

July 27, 2023

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OECD-NEA High Temperature Test Facility Benchmark Progress and Updates

DOE ART Gas-Cooled Reactor (GCR) Review Meeting

Virtual Meeting

July 25 – 27, 2023

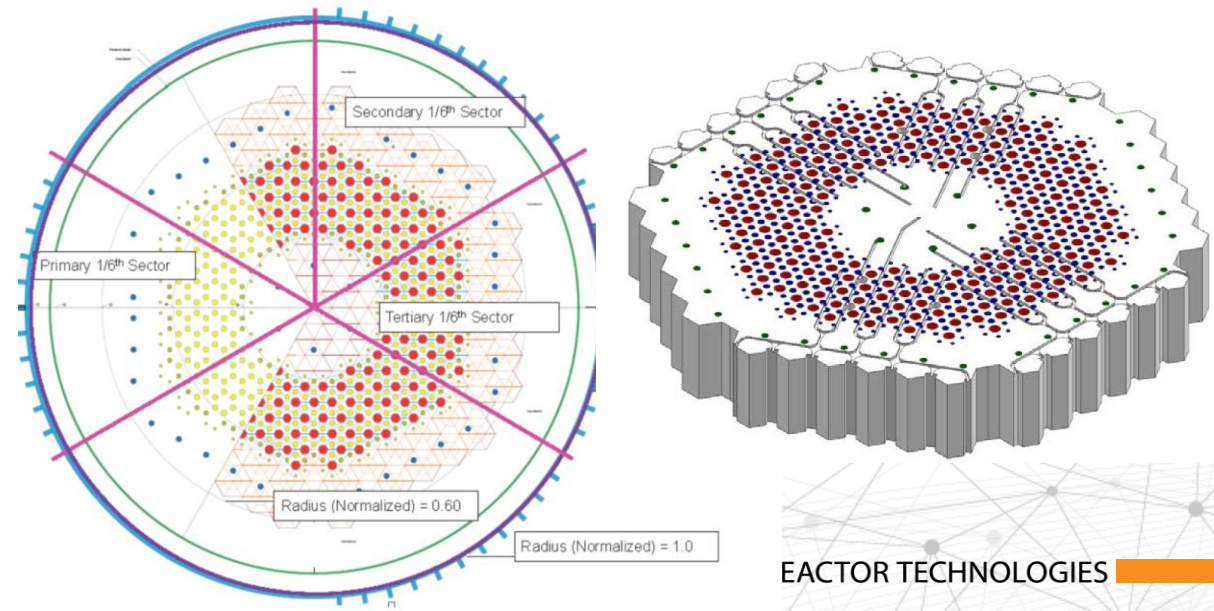
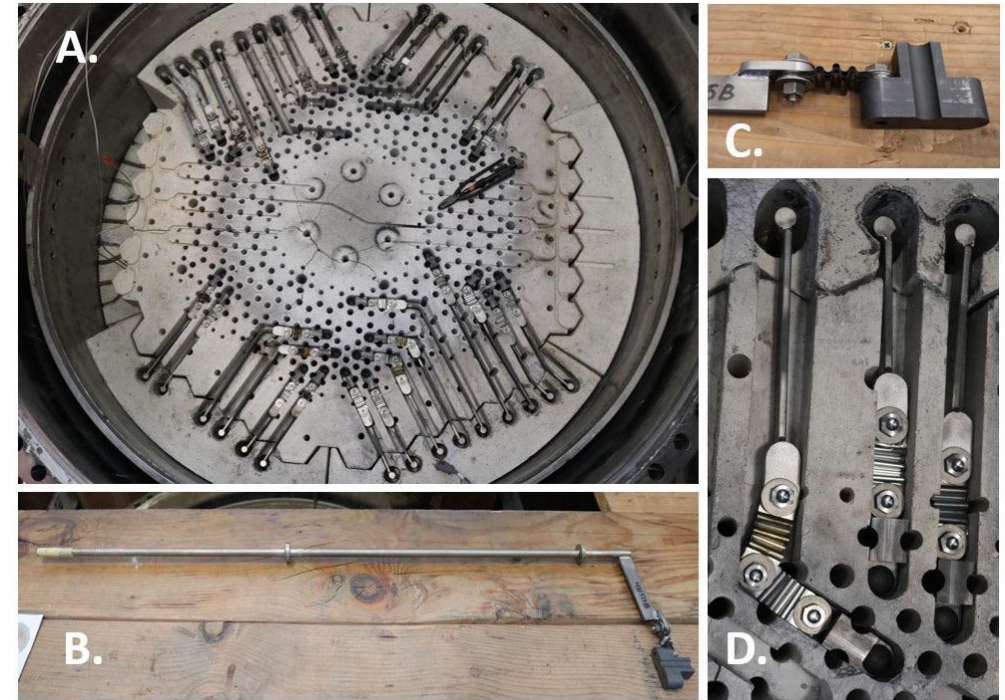


Introduction

- Prismatic HTGRs are a concept approaching deployment as microreactors
 - USNC
 - BWXT
 - Radiant Nuclear
- 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.

