INL/CON-23-72699-Revision-0

Best-estimate Modeling of the High Temperature Test Facility with RELAP5-3D

May 2023

Changing the World's Energy Future

Robert Forrester Kile

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ART Advanced Reactor Technologies

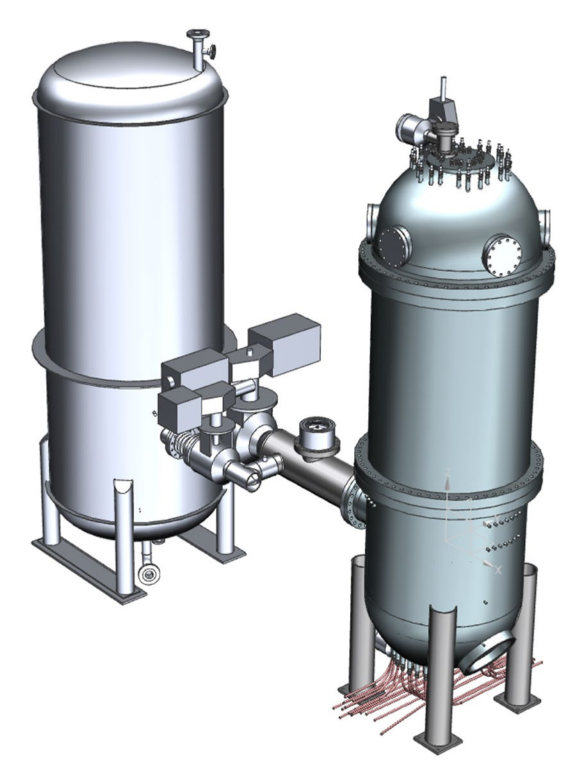
GAS-COOLED REACTORS

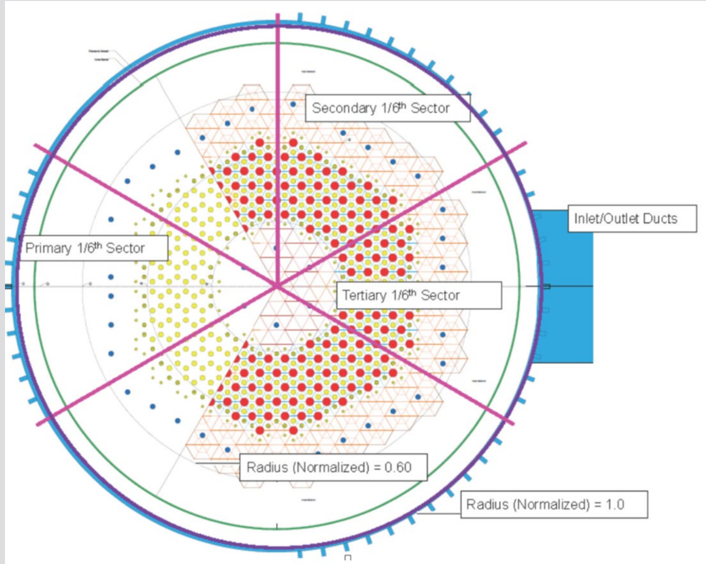
Introduction

- Prismatic HTGRs are a concept of interest for deployment as microreactors
  - BWX Technologies, Inc. (BWXT)
  - Ultra Safe Nuclear Corporation (USNC)
- While plenty of validation data exist for standalone neutronics or multiphysics modeling of prismatic HTGRs the availability of integral effects standalone thermal-hydraulics validation data is more limited
- The High Temperature Test Facility (HTTF) provides data for prismatic HTGR thermal hydraulics validation
- HTTF data are being used as the basis for an HTGR integral effects thermal hydraulics benchmark
- RELAP5-3D is a systems code with a long history of prismatic HTGR modeling, including the MHTGR-350 benchmark, but it has not yet been validated for these systems
- Goal of this work was to validate RELAP5-3D for these applications

High-Temperature Test Facility Background

- HTTF is a ¼ length scale representation of a prismatic block-type HTGR called the Modular High-Temperature Gas-Cooled Reactor (MHTGR)
- The core is heated through 210 graphite resistive heater rods
- HTTF contains over 500 instruments that provide considerable amounts of high-quality, time-dependent data for pressures, temperatures, power, and other key parameters
  - Unfortunately, no measurement of primary coolant flow rate
- HTTF has a reactor cavity cooling system outside the vessel that serves as the heat sink during pressurized and depressurized conduction cooldown (PCC and DCC) transients
- Core blocks are made of an Al_2O_3-based ceramic (Greencast 94-F)
- Helium temperature rise through the core is identical to MHTGR

