GAS-COOLED REACTOR
ADVANCED REACTOR TECHNOLOGIES PROGRAM

July 29, 2025

Current Status of the HTGR T/H Benchmark and RELAP5-3D Validation Activities

Robert F. Kile, Aaron S. Epiney

Advanced Reactor R&D Engineer – Idaho National Laboratory

INL/CON-25-86028

DOE ART GCR Review Meeting

Hybrid Meeting at INL

July 29–30, 2025

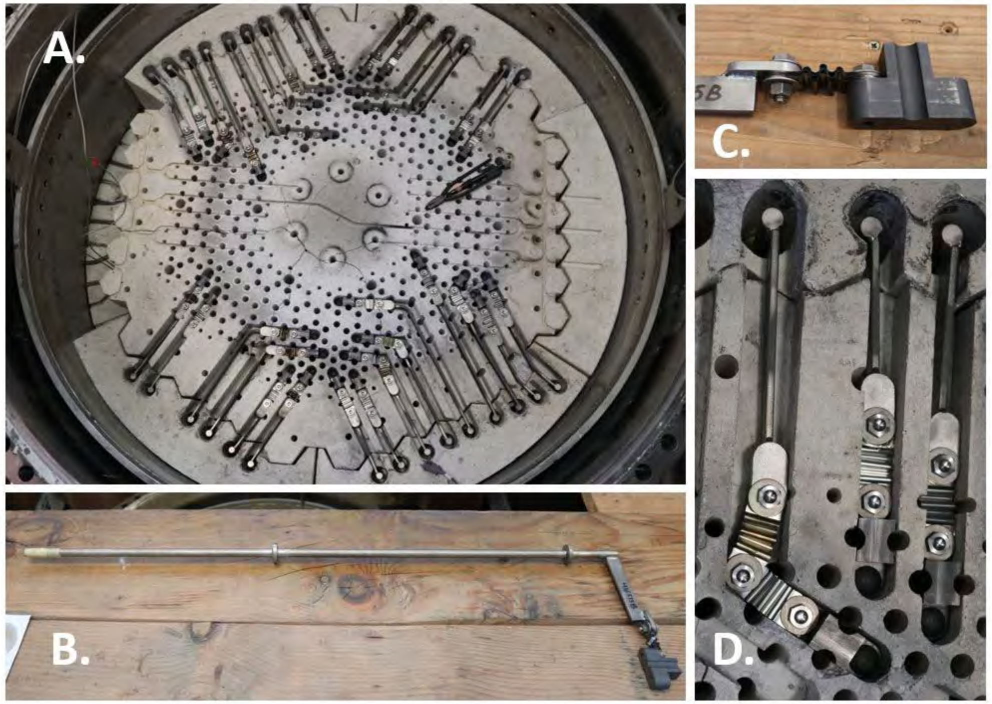
Introduction

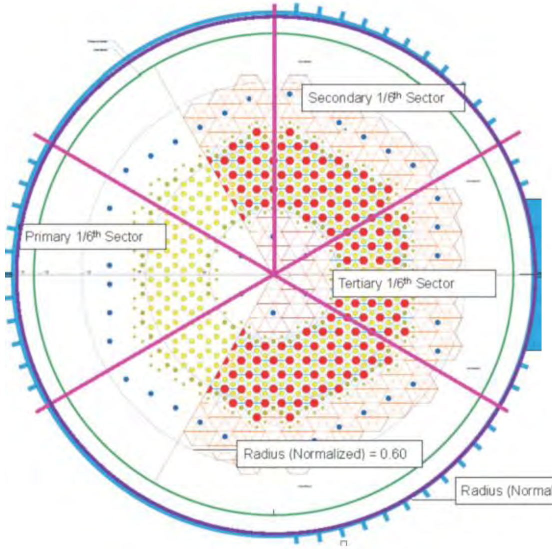
- Prismatic High Temperature Gas-cooled reactors (HTGRs) are a concept approaching deployment
  - BWXT
  - Radiant Nuclear
- Deploying these reactors requires modeling and simulation tools that have been validated for these systems, but most thermal hydraulics modeling and simulation tools were developed and validated for Light Water Reactors (LWRs)
  - Objective in this work is to validate RELAP5-3D for prismatic HTGR modeling based on High Temperature Test Facility (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 HTTF
  - In collaboration with Argonne National Lab/NEAMS Program, Oregon State University, Canadian Nuclear Labs, NRG, KAERI

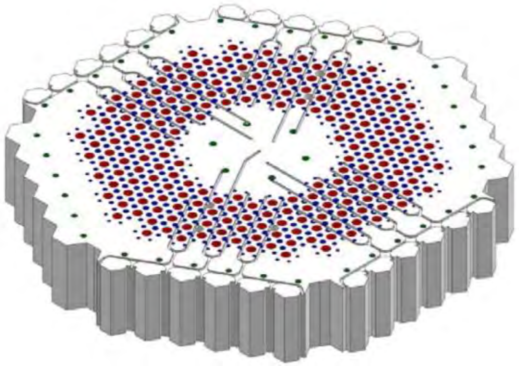
Benchmark Overview and Status

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



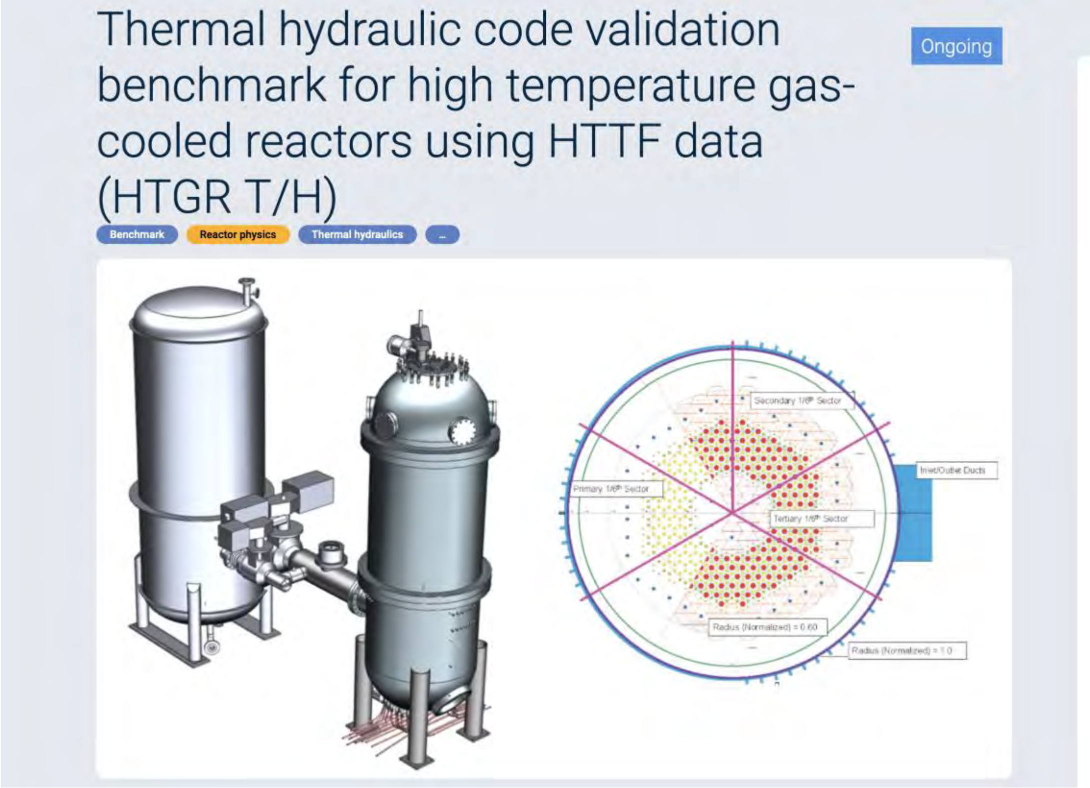




Gutowska, I. and Woods, B., “OSU High Temperature Test Facility Design Technical Report,” OSU-HTTF-ADMIN-005-R2, Oregon State University, Corvallis, OR, 2019.