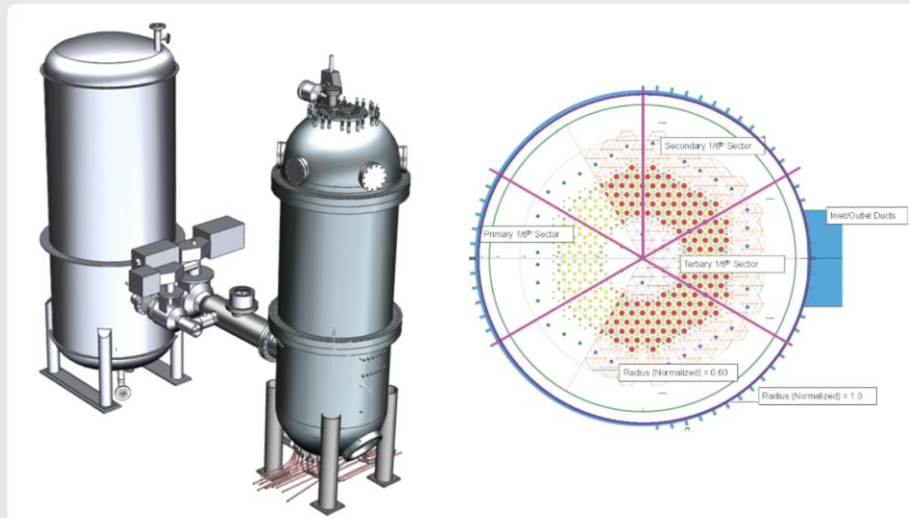
OECD-NEA High Temperature Gas-Cooled Reactor Thermal Hydraulics Code Validation Benchmark

- Benchmark is being spearheaded by ART-GCR
 - Input from INL, ANL, OSU, UTK, 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