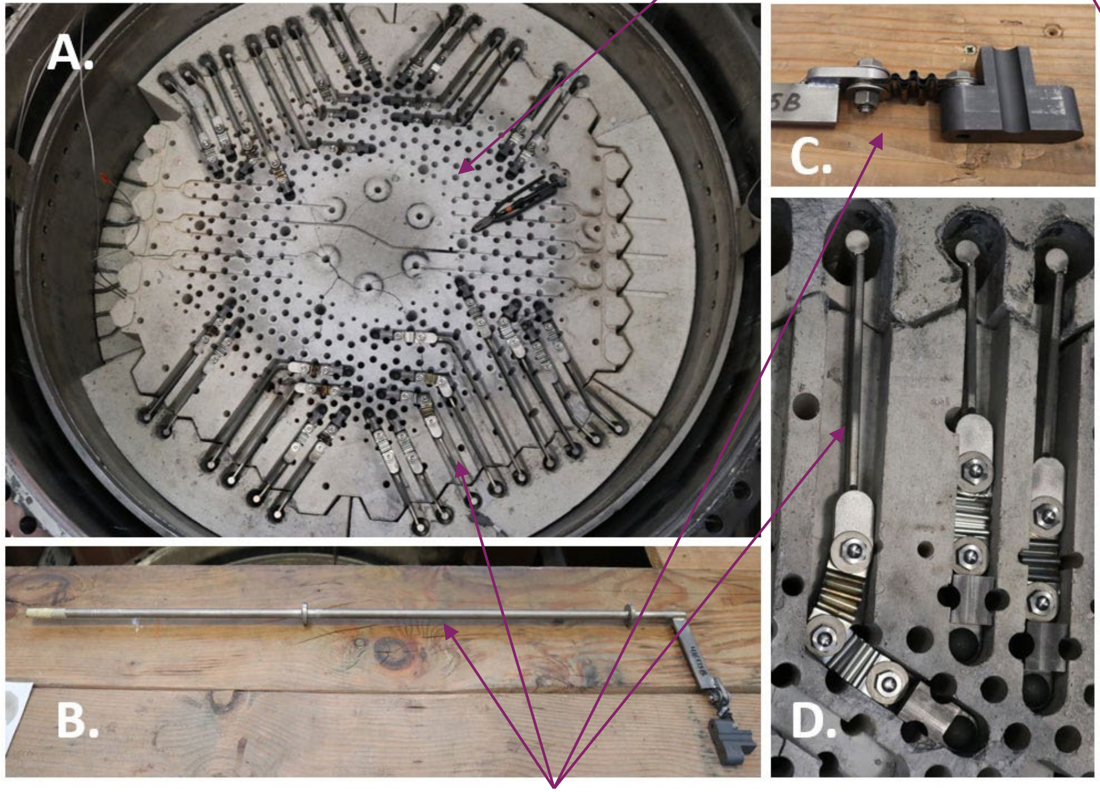


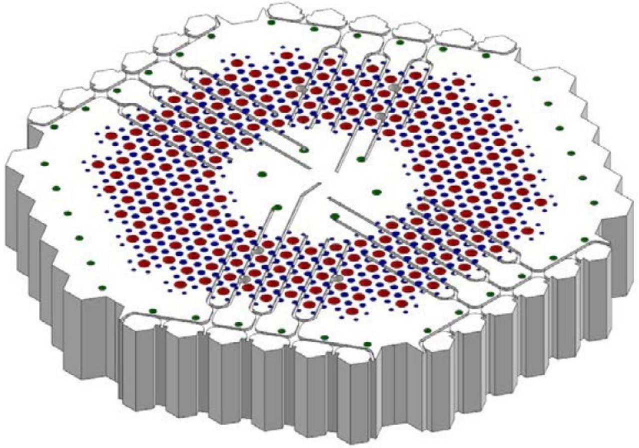


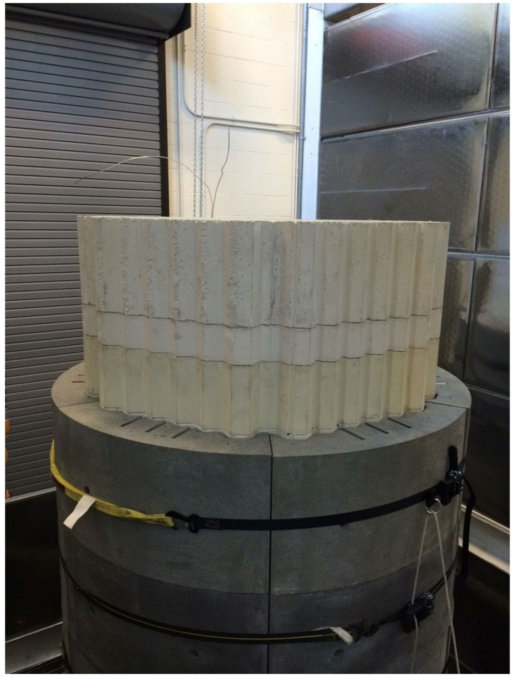
Gutowska, I., Woods, B. "OSU High Temperature Test Facility Design Technical Report," Oregon State University, Corvallis, OR, OSU-HTTF-ADMIN-005-R2 Attachment C, 2019.

HTTF Appearance

Core blocks





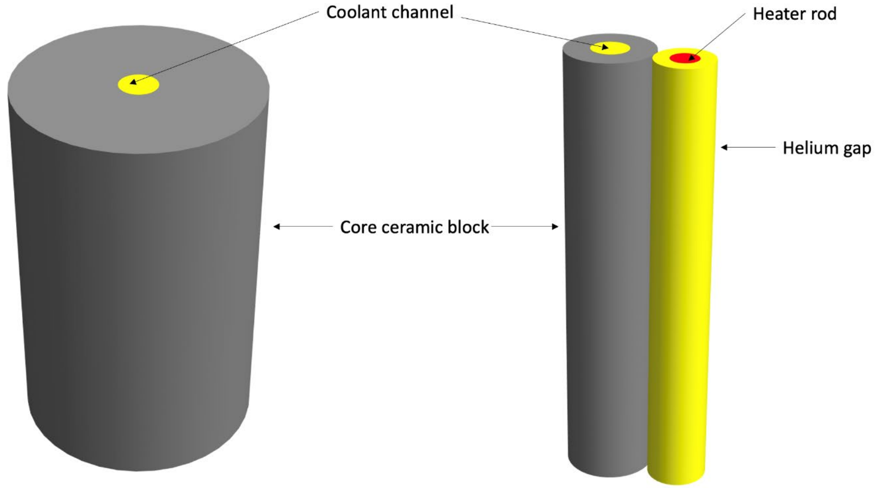


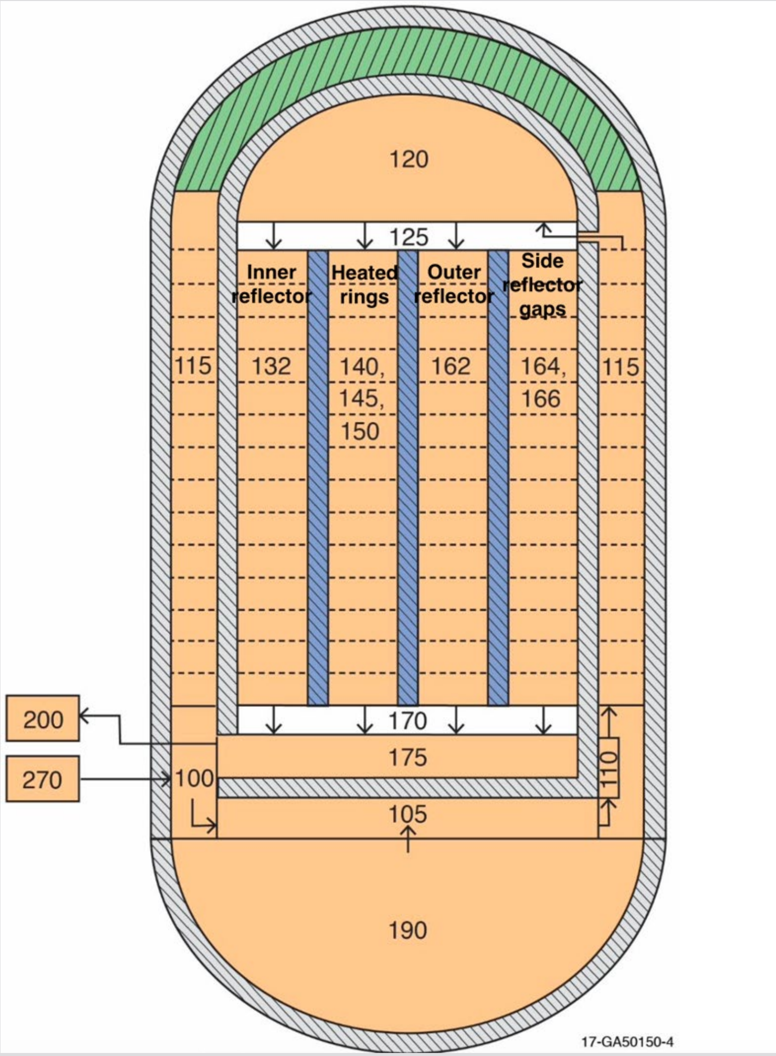
Heater rod connections

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

RELAP5-3D Ring Model of HTTF

- Descends from the Paul Bayless ring model
- Core is modeled as a set of concentric rings
  - 3 rings represent inner reflector
  - 3 rings represent area containing heater rods
  - 3 rings 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
- Rings containing coolant channels have to be modeled with unit cell approach



