INL/CON-23-72754-Revision-0

Lessons Learned from RELAP5-3D Modeling of HTTF

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Changing the World's Energy Future

Robert Forrester Kile

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ART Advanced Reactor Technologies
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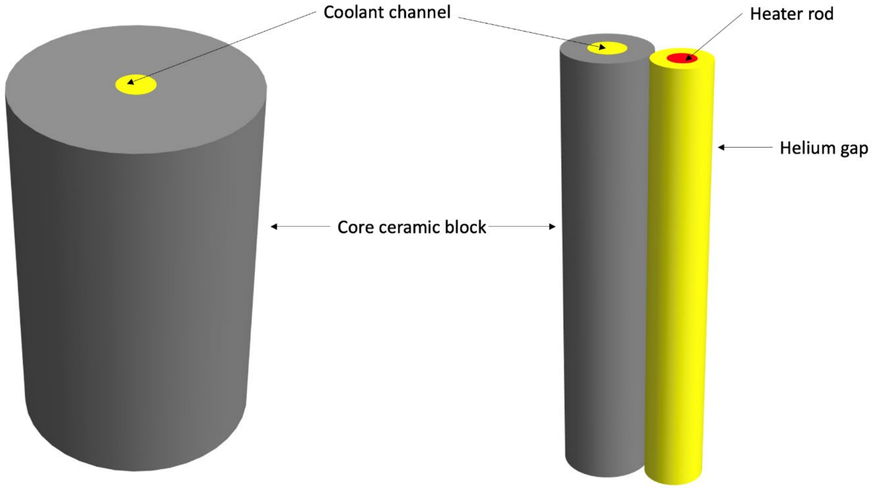
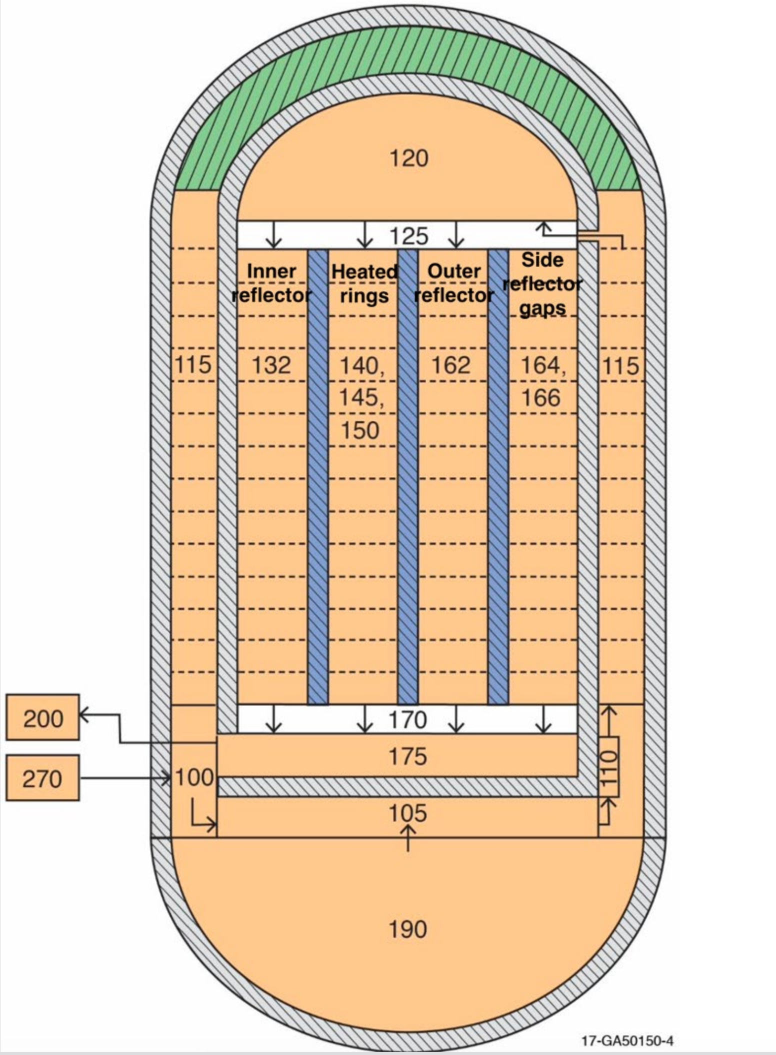
RELAP5-3D Ring Model of HTTF

- Descends from the Paul Bayless ring model developed from 2015-2018
- 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