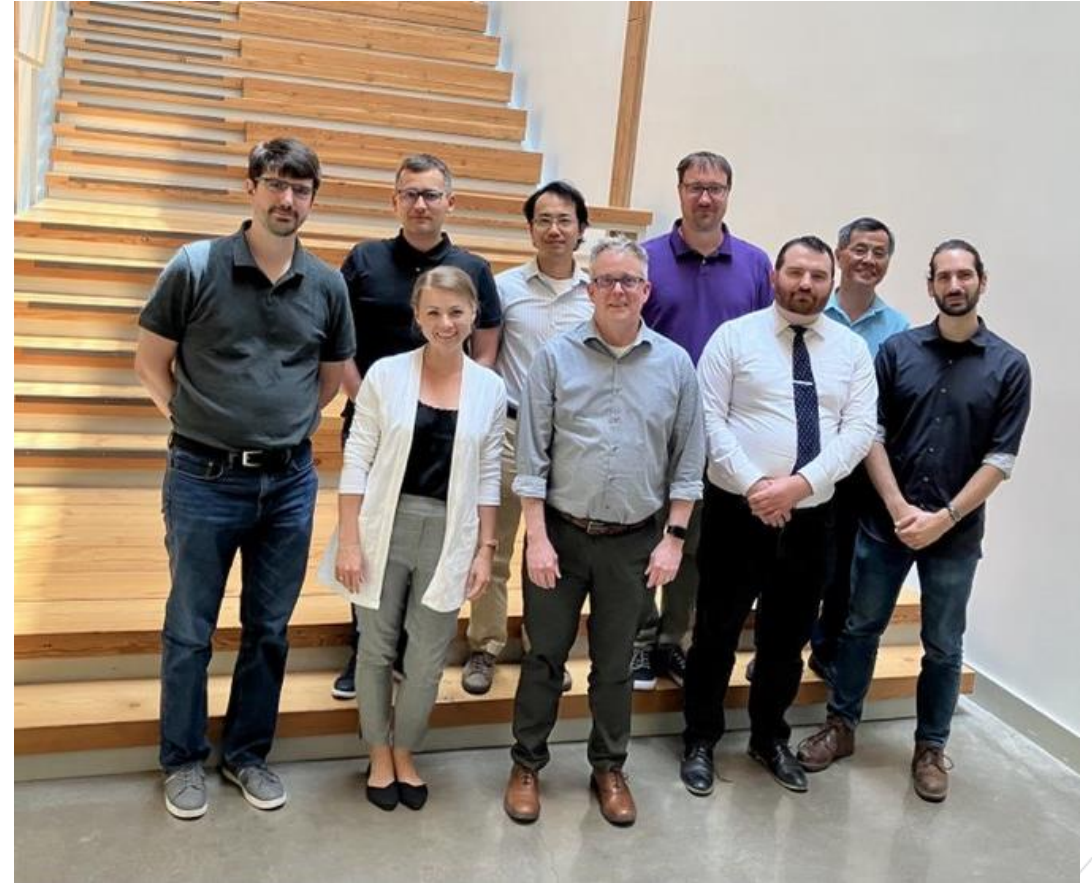
Benchmark Problems and Exercises

- 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)
- This FY has included RELAP5-3D modeling of Problem 2 and Problem 3 Exercises 1 and 2, but 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

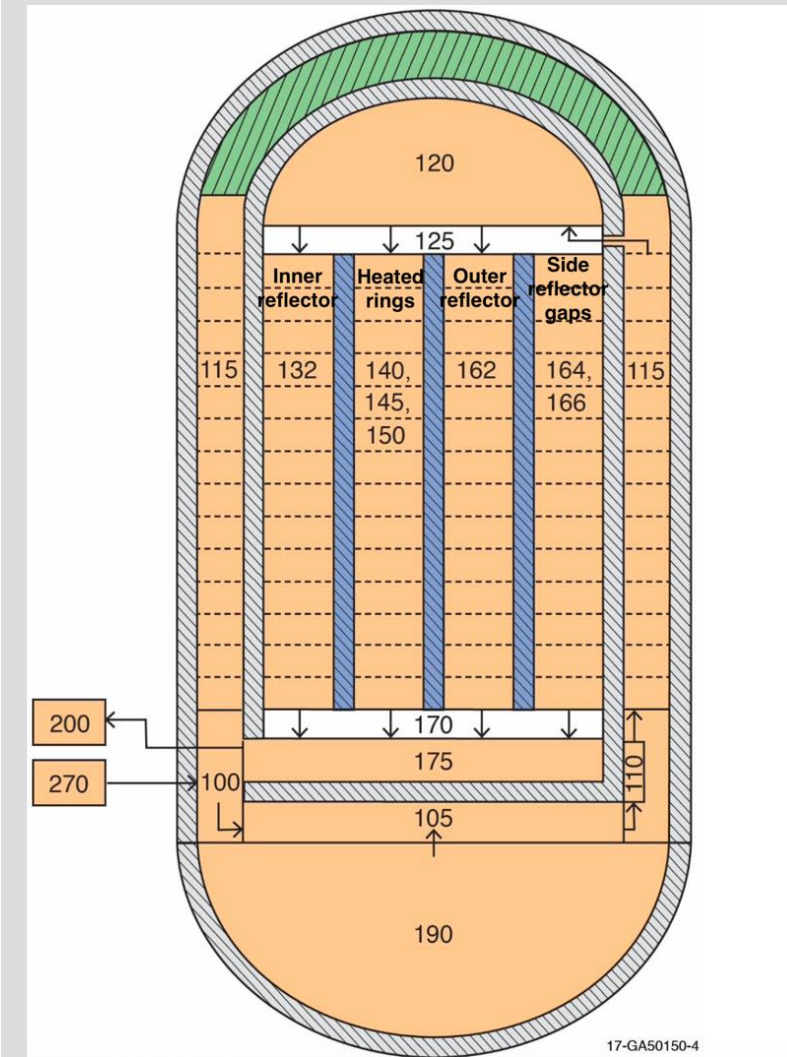
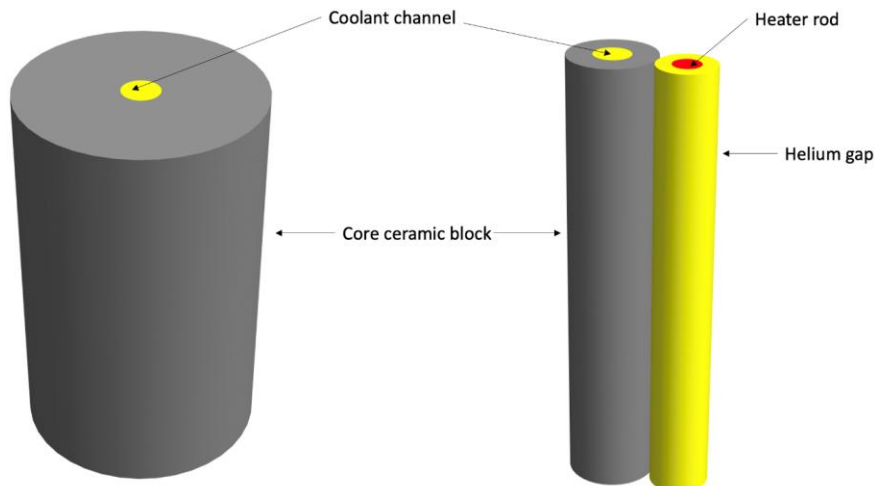
Benchmark kickoff meeting was June 5-6 at Oregon State University

