INL/MIS-24-80242-Revision-0

RELAP5-3D HTGR Validation Work at Idaho National Laboratory

September 2024

Changing the World's Energy Future

Robert F. Kile

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

INL/MIS-24-80242-Revision-0

RELAP5-3D HTGR Validation Work at Idaho National Laboratory

Robert F. Kile

September 2024

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

September 4, 2024

Robert F. Kile
Advanced Reactor Research and Development Engineer

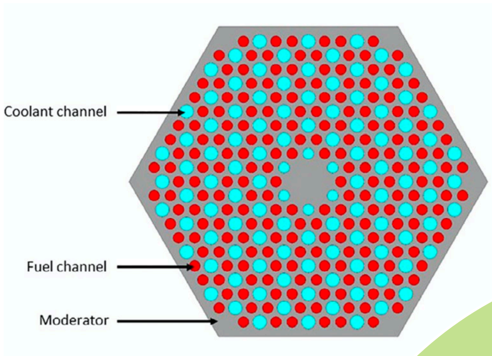
RELAP5-3D HTGR Validation Work at Idaho National Laboratory

Idaho National Laboratory

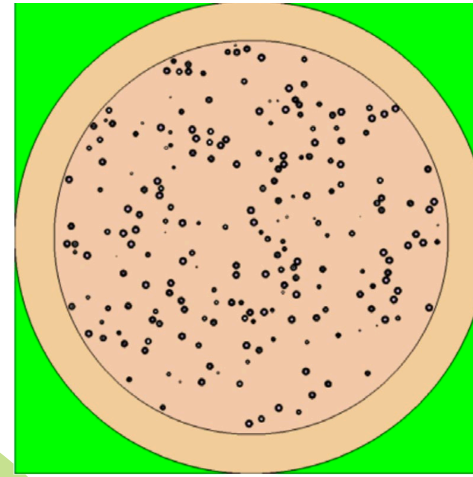
Who am I?

- Bachelor of Science in Nuclear Engineering from Purdue University, 2018
- Master of Science in Nuclear Engineering from University of Tennessee 2020
- PhD in Nuclear Engineering from University of Tennessee in 2023
- Interests in the following areas:
  - Neutronics and thermal hydraulics modeling of non-LWRs
  - Code validation
  - Pebble bed equilibrium modelling

Overview of High-Temperature Gas-Cooled Reactors



- TRISO fuel
- Graphite moderator
- Helium coolant
- High pressure (5-7 MPa)
- Downward coolant flow
- Low power density



Prismatic Block Reactor

- Basic fuel element is a hexagonal block
- Blocks stacked on top of each other
- Shuts down for refueling outages

Pebble Bed Reactor

- Basic fuel element is a graphite pebble
- Pebbles packed into a bed
- Online refueling

[1]Lu, C. et al., "Fully ceramic microencapsulated fuel in prismatic high-temperature gas-cooled reactors: Analysis of reactor performance and safety characteristics," *Annals of Nuclear Energy*, vol. 114 (2018), pp 277-287

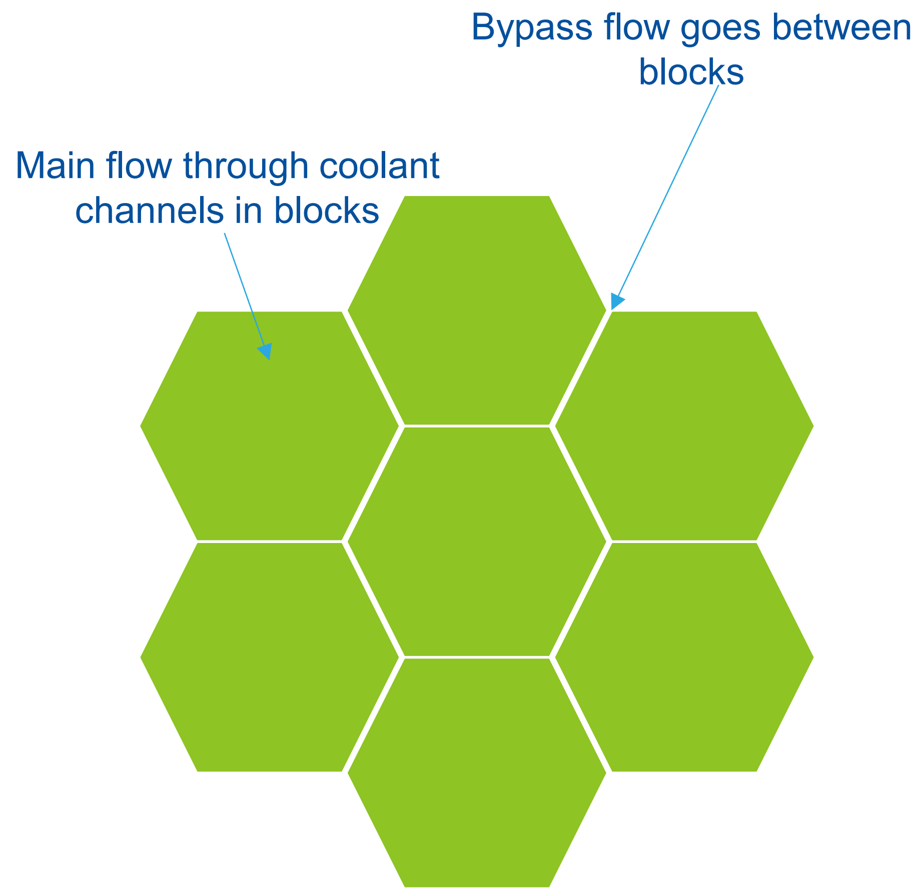
[2]Bostelmann, F. et al., "SCALE capabilities for high-temperature gas-cooled reactor analysis," *Annals of Nuclear Energy*, vol 147 (2020) https://doi.org/10.1016/j.anucene.2020.107673

Prismatic-block HTGRs have historical application and ongoing interest

Reactor	Type	Power (MW_t)	Years of Operation	Location
Ultra High-Temperature Reactor Experiment	Research	3	1959-1971	Los Alamos NM, USA
Peach Bottom 1	Commercial	115	1967-1974	Delta PA, USA
Fort St. Vrain	Commercial	842	1979-1989	Platteville, CO, USA
High Temperature Engineering Test Reactor (HTTR)	Research	30	1998-Present	Ōarai, Ibaraki, Japan
Micro-Modular Reactor (MMR) (USNC)	Concept	15-30	Late 2020s	N/A
BWXT Advanced Nuclear Reactor (BANR)	Concept	50	Late 2020s	N/A

