GAS-COOLED REACTOR
ADVANCED REACTOR TECHNOLOGIES PROGRAM

May 14, 2026

RELAP5-3D in the High Temperature Gas-cooled Reactor Thermal Hydraulics Benchmark

Presented by Robert Kile

Idaho National Laboratory – Nuclear Reactor Technology Division

International RELAP5 Users' Group Meeting

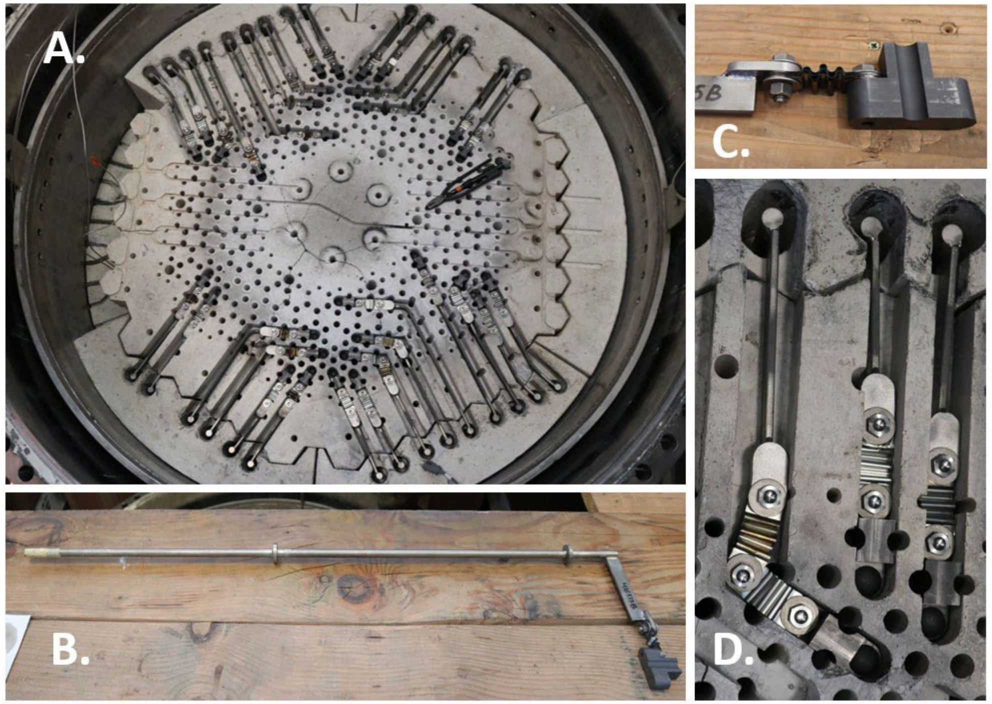
Idaho National Laboratory

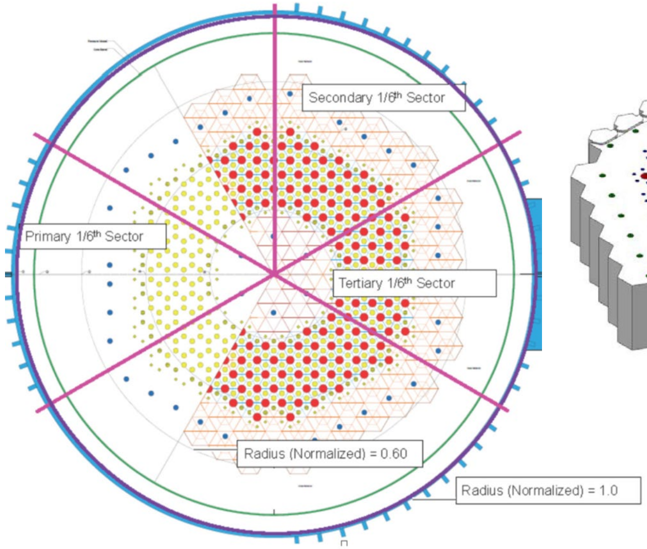
May 18-21, 2026

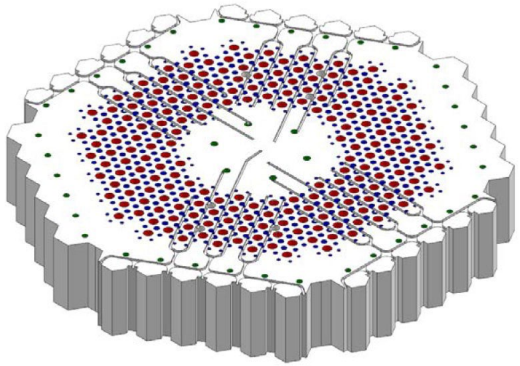
Benchmark Overview and Status

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.

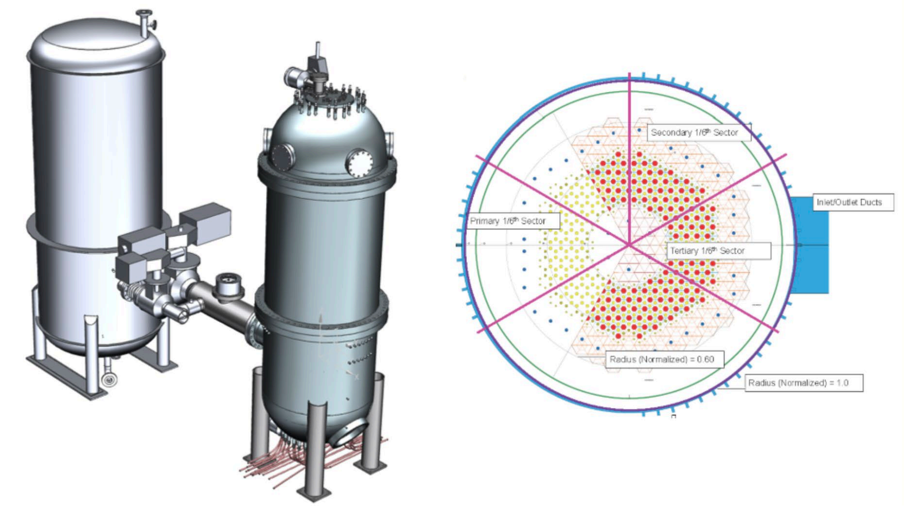
OECD-NEA High Temperature Gas-Cooled Reactor Thermal Hydraulics Code Validation Benchmark

- 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

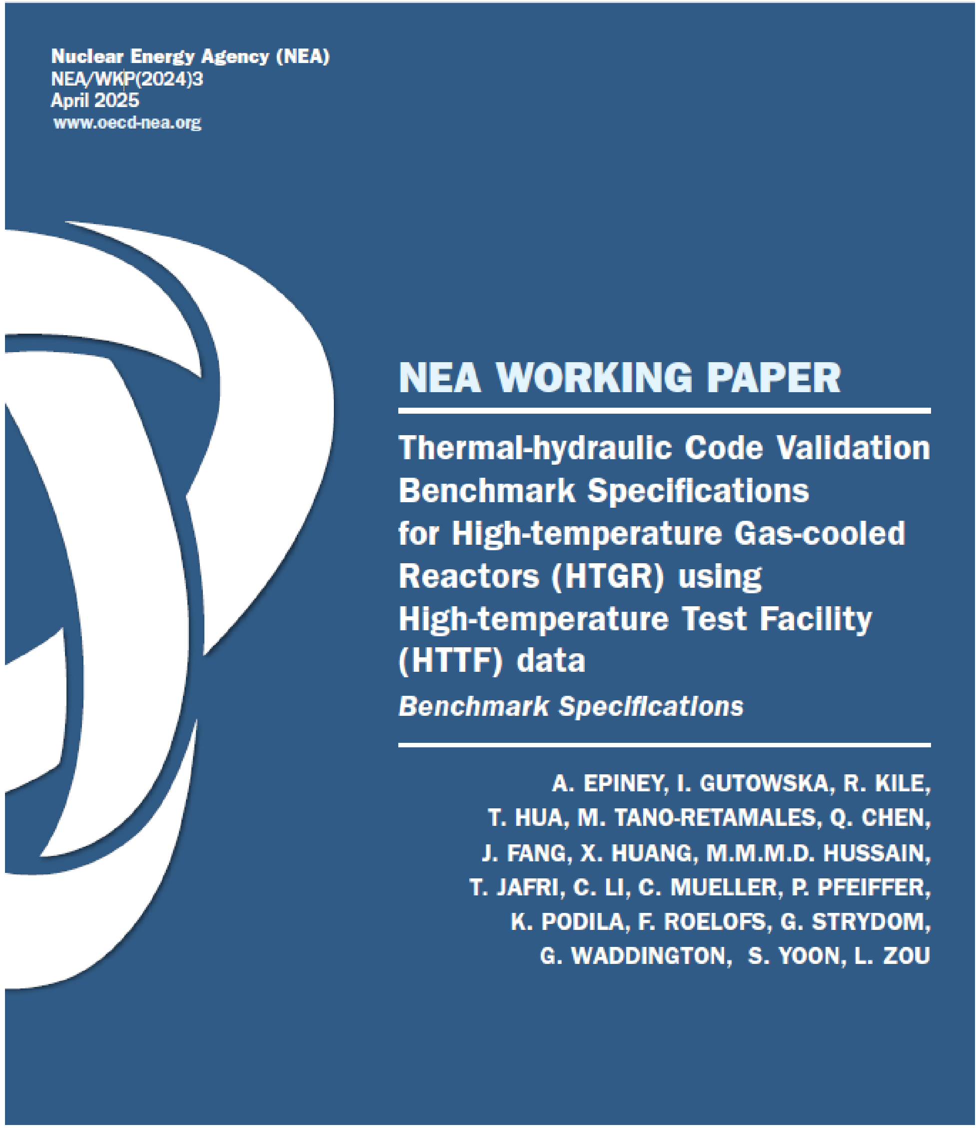
- Benchmark is broken down into 3 problems representing different physical phenomena
- Problems are broken down further into exercises, which represent different modeling approaches
  - Exercise 1: Code-to-Code comparison, fixed boundary conditions
  - Exercise 2: Code-to-Data comparison, open boundary 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