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



Benchmark Problems and Exercises

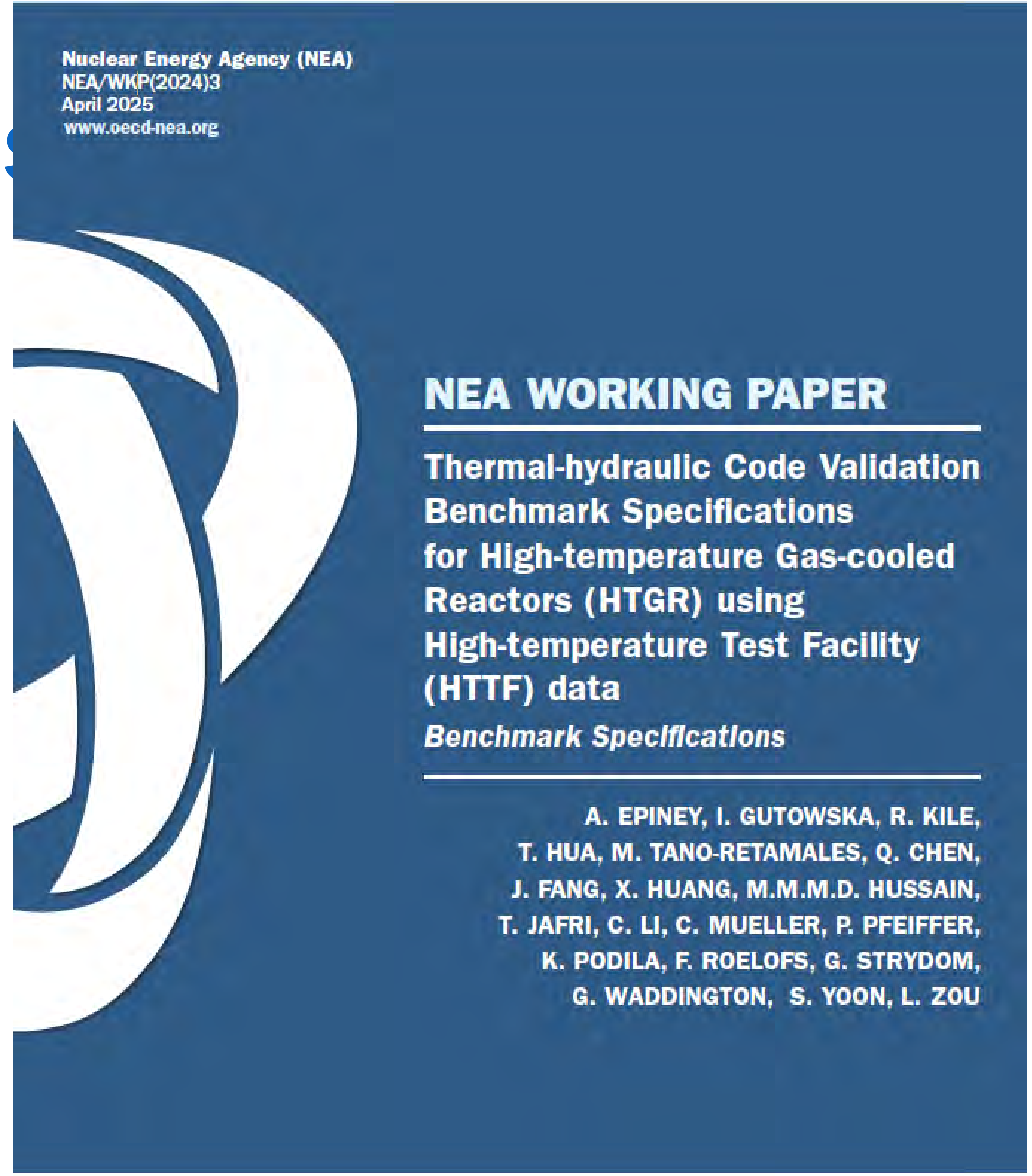
- Benchmark is broken down into 3 problems representing different physical phenomena
- Problems are broken down further into exercises, which represent different modeling approaches
  - Exercise 1: Code-to-Code comparison, fixed boundary conditions
  - Exercise 2: Code-to-Data comparison, open boundary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

A. EPINEY, I. GUTOWSKA, R. KILE, T. HUA, M. TANO-RETAMALES, Q. CHEN, J. FANG, X. HUANG, M.M.M.D. HUSSAIN, T. JAFRI, C. LI, C. MUELLER, P. PFEIFFER, K. PODILA, F. ROELOFS, G. STRYDOM, G. WADDINGTON, S. YOON, L. ZOU

Participants I

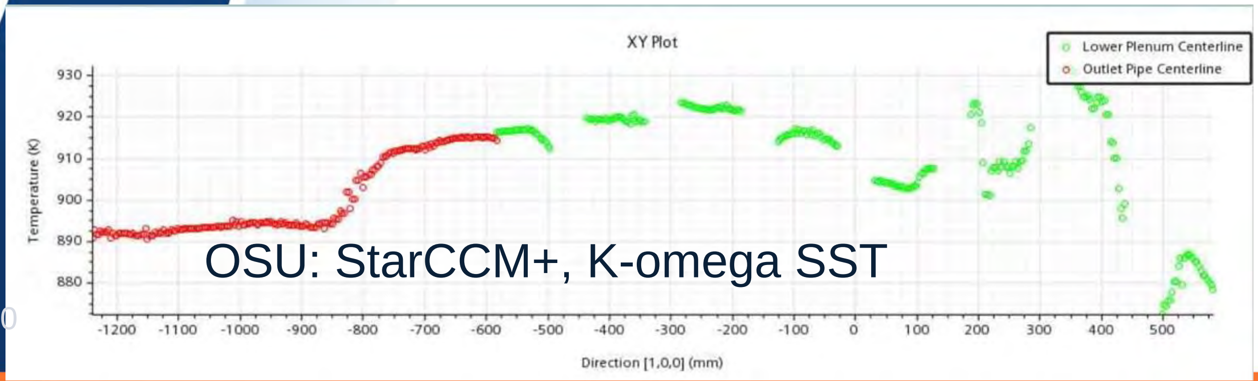
- **13 countries, 31 institutions**
  - **Belgium**: Von Karman Institute (VKI), Tractebel
  - **Bulgaria**: Sofia University
  - **Canada**: Canadian Nuclear Laboratories (CNL), McMaster University, Canadian Nuclear Safety Commission (CNSC)
  - **Finland**: Technical Research Centre of Finland (VTT)
  - **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