Challenges with modeling block-type HTGRs

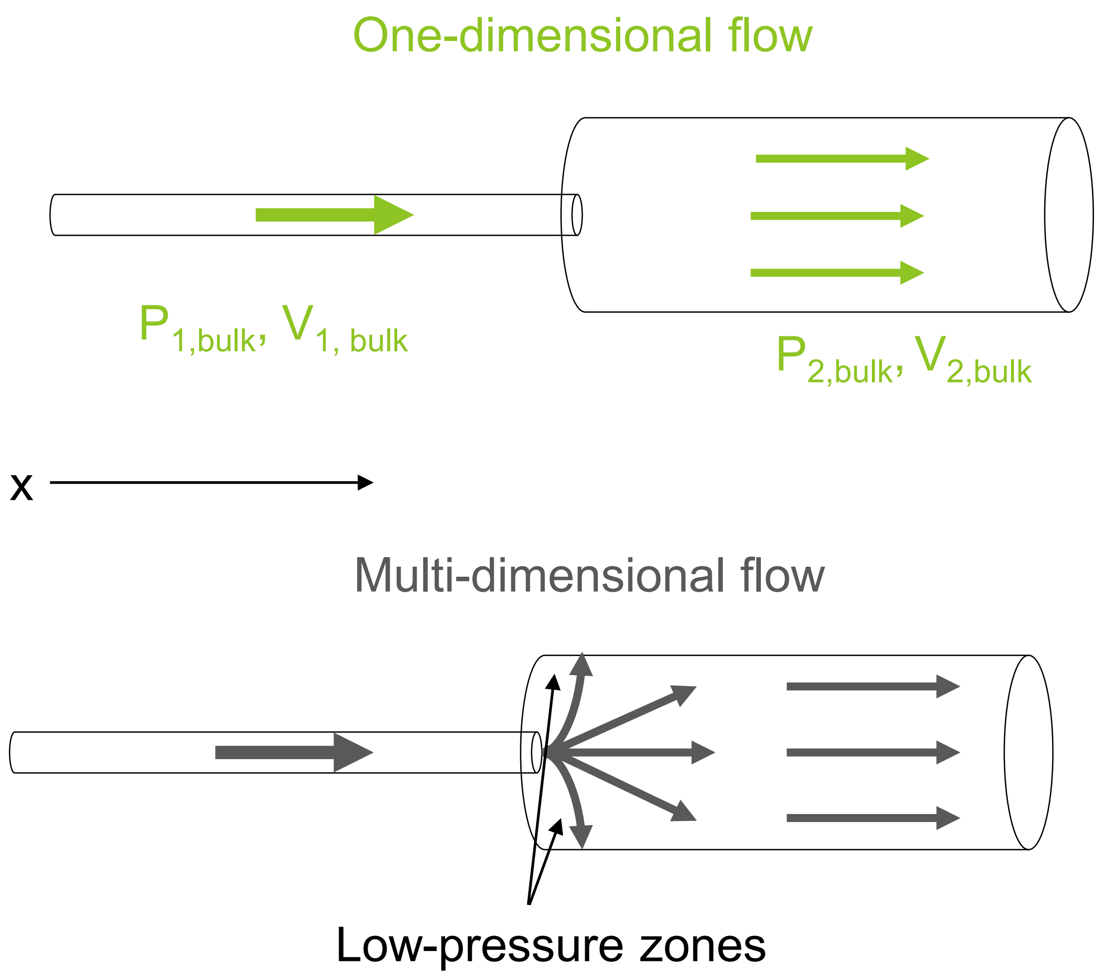
- Bypass flow and cross flow lead to significant uncertainty in flow distributions
  - Bypass flow is typically on the order of 12-18%
  - Gaps arise due to manufacturing tolerances and graphite dimensional changes
- High temperatures and local temperature variations make measuring local temperatures and pressures challenging
- None of these challenges are necessarily insurmountable or mean we shouldn’t build these reactors



RELAP5-3D

- Systems thermal hydraulics code developed at INL capable of modeling plant response to transients in reactors
  - One-dimensional fluid flow
  - Models for conduction, convection, and radiation heat transfer
  - Models for reactor point kinetics
  - Lower fidelity than CFD, but capable of modeling much more of the system and requires far less computing power
- Code has extensive history being applied to prismatic block gas-cooled reactor problems
- Limited validation basis for HTGR modeling applications
  - This work expands the validation basis for HTGR modeling with RELAP5-3D
  - Much of the validation has been from separate effects facilities

One-dimensional vs multi-dimensional flow



Code validation is essential for deploying new reactors

- Most thermal hydraulics modeling and simulation tools used today were developed for LWRs
- Application for HTGRs is outside the validation basis for most modeling tools
- Validating codes for prismatic HTGRs requires experimental data relevant to these systems
  - Thermal hydraulics validation for pebble beds is different from validation for prismatic block reactors

Separate vs. Integral Effects Testing

Separate Effects

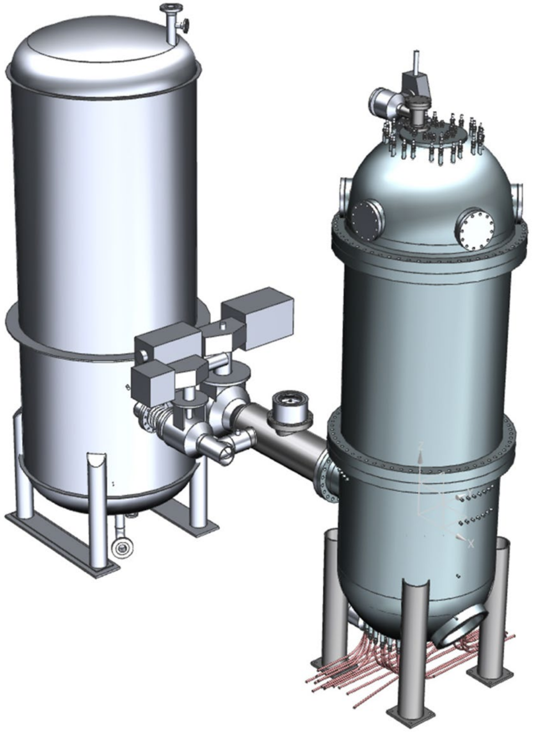
- Aims to predict a single phenomenon or small number of phenomena
  - Heat transfer coefficient, frictional pressure drop, bypass flow, etc.
- Can be used to develop or validate correlations for specific physical phenomena

