Thermal-fluid Area Overview

NEAMS Annual Review: Fast-Reactors

May 29th, 2025

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Argonne National Laboratory

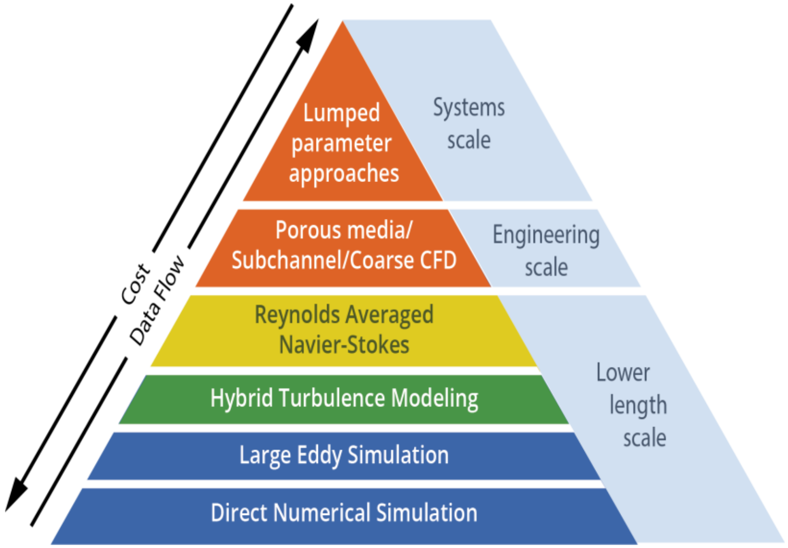
Thermal-hydraulics modeling in NEAMS - I

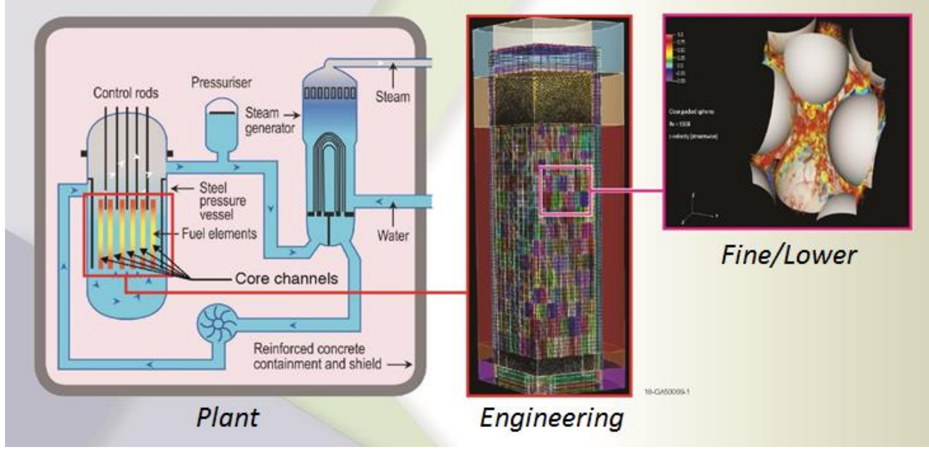
The thermal-hydraulic technical advances the state of the art of thermal-hydraulic simulations by researching novel new solution strategies for challenging real-world heat and fluid flow issues that affect advanced reactor designs or still affect the current fleet of deployed Light Water Reactor nuclear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

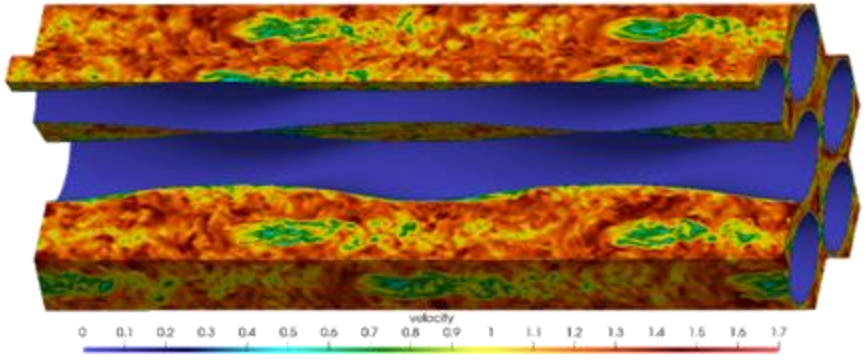
- Resolving all scales for a realistic engineering system of interest is often computationally not feasible.
- On the other hand, if scales are not resolved, <u>closures need to be provided to ensure reasonable accuracy</u>, as all scales contribute to the dynamics.
- <u>Multiscale/multi-resolution simulation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



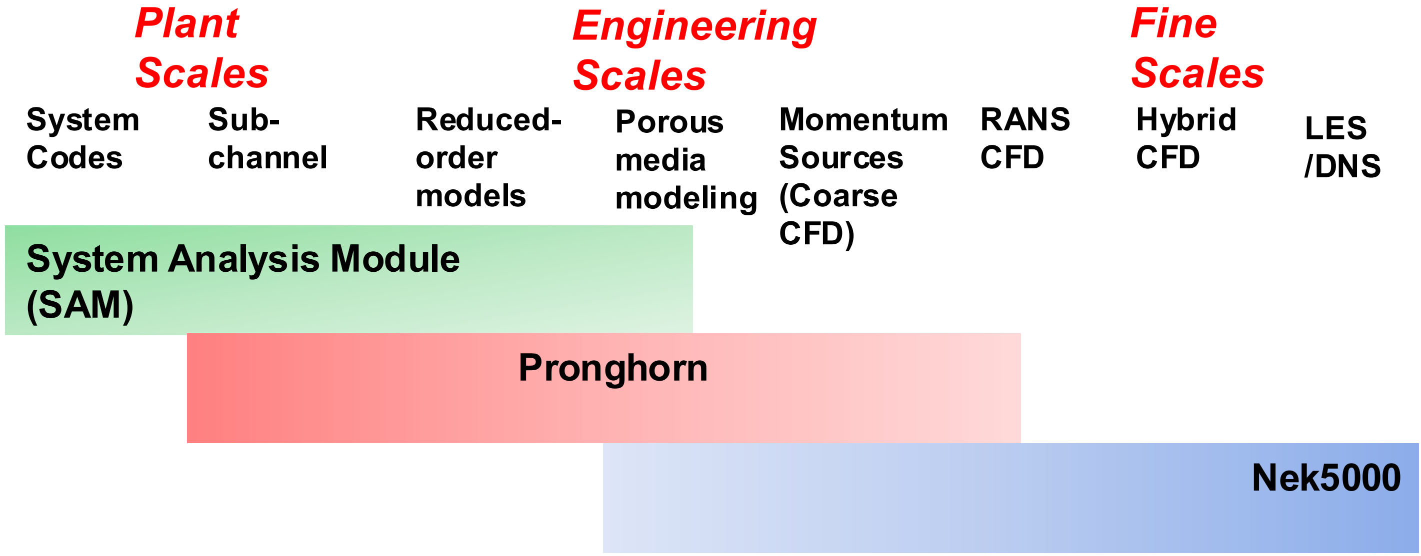


Thermal-hydraulics modeling in NEAMS - II

- **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.

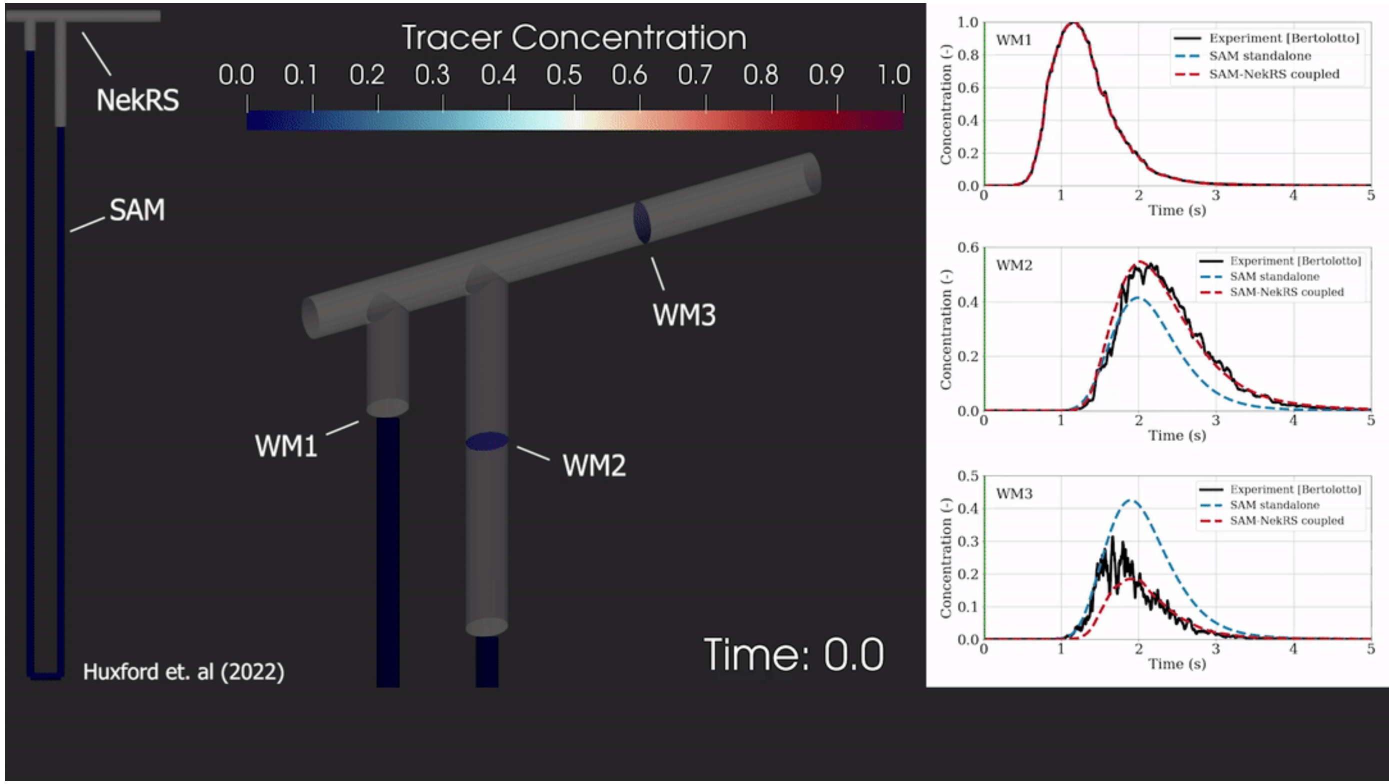


Flow in a twisted tube HX.



Unique Capability: Multiscale Coupling

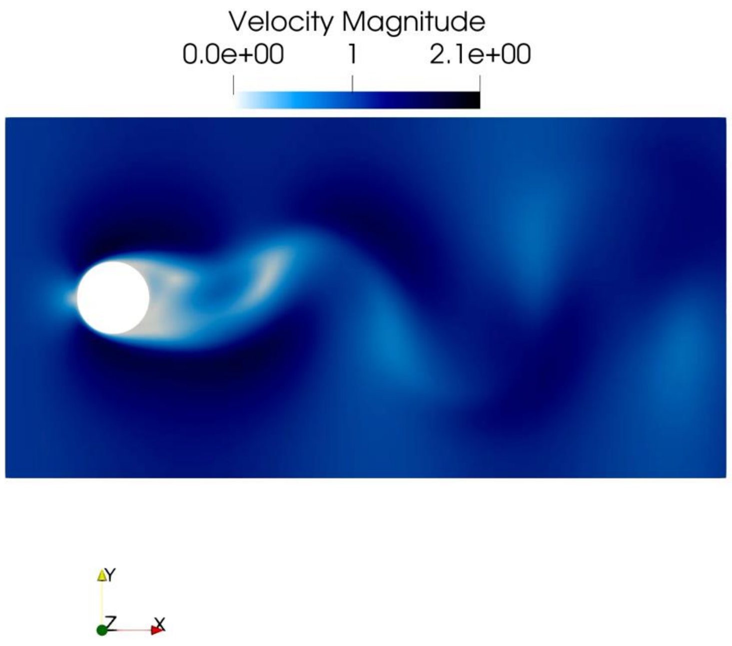
- **Full Multiscale software stack**
- **Overlapping domain coupling**
  - High-fidelity where you need it most
  - Modeling of a double T-junction demonstrated with SAM/Nek
  - Used also to couple SAM and Pronghorn and SAM-SCM
- **Multiscale bridging through closure model development**
- **Using NekRS high-fidelity results to improve**
  - Turbulence models in Pronghorn
  - Heat transfer coefficients for complex geometries in SAM



Content courtesy of Aaron Huxford (U. Mich), V. Coppo Leite (PSU), E. Merzari (PSU), L. Zou (ANL), V. Petrov (U. Mich), Annalisa Manera (ETH)

Thermal-fluids presentations today

- Development of an advanced 1-D mixing model in SAM (E. Cervi)
- High-Fidelity Simulations Using Nek for the NACIE-UP Benchmark (D. Shaver)
- Subchannel capability and CDAP model development (A. Karahan)
- For questions contact us at ebm5351@psu.edu or rhu@anl.gov