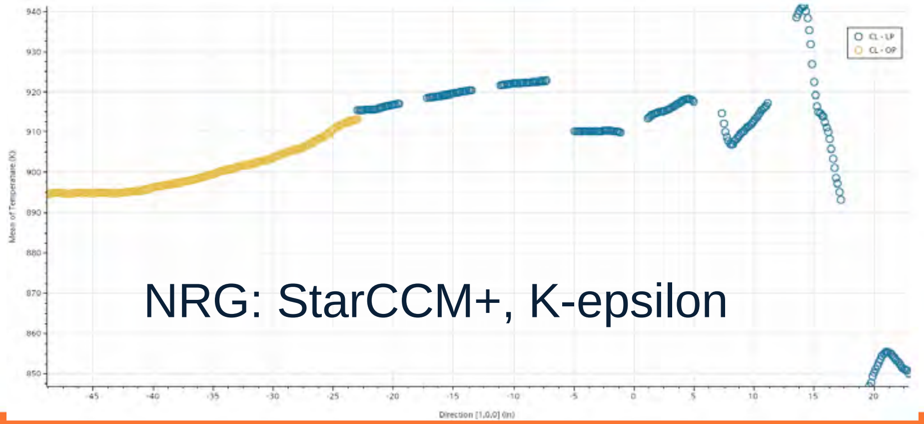
- continued
  - **Switzerland**: Paul Scherrer Institute (PSI)
  - **Turkey**: Istanbul Technical University (ITU)
  - **United Kingdom**: Jacobs, Bangor University, National Nuclear Laboratory (NNL)
  - **United States**: North Carolina State University (NCSU), Idaho National Laboratory (INL), Argonne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

Status of Benchmark Problem 1: Lower Plenum

- Lead: Oregon State University (Izabela Gutowska)
  - Coupled problems: Idaho National Laboratory (Mauricio Tano Retamales / Sinan Okyay)
- 13 participants registered for Problem 1 Exercise 1 **(+1 form last year**):
  - ANL, INL, OSU, CNL, NRG, CEA, Framatome, Gachon University, NCBJ, NCSU, NINE, Tractebel, **von Karman Institute for Fluid Dynamics (VKI)**
- 6 participants registered for Problem 1 Exercise 2 (**all new**):
  - INL, CNL, Framatome, NCSU, NRG, OSU
- Quarterly meetings
- Example solution: Temperature distribution across the domain centerline

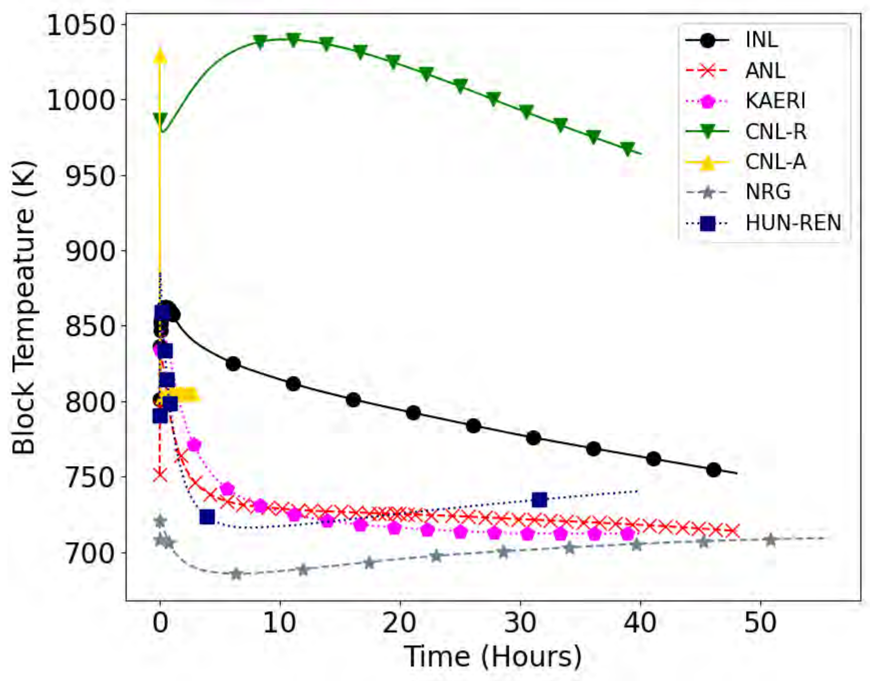


OSU: StarCCM+, K-omega SST


NRG: StarCCM+, K-epsilon

Status of Benchmark Problem 2: DCC

- Lead: Idaho National Laboratory (Robert Kile)
- 11 registered participants (**up 3 from last year**):
  - ANL, CNL, Framatome, INL (**two solutions**), Numerical Advisory Solutions, NCSU, NRG, Tractebel, **KAERI**, **Hungary (CER-EK)**
  - Currently collecting results for Exercise 1C and 2
  - Still waiting on some Exercise 1C Results
- Next quarterly joint with Problem 3
- Sample results from Exercise 1B shown on right

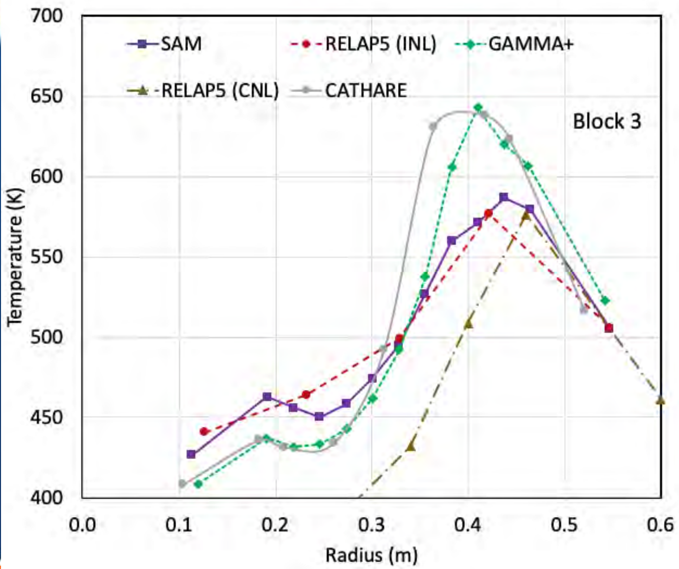


Block temperatures during the DCC in the outer portion of the reactor core near the top of the reactor.

