INL/CON-22-70170-Revision-0

Coupled Multiphysics Primary Loop Simulations of the Mk1-FHR in the Virtual Test Bed

November 2022

Changing the World's Energy Future

Guillaume Louis Giudicelli, Cole M Mueller, Jun Fang, Thanh Q. Hua, Daniel Nunez, Abdalla Abou Jaoude

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ANS Winter 2022

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Mission Statement

NRIC: Deliver successful demonstration and deployment of advanced nuclear energy

- **EBRII Test Bed (DOME)**
- **ZPPR Test Bed (LOTUS)**
- **Virtual Test Bed (VTB)**: Accelerate deployment of advanced reactors by leveraging state-of-the-art ModSim tools developed by NEAMS program

Ok but what is it?

Reactor Demonstrations

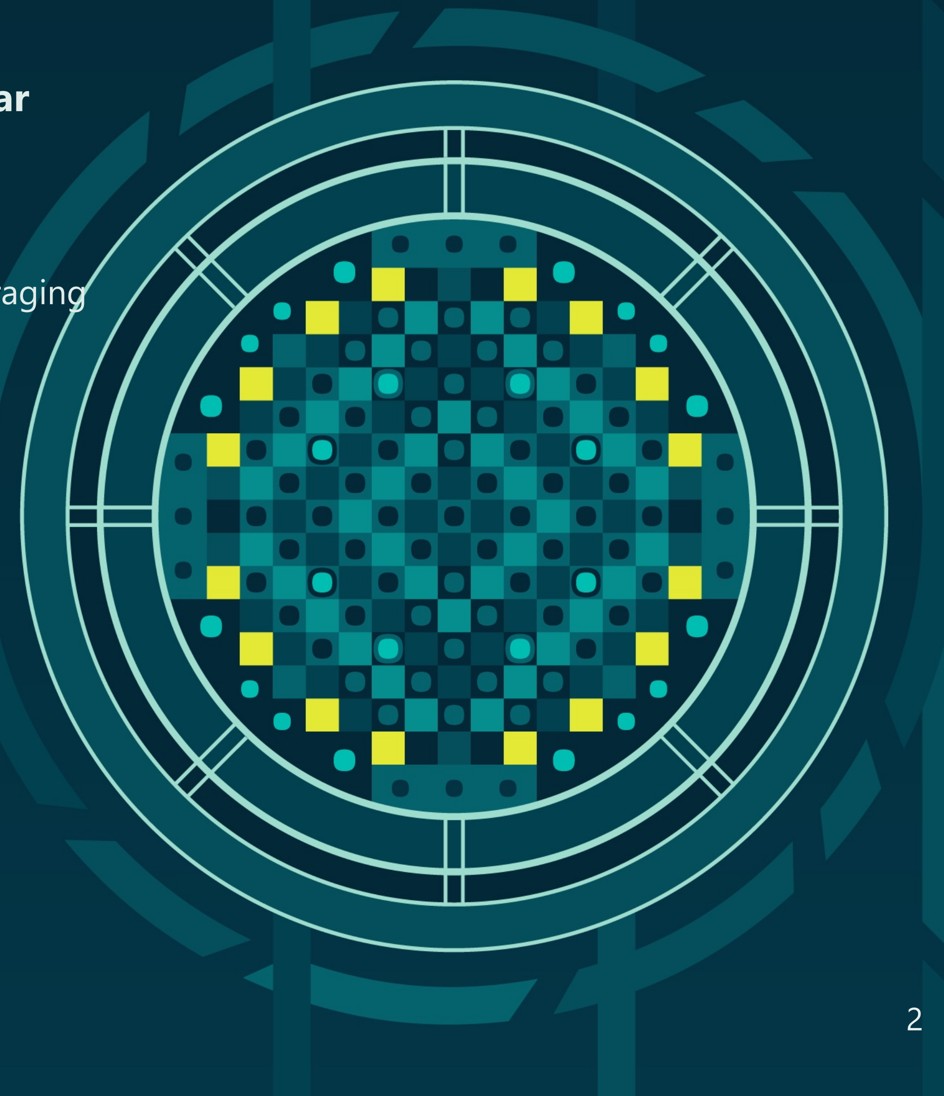
1) Model Development

Leverage codes supported by NEAMS to provide powerful, highly-adaptable simulations:

- Analysis Tools
- Problem benchmarks
- Testing capabilities
- Safety review

2) Model Repository

- Storing and showcasing open use-cases
- Stewardship of industry-relevant models
- Integration with code development framework to avoid legacy issues



The VTB Repository

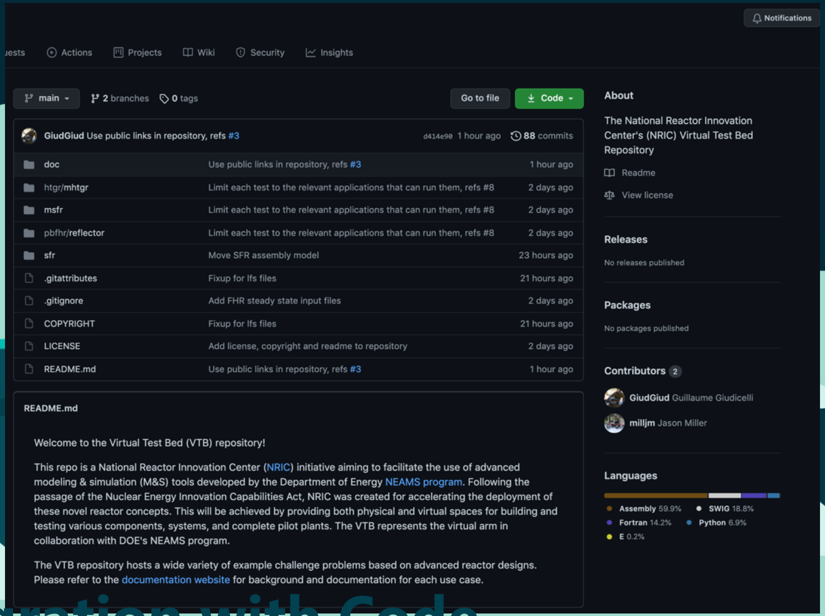
https://mooseframework.inl.gov/virtual_test_bed