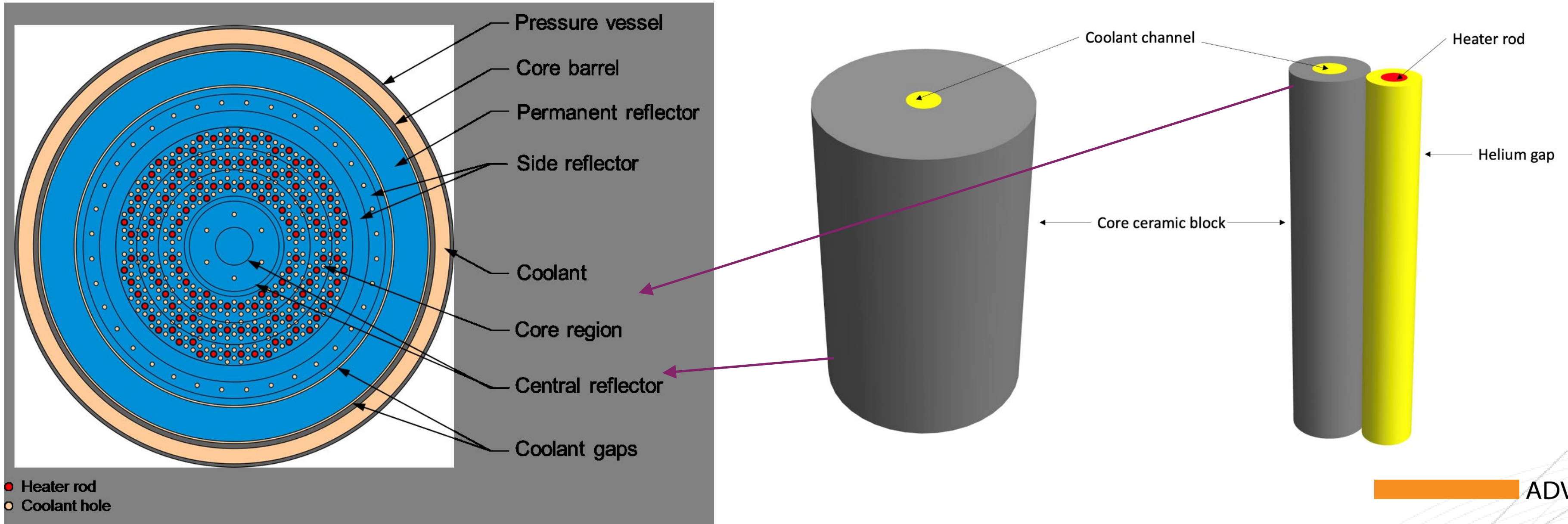




Ring model description can be found in: Bayless, P., "RELAP5-3D Input Model for the High Temperature Test Facility," Idaho National Laboratory, Idaho Falls, ID, INL/EXT-18-45579, 2018.

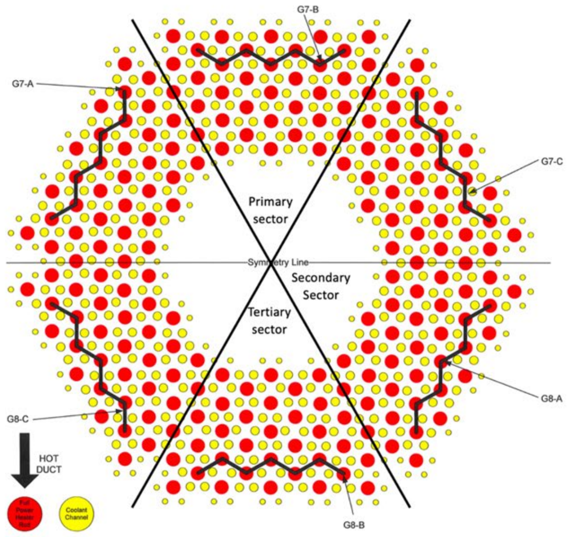
Key assumptions in the ring model

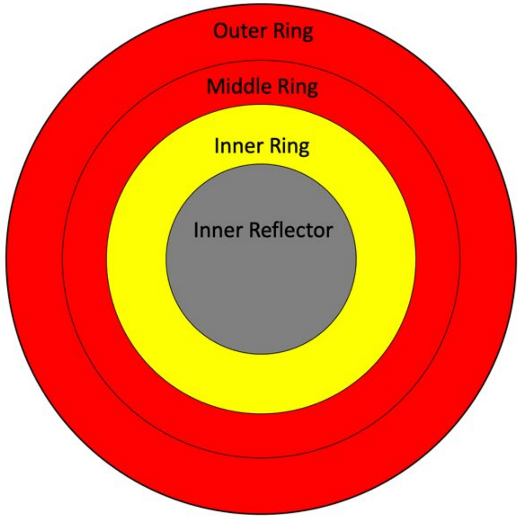
- The behavior in the core is axisymmetric about the z-axis
- Behavior in the core region can be captured by 3 rings
- Each ring contains 1 heat structure representing the entire core block in that region
- Each ring contains 1 coolant channel that is representative of all the coolant channels in that region
- Each ring contains 1 heat structure representing all the heater rods in that region
- Only radiation and no conduction between the following
  - Heater rods ↔ Core blocks
  - Outer reflector ↔ Permanent reflector
  - Permanent reflector ↔ Core barrel
  - Core barrel ↔ Core vessel
  - Core vessel ↔ RCCS panels
- No cross-flow junctions between blocks, so all coolant exits the core at the same channel where it entered the core



PG-27 modeling with the ring model

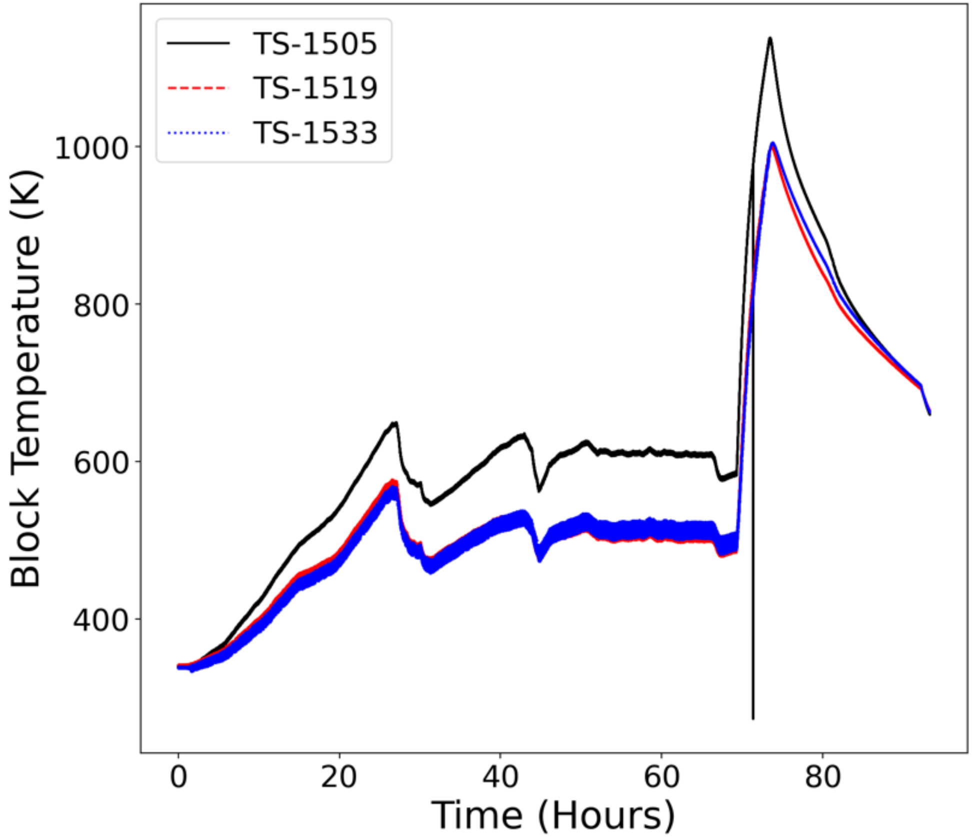
- In PG-27, only heater rods in the outer portion of the core are used
- These heater rods straddle the middle and outer rings in the RELAP5-3D model
- 20% of heater rod volume (42 of 210 rods) was used in the experiment, but ***<u>73%</u>*** of heater rod volume was used in the RELAP5-3D model
  - Even if all the heat was generated in just the outer ring, it would be 43% of the heater rod volume
- We developed models that preserved the total power in the experiment, but in doing so we distorted the power density in the active heater rods