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 Specifications

- Problem 1: two exercises
- Problem 2: three exercises
  - Exercise 1 is broken into 3 sub-exercises
    - 1A: Full-power steady state
    - 1B: DCC from full-power steady state
    - 1C: PG-29-like DCC
- Problem 3: three exercises
  - Exercise 1 is broken into four sub-exercises
    - 1A: Full-power steady state
    - 1B: PCC from full-power steady state
    - 1C: PG-27-like low-power steady state
    - 1D: PG-27-like low-power PCC

The specifications V1 published April 2025


Nuclear Energy Agency (NEA)
NEA/WKP(2024)3
April 2025
www.oecd-nea.org

NEA WORKING PAPER

Thermal-hydraulic Code Validation Benchmark Specifications for High-temperature Gas-cooled Reactors (HTGR) using High-temperature Test Facility (HTTF) data

Benchmark Specifications

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Participants I (Registered)

- **13 countries, 31 institutions**
  - **Belgium**: Von Karman Institute (VKI), Tractebel
  - **Bulgaria**: Sofia University
  - **Canada**: Canadian Nuclear Laboratories (CNL), McMaster University, Canadian Nuclear Safety Commission (CNSC)
  - **Finland**: Technical Research Centre of Finland (VTT)
  - **France**: Framatome, Électricité de France (EDF), French Alternative Energies and Atomic Energy Commission (CEA), Institut de radioprotection et de sûreté nucléaire (IRSN)
  - **Hungary**: Hungarian Research Network (EK-CER)
  - **Italy**: Nuclear and Industrial Engineering (NINE)
  - **Korea**: Korea Atomic Energy Research Institute (KAERI), Gachon University, Ulsan National Institute of Science & Technology (UNIST)
  - **Netherlands**: Nuclear Research and Consultancy Group (NRG)

Participants II (Registered)

- continued
  - **Switzerland**: Paul Scherrer Institute (PSI)
  - **Turkey**: Istanbul Technical University (ITU)
  - **United Kingdom**: Jacobs, Bangor University, National Nuclear Laboratory (NNL)
  - **United States**: North Carolina State University (NCSU), Idaho National Laboratory (INL), Argonne National Laboratory (ANL), Oregon State University (OSU), Texas A&M, University of Michigan, University of Illinois Urbana-Champaign, Numerical Advisory Solutions

Benchmark Status

- Final report is being compiled
- Fourth International Workshop on the HTGR T/H Benchmark was held in Ontario, Canada May 14, 2026 – Some participants are revising their models based on comparisons presented at the workshop
- Final report will be submitted to the Organization for Economic Cooperation and Development – Nuclear Energy Agency this fiscal year

The Role of RELAP5-3D in this benchmark

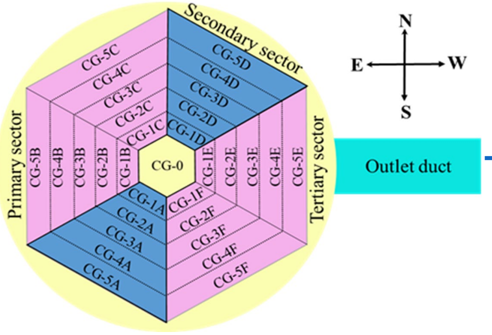
- Defining conditions for analysis
  - Boundary conditions for CFD Analysis
  - Defining Error Scaling Conditions
- RELAP5-3D solutions submitted by INL
  - Problem 2
  - Problem 3

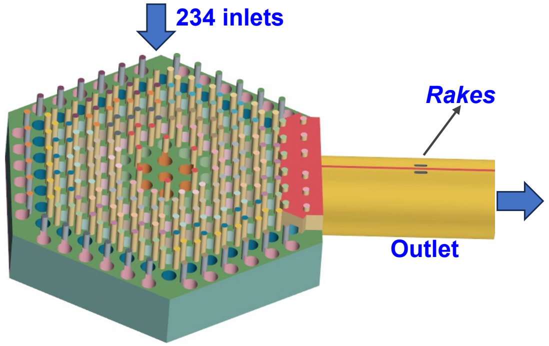
Development of Problem 1 Boundary Conditions

Problem 1 Exercise 1: Code-to-Code Comparison

- Boundary conditions for Problem 1 Exercise 1 were developed using a RELAP5-3D model from Canadian Nuclear Laboratories
- RELAP5-3D model of full-power steady state was used to generate inlet temperature and flow distribution

Parameter	Value
Helium Inlet Temperature (K)	500.0
Helium Pressure (MPa)	0.7
Helium Flow Rate (kg/s)	1.0
RCCS Inlet Temperature (K)	313.2
RCCS Pressure (MPa)	0.1
RCCS Flow Rate (kg/s)	1.0
RCCS Cavity Air Inlet Temperature (K)	300.0
RCCS Cavity Air Flow (g/s)	25.0
Core Power (MW)	2.2