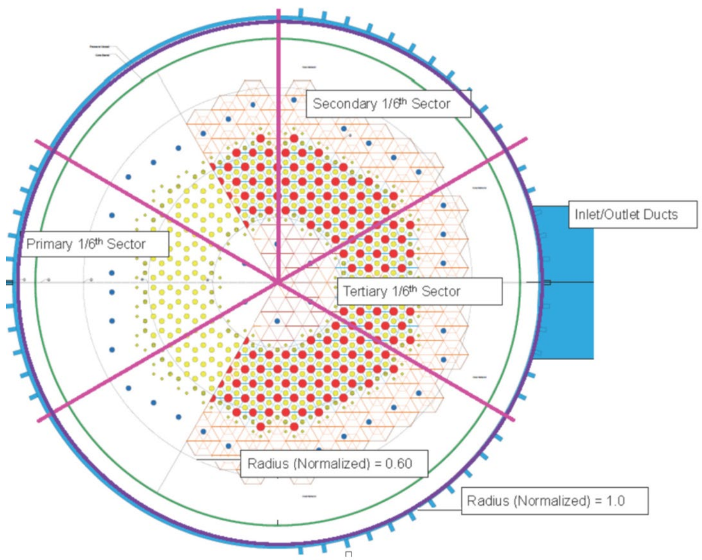
Integral Effects

- Aims to understand response of an entire reactor or plant system, including all relevant effects
- Accounts for interactions between effects
- Can be used to validate modeling and simulation tools for novel reactor systems

High Temperature Test Facility

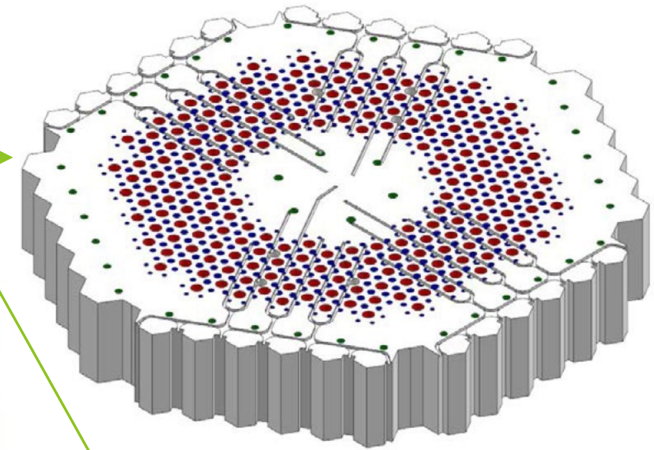
- The High-Temperature Test Facility (HTTF) is a 1/4 length scale representation of a prismatic block reactor called mHTGR-350 built at Oregon State University (OSU)
- Electrically heated up to 2.2 MW
- Intended for verification and validation of gas-cooled reactor thermal hydraulics modeling
- Facility includes > 500 instruments
- Core blocks are made of an Al_2O_3-based ceramic