- Hybrid kickoff meeting had 48 participants from 13 countries
- 9 technical talks from 7 institutions representing 5 countries
 - Not including presentations describing the benchmark itself
- Interest from National Labs, Universities, and Industry
- Currently soliciting feedback on benchmark specifications from participants to ensure everyone is on the same page when they start work
- Special thanks to Prof. Iza Gutowska at OSU for hosting the meeting



RELAP5-3D Model of HTTF

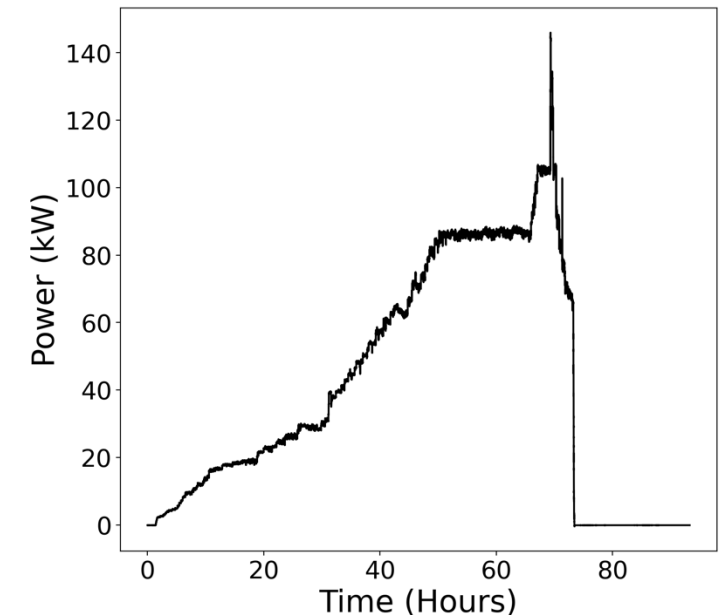
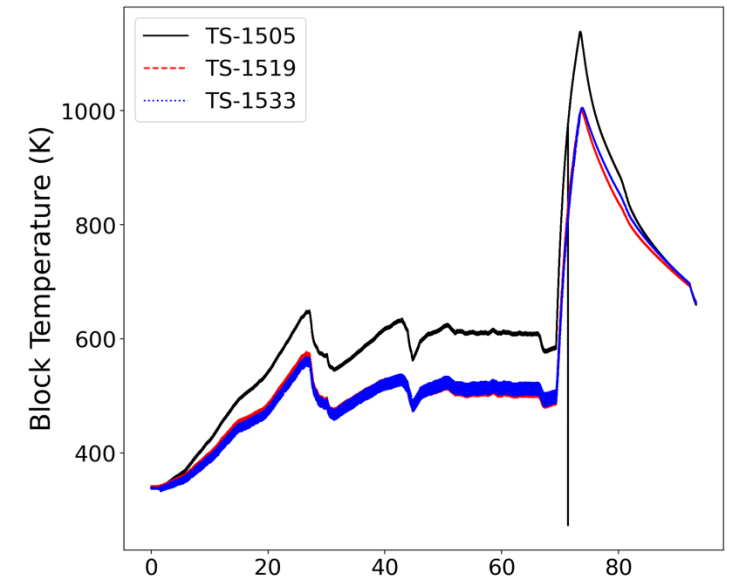
- Descends from the INL model published in 2018
- Core is modeled as a set of nested heat structures
 - 3 represent inner reflector
 - 3 represent area containing heater rods
 - 3 represent outer reflector
 - Permanent side reflector is modeled as a single piece
- Core divided into 14 axial levels
 - 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.