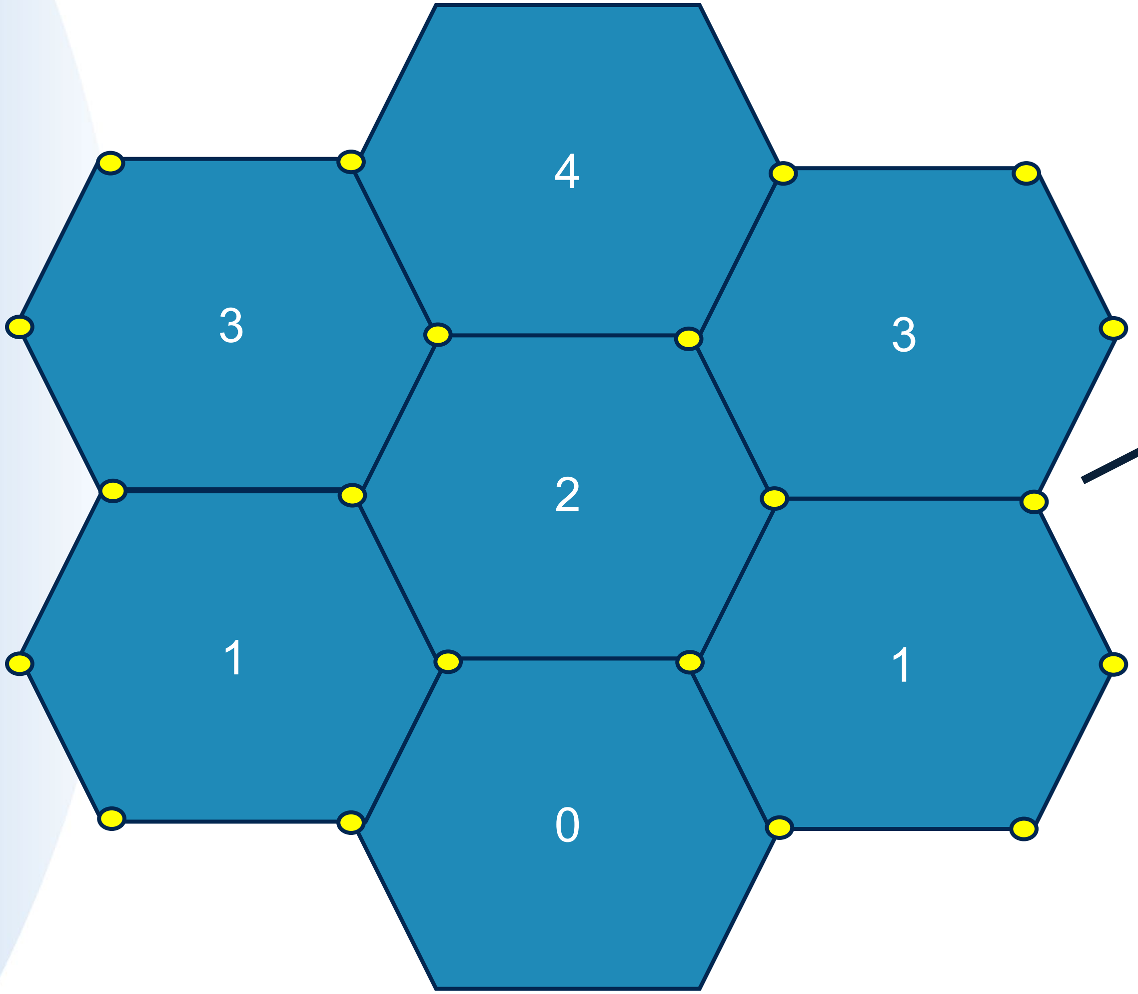


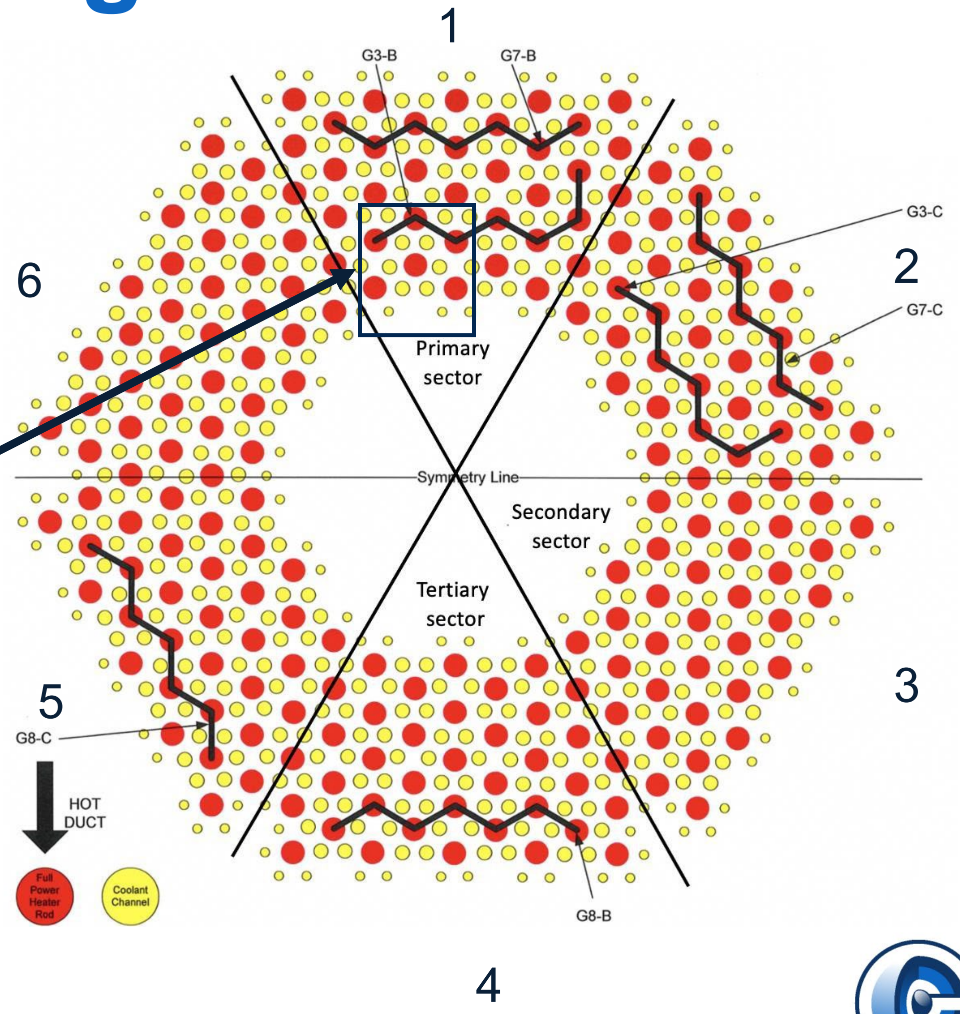


Problem 1 Exercise 2: Code-to-Data Comparison

- Boundary conditions informed by INL 6-sector RELAP5-3D model based on best-estimate PG-28 boundary conditions
- INL RELAP5-3D model is based on hex-unit cells
- Needed heat generation profile that includes asymmetric heat generation

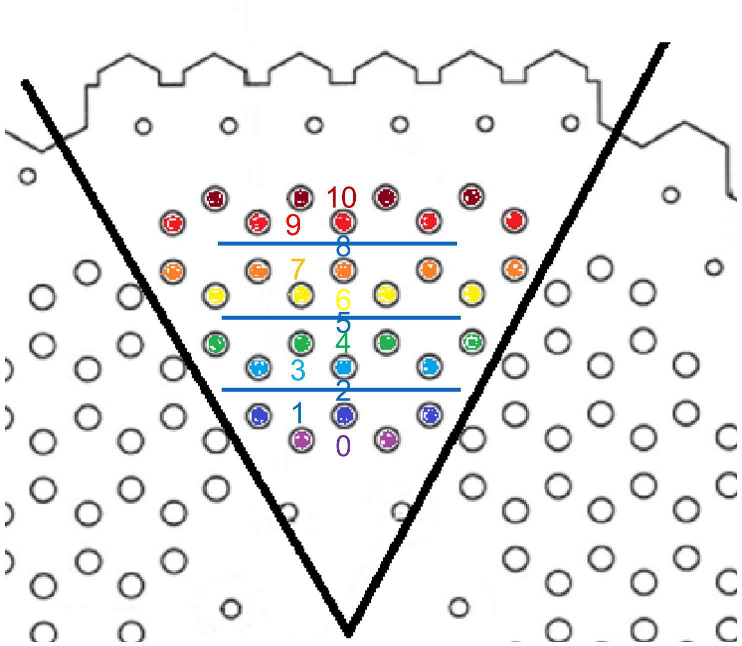
RELAP model is based around a hex unit cell rather than rings





Boundary conditions were mapped from hex space into CFD grid coordinates

- RELAP unit cells were based on the core rather than the plenum inlet
- Cells 2, 5, and 8 did not directly overlap a lower reflector coolant channel and were mapped to collectors