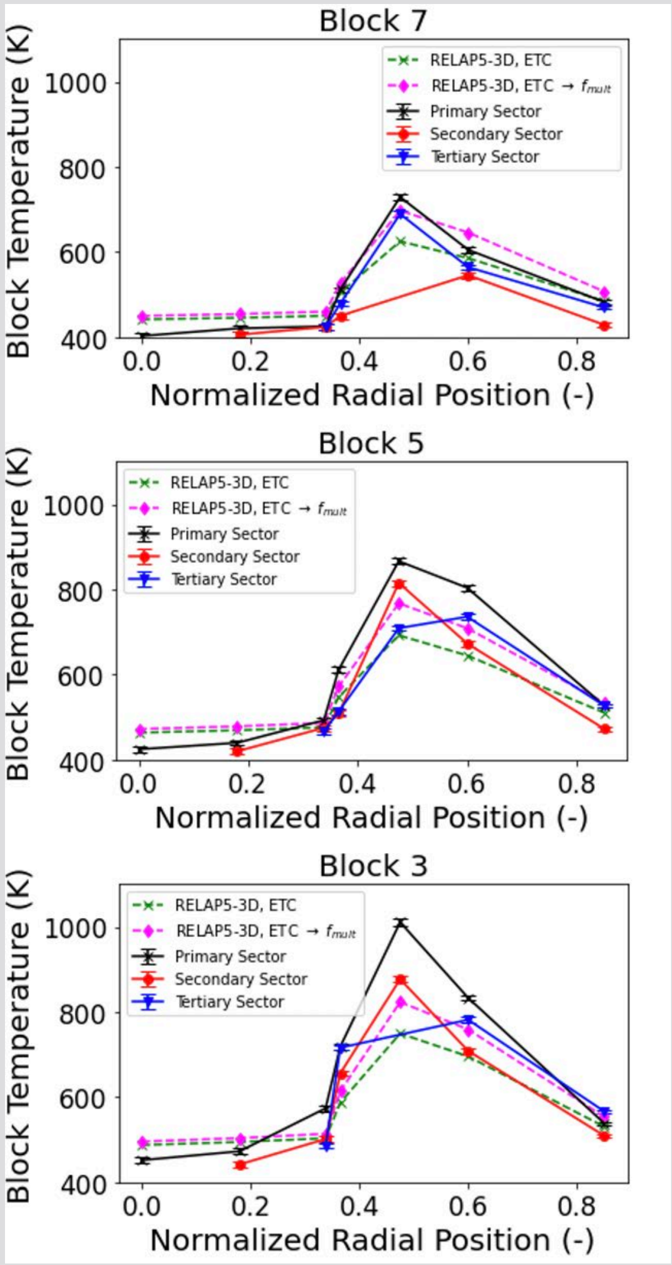
PG-27 has an extended steady state useful for calibration purposes

- From hours 55-65, power and temperatures are in steady-state
- We can use this steady-state to calibrate relevant steady-state parameters
  - Coolant flow rate
  - Thermal conductivities
  - Flow distribution
- Flow rate ramps up again around 66 hours until PCC starts at ~69 hours
- Flow rate from 55-65 hours is ~70 g/s



