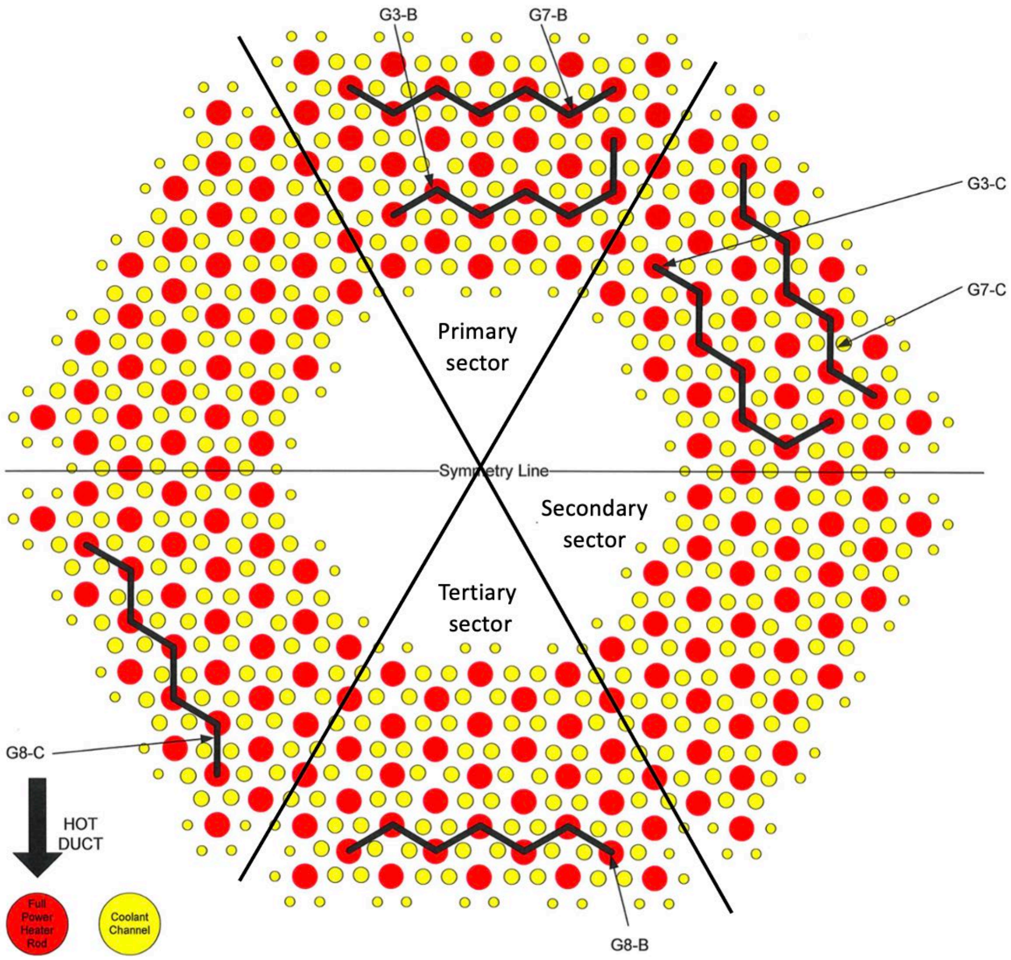
- In experiment, heat is generated in 20% of the heater rods
- In RELAP5-3D model, heat is generated in 73% of the heater rods
  - This is a result of the nodalization of the model
  - Model was developed prior to the experiments, and location of heater rods in experiment unfortunately straddles ring boundaries in the model
- Peak power density is significantly different in RELAP5-3D, which likely leads to the smaller temperature rise
- RELAP5-3D block temperatures are also over a much larger volume than local TCs will be able to detect





Ongoing Work

- Development of a RELAP5-3D model with more rings to better capture the effects of very local heat generating in HTTF
  - Model will have more rings and have unique heat structures for each 1/6 azimuthal sector of the core, which is useful for Problem 2 (PG-29) modeling
- Repeat previous calibration analyses with new model



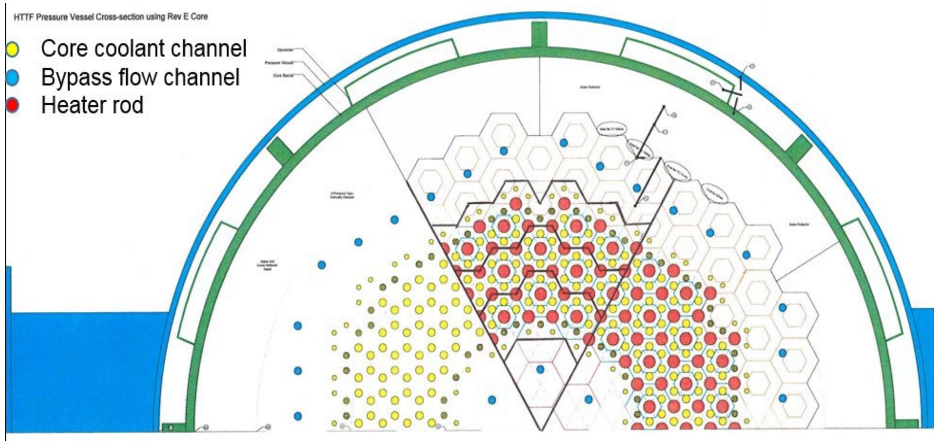
Unit Cell Comparison

Old Model

- Unit cell is centered on a heater rod and uses heater rods as the corner locations