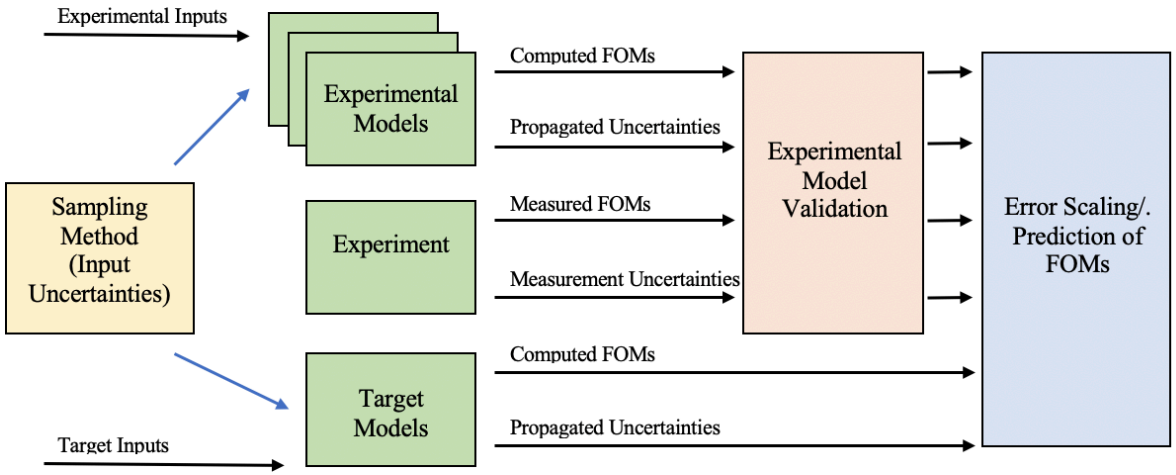


		FRACTIONAL CONTRIBUTION TO RING #										
		0	1	2	3	4	5	6	7	8	9	10
HEX GROUP	0	1/2	1/2	0	0	0	0	0	0	0	0	0
	1	1/6	2/3	0	1/6	0	0	0	0	0	0	0
	2	1/6	1/3	0	1/3	1/6	0	0	0	0	0	0
	3	0	1/6	0	1/2	1/3	0	0	0	0	0	0
	4	0	0	0	1/3	1/2	0	1/6	0	0	0	0
	5	0	1/6	0	1/6	1/3	0	1/6	1/6	0	0	0
	6	0	0	0	0	1/6	0	1/2	1/3	0	0	0
	7	0	0	0	0	0	0	1/3	1/2	0	1/6	0
	8	0	0	0	0	0	0	1/6	1/3	0	1/2	0
	9	0	0	0	0	0	0	0	1/6	0	1/2	1/3
	10	0	0	0	0	0	0	0	0	0	1/2	1/2

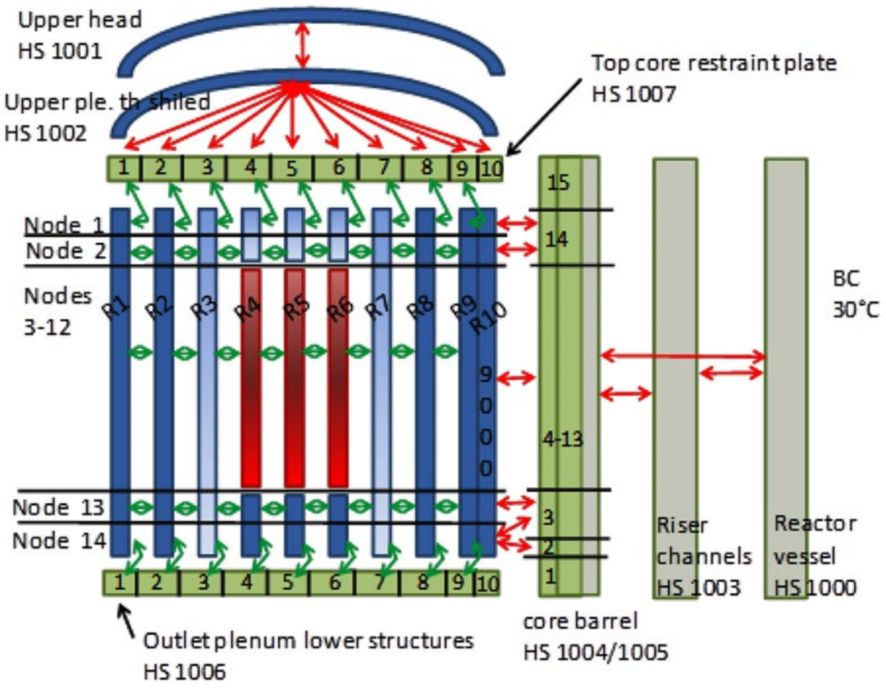
Development of Problem 2 and 3 Error Scaling Conditions

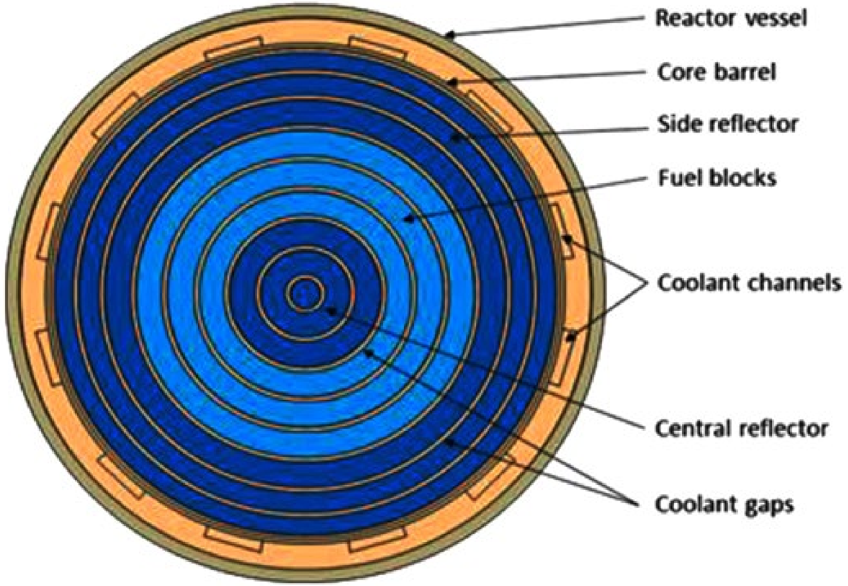
What is error scaling?

- HTTF is a scaled test facility for the MHTGR-350
- We performed validation analysis based on HTTF, but what does that mean for the MHTGR-350?
  - Power is 175x higher than HTTF
  - Reactor volume is 64x bigger than HTTF
- If we do uncertainty quantification using our HTTF models, what does that tell us about code capabilities for the MHTGR-350?



We have an existing RELAP5-3D model of the MHTGR-350 to generate results for the target plant





Two approaches used in this benchmark

Hierarchical Two-Tiered Scaling (H2TS)

- Assess the value of dimensionless parameters between models of the scaled facility (HTTF) and the target application (MHTGR-350)
- Calculate a “distortion factor” between the scaled facility and target application

Representativity

- Generate sensitivity matrices for scaled facility and target application
- Perform vector projection of scaled facility sensitivity matrix onto target application sensitivity matrix
- Calculate a parameter called “Representativity” which is essentially the magnitude of the vector projection

