Thermal-fluids Area Overview

Elia Merzari, Rui Hu

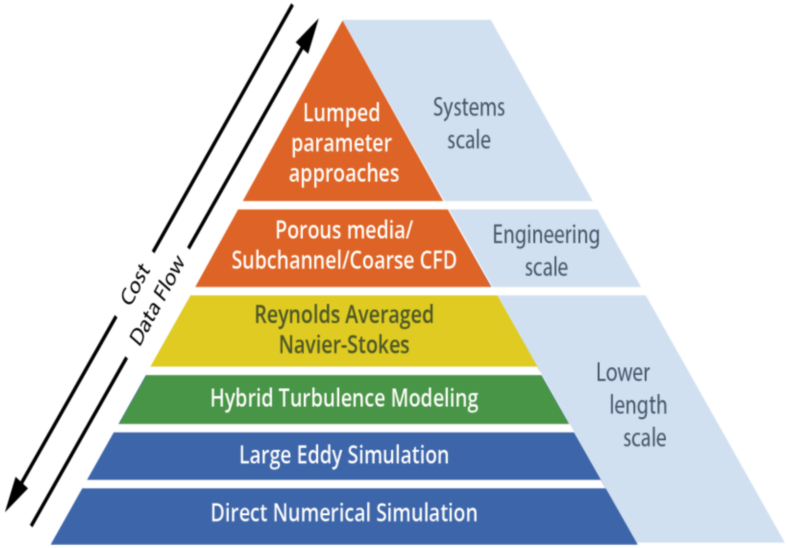
Argonne National Laboratory

May 8th, 2025

Thermal-hydraulics modeling in NEAMS - I

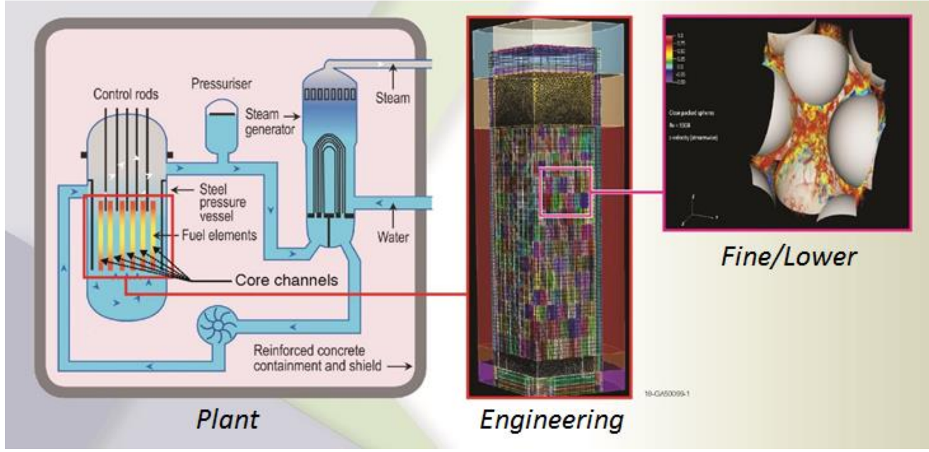
The thermal-hydraulic technical advances the state of the art of thermal-hydraulic simulations by researching novel new solution strategies for challenging real-world heat and fluid flow issues that affect advanced reactor designs or still affect the current fleet of deployed Light Water Reactor nuclear reactors.

- The economics of most advanced reactor designs relies on achieving higher temperatures that the current fleet.
- This poses severe challenges in terms of materials and puts an onus on thermal-hydraulic models to provide accurate assessment of hot spots.
- A reduction of uncertainty on thermal-hydraulic prediction has potential for a substantial economic benefit and to ultimately accelerate deployment.



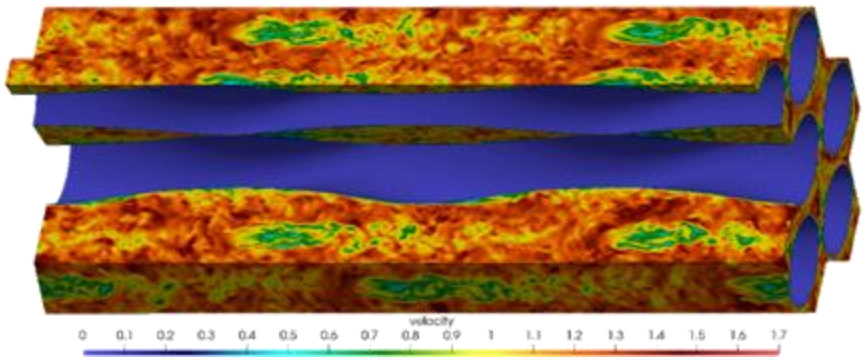
Thermal and Fluid Flow phenomena involve a wide range of length and time scales

- Resolving all scales for a realistic engineering system of interest is often computationally not feasible.
- On the other hand, if scales are not resolved, <u>closures need to be provided to ensure reasonable accuracy</u>, as all scales contribute to the dynamics.
- <u>Multiscale/multi-resolution simulation hierarchy</u>

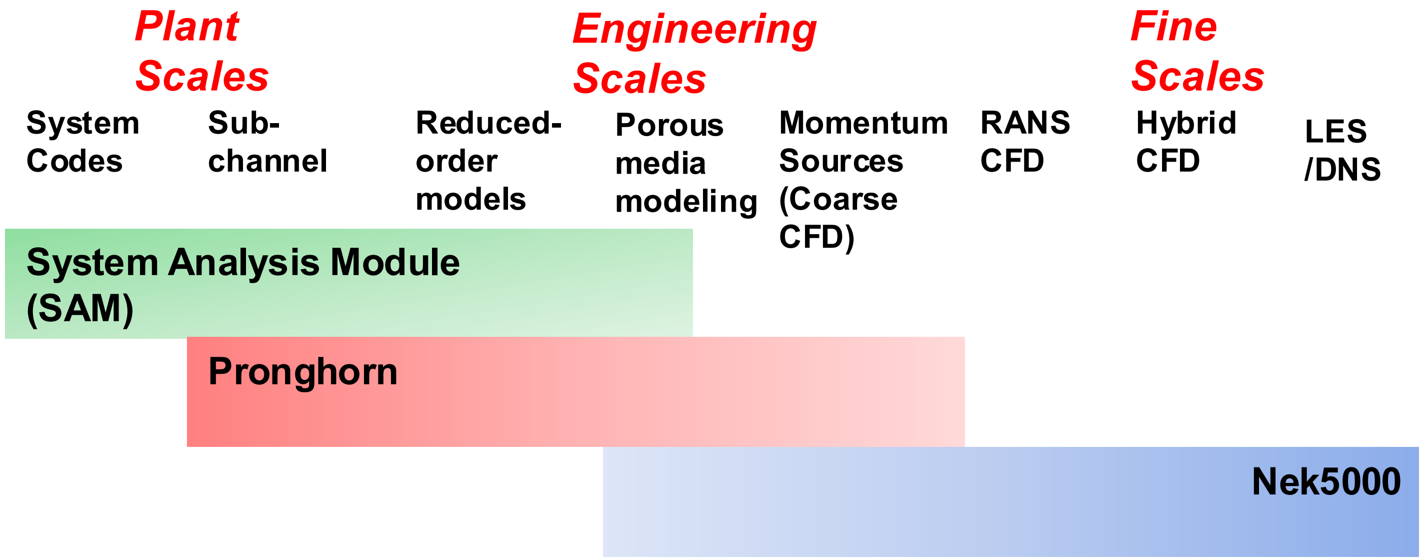


Thermal-hydraulics modeling in NEAMS - II

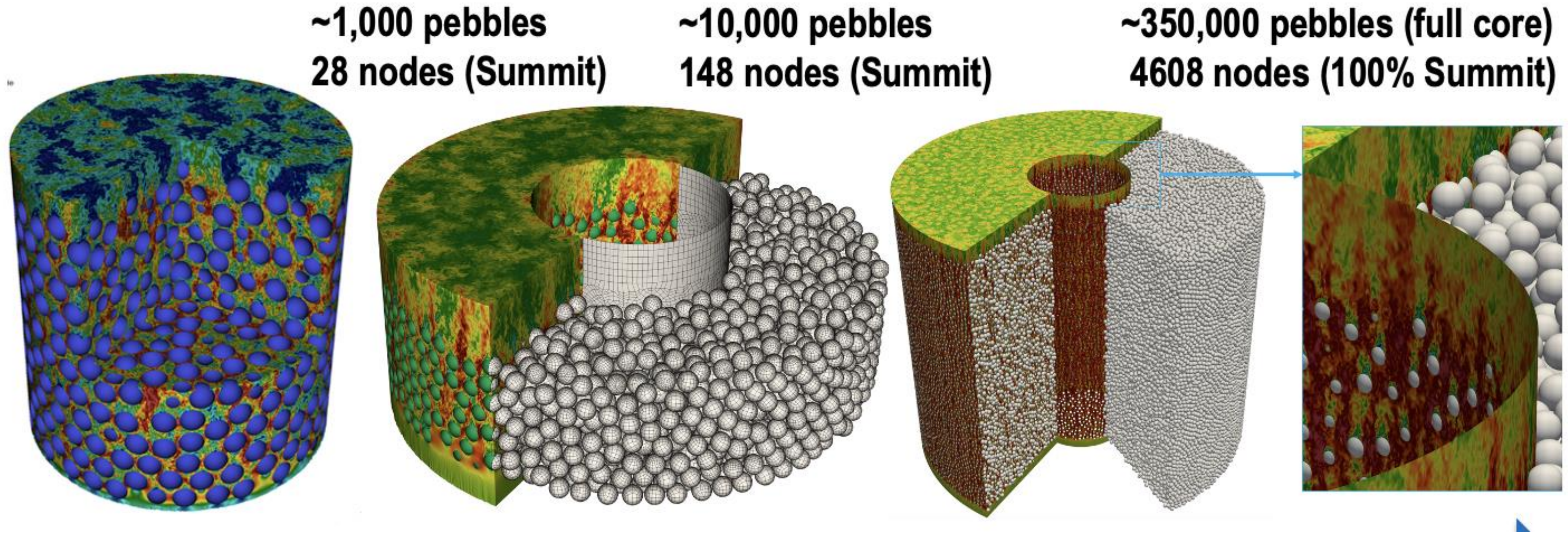
- **SAM**
  - Trustworthy and practical plant-level system analysis tool for advanced reactors
  - Advances in software environments and design, numerical methods, and physical models thanks to **MOOSE**.
- **Pronghorn**
  - Engineering scale environment build on **MOOSE**
  - Coarse CFD, subchannel and distributed resistance
- **Nek5000/NekRS/Cardinal**
  - Open Source, Spectral element high-fidelity code
  - Proven scalability beyond a million MPI ranks (Gordon Bell prize). Now GPU-capable (NekRS).
  - Extensive code verification and validation
  - *Couples to MOOSE and OpenMC through **Cardinal***
- **Sockeye**
  - Engineering scale heat-pipe heat transfer code.
  - Relies on THM module of MOOSE.
- **CTF**
  - LWR subchannel code.
  - Part of VERA.



Flow in a twisted tube HX.