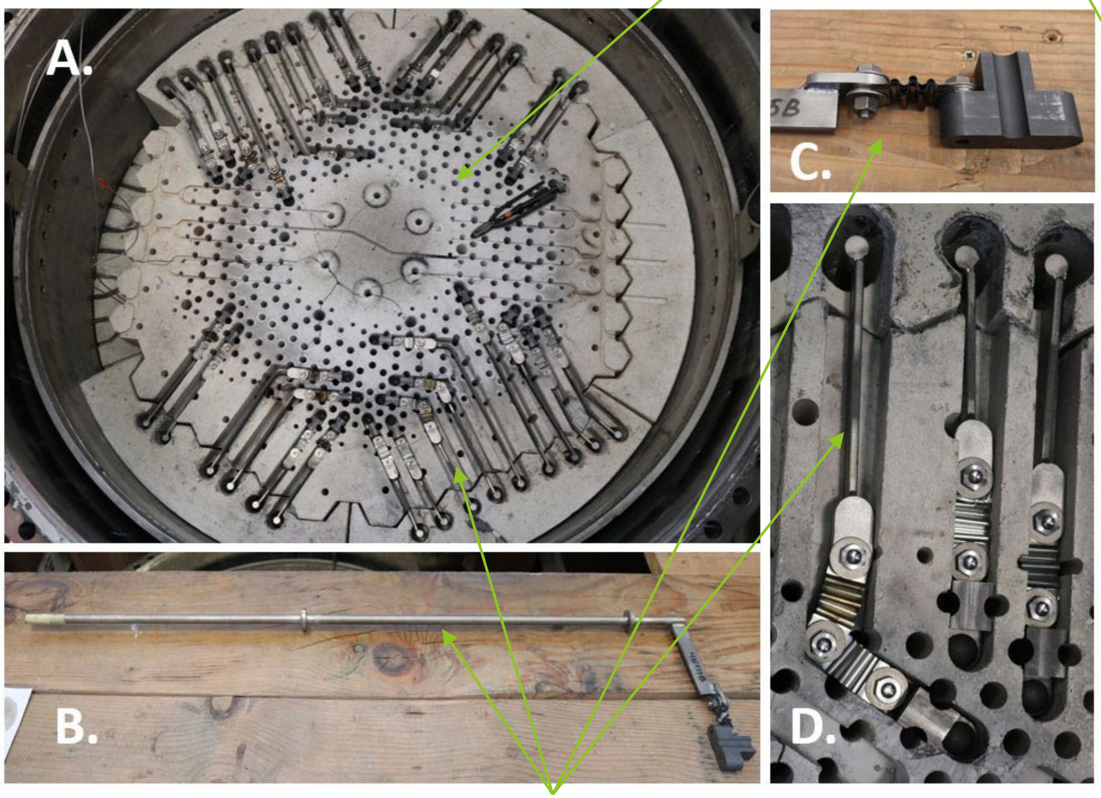


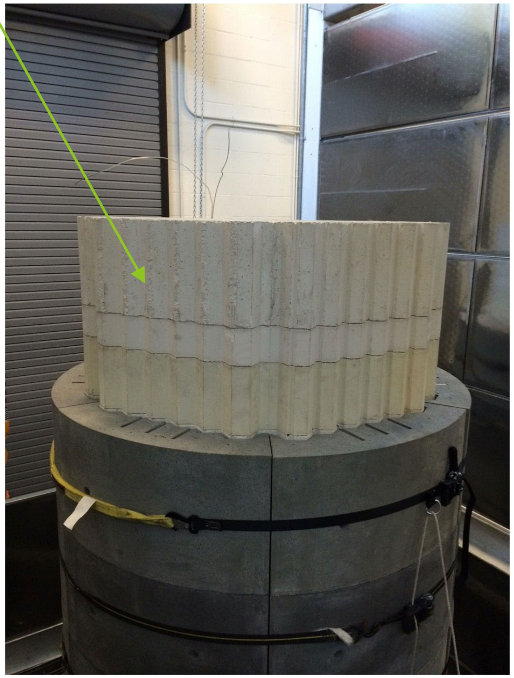


HTTF Background

Core blocks





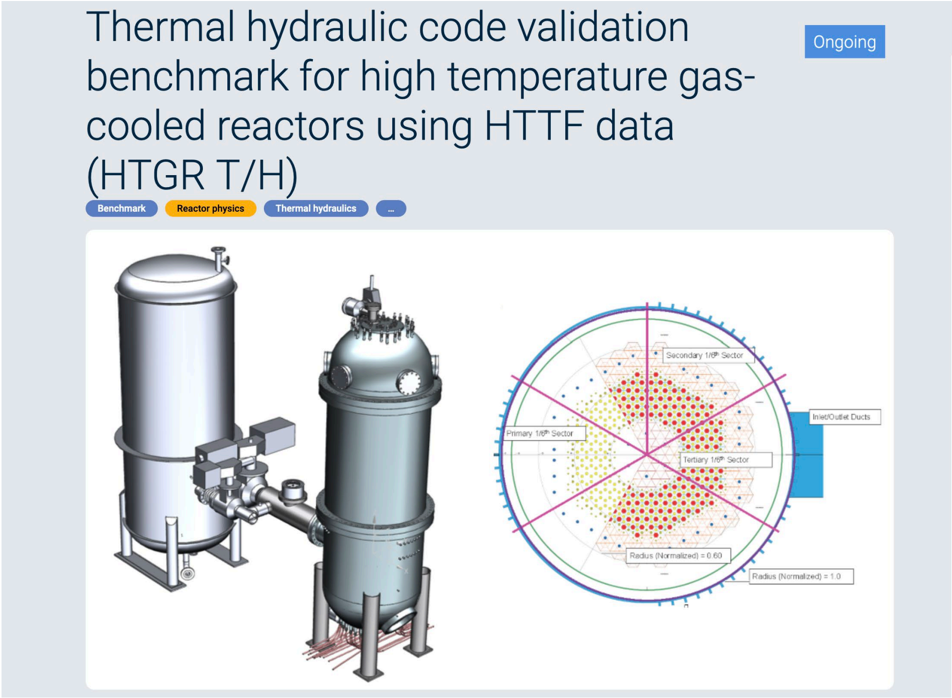


Heater rod connections

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

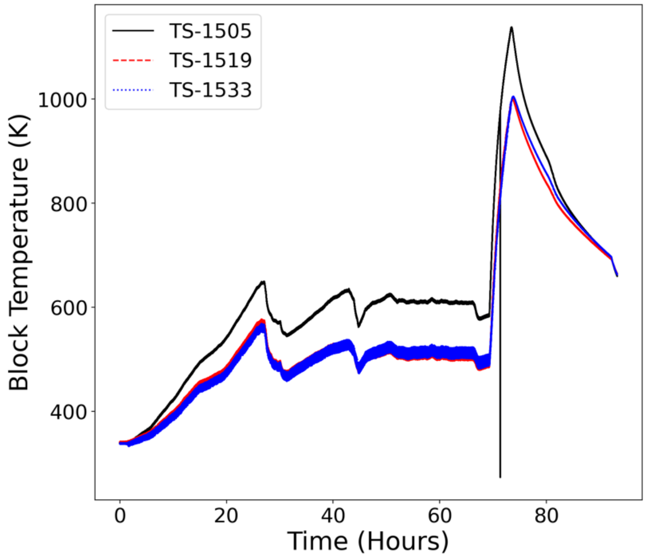
OECD-NEA High Temperature Gas-Cooled Reactor Thermal Hydraulics Code Validation Benchmark

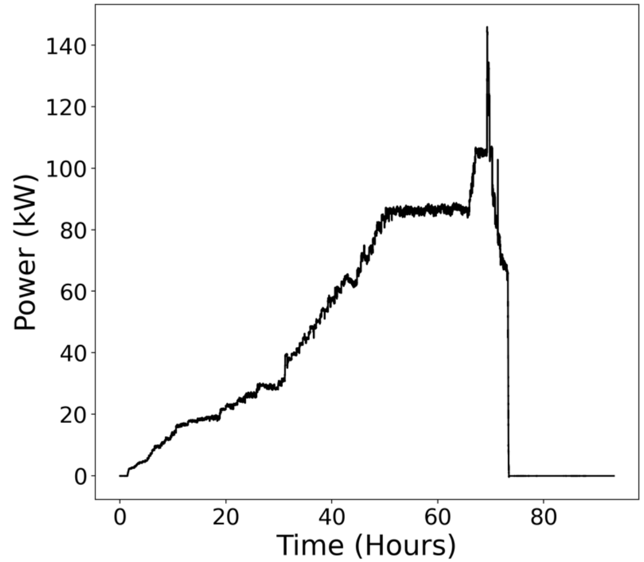
- Benchmark is being spearheaded by ART-GCR
  - Input from INL, ANL, OSU, UTK, CNL and NRG
- Benchmark includes problems for lower plenum mixing, depressurized conduction cooldown (DCC), and pressurized conduction cooldown (PCC)
- Benchmark problems include exercises for code-to-code comparison, best-estimate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