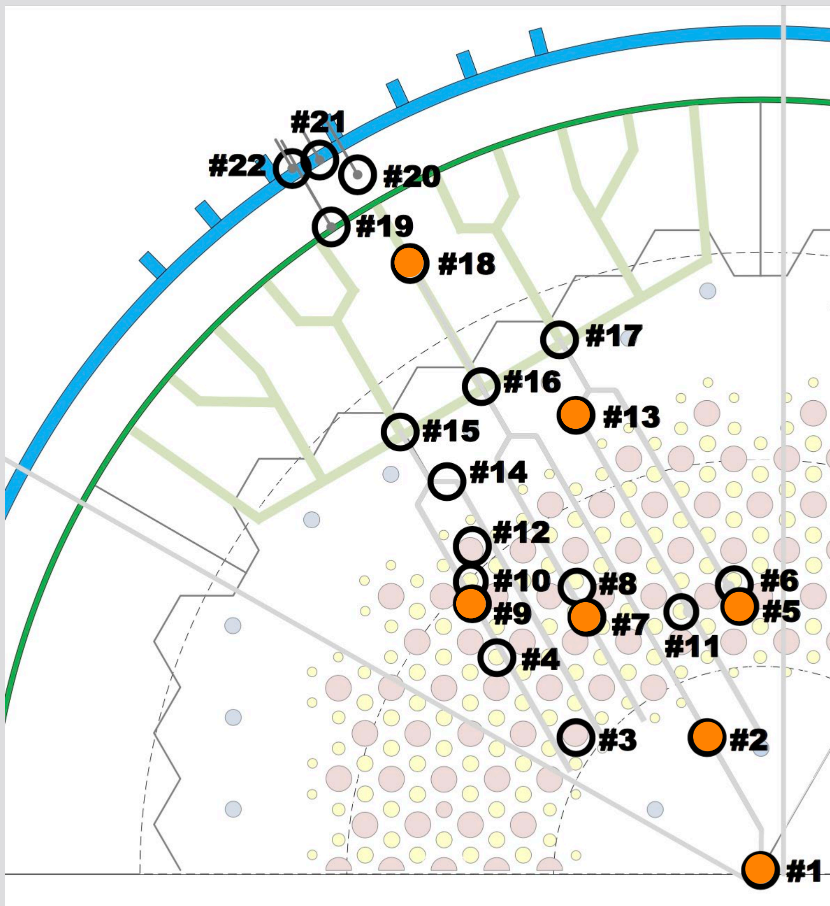


Ring model description can be found in: Bayless, P., “RELAP5-3D Input Model for the High Temperature Test Facility,” Idaho National Laboratory, Idaho Falls, ID, INL/EXT-18-45579, 2018.

Instruments and RELAP5-3D channels

- Core is divided into 1/6th azimuthal sectors, 3 of which are instrumented
- Instrumentation locations in a sector can be seen in the figure on the right
- Primary concerns in this work are block and helium temperatures
- Orange dots indicate location of block temperature thermocouples (TCs)
  - Positions 5, 7, and 9 are represented the inner, middle, and outer core ring block temperatures respectively in the RELAP5-3D model
- Helium temperature TCs are located at positions 6, 8, and 10
- TC uncertainty given by the following relationship

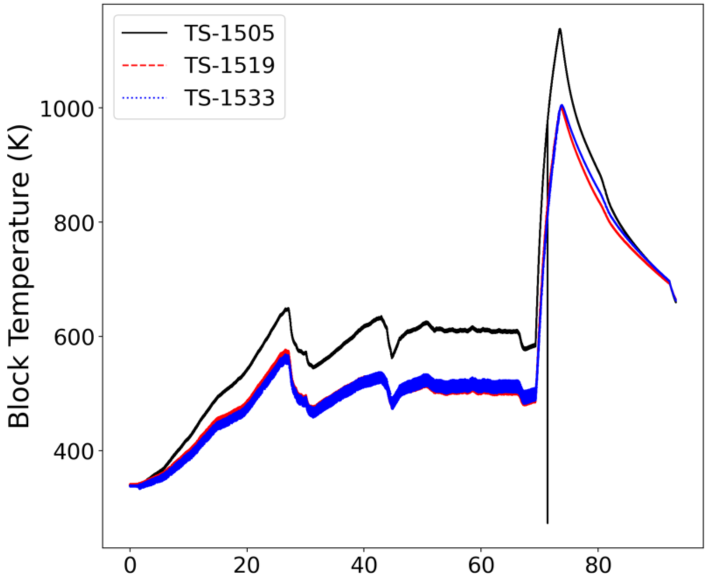
$$\sigma_{total}[°C]\begin{cases} 3.285, & 0°C < T < 600°C \\ \sqrt{2.174^2 + (0.004 \times T[°C])^2}, & 600°C < T < 1450°C \end{cases}$$

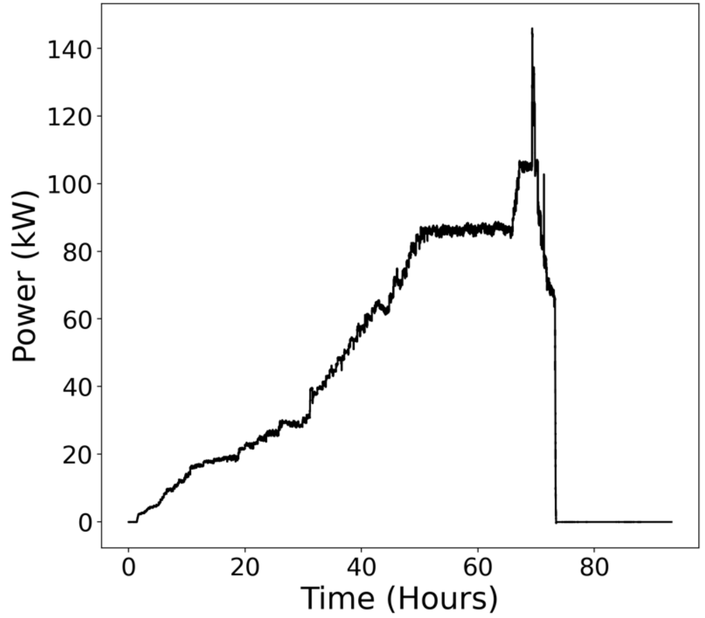


Adapted from: Gutowska, I., Woods, B., “Instrumentation Plan for the OSU High Temperature Test Facility,” Oregon State University, Corvallis, OR, OSU-HTTF-ADMIN-005-R2 Attachment C, 2019.