Unique Capabilities

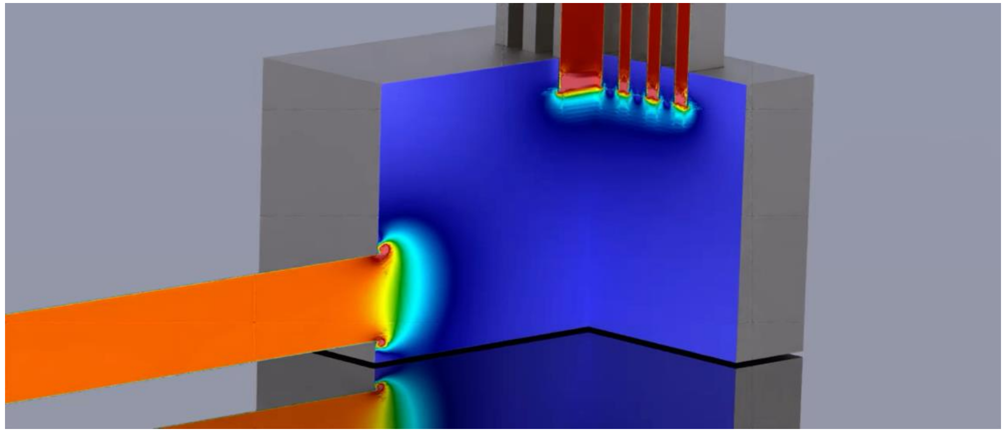


NekRS is enabling full core simulations at high resolution for HTGRs and FHRs

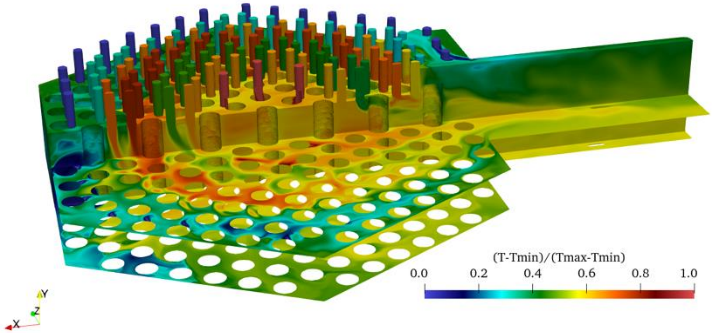
Thermal-fluids presentations today

- Enhancements in System-level T/H Modeling for HTGRs and FHRs (Ling Zou)
  - Ling will provide an overview of recent advancements in the modeling of HTGRs and FHRs at the system level.
- Engineering-Level T/H Modeling for HTGRs and FHRs (David Reger)
  - David will provide an overview of engineering scale capabilities, including multiscale coupled simulations.

Reach out to Elia Merzari (ebm5351@psu.edu for questions)



Modeling of an RCCS experiment with NekRS



HTTF facility – Modeling with NekRS

Enhancements in System-level T/H Modeling for HTGRs and FHRs

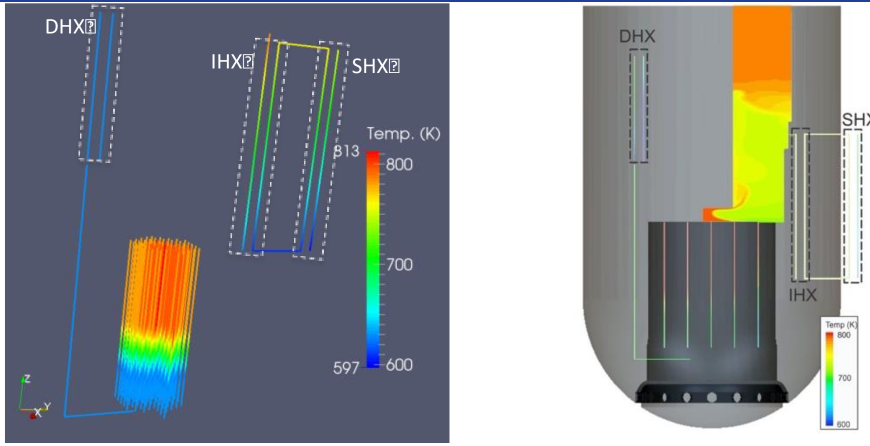
Ling Zou, Rui Hu, Thanh Hua, Gang Yang, Zhiee Jhia Ooi, Yeongshin Jeong

Argonne National Laboratory

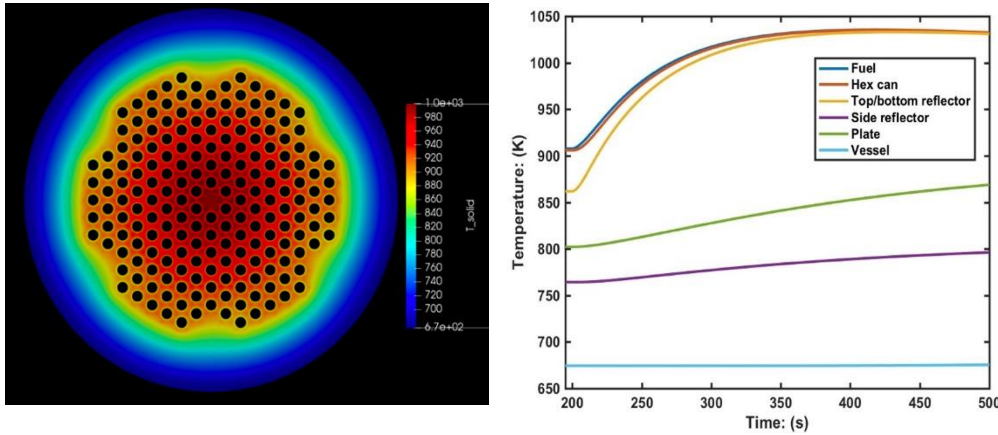
May 8th, 2025

SAM – NEAMS' System Analysis Tool

- SAM is the major system analysis code mainly sponsored by the NEAMS program, aiming for advanced non-LWR safety analysis – covering almost all non-LWR concepts;
- Advances in software engineering, numerical methods, and physical models (built-on MOOSE framework and its libraries);
- Advanced modeling features for various phenomena in advanced reactors;
- Flexible multi-scale multi-physics integration with other MOOSE- or non-MOOSE-based tools;
- Part of BlueCRAB for confirmatory calculations of licensing applications at USNRC.

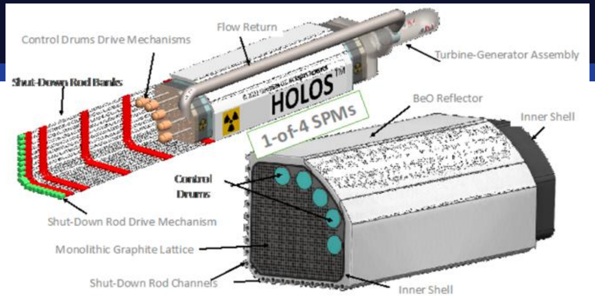


Stand-alone and Coupled SAM and CFD code simulations of SFR

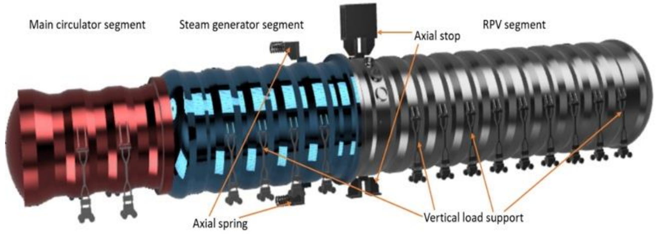


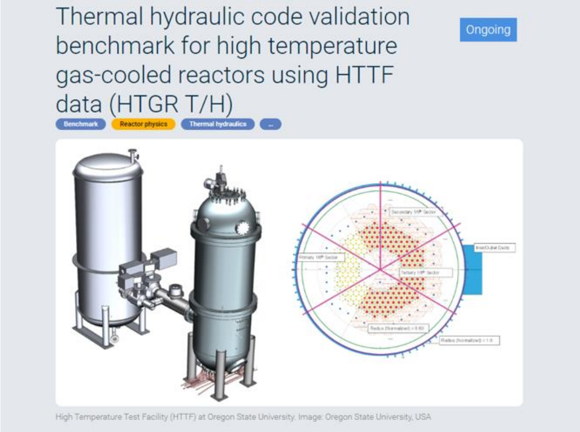
Transient multi-physics simulation of heat-pipe-cooled micro-reactor

Applications and Stakeholder Engagement



- ***NRC*** reference plant model development: PB-HTGR and PB-FHR
- ***Kairos Power***: long-term close collaboration on SAM/KP-SAM, safety analysis activities.
- ***MIT/BA***: SAM was used to support the HC-HTGR core thermal fluid analysis and RCCS design tasks.
- ***HolosGen***: SAM/Griffin were used to support Holos-Quad thermal fluid and neutronics analysis.
- ***OECD/NEA HTTF T/H benchmark***:
  - SAM and nek5000/nekRS were used for code benchmark/validation
  - In close collaboration with ART-GCR program, and international collaborations.
- Extensive code ***validation and demonstration*** of HTGR and FHR application
  - OECD/NEA HTTF, PBMR-400, gPBR200, MHTGR (for GCR applications)
  - CIET (for FHR applications)





Main Capabilities

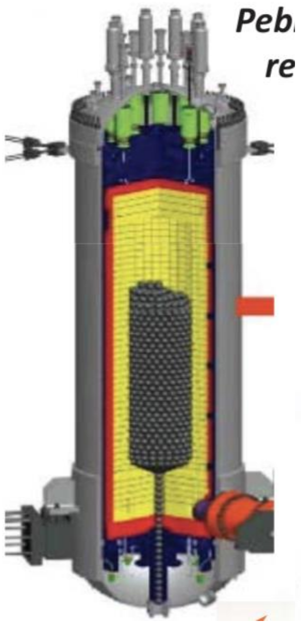
- Focusing on providing system-level safety analysis capabilities to support HTGR and FHR designs in dealing with normal operating and a wide range of transient events.

Reactor Type	TH-neutronics coupling	Type of Conditions/Events
PB-HTGR	Yes	Normal operating, PCC, DCC, Reactivity Insertion, BOP perturbation
Prismatic HTGR (vertical/horizontal layout)	Yes	Normal operating, PCC, DCC, Reactivity Insertion, BOP perturbation
PB-FHR	Yes	Normal operating, SBO, Loss of Heat Sink, Reactivity Insertion, PLOF, ULOF, Overcooling (freezing)

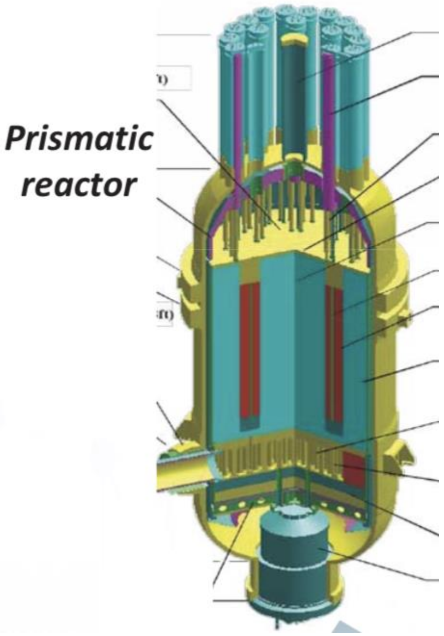
Complex HTGRs/FHRs Thermal-fluids Behaviors

- PB-HTGRs, PB-FHRs, and prismatic HTGRs exhibit more complex multi-dimensional multi-scale thermal fluid behaviors.
- They share some common T/H features and therefore requirements on thermal-hydraulic analysis capabilities:
  - Decay heat removal pathway – core to vessel to RCCS – changes significantly compared to normal operating condition, requires multi-dimensional and multi-scale capability.
  - Bypass flow represents a significant uncertainty in T/H analysis.
  - Both pebble and TRISO kernel temperatures require additional scales to capture.