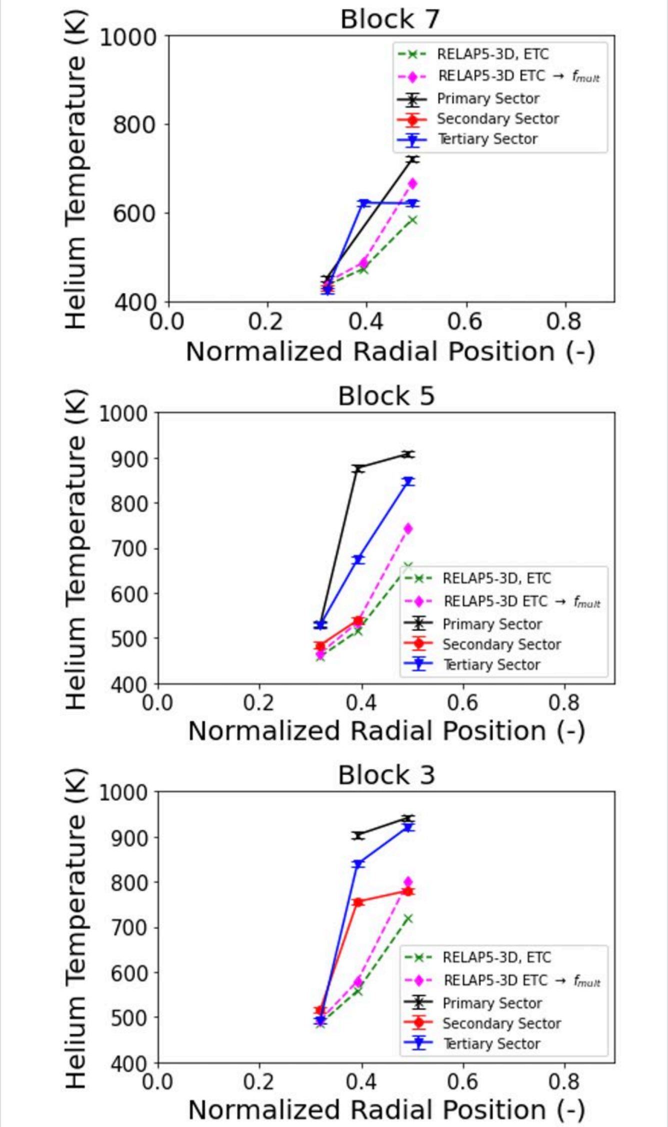
Developed a calibrated thermal conductivity from PG-27

- Based on relationships for effective thermal conductivity (ETC) in one-dimensional systems codes, the ETC should be 75-80% of the bulk block thermal conductivity
- Calibrated ETC was 36% of the bulk block thermal conductivity, and temperatures in the outer ring of the core (TC location 9, normalized radius 0.475) were still too low
- Could improve the prediction by doubling friction in the outer ring, but that may just be masking a defect with the ring model
  - Absent flow distribution data, this is not a reasonable parameter to investigate, but we have to be cognizant of the fact that it could just be fitting the steady-state data rather than capturing the physics

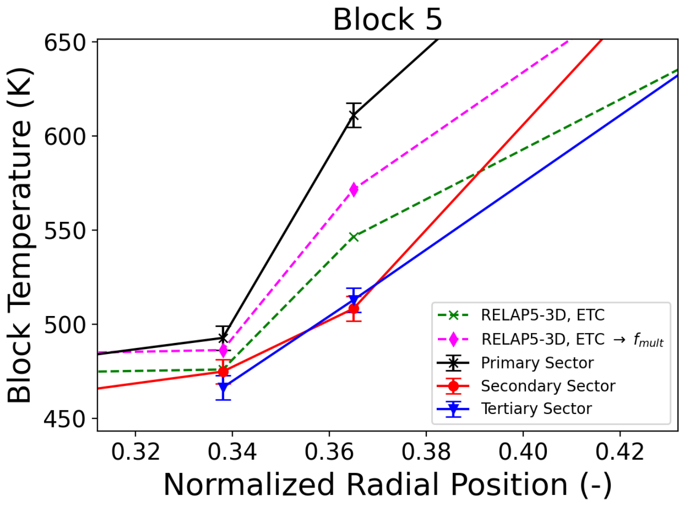


Helium temperature may provide some additional insight

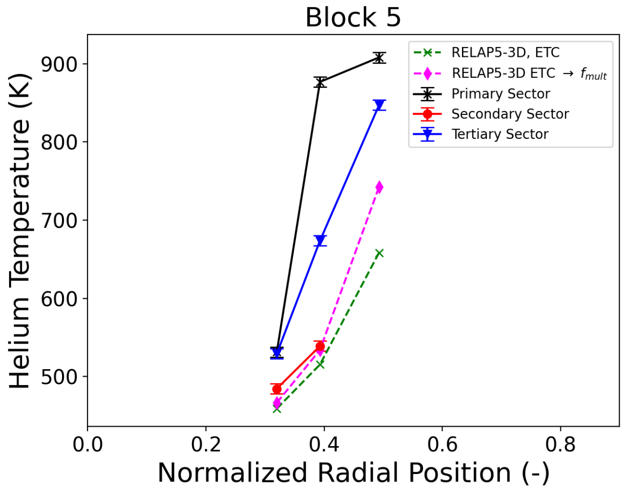
- Helium temperatures suggest that increasing the friction in the outer ring captures the steady-state results better than not doing so
- Doing so captures local power-to-flow ratios better given the distortions in power density introduced by the ring model, but it is likely just masking the power density issues rather than capturing reality better
- Helium temperatures in RELAP5-3D generally track best with secondary sector TC readings, where those readings are available
- Something is causing significant differences in helium temperature in each of the instrumented sectors of the core, but the ring model cannot capture that

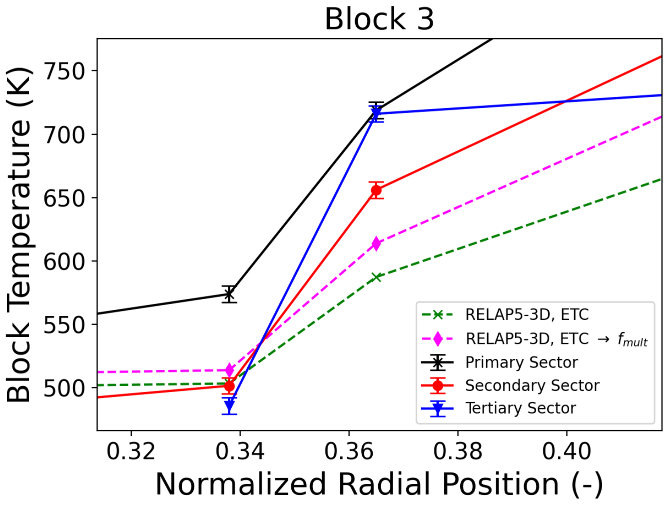


Something is happening in the middle ring between block 5 and block 3 that the RELAP5-3D models are not capturing