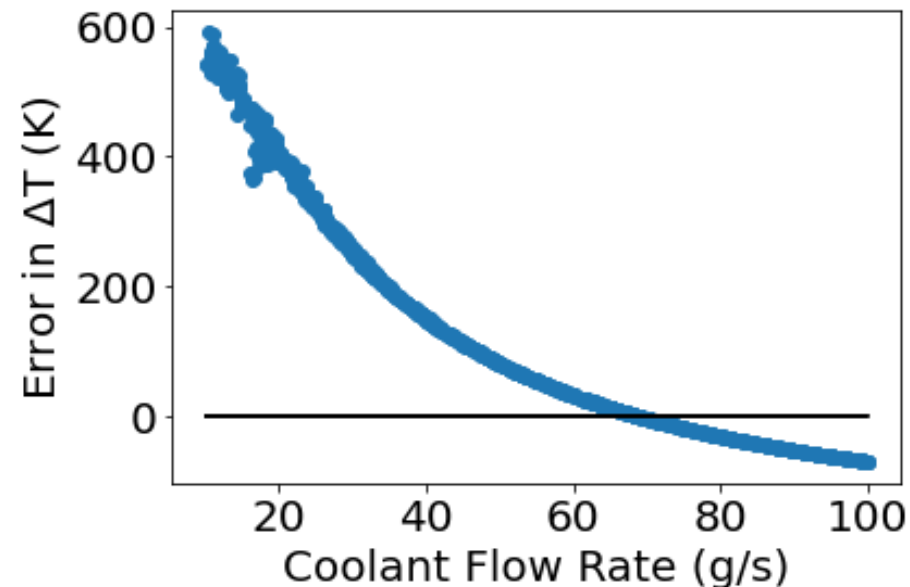
Validation studies with RELAP5-3D start with PG-27

- 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



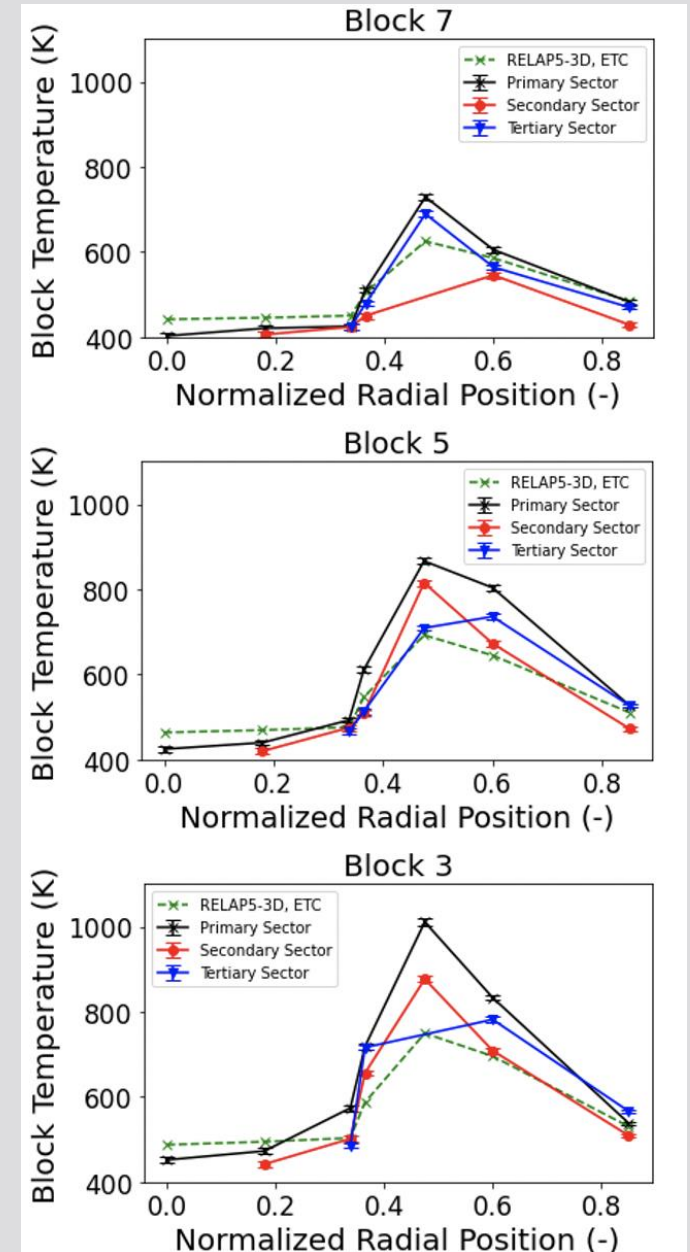
Helium flow rate provides the first-order effect on temperatures

