Evaluation of Representativity of the High Temperature Test Facility Using RELAP5-3D

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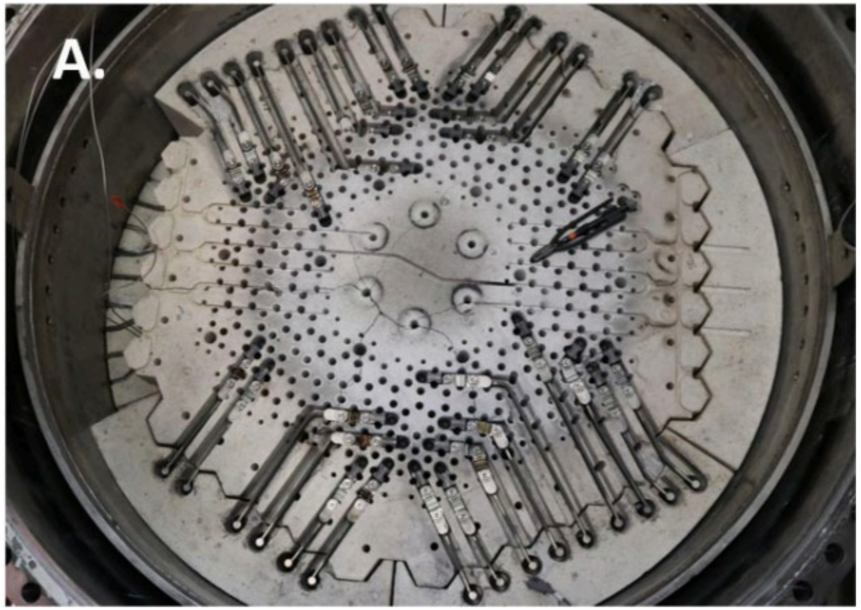
Introduction

- The prismatic HTGR is a relatively mature system design that has existed since the mid-20th century and have had several demonstration reactors
  - Peach Bottom 1, Fort St. Vrain, High Temperature Test Reactor
- Validation of these computational tools is essential to ensure that these models are accurately representing the physics of HTGR systems
  - Several existing computational tools have been validated only for light water reactors
- Experimental facilities, such as the High Temperature Test Facility (HTTF), provide valuable data that can be applied for HTGR thermal-hydraulics validation
- The Organisation of Economic Cooperation and Development Nuclear Energy Agency's (OECD/NEA) thermal-hydraulics benchmark provides a well-defined set of physics phenomenon and exercises for HTTF to assist in the HTGR validation space

Background

Overview of the High Temperature Test Facility

- HTTF is an integral test effects facility located at Oregon State University
- The HTTF core is scaled to 1/4-length and 1/64-volume of the General Atomics 350 MW_{th} modular high temperature gas-cooled reactor (MHTGR-350)
  - Rated Power: 2.2 MW_{th}
  - Heated by graphite resistive heater rods
- Several HTTF experiments have been chosen to define the problems identified by the OECD/NEA benchmark[2]



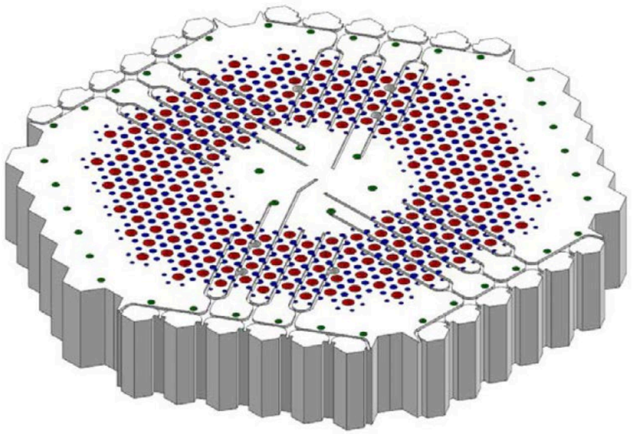
Upper view of HTTF core[1]

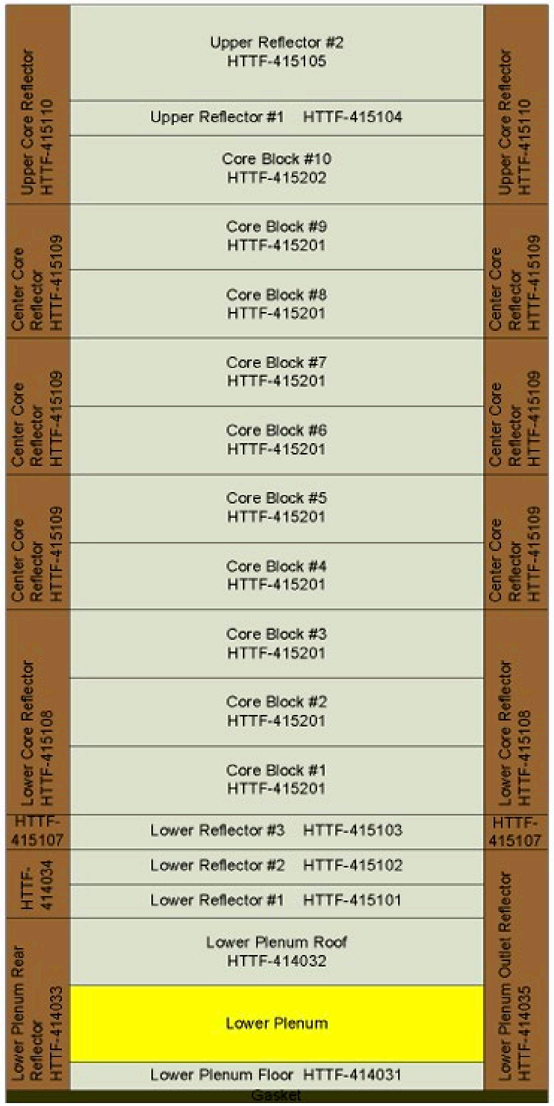
1. Woods, B. 2019. "OSU High Temperature Test Facility Design Technical Report, Revision 2." OSUHTTF-TECH-003-R2, Oregon State University, Corvallis, OR. https://www.osti.gov/biblio/1599410.
2. A. Epiney, G. Strydom, M. Tano, S. Yoon, C. Mueller, R. Kile, I. Gutowska, T. Hua, L. Zou, J. Fang, K. Podila, X. Huang, Q. Chen, T. Jafri, G. Waddington, P. Pfeiffer, C. Li, M. Hussain and F. Roelofs, "Thermal hydraulic code validation benchmark specifications for high temperature gas-cooled reactors (HTGR) using high temperature test facility (HTTF) data," OECD/NEA, 2024.