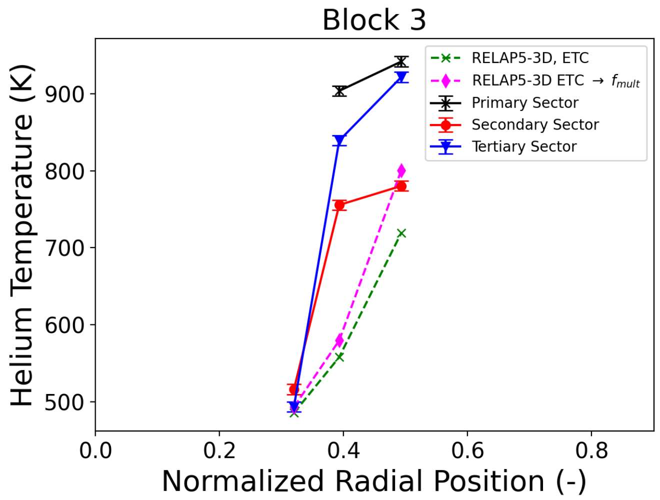


Temperature well-predicted



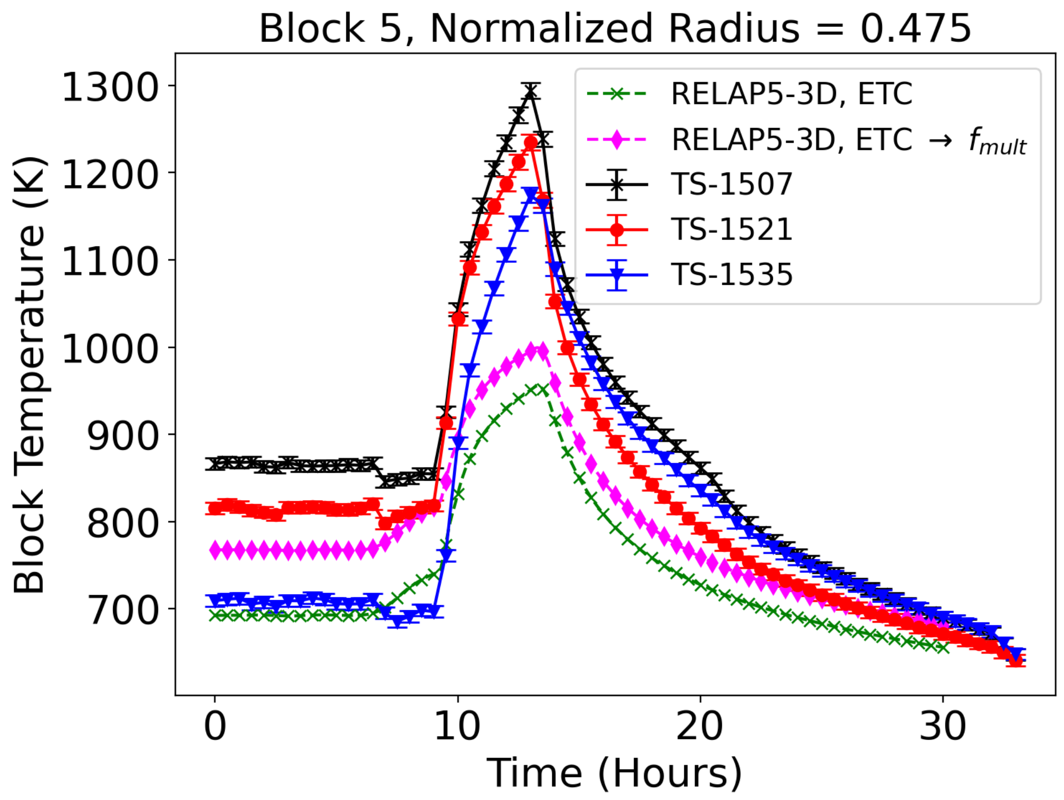


Temperature significantly under-predicted



Transient temperature rise too low

- 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

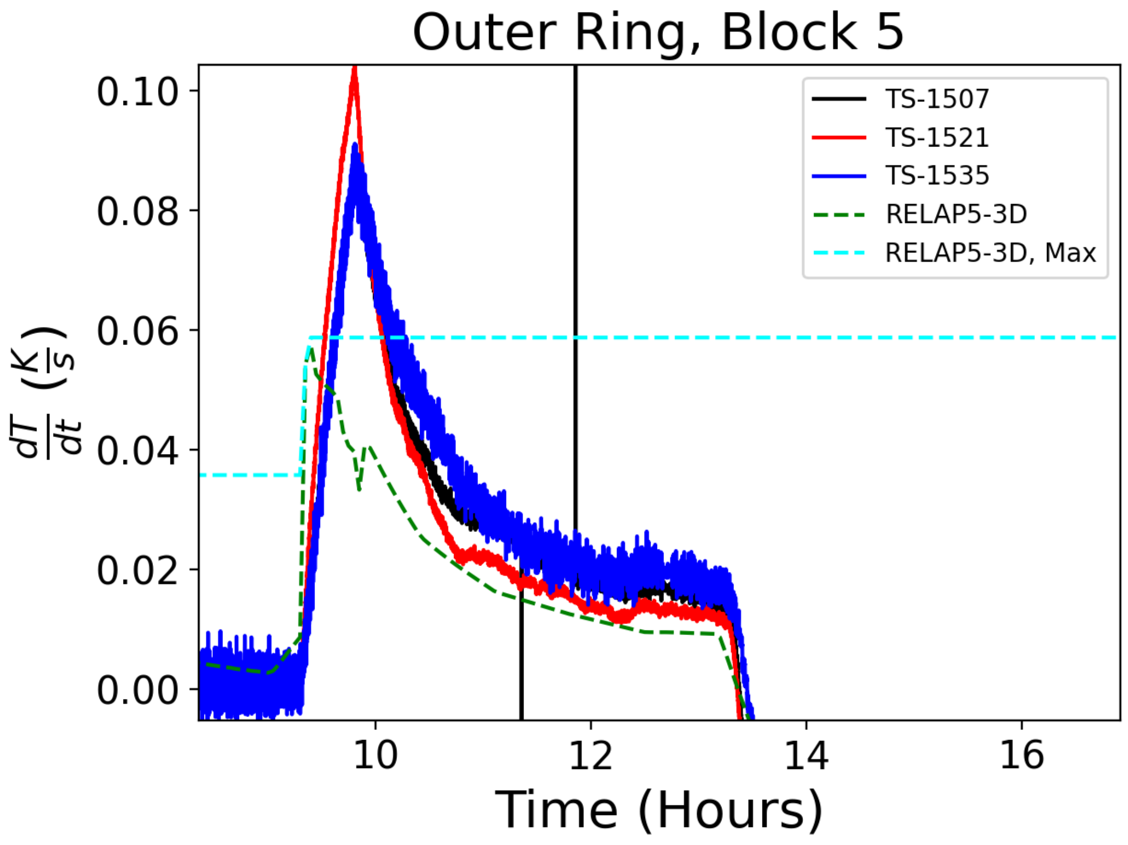


Measured|Standalone ETC|ETC + friction calibration temperature rise

	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

RELAP5-3D temperature derivative is too low

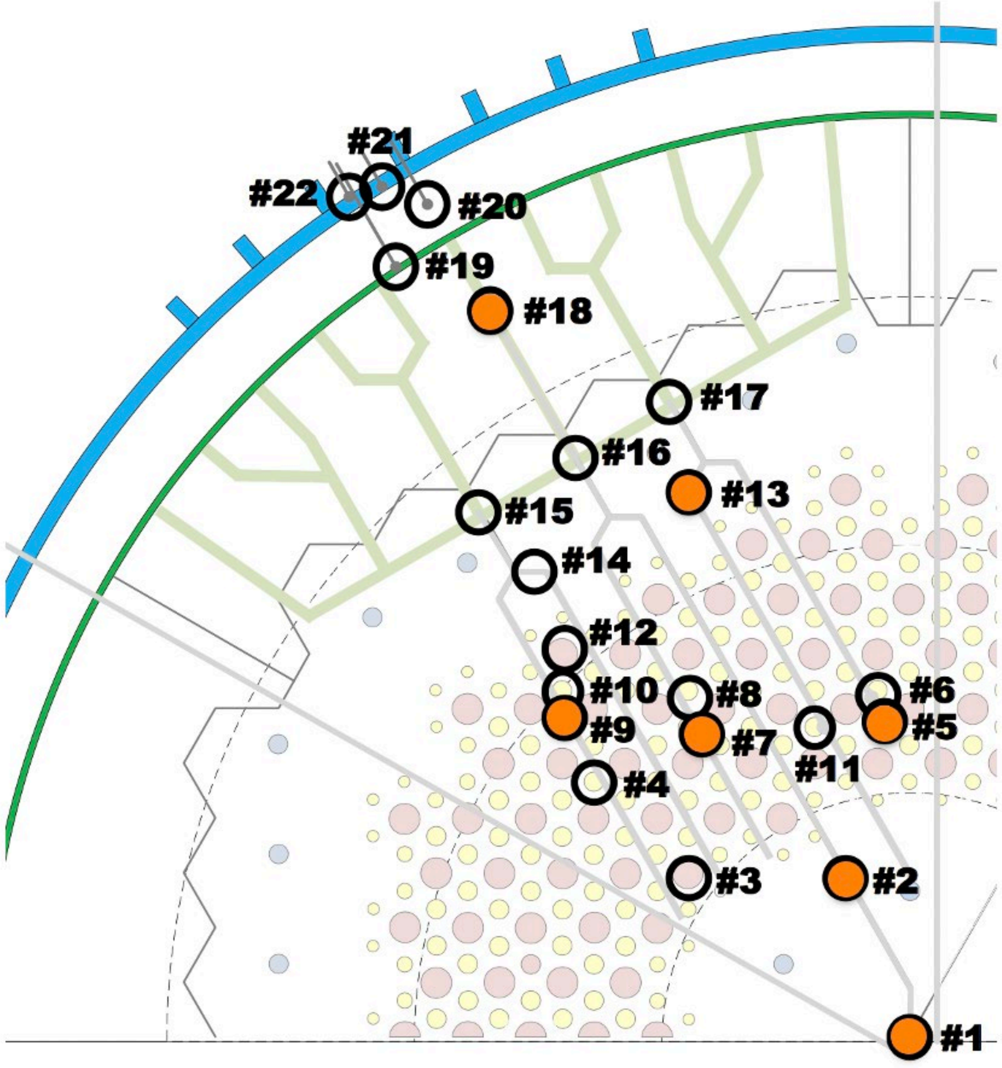
- Temperature derivative in RELAP5-3D is too low compared to the measured temperature data
- Measured derivative is the instantaneous derivative in TC reading
  - Measured data were first smoothed with a moving average (30-minute window)
  - Second-order central differencing for interior data points. Forward differencing for first data point and backwards differencing for last
- Shape of derivative in RELAP5-3D is consistent with the experiment, but the magnitude is too low



$$\rho c_p \frac{dT}{dt} = k\nabla^2 T + q'''$$

Ring temperature vs. TC reading

- Ring is over a very large volume
  - Outer ring corresponds to 43% of the core volume in RELAP5-3D
- If only part of the ring is heated, then heat structure temperature in the ring will not closely correspond to local TC reading
- Ring model only includes 1 heat structure representing all the heater rods in that ring, so heater rod temperatures ***will*** be wrong unless all heater rods in that ring are active and generating an equal share of the power
  - If temperature of the heat source is too low, block temperatures will also be too low
- TC is a local reading. Particularly important is that the TC in location 9 is very near an active heater rod