1. Documentation

Detailed explanation of models

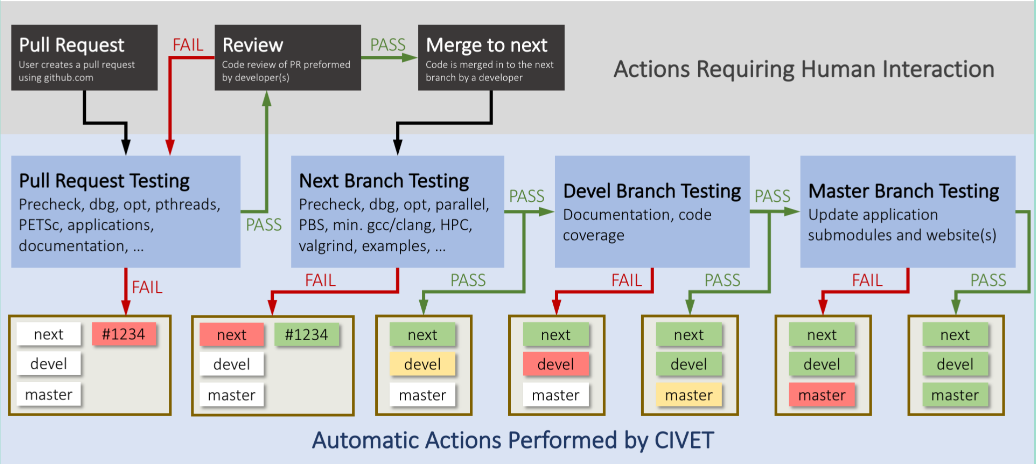
2. GitHub Repo

Ability to clone and contribute to models



3. Integration with Code Development

Continuous testing of models against codes using CIVET



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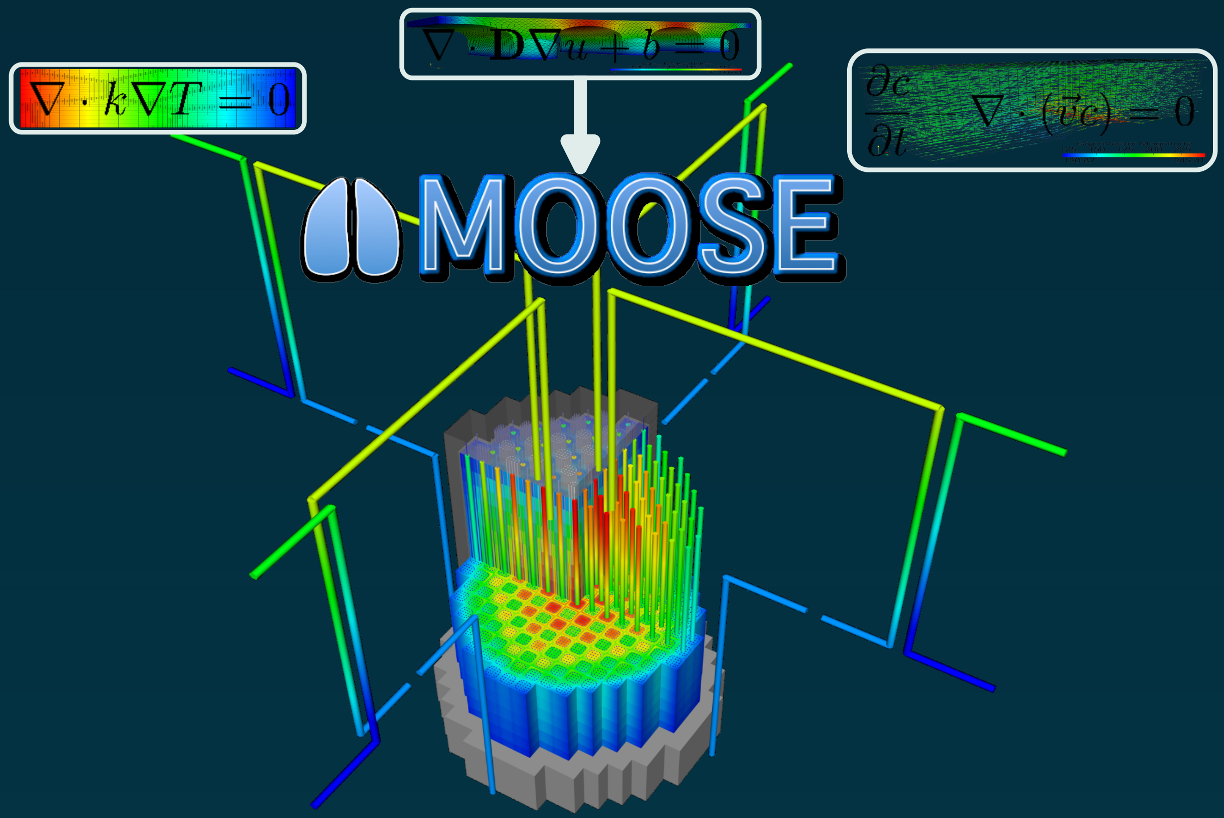
MOOSE Framework



What is MOOSE?

- Multiphysics framework to capture various reactor physical phenomena (neutronics, hydraulics, heat conduction, fuel performance etc.)
- Finite element based (with new finite volume capability) and massively parallelizable
- Standardized input structure
- Nuclear SQA compliant

Why Multiphysics?

- Reactors are inherently Multiphysics
- Upcoming reactor designs rely on non-traditional Multiphysics effects (e.g. Core expansion, heat pipes, molten fuel, fluidized beds, porous flow, etc.)
- Predictive Multiphysics enables the study of:
  - Power uprates, material changes, design/safety basis, accident scenarios, design feasibility, moderator choice, fuel loading optimization, material degradation, etc.

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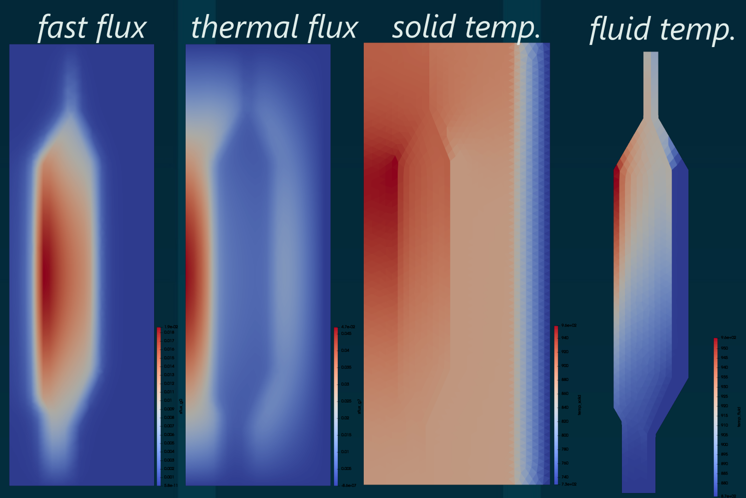
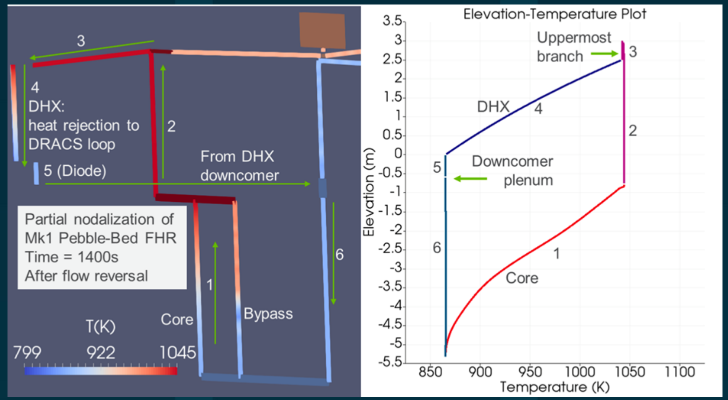
Pebble Bed Fluoride-Salt-Cooled High Temperature Reactor (PB-FHR)

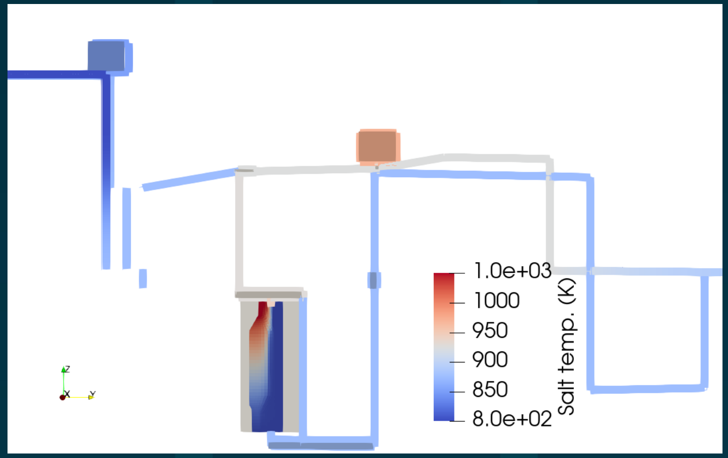
- Core Model
  - ***Griffin***: Multigroup diffusion
  - ***Pronghorn***: Navier-Stokes Finite Volume porous media equations with PBR closures with a multiscale fuel treatment
- System Model
  - ***SAM***: 1-D systems level thermal-hydraulics model of the primary, secondary, and DRACS loops
  - Steady state and a loss of flow (LOF) transient
- Coupled Core+System Model
  - ***SAM***: 1-D systems
  - ***Griffin+Pronghorn***: 2-D Core Model
  - Steady-state coupled conditions