HTTF Core

- The HTTF core consists of 10 stacked axial blocks between a lower and upper reflector
  - Block material: Greencast 94-F ceramic
- Radially, there is a central cylinder, inner reflector, 9 heater rod rings, outer reflector, and permanent side reflector
- Finally, the core is divided into 6 azimuthal sectors, with the primary sector being the most heavily instrumented

Axial core blocks[1]





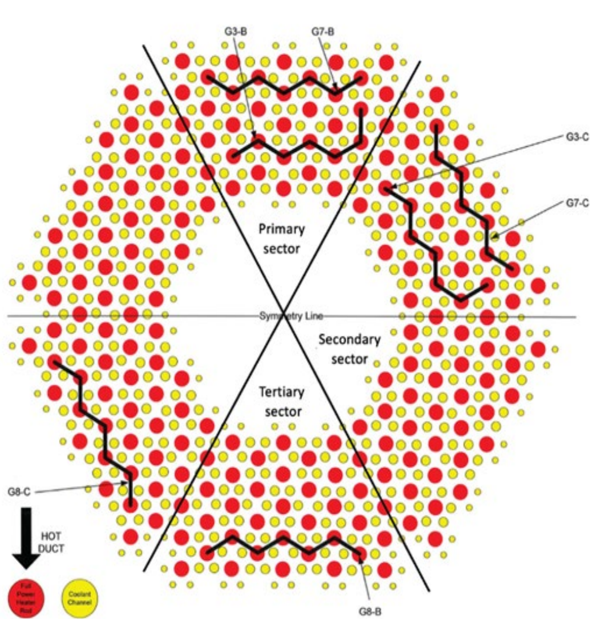
Axial diagram of HTTF core[1]

1. Woods, B. 2019. “OSU High Temperature Test Facility Design Technical Report, Revision 2.” OSUHTTF-TECH-003-R2, Oregon State University, Corvallis, OR. https://www.osti.gov/biblio/1599410.

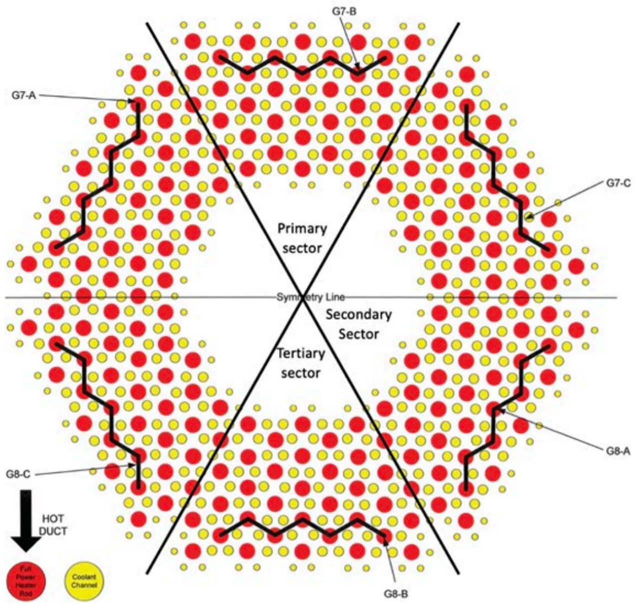
HTTF Experiments

- PG-29 demonstrates a depressurized conduction cooldown (DCC) transient
  - Loss of forced cooling due to a rupture in the coolant-pressure boundary
  - Asymmetric heater rod configuration
- PG-27 represents a pressurized conduction cooldown (PCC)
  - Loss of forced cooling due to pump failure, coolant-pressure boundary remains intact
  - Azimuthal symmetry in heater rod configuration
- Black zigzag lines indicate active heater rod configuration for each experiment

PG-29[1]



PG-27[1]



1. R. Kile, J. L. Barthle and A. S. Epiney, "Comparison of Results between the Legacy and Refined RELAP5-3D Models of the High Temperature Test Facility in Exercises 1 and 2 of the HTTF Benchmark," Idaho National Laboratory, Idaho Falls, 2024.

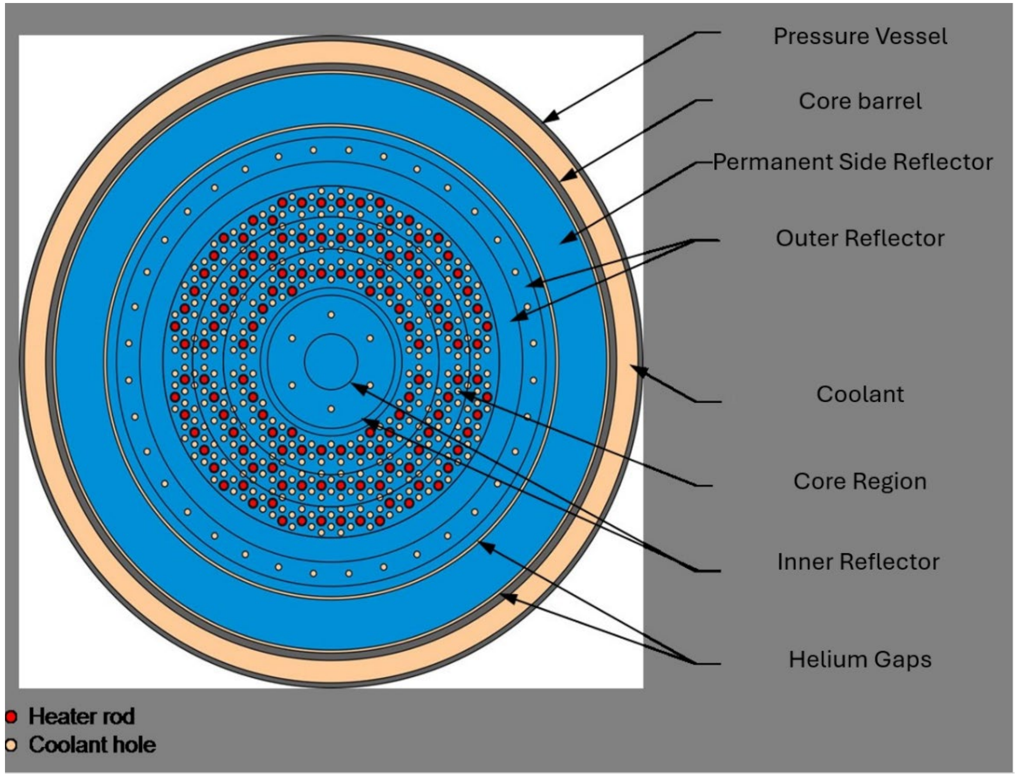
Related Benchmark Problems/Exercises

- Exercise 3: Error Scaling to the MHTGR-350[1]
  - Quantify how well the HTTF experiments capture the physics of phenomena in the full-sized plant facility (MHTGR-350)
  - Perform a sensitivity study based off specified experimental, code, and thermal property uncertainties
  - Compare uncertainties in HTTF to uncertainties in the Modular High Temperature Gas-cooled Reactor (MHTGR-350)
- Problem 2: Depressurized Conduction Cooldown (PG-29)
- Problem 3: Pressurized Conduction Cooldown (PG-27)

1. A. Epiney, G. Strydom, M. Tano, S. Yoon, C. Mueller, R. Kile, I. Gutowska, T. Hua, L. Zou, J. Fang, K. Podila, X. Huang, Q. Chen, T. Jafri, G. Waddington, P. Pfeiffer, C. Li, M. Hussain and F. Roelofs, "Thermal hydraulic code validation benchmark specifications for high temperature gas-cooled reactors (HTGR) using high temperature test facility (HTTF) data," OECD/NEA, 2024.

Legacy RELAP5-3D Model of HTTF

- The legacy model divides the core into 3 annular cells representing the inner, middle, and outer core regions
  - The volume of the core block and the flow area of the coolant channel are preserved in each cell
- Each of these cells are centered around the pipe component representing the coolant channel
  - Makes up the left (inner) boundary condition of the core block heat structures
- There are 9 total heater rod rings in HTTF
  - The partial active heater rod configurations in the experiment were not perfectly represented in the coarse nodalization of the Legacy model
  - As a result, the power density was smeared across the 3 cells, leading to potential limitations in the model predictions



Legacy model nodalization of HTTF core[1]

1. P. D. BAYLESS, "RELAP5-3D Input Model for the High Temperature Test Facility," INL/EXT-18-45579, p. 268, Idaho National Laboratory (June 2018); https://doi.org/10.2172/1811538.