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

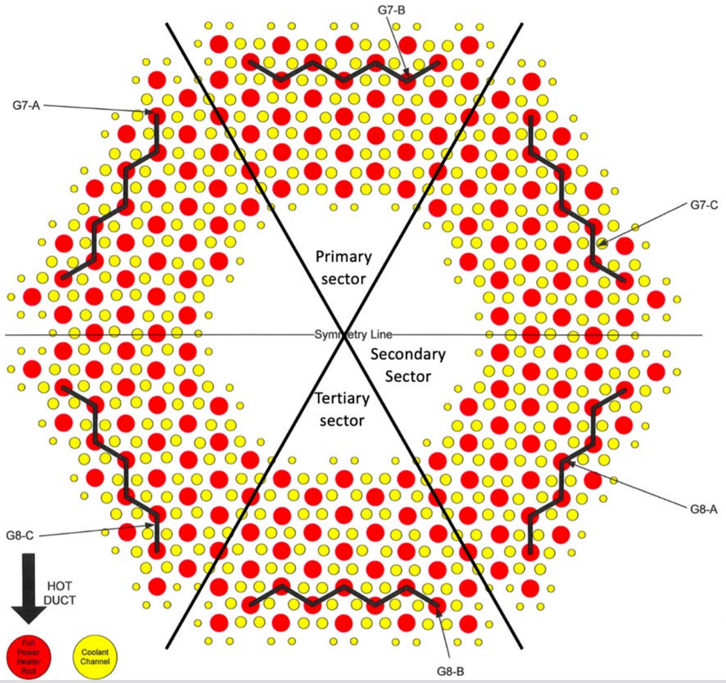
- PG-27 is an experiment representing the pressurized conduction cooldown (PCC)
- Extended steady state from 50-65 hours provides an opportunity to do a steady-state calibrate then test the calibration against transient behavior
- PCC initiated at a time of 69 hours
- Primary focus is block temperatures at TC locations 5, 7, and 9 at blocks 3, 5, and 7
- 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





Operating heaters are in the outer part of the core

- 42 of 210 heater rods are used in PG-27
  - Heater banks 102 and 108
- In RELAP5-3D, this leads to 87.5% of heat generated in the outer ring and remaining 12.5% generated in the middle ring
- Azimuthal symmetry in the heaters is ideal for ring model
- Power in banks 102 and 108 is nearly identical
- Power shut off at 73 hours, after which point facility is entirely in cooldown mode

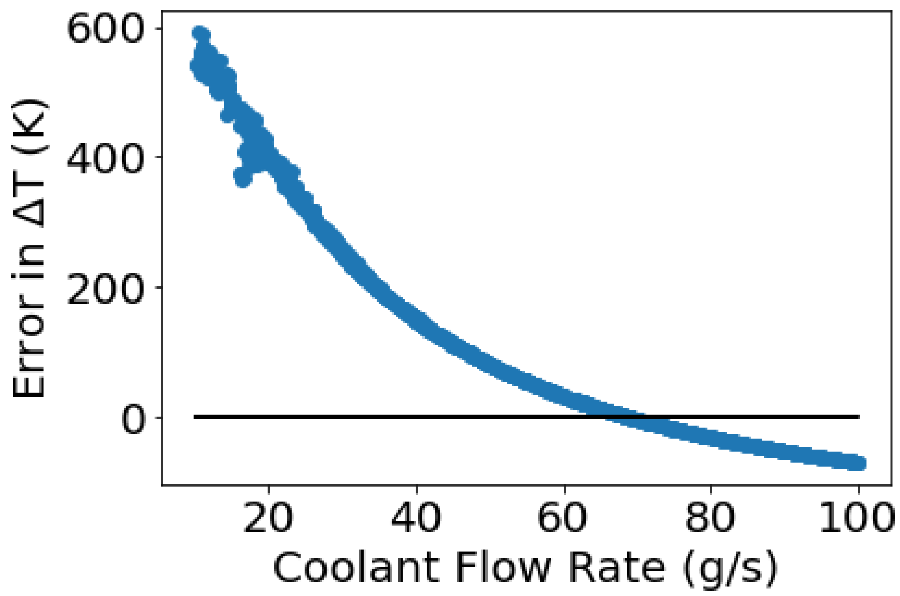


Boundary Conditions based on measured data

- PG-27 data were provided by OSU
- Technique for reading measured data into RELAP5-3D was developed by Epiney
    1. Smooth data using a rolling average (30-minute window)
    2. Randomly sample 50 points in the smoothed data and use those as part of the input
    3. Sample the 50 points in the smoothed data with the largest derivatives to capture the change in state of the facility (Power ramping up, power shutting off, flow dropping, etc)
    4. For power over time, integrate new curve and compare to integral of smoothed curve. Apply scalar multiplier to conserve total energy
- This approach was used to meet limitations of RELAP5-3D inputs
    - One data point every half second for 90 hours is too much input
- Models used the conditions at 60 hours as the initial conditions

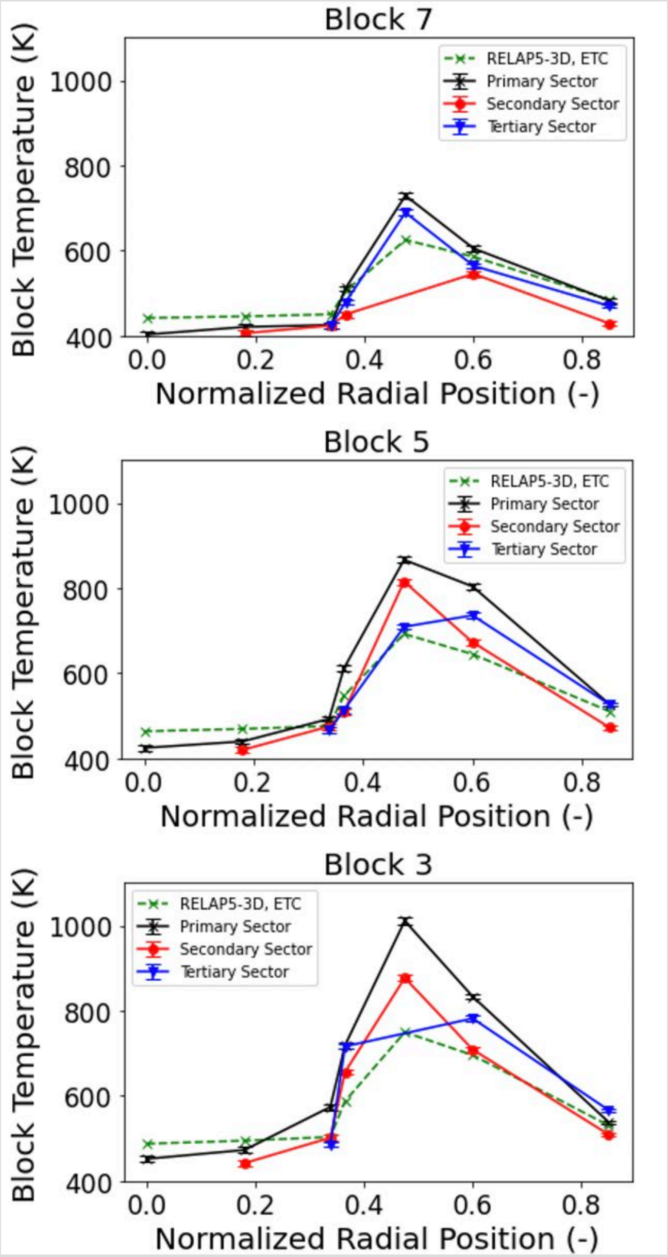
Helium flow rate provides the first-order effect on temperatures