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

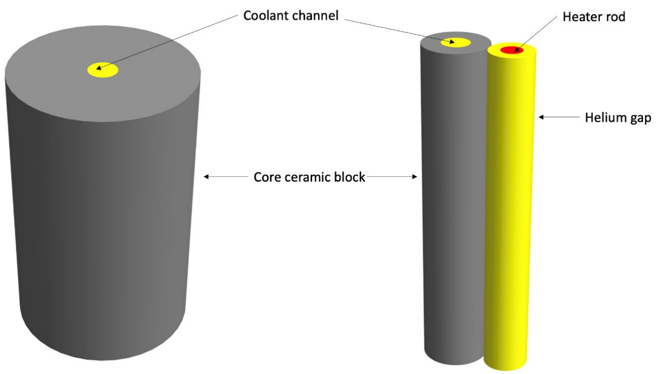
- PG-27 is an experiment representing the pressurized conduction cooldown (PCC)
- Extended steady state from 50-65 hours provides an opportunity to do a steady-state calibrate then test the calibration against transient behavior
- PCC initiated at a time of 69 hours
- Heaters shut off at 73 hours
- Primary 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
- This is Problem 3 Exercise 2 of our benchmark

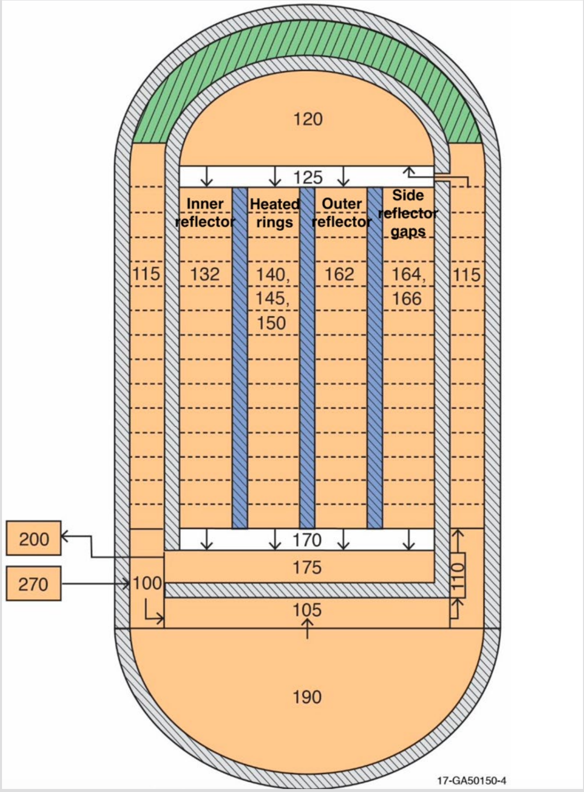




Legacy RELAP5-3D Model of HTTF

- 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



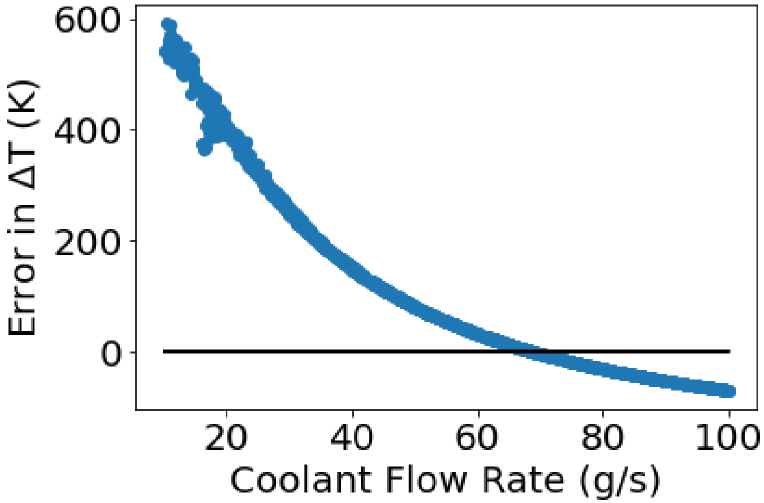


RELAP5-3D model description can be found in: Bayless, P., "RELAP5-3D Input Model for the High Temperature Test Facility," Idaho National Laboratory, Idaho Falls, ID, INL/EXT-18-45579, 2018.

Validation Studies with the Legacy Model

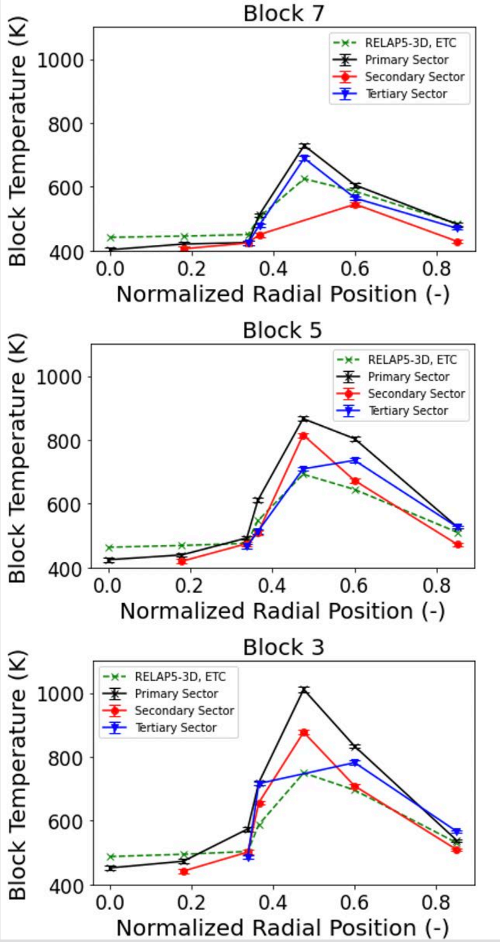
Helium flow rate provides the first-order effect on temperatures

- Calibrated helium flow rate based on the difference between measured and RELAP5-3D temperature rise from inlet to outlet 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