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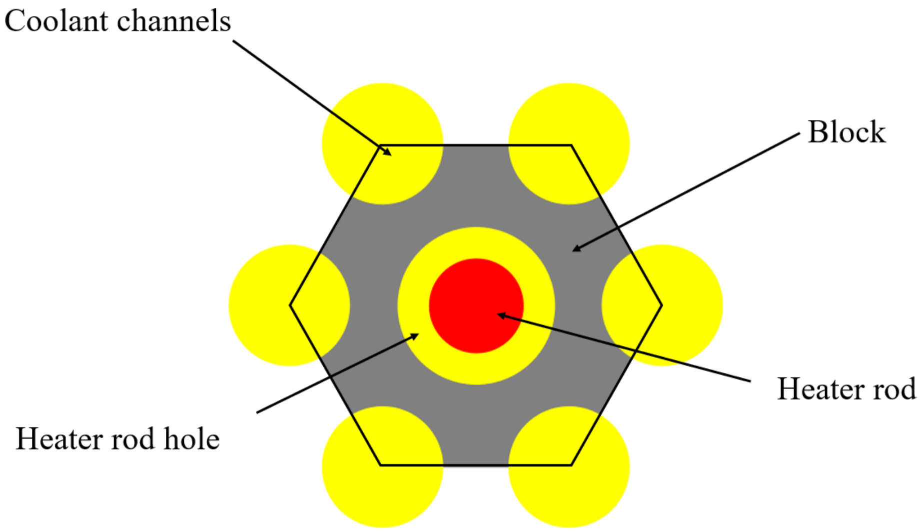
New RELAP5-3D Model of HTTF

- The New model addresses the limitations of the Legacy model by taking a finer nodalization approach
  - Each of the 9 heater rod rings are included in the new model
  - The New model also models each of the 6 azimuthal sectors, allowing for the capture of the asymmetric heating in PG-29
- Allowed for the more accurate mapping of the heater rod configurations observed in both experiments
- The New model demonstrated improvements in predicting initial temperatures when compared to HTTF data[2]

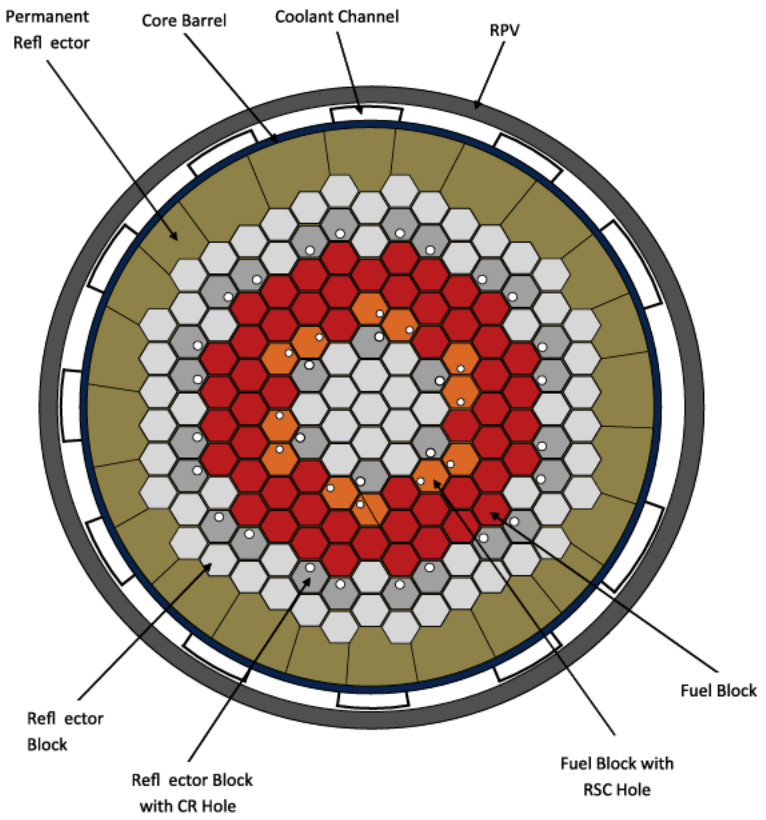


Hexagonal partition used to calculate unit cell volume and equivalent flow area for each ring[1]

1. R. KILE, J. L. BARTHLE, and A. S. EPINEY, “Comparison of Results Between the Legacy and Refined RELAP5-3D Models of the High Temperature Test Facility in Exercises 1 and 2 of the HTTF Benchmark,” INL/RPT-24-80304, p. 78, Idaho National Laboratory (2024).
2. R. KILE, J. BARTHLE, and A. EPINEY, “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* (submitted for publication).

MHTGR-350

- The Modular High Temperature Gas-cooled Reactor (MHTGR-350) is a prismatic HTGR design developed by General Atomics[1]
  - Nominal Power: 350 MW_{th}
    - Core is in decay heat mode for most of the transient
  - Coolant Pressure: 6.39 MPa
  - Mass Flow Rate: 157.1 kg/s
- The MHTGR-350 design was developed to serve as a well-defined benchmark definition for HTGRs
- The MHTGR-350 is a well-documented design that has been thoroughly used in the literature and previous benchmarks
- A RELAP5-3D model of MHTGR-350 was used in this error scaling study

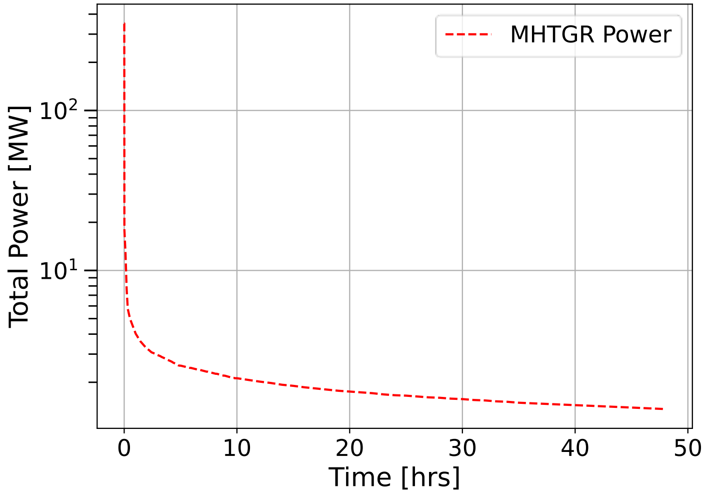


Schematic of MHTGR-350 core[1]

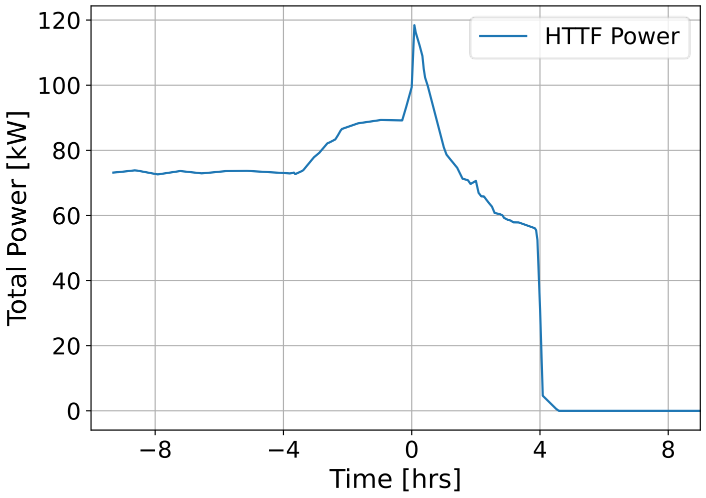
1. H. GOUGAR et al., "Prismatic Coupled Neutronics/Thermal Fluids Transient Benchmark of the MHTGR-350 MW Core Design," OECD/NEA (2010).