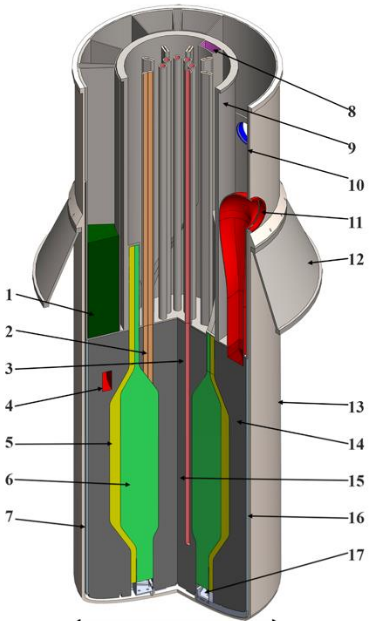
PB-HTGR



Prismatic HTGR

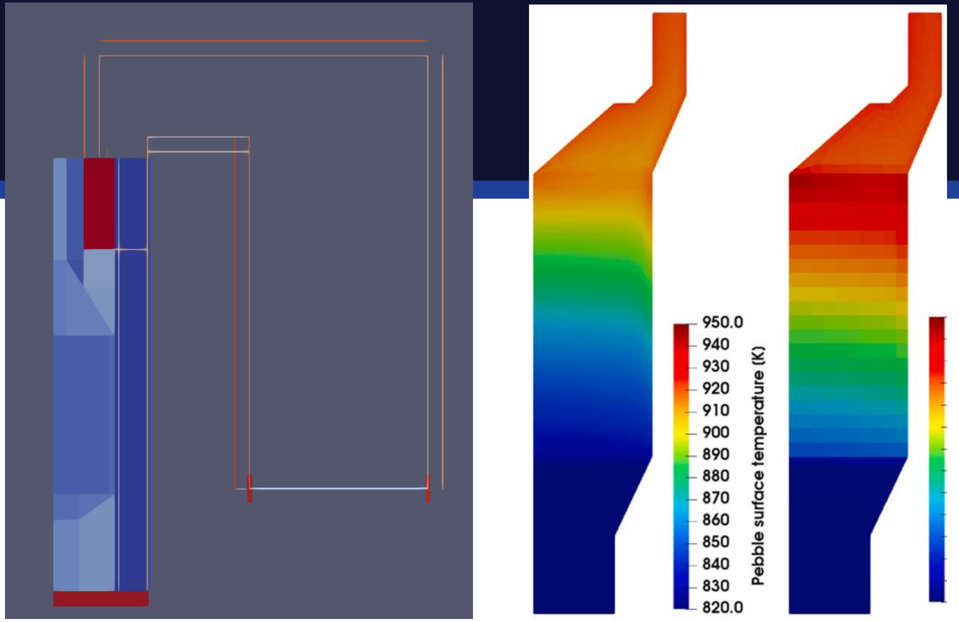


PB-FHR

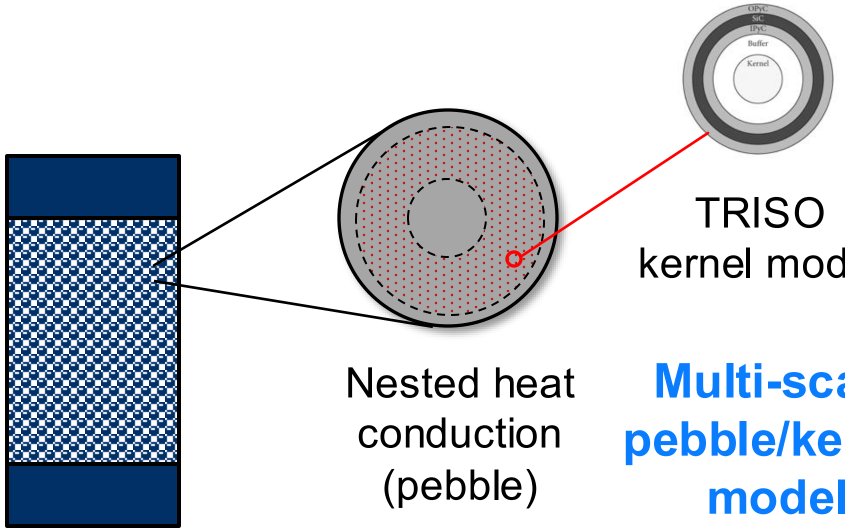


Multi-scale PBR Modeling

- Multi-dimensional porous-medium flow model for core (Pronghorn) and 1D flow network for the rest of the system. Domain overlapping (D.O.): using Picard iterations.
  - Single-solve (S.S.): tightly coupled and solved in SAM also available.
- Multi-scale models are needed to compute pebble and TRISO kernel temperatures and the porous-medium flow model. MultiApp simulation with Pronghorn and other multiphysics codes.
  - One-dimensional pebble heat conduction model nested in the porous-medium flow model, tightly coupled in SAM also available.
- *More details on domain overlapping in the next talk.*



Integrated 1D/3D fluid model



TRISO kernel model

Nested heat conduction (pebble)

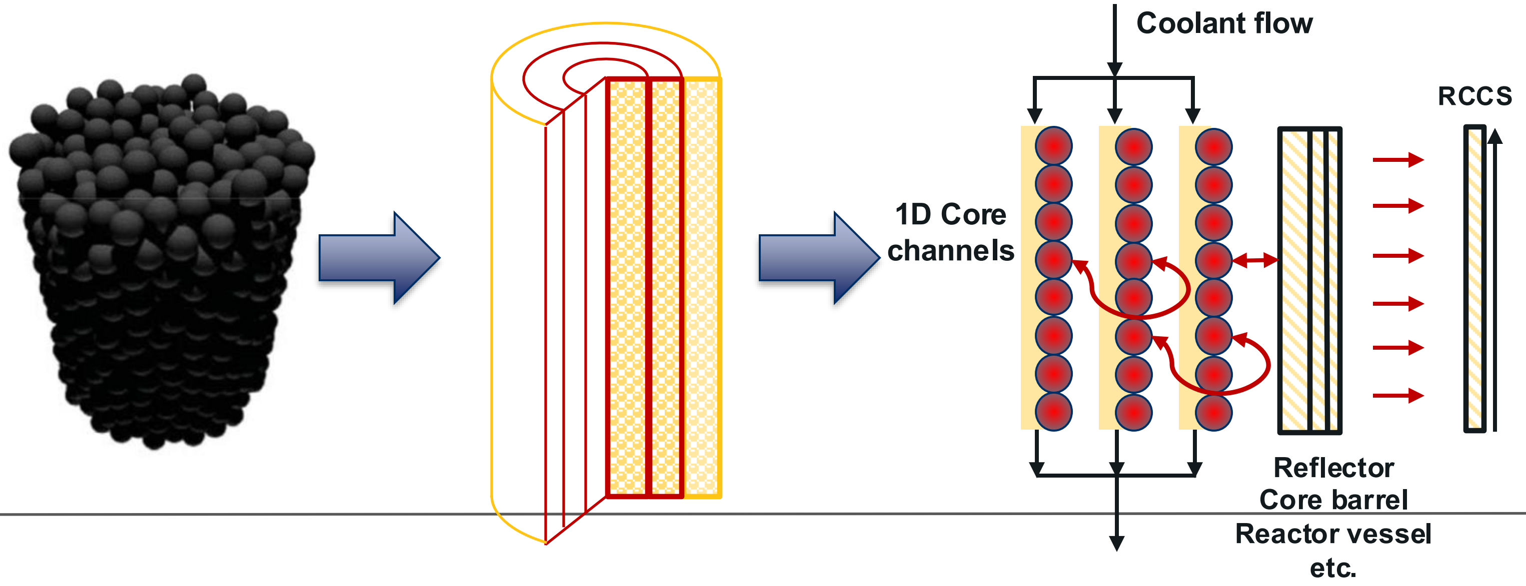
Multi-scale pebble/kernel model

Porous-medium flow (pebble bed)

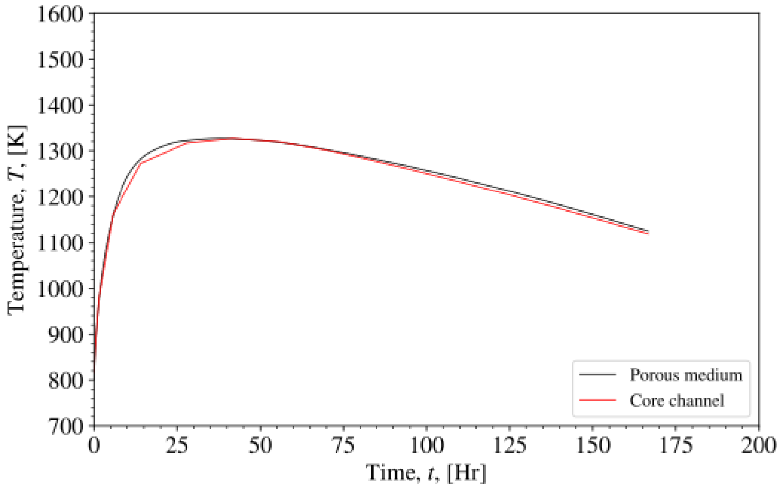
Core-Channel Method for PBRs

- The pebble bed core is treated as columns of concentric cylinder (center) and annulus, all modeled with the one-dimensional *CoreChannel* component. The fast-running option.
- Heat conduction within pebble bed and bed-to-reflector is modeled with SAM's built-in component.
- Good accuracy for scenarios when core cross flow not significant.

Concept of *CoreChannel* for PBR



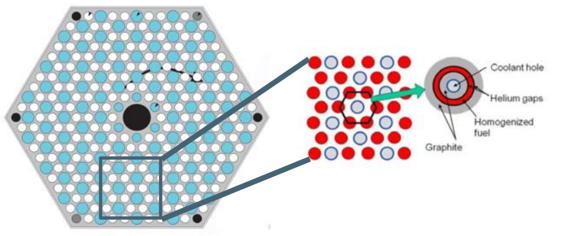
Depressurized conduction cooldown (DCC): comparing with porous-medium model result



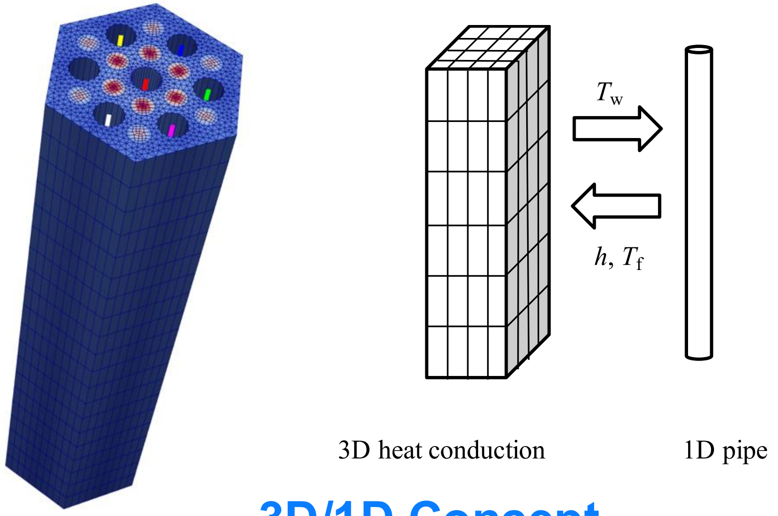
Prismatic HTGR Multi-resolution Methods

The complexity of core geometry and thermal fluid behaviors in prismatic HTGRs requires different methodologies (resolutions) for different analysis purposes.