- 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



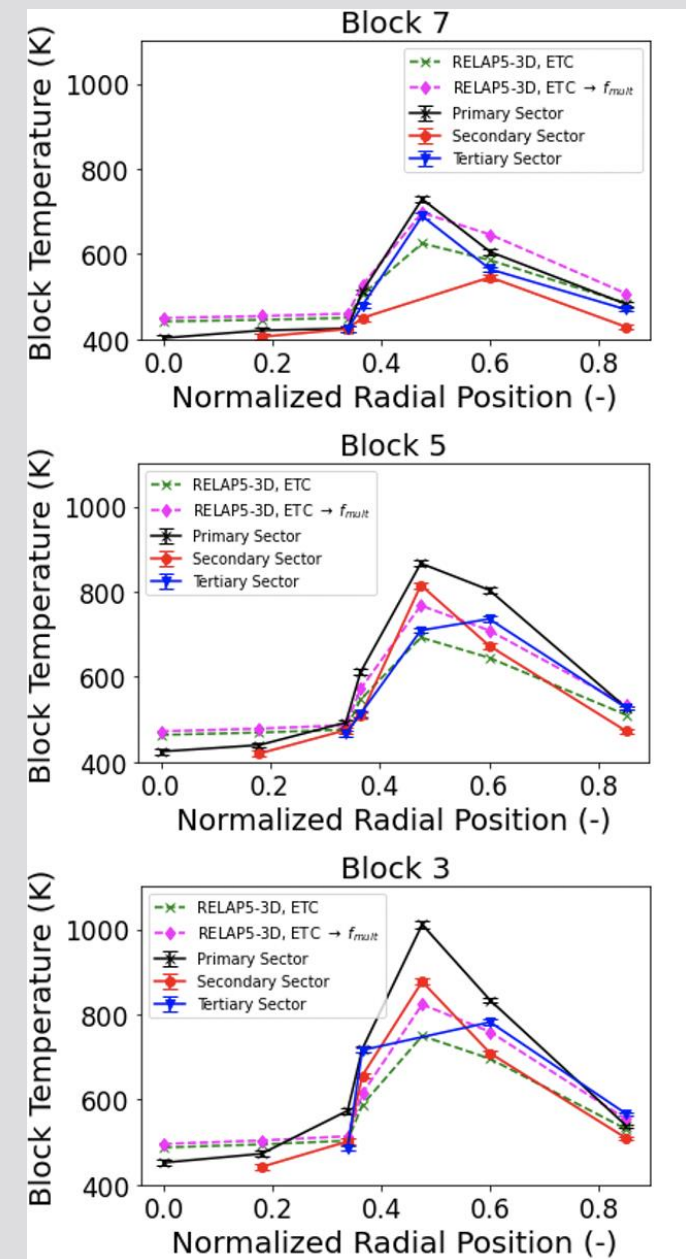
Calibrated block thermal conductivities

- 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

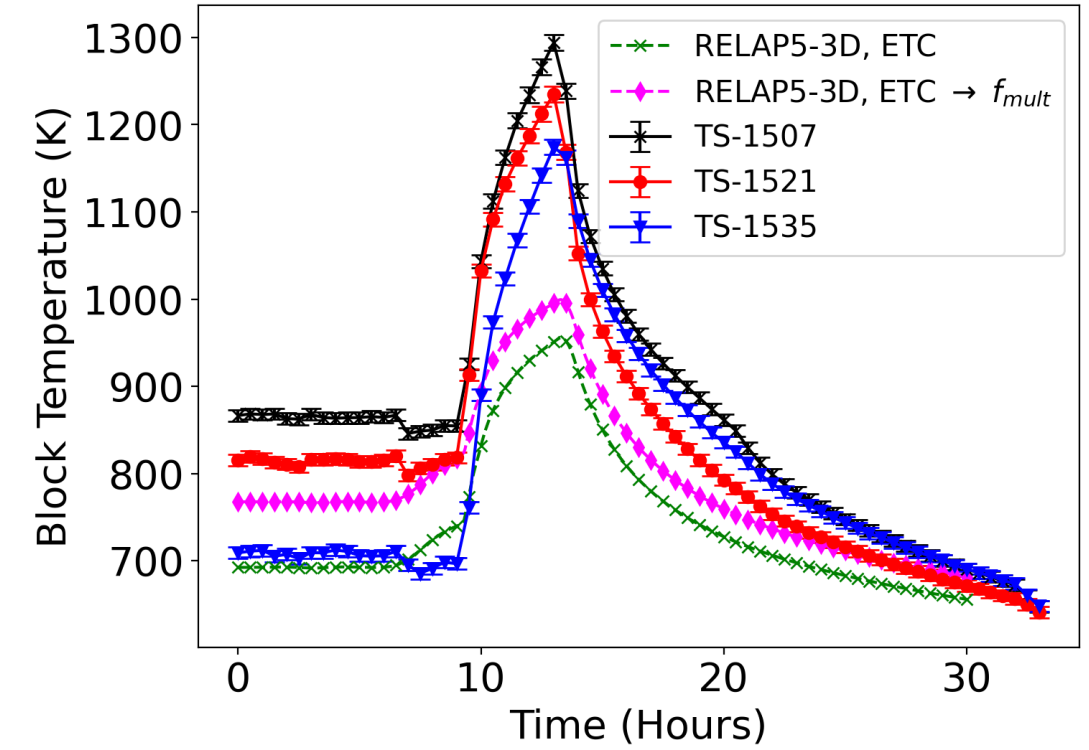
- Inner reflector temperatures are worse, not better
- Inner ring is not improved
- Middle ring no longer well-predicted at block 7. Now well-predicted only at block 5
- Outer ring temperatures were always better with the increased friction, but block 3 still too low
- Outer reflector now worse at block 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