Core coupled physics predictions



SAM fluid temperature 1400s during the LOF transient



Salt temperature distribution in core (Pronghorn) and system (SAM)

Mk1-FHR

- 20% enr. Fuel contained in TRISO inside pebbles
- Fluoride salt coolant
- High temperature

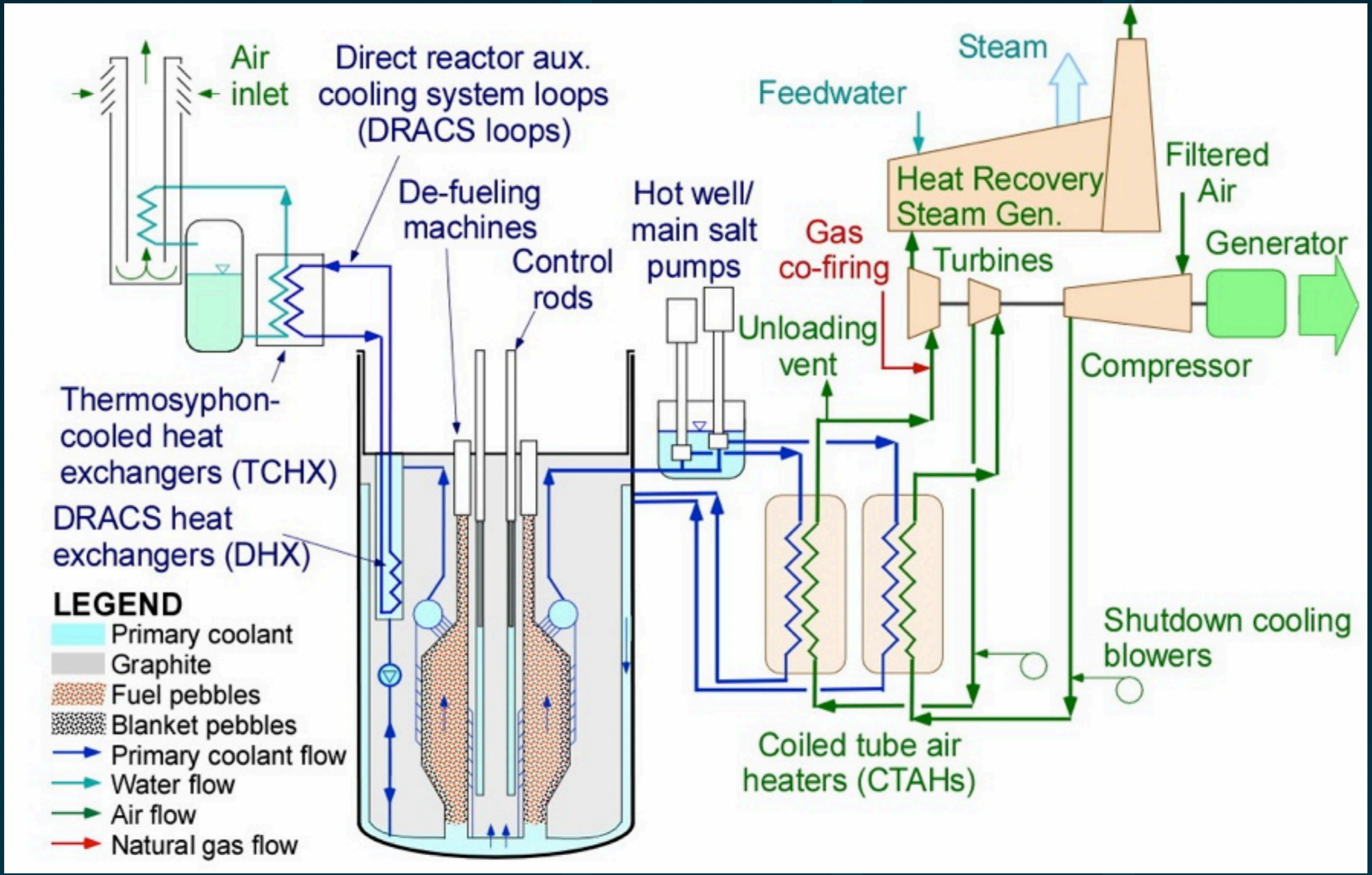


Figure from "Technical Description of the "Mark 1" Pebble-Bed Fluoride-Salt-Cooled High-Temperature Reactor (PB-FHR)" Tech. Report by UCB

Griffin

Capabilities

- Flexible, extensible reactor physics using the MOOSE framework
- Collaboration between INL and ANL development teams
- Range of mesh-based MG deterministic solvers (CFEM/DFEM/HFEM w/ SN/PN/diffusion)

FY 22 Highlights

- Enabled multiphysics time-dependent solutions with the SN solver
- Initial implementation of HFEM-PN solver and pin power reconstruction
- Initial fast reactor and thermal reactor cross section generation workflows
- Improved SQA documentation and first official release November 2022

Planned FY 23

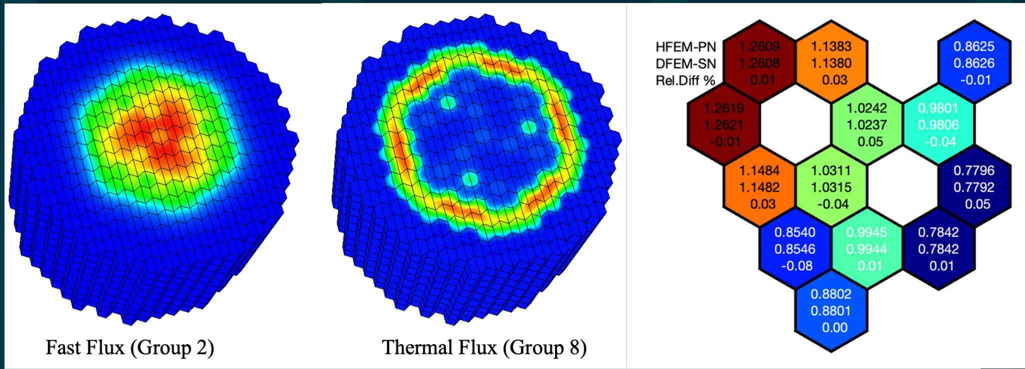
- PBR workflow (cross sections, burning-in to equilibrium core, sensitivity analysis)
- SFR workflow (cross sections, equilibrium core, sensitivity analysis)

Access

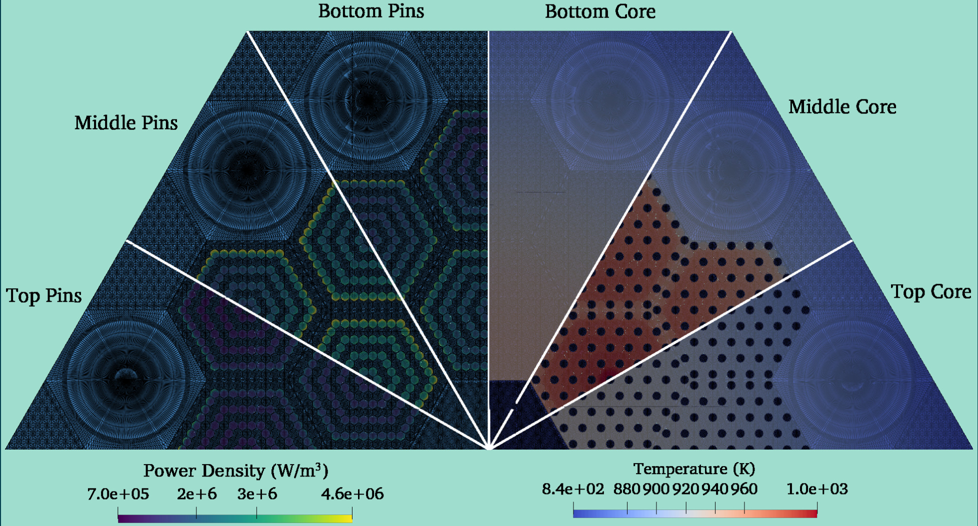
- Get access to Griffin through INL's Nuclear Computational Resource Center (https://inl.gov/ncrc/) or by contacting nera-software@anl.gov