- Unit-cell method is a traditional methodology allowing for system-level full core simulation of prismatic HTGR suitable for fast running simulations.
- The 3D heat conduction – 1D flow method fills a significant capability gap in prismatic HTGR simulations. The fundamental ideal is to model the solid part with fully-resolved mesh while the flow channels are modeled as one-dimensional flow.
- Homogenized 3D heat conduction model, further reduced computation cost, is suitable for transient simulations.



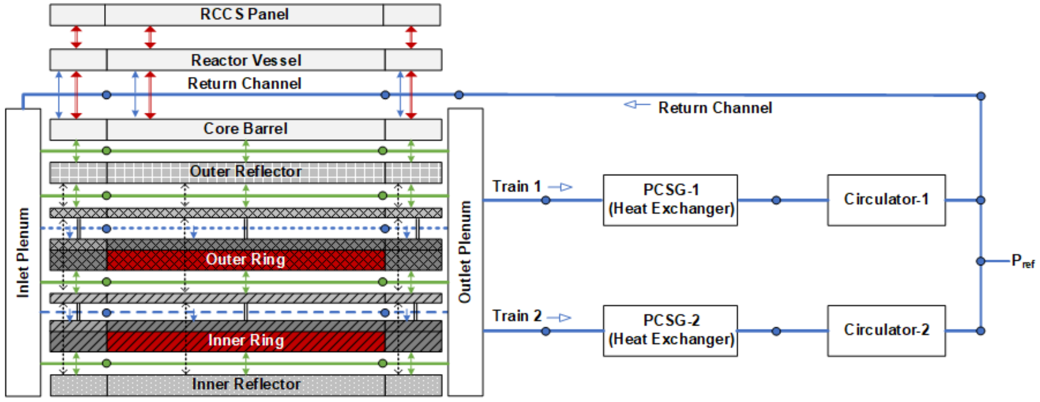
Unit-cell Approach

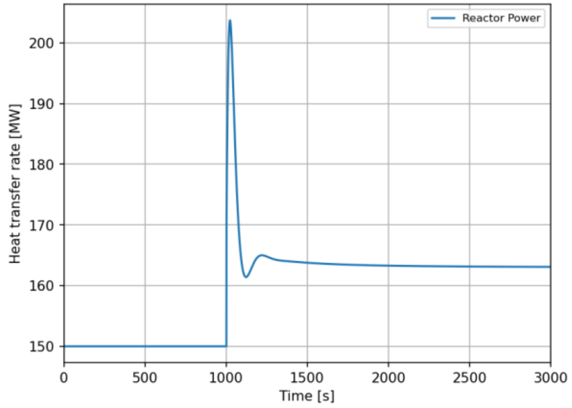


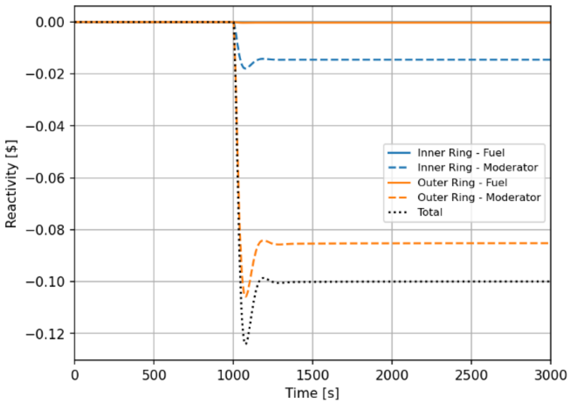
3D/1D Concept

Prismatic HTGR Application Examples

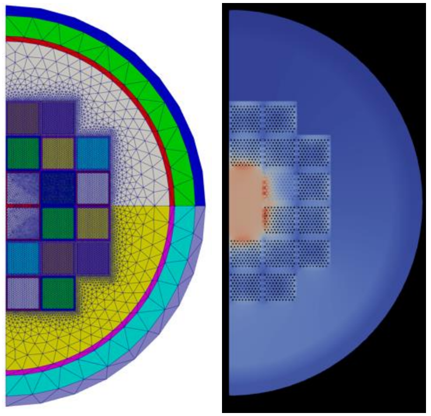
- An example of unit-cell full core model in combination of SAM PKE model for a reactivity insertion event.

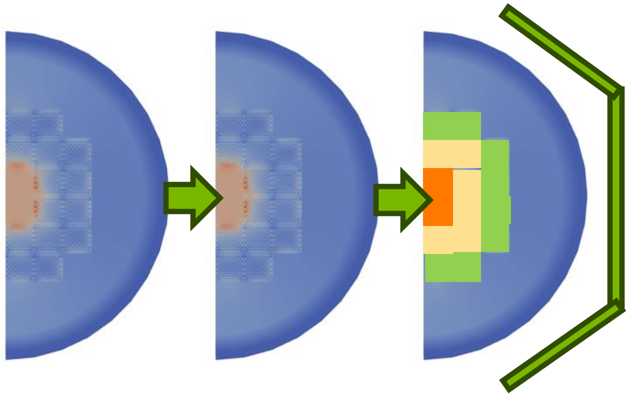


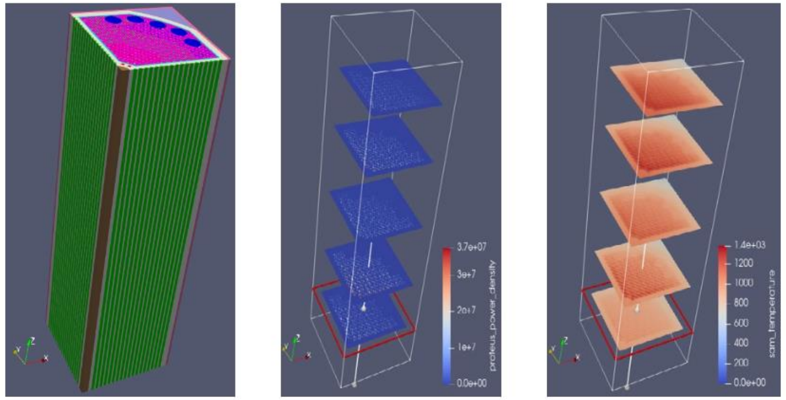




- Examples of 3D/1D multi-scale prismatic HTGR simulations.







(a) Geometry (b) Power (c) Temperature

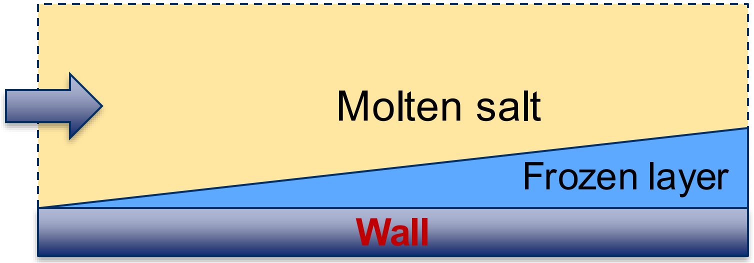
High-resolution core T/H analysis

Full core *transient* model with high-resolution and homogenized 3D mesh

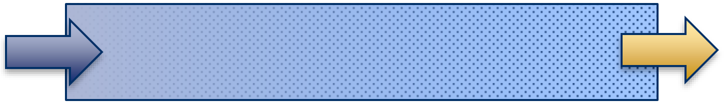
Coupled T/H and neutronics high-resolution simulation

Other Special Models

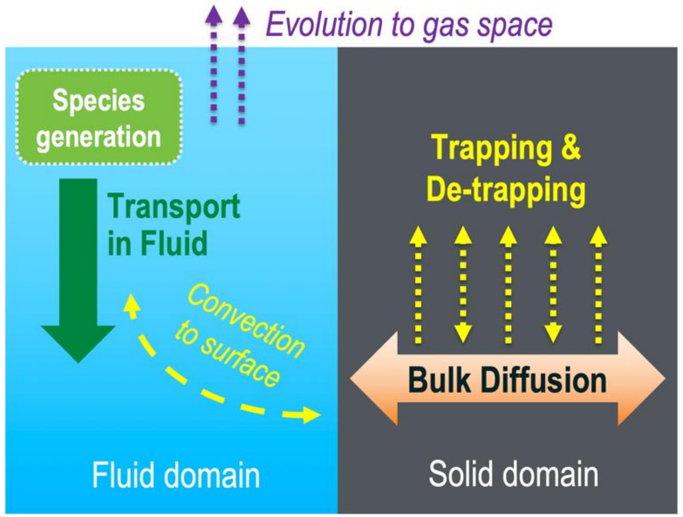
- For the modeling and simulation needs of HTGRs and FHRs, many special models are being implemented and further improved in SAM. This includes:
- One-dimensional freezing model, assuming salt freezes on one side of the flow channel due to external cooling, for FHR applications.
- Multi-component gas flow model and graphite oxidation model for air-ingress and steam-ingress transient in HTGRs.
- Tritium transport model that captures tritium generation, convection, trapping (in graphite), and permeation (through metallic structures).



Freezing Model



Multicomponent Gas Mixture model



Tritium Transport Model

Summary/Future Work

- HTGRs and FHRs exhibits more complex thermal fluid behaviors compared to other types of reactors, requiring multi-dimensional and multi-scale modeling capabilities.
- Leveraging MOOSE framework, multi-scale modeling features to support such needs are available in SAM, as well as coupling with other codes for multi-scale multi-physics capabilities.
- Different modeling capabilities (spatial resolutions) and flexible modeling strategies are implemented for different modeling purpose.
- Special physical models are being developed and/or further improved to support HTGRs and FHRs applications.
- Future work are planned to support HTGRs, FHRs modeling and simulation needs. Examples include:
  - Air/steam-ingress modeling capability including multi-component gas mixture and graphite oxidation model.
  - Source term evaluation, e.g., gaseous fission products transport in salt system, aerosol generation, salt spill.

References

Journal Articles

1. Ling Zou, Thanh Hua, Zhiee Jhia Ooi, Jun Fang, and Rui Hu, “Thermal Fluid Modeling Approaches in SAM for High Temperature Gas-Cooled Reactor Applications,” Nuclear Technology, 2024, DOI:10.1080/00295450.2024.2410623
2. Aaron Huxford, Ling Zou, Rui Hu, Victor Petrov, and Annalisa Manera, “Validation of a Hybrid Domain Overlapping Coupling Between SAM and CFD Against the TALL-3D Transients,” Nuclear Technology, 2024, DOI: 10.1080/00295450.2024.2352665
3. Huxford, Aaron, Victor Coppo Leite, Elia Merzari, Ling Zou, Victor Petrov, and Annalisa Manera, “A hybrid domain overlapping method for coupling System Thermal Hydraulics and CFD codes,” Annals of Nuclear Energy, 189 (2023): 109842.
4. Ling Zou, Quan Zhou, Dan O’Grady, Rui Hu, Alex Heald & Haihua Zhao, “Verification and Demonstration of One-Dimensional Freezing Model in SAM for Salt-Cooled Reactor Analysis Applications,” Nuclear Technology, 2024, DOI:10.1080/00295450.2024.2377522
5. Hu, Guojun, Ling Zou, Daniel J. O'Grady, and Rui Hu. "An integrated coupling model for solving multiscale fluid-fluid coupling problems in SAM code." Nuclear Engineering and Design 404 (2023): 112186.
6. Thanh Hua, Ling Zou, and Rui Hu, “Code Benchmark of the HTTF Pressurized Conduction Cooldown Test Using SAM,” Nuclear Science and Engineering, 197:10, 2660-2672, 2023. DOI: 10.1080/00295639.2023.2186163
7. Zou, Ling, Guojun Hu, Dan O'Grady, and Rui Hu, “Explicit modeling of pebble temperature in the porous-media model for pebble-bed reactors,” Progress in Nuclear Energy, 146 (2022): 104175.
8. Zhiee Jhia Ooi, Thanh Hua, Ling Zou, and Rui Hu, “Simulation of the High Temperature Test Facility (HTTF) Core Using the 2D Ring Model with SAM,” Nuclear Science and Engineering, 2022. DOI: 10.1080/00295639.2022.2106726

Conference Papers

1. Zhiee Jhia Ooi, Ling Zou, Thanh Hua, Jun Fang, Rui Hu, “System Level Modeling of a Generic Pebble Bed High-Temperature Gas-Cooled Reactor (PB-HTGR) with SAM and Griffin,” 20th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-20), Washington, D.C., August 20–25, 2023.
2. Taiyang Zhang, Thanh Hua, Zhiee Jhia Ooi, Ling Zou, Caleb S. Brooks, “Modeling the Prismatic HTGR Core in SAM by Representative Channels,” 20th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-20), Washington, D.C., August 20–25, 2023.
3. Travis Mui, Rui Hu, Quan Zhou, “Integration of a tritium transport model in SAM for FHR modeling,” 2022 ANS Winter Conference and Technology Expo, Phoenix, AZ, November 13–17, 2022.
4. Changho Lee, Brent Hollrah, Kristina, Nicolas E. Stauff, Ling Zou, and Claudio Filippone, “High Fidelity Multiphysics Simulation of Holos Quad Micro Reactor Design,” 2022 ANS Winter Conference and Technology Expo, Phoenix, AZ, November 13–17, 2022.