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

Block 5, Normalized Radius = 0.475

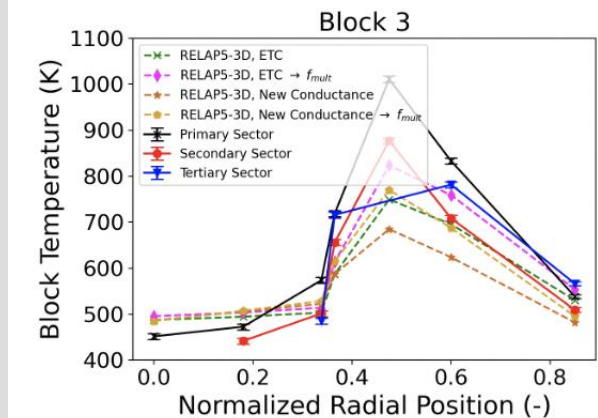
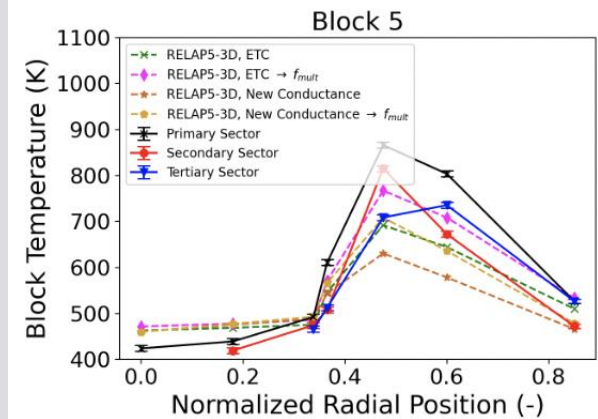
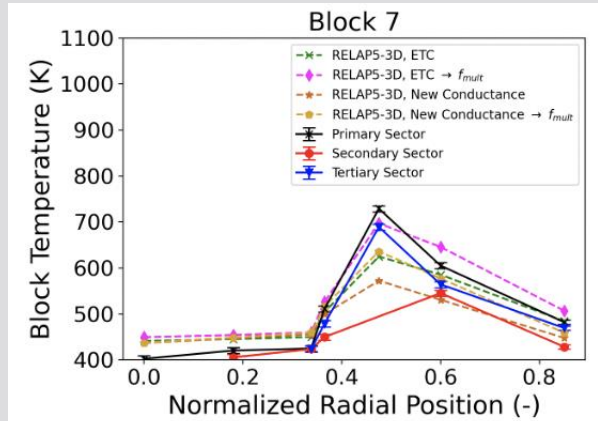


Measured | Standalone ETC | ETC + friction calibration temperature rise

	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

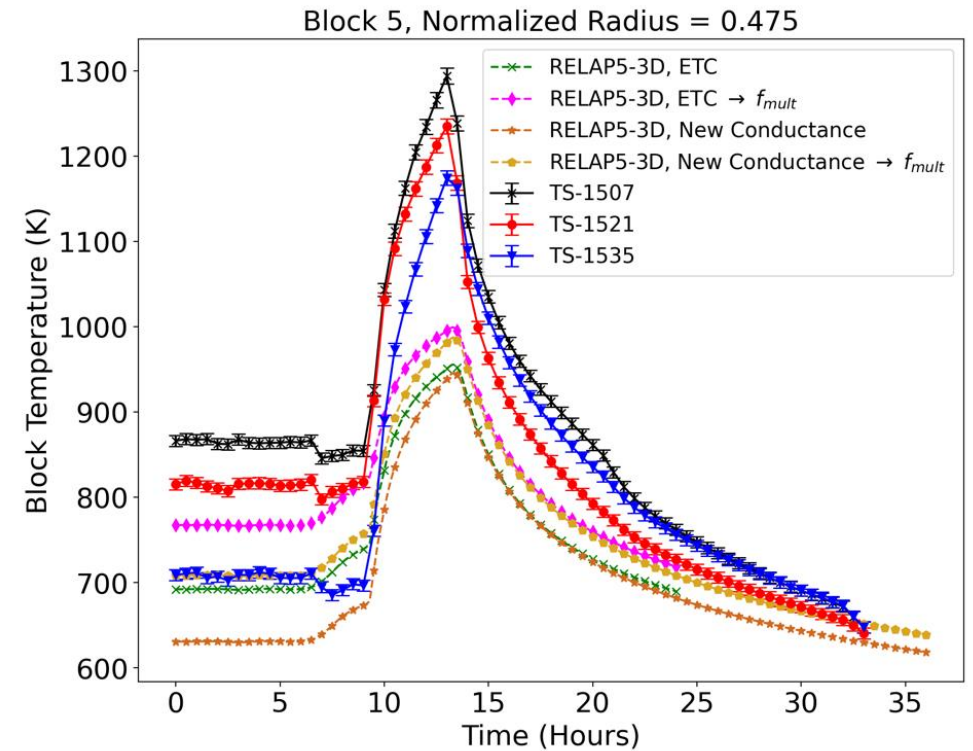
Revisited radial conduction in the model