New Model

- Unit cell is centered on a heater rod and uses adjacent coolant channels as the corner locations



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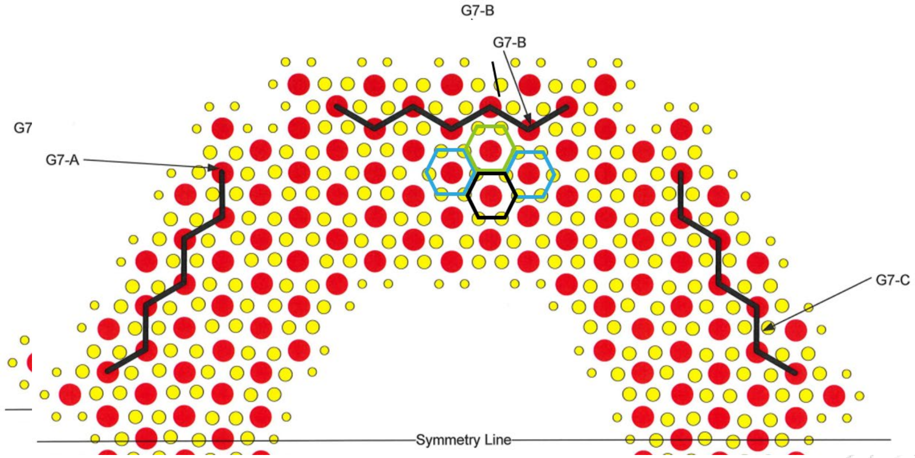
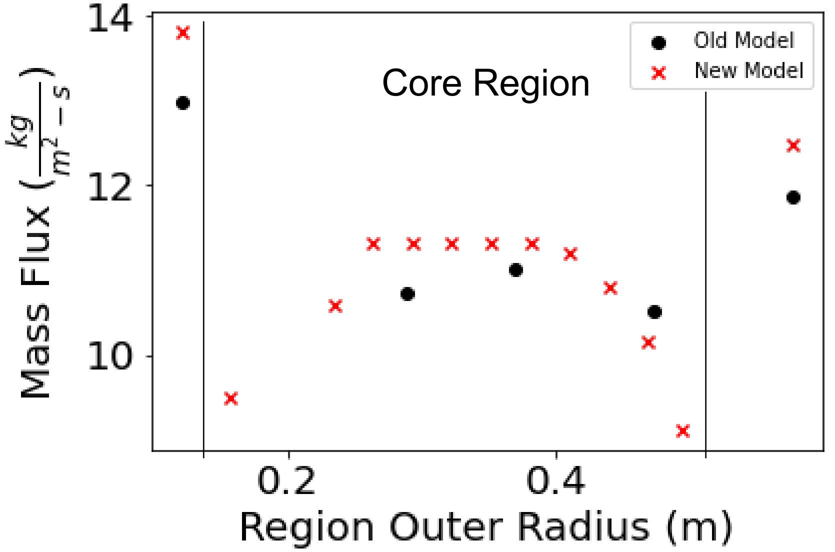


Preliminary hydrodynamic results

- Axial nodalization revised to better map to physical objects in the core
- At the inner and outer radial regions of the active core, smaller coolant channels are used
  - Hydraulic diameters of the inner and outer core channels differ, leading to different pressure drops
- Hydrodynamics for new model show greater detail but comparable results so far
- Working on implementation of heat structures and enclosures



Type and number of coolant channels in the core

	Small	Medium	Large
Diameter (cm)	0.9525	1.2700	1.5875
#	96	96	324

Lessons learned

- The model predicts steady-state temperatures reasonably well
- The model captures trends in the data but cannot reproduce exact values
  - This is consistent with other HTTF analyses in the literature
- Underprediction in transient temperature rise is likely due to the power density distortions
- Model was developed before the experiments were conducted, and if power was distributed uniformly throughout the facility, the model ***may*** have reproduced measured temperatures
- **Lesson:** Models should be built to account for the very local heat generation in HTTF experiments

Conclusions

- HTTF Benchmark is off to a strong start, with interest from around the world
- RELAP5-3D validation activities based on HTTF have shown an ability to reproduce trends in the HTTF data, but reproducing specific HTTF values is a challenge
- This is high-value work with an international impact
- This work will accelerate the deployment of prismatic HTGR microreactors by providing an opportunity for designers to assess their codes against experimental data and solutions from other codes

Acknowledgements

- Thanks to Aaron Epiney at INL for his work overseeing the benchmark and his technical insight on development of the new model
- Thanks to all of the benchmark organizers for their hard work and dedication
- Special thanks to Prof. Nicholas R. Brown at the University of Tennessee, Knoxville for overseeing much of this work which was included in my dissertation
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