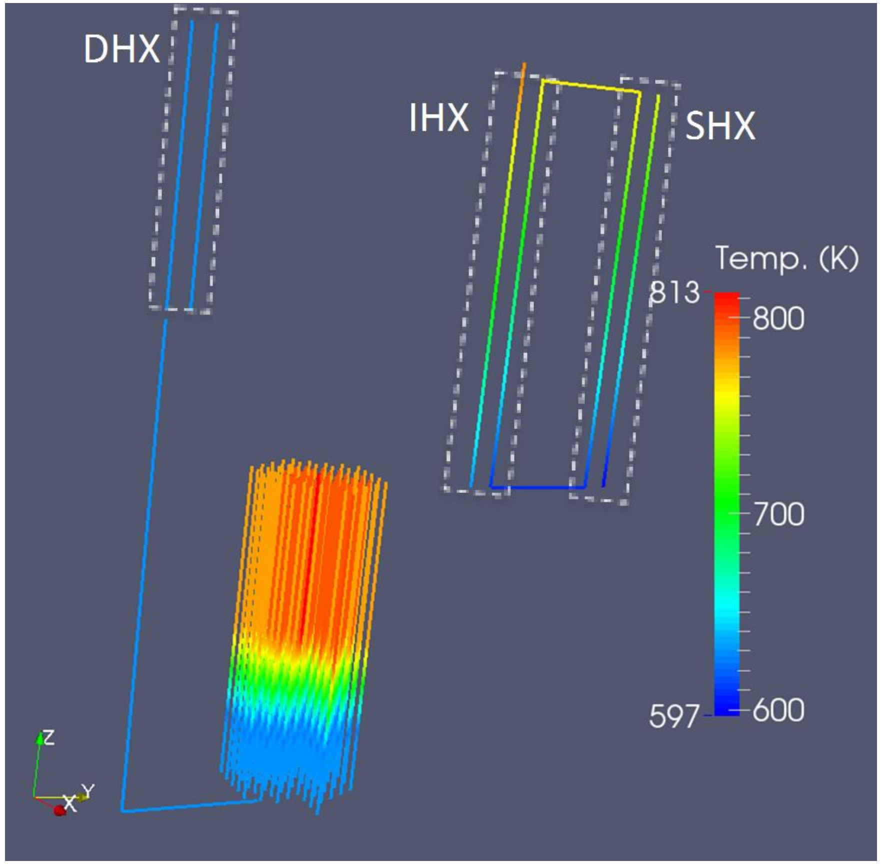
FIV capability is available on GPUs (coupling to MOOSE structural mechanics capabilities). – David Reger

Development of an advanced 1-D mixing model in SAM

Eric Cervi, Ling Zou, Rui Hu

Introduction

- SAM is a modern system thermal-hydraulics code, developed at Argonne National Laboratory under the DOE-NE NEAMS Program.
  - Tailored for advanced nuclear systems (including LMFR, GCR, FHR and MSR) – with focus on safety and performance evaluation.
- SAM is based on the MOOSE framework, leveraging its numerical libraries, meshing capabilities and software infrastructure.
- **Specific/Relevant LMFR capabilities:**
  - Radial (inter-assembly) heat transport modeling in the core.
  - Enhancements for thermal mixing and stratification modeling
  - Flexible reactivity feedback models considering structural deformations.
  - Materials models (lead corrosion)
- Extensive SFR V&V and Demonstrations
  - EBR-II, FFTF, SET/IET
  - Multi-physics simulation of ABTR transients



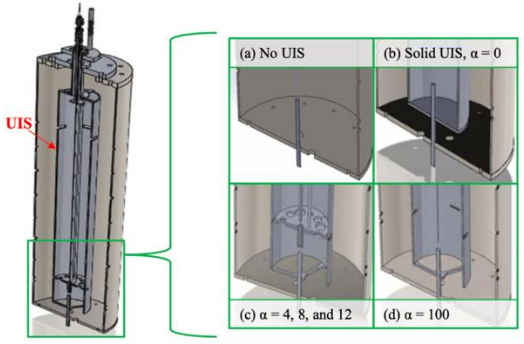
Introduction

- A key application of SAM is the analysis of thermal mixing and stratification, which arise when fluids at different temperatures interact in large pool regions or tanks.
- In pool-type reactors, such as sodium-cooled fast reactors (SFRs), this may occur during operational and transient scenarios.
- This may impact crucial phenomena such as the establishment of natural circulation, which is vital for the passive cooling of many next-generation nuclear reactors.

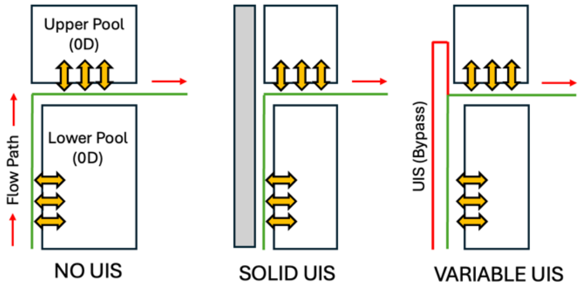
- Thermal mixing and stratification are key to the inherent safety of these systems, necessitating suitable mathematical models and numerical tools to simulate them.

Development of a new mixing and stratification model

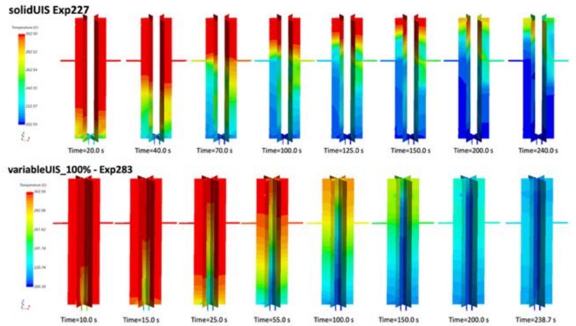
- Under DOE NEAMS program, a 1D model was developed in SAM for thermal mixing and stratification in large enclosures:
- The goals are:
  - Capturing stratification effects in reactor transient applications (e.g., sodium fast reactor pools);
  - Overcoming the limitations of state-of-the-art models approaches.



***The Thermal Stratification Test Facility (TSTF) Benchmark Case** (University of Wisconsin-Madison)*



SAM models for various experimental configuration in the TSTF.



CFD simulations of the TSTF

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- The goals are:
  - Capturing stratification effects in reactor transient applications (e.g., sodium fast reactor pools);
  - Overcoming the limitations of state-of-the-art models approaches.

➡ Lumped parameter approaches:

- Simple and computationally inexpensive.
- Affected by several modelling simplifications that limit their applicability.

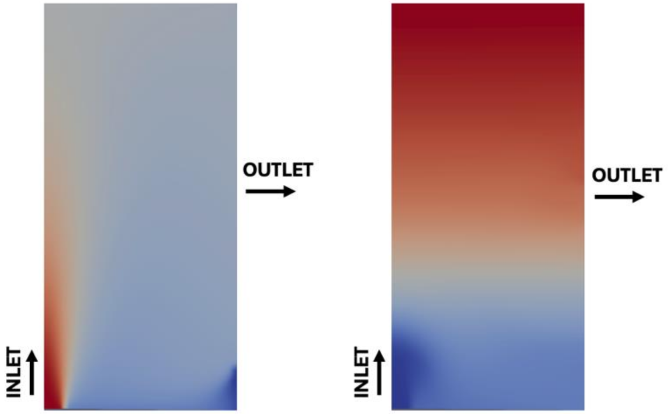
➡ CFD approaches:

- Can provide a high-resolution description of pools and of the complex multi-dimensional phenomena occurring therein.
- Computationally expensive.
- Require complex multiscale techniques for coupling with system analysis codes.

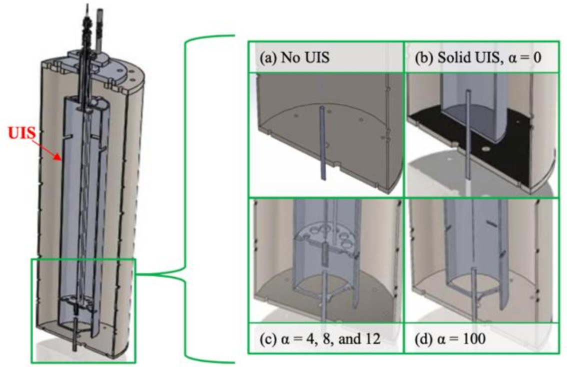
Expectations

The new model aims to describe different flow configurations, including:

- Hot jets flowing into a colder pool;
- Cold jet flowing into a hotter pool;
- Presence of internal obstacles and upper internal structures;
- Delay effects due to the thermal inertia and finite extension of the pool.



HOT JET (CFD)   COLD JET (CFD)

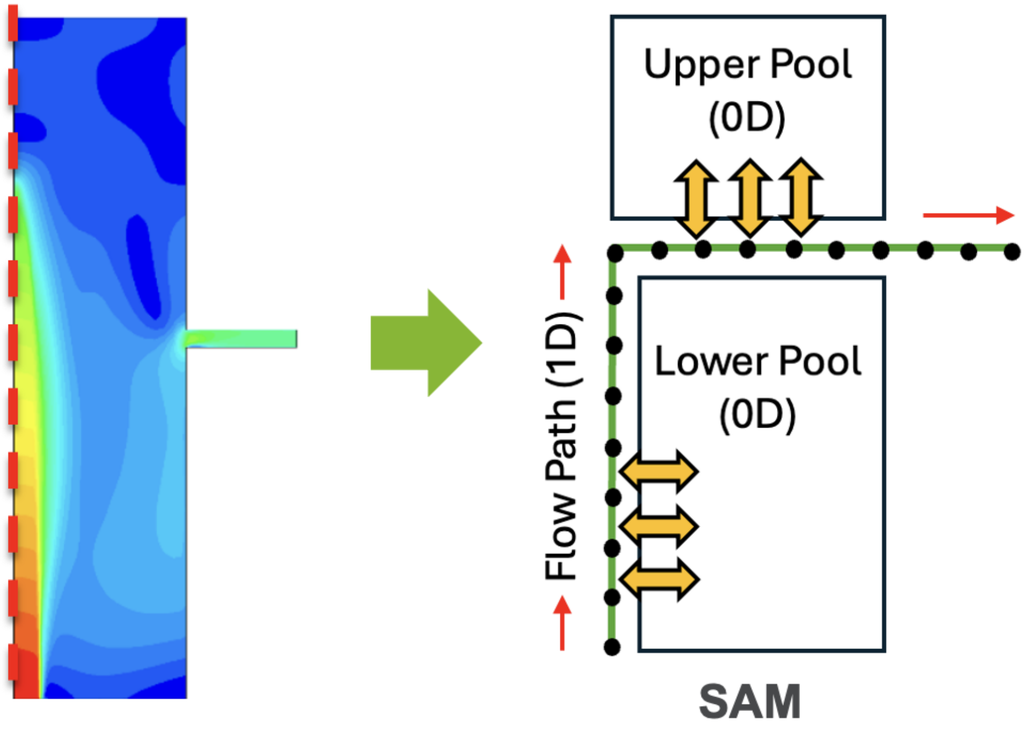


FLOW WITH INTERNAL OBSTACLE

The modelling approach

To model this, the following setup was adopted:

- The jet flow in the lower part of the tank is modeled as a vertical 1D channel, followed by a horizontal channel representing flow in the upper part of the pool.
- The lower and upper portions of the tank are modeled as 0D volumes.
- Heat exchange occurs in between the 1D jets and 0D pools.
- Suitable closure relations are adopted to describe this heat exchange. This allows distinguishing between the two scenarios arising with hot and cold jets.

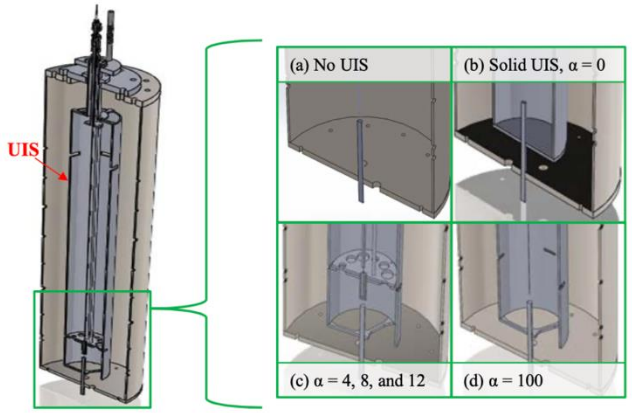


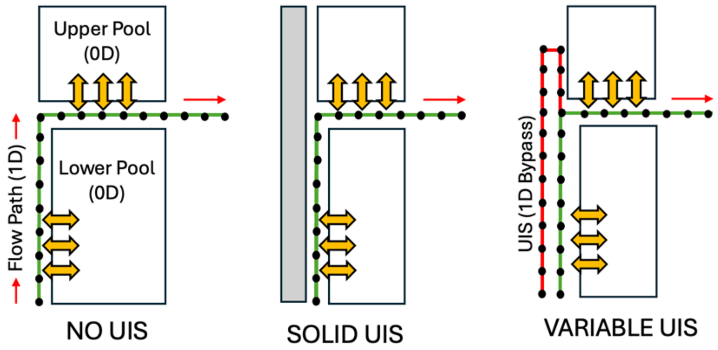
Validation: the TSTF benchmark

The Thermal Stratification Test Facility (TSTF), developed at UW Madison, was simulated for validation purposes.

Features:

- Forced convection experiments in which colder sodium is injected into a pre-heated test section, inducing stratification.
- An upper internal structure (UIS) with different configurations is placed inside the test section:
  - No UIS;
  - Solid UIS;
  - ”Porous” UIS with variable flow area.



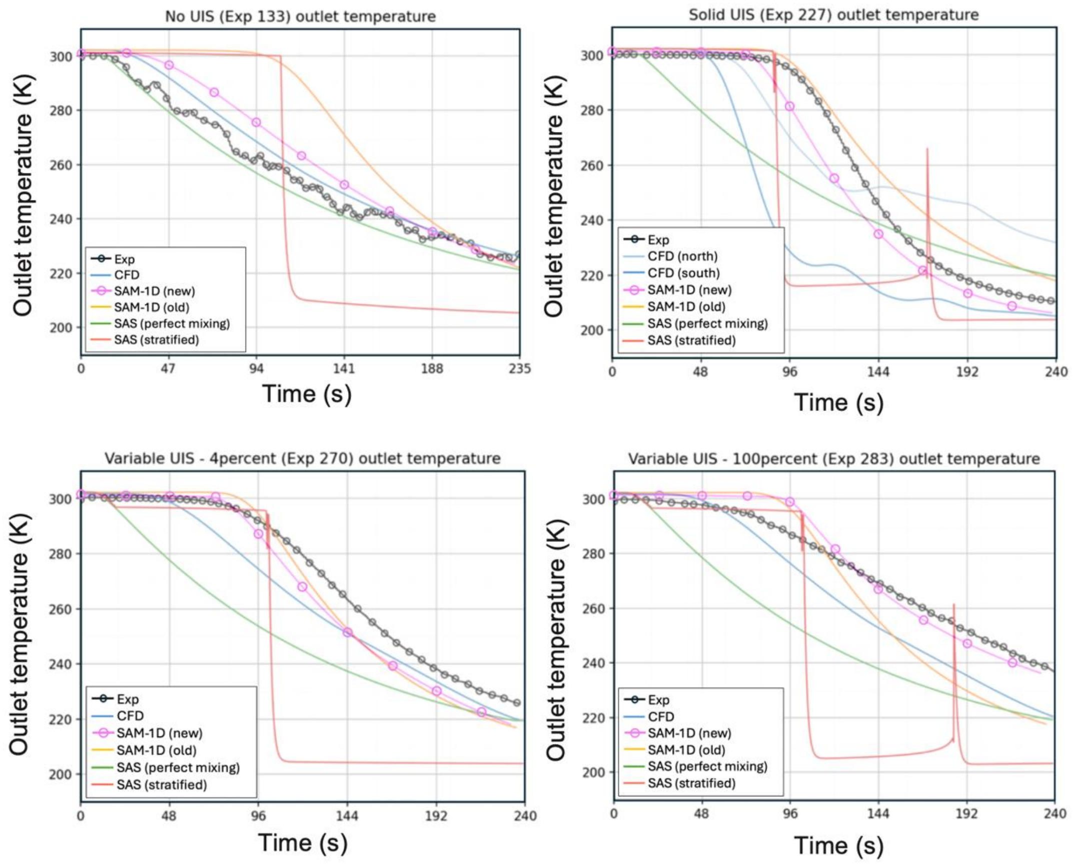


Validation: the TSTF benchmark

Validation against the TSTF facility was successfully carried out.