- 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



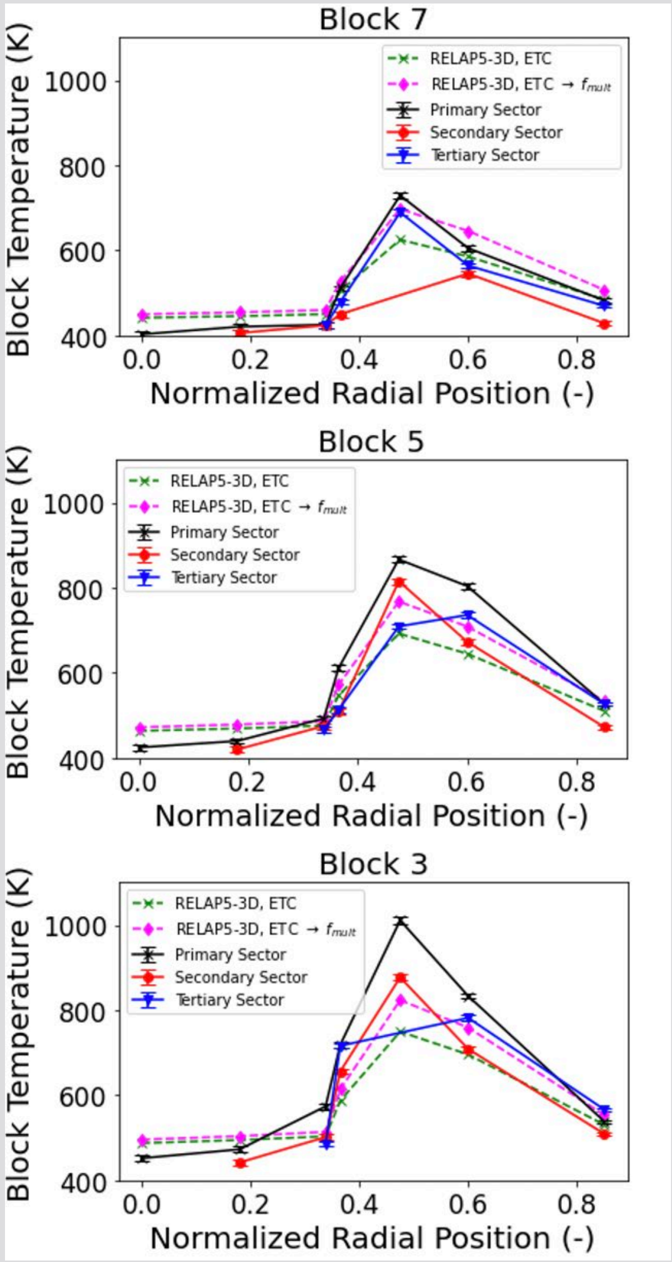
Calibrated block thermal conductivities

- 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



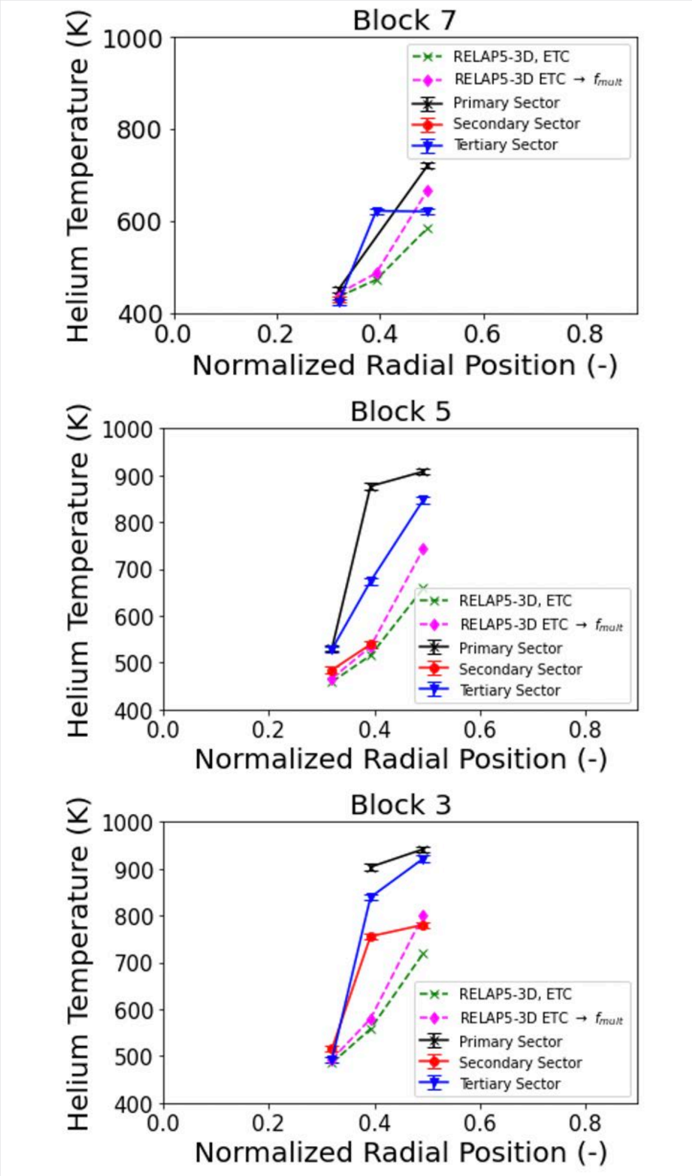
Increased friction to improve outer ring temperatures