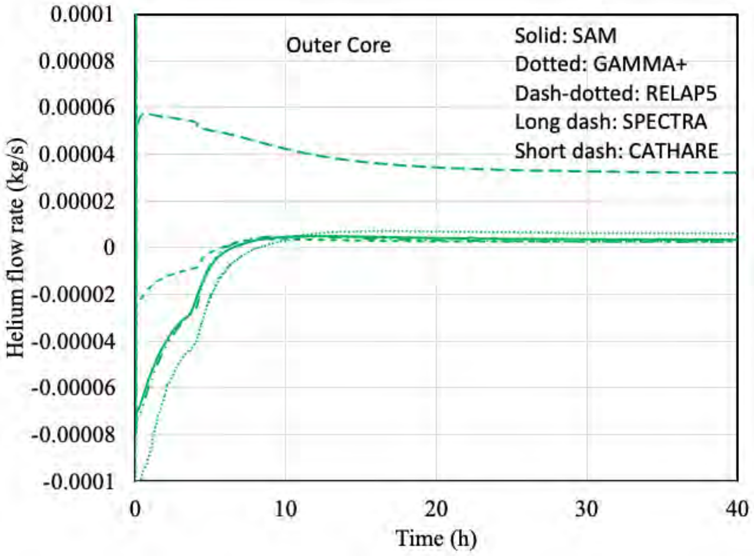
Status of Benchmark Problem 3: PCC

- Lead: Argonne National Laboratory (Thanh Hua)
- Eleven institutions have registered for Problem 3 (**no change**):
  - INL, ANL, CNL, NRG, KAERI, NCBJ, Framatome, McMaster University, Numerical Advisory Solutions, NC State University, and Tractebel
  - ANL, INL, KAERI, CNL, NRG, HUN-REN-EK have submitted results for Problem 3: Ex 1C, 1D (low power steady state and PCC). Results will be presented in upcoming NURETH-21 conference (9/25)
- Problems 2 and 3 joint quarterly meetings

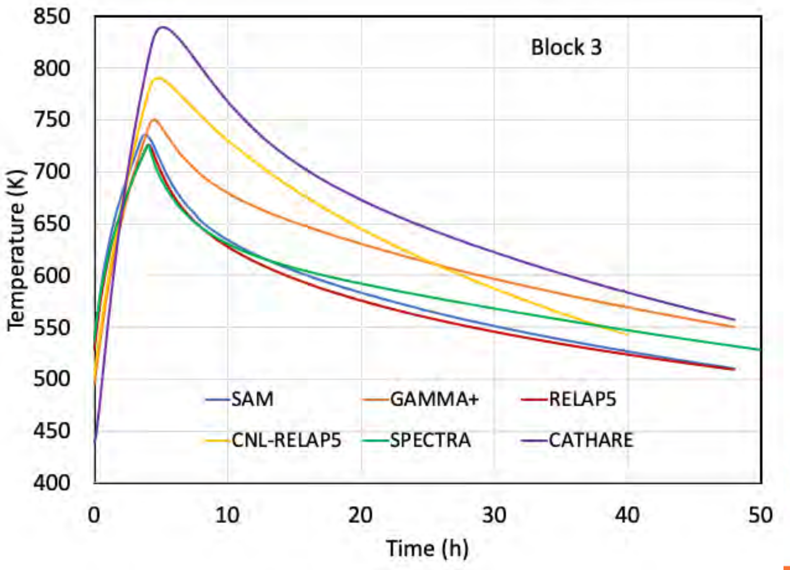
Steady state coolant temperature in core



Transient natural circulation flow rate



Transient solid temperature



Publications

- Specifications published April 2025

- Publications
  - Problem 1:
    - Nakhnikian-Weintraub, B., Gutowska I., Woods, B., Initial Results of Scaled MHTGR Lower Plenum CFD Analysis, NUTHOS-14, August 25-28, Vancouver, BC, 2024.
    - Nakhnikian-Weintraub, B., Hussain, M. M., M., D., Gutowska I., Progress Towards the Lower Plenum Mixing Test of the High Temperature Test Facility Benchmark by NRG and OSU, Advances in Thermal Hydraulics, November 17-21, Orlando, FL, 2024.
  - Problem 2 and 3:
    - Kile, Robert F. et al., "Code Benchmark of a Depressurized Conduction Cooldown Transient in the High Temperature Test Facility*," Proceedings of Advances in Thermal Hydraulics*, Orlando, FL, November 18-21, 2024.
    - Epiney, Aaron. Et al., "Nuclear Energy Agency (NEA) High-Temperature Test Facility (HTTF) Thermal-Hydraulics Benchmark: Error Scaling Exercise", Proceedings of American Nuclear Society (ANS), annual meeting, June 2025
    - Submitted a joint paper (P3 Ex1A/1B) for presentation at 2024 ICAPP conference (June 2024, Las Vegas): Thanh Hua, Robert Kile, Sung Nam Lee, Ling Zou, Aaron Epiney, "Code Benchmark of Pressurized Cooldown Transient in the High Temperature Test Facility."
    - Submitted a joint paper (P3 Ex1C/1D) for presentation at 2025 NURETH-21 conference (Sept 2025, South Korea): Thanh Hua et al., "Benchmarking Low-Power Pressurized Cooldown Transient in the High Temperature Test Facility."
    - CNL: Plan to publish ARIANT and RELAP5-3D simulations predictions in NUTHOS-14 (problem 2 and 3).
    - INL Planned Publication on Problems 2 and 3 Exercise 2: Kile, R. F., Barthle, J. L., Epiney, A. S., "Validation Studies of RELAP5-3D for High-Temperature Gas-Cooled Reactor Analysis using a Refined RELAP5-3D Model of the High Temperature Test Facility," *Nuclear Technology,* (coming soon).

Benchmark Key Takeaways

- This benchmark has huge international interest in every problem
- We are progressing in the benchmark including advancing to the validation stage of our problems
- Development of error scaling templates for participants is ongoing
- Original target date for publication of final report was December 2025, now targeting May 2026