- In all cases, the tank outlet temperature is in good agreement with the experimental data.
- The prediction of the initial delay is greatly improved compared to other simplified approaches.
- Improved accuracy compared to other reduced models (such as 0D lumped parameter approaches and the old 1D SAM model);
- No need for external coupling with CFD tools (which is challenging in terms of runtimes and multi-scale coupling).

Low flow rate experiments (10 gpm)



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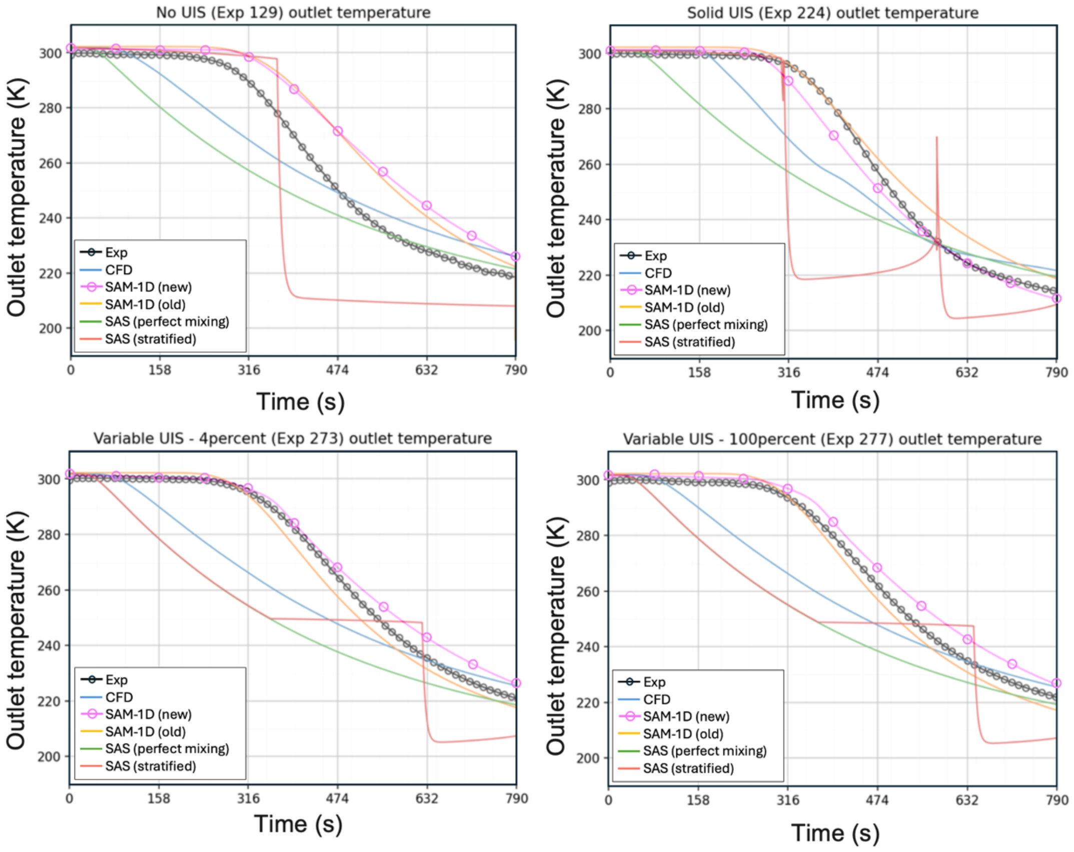
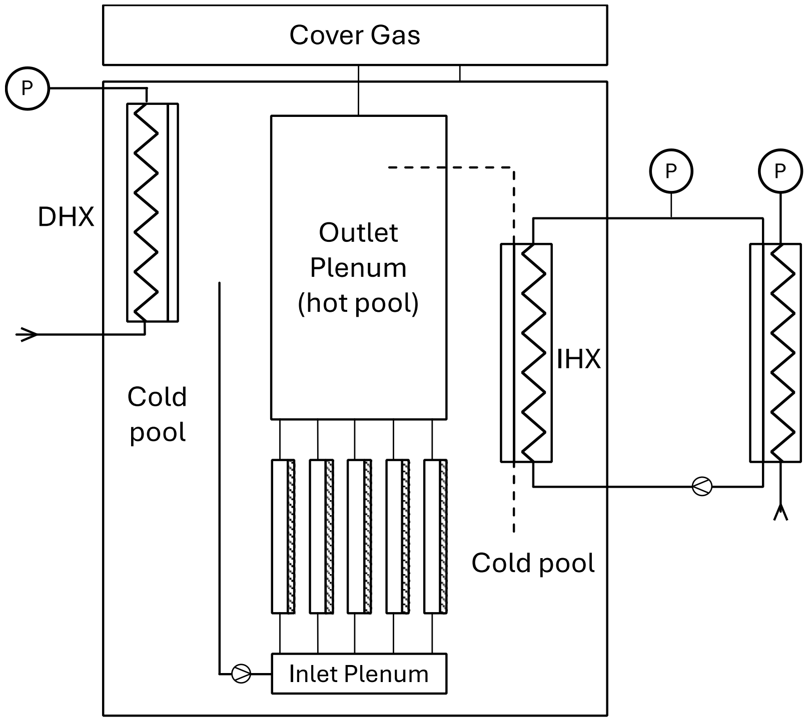
Low flow rate experiments (3 gpm)



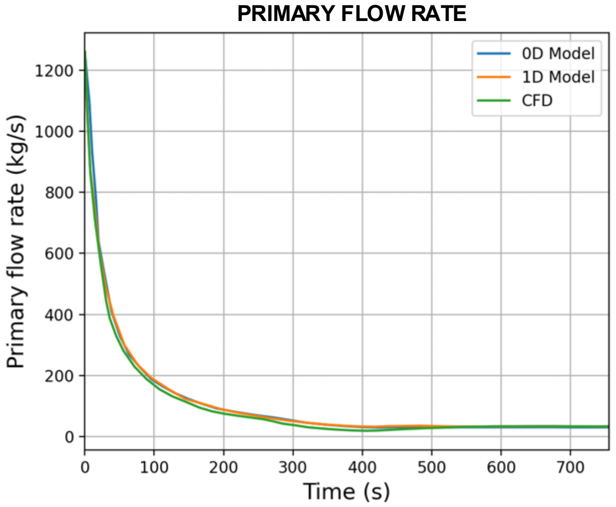
Transient simulation of SFR

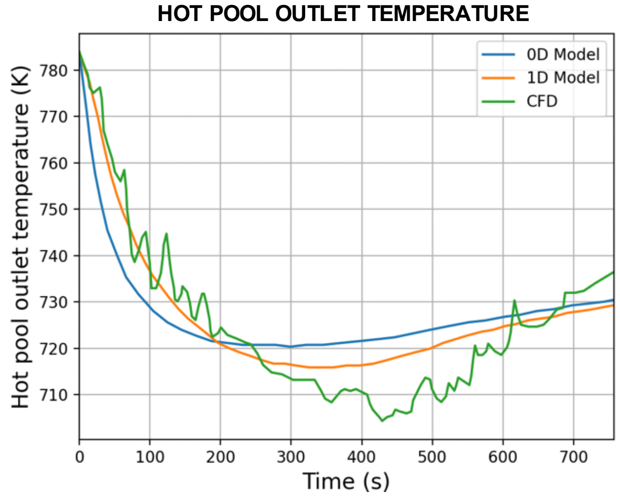
- The new model was applied to the simulation of the ABTR power plant.
- The goal is to test the new model with concurrent phenomena (including neutronics, natural circulation).



Transient simulation of SFR

- The new model was applied to the simulation of the ABTR power plant.
- The goal is to test the new model with concurrent phenomena (including neutronics, natural circulation).
- Comparisons were carried out with a 0D approach and a coupled SAM + CFD simulation.
- Compared to the 0D approach, the 1D model aligns more closely with CFD:
  - Better prediction of the minimum temperature.
  - Better timing prediction (i.e., when the minimum occurs).





Conclusions

- A new 1D model for thermal mixing and stratification was developed and implemented within SAM.
- The model was verified and validated against experimental data, overcoming limitations of existing approaches:

  - Higher accuracy than simplified models.

  - Comparable accuracy to CFD with lower computational cost.

  - Enhances SAM's ability to model thermal effects without external CFD coupling.
- Future work aims to improve closure laws and validate the model across wider conditions.
- The model is being used to develop a reference multiphysics model of the ABTR for the US NRC.

High-Fidelity Simulations Using Nek for the NACIE-UP Benchmark

NEAMS Annual Review: Fast Reactors

May 29th, 2025

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[2]Pennsylvania State University
[3]North Carolina State University

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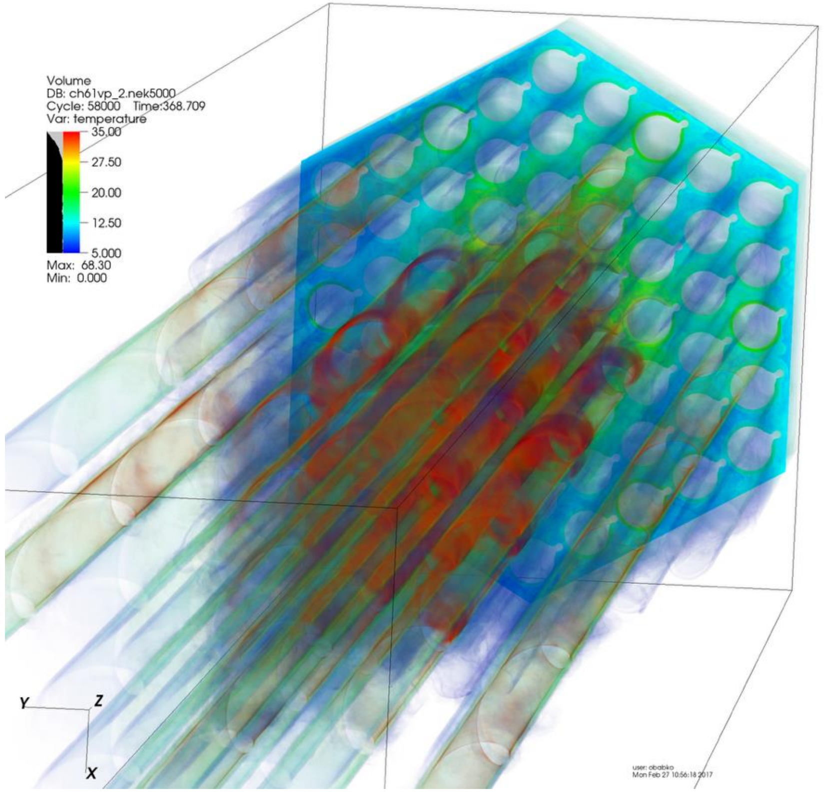
Introduction

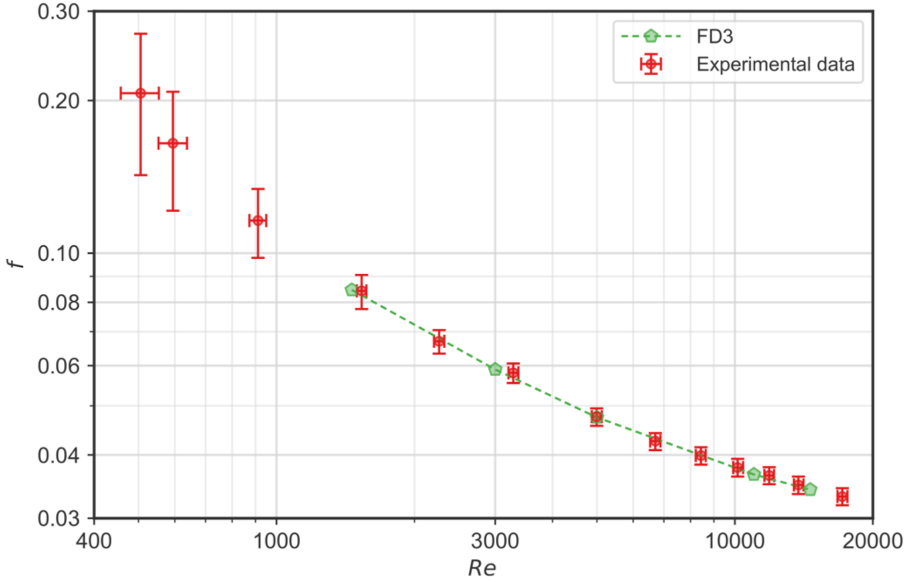
- NekRS is the GPU-enabled NEAMS high-fidelity CFD tool
  - Highly scalable, capable of running well on a laptop to the largest computers in the world
  - Solves the incompressible or low-Mach Navier-Stokes equations with energy and passive scalar transport on high-order hexahedral elements
  - Includes capabilities for Reynolds-averaged Navier-Stokes (RANS), large eddy simulation (LES), hybrid, and direct numerical simulation (DNS) turbulence models
  - Extensive use in nuclear power applications, LMFRs specifically
  - *Development of capabilities and validation for fast reactor relevant phenomena have been demonstrated and continue to be extended*
  - Open source (https://github.com/Nek5000/nekRS)
- Cardinal is the NEAMS wrapper for NekRS/MOOSE
  - Couples NekRS to the MOOSE tools for multiscale and multiphysics analysis
  - Open source (https://github.com/neams-th-coe/cardinal)