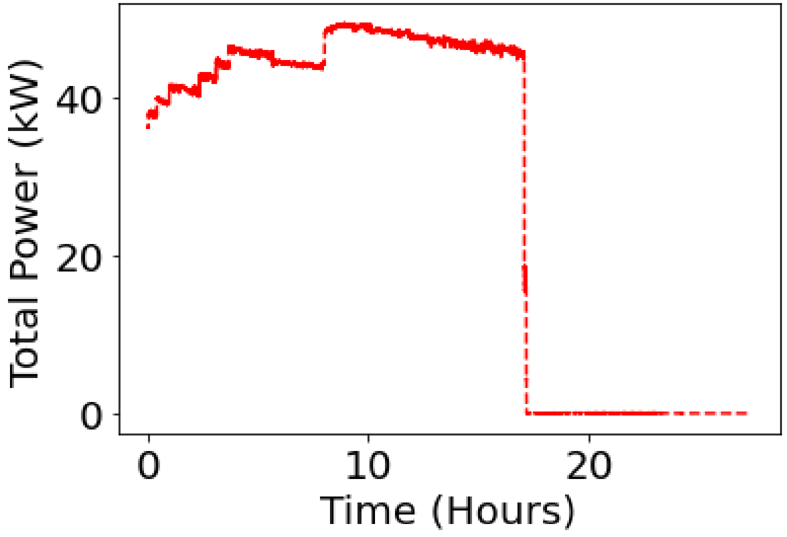


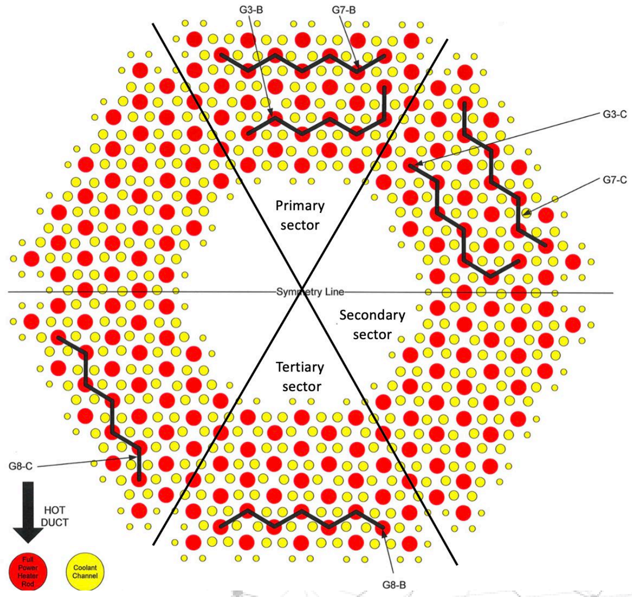
Major lessons from PG-27 modeling

- The ring model fails to predict the transient temperature rise, even when it can predict the steady-state temperature
- Underprediction in transient temperature rise is likely due to the power density issues
- Ring model was developed before the experiments were conducted, and if power was distributed uniformly throughout the facility, it ***may*** have reproduced measured temperatures
- **Lesson:** Models should be built to account for the very local heat generation in HTTF experiments
- **Lesson:** Ring model is incapable of incorporating crossflow or bypass flow that ***may*** have occurred
- **Lesson**: Big rings may not be capturing local TC readings because local temperature may differ from the average temperature in a ring

PG-29 modeling with the ring model

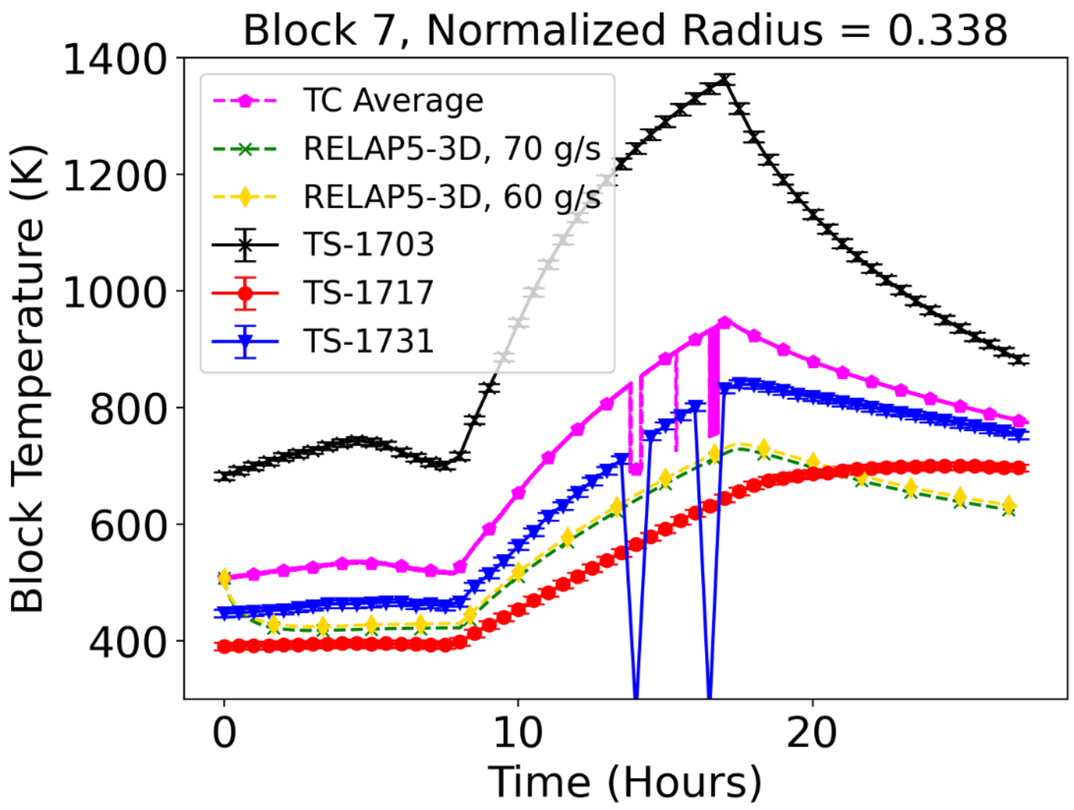
- Asymmetry of heat generation cannot be captured by the ring model
- The same power density problems that were present in PG-27 modeling will also be present here
  - Based on the heater rods used in the primary sector, heat generation is spread throughout the entire ring model
- We assumed each set of heater banks provided equal amounts of heat generation