MHTGR-350 results for both approaches were generated with RELAP5-3D

RELAP5-3D Validation Based on HTTF

Two HTTF experiments shown here

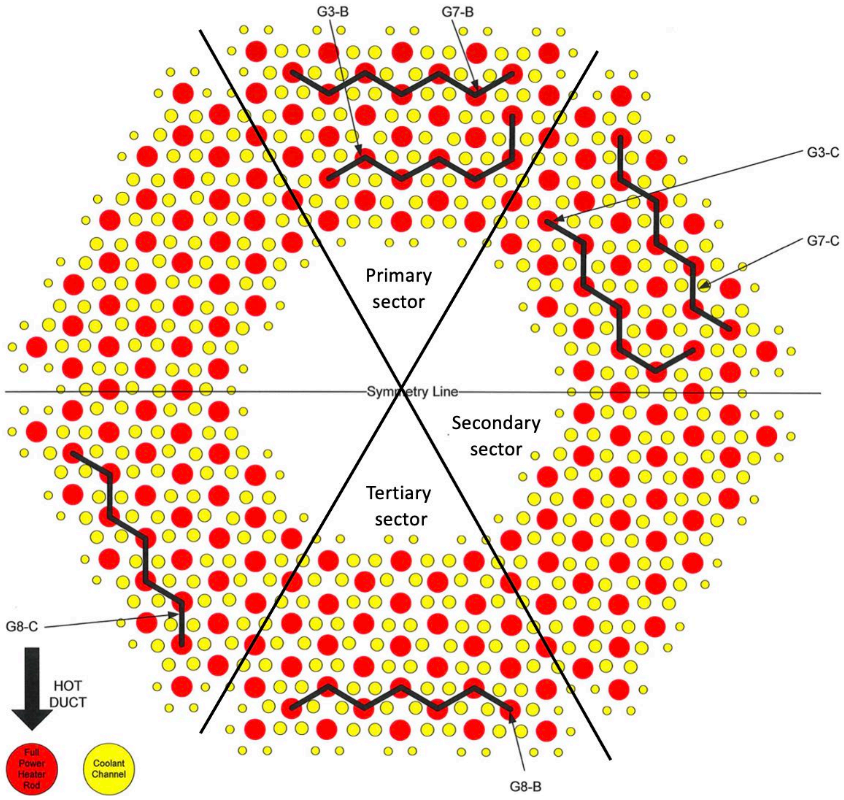
PG-29

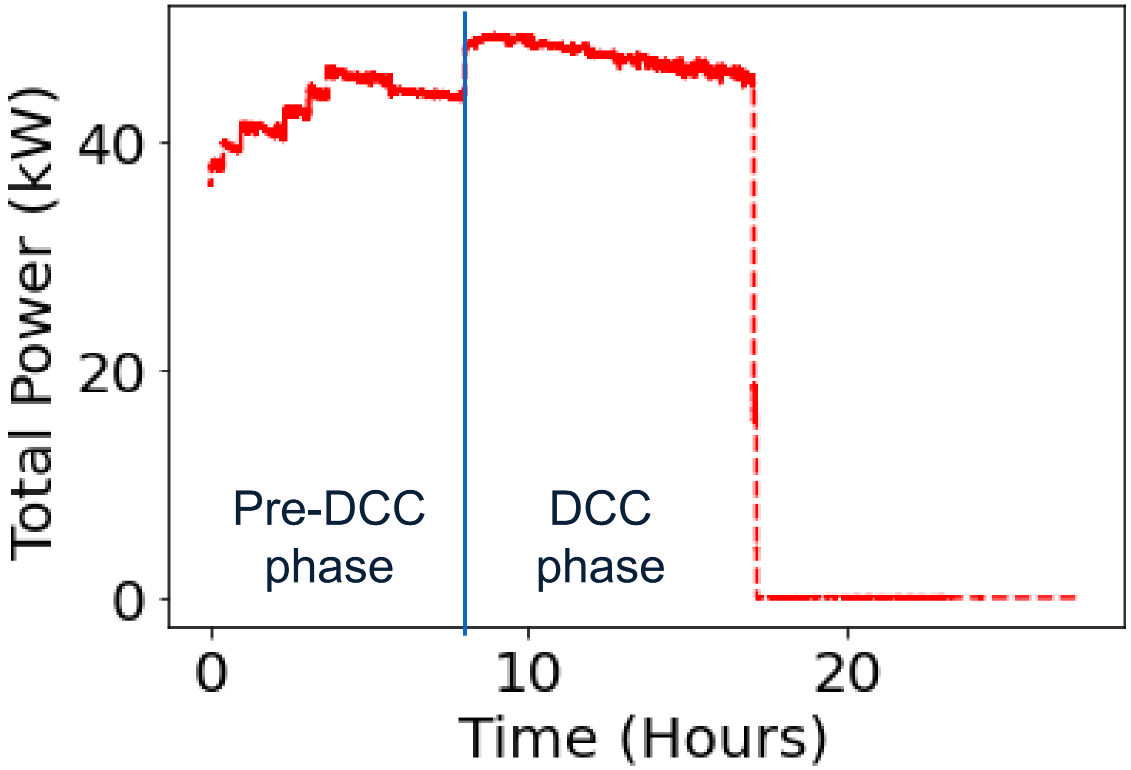
- Depressurized Conduction Cooldown (DCC)
- DCC starts at 8 hours but no steady state
- Asymmetric power distribution
- Includes comparisons with other codes

PG-27

- Pressurized Conduction Cooldown (PCC)
- PCC starts at 9.3 hours
- Symmetric Power distribution
- Comparison between 2 RELAP models, but no comparison to other codes

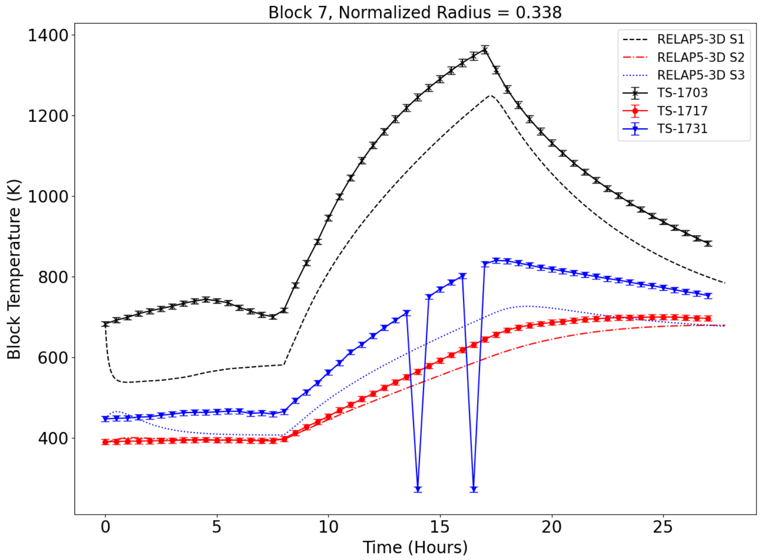
Problem 2 is the Depressurized Conduction Cooldown, based on PG-29

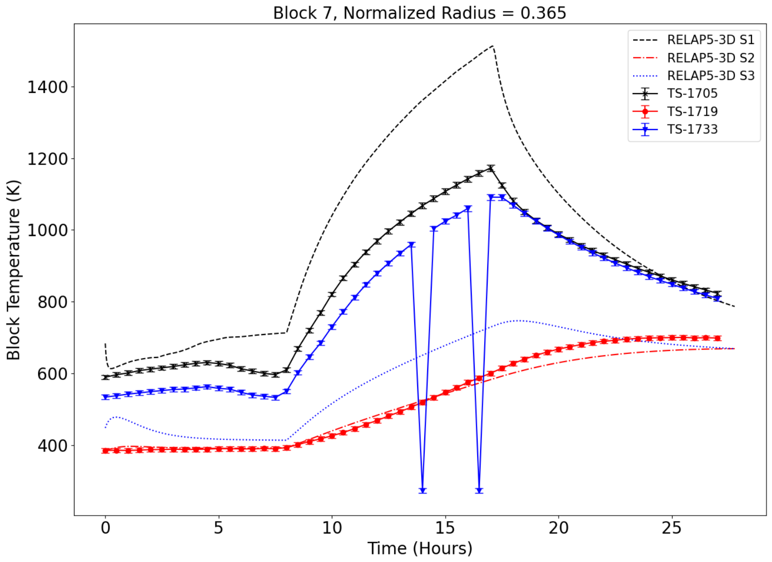


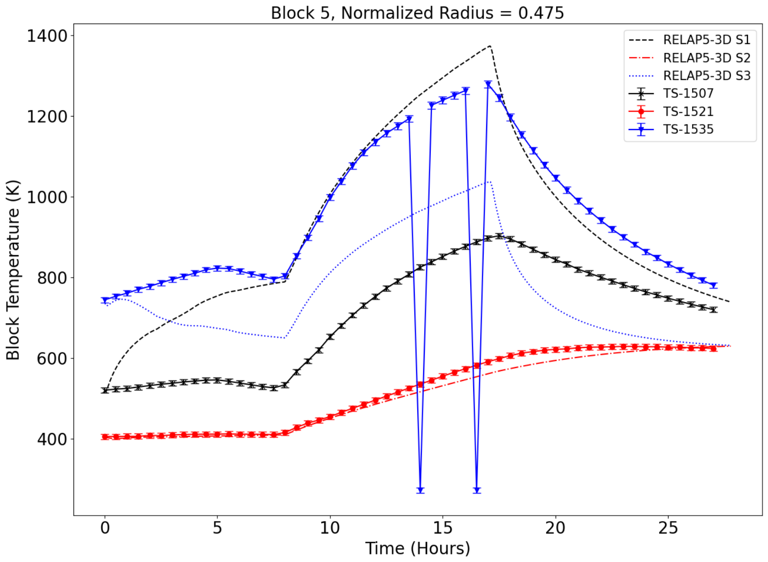


Started from the assumption that power is distributed uniformly among all active rods

- Moving radially outward, we would significantly overpredict temperature in the primary sector and underpredict in the tertiary sector