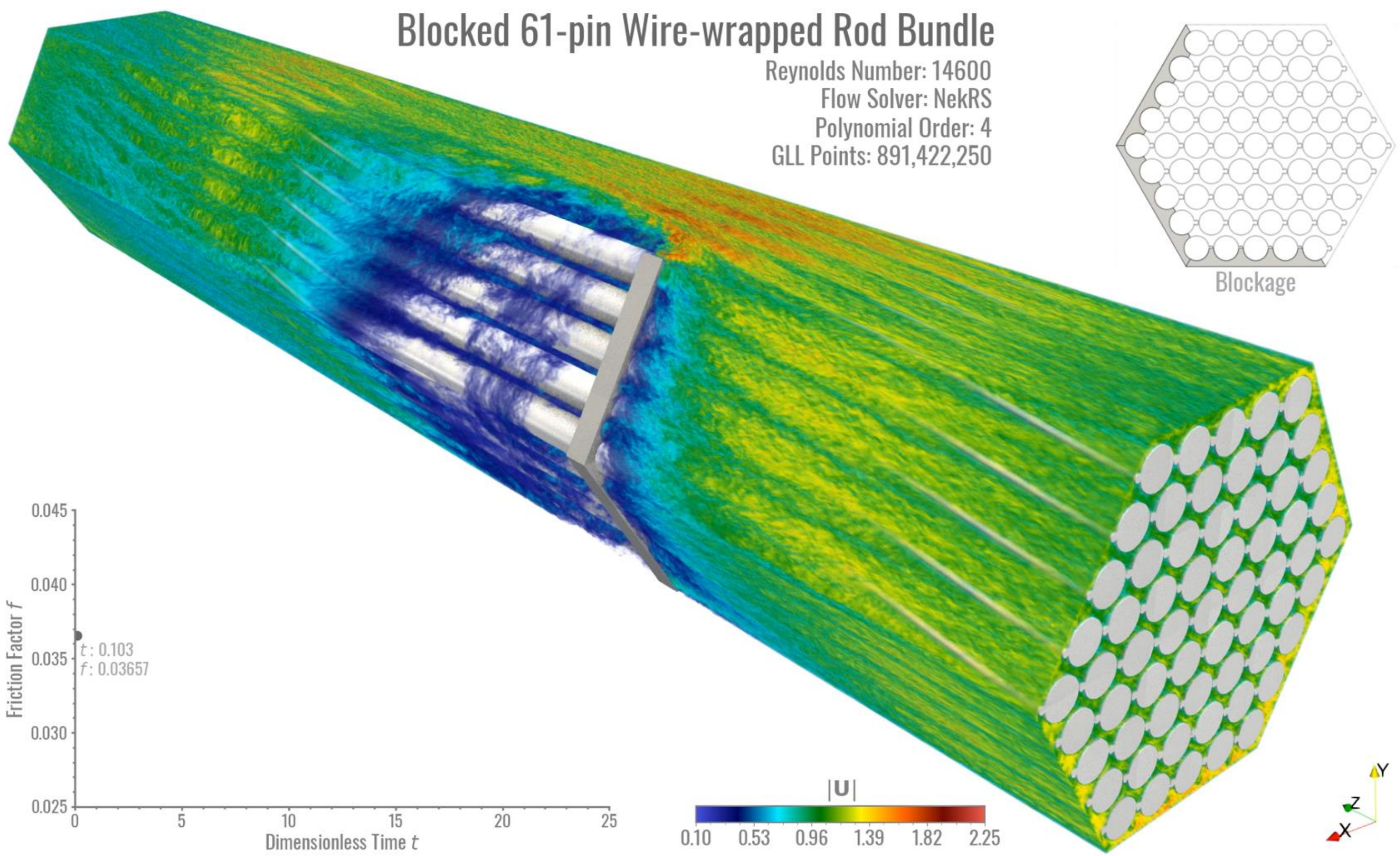


Simulation of flow in a non-uniformly heated 61-pin assembly

Capabilities – Flow Blockages

- Validation for pressure drop in blocked bundle in coordination with ART-FR
- Pressure drop values measured experimentally at Texas A&M
- Relative errors between NekRS and experiment were ~ 1%

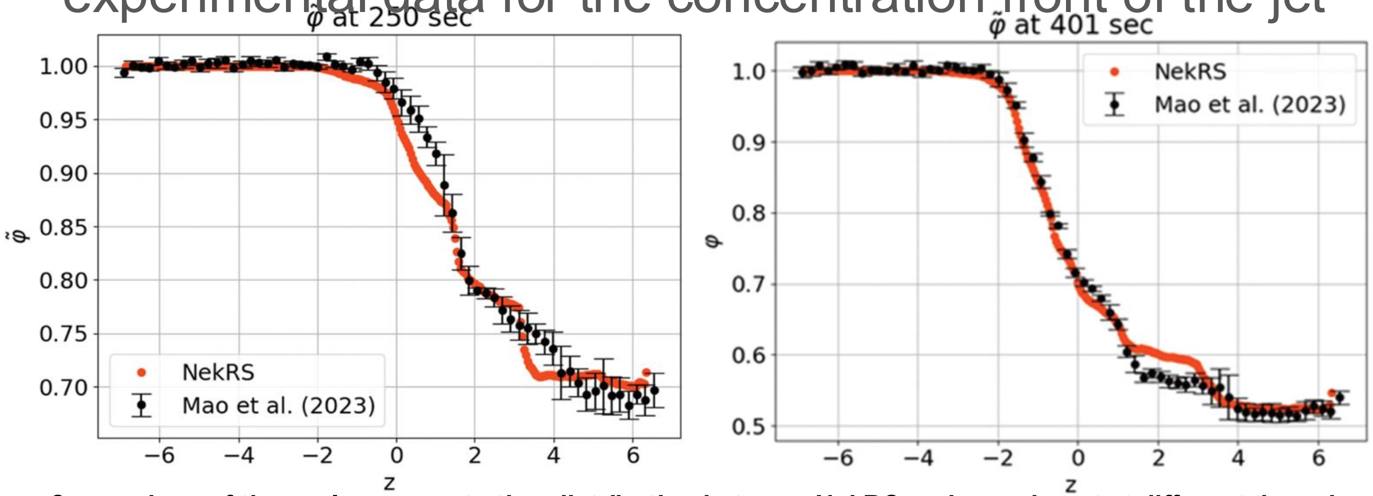




D. Dai, et al. "High-Fidelity CFD Assessment of Flow Resistance in a 61-pin Wire-Wrapped Assembly with Partially Blocked Channels", *Nucl. Sci. and Eng.* (2025, Submitted)

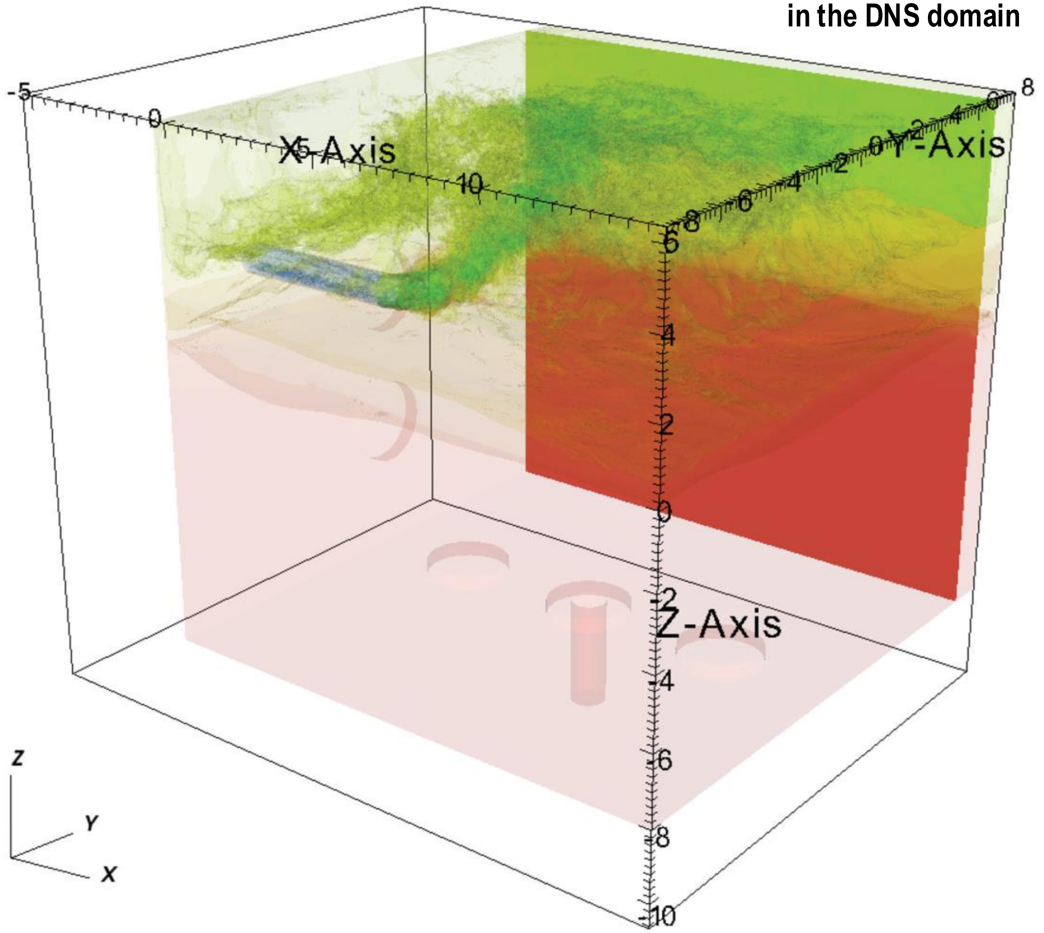
Capabilities – Thermal Stratification

- Thermal stratification demonstrated for injection of a buoyant fluid jet into an enclosure as part of the university-led NEAMS Integrated Research Project
  - DNS performed at NCSU
  - Experiments performed at U. Michigan
- Overall excellent agreement between NekRS and experimental data for the concentration front of the jet



Comparison of the scalar concentration distribution between NekRS and experiment at different times in the enclosure

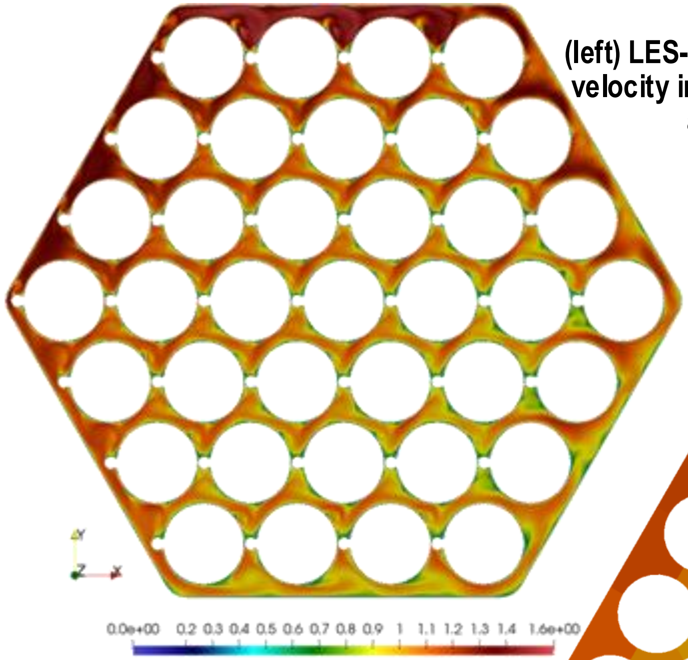
Instantaneous volumetric rendering of the scalar concentration in the DNS domain



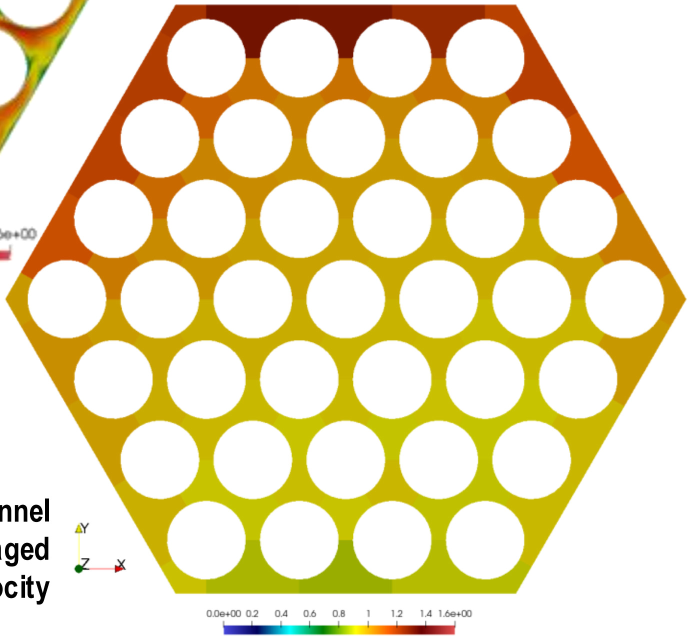
C.-K. Tai, et al. "High-Fidelity Simulation of the Light-to-Dense Stratification in the HiRJET Facility", *Nucl. Tech.* (2024)
J. Mao, et al. "Validation of RANS-Based Turbulence Models Against High-Resolution Experiments and DNS for Buoyancy-Driven Flow with Stratified Fronts", *Nucl. Sci. Eng. 198, 1404 (2023)*

Additional Capabilities/Demonstrations

- Thermal striping with stress analysis through Cardinal/MOOSE
- Demonstration of validation for flow-split in wire-wrapped bundles in collaboration with the TerraPower Natrium ARDP
- Multiscale bridging
  - Direct comparison with subchannel codes through Cardinal
  - Development of turbulence models and additional closures using high-fidelity data