Power Profiles

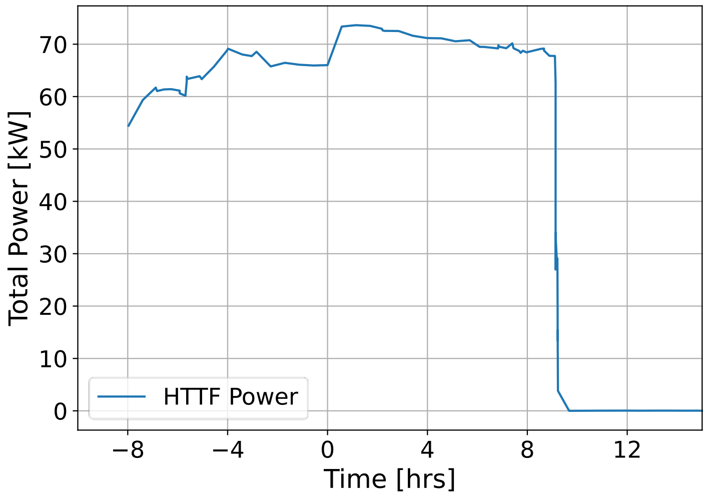
MHTGR-350



PG-27

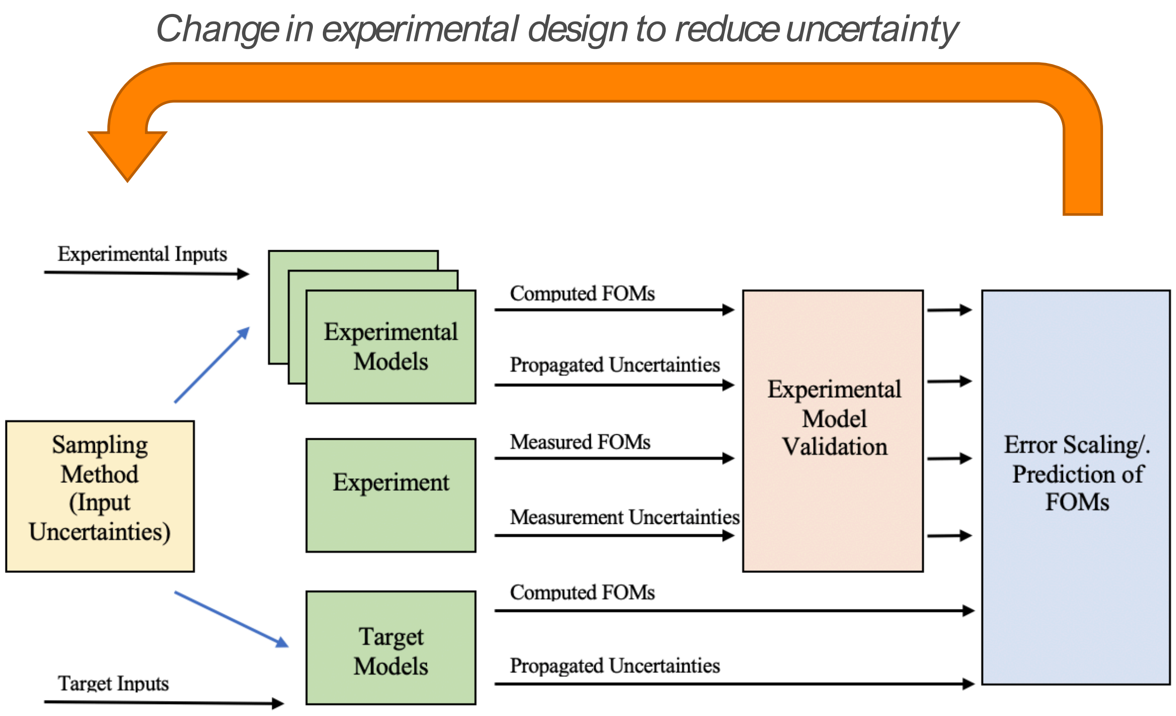


PG-29



Error Scaling

- Extrapolation of validation of the target design
  - MHTGR-350
- Experimental validation and verification is only the first step
- An approach to assess scaled experiments
- Can inform experimental design to result in the largest reduction in uncertainty in the target design



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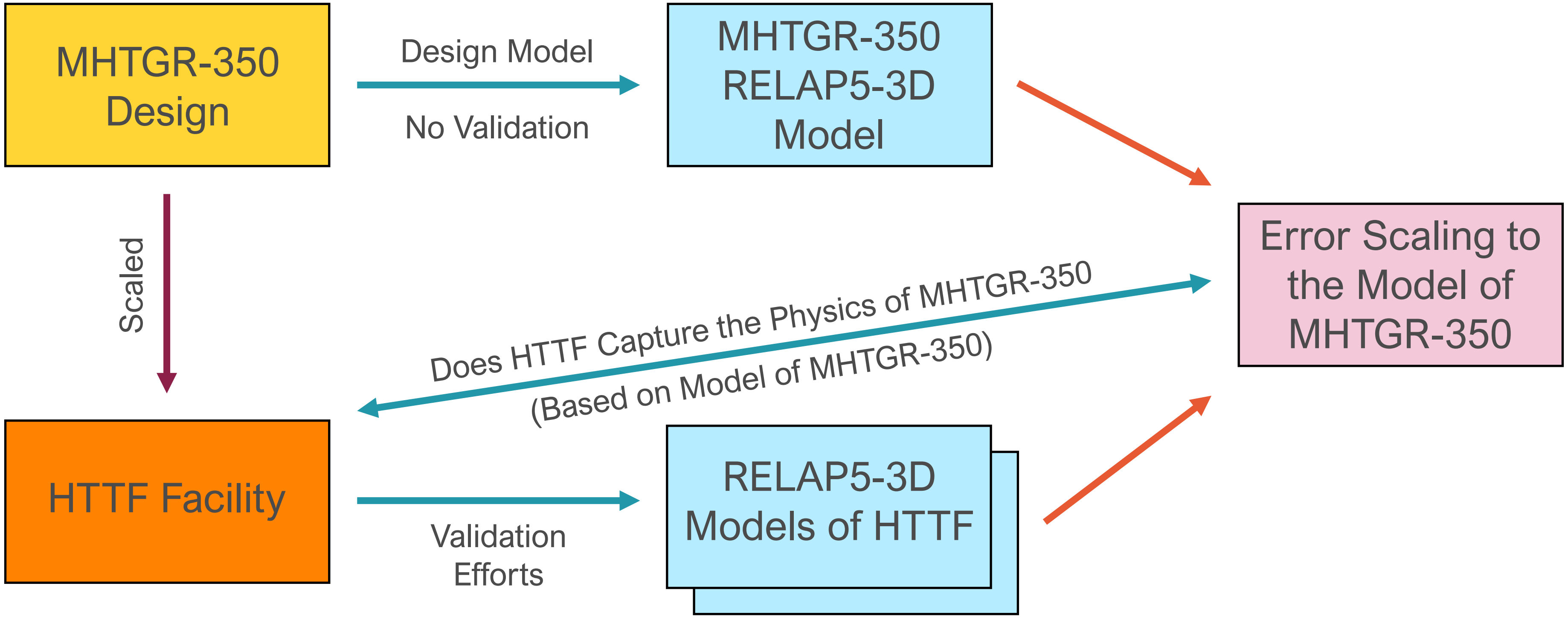
Representativity

$$R^{FOM} = \left| \frac{\left(\overrightarrow{S_{Exp}^{FOM}} \circ \overrightarrow{\Delta P_{Sim}^{1/2}}\right) \cdot \left(\overrightarrow{S_{Plant}^{FOM}} \circ \overrightarrow{\Delta P_{Sim}^{1/2}}\right)}{\left\| \overrightarrow{S_{Exp}^{FOM}} \circ \overrightarrow{\Delta P_{Sim}^{1/2}} \right\| \left\| \overrightarrow{S_{Plant}^{FOM}} \circ \overrightarrow{\Delta P_{Sim}^{1/2}} \right\|} \right|$$