RELAP5-3D Validation Activities

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

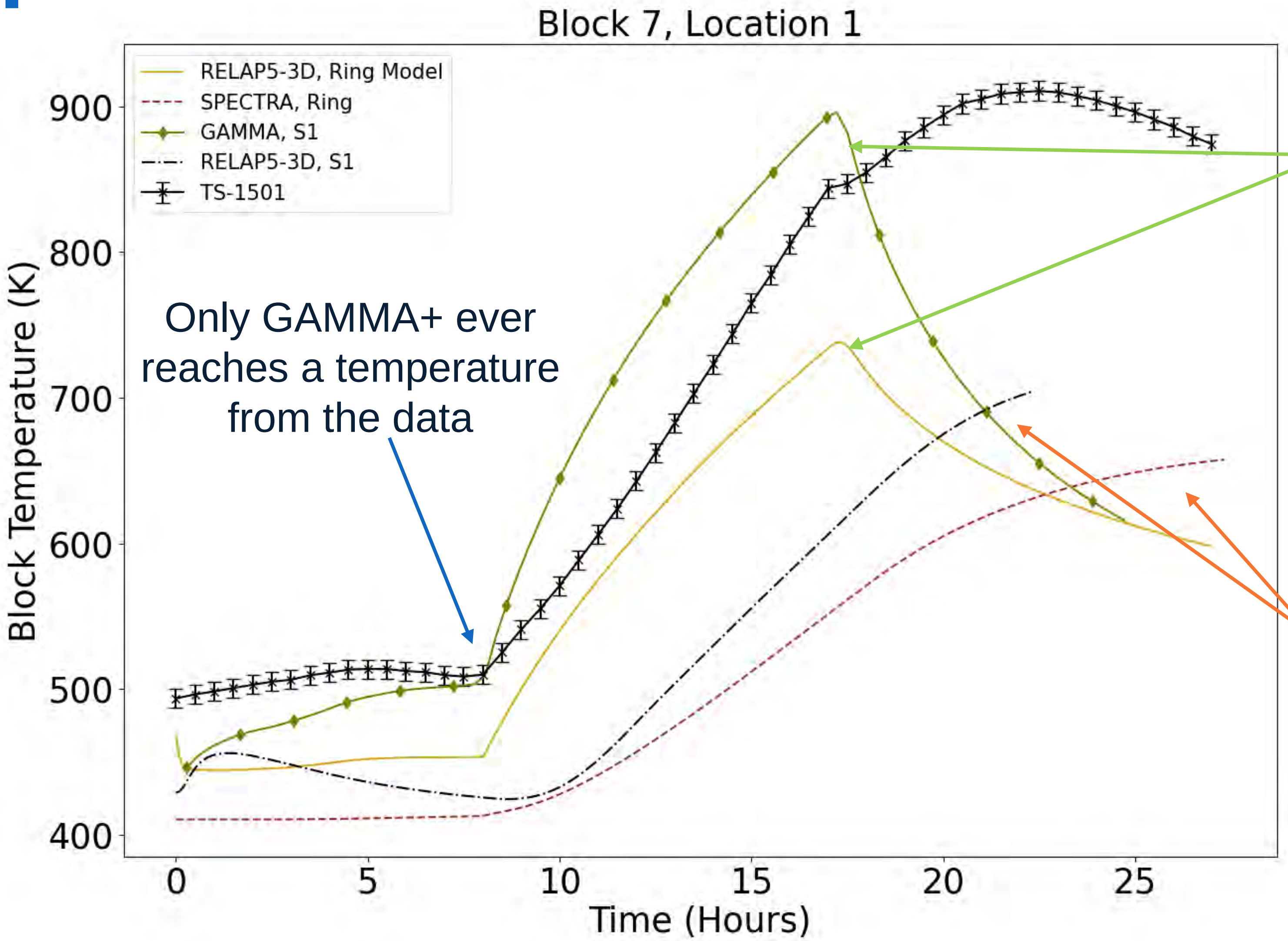
PG-27

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

RELAP5-3D Validation Activities

PG-29

Inner Reflector Temperatures Are Not Reproduced Well

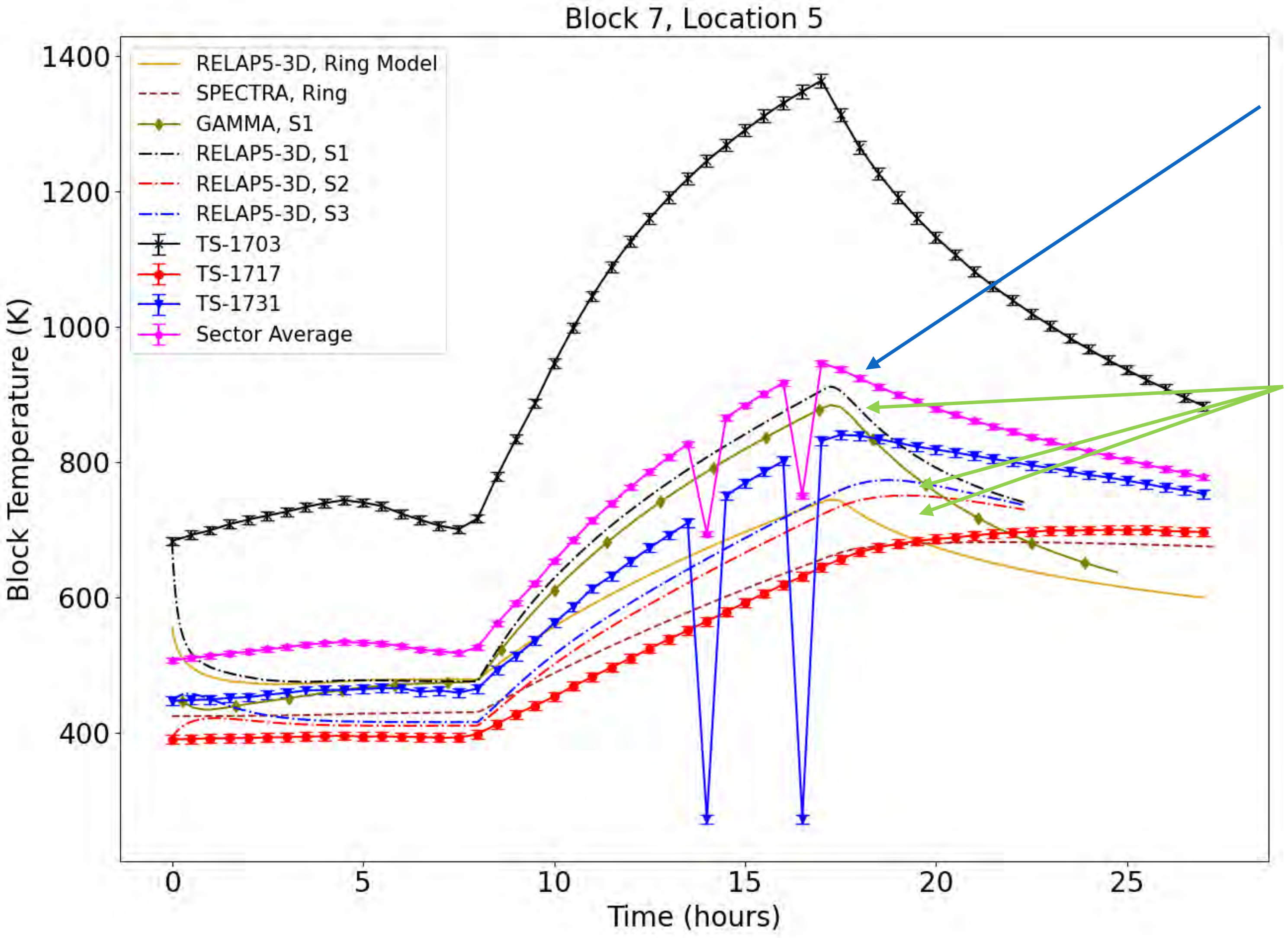


Only GAMMA+ ever reaches a temperature from the data

GAMMA+ and RELAP5-3D ring models reach peak temperature too soon

RELAP5-3D sector and SPECTRA ring models reach peak temperatures too late