Resources: Discourse forum through INL HPC account

- Points of Contact:
- Javier Ortensi (javier.ortensi@inl.gov) Changho Lee (clee@anl.gov)



HFEM-PN Solver



MP transient calculation

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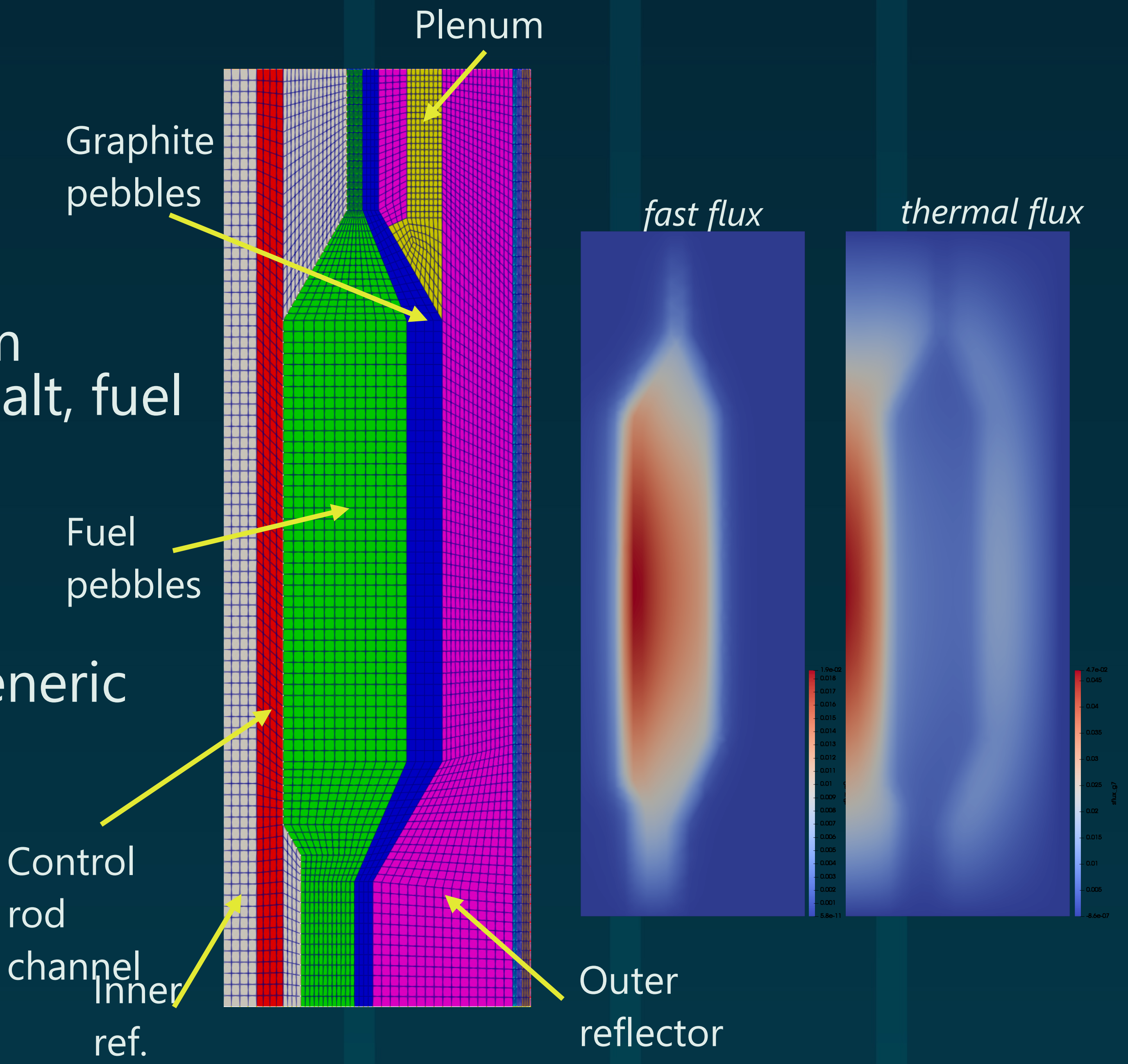
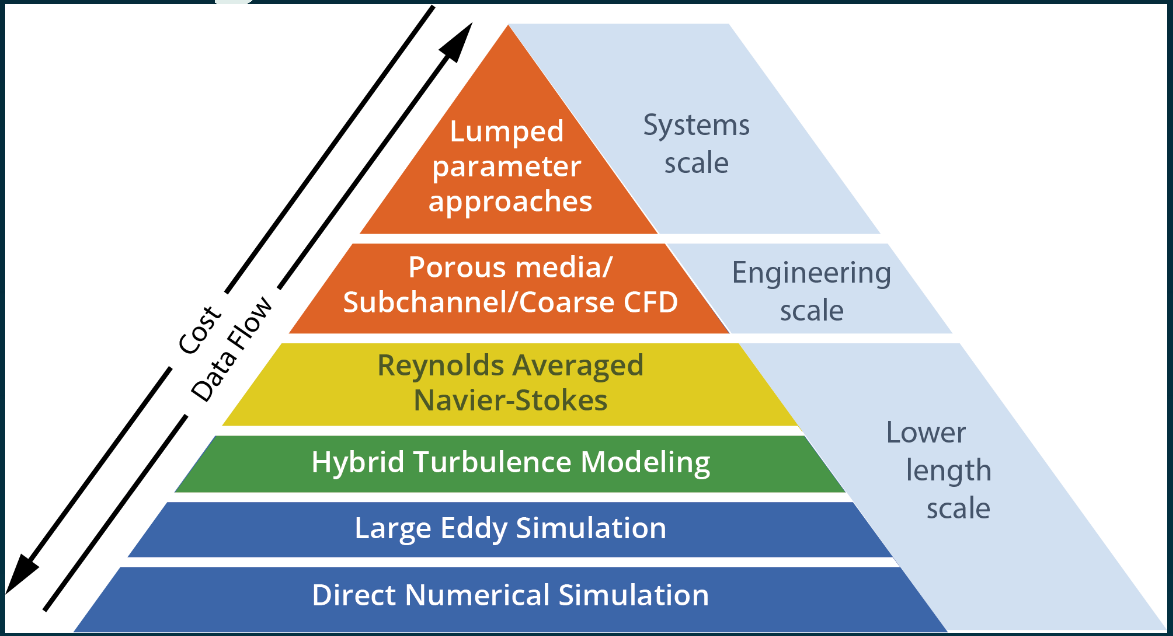
Griffin core model

- Fresh core
- 8g diffusion XS generated from coarse Serpent tabulation on salt, fuel temperature

- Presented at ANS Winter 2021
- Slated to be superseded by Generic PB-FHR model



Pronghorn



Modeling options and approach

Pronghorn Development and Analysis Group, "Pronghorn: a coarse mesh thermal-hydraulics application based on MOOSE for advanced reactor concepts," NUC workshop - Innovations in advanced reactor design, analysis, and licensing, Raleigh, NC, USA, 2019.