- $\overrightarrow{S_i^{FOM}}$: Sensitivity Vector for Figure of Merit FOM
- $\overrightarrow{\Delta P_i}$: Variance vector for input parameters
- R^{FOM}: Representativity Factor for given FOM

- Representativity quantifies how well an experiment captures the physics of the plant model
- Compares the alignment of sensitivity vectors for the experimental and plant models
- A Representativity Factor of 1 indicates that the experiment leads to the largest reduction of uncertainty in the target model, it is most "representative"
  - Strong Representativity: $R^{FOM} > 0.8$
  - Moderate Representativity: $0.4 < R^{FOM} < 0.6$
  - Weak Representativity: $R^{FOM} < 0.4$

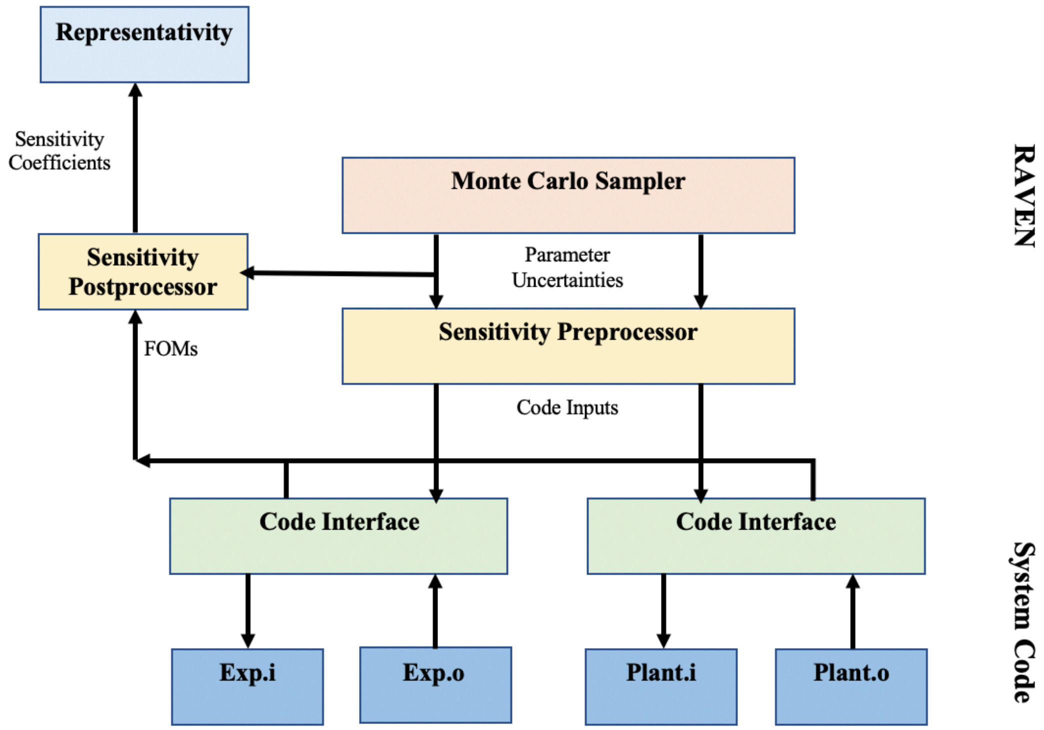
Error Scaling to the MHTGR-350



Methodology

Contributions to Exercise 3

- The key deliverables to Exercise 3 includes representativity factor calculations of the INL model for the following figures of merit:
  - Time Dependent Maximum Block Temperature
  - Time Dependent Coolant Outlet Temperature
- Develop a template that can perform all necessary steps and calculations so that other benchmark participants can use it for their respective models
  - “Black box” method for calculating representativity



Representativity Template

- The Risk Analysis Virtual Environment (RAVEN) framework was used to develop the representativity template and perform the sensitivity analysis and necessary postprocessing
- RAVEN is a powerful tool developed by INL that can employ various sampling strategies and and interface with any code[1]

- Parametric sweeps
- (Sampler)

- Sensitivity analysis
- (Postprocessor)

- Set timeseries to start at onset of transient
- (External Postprocessor)

- Harmonize parameter names for HTTF and MHTGR-350
- (External Postprocessor)

- Synchronize HTTF and MHTGR-350 timeseries
- (Postprocessor)

- Calculate representativity factors
- (External Postprocessor)

1. A. Alfonsi, C. Rabiti, D. Mandelli, J. Cogliati, C. Wang, P. W. Talbot, J. Zhou, P. Burli and M. G. Abdo, RAVEN User Guide, Idaho Falls: Idaho National Laboratory, 2023.

Parameters (Normal Distribution)

- These uncertainties were listed in the experimental instrumentation document released for HTTF[1]
- Intrinsic uncertainties from the sensors are also known as types of aleatory uncertainties
- Aleatory uncertainties can be represented by a normal distribution

Parameter:	Mean:	Standard Deviation:	Justification:
RCCS Inlet Temperature $[K]$	313.5	2.142	Listed uncertainty in thermocouple
Heater Rod Power [%]	100.0	8.460	Propagated uncertainty in voltage and current instruments
Helium Inlet Temperature $[K]$	361.3	2.142	Listed uncertainty in thermocouple

1. B. Woods, "Instrumentation Plan for the OSU High Temperature Test Facility," OSU, Corvallis, 2019.

Parameters (Uniform)

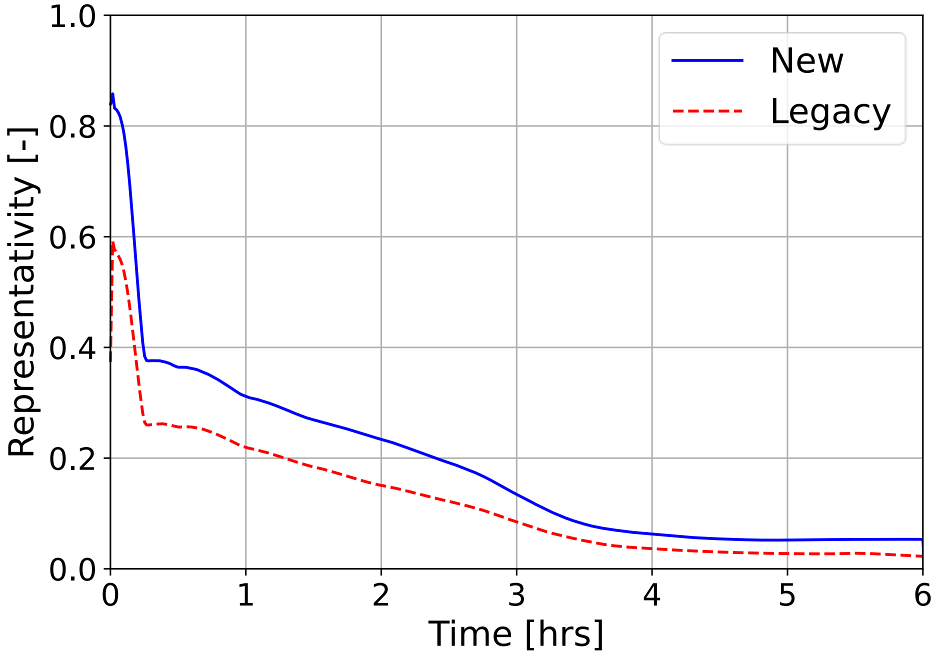
- The following parameters have unknown uncertainties and are considered epistemic
- These uncertainties were defined by available literature and have uniform distributions