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



Major lessons from PG-29 modeling

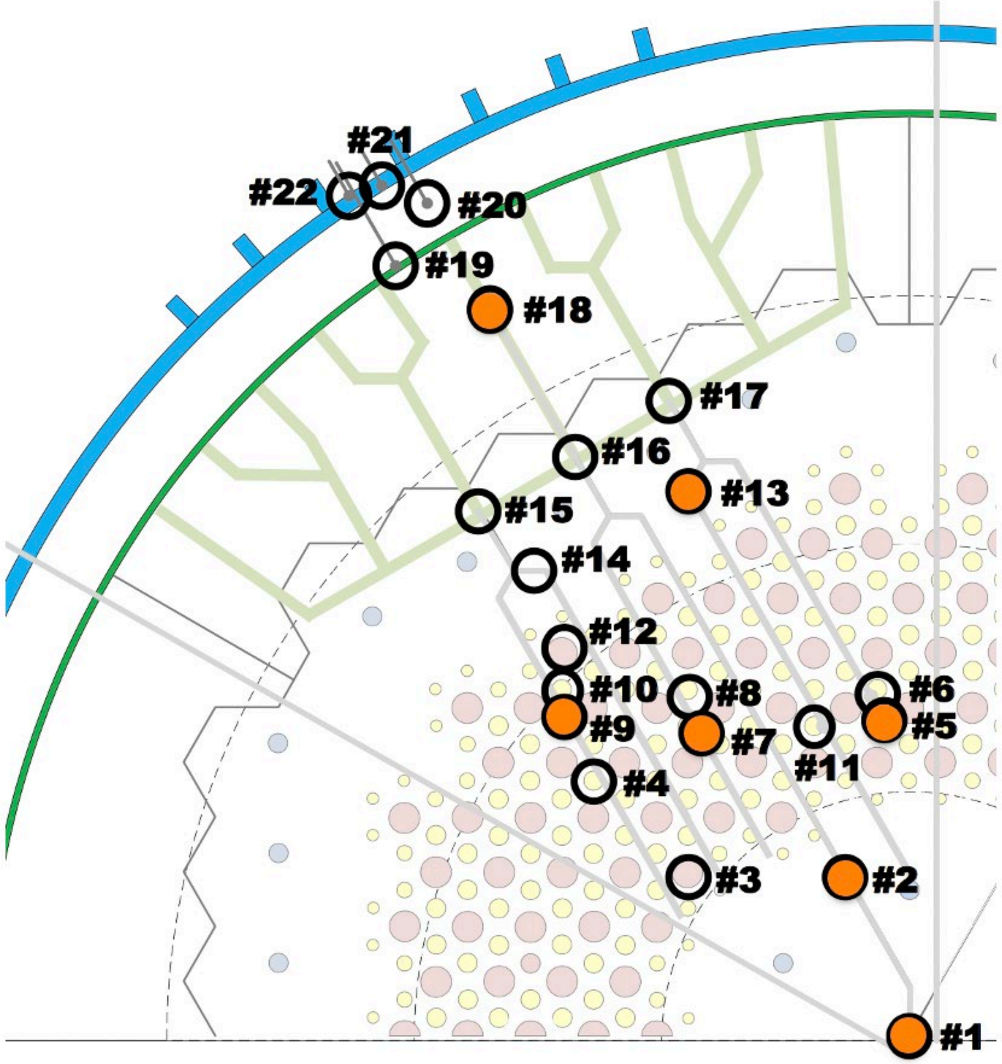
- **Lesson:** The same general underprediction in temperatures during the transient is present in PG-27 and PG-29
  - Problems with power density are exacerbated in PG-29
- **Lesson:** To model PG-29 well, the active core should be modeled in 1/6 azimuthal segments that can communicate through conduction
- **Lesson:** Mean temperature from primary, secondary, and tertiary sector may provide useful trendline for comparison, particularly when sectors aren’t modeled, but it is unlikely that systems code results can be expected to reproduce mean temperature exactly

Overall Lessons Learned

- The RELAP5-3D ring model is too coarsely nodalized to capture HTTF behavior from PG-27 or PG-29 accurately
  - We need more, smaller rings
  - We are capturing the total power but are significantly distorting the power density in the heater rods
- Neglecting the possibility for crossflow or bypass flow may be introducing additional errors
- Without unique heat structures for each azimuthal sector, PG-29 behavior can only be approximated through comparison to the mean TC reading
  - This requires more working TCs than comparing to individual readings
- The thermal conductivity calibration used in this work is likely an overcorrection based on the power density problems

Future RELAP5-3D Modeling of HTTF

- INL plans to develop a new HTTF RELAP5-3D model with a finer nodalization
  - Model each ring of heater rods as a separate heat structure
  - Model each of the azimuthal sectors
- We can repeat previous calibration analyses using the new model and assess the performance of the code using a model that better captures local temperatures and power density
- New calibrations with higher-fidelity model can provide greater insight into RELAP5-3D capabilities for prismatic HTGR analysis



Acknowledgments

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