Engineering-Level T/H Modeling for HTGRs and FHRs

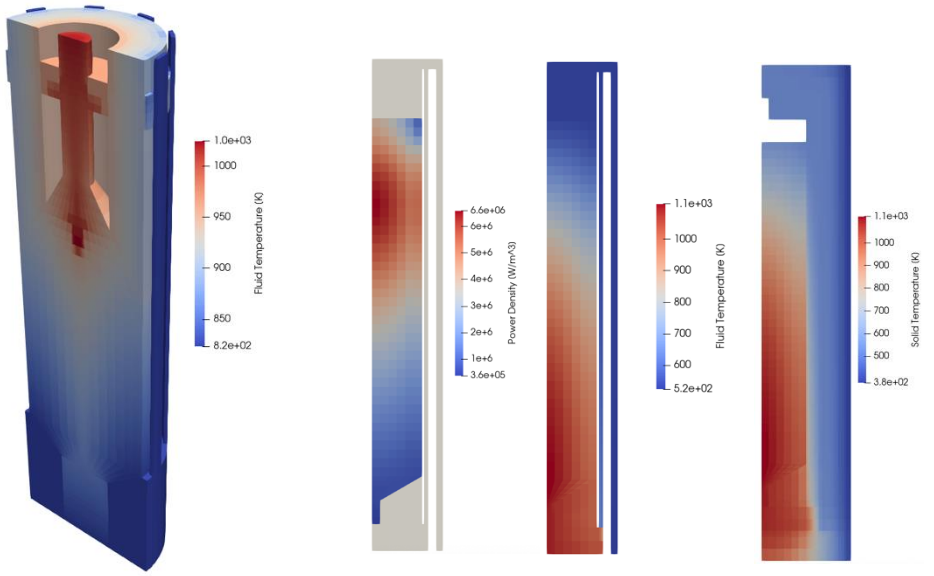
David Reger, Lise Charlot, Mauricio Tano, Victor Coppo Leite

Idaho National Laboratory

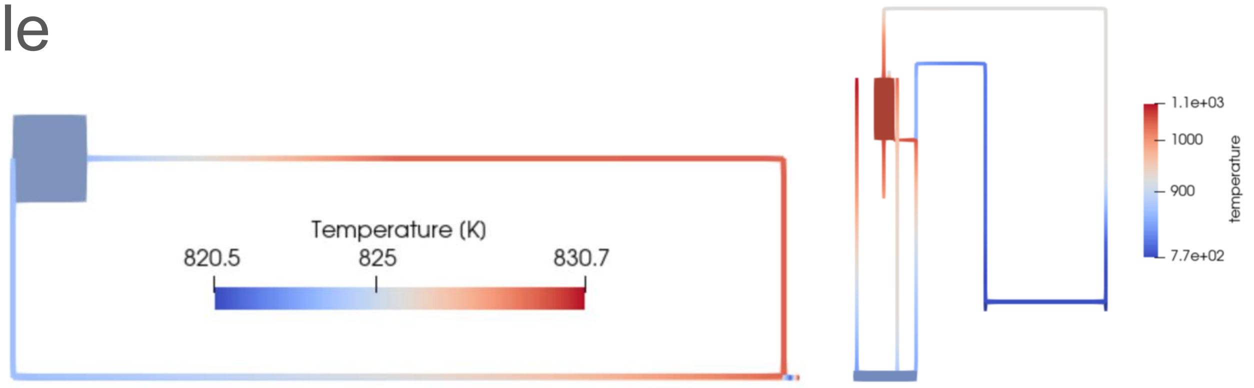
May 8th, 2025

Relevant NEAMS TH Toolkit

- **Pronghorn:** Intermediate-fidelity multidimensional coarse-mesh CFD code
  - Finite volume discretization
  - Incompressible or weakly compressible
  - Porous media models and RANS models



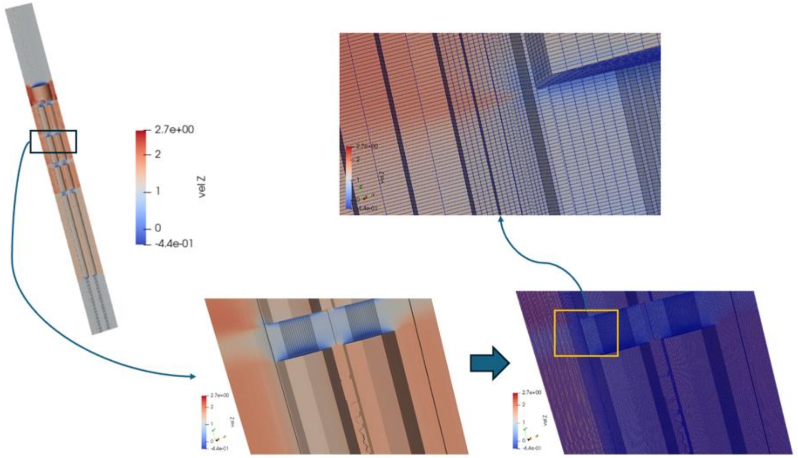
- **SAM:** System-level code for plant-scale simulations
  - Finite element discretization
  - 1D or 0D components



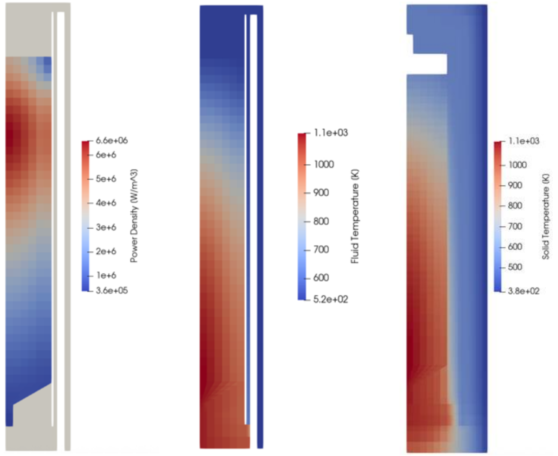
Pronghorn Capabilities

- Coarse-mesh CFD
- Porous flow modeling with a wide range of correlations
- RANS turbulence modeling with several turbulence models
- Two-phase flow using drift flux or Eulerian-Eulerian model
- **Straightforward coupling to neutronics and other physics within the MOOSE framework**
- **Level of resolution appropriate for full core modeling**

RANS Simulation for ATFS

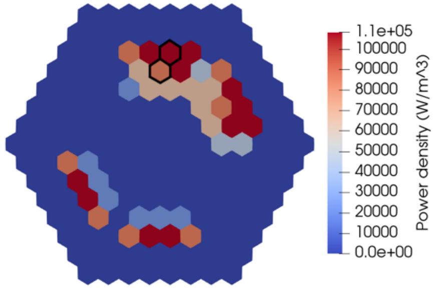


Coupled Porous Media/Neutronics calculations

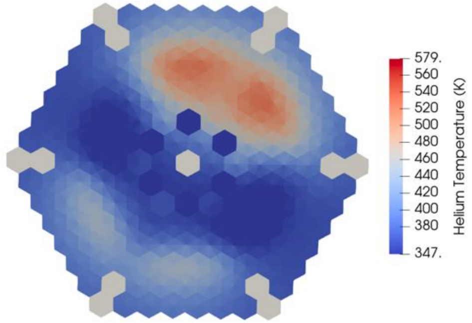


Prismatic HTGR modeling with Pronghorn

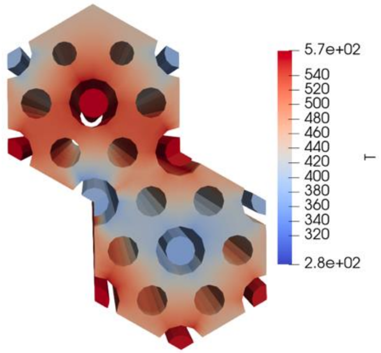
- 3D porous media approach coupled with subscale detailed assembly-level models
- Participation to the OECD- NEA HTGR benchmark using the HTTF
- 2D axisymmetric porous media approach using effective thermal conductivity leading to reasonable results for HTTF PG27 steady state and pressurized conduction cooldown
  - Transient trends are well reproduced
  - Large uncertainties in the experiment (no mass flow rate measurement)



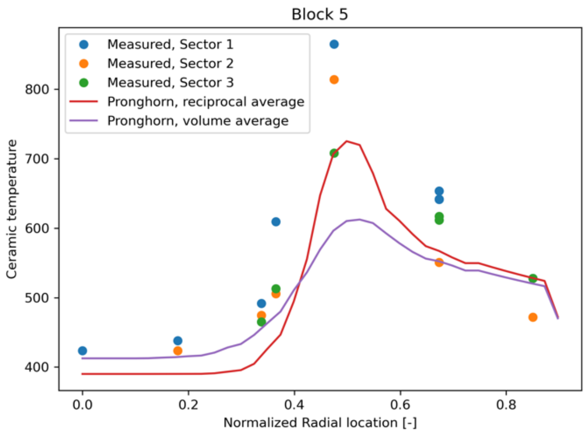
HTTF PG-29 heated assemblies



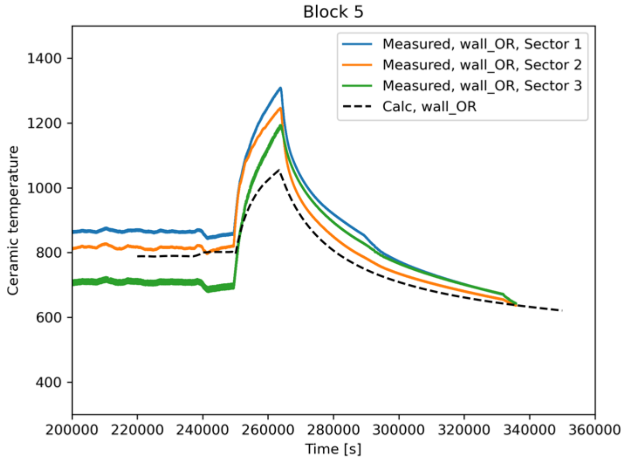
Helium temperature distribution for PG29 steady state conditions