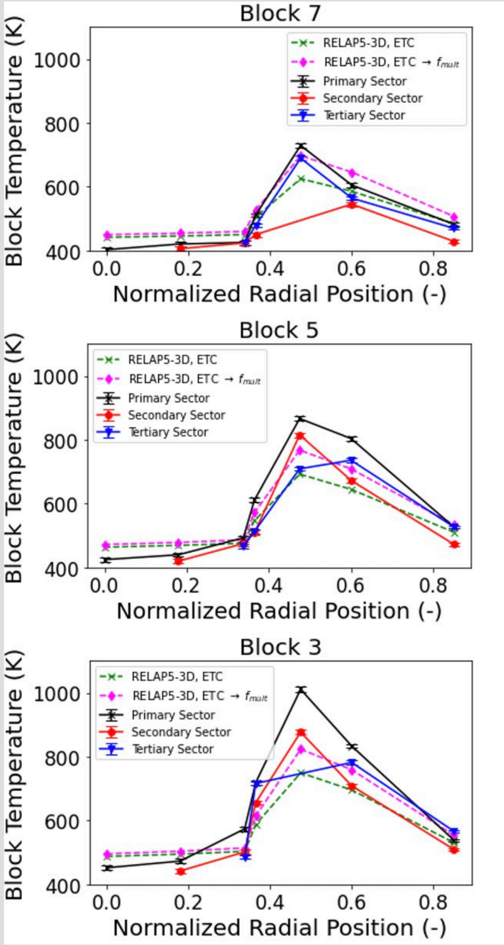
Calibrated block thermal conductivities

- 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



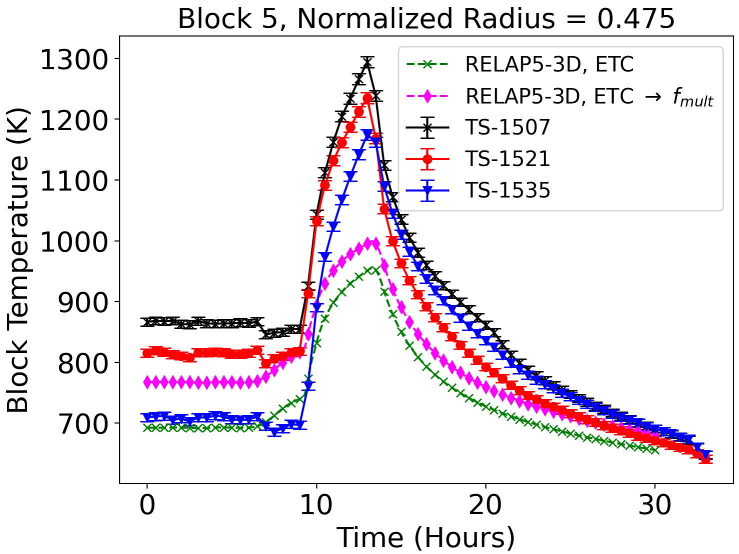
Increased friction to improve outer ring temperatures

- 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

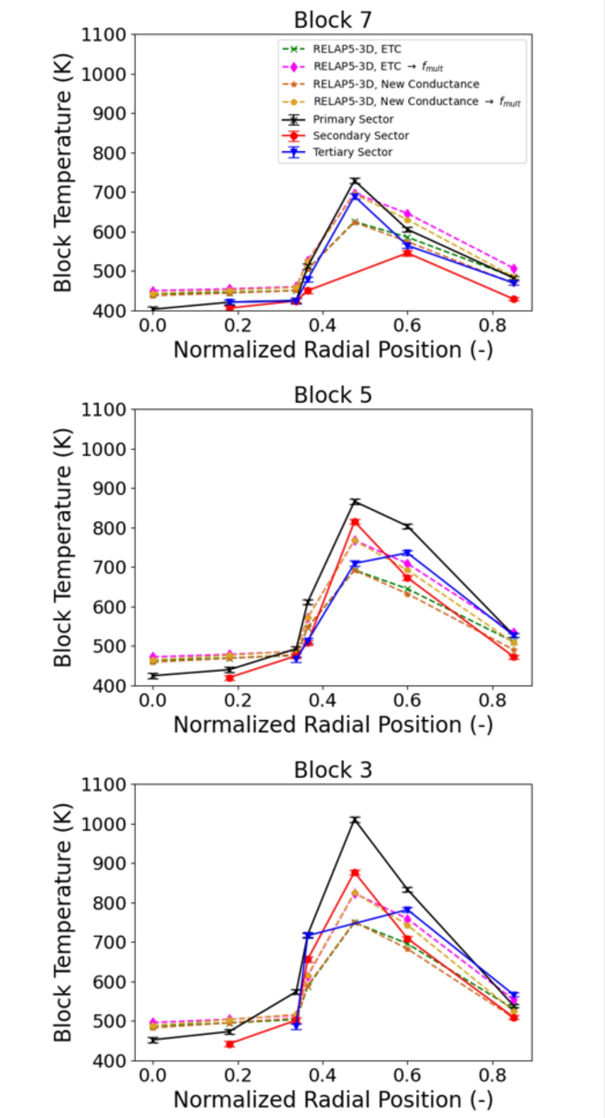


Measured|Standalone ETC|ETC + friction calibration temperature rise

	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

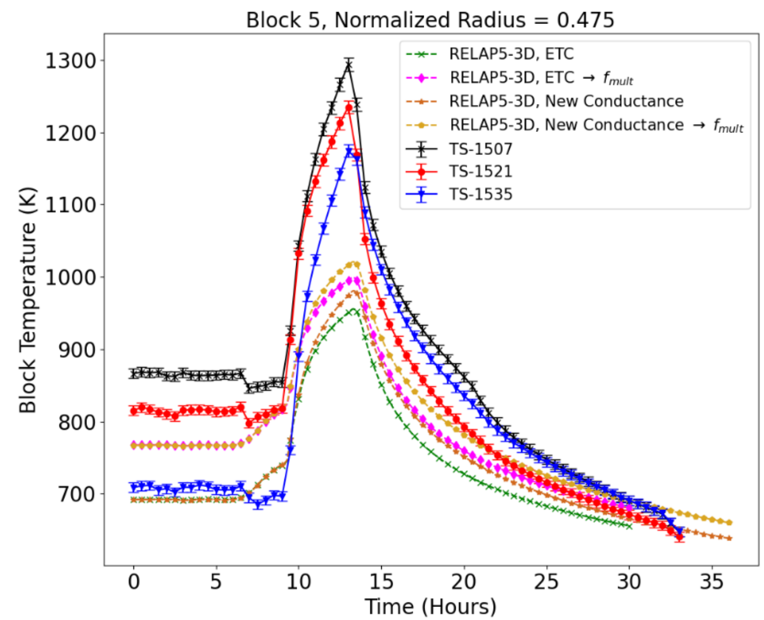
Revisited radial conduction in the model

- 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
- 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?**
- Why do temperatures measured by the different TCs differ by 100+ K?