Capabilities

- Based on the Idaho National Laboratory Multiphysics Object-Oriented Simulation Environment (MOOSE)
- Direct coupling with other MOOSE-based applications
- Developed following INL's SQA plan
- Multidimensional flow simulations for steady state and transient analysis
- Plethora of correlations built into the code for different type of reactor analyses
- Possibility to implement custom correlations and material properties without the need of accessing the source code.
- All parameters and correlations are exposed opening the possibilities to uncertainty quantification studies.
- Structured and unstructured mesh.
- Finite element method (FEM) with stabilization and finite volume method (FVM) with different interpolation schemes.

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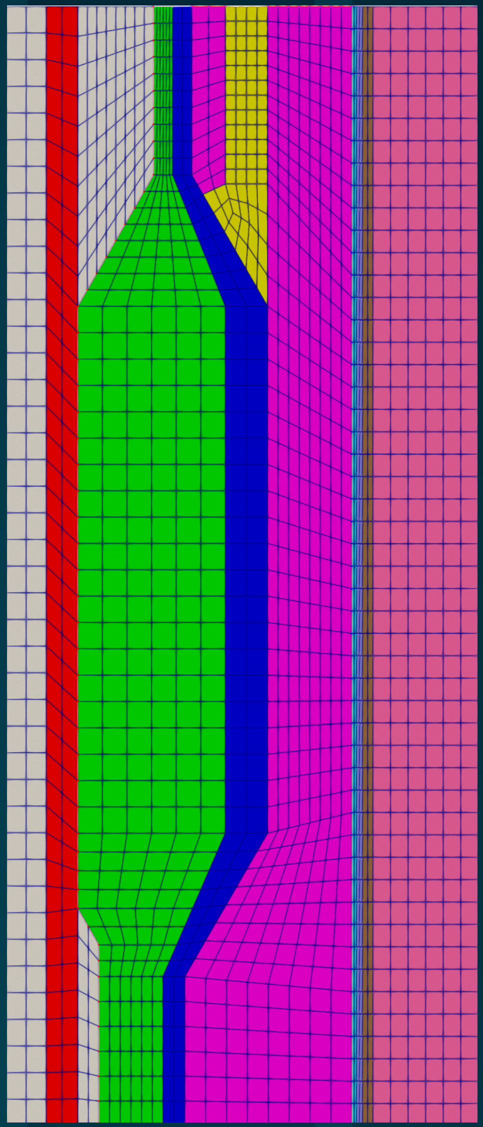
Pronghorn flow model

- Navier-Stokes Finite Volume porous media equations with PBR closures with a multiscale fuel treatment
- Coarse mesh, 2D RZ model
- Distributed 1D pebble models sampled at various locations of the mesh



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Griffin – Pronghorn coupling

