ANL/NSE-23/51

Development and Porting of Nuclear Reactor Computational Models for the NRIC Virtual Test Bed in FY23

Nuclear Science and Engineering Division

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prepared by
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Abstract

The U.S. DOE's National Reactor Innovation Center (NRIC) hosts an open-source website and associated GitHub repository called the Virtual Test Bed (VTB) on which computational models for advanced reactors are documented and shared with the reactor community. In FY23 under the NRIC program, computational models for nuclear reactor analysis were developed and contributed to the VTB GitHub repository during FY23 by contributors at Argonne National Laboratory. Other models developed outside of NRIC were also ported to the VTB as part of this work, serving a broader mission to make computational reactor analysis models more widely available to the reactor community.

The model development activities focused on demonstration of gas-cooled microreactor models including computational fluid dynamics simulations of flow through an industry-inspired air jacket design, and simulation of multiphysics transients for a gas-cooled microreactor assembly. Additionally, development of a molten salt reactor (led at Idaho National Laboratory) was supported through Argonne's expertise in multigroup cross sections generation. Models for these two reactor types were targeted due to their relevancy to NRIC's Demonstration of Microreactor Experiments (DOME) and Laboratory for Operation and Testing in the U.S. (LOTUS) physical test beds, which are slated to host microreactor and molten salt reactor experiments.

The model porting activities consisted of developing detailed documentation for several physics models which originate from the Nuclear Energy Advanced Modeling and Simulation (NEAMS) program. We include only contributions from Argonne National Laboratory in this report.

Contents

1 Introduction

The U.S. Department of Energy National Reactor Innovation Center (NRIC) hosts the Virtual Test Bed (VTB) [1] website and associated GitHub repository, on which computational models for advanced reactors are documented and openly shared with the reactor community in order to increase accessibility of advanced modeling and simulation tools and promote best practices.

In FY23, Argonne National Laboratory (ANL) contributed several computational models to the VTB by developing original models and by porting models originally developed under the Nuclear Energy Advanced Modeling and Simulation (NEAMS) program [2]. The models leverage NEAMS physics applications based on the Multiphysics Object Oriented Simulation Environment (MOOSE) [3] as well as a small number of applications not based on the framework.

Model development activities focused on gas-cooled microreactor models including computational fluid dynamics simulations of flow through an industry-inspired air jacket design, and simulation of multiphysics transients for a gas-cooled microreactor assembly. Additionally, ANL supported the development of a molten chloride salt reactor model along with Idaho National Laboratory (INL) by developing multigroup cross section generation procedures and generating the multigroup cross section data. Models for these two reactor types were targeted due to their relevancy to NRIC's Demonstration of Microreactor Experiments (DOME) and Laboratory for Operation and Testing in the U.S. (LOTUS) physical test beds, which are slated to host microreactor and molten salt reactor experiments.

Argonne also ported several models which were developed in NEAMS. These porting activities consisted of developing (1) development of the documentation describing the model and results, (2) clearance by relevant parties (program, laboratory, industry if applicable) for public release, (3) contribution of the model via initiation of a GitHub pull request which makes the model public on the development side of the repository, (4) peer review of the model and implementation of automated testing, and (5) acceptance and merging of the model to the main VTB website and repository.

2 Model Development Activities

2.1 Gas-cooled microreactor control rod ejection transient multiphysics model

POC: Ahmed Abdelhameed (ANL)

Code(s): Griffin, Bison, SAM

NRIC VTB supported the development of a model for a gas-cooled microreactor (GC-MR) assembly undergoing inadvertent control rod ejection resulting in reactivity insertion. The analysis utilizes a GC-MR assembly design (see Figure 1) originally developed at Argonne under NEAMS and previously demonstrated with a flow blockage transient in FY22 [4]. The assembly contains graphite structure, TRISO fuel blocks with 19.95 at% LEU fuel, YH2 moderator pins with an envelope of FeCrAl, along with burnable poison blocks, a central shutdown rod, and upper/lower BeO reflector regions. As depicted in Figure 1, the GC-MR employs helium coolant channels, burnable poison blocks, and a centrally positioned control rod. Table 1 describes the primary technical specifications of the microreactor assembly.

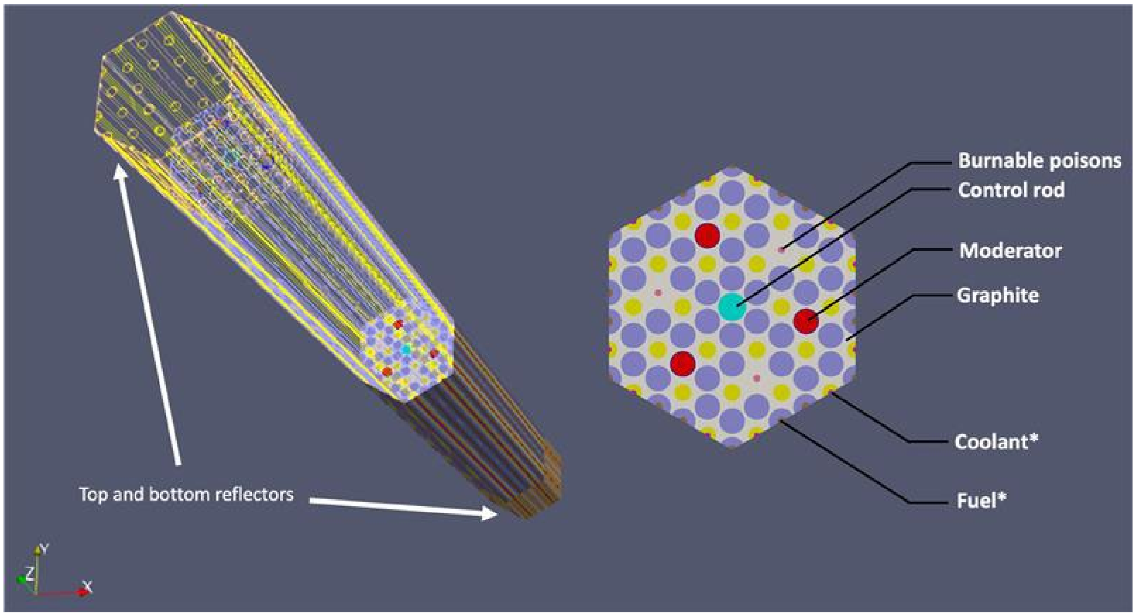

Figure 1. GC-MR assembly model (mesh contains both prismatic and hexahedral elements)

Table 1. Key technical parameters of the GC-MR assembly

Parameter (unit)	Value
Power	
Reactor Power (kWt)	225
Materials	
Fuel	TRISO, 40% packing fraction
Coolant	He
Moderator	