- 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



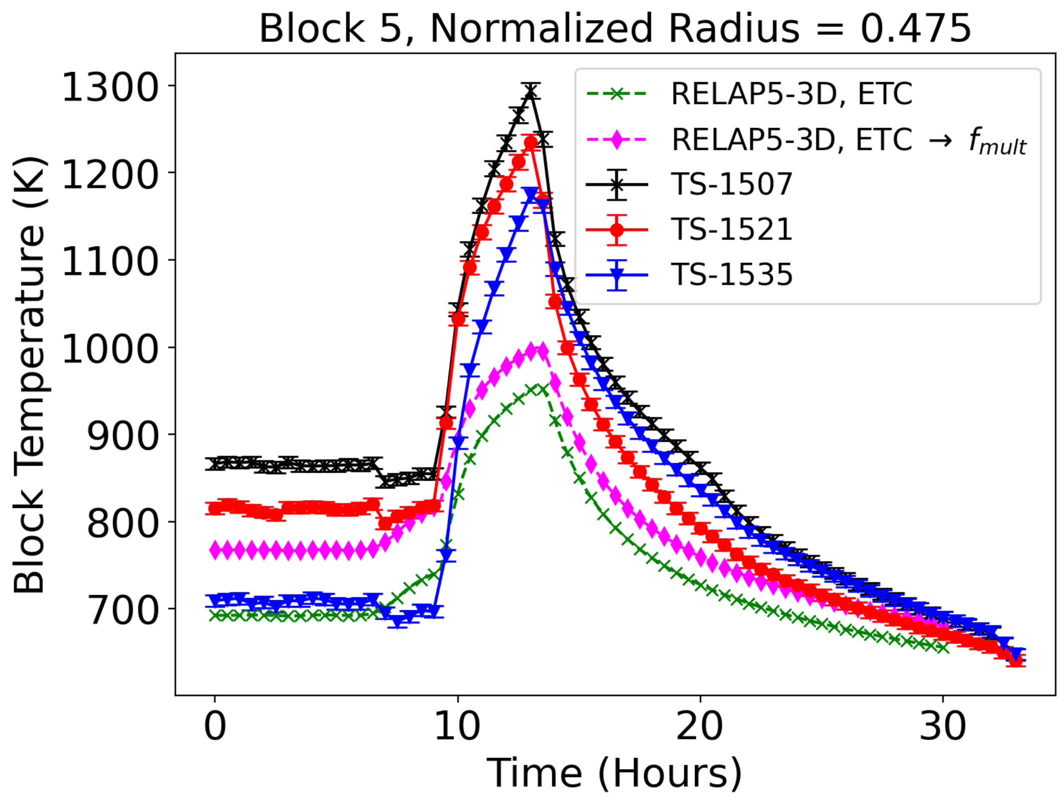
Helium temperatures suggest increased friction may be better

- Block 7, inner ring temperature well-predicted in both calibrations, outer ring only well-predicted with increased friction
- Block 5 high friction calibration predicts temperature well in the middle ring
  - Outer ring temperature might be well-predicted with high friction calibration if there were a secondary sector TC, but it is impossible to be certain of that
- Block 3 high friction calibration predicts inner and outer ring temperatures well but not middle ring
- High friction calibration predicts temperatures better everywhere, but is that because high friction is more representative of HTTF conditions, or is it just masking errors in the model?