- Power & Temperature fields

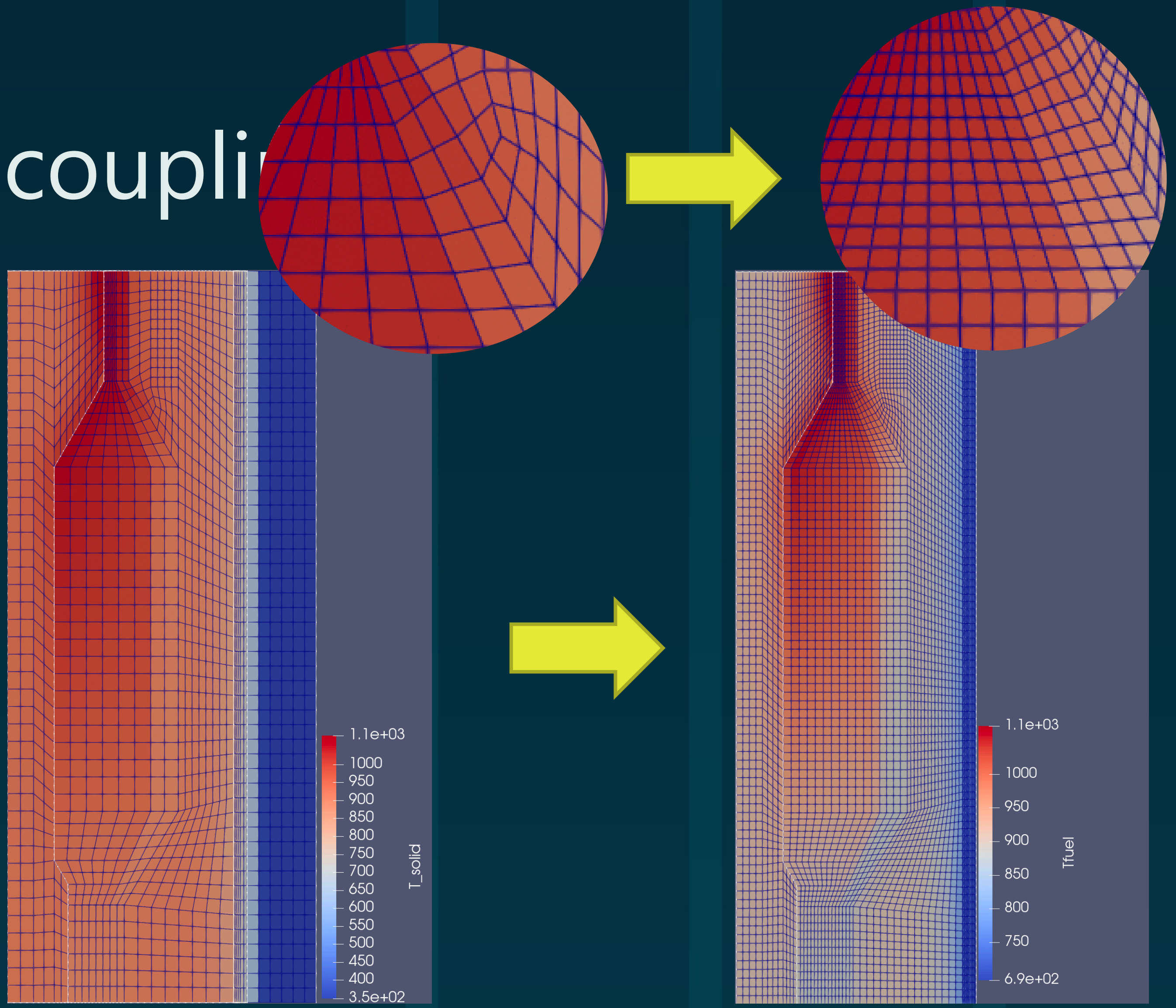
Interpolated

- Preserve power during transfer

Here: mesh align and only 1e-6 norm error

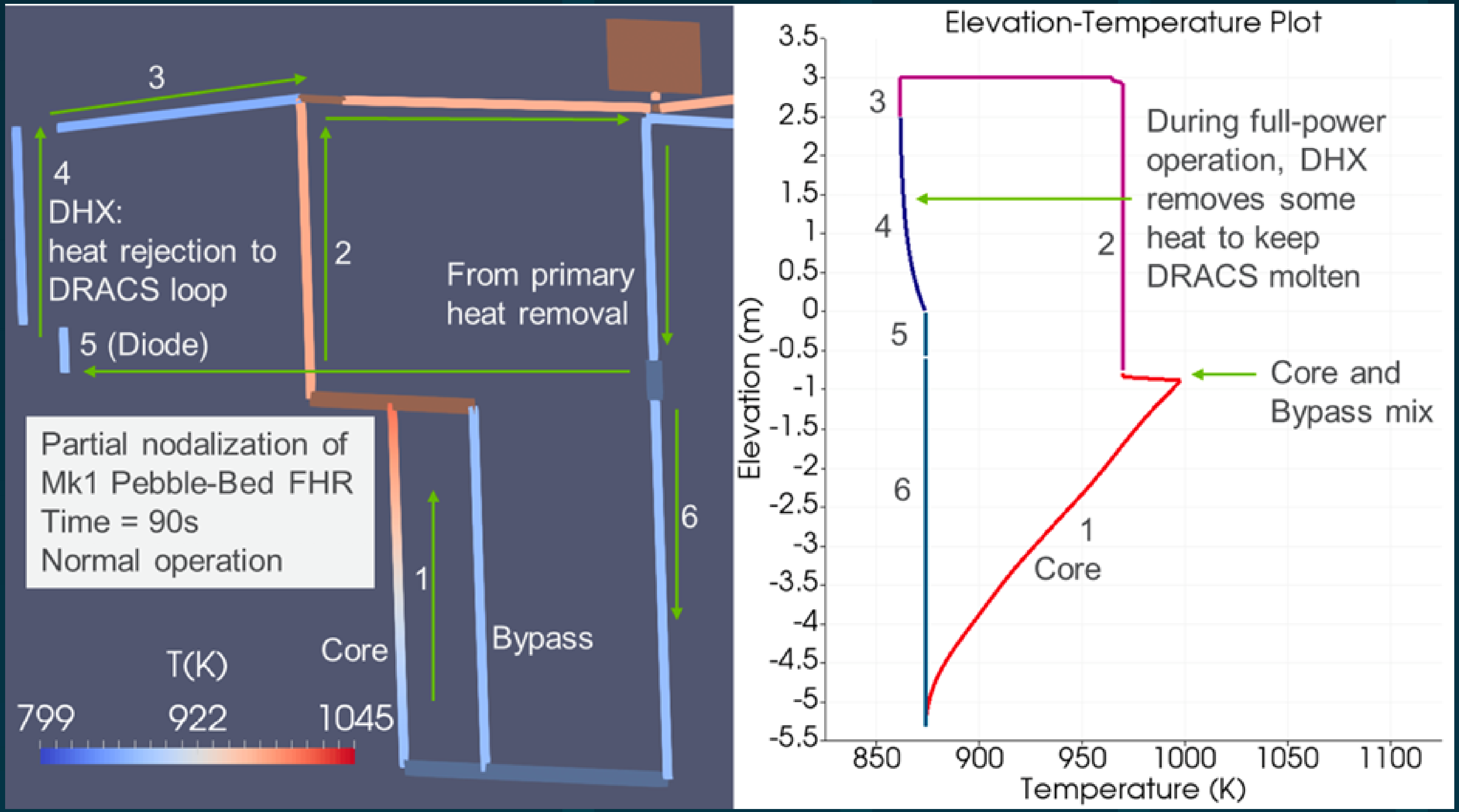
General case:

renormalization



SAM primary loop model

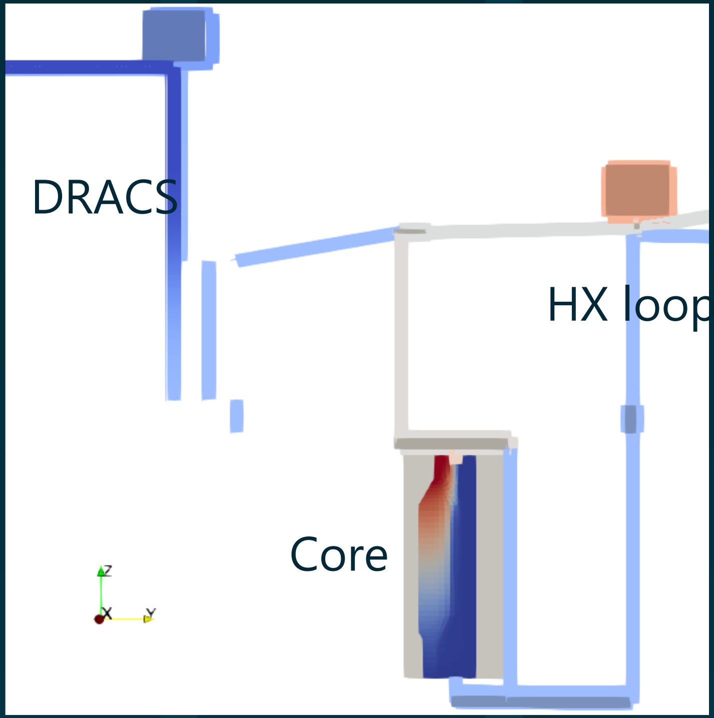
- Standalone simulation **on VTB** with **1D-core** which will be substituted for Pronghorn multi-D core
- Steady state and ULOF transients available



Ref: Benchmark Simulation of Natural Circulation Cooling System with Salt Working Fluid Using SAM, 2017

Pronghorn – SAM coupling

- Exchange pressure, temperature, velocities on core inlet and outlet
- SAM: component with postprocessor BCs
- New boundary conditions in Pronghorn:
  - Mass/momentum/energy flux BCs
  - Velocity / temperature Dirichlet BCs also work
- Tally of mass/energy flow rates using a newly developed *VolumetricFlowRate* postprocessor



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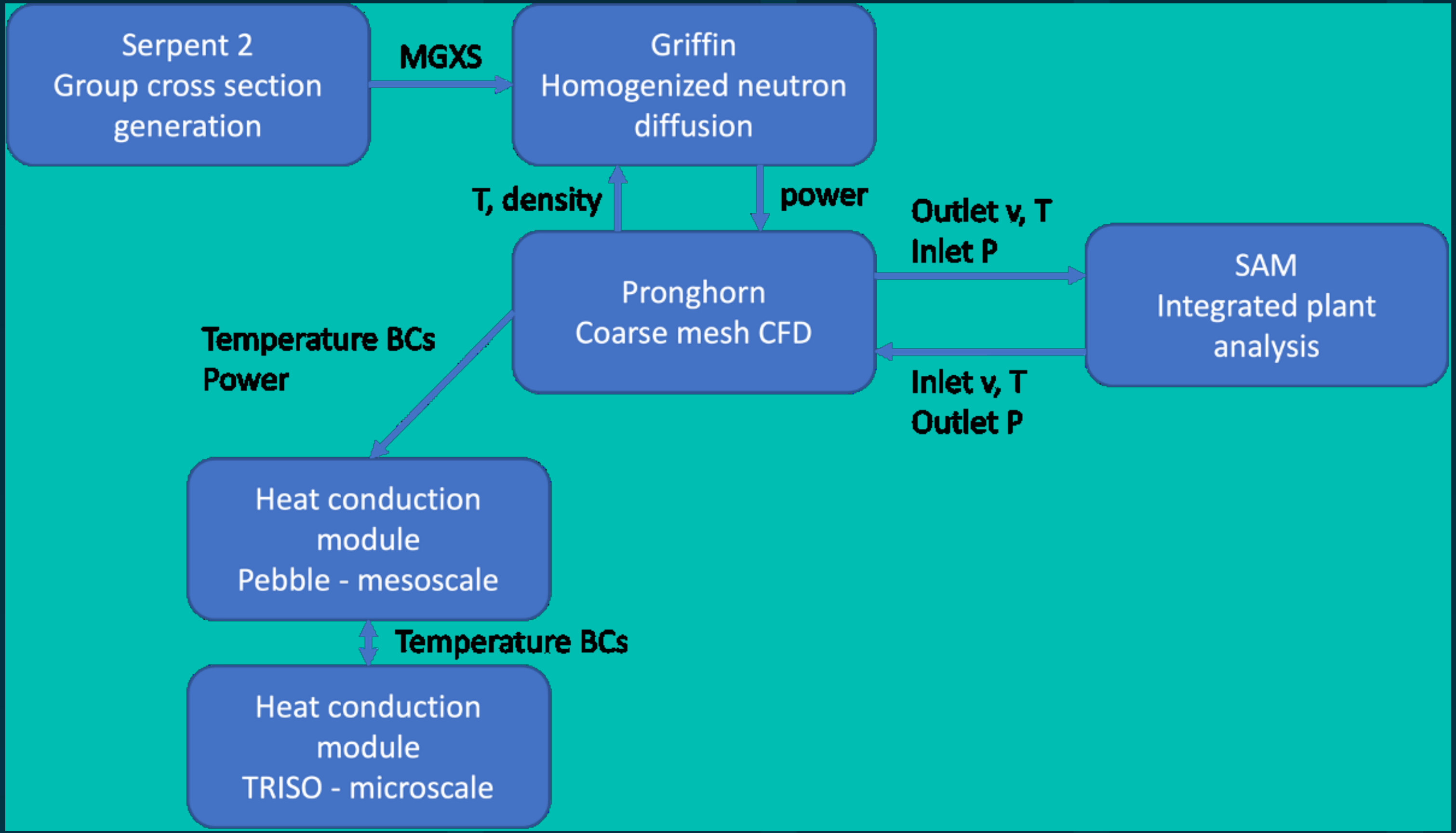
Summary of the multi-physics coupling