Detailed solid temperature distribution in hotter assemblies



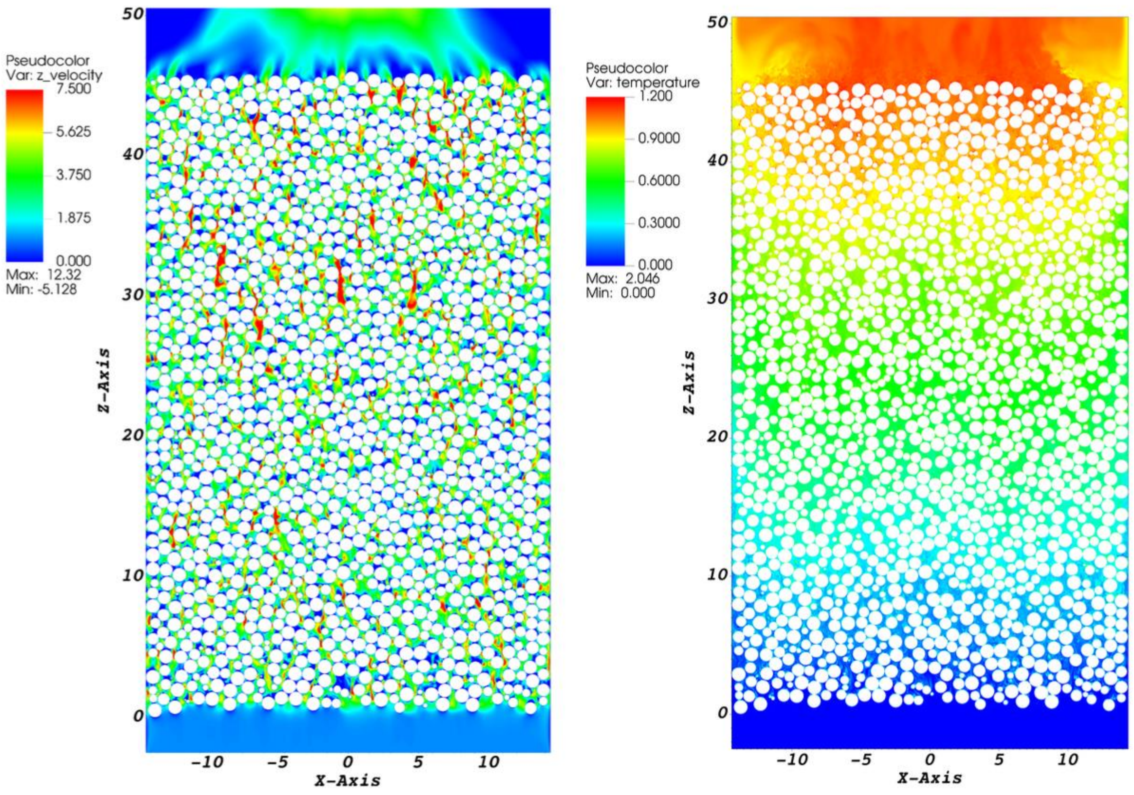
HTTF PG-27 mid core steady state temperatures



HTTF PG-27 transient: mid core temperature in the core outer ring

New Correlations for PBRs

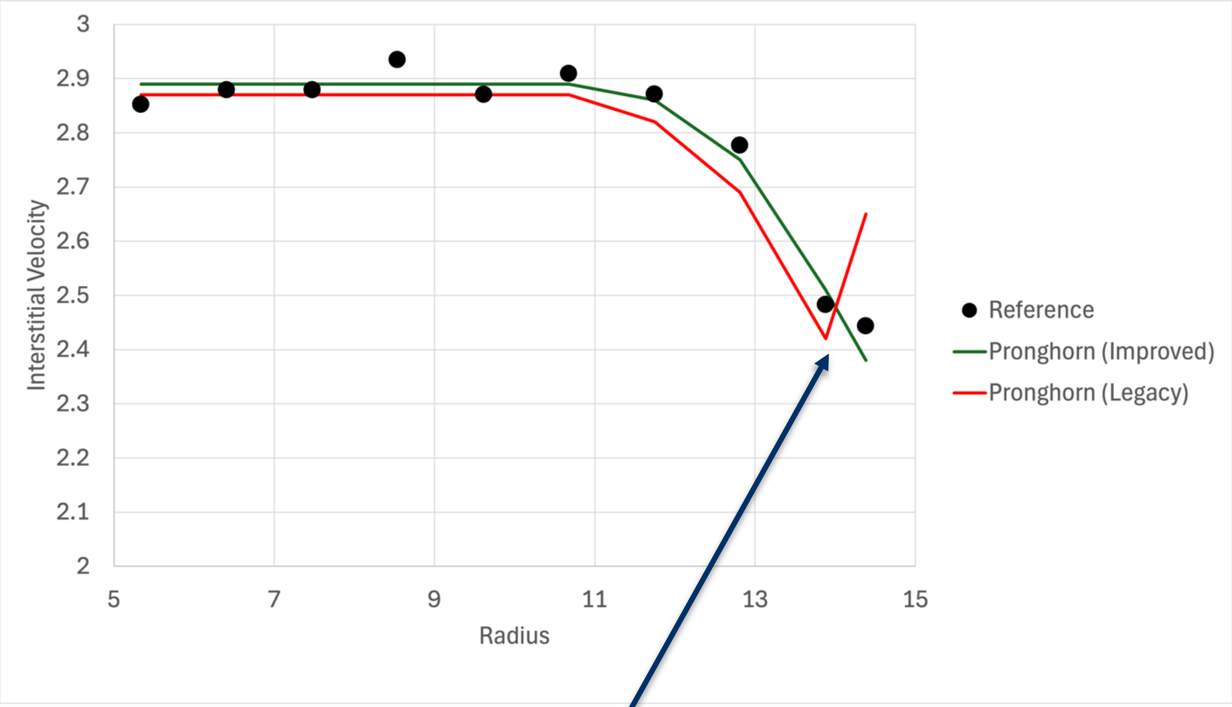
- Improved correlations for pressure drop and heat transfer were developed within NEAMS using a “high-to-low” method with NekRS
- These improved correlations have been implemented in Pronghorn, allowing for better modeling of near-wall effects
- Results for helium are presented in an earlier publication. Current comparisons are performed with a salt coolant
- Recently extended NekRS for radiation

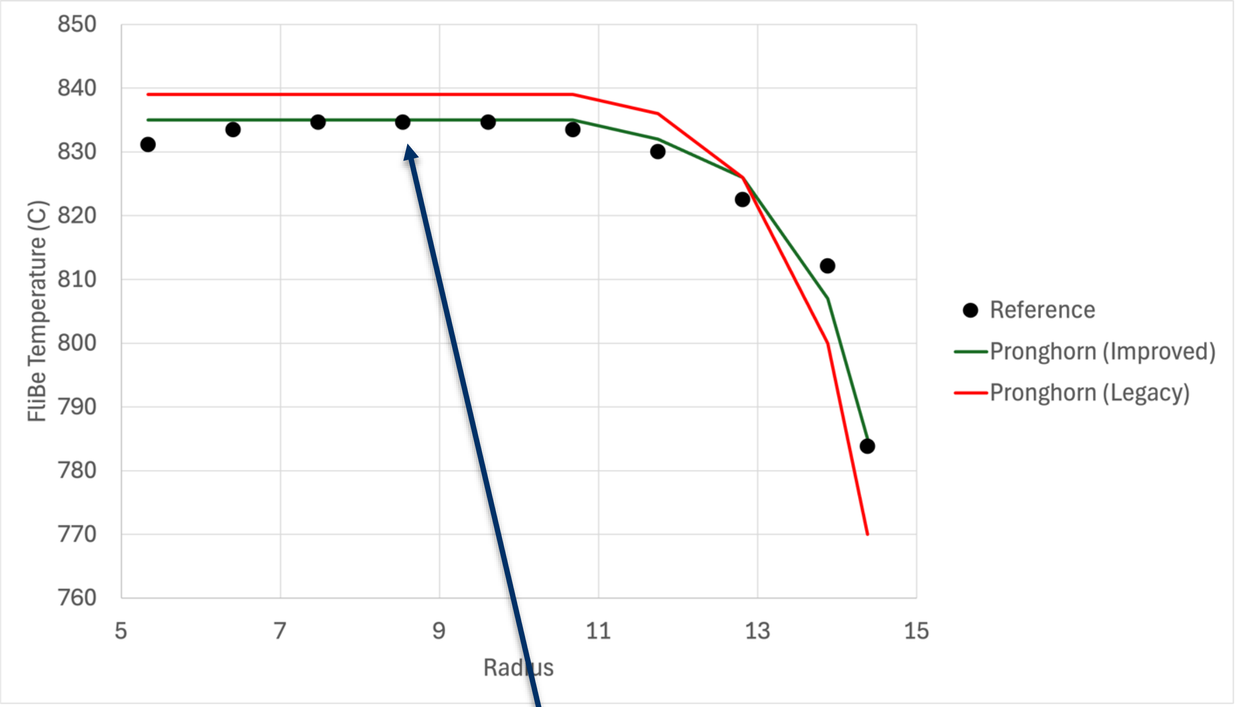


(a) velocity field (b) temperature field

Reger, D. et al, “*Improving the modeling of near-wall interphase heat transfer in porous media models of Pebble Bed Reactors*,” Nuclear Engineering and Design, 427, 2024