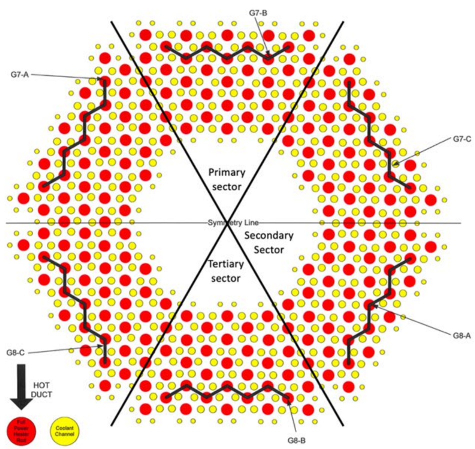


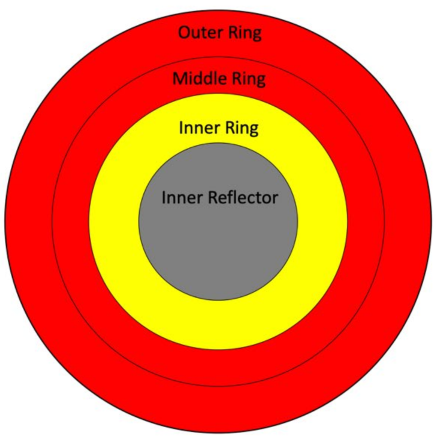
Measured|Standalone ETC|ETC + friction calibration temperature rise

	Inner Ring	Middle Ring	Outer Ring
Block 7	480|336|358	552|349|363	505|327|294
Block 5	487|326|347	504|330|341	453|289|254
Block 3	424|311|331	426|308|317	322|256|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

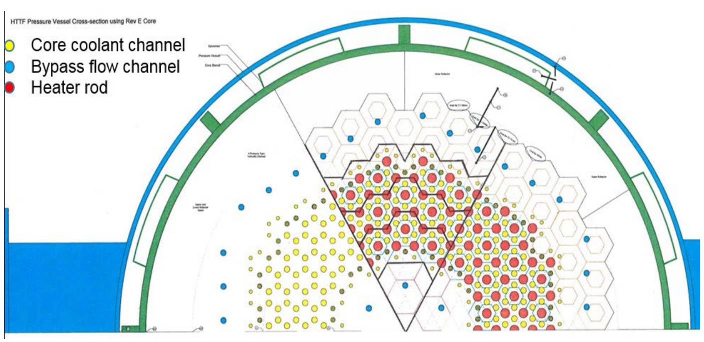


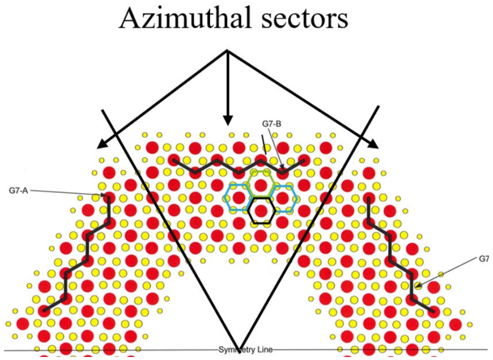


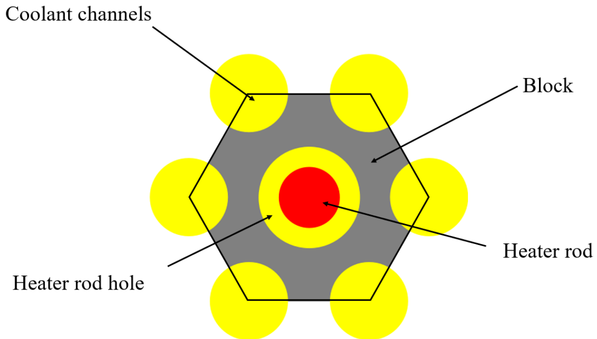
Development of a new RELAP5-3D Model of HTTF

Comparing unit cells

- The old model used a hex block unit cell as shown in the figure on the left
- The new model uses a smaller hex block unit cell as shown in the figure on the right
- The new model also includes separate azimuthal sectors to capture azimuthal asymmetry
- Heater rods used in PG-27 straddle the boundaries of “rings” in the old model
  - Old model was built well before experiments were done, and the location of the active heater rods was not known a priori



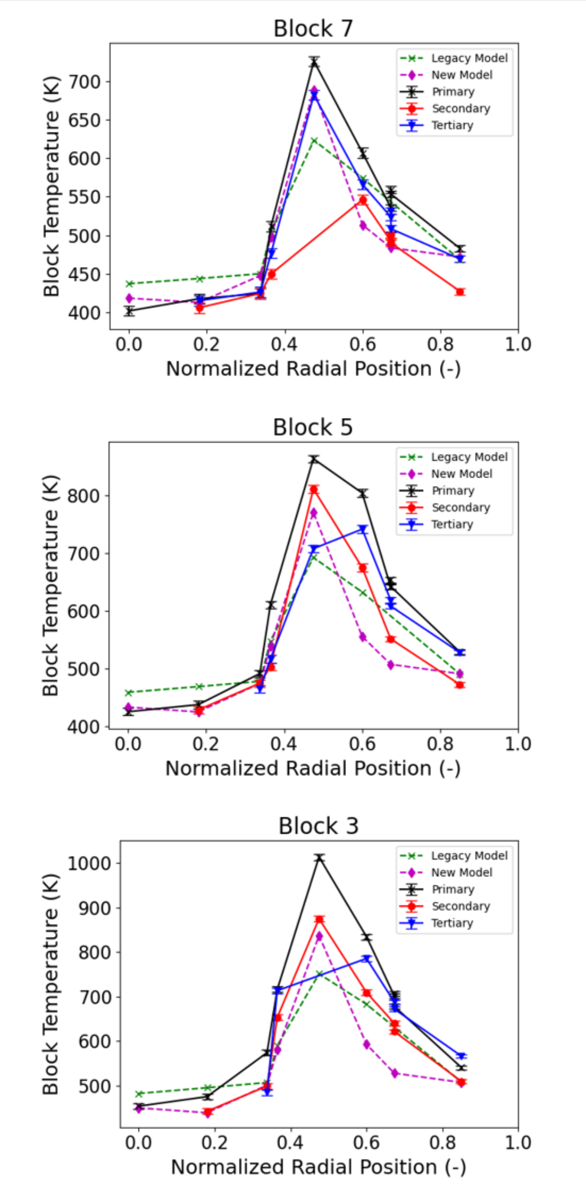




Bayless, P., “RELAP5-3D Input Model for the High Temperature Test Facility,” Idaho National Laboratory, Idaho Falls, ID, INL/EXT-18-45579, 2018.