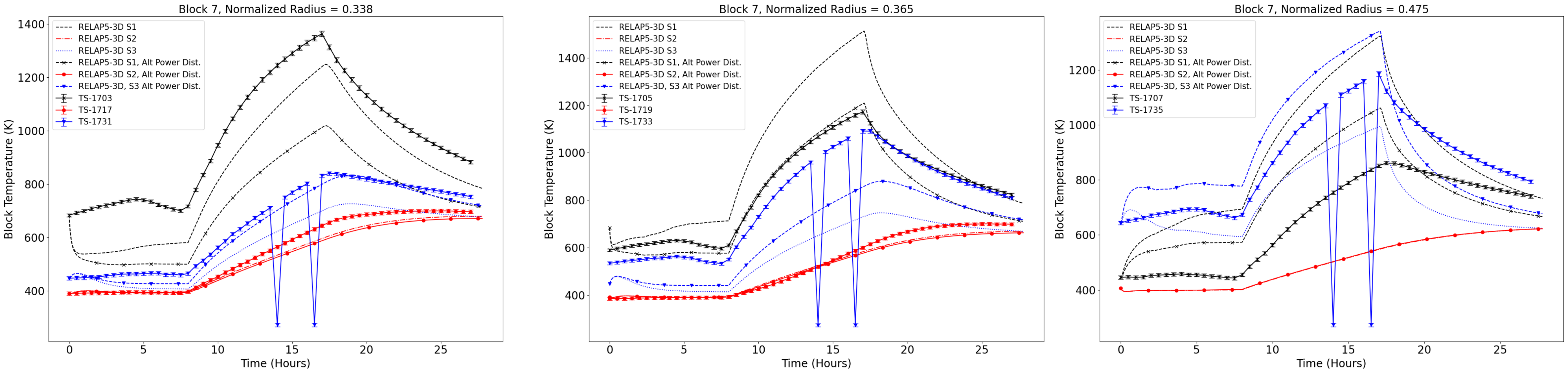




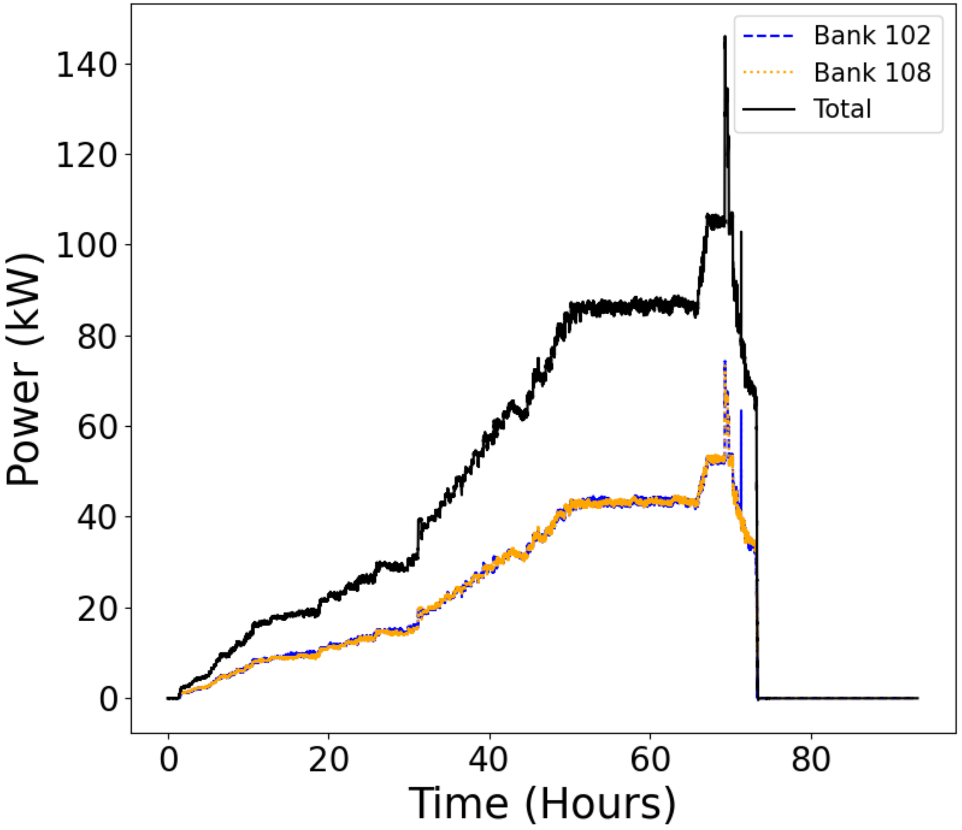


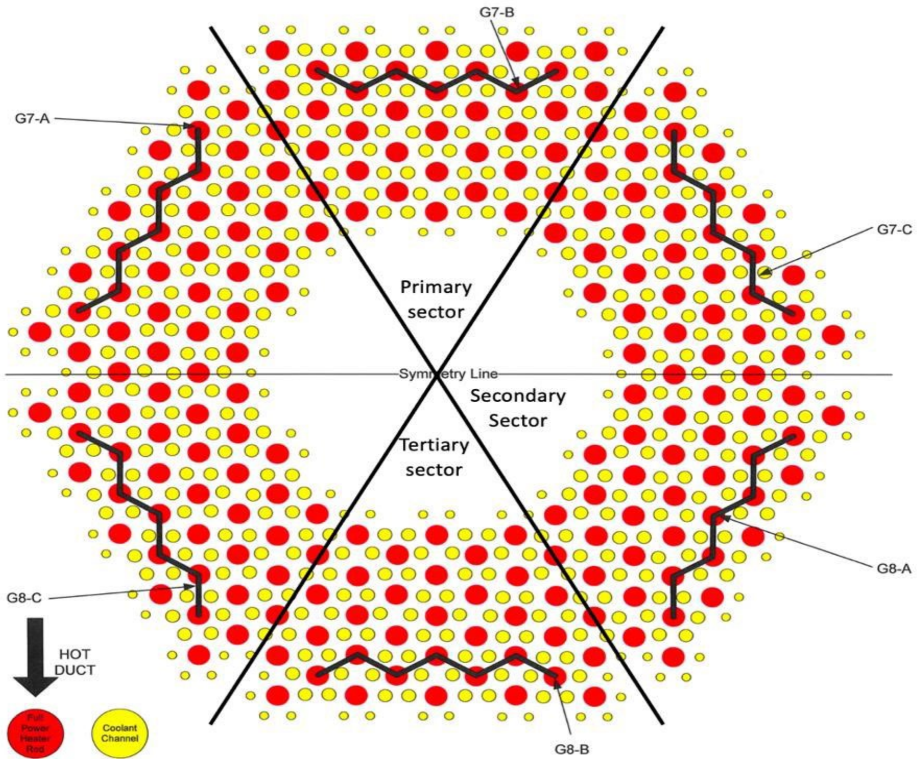
What if the power per sector was uniform?

- We tested that and saw much better performance in the outer core
- While predictions are now fairly good in the core, no predictions in the inner or outer reflectors were good