(left) LES-predicted velocity in a 37-pin assembly

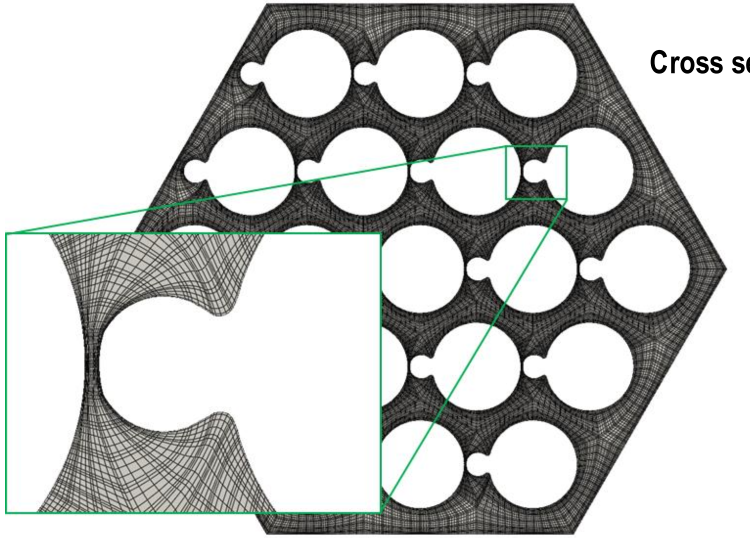


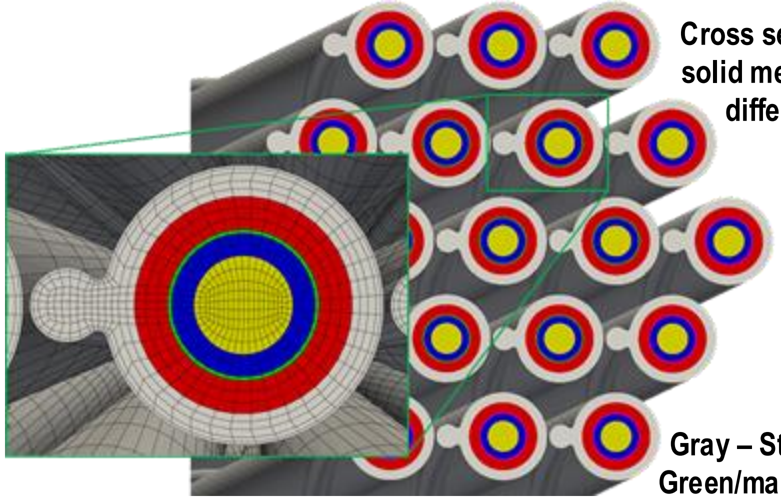
(right) subchannel averaged velocity

D. Shaver, et al. "Validation of NekRS for Flow-Splitting in a Wire-Wrapped Fuel Pin Bundle", *Proc. 21st Int'l Conf. on Nucl. Reactor Thermal Hydraulics (NURETH-21), Busan, Korea, 2025 (submitted)*

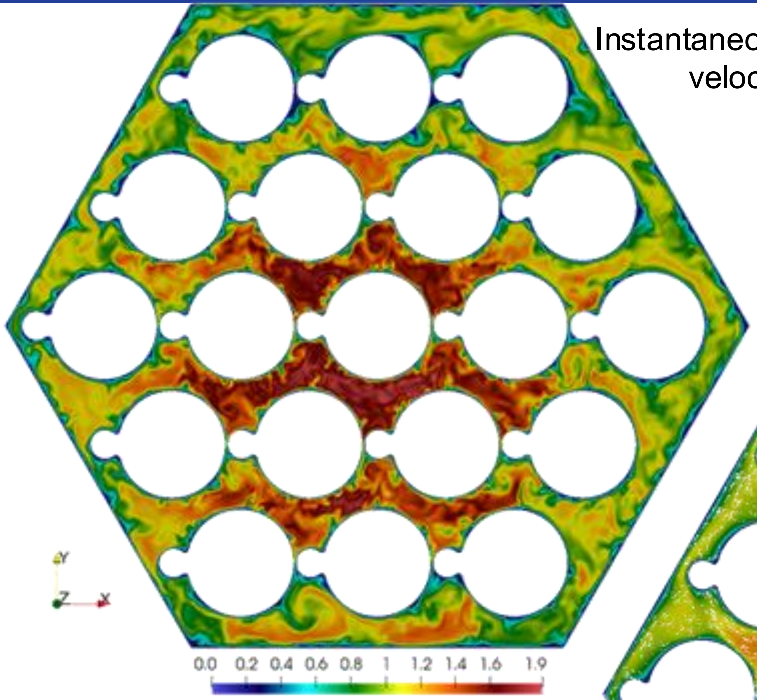
NACIE-UP Model – Heat transfer benchmark

- IAEA Coordinated Research Project in collaboration with ART-FR
- NekRS and Cardinal were used to model the NACIE-UP facility, located at the University of Pisa, Italy
- A lead-bismuth eutectic cooled loop with a 19-pin wire-wrapped fuel pin simulator (FPS) test section
  - Pins are electrically heated and controlled independently
  - Total length of FPS is 5.5 wire pitches with a 2.3 pitch-length heated section near the top
  - Thermocouple measurements of temperature for multiple heating configurations are available
- Both LES and RANS models were demonstrated in NekRS
  - LES results are time-averaged to obtain steady-state values
  - The wall-resolved standard k-τ RANS model was used with simple gradient diffusion hypothesis to account for buoyancy
- Cardinal couples NekRS to MOOSE for the solid conduction model



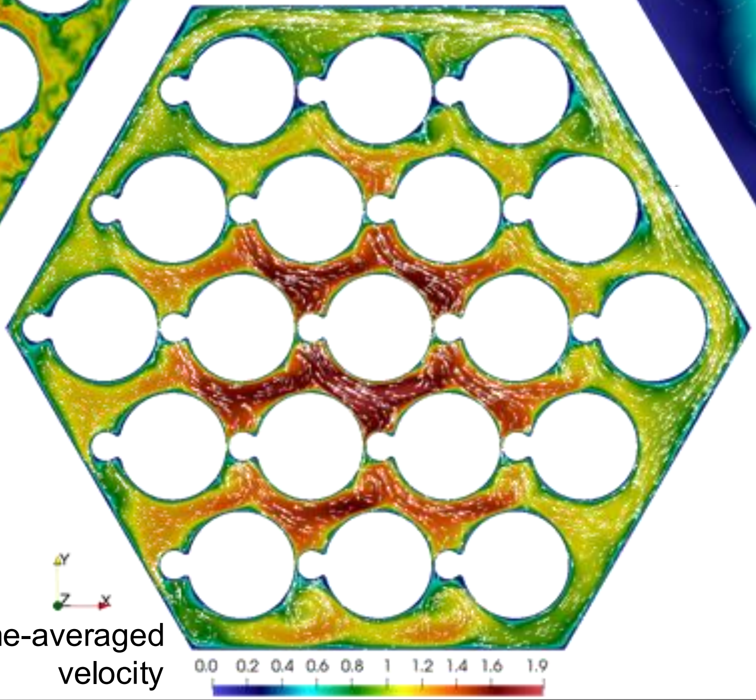


Results – Symmetric Heating (LES)



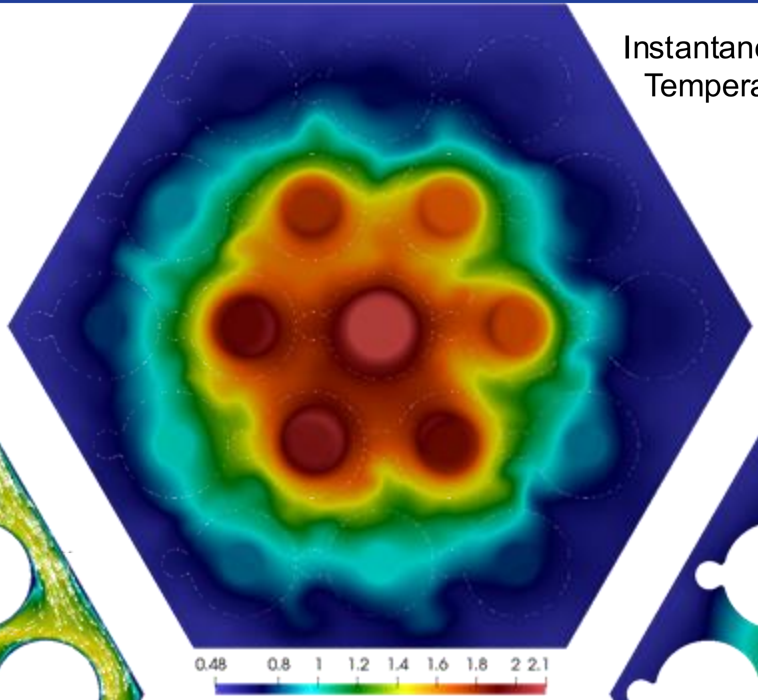
Instantaneous velocity

- Large-scale circulation pattern is observed around the assembly



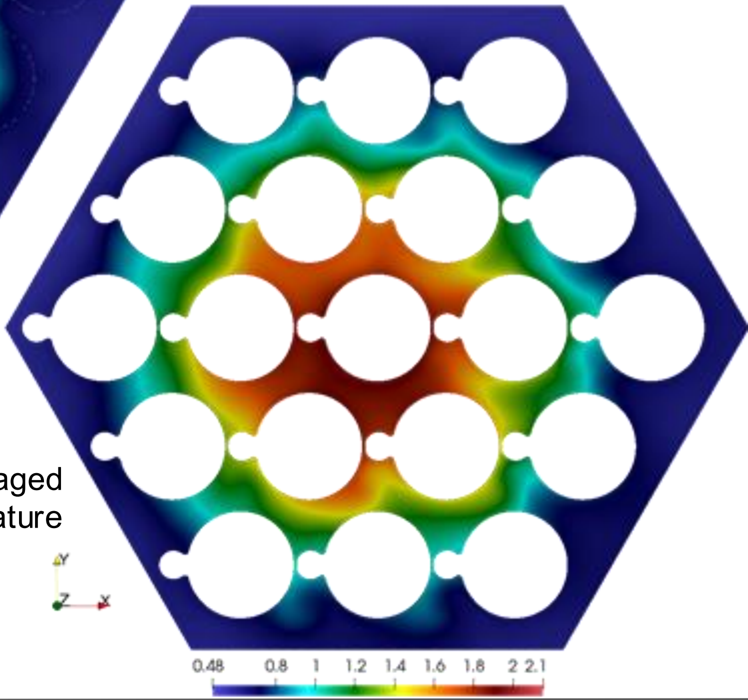
Time-averaged velocity

- The effect of buoyancy is clearly seen in the accelerated velocity around the central heated pins



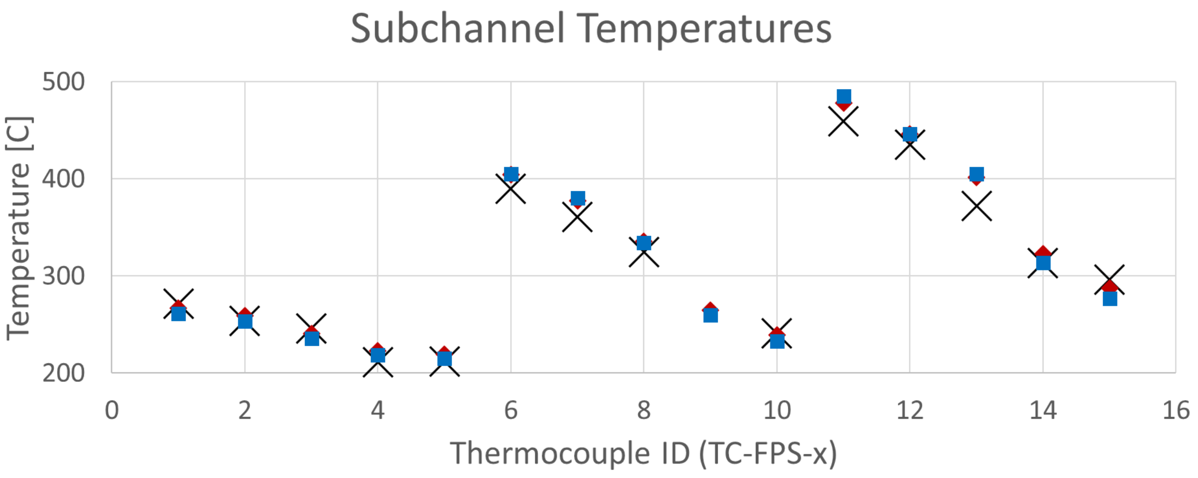
Instantaneous Temperature

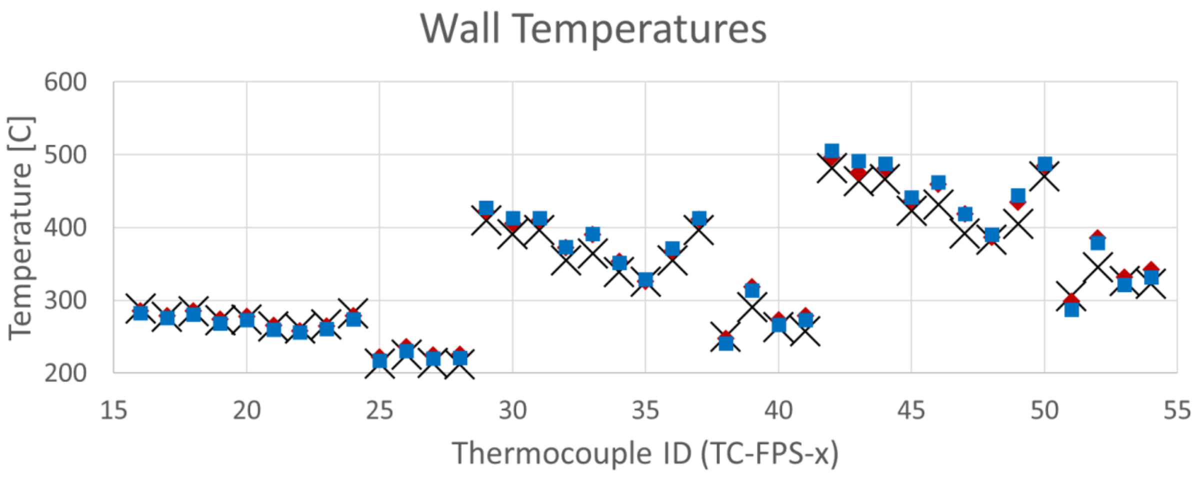
- The instantaneous temperature profile is continuous across both the fluid and solid domains