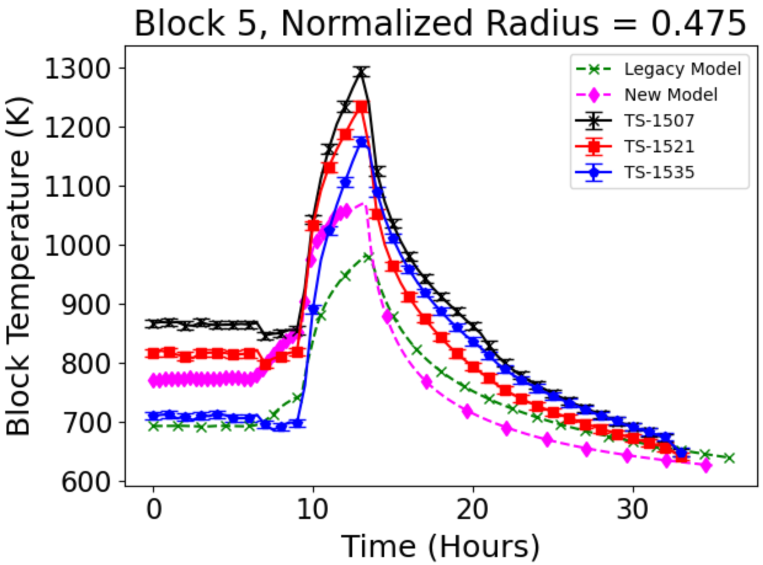
Comparing new and legacy models for PG-27 steady state

- We implemented the same flow rate and the same ETC in the new model as the legacy model
- The new model predicts block temperatures better in most locations, but in the outer reflector, the temperature is predicted worse in the new model than the legacy model
- Particularly important is the improvement in temperature at a normalized radius of 0.475, because this is the area where heat is being generated
- Agreement improves the higher in the core we are



Transient performance with the new model is better in parts of the core

- The new model predicts the transient temperature better until after the heaters are shut off
- New model also starts from a higher initial temperature
- Temperature rise in the new model is not considerably different in most locations
- In the core, we can generally conclude that the new model performs better, but not by much

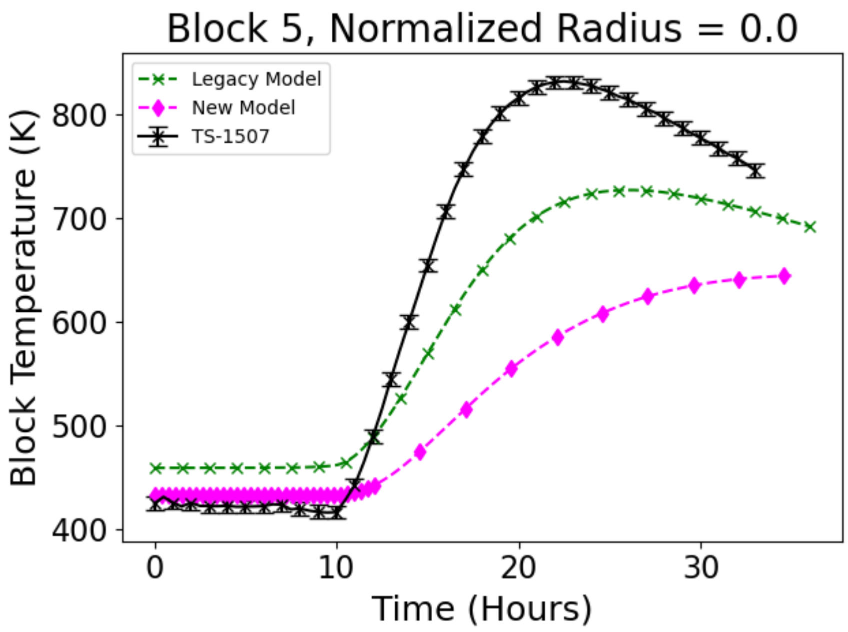


Measured|Legacy Model|New Model temperature rise

	Inner Ring	Middle Ring	Outer Ring
Block 7	480|336|316	552|349|342	505|327|322
Block 5	487|326|323	504|330|348	453|289|301
Block 3	424|311|313	426|308|327	322|256|258

Transient behavior in the reflector regions is worse with the new model

- Some simplifying assumptions on conduction within the core were removed when the new model was developed
- Under a variety of conditions, the new model has generally shown slower heat and slower long-term cooldown than the legacy model
- There is likely room to improve the performance of the new model in the reflectors
  - Reflectors do not need the ETC, but all activities thus far have used ETC in the reflectors



Conclusions

- The legacy RELAP5-3D model captured trends in PG-27 in both steady-state and transients but struggled to reproduce measured values
- Using the new model, we were better able to capture steady-state temperatures during PG-27
- The new model predicts temperatures in the core better than the legacy model, but behavior in the reflectors is generally worse
- Predicted temperature rise does not change significantly between the legacy and new models
- There is likely still room to improve our models, but we gained more insight into RELAP5-3D capabilities from this analysis
- We have not yet definitively answer the question "Can RELAP5-3D be used for prismatic HTGR analysis," but we have increased our knowledge about the problem

Acknowledgements

- This work was funded by the United States Department of Energy Office of Nuclear Energy's Advanced Reactor Technologies – Gas Cooled Reactor Campaign
- Special thanks to Jonathan Barthle, who implemented PG-27 conditions in the new model and ran the new PG-27 models
- Thanks to the organizers of the OECD-NEA HTTF Benchmark
- 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

Idaho National Laboratory

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy. INL is the nation's center for nuclear energy research and development, and also performs research in each of DOE's strategic goal areas: energy, national security, science and the environment.