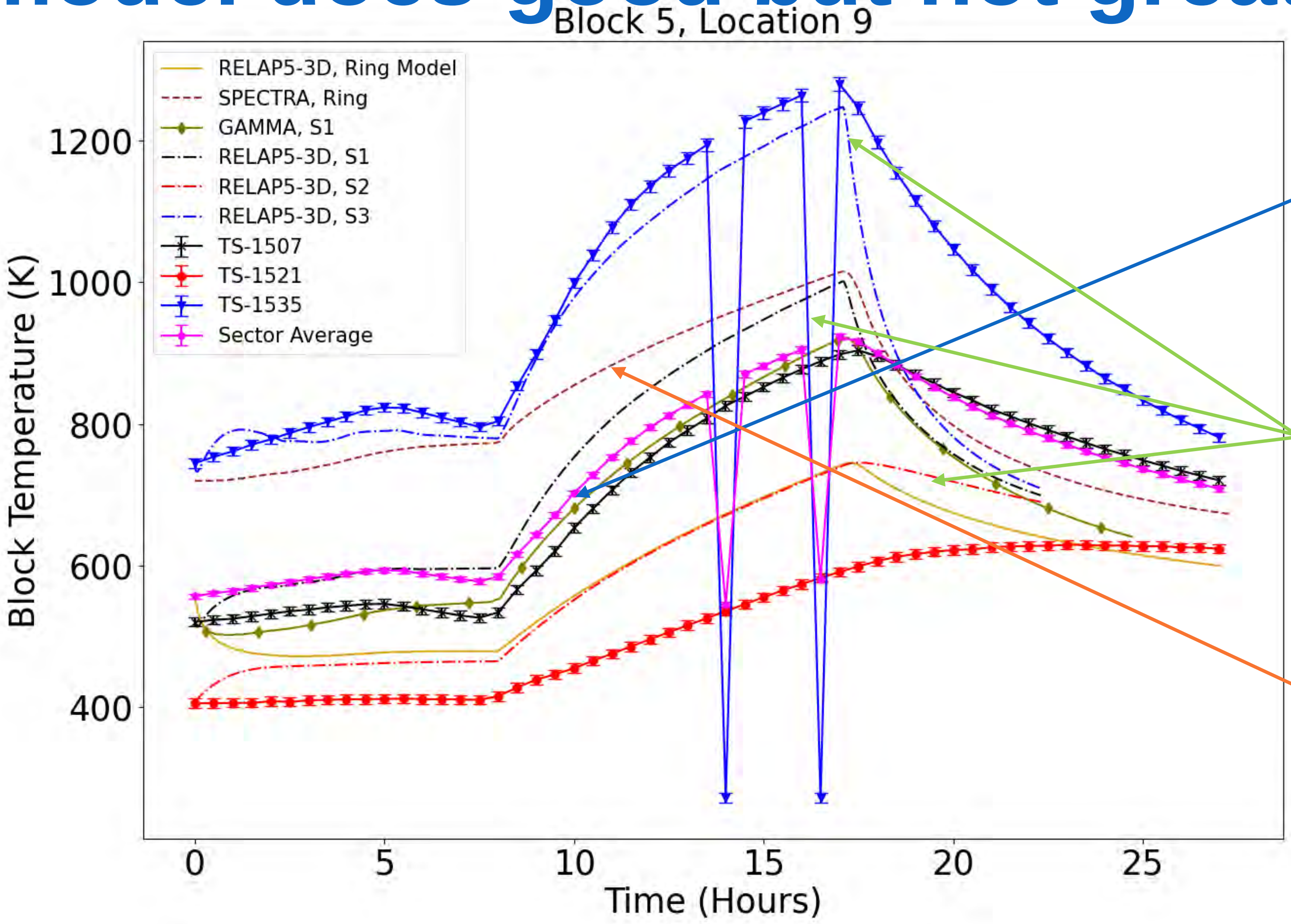
In inner core, all models struggle



Average temperature is always underpredicted

RELAP5-3D sector model underpredicts heated sectors temperatures and overpredicts unheated sector

In Outer Core, RELAP5-3D Sector model does good but not great job



GAMMA+ (KAERI) is closest to the average temperature

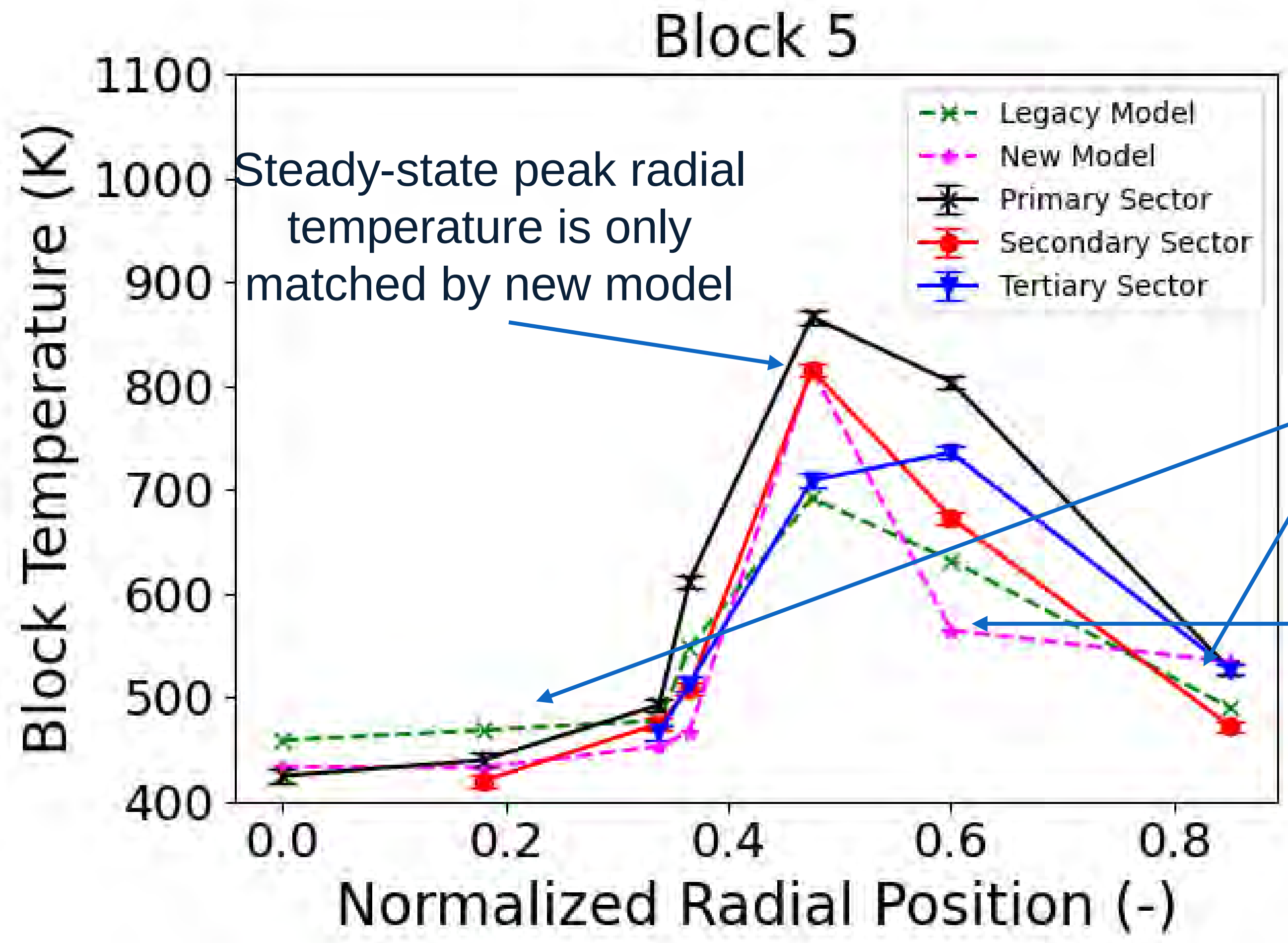
INL Sector model overestimates primary and secondary sector temperatures but underestimates tertiary sector temperature