- Initialization simulation with only fluids (SAM and Pronghorn)
- Steady state and transient use the same coupling
- Transient restarts from steady state



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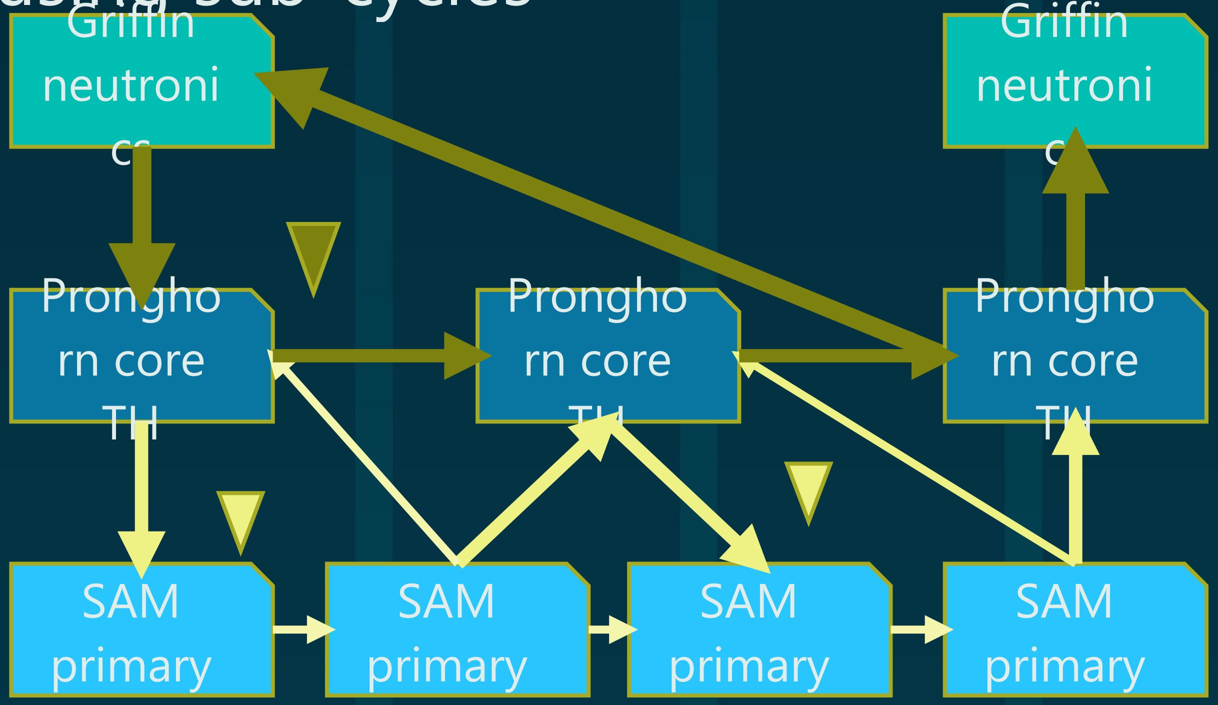
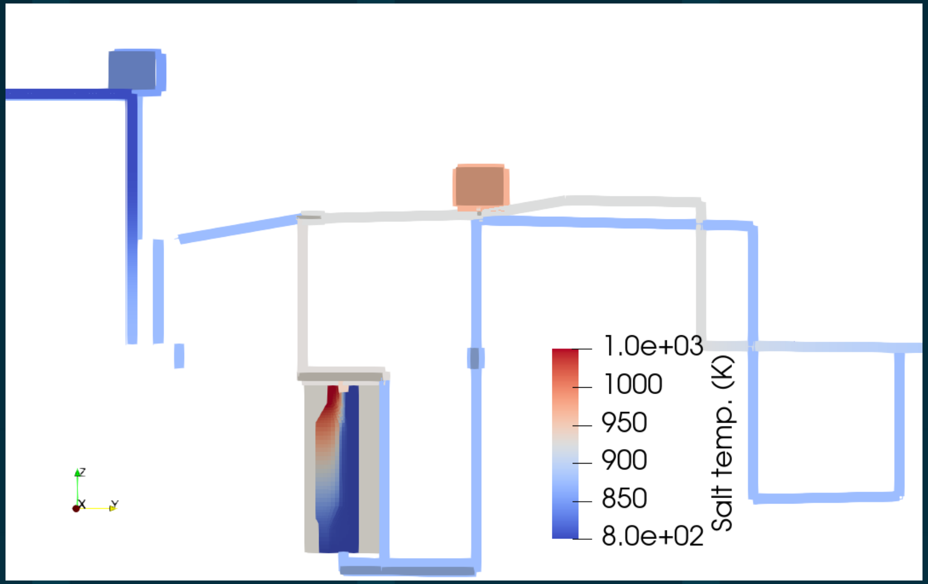
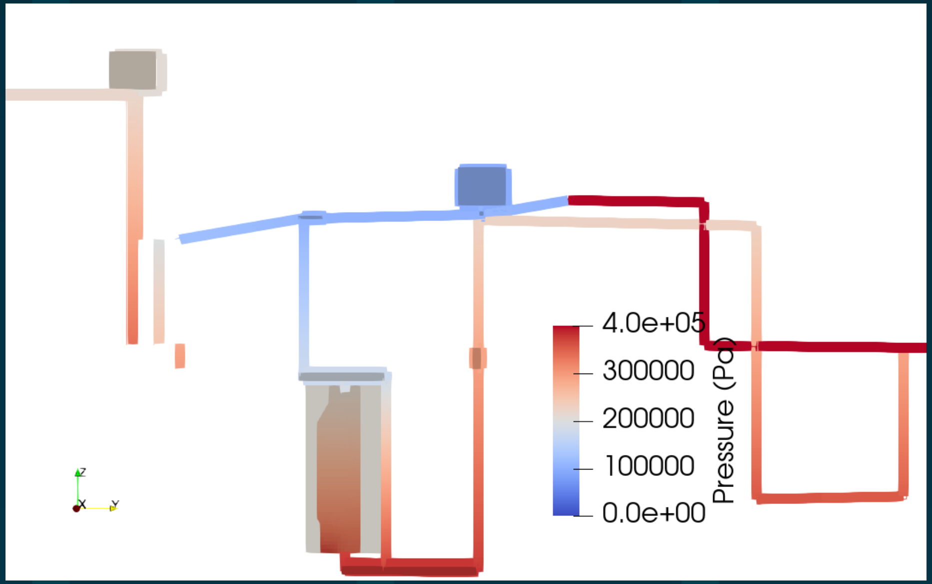
Summary coupling model

- Nested fixed-point iterations
- Different physics have different time step requirements
- Naturally handled by MOOSE using sub-cycles
- May use different time integration schemes for each physics