Parameter:	Lower Bound:	Upper Bound:	Justification:
Primary Coolant Mass Flow Rate $[kg/s]$	0.600	0.900	Calculated mass flow rates from benchmark participant models
Core Block Emissivity [-]	0.500	0.950	Al_2O_3 Bayless Curve
Heater Rod Emissivity [-]	0.810	0.900	Graphite values
Permanent Side Reflector Emissivity [-]	0.500	0.900	SiC values
Coolant Channel Flow Factor $[mm]$	± 0.200		UAM benchmark values
Thermal Conductivity/Conductance of Blocks [%]	± 12.00		Maximum allowable scalar without possible overlap between temperature dependent values
Dittus-Boelter Correlation [%]	± 25.00		RELAP5-3D specified uncertainty
Gnielinski Correlation [%]	± 20.00		Empirical uncertainty

Results

DCC Results: Block Temperature

- Note that $t = 0\ s$ aligns with the start of the DCC
  - Before $t = 0\ s$ is the pre-transient period
- Both models predict a relatively high representativity at $t = 0\ s$
  - Expectedly, the sensitivity vectors are aligned with MHTGR-350 in the pre-transient
- Immediately after the initiation of the DCC, the representativity drops and trends to below 0.1
  - The maximum block temperature sensitivity vectors predicted for PG-29 are not aligned with the MHTGR-350 during the DCC
- While there is some variation, both models predict comparable representativity results



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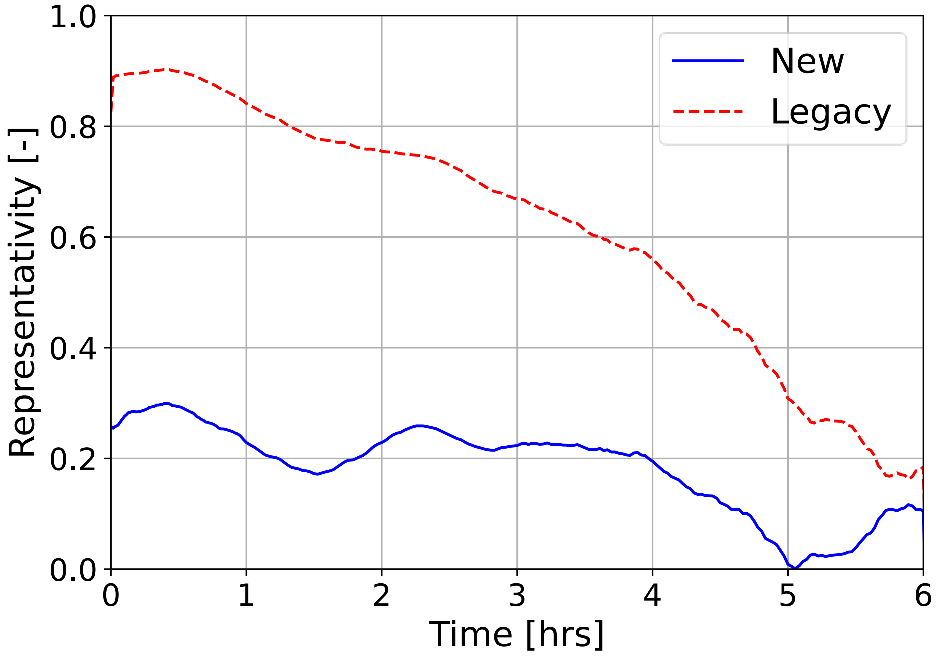
DCC Results: Coolant Outlet Temperature

- The New model consistently predicts a low representativity between 0.1 and 0.2
- The Legacy model predicts an initial representativity that is higher than that of the New model
  - However, eventually trends towards agreement with the New model at the low representativity below 0.2
- Suggests that the sensitivity vectors for the Legacy model more closely align with that of MHTGR-350 for the first several hours
  - Legacy and MHTGR-350 models adopt similar core modeling methodologies
- Overall, both models indicate that the coolant outlet behavior in HTTF is not representative of MHTGR-350 during the DCC



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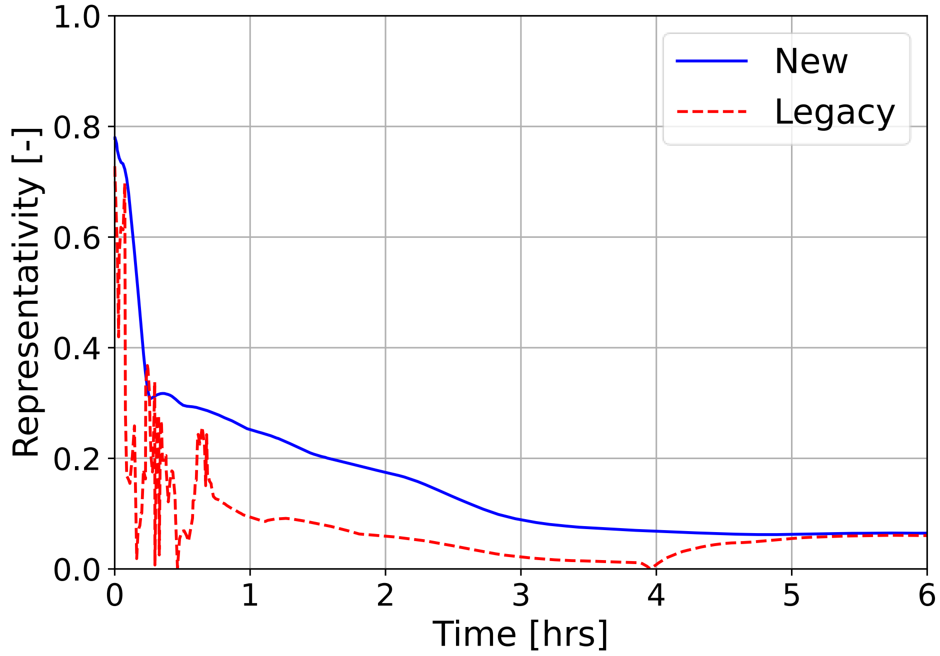
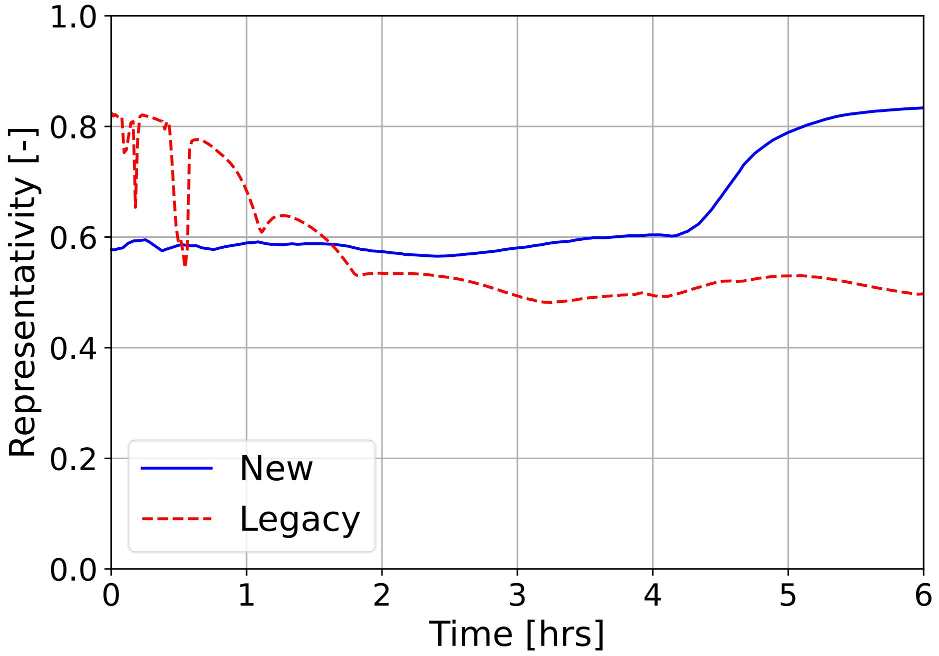
PCC Results: Block Temperature