SPECTRA overpredicts average temperature

RELAP5-3D Validation Activities

PG-27

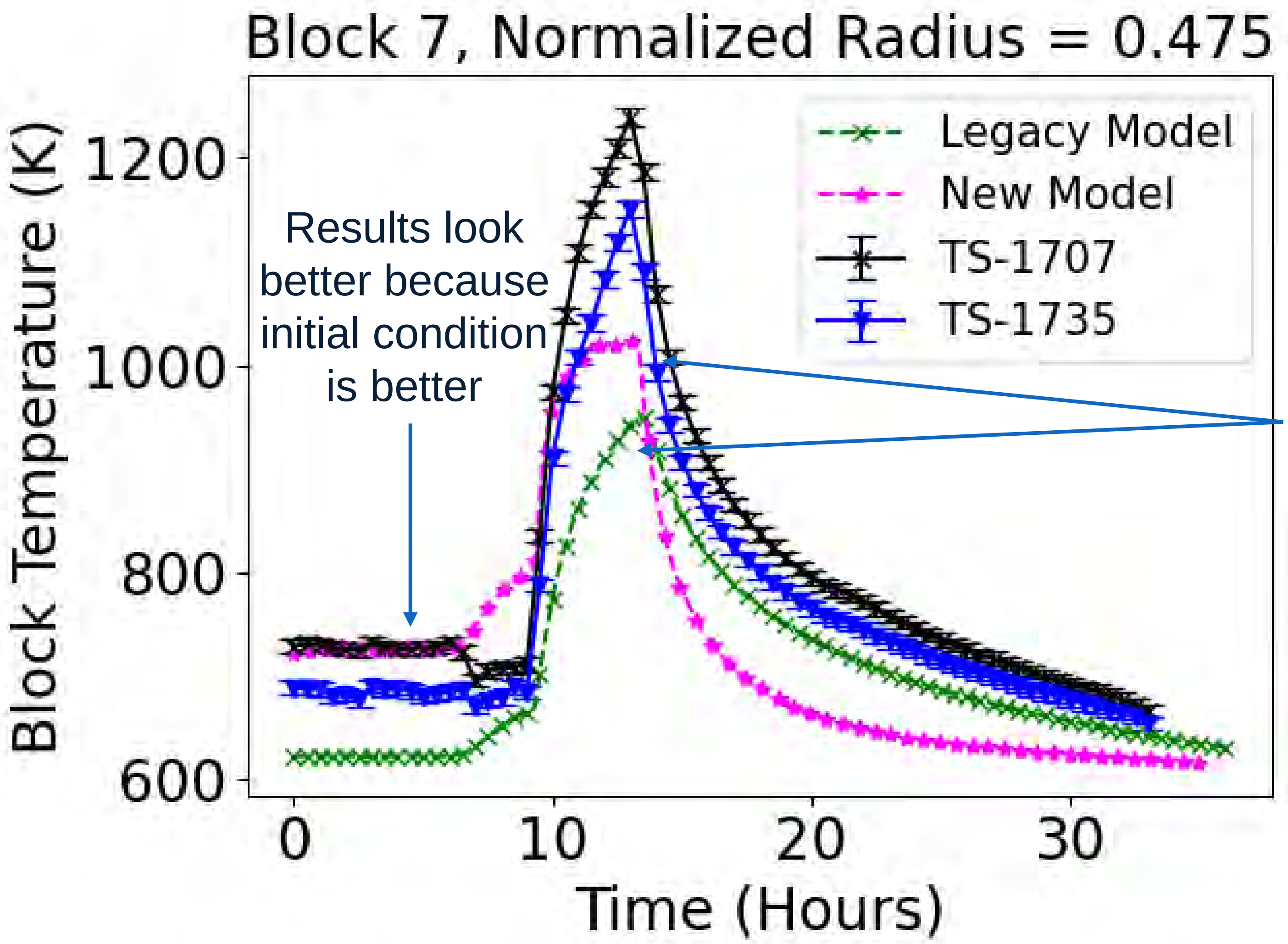
New model shows considerably improved steady-state temperatures



Inner and permanent reflector temperatures are well-predicted

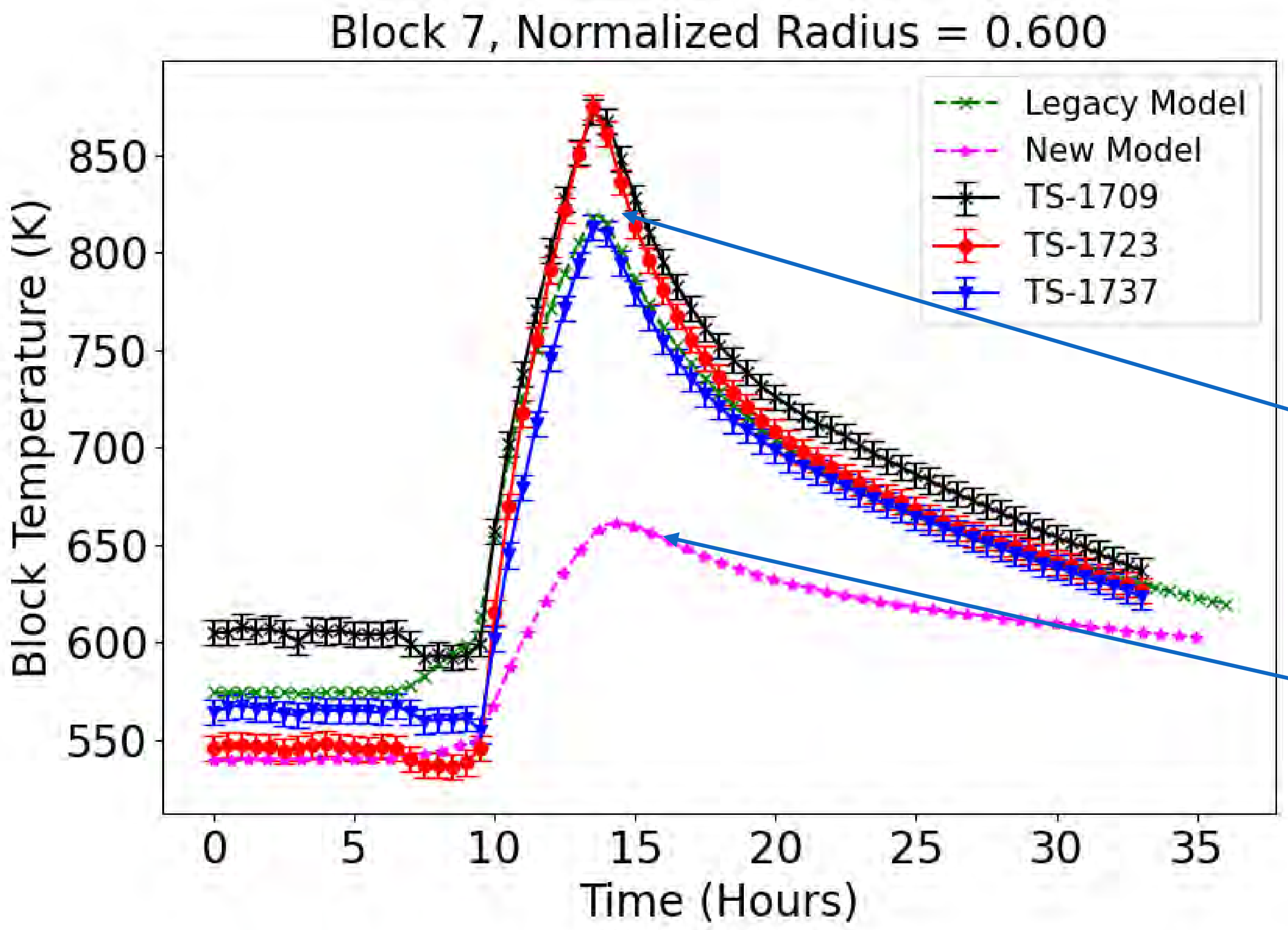
Outer reflector temperature is poorly matched due to differences in heat structure model