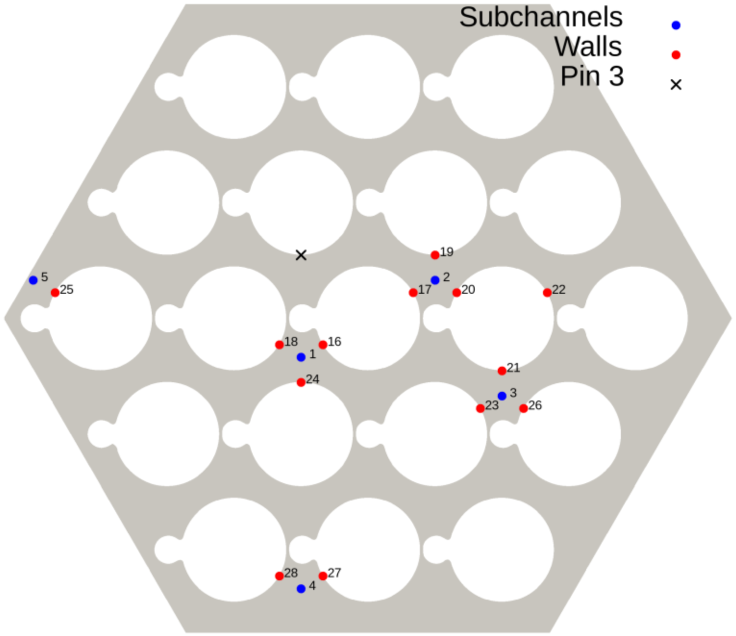
Time-averaged Temperature

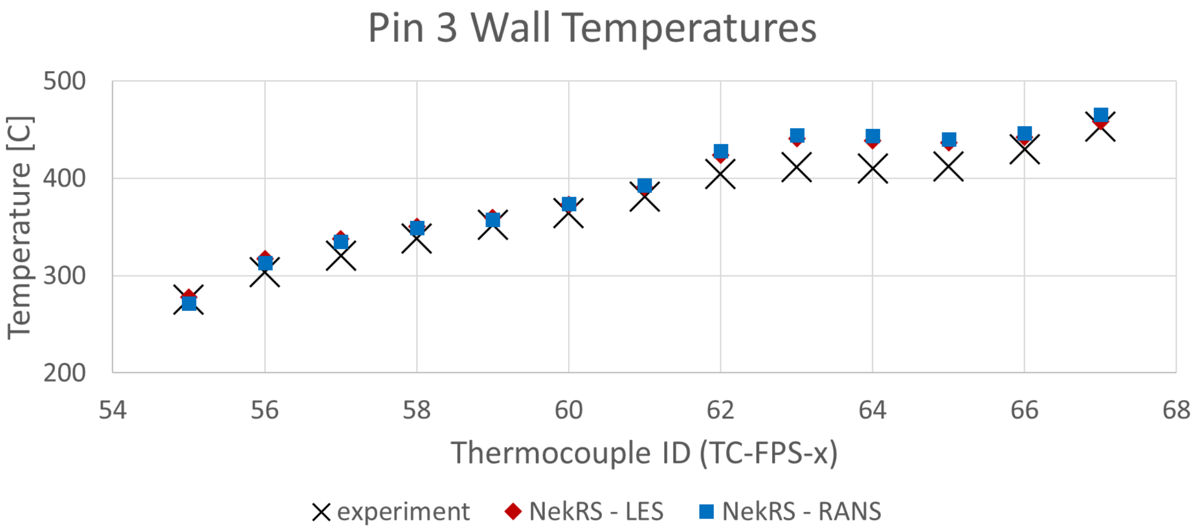
Results – Comparison to Experiment (RANS and LES)





- Overall good agreement with experimental measurements, within ~8% difference
- LES and RANS results agree very well with each other, within ~3% difference





NACIE-UP Conclusions and Future Work

- Both RANS and LES showed good agreement with experimental data for temperature predictions
  - The agreement is consistent for all experimental cases
  - Demonstrates that NekRS can be used to accurately predict heat transfer for liquid metals in wire-wrapped geometries
- RANS and LES models agree very well for these conditions
- Future work
  - Additional experimental data is expected for the asymmetric case
  - Results will be further processed to inform heat transfer and subchannel mixing coefficients
  - Further comparisons of turbulent quantities (eddy viscosity, turbulent kinetic energy, turbulent Prandtl number, etc.) between the LES and RANS results will be used to inform advanced turbulence model development

SCM: Subchannel Analysis Module

Aydin Karahan*, Vasileios Kyriakopoulos**, Mauricio Tano**, Gang Yang*

* Argonne National Laboratory

** Idaho National Laboratory

NEAMS Fast Reactor Meeting

May 29, 2025

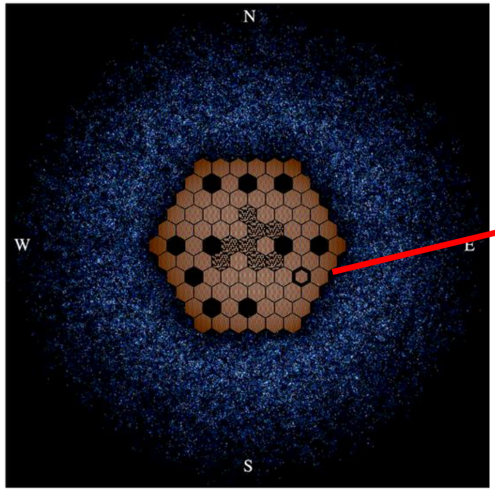
SCM Capabilities and Limitations

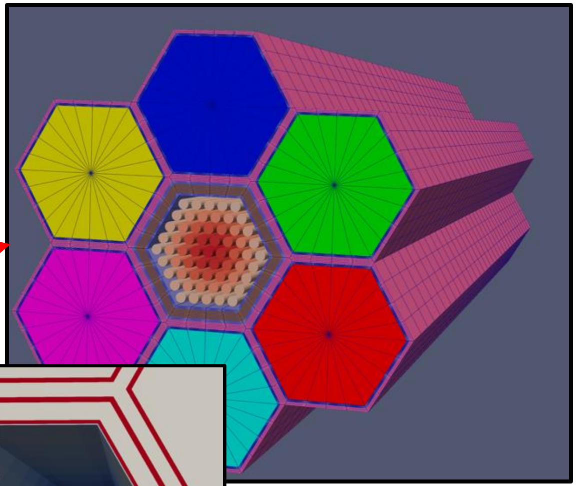
Subchannel Thermal-Fluids

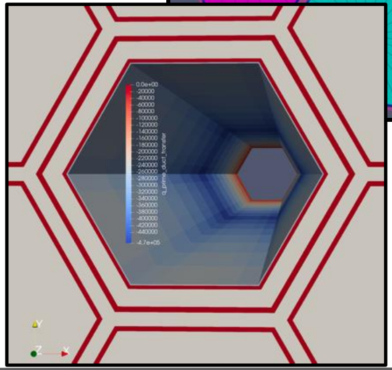
- Predictive subchannel modeling for LWR and liquid-metal cooled Fast Reactor fuel bundles.
- Includes a 1D finite-volume heat conduction model in developmental version.
- A robust implicit numerical algorithm to improve numerical performance in challenging scenarios such as blockages and low flow conditions.

Coupling Capabilities

- Couple to BISON and MOOSE modules for detailed modeling of pin and duct wall
- Couple to Griffin for reactor physics, Pronghorn for full core analysis and SAM for full plant analysis.







CDAP (developmental version)

- Evaluates potential of cascade of fuel pin failures.

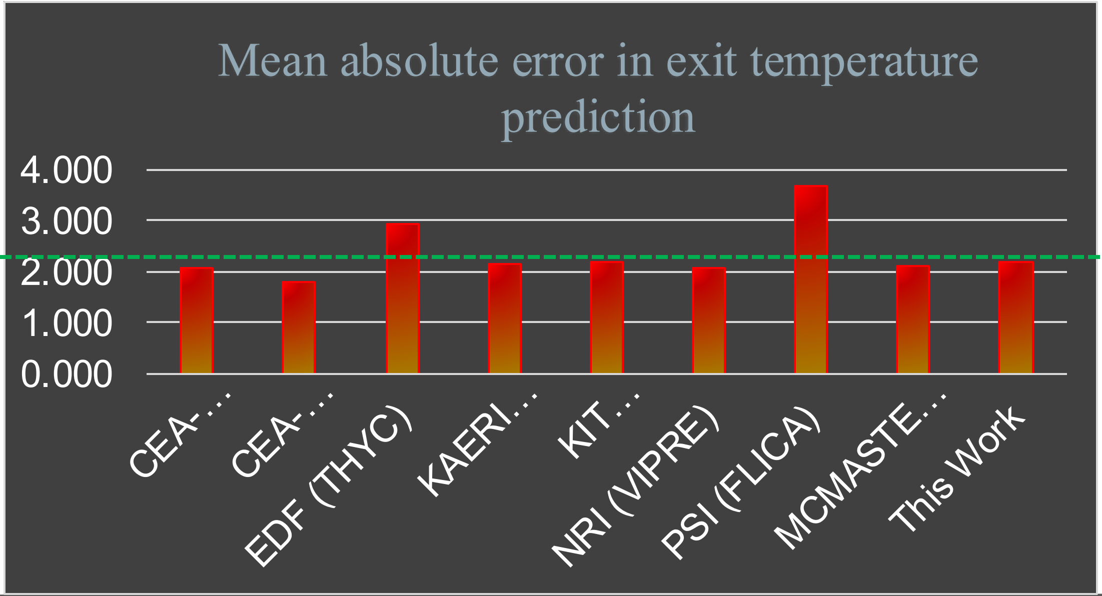
Limitations

- Coolant boiling is not modeled.
- SCM relies on inlet mass flow rate and outlet pressure boundary conditions.

Verification & Validation

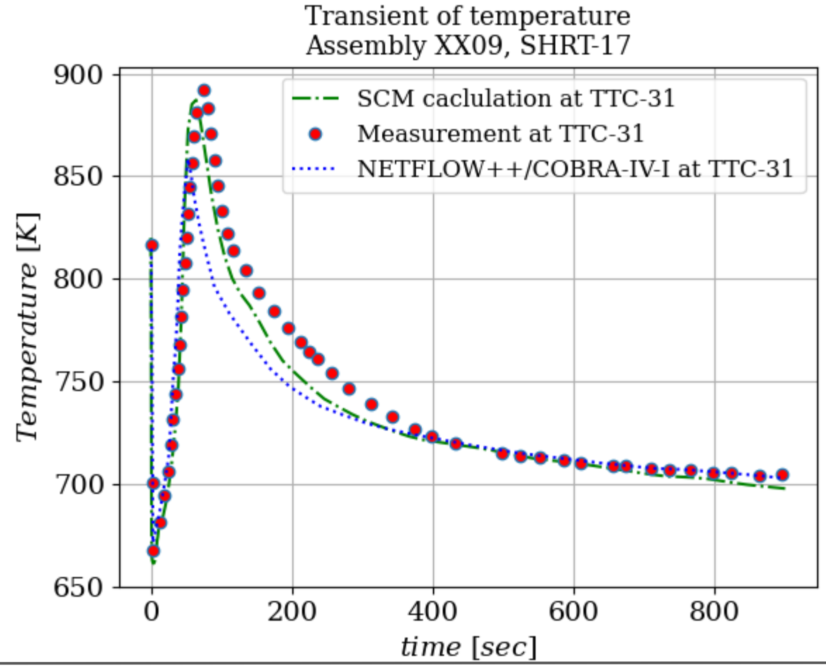
Water cooled, square assemblies

- Friction model verification
- Enthalpy mixing model verification
- Turbulent diffusion coefficient calibration
- Turbulent modeling parameter calibration
- PSBT (5X5) **temperature mixing** validation
- PNNL (2X6) **free/forced convection** validation
- PNNL (7X7) **sleeve blockage** validation

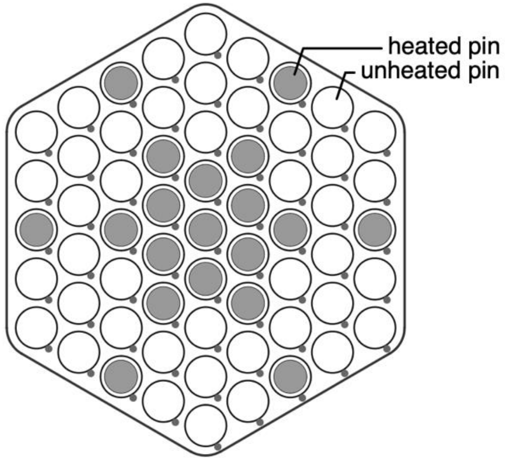


Liquid Metal cooled, hexagonal assemblies

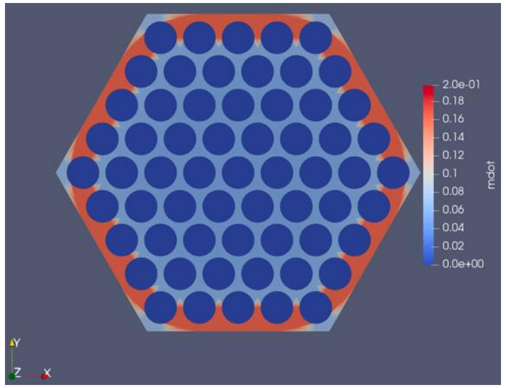
- ORNL 19-pin **enthalpy mixing** benchmark
- Toshiba 37-pin **crossflow redistribution** benchmark
- THORS FFM-(3A,2B,5B) **flow blockage** benchmark
- EBR-II SHRT **loss of flow** validation
- Areva FCTF **deformed duct** validation