New Correlations for PBRs

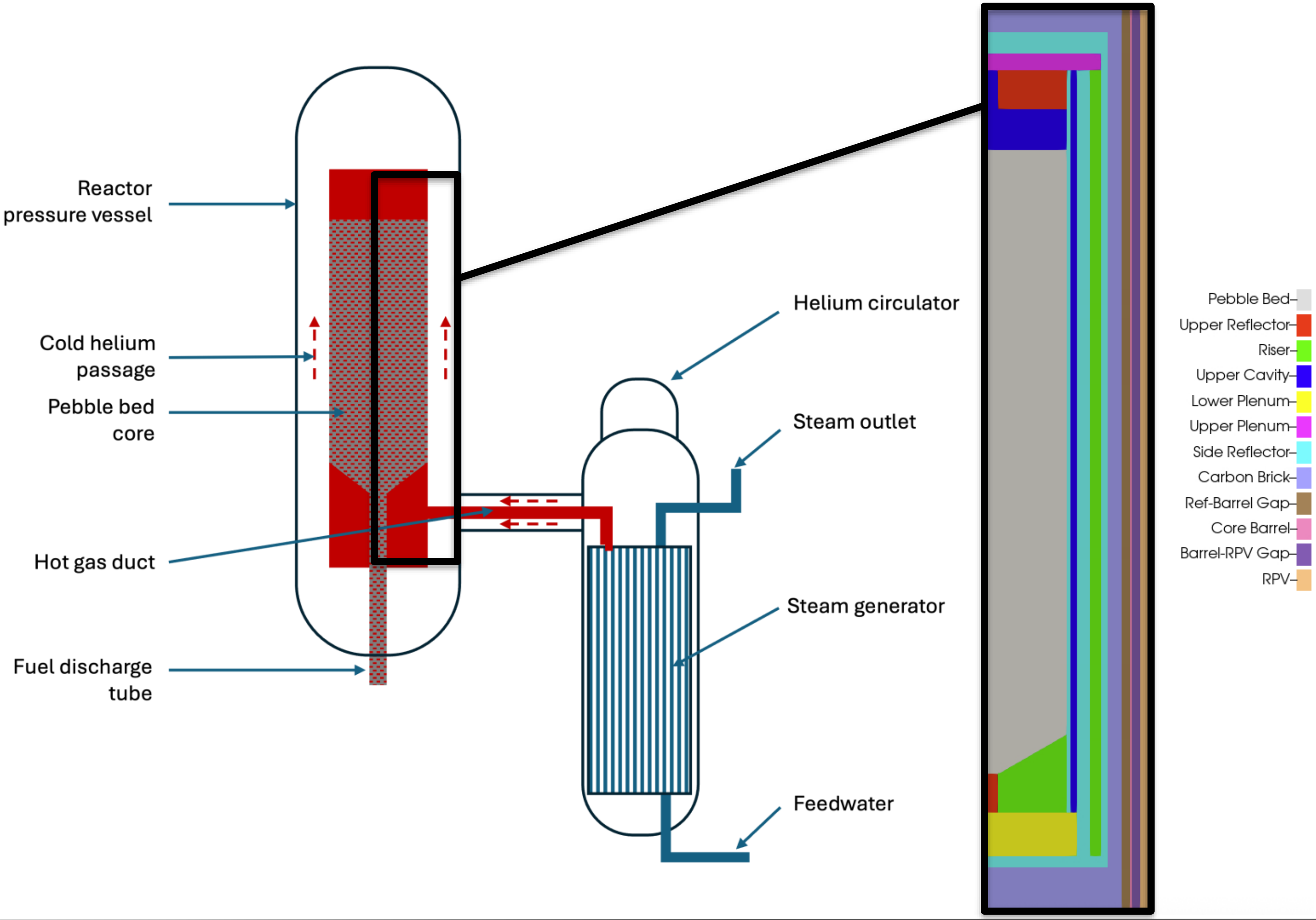




Improved agreement between porous media and LES, particularly near the wall

Fluid temperature distribution also sees improvement

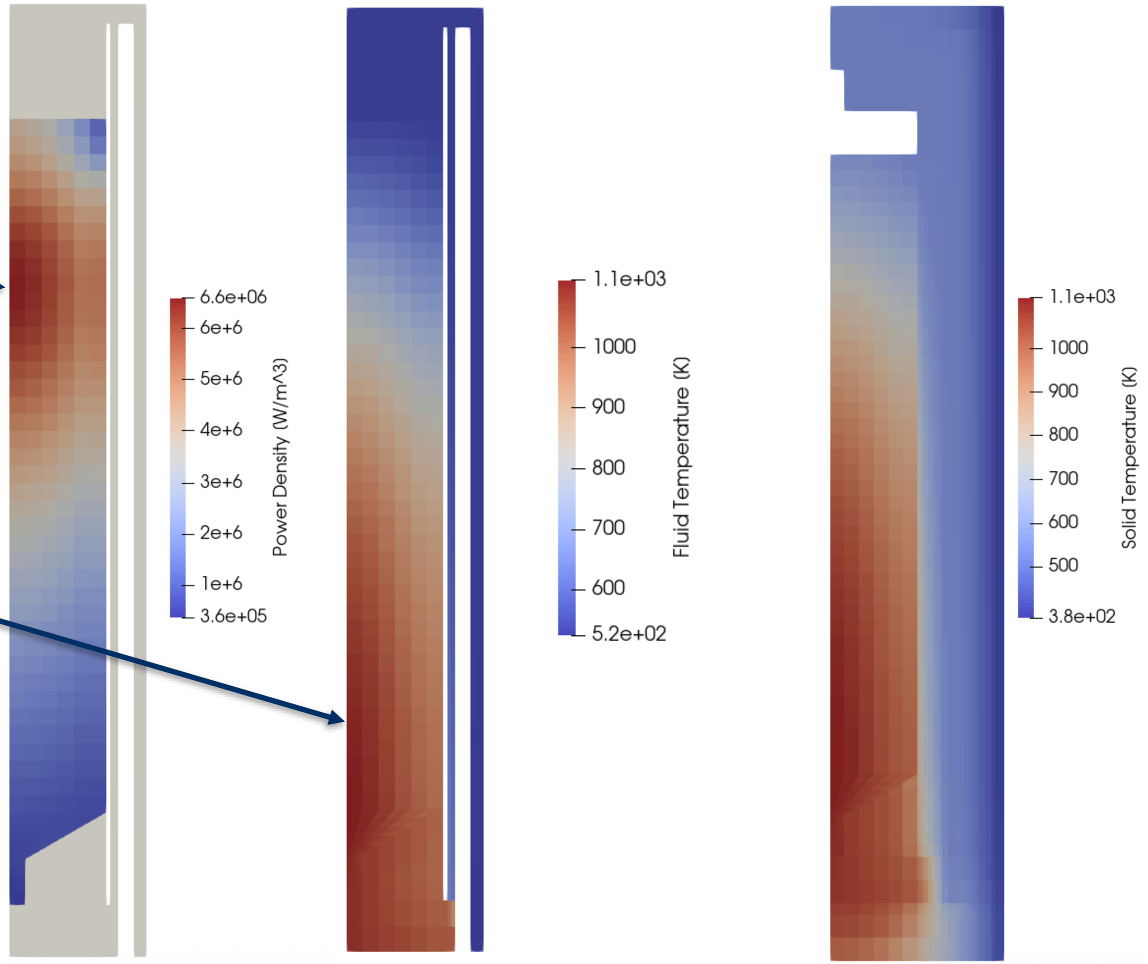
HTR-PM Porous Media Simulation



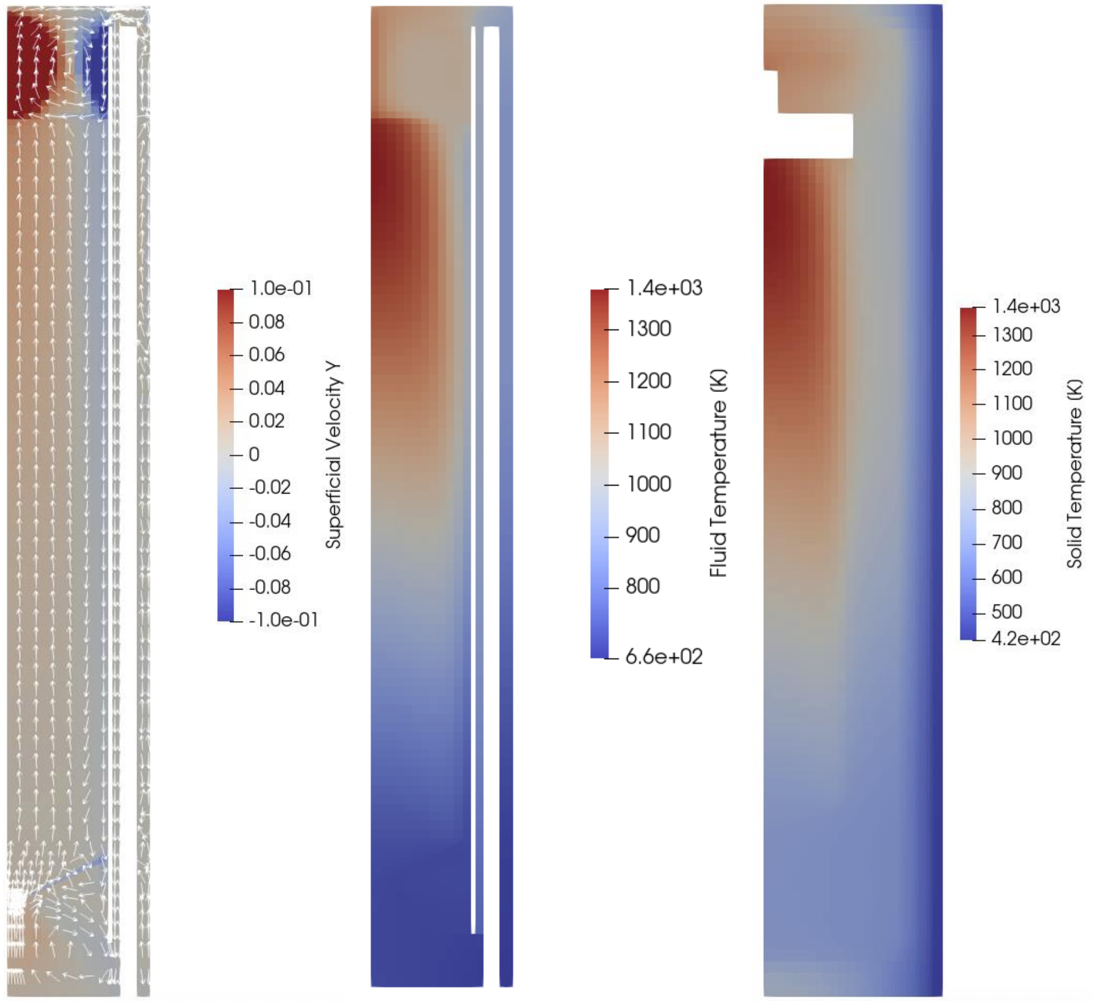
- 2D RZ porous media core TH model in Pronghorn, Griffin diffusion model for neutronics
- Helium coolant at 6MPa and operational flow rate of 96 kg/s
- KTA correlation for drag and heat transfer
- ZBS correlation for effective solid conductivity (accounts for conduction and radiation heat transfer)
- Model developed in collaboration with the NRC

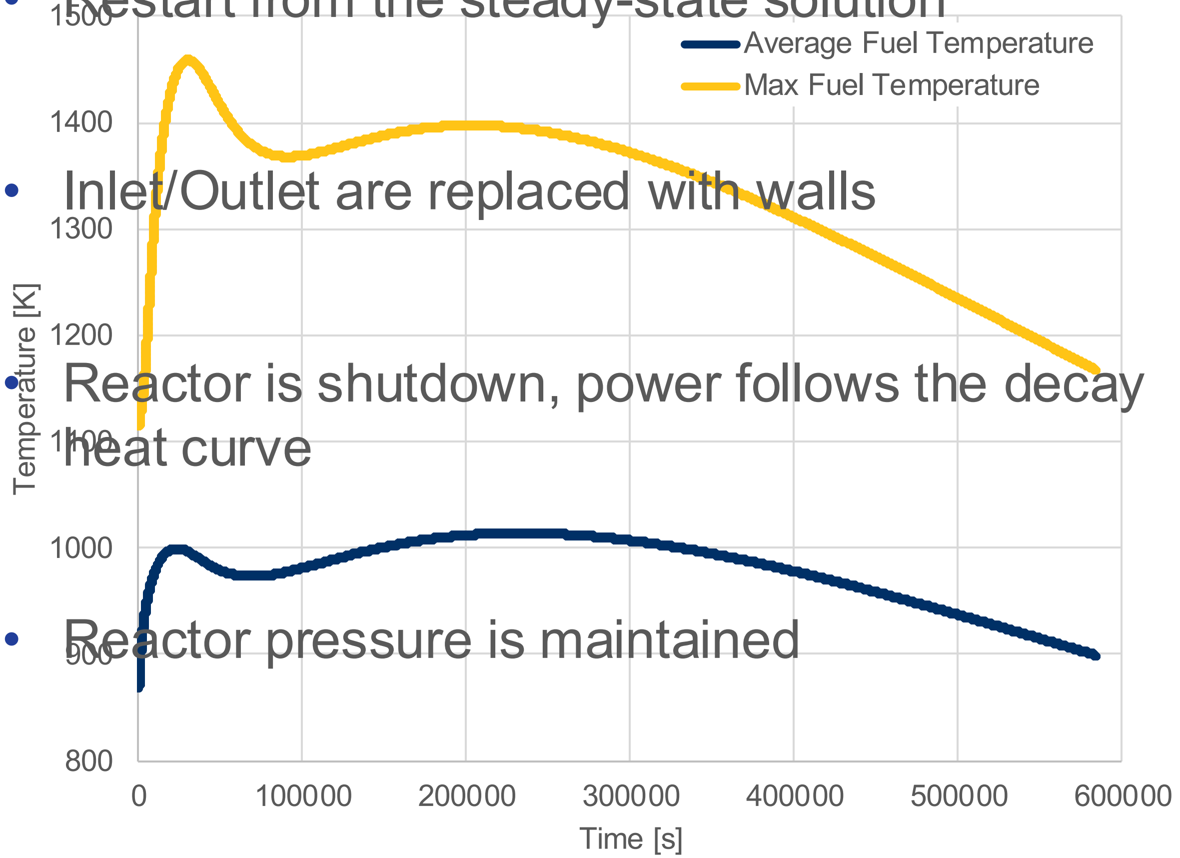
HTR-PM: Steady-State

- Core Temperature rise of 500K
- Power peak near the top center of the core
- Temperature peaks near the bottom center of the core