Transient temperatures rise less in the new model



Peak temperature is higher but temperature rise is lower

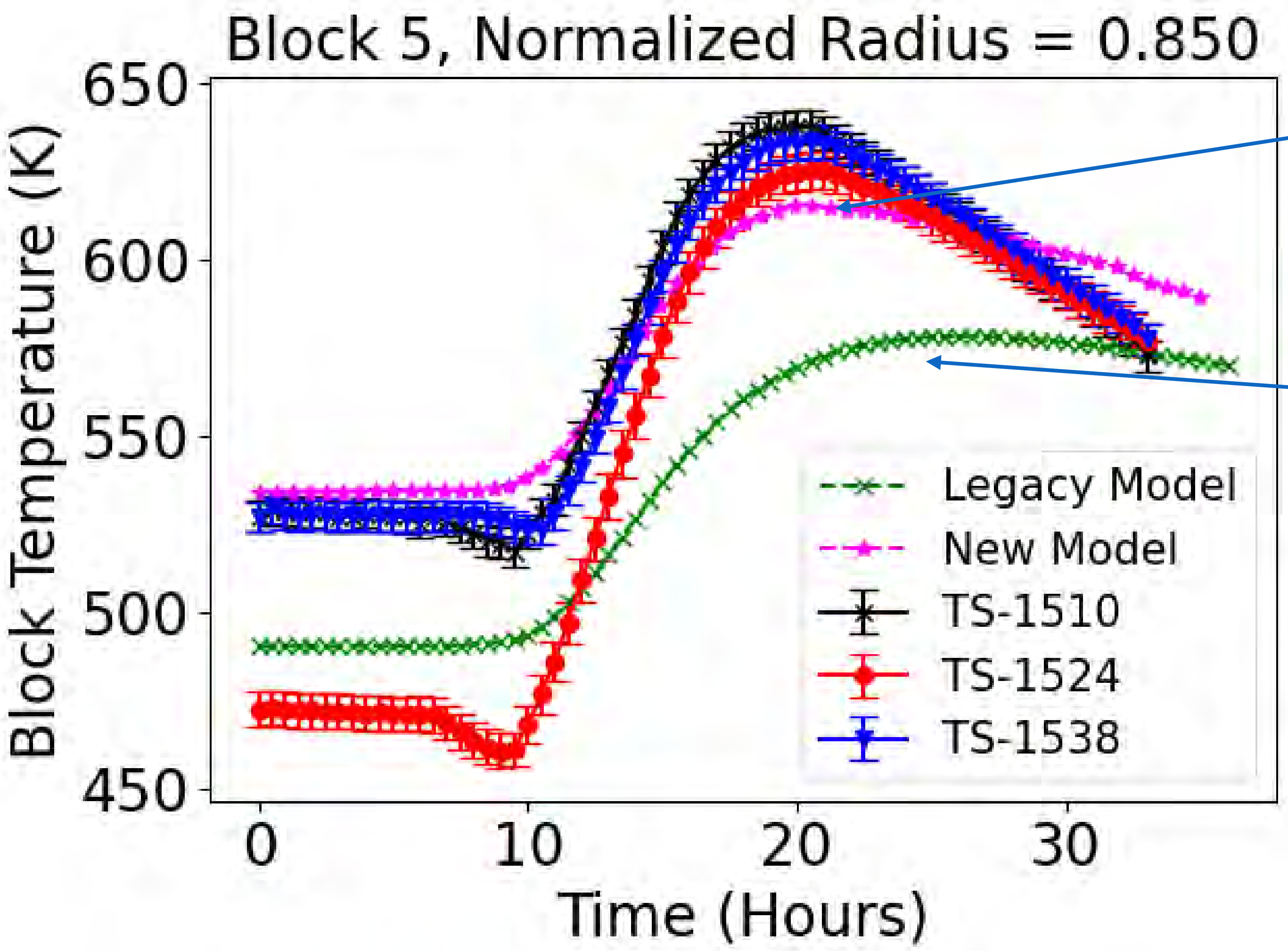
Performance in some reflector regions is worse due to new assumptions



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

- The HTGR T/H Benchmark is proceeding, though the final report will be pushed back ~6 months due to some complications that arose
- 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

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Special thanks to all our benchmark organizers

Robby Kile

robert.kile@inl.gov

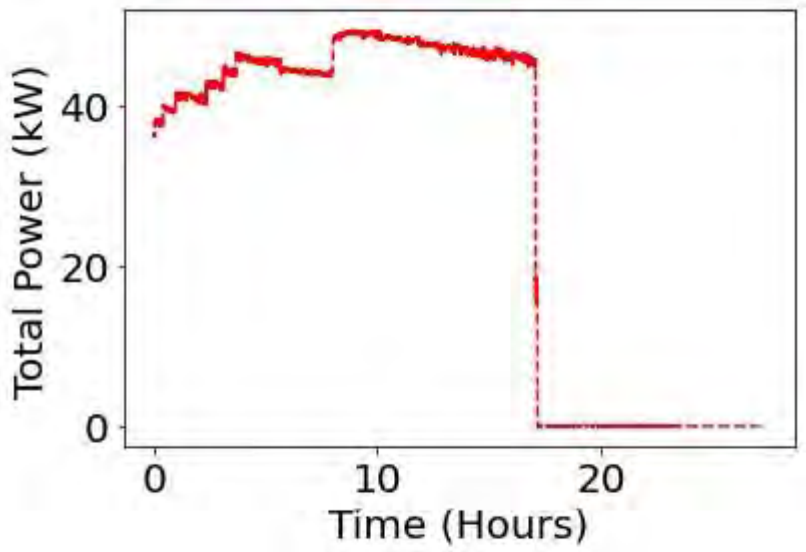
208-526-0928

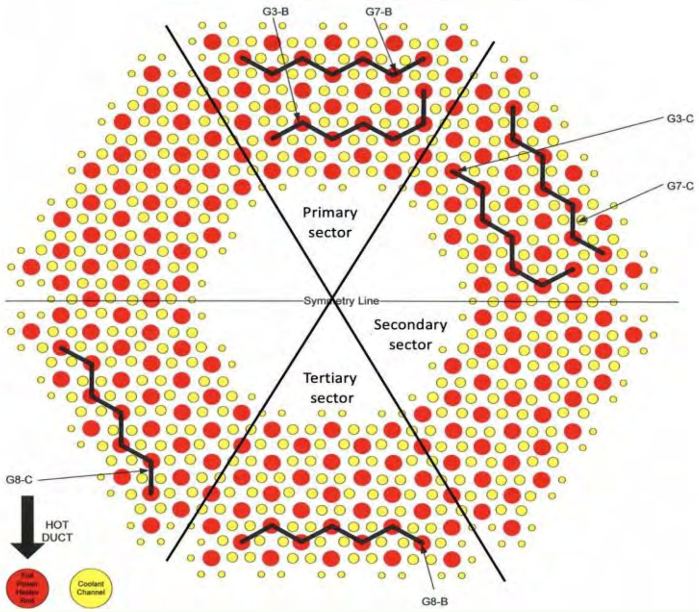
U.S. DEPARTMENT OF ENERGY

INL Idaho National Laboratory

PG-29 Power and Power Distribution

- We know the total power but not the power distribution
- We have investigated 2 power distributions:
  - Equal power in each active rod
  - Equal power in each heated sector
- More complex power distributions may be necessary for perfect agreement, but





PG-27 Power Distribution

- Power is concentrated in the outer rings
- Power distribution is symmetric
- We assume each rod in the G7 bank has the same power and each rod in the G8 bank has the same power