Problem 3 is the pressurized conduction cooldown, based on PG-27

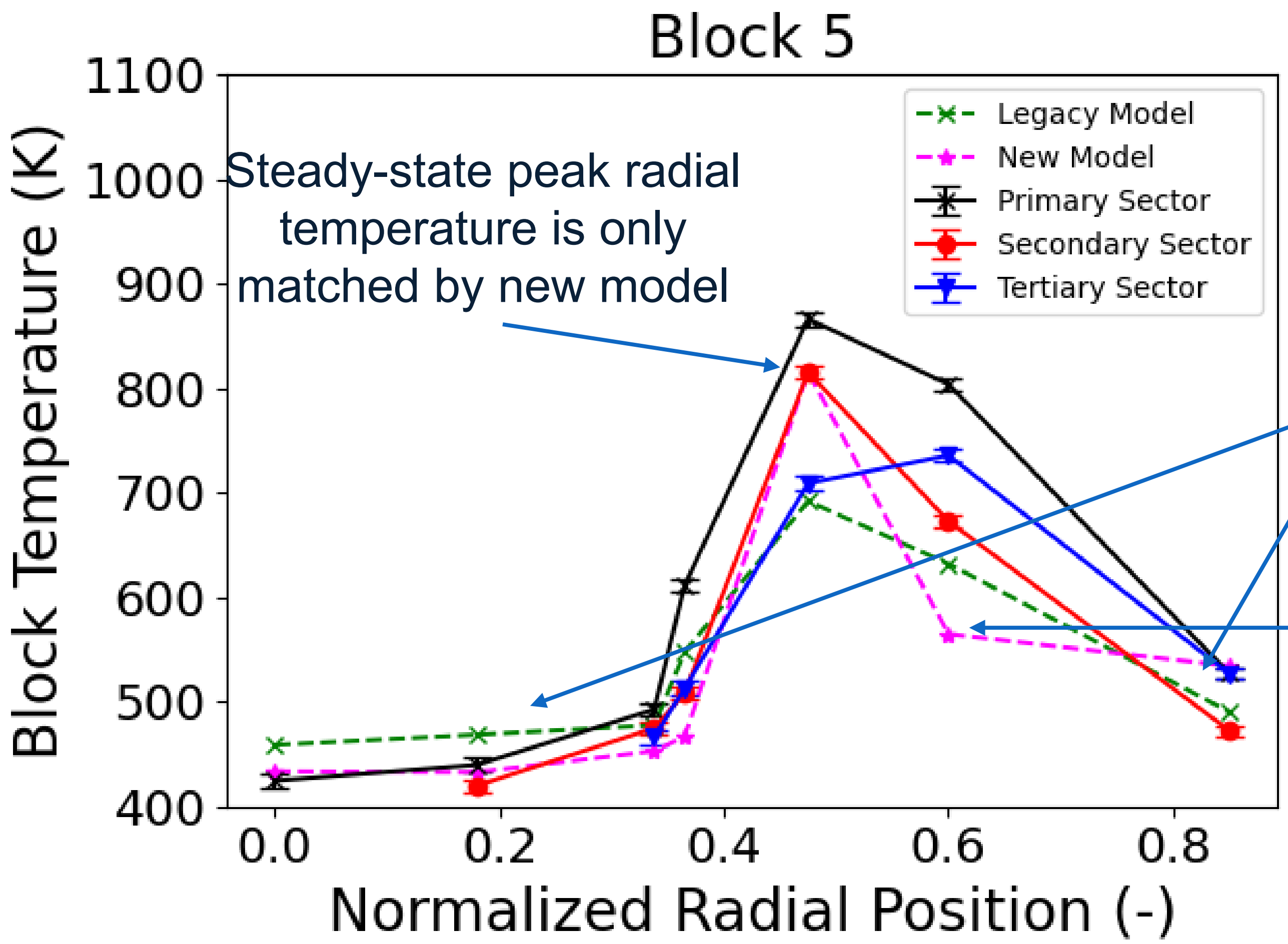




We compared 2 models against PG-27

- Legacy model was developed from 2015-2018
  - Modeled core with concentric “ring” approach
  - 3 unit cells for inner reflector
  - 3 unit cells for core
  - 3 unit cells for outer reflector
  - 1 unit cell for permanent side reflector (PSR)
- New model was developed from 2023-2025
  - Modeled 6 individual sectors
  - 1 central ring
  - 1 inner reflector cell per sector
  - 9 heater rod cells per sector
  - 11 coolant cells for core per sector
  - 2 unit cells for outer reflector per sector
  - 1 unit cell for permanent reflector per sector

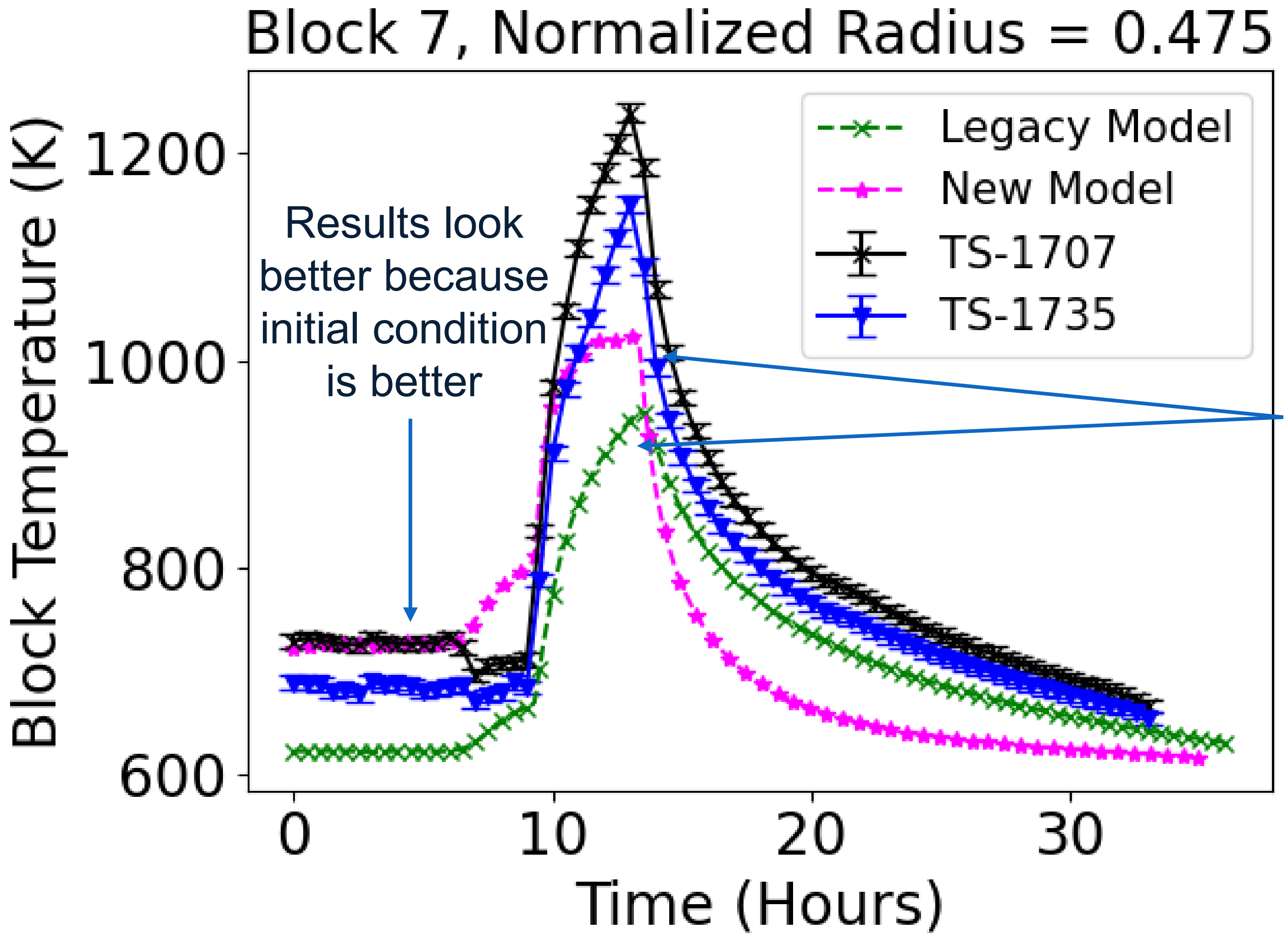
New model shows considerably improved steady-state temperatures



Inner and permanent reflector temperatures are well-predicted

Outer reflector temperature is poorly matched due to differences in heat structure model