HTR-PM: PLOFC



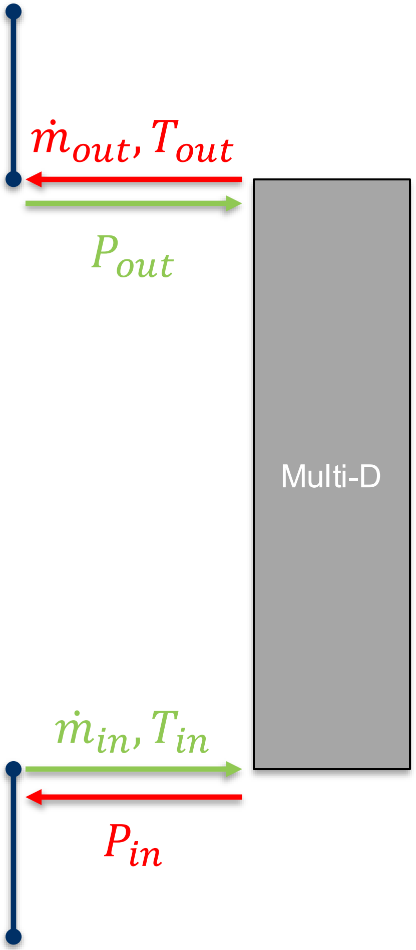


- Restart from the steady-state solution
- Inlet/Outlet are replaced with walls
- Reactor is shutdown, power follows the decay heat curve
- Reactor pressure is maintained

Overlapping Domain Coupling

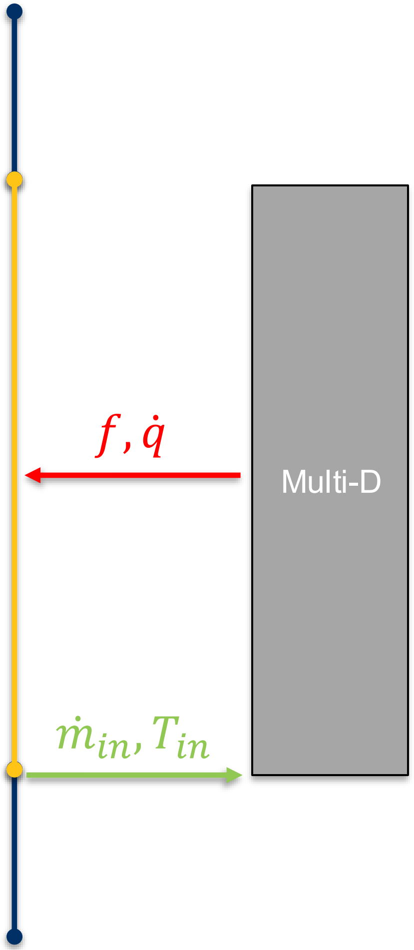
Segregated Domain

- System-level domain and Multi-D domain are segregated
- Boundary conditions are passed at the endpoints
- Suffers from coupling instability in many cases



Overlapping Domain

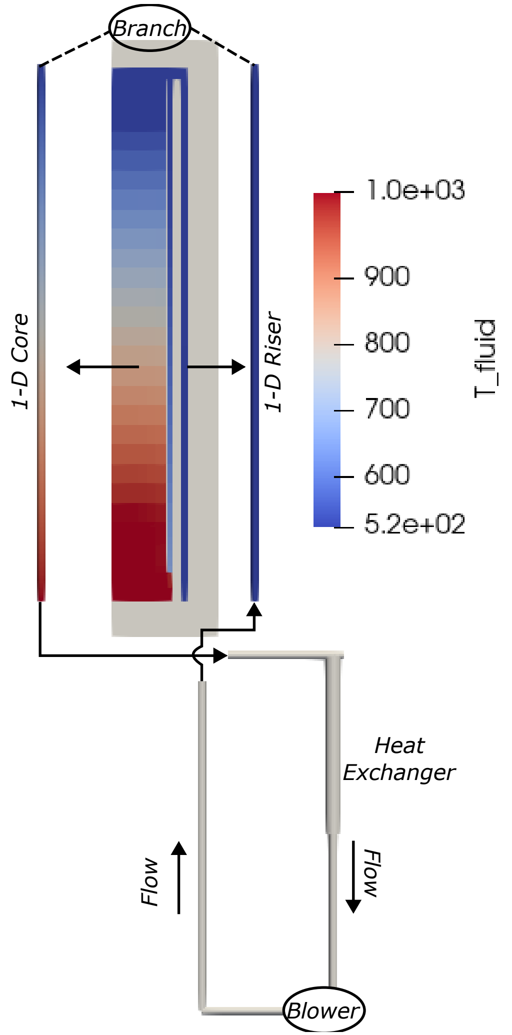
- System-level contains an overlapped surrogate component
- Determines a friction factor and heat source to preserve the Multi-D pressure drop and enthalpy rise in the surrogate
- Improves coupling stability



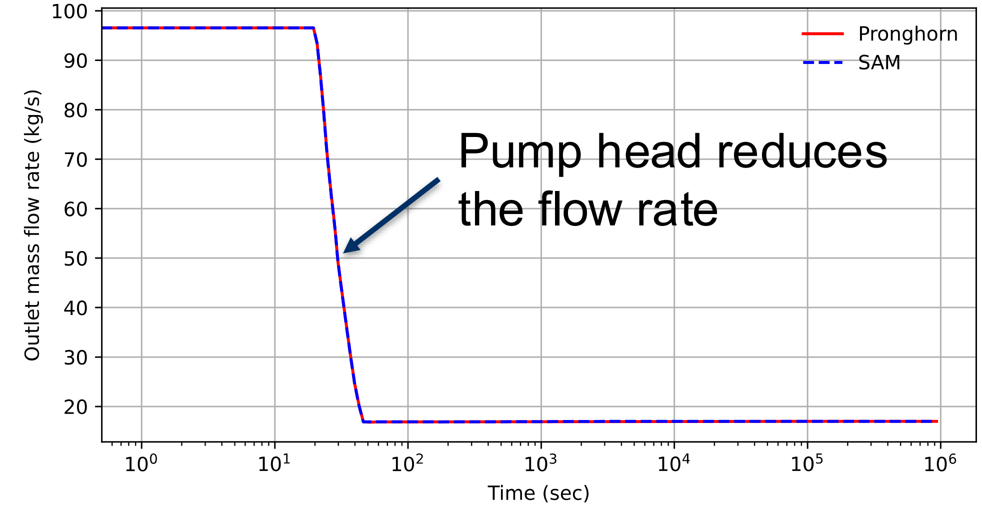
Overlapping Domain Coupling: Recent Progress

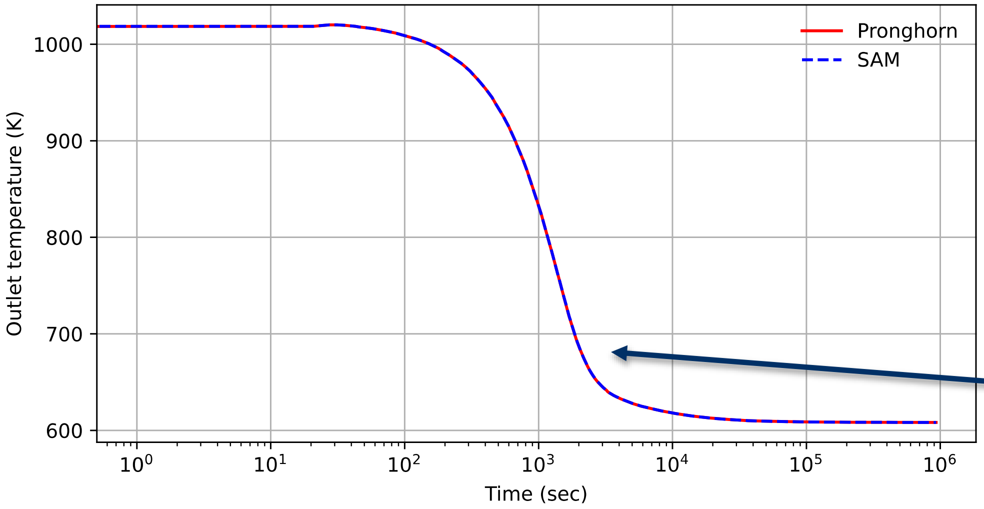
- Applied to the HTR-PM model, where the core and riser are overlapped components in SAM

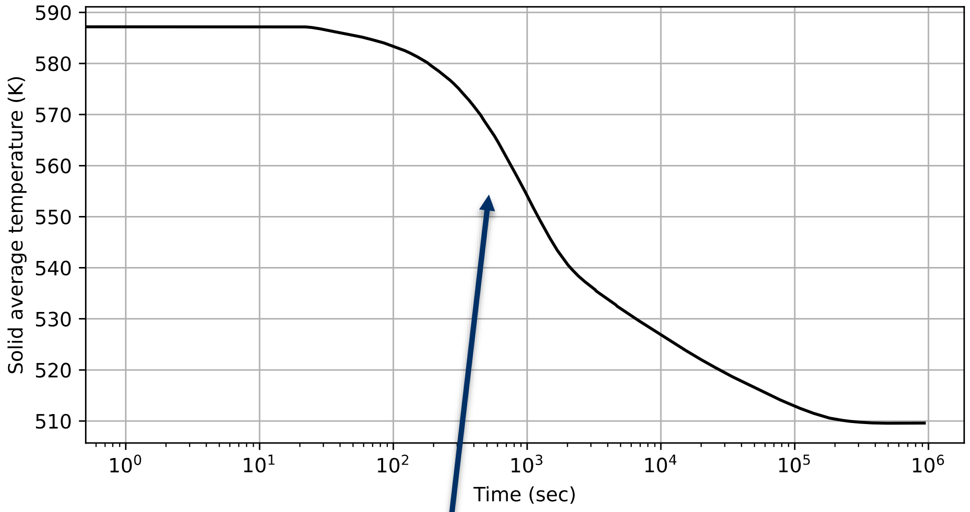
- Performing a simplified PLOFC, where the power and pump head are linearly decreased to 3% of their nominal value over 25s



Overlapping Domain Coupling: Simplified PLOFC







Mass flow rate reduction is less than the power reduction, leading to a decrease is fluid and solid temperatures

Conclusions

- Pronghorn is being applied for coarse-mesh simulation of prismatic and pebble bed HTGRs and FHRs
- An overlapping domain coupling methodology is being developed to couple engineering-scale simulations with system-scale simulations
- Future work
  - Develop this coupling method to expand its applicability to a wide range of transients (low flow conditions, buoyancy-driven flows, multiple inlets/outlets)
  - Develop and demonstrate capabilities to support air or steam ingress scenarios
  - Streamline high-to-low correlation development process

U.S. DEPARTMENT of ENERGY

Office of Nuclear Energy