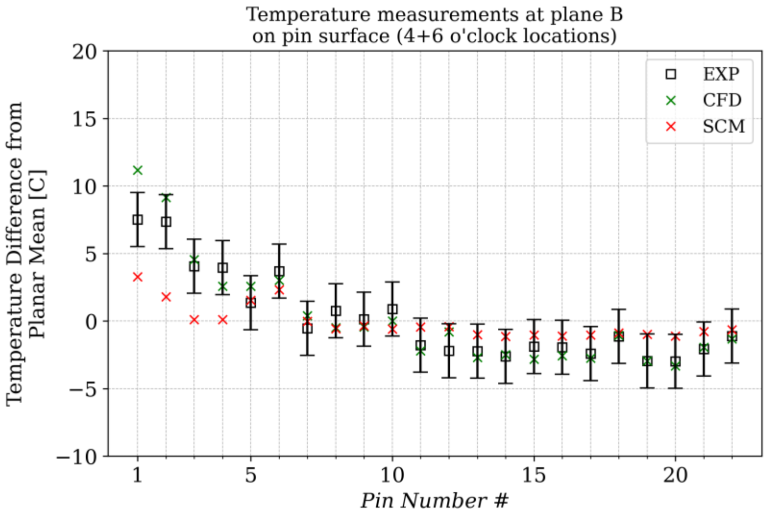


Areva FCTF (Duct Deformation)

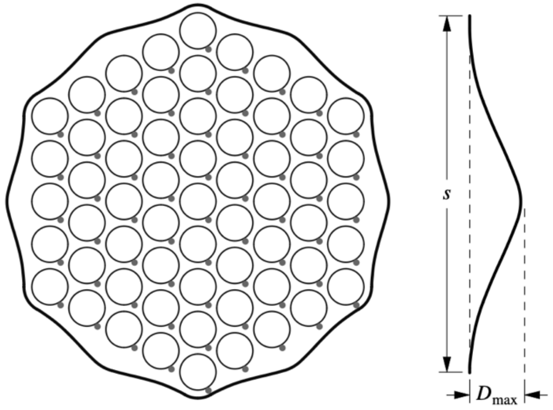


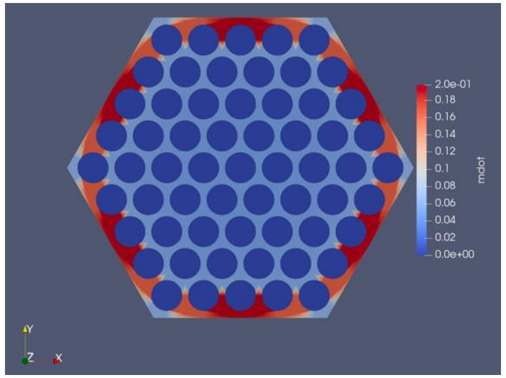
Mass flow field 2 wire pitch above heated section inlet

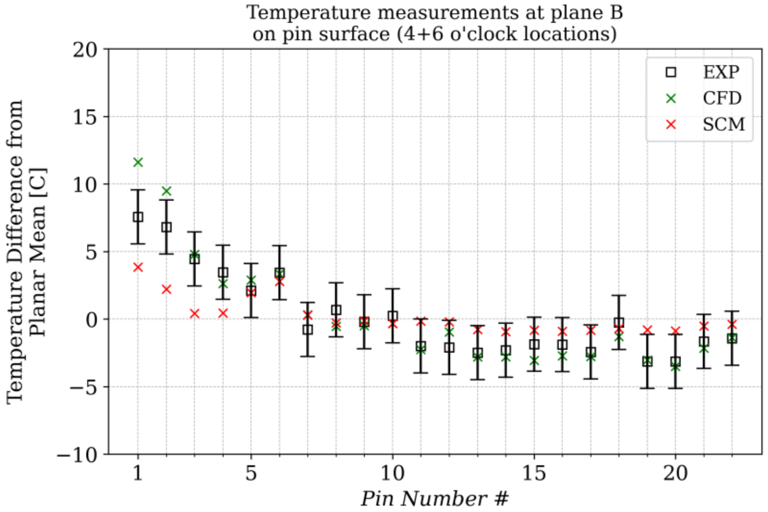




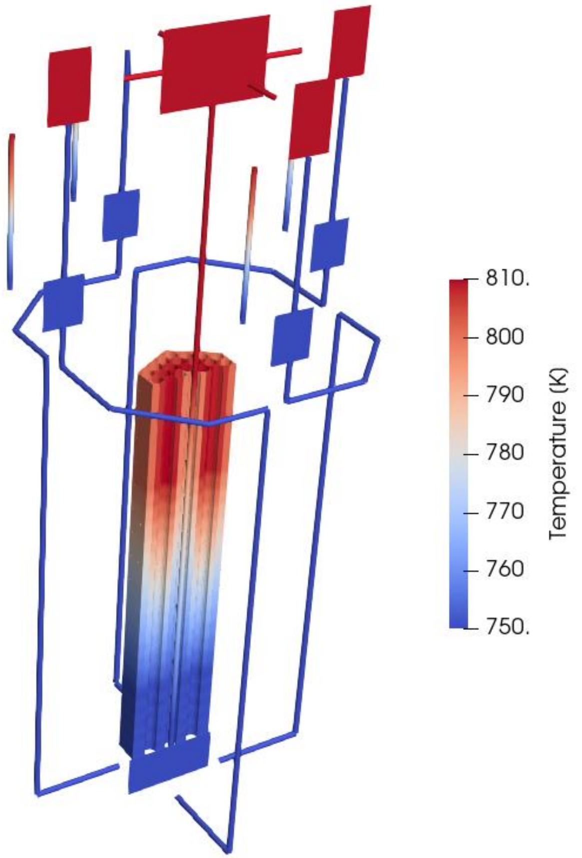
Plane B is 4.4167 wire pitch above heated inlet section



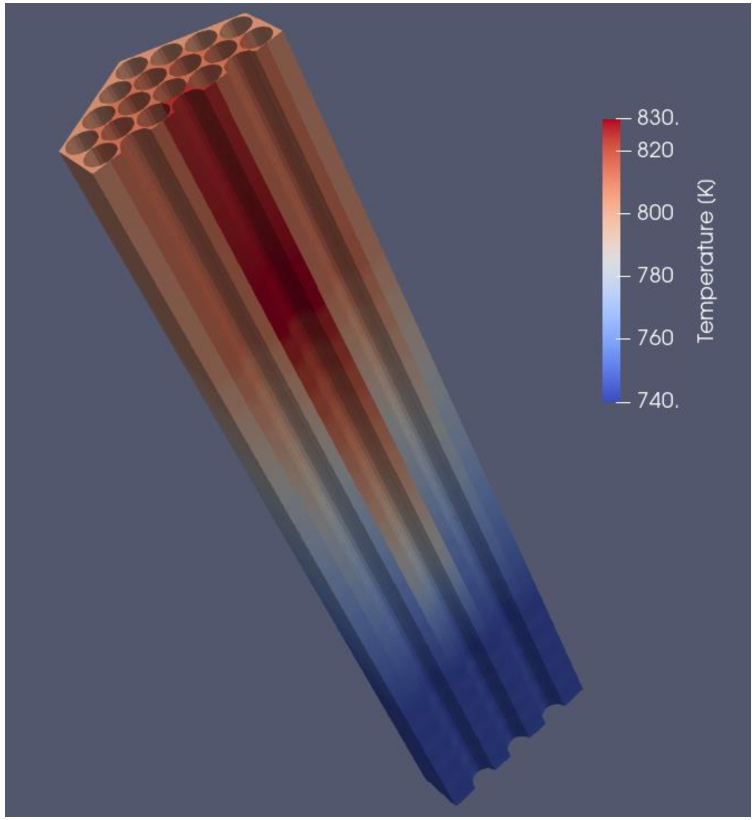




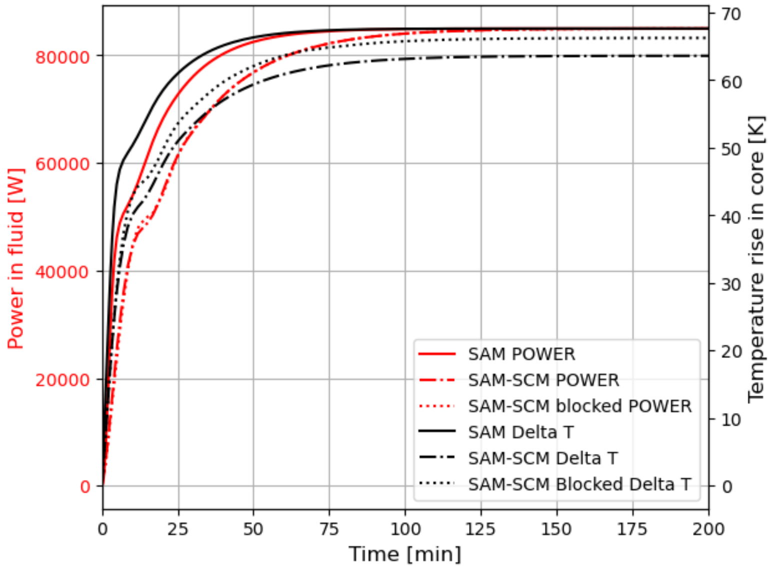
MARVEL (SCM/SAM coupling)



MARVEL SAM/SCM coupled simulation.
Unblocked core



MARVEL SAM/SCM blocked core simulation (80% area reduction and a form loss of 2 around center pin)

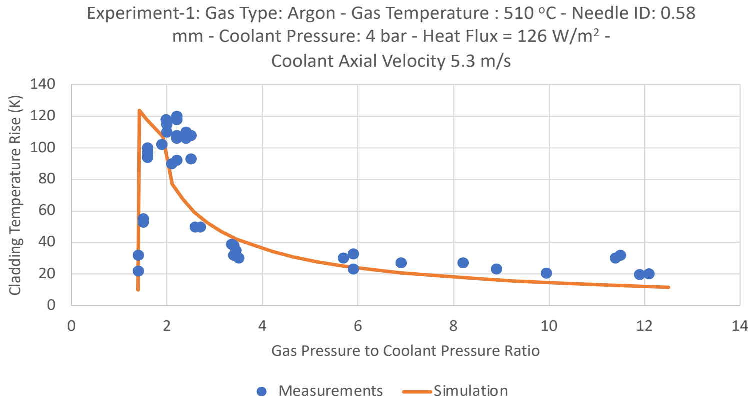


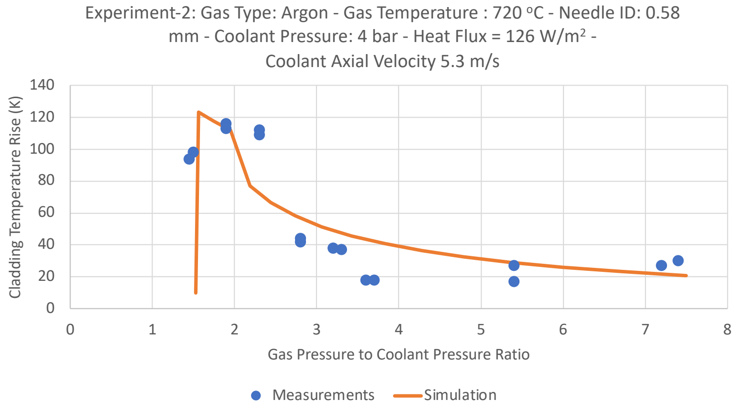
Clad DAmage Propagation (CDAP) of SCM

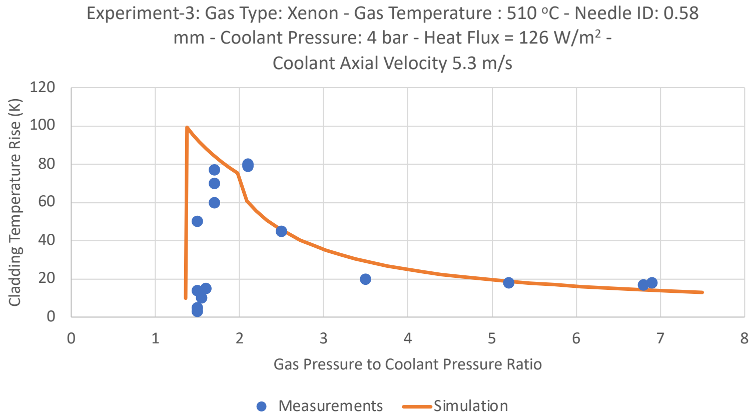
- CDAP computes
  - fuel cladding chemical interaction, cladding stress, and creep damage during the transients
  - the next fuel pin failure using probabilistic methods and possibility of cascade of fuel pin failures
  - the post-failure dispersal of the fuel pin and the corresponding heat transfer degradation to the target impinging fuel pins
  - Two-phase flow behavior in coolant flow channel and associated degradation in heat transfer coefficient and coolant inlet flow rate
- Leverages subchannel capability to characterize individual pin failures and its effect on surrounding pins

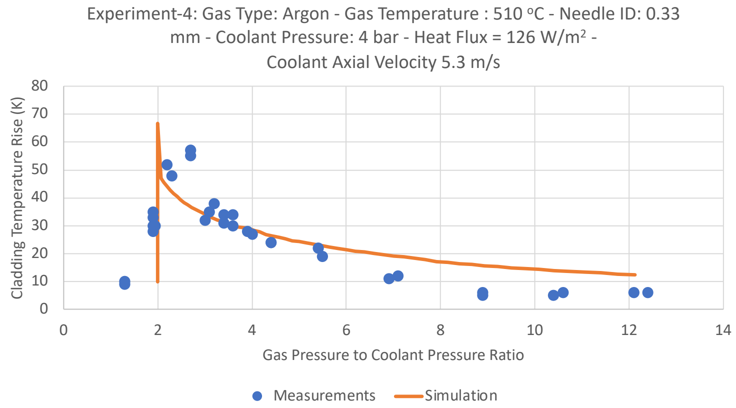
Separate effect tests validation

- Initial validation effort leveraged existing submerged gas jet impingement tests on heated target [1]
- A significant heat transfer degradation at impinging surface at low pressure conditions due to inefficient droplet entrainment and gas blanketing.