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

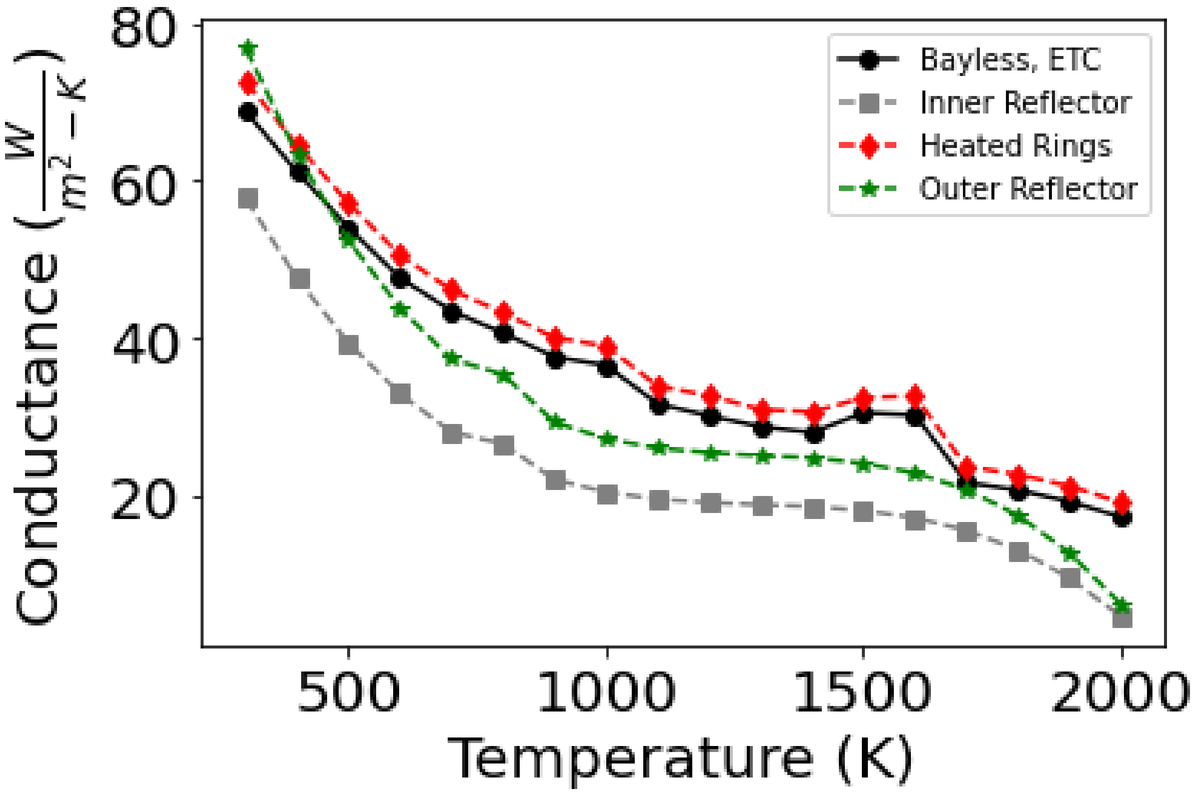


Measured|Standalone ETC|ETC + friction calibration temperature rise

	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

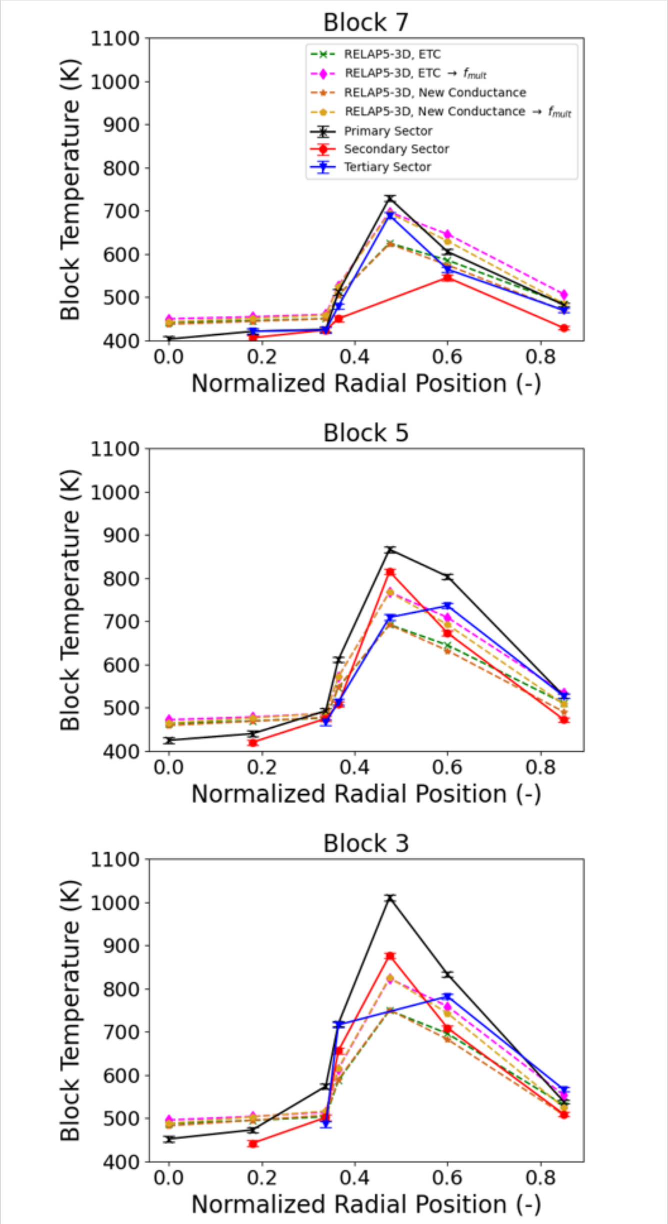
Revisiting radial conduction

- Developed new radial conduction models that removed some of the simplifying assumptions made in the ring model
  - Line labeled “Bayless, ETC” is the old conductance using the calibrated ETC
- Unique conductance between heat structures in each enclosure rather than a single temperature-dependent conductance with a temperature-independent scaling factor
- New conductance was slightly higher in heated rings but lower in reflectors



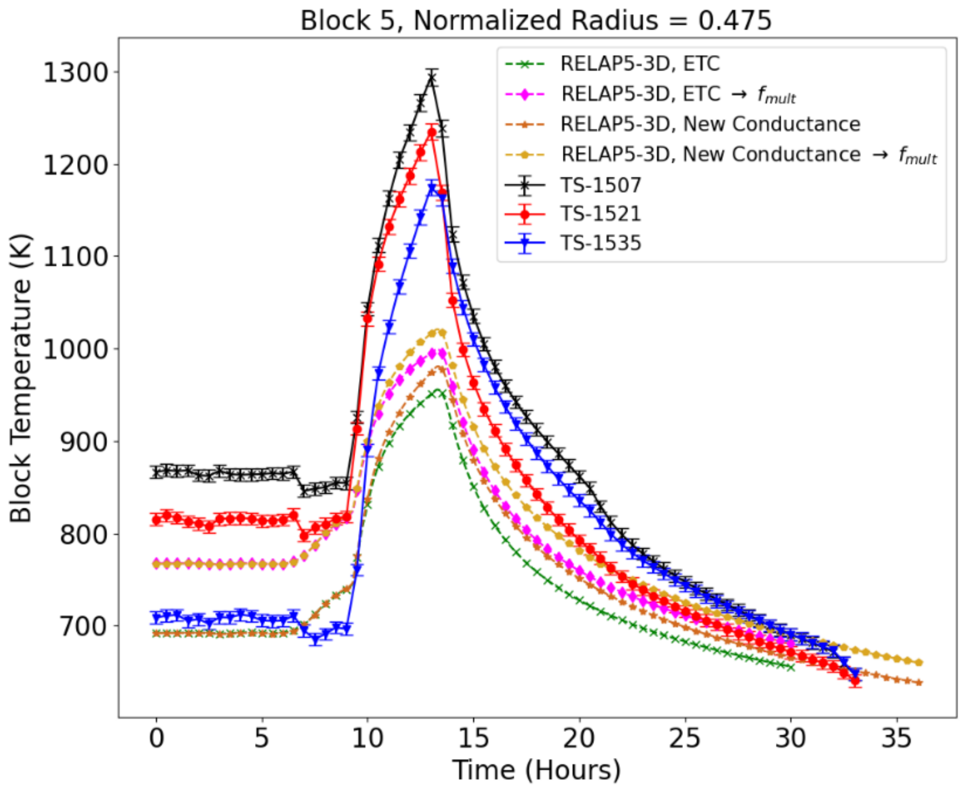
New conduction model makes only small differences in steady-state temperatures

- 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?

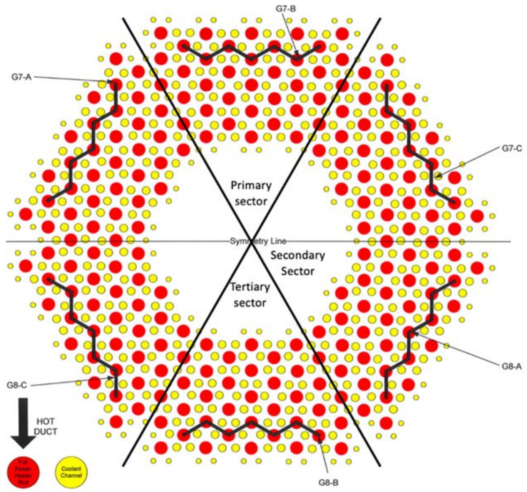


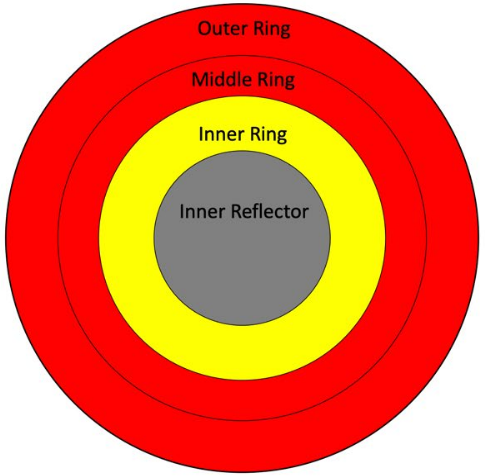
Measured|Standalone ETC|ETC + friction calibration temperature rise

	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 coarse nodalization of the model
- Peak power density is significantly underpredicted in RELAP5-3D, which likely leads to the insufficient temperature rise
- RELAP5-3D block temperatures are also over a much larger volume than local TCs will be able to detect