Results – relaxation to steady state





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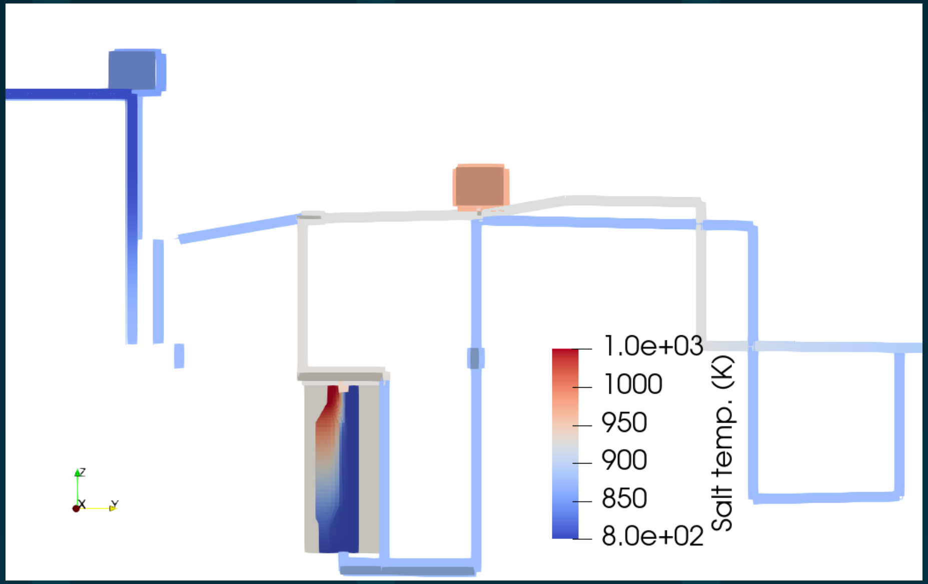
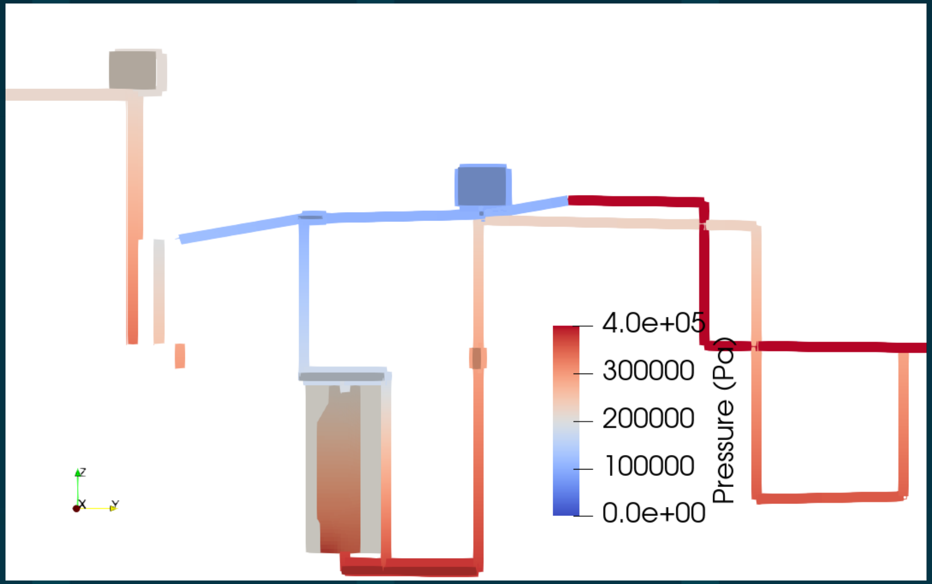
Results – null transient





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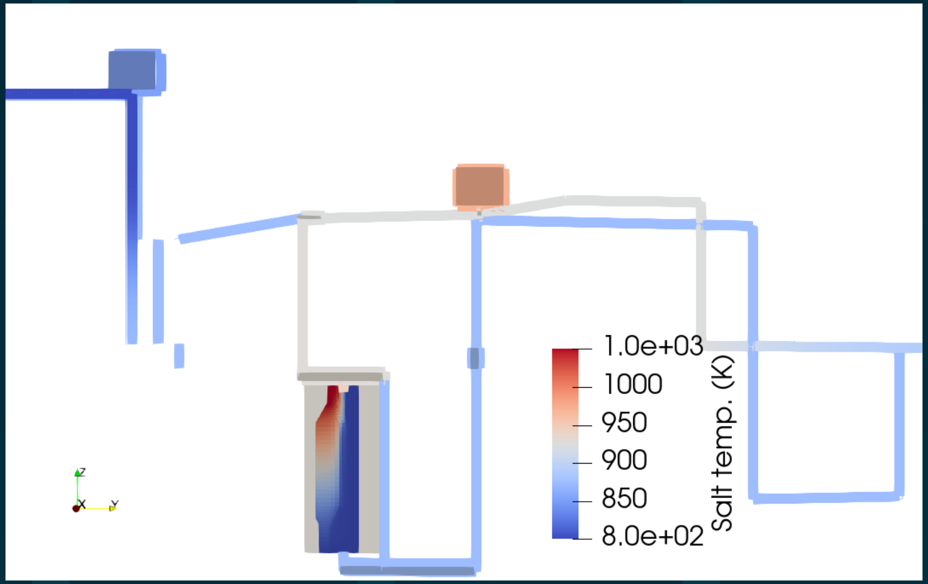
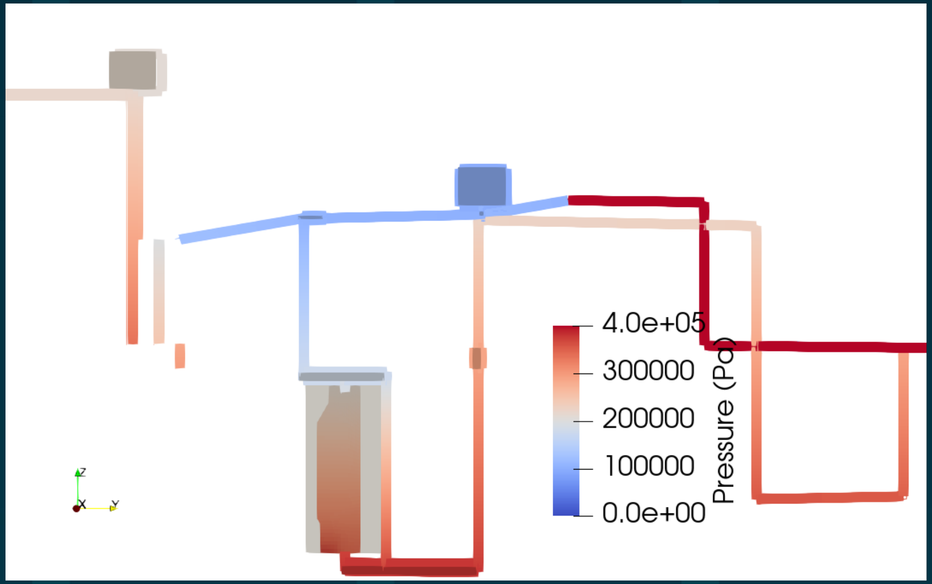
Results – flow-variation





Related works coming to the VTB

- MSR SAM-Pronghorn coupling with domain overlapping approach
  - "Coupled Griffin-Pronghorn-SAM Model of a Molten Salt Fast Reactor System Transient in the Virtual Test Bed"
  - Just before this talk!
  - In a PR to the VTB

- Generic FHR multiphysics plant model with depletion
  - Developed by Reactor Analysis group at INL
  - Coming soon to the VTB!

Summary

- Coupled SAM-Pronghorn-Griffin multiphysics model of the primary loop
  - Griffin – Pronghorn for the core model
  - SAM for the primary
  - Coupled through pressure – velocity – temperature boundary conditions in a domain-segregated approach
  - Example of coupling simulations together, shown at VTB Tech Talk
- Coupling using the MultiApps-Transfer approach
- SAM-Pronghorn is most challenging coupling
- Coupling performance:
  - Max iterations observed:
  - Max stable timestep size:

- Funding acknowledgements: NEAMS & NRIC/VTB
- References: