INL/CON-24-81516-Revision-0

Multiscale Thermal-hydraulic analysis of the MARVEL micro-reactor using coupled MOOSE Subchannel (SCM) and SAM

September 2025

Vasileios Kyriakopoulos, Lise Charlot, Mauricio Eduardo Tano Retamales

INL/CON-24-81516-Revision-0

Multiscale Thermal-hydraulic analysis of the MARVEL micro-reactor using coupled MOOSE Subchannel (SCM) and SAM

Vasileios Kyriakopoulos, Lise Charlot, Mauricio Eduardo Tano Retamales

September 2025

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

NURETH-21 21st International Topical Meeting on Nuclear Reactor Thermal Hydraulics
August 31 (Sun) - September 5 (Fri), 2025
BEXCO · Busan, Korea
www.nureth-21.org

Multiscale Thermal-hydraulic analysis of the MARVEL microreactor using a coupled SCM and SAM simulation

Vasileios Kyriakopoulos, Lise Charlot, Mauricio Tano, Guillaume Giudicelli
Idaho National Laboratory
1955 Fremont Ave, Idaho Falls, ID 83415
vasileios.kyriakopoulos@inl.gov; lise.charlot@inl.gov; mauricio.tanoretamales@inl.gov;
guillaume.giudicelli@inl.gov

ABSTRACT

The MARVEL microreactor was modeled through a coupled simulation of SAM and SCM. This multiscale coupled simulation was performed as an exercise to demonstrate the compatibility and applicability of these codes for microreactor thermal-hydraulic analysis. Coupling of the SCM and SAM codes for multiscale modeling of this microreactor design, was achieved through a domain overlapping approach. In this demonstration, a transient SAM simulation provided boundary conditions to SCM, and SCM provided a core pressure drop to SAM. The transient chosen was the start-up transient of the MARVEL microreactor, which is a buoyancy driven, natural convection flow created by the heated core. Two core configurations where considered: the default one and one with an obstruction around the center fuel pin.

KEYWORDS
MARVEL, SCM, SAM, SFR

1. INTRODUCTION

A handful of microreactor designs are under development in the United States, incorporating an aggressive timeline to deployment. These compact reactors will be small enough to transport by truck and could help solve energy challenges in several areas, ranging from remote commercial or residential locations to military bases and industrial installations (chemical plants, AI data centers, steel/hydrogen production, etc.). Microreactor designs vary, but most would be able to produce 1–50 MW of thermal energy directly usable as heat, or convertible to electric power.

The microreactor applications research validation and evaluation (MARVEL) reactor is a 85 kWth, thermal spectrum, sodium-potassium eutectic (NaK)-cooled microreactor developed under the leadership of Idaho National Laboratory (INL) via the U.S. Department of Energy's Microreactor Program. This microreactor, once operational, can be used by researchers and technology developers to gain operational experience and advance the technical maturity of microreactor concepts. It is designed to use Training, Research, Isotopes, General Atomics (TRIGA) international fuel (20% enriched) and operate at high enough temperatures to serve as a heat source for power production via Stirling engines or other power conversion systems for microgrid applications.

The success and adoption of microreactor designs such as MARVEL and others, depends on their safety characteristics and efficiency, both of which are tied to reactor core performance. It is important to demonstrate that a fuel design can operate reliably at high burnups, high power densities, and high coolant temperatures. The operational limitations involved, such as clad thermal creep, corrosion, and clad wastage formation, are all highly temperature-dependent phenomena. Consequently, accurate prediction of temperature distributions in the core, during normal operation, as well as during transients, is key to demonstrating the safety of these designs. As a result, validated codes and models are needed to evaluate the passive safety features, design, and performance of microreactors.

The nuclear energy advanced modeling and simulation (NEAMS) program has developed several thermal hydraulics codes, including the subchannel module (SCM) and the system analysis module (SAM), both of which are based on the multiphysics object oriented simulation environment (MOOSE) framework. MOOSE is an open-source, finite element framework upon which a variety of physics applications are built, including several that are highly relevant to microreactors [1,2].

Subchannel codes like SCM are thermal-hydraulic codes that offer an efficient compromise between computational fluid dynamics codes and system codes, when simulating a nuclear reactor core. They use a quasi-3D model formulation and a subchannel discretization that allows for a finer mesh than system codes, without entailing the high computational costs of computational fluid dynamics (CFD). Integration of the conservation equations (momentum, energy, mass) over the subchannel volumes, along with the appropriate closure models, produces the subchannel equations. Various subchannel codes have been developed or adapted to liquid-metal reactor designs.

SCM [3], was developed to model single-phase flows through liquid-metal-cooled, wire-wrapped fuel pins ordered in a triangular lattice [4,5]. SCM is ideal for modeling the thermal-hydraulic phenomena in the MARVEL core, because the MARVEL core is very similar, to a traditional hexagonal ducted, sub-assembly. However, the subchannel analysis is only applicable to the core region, and modeling the loop feedback in MARVEL is important because the flow is driven by natural convection. This can be addressed by coupling a core modeled in SCM to a plant loop modeled in SAM.

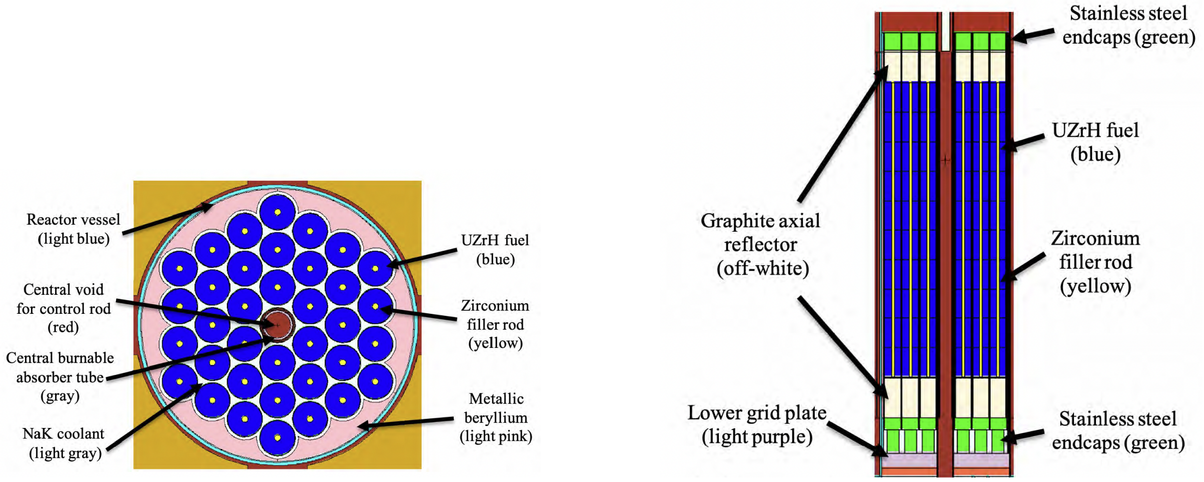
SAM is a modern system analysis tool being developed at Argonne National Laboratory (ANL) for advanced non-LWR safety analysis. It aims to provide fast-running, whole-plant transient analyses capability with improved-fidelity for various advanced reactor types including liquid-metal-cooled, molten-salt cooled and fueled, gas-cooled, and heat-pipe-cooled reactors. SAM takes advantage of advances in physical modeling, numerical methods, and software engineering, to enhance its user experience and usability. It utilizes an object-oriented application framework (MOOSE), and its underlying meshing and finite-element library (libMesh) and linear and non-linear solvers (PETSc), to leverage the modern advanced software environments and numerical methods.

Measurements collected from the operation of the MARVEL microreactor can also be leveraged for the validation of NEAMS tools. A multiphysics model is currently under development [7]. The primary and secondary loops have been modeled using standalone SAM, and preliminary results showed some radial and azimuthal variations in the pin power profiles. Thus, a higher-fidelity approach than 1D is desirable for improving the accuracy of the results.

For this purpose, a multiscale coupled simulation was developed: SCM is used for a subchannel model of the reactor core and SAM, was used as a system model of the reactor's power conversion system (PCS) and a simplified representation for the core. This example serves as a demonstration case for the compatibility and applicability of using a SAM-SCM coupled simulation to perform thermal-hydraulic analyses of microreactors.

2. THE SAM-SCM COMPUTATIONAL MODEL

MARVEL is a natural-convection-cooled, sodium-potassium microreactor anticipated to generate 85 kW of thermal energy. It will operate within Idaho National Laboratory's Transient Reactor Test Facility and is being developed by the U.S. Department of Energy's Microreactor Program. MARVEL will be used to test microreactor applications, generate operational data, and pave the way for commercial demonstrations. The SCM code was modified so as to be able to model MARVEL's unique core geometry, presented in Figure 1. The dimensions of the actual MARVEL microreactor are not presented in this publication due to export control considerations.



(a) Lateral cross section.

(b) Axial cross section.

Figure 1. MARVEL core cross sections.

Compared to a “traditional” hexagonal, ducted sub-assembly with fuel pins in a triangular lattice, the MARVEL core only differs in the shape of the peripheral subchannels, since instead of straight flat sides, the MARVEL core sides, conform to the circular shape of the peripheral fuel pins, allowing for but a small gap. The SCM modification consists of creating a couple of new, custom objects that calculate the modified surface area and wetted-perimeter of the peripheral subchannels. The MARVEL core has a lower reflector and an upper reflector that are located before and after the heated part of the core, which have the same geometry but are unheated.

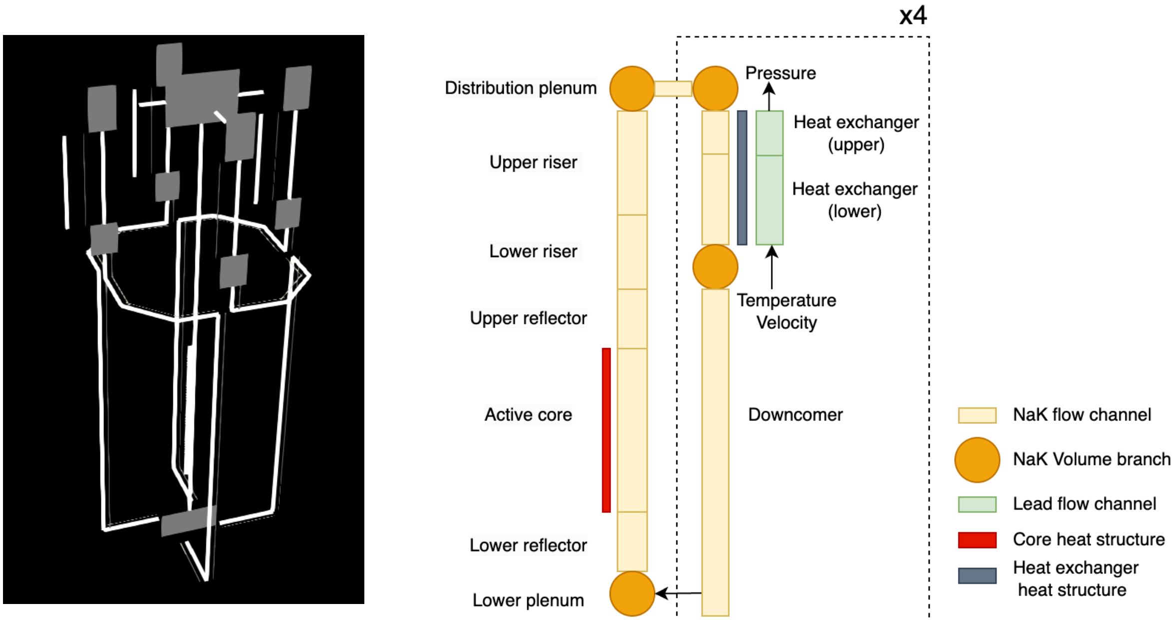
MARVEL’s PCS is a 4-loop hydraulic circuit, assembled to efficiently transport nuclear fission heat from the nuclear fuel to the heat addition section of the secondary coolant system by utilizing natural circulation of liquid NaK, while also maintaining the reactor fuel at a suitable operating temperature. The PCS also transfers decay and sensible heat to the ultimate heat sink, the reactor cavity pit, via heat conduction and convection following any reactor shutdown.

This work leveraged the SAM model described in [7]. The SAM model, a diagram of which is shown in Figure 2, uses a single flow channel for the core and reflector regions, coupled with a heat structure to represent the fuel rods. It included all the major components of the PCS, with all four loops being explicitly modeled. The secondary side of the heat exchanger was modeled using a flow channel and inlet/outlet boundary conditions.

Coupling between the SCM and SAM codes for multiscale modeling of MARVEL was achieved through a domain overlapping approach in which SCM models the core, including the top and bottom reflectors, and SAM models the entirety of the system (core and loop). SAM was the main application driving the transient analysis, whereas SCM operated as a sub-application running in steady state. Running SCM in steady state increased the computational efficiency without compromising accuracy, since the NaK coolant can be considered incompressible.

The coupling was implemented seamlessly out of the box—without requiring any additional coding—by utilizing the Multi-App functionality in MOOSE, post-processor transfers, and the built-in capability of the SAM flow channel component to derive a friction factor based on a user-specified pressure gradient. Users simply need to activate the coupling scheme and define the transferred quantities between the two codes.

More specifically, SAM sends to SCM, the mass flux and coolant temperature at the inlet of the core, the power transferred from the fuel pins into the coolant in the core region and the pressure at the outlet of the core. After its solve, SCM returns the pressure drop across the core. SAM calculates the required pressure gradient for the core component by dividing the



(a) 3D rendering of the SAM model.

(b) Diagram of the SAM model.

Figure 2. SAM model of the MARVEL primary loop [7].

pressure drop by the core length, and a friction factor is computed internally in SAM to match the pressure gradient.

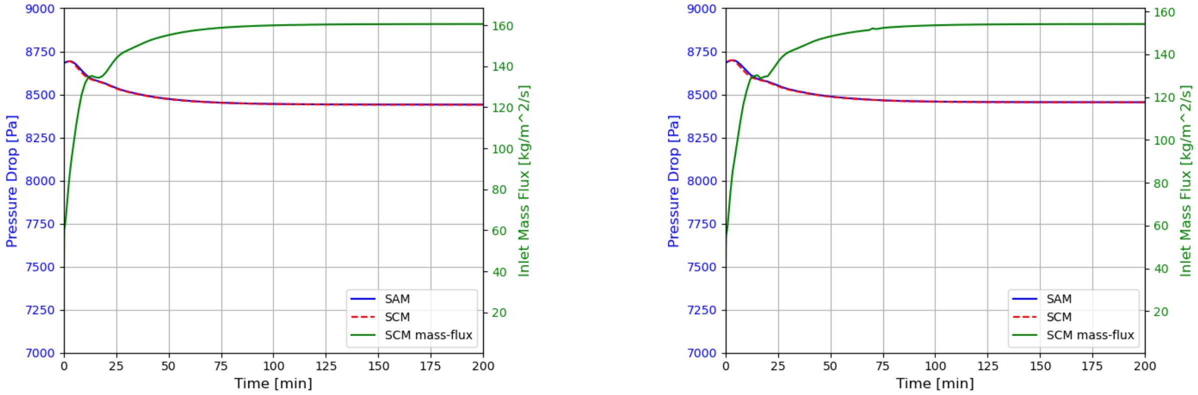
For transient calculations, it is important to account for the thermal inertia in the fuel pins. Since the fuel pins are not included in the SCM model, the power to the coolant during the transient is calculated by the SAM model, which includes heat structure modeling for the fuel pins. In future work, the fuel pins will be modeled by a specific BISON model and the power to the coolant will be transferred from BISON to SCM on a pin-by-pin basis. The closures models (friction, turbulent diffusion) implemented in SCM for hexagonal-ducted assemblies have been presented in [4].

3. RESULTS

Three startup-transient simulations of standalone SAM, coupled SAM-SCM and coupled SAM-SCM with core blockage, were run until steady state conditions are reached. In the blocked case, a blockage was simulated in SCM, specifically on the six subchannels around the central unheated pin. The assumed flow area reduction of the blocked subchannels was 80% and a local pressure form loss coefficient of 2 was applied. The axial blockage location was from 0.3 to 0.4 meters. The selection of the blockage parameters is arbitrary since there are no validation data for this type of reactor yet and there is no ubiquitous accepted way of simulating blockages in subchannel subassemblies beyond exercising engineering judgement.

In all simulations, power was assigned to the fuel pins, and natural circulation flow was initiated in the core and the loop before reaching steady state. The time to steady state is about 75 minutes for all simulations. The pressure drop across the core and the mass flux at the core inlet are plotted in Figure 3, demonstrating that the pressure drop calculated by the SCM model is properly transferred and applied in the SAM model. We notice that the steady state mass flux for the blocked core is lower.

A visualization of the coolant temperature field of the coupled SAM-SCM simulation at steady state is given in Figure 4a. The temperature distribution at the core exit is shown in Figure 4b. The coolant temperature is hotter between the first and second pin ring in the core



(a) Unblocked.

(b) Blocked.

Figure 3. Pressure drop across the heated core (left axis) and the mass flux at the core inlet (right axis) for a coupled simulation.

compared to the center/edge subchannels and the lower reflector region. This demonstrates SCM's capability to provide a higher fidelity resolution of the temperature field, hence to better predict hot spots within the core in comparison to the simpler SAM model.

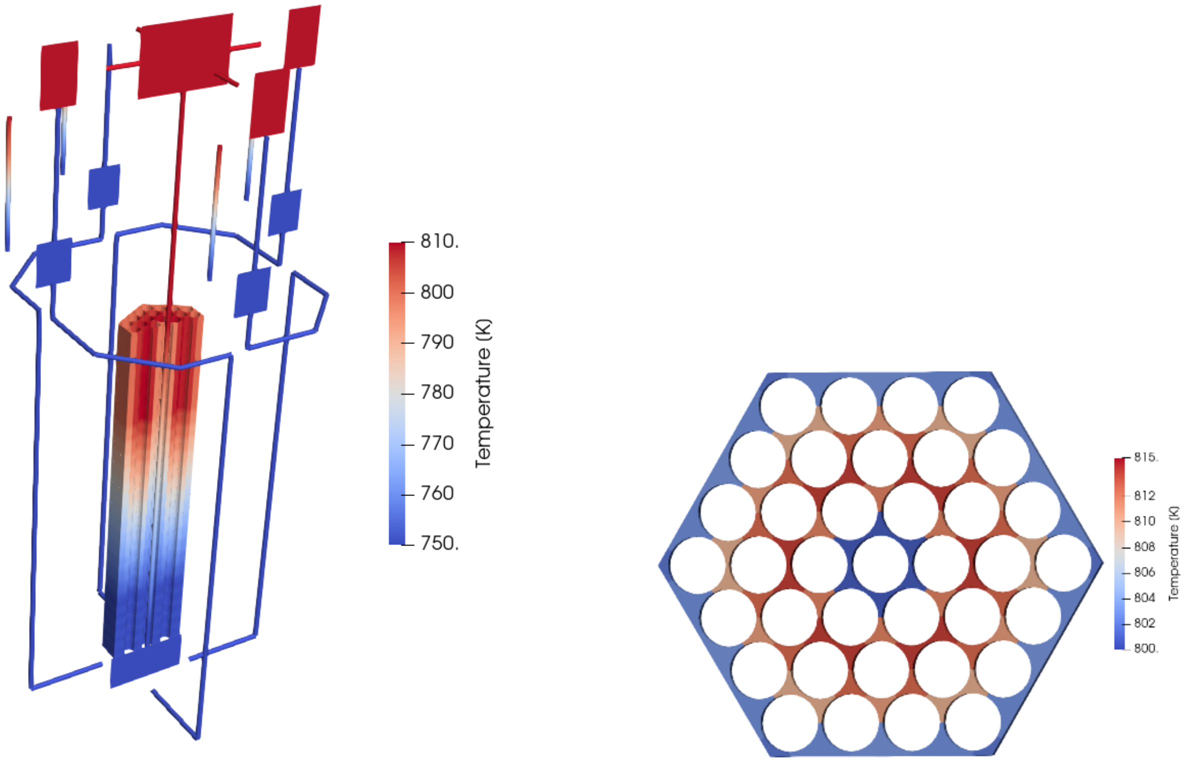
Table 1 compares the steady-state results obtained via the SAM standalone model and the SAM-SCM coupled models. The mass flow rate is higher in the coupled model than in the standalone one, meaning that the friction factor calculated by SCM is lower than that calculated by the SAM standalone model. Note that although both models use the Cheng-Todreas correlations, the SAM standalone model only has one channel for the whole core, while SCM calculates the friction factor for each individual subchannel. This results in a slightly lower temperature rise in the core for the coupled model.

The coupled SAM-SCM simulation with blocked core exhibits a lower mass-flow rate and slightly higher temperature at the core outlet compared to the coupled SAM-SCM simulation with unblocked core. This is expected as the inclusion of the blockage increases the equivalent friction factor in SAM. Overall, the values are similar to each other for all cases examined.

Table 1. Comparisons of key quantities.

	SAM standalone	Coupled SAM-SCM	Coupled SAM-SCM Blocked
Core mass flow rate [kg/s]	1.43	1.52	1.46
Core inlet temperature [K]	744	746	745
Core outlet temperature [K]	812	809	811
Core pressure drop [Pa]	8462	8441	8454

The evolution of the core mass flow rate, power in the core and temperature rise in the core, for the SAM standalone, SAM-SCM coupled and SAM-SCM coupled with blocked core models, is shown in Figure 5. As expected the blocked core model predicts lower flow rate and higher temperature rise in the core than the unblocked case. It should be noted that these values are average values over the whole core flow area. If, we want to have a better understanding of the effect of the core blockage, we need to use the SCM results that offer a subchannel discretization. For this reason we plot the temperature field in an axial slice of the core flow field seen in Figure 6. We notice a considerable rise in the core coolant temperature after the blockage which is consistent with previous blockage studies [4]. The highest subchannel temperature in the unblocked case is 815 K. and in the blocked case it is 830 K. This local

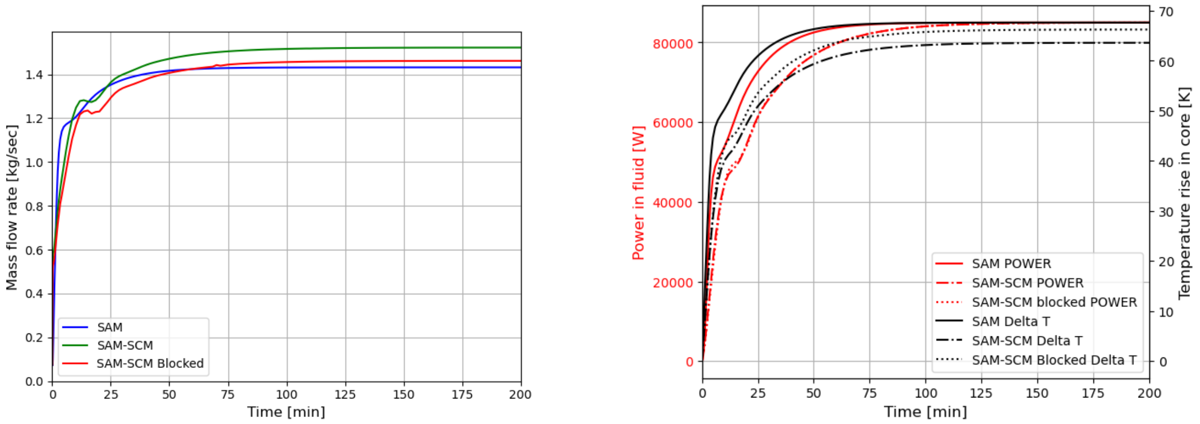


(a) Temperature distribution for the coupled model.

(b) Temperature distribution at the core outlet.

Figure 4. Coolant temperature distribution at steady state for the unblocked core simulations.

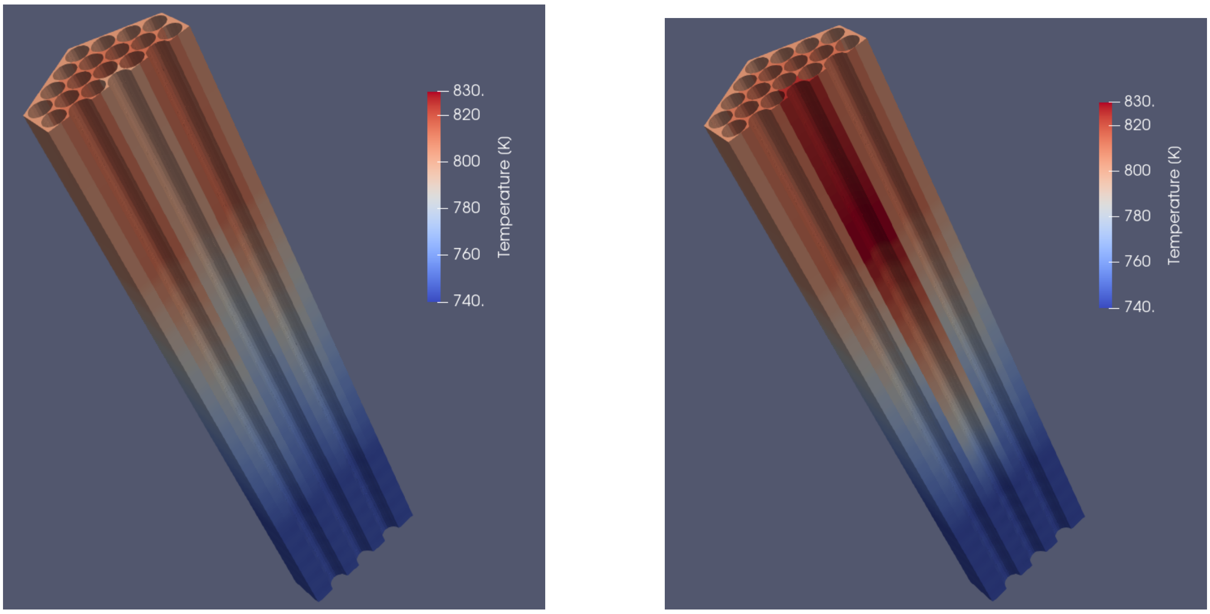
temperature rise would not be noticeable judging by the SAM results alone. It takes a higher fidelity code such as SCM to notice these types of fluctuations inside the core region.