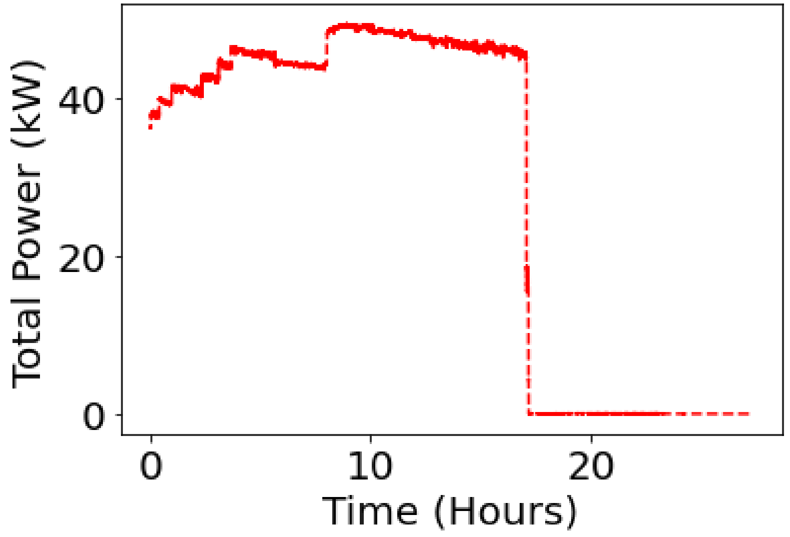


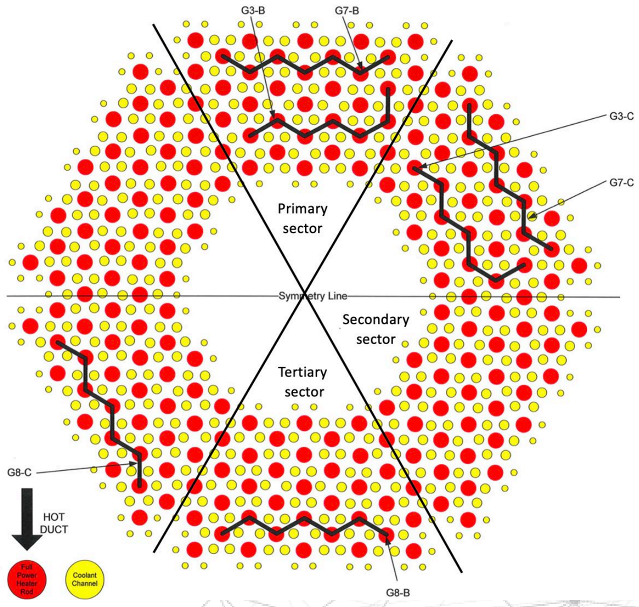
Which calibration is best?

- This is a good question, but there isn't a single calibration that's best at everything
  - If the concern is matching steady-state temperatures, best model is the ETC + friction calibration with the old radial conduction model
  - If the concern is matching the transient temperature rise, best model is the standalone ETC calibration with the new conduction model
- If there were flow distribution data, it would be easier to determine whether increasing friction in the outer ring was improving fidelity or simply masking errors introduced by the modeling assumptions
- We have chosen the standalone ETC calibration with the new conduction model as the best calibration, because predicting the transient temperature rise well is important

PG-29 provides limited verification of the ETC calibration

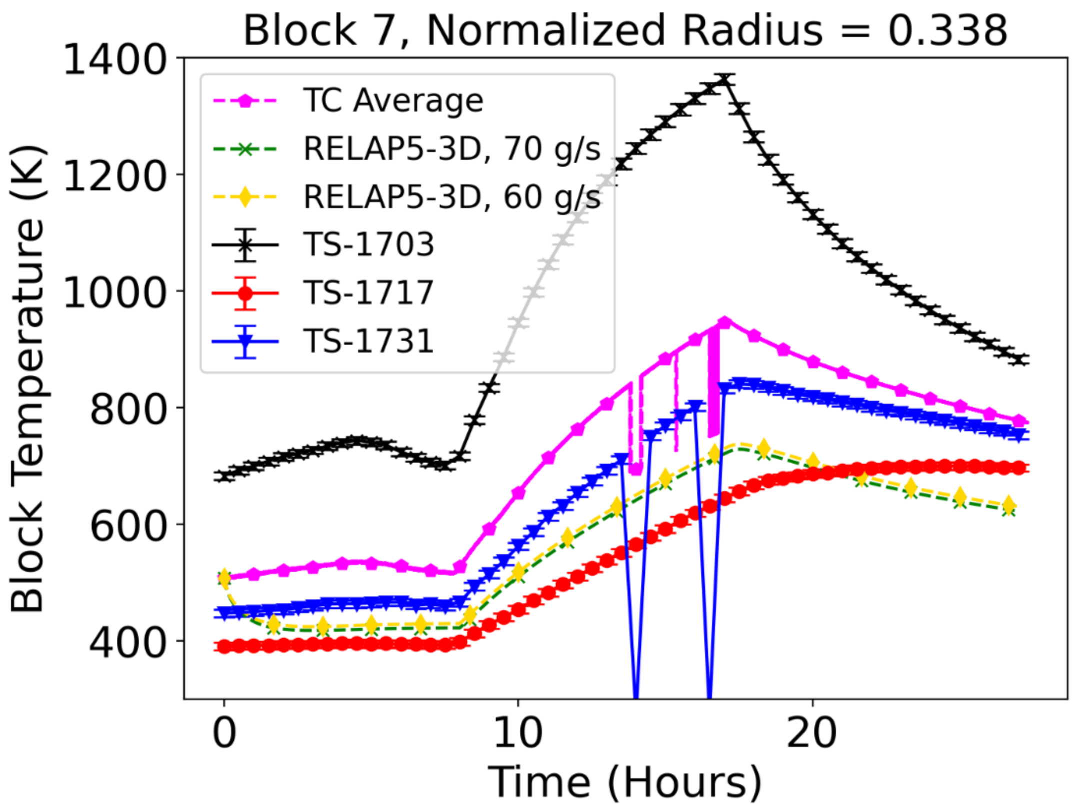
- To further investigate the best calibration, we applied it to a low-power DCC experiment called PG-29
  - PG-29 immediately followed the lower plenum mixing experiment PG-28
- The limitations of the ring model mean we can't do a direct comparison of RELAP5-3D predictions to measured HTTF data here
- Ring model has power density problems mentioned before
- Ring model cannot capture azimuthal asymmetry
- **Goal:** RELAP5-3D predicts temperatures within the spread of PG-29 data
- Transient initiated at 8 hours
- Heaters shut off at 17 hours





PG-29 models do as well as can be expected given the limitations of the RELAP5-3D model

- Initial temperature was defined as the average of all working TCs at that location
- Temperatures are between the unheated (secondary) and heated sector temperatures when the heater rods are active
- After heater rods are shut off, RELAP5-3D temperatures fall below measured secondary sector temperature
  - Secondary sector can be heated azimuthally from heated parts of the core
  - RELAP5-3D model cannot capture that behavior, only transfers heat axially and radially
  - Lower power densities in the heated parts of the core also lead to lower initial temperatures



Conclusions

- The RELAP5-3D ring model used in this analysis captures trends in the data but cannot reproduce the measured temperature rise during the transients
- The symmetric ring model cannot reproduce measured PG-29 temperatures
- The inability to reproduce measured temperature data is primarily attributed to the coarse radial nodalization of the model rather than due to RELAP5-3D deficiencies
- We believe RELAP5-3D is likely capable of capturing HTTF behavior better, but a more detailed model is required

Acknowledgements

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