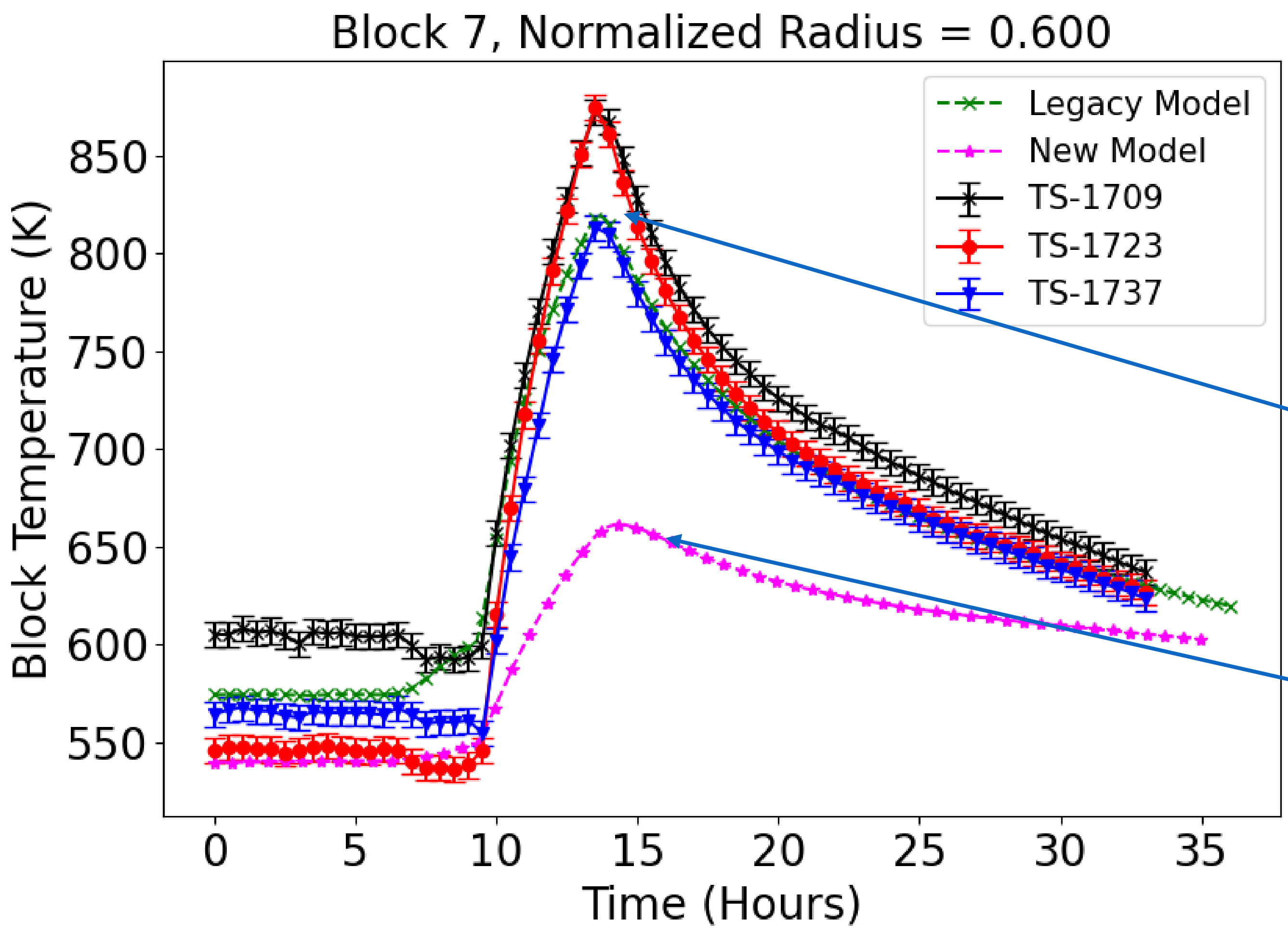
Transient temperatures rise less in the new model



Results look better because initial condition is better

Peak temperature is higher but temperature rise is lower

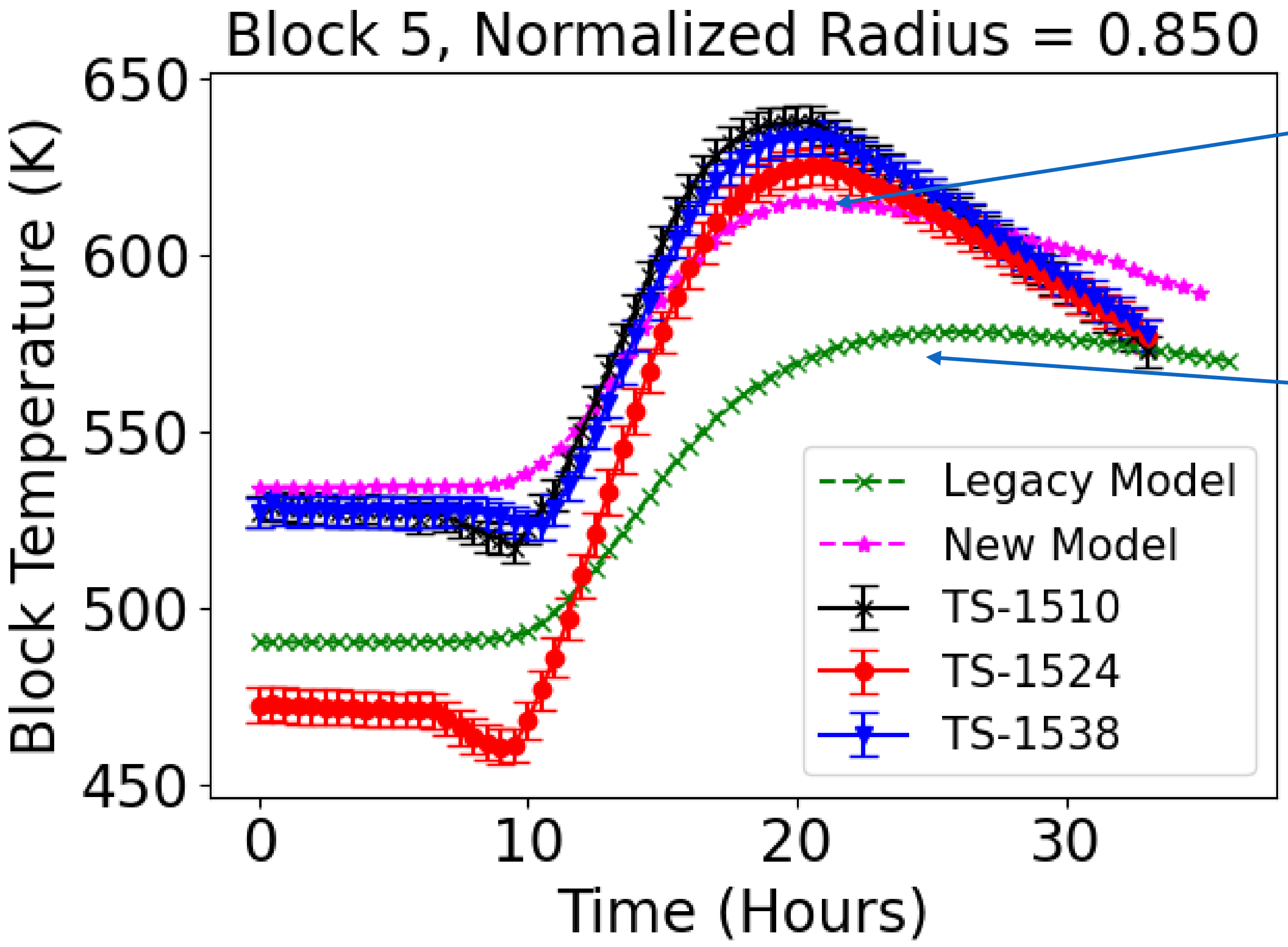
Performance in some reflector regions is worse due to new assumptions



Legacy model predicts temperature in the outer reflector region beautifully

New model has good initial condition but much too low transient

Performance in permanent reflector is better with new model



Temperature rise is slightly too low in new model, but temperatures are close to measured ones

Temperature rise in legacy model is between that of secondary sector and other two, but transient temperatures mostly outside uncertainty range

RELAP5-3D Validation Activity Summary

- RELAP5-3D results for sector model with PG-29 show struggles away from heat sources but good performance in the heated regions
- Refined RELAP5-3D model predicts better steady-state temperatures but lower temperature rise in PG-27
- RELAP5-3D captures trends very well, but systems code level resolution will probably never capture thermocouple values perfectly without extreme calibration

Wrapping Up

- RELAP5-3D has played a ***huge*** role in this benchmark
- The HTGR T/H Benchmark is proceeding with the final report being drafted now
- RELAP5-3D validation based on PG-29 shows that the new model can capture asymmetry and reproduces temperatures reasonably well near active heaters but struggles in other locations
- RELAP5-3D validation based on PG-27 shows improved steady-state performance but lower transient temperature rise

Acknowledgements

- Thank you all of the benchmark organizers and participants for their hard work these last few years
- Special thank you to Jonathan Barthle for his work postprocessing a large number of results
- This work was funded by the United States Department of Energy – Office of Nuclear Energy's Advanced Reactor Technologies – Gas-cooled Reactor Program

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