- Similar to the DCC, $t = 0\ s$ aligns with the initiation of the PCC
  - PG-27 has an extended steady-state before the start of the PCC
- Both models predict a high representativity for the steady-state
- Once the PCC begins, the representativity quickly drops to below 0.1 (just like the DCC)
- Similar representativity behavior across both experiments and models suggest a potential limitation across HTTF for block temperature behavior



PCC Results: Coolant Outlet Temperature

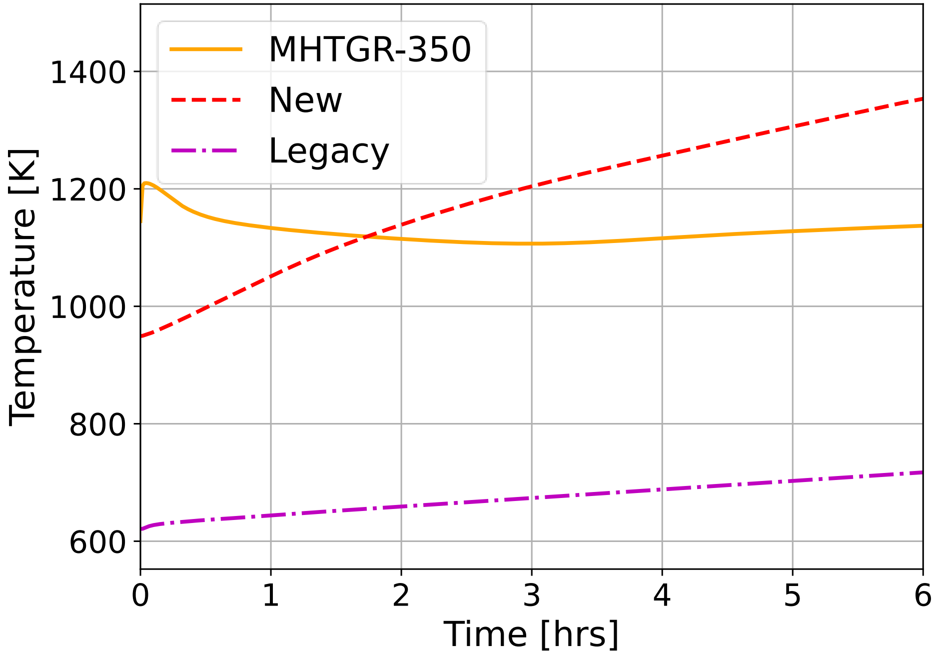
- For the coolant outlet temperature, both models predict a representativity between 0.5 and 0.6 for a majority of the PCC
- Relatively higher representativity than observed during the DCC
- Both models suggest that the coolant outlet temperature during PG-27 is moderately representative of MHTGR-350 during the PCC



Discussion

Comparison of Block Temperatures

- The maximum block temperature for HTTF predicted by both models are compared to the MHTGR-350 during the DCC
- MHTGR-350 block temperature quickly increases and decreases sharply within the first hour of the DCC
- Both models predict that the HTTF block temperatures slowly increase throughout most of the experiment
  - Temperatures do not begin to decrease until the heater rods are turned off
- The drastic temperature differences drive the divergence of the sensitivity vectors
  - Results in the low representativity seen for both experiments



Heat Conduction Equation

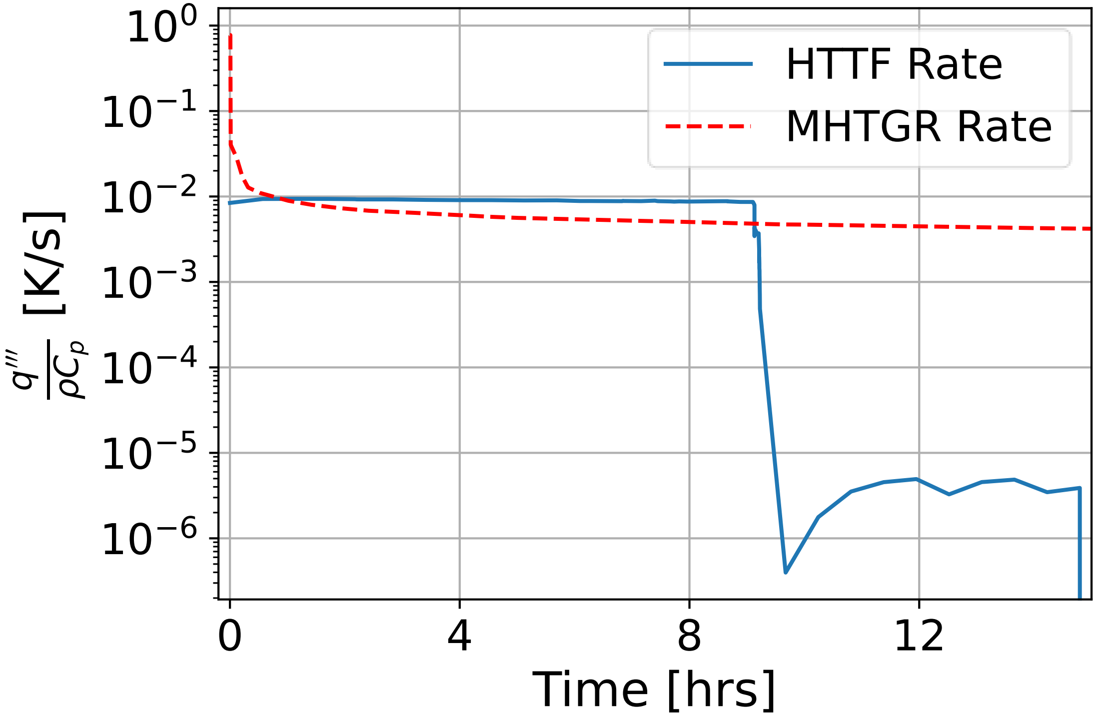
$$\alpha \nabla^2 T + \frac{q'''}{\rho C_p} = \frac{\partial T}{\partial t}$$

- α: Thermal diffusivity $(k/\rho C_p)$
- q''': volumetric heat generation
- ρC_p: Volumetric heat capacity

- Referring to the heat conduction equation can help explain why HTTF experiments are not representative of MHTGR-350
- Comparison of the term $(q'''/\rho C_p)$ between the two facilities helped to identify significant differences in heat generation

PG-29 (DCC)