(a) Core mass flow rate

(b) Power to the fluid and temperature rise evolution

Figure 5. Core mass flow rate, power and temperature during the startup transient.



(a) Unblocked core. **(b)** Blocked core.

Figure 6. Temperature field in the core.

4. CONCLUSIONS

A multiscale thermal hydraulics model of the MARVEL PCS was developed using SCM for the core and SAM for the loop. SAM and SCM exhibit the synergy expected from the fact they are both MOOSE-based applications. The overlapping domain coupling was achieved without any additional coding. The fact that the subchannel simulation provides a more detailed distribution of the coolant temperature in the core will increase the accuracy in detecting potential hot spots within the core. This is particularly apparent in the case where SCM models a blockage or an obstruction inside the core. Directly after the blockage we notice a considerable rise in the core coolant temperature that would not be observable otherwise (standalone SAM). Future work will focus on integrating this coupled SAM-SCM approach with the MARVEL multiphysics model developed by the Micro-Reactor Applications Drivers area within the NEAMS program. This coupling methodology will also be applied to model the Primary Cooling Apparatus Test so as to validate this approach.

ACKNOWLEDGMENTS

This work was funded by the Office of Nuclear Energy of the U.S. Department of Energy, through the Nuclear Energy Advanced Modeling and Simulation (NEAMS) program, under contract no. DE-NE0008983. MOOSE Subchannel development is being carried out under the auspices of Idaho National Laboratory, a contractor of the U.S. Government, under contract no. DEAC07-05ID14517. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allows others to do so, for U.S. Government purposes.

REFERENCES

1. Giudicelli, Guillaume and Lindsay, Alexander and Harbour, Logan and Icenhour, Casey and Li, Mengnan and Hansel, Joshua E and German, Peter and Behne, Patrick and

Marin, Oana and Stogner, Roy H and others, “3.0-MOOSE: Enabling massively parallel multiphysics simulations,” *SoftwareX*, **26**, pp. 101690 (2024).

2. R. Martineau and D. Andrs and R. Carlsen and D. Gaston and J. Hansel and F. Kong and A. Lindsay and C. Permann and A. Slaughter and E. Merzari and Rui Hu and A. Novak and R. Slaybaugh), “Multiphysics for nuclear energy applications using a cohesive computational framework,” *Nuclear Engineering and Design*, **367** (0029-5493), pp. 110751 (2020).
3. Kyriakopoulos Vasileios and Tano Mauricio and Ragusa Jean, “Development of a Single-Phase, Transient, Subchannel Code, within the MOOSE Multi-Physics Computational Framework,” *Energies*, **15** (11), pp. 3948 (2022).
4. Kyriakopoulos Vasileios and Tano Mauricio and Karahan Aydin, “Demonstration of Pronghorn’s Subchannel Code Modeling of Liquid-Metal Reactors and Validation in Normal Operation Conditions and Blockage Scenarios,” *Energies*, **16** (6), pp. 2592 (2023).
5. Tano Mauricio and Kyriakopoulos Vasileios and McCay James and Arment Tyrell, “Validation of Pronghorn’s subchannel code using EBR-II shutdown heat removal tests: SHRT-17 and SHRT-45R,” *Nuclear Engineering and Design*, **416**, pp. 112783 (2024).
6. Hu Rui and Zou Ling and O’Grady Daniel and Mui Travis and Ooi Zhiee Jhia and Hu Guojun and Cervi Eric and Yang Gang and Andrs David and Lindsay Alex and others, “SAM: A Modern System Code for Advanced Non-LWR Safety Analysis,” *Nuclear Technology*, (0029-5450), doi:10.1080/00295450.2024.2409601 (2024).
7. Stefano Terlizzi and Lise Charlot, “Towards a NEAMS-based high-fidelity model of the MARVEL reactor,” *Idaho National Laboratory*, (INL/RPT-24-80887), (2024).