- 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
- Block 7 middle ring now well-predicted in ETC + friction calibration
 - This was the only instance in which a temperature that was previously too high is now well-predicted
- Block 5 is the only outer ring location well-predicted with the new conduction model, and then only with the ETC + friction calibration
- Higher conductance in heated portion of the core leads to lower temperature gradients there



PG-27 transient with new conduction

- Steady-state temperatures may be worse, but 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?**
- Why do temperatures measured by the different TCs differ by 100+ K?

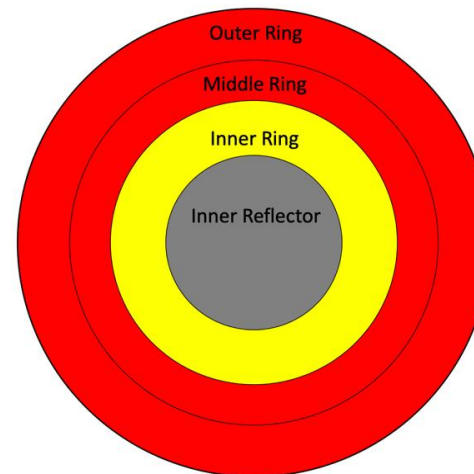
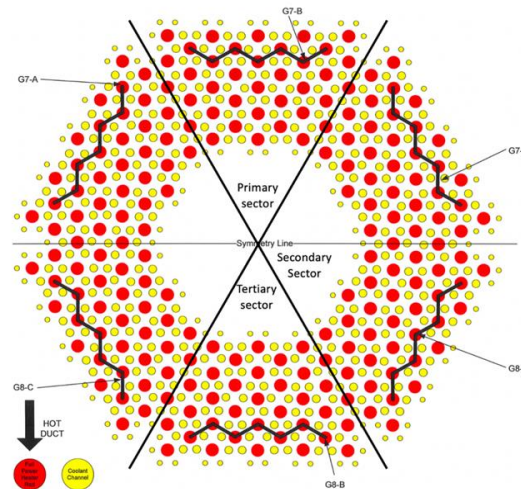


Measured | Standalone ETC | ETC + friction calibration temperature rise

	Inner Ring	Middle Ring	Outer Ring
Block 7	480 308 333	552 327 344	505 345 320
Block 5	487 292 318	504 306 319	453 315 279
Block 3	424 272 298	426 282 293	322 285 244

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



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
- **Lesson:** Big rings may not be capturing local TC readings because local temperature may differ from the average temperature in a ring
- There are still some open questions such as why TCs in different sectors sometimes provide significantly different readings



Future Work

- Benchmark specifications will be finalized and published this fall
- Overseeing the execution of the early parts of the benchmark
- Perform Exercise 3 calculations for Problems 2 and 3
- 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 modeling
- Repeat previous calibration analyses with new model

Publications

- One journal article published, one conference summary published, and one journal article submitted for publication
 - Kile, R. F., Epiney, A. S., Brown, N. R., “High Temperature Test Facility sensitivity and calibration studies to inform OECD-NEA benchmark calculations,” *Nuclear Engineering and Design*, vol. 404 (2023), <https://doi.org/10.1016/j.nucengdes.2023.112178>
 - Kile, R. F., Epiney, A. S., Brown, N. R., “RELAP5-3D Solutions to Exercise 1 of the OECD-NEA HTTF Benchmark,” *Transactions of the American Nuclear Society*, vol. 128 (2023).
 - Kile, R. F., Epiney, A. S., Brown, N. R., “RELAP5-3D Validation Studies Based on the High Temperature Test Facility,” *Nuclear Engineering and Design*, Submitted for Publication (2023).
- Additional presentations at the OECD-NEA WPRS Benchmark workshop and the Benchmark Kickoff Meeting



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 work has produced 1 peer-reviewed journal article and 1 conference summary, and 5 additional presentations
- An additional peer-reviewed journal article has been submitted
- 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

- We extend thanks to all of the benchmark organizers for their hard work and dedication
- This research made use of the resources of the High Performance Computing Center at INL, which is supported by the Office of Nuclear Energy of the U.S. Department of Energy and the Nuclear Science User Facilities under Contract No. DE-AC07-05ID14517