- The heat generation term is plotted for MHTGR-350 and PG-29
- $q'''/\rho C_p$ in MHTGR-350 is 2 orders of magnitude higher than that of HTTF in the pre-transient
  - ρC_p is comparable across facilities
  - q''' is notably different:
    - MHTGR-350: 2.44 MW/m^3
    - HTTF: 0.03 MW/m^3
- The power during PG-29 aligns closely with the decay heat of MHTGR-350
  - There is not representative full-power steady-state during PG-29



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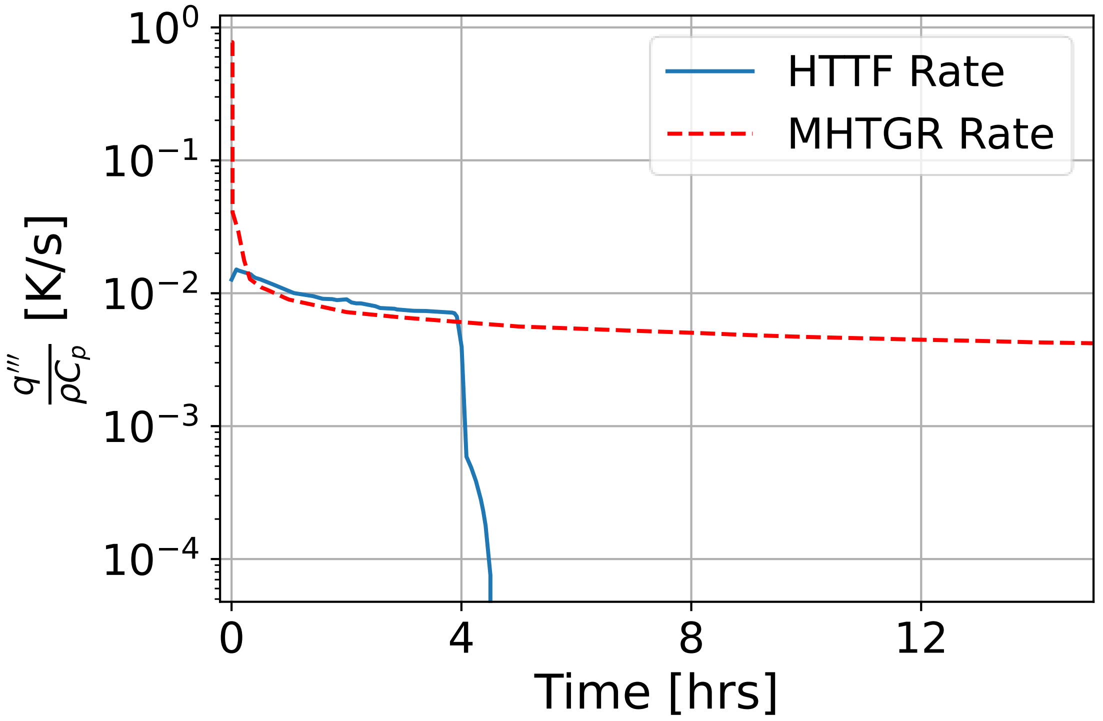
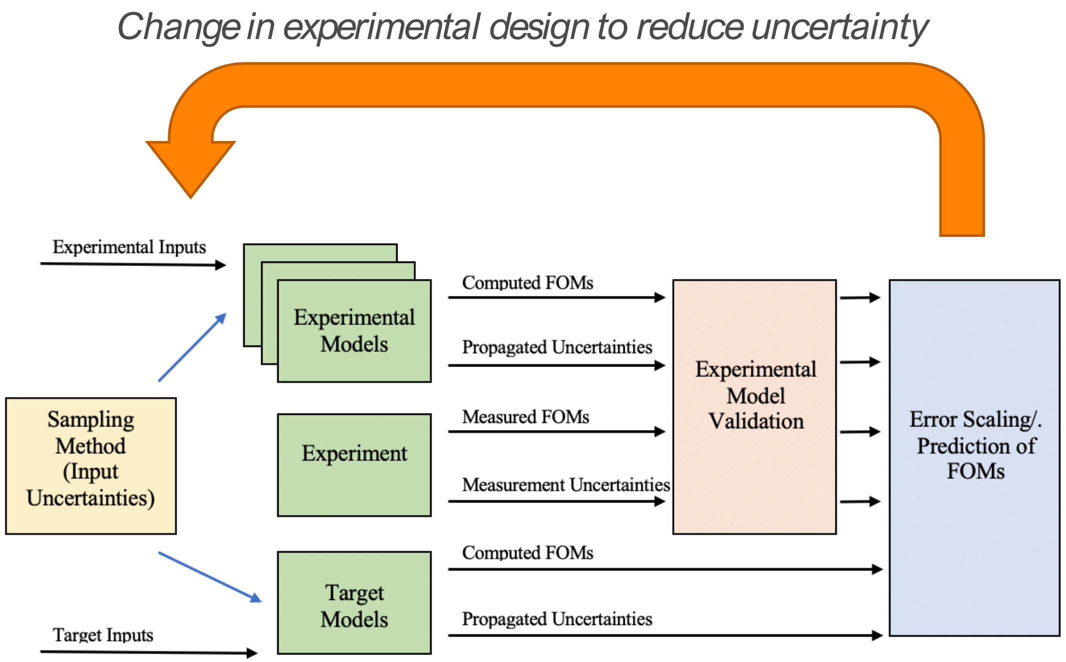
PG-27 (PCC)

- The heat generation term is once again roughly 2 orders of magnitude lower in HTTF than MHTGR-350
  - Large differences in q''':
    - MHTGR-350: 2.44 MW/m^3
    - HTTF: 0.05 MW/m^3
- Once again, HTTF power emulates the decay heat of MHTGR-350
  - No full-power steady-state in HTTF
- The significantly larger heat generation in MHTGR-350 drives the more rapid temperature changes observed in the comparisons between the two facilities



Closing the Validation Loop

- The heater rod powers were constrained to ensure that the heat-up limits of Greencast 94-F were not reached
- Simulations of the ceramic core concluded that crack propagation was possible for the rated power of HTTF[1]
  - Heat-up rates were reached during PG-27 start-up[2]
  - The operating power of both experiments targeted the decay heat of MHTGR-350
- Future experimental facilities will have to consider the limitations of materials such as Greencast 94-F
- A future study of the same experiments at HFP and MHTGR-350 would be valuable



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2. S. CADELL and B. WOODS, "OSU High Temperature Test Facility Test Acceptance Report: PG-27 Low Power (<350) Complete Loss of Flow, 2 Heaters," Oregon State University, Corvallis (2019).

Conclusions

- Two RELAP5-3D models of HTTF were employed for an error scaling analysis to the MHTGR-350 during a DCC and PCC
  - Maximum block temperature and coolant outlet temperature were evaluated as figures of merit
- Both models consistently predicted that HTTF was not representative of MHTGR-350 in simulating the maximum block temperature for both transients
- HTTF coolant outlet temperature was moderately representative of MHTGR-350 for the PCC, but not representative during the DCC
  - Major depressurization differences between MHTGR-350 and HTTF
- Limitations in HTTF prohibited the full-power steady state for both experiments, resulting in major differences in block temperature behavior, resulting in the low representativity observed

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4. A. Epiney, G. Strydom, M. Tano, S. Yoon, C. Mueller, R. Kile, I. Gutowska, T. Hua, L. Zou, J. Fang, K. Podila, X. Huang, Q. Chen, T. Jafri, G. Waddington, P. Pfeiffer, C. Li, M. Hussain and F. Roelofs, "Thermal hydraulic code validation benchmark specifications for high temperature gas-cooled reactors (HTGR) using high temperature test facility (HTTF) data," OECD/NEA, 2024.

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