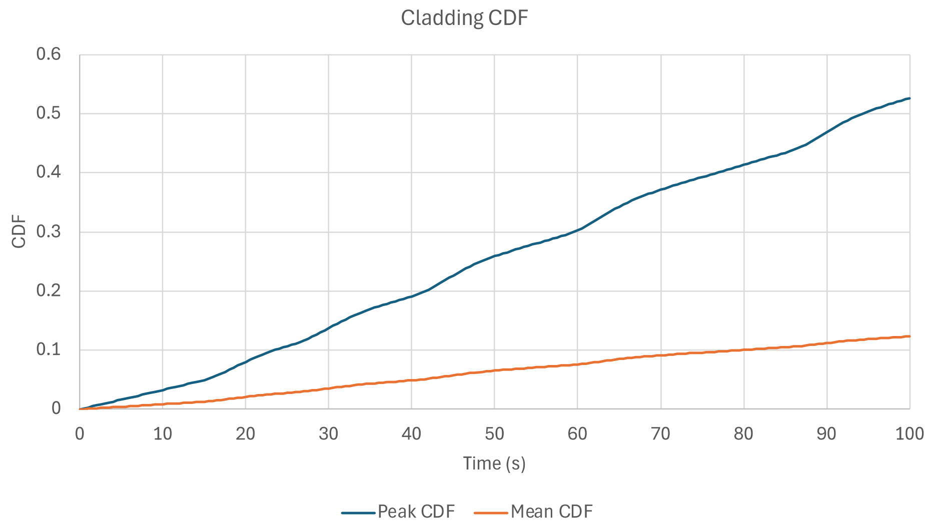


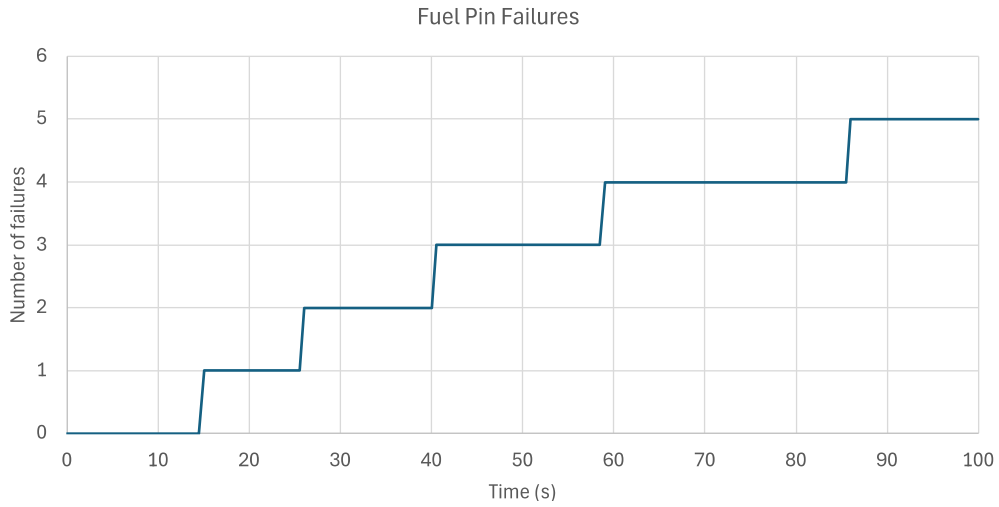


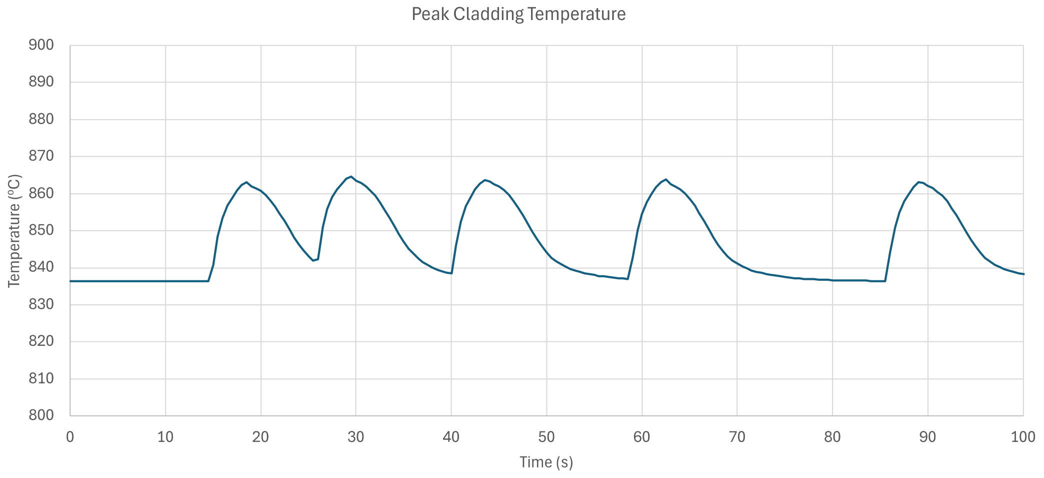


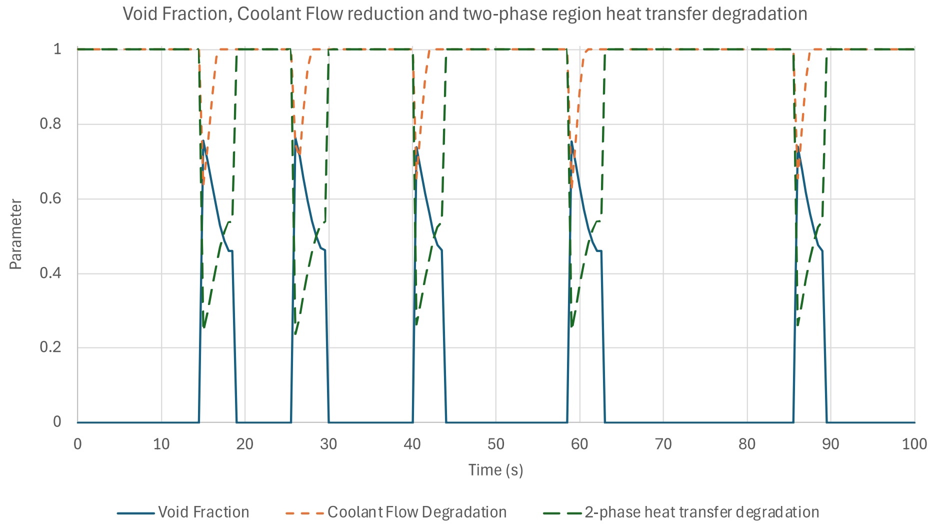
[1] J. B. VAN ERP, T. C. CHAWLA, H. K. FAUSKE, "An Evaluation of Pin-to-Pin Failure Propagation Due to Fission Gas Release in Fuel Subassemblies of Liquid-Metal-Cooled Fast Breeder Reactors," *Nuclear Engineering & Design*, **31**, pp. 128-150, (1974).

CDAP Demonstration Example-1: 37-pin bundle – High Burnup Metallic Fuel Pin. Transient peak cladding temperature is 836 °C prior to cladding failures.

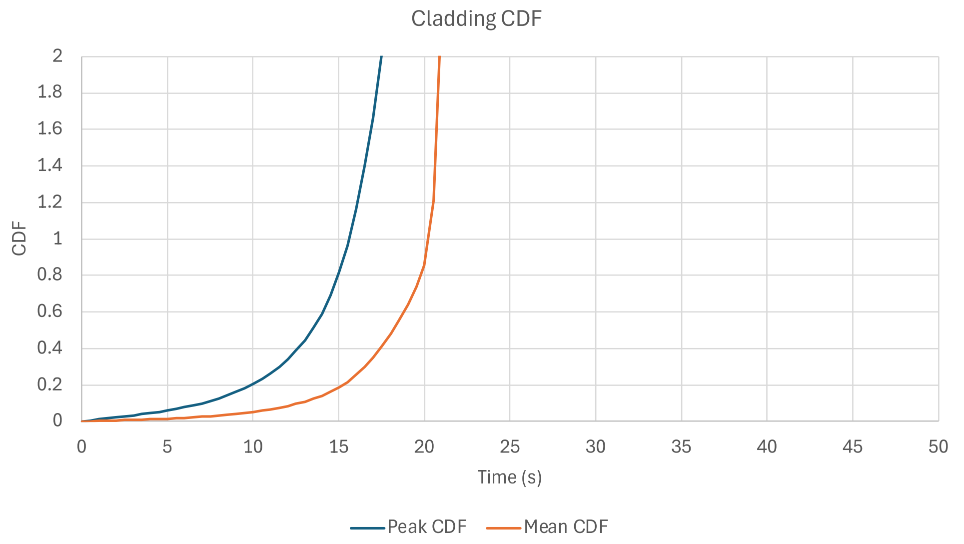


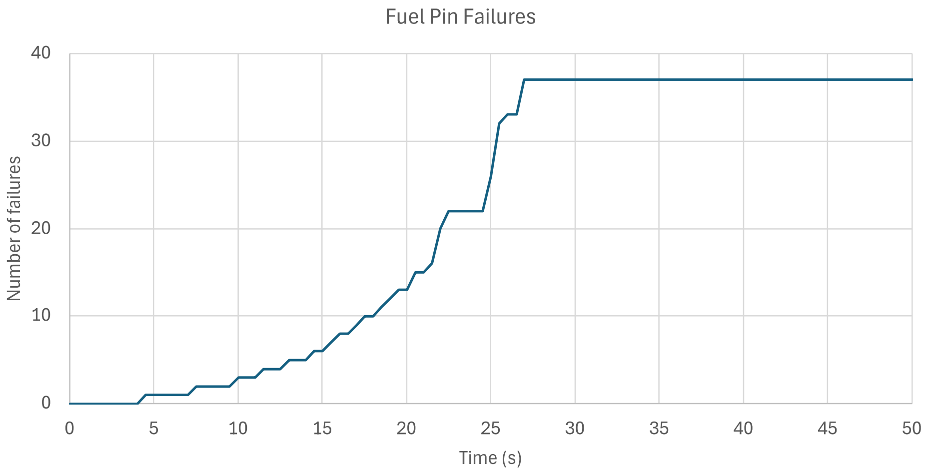


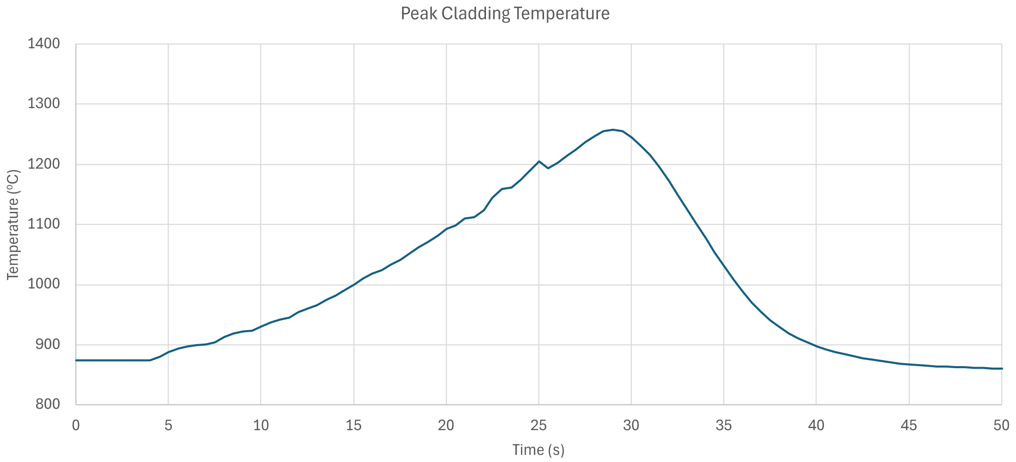


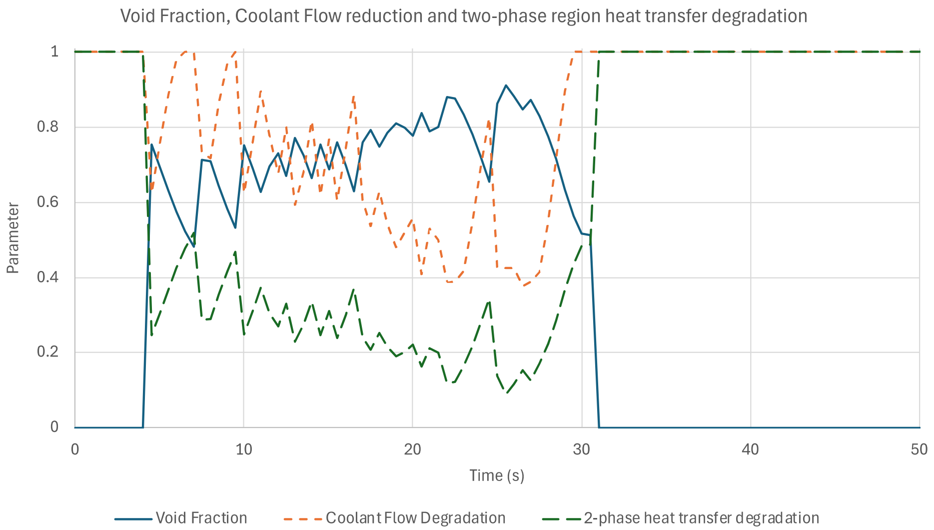


CDAP Demonstration Example-2: 37-pin bundle – High Burnup Metallic Fuel Pin. Transient peak cladding temperature is 874 °C prior to cladding failures.









Summary and Future Work

- MOOSE SCM: Coolant Thermal-Hydraulics
  - Proven robust in simulating coolant thermal-hydraulic behavior during normal operation and transients
  - Demonstrated coupling with other physics tools such as SAM/Pronghorn/Griffin
  - Applicable to fuel pin and flow channel geometric changes
  - Supports fuel bundle distortion analysis
- CDAP: Fuel Failure Cascade Modeling
  - Assesses the risk of a cascading of fuel pin failures
  - Demonstration planned for UTOP and USBO/ULOF scenarios.
  - OSU experiments will be used to validate CDAP model.
  - CDAP and 1D heat conduction models will be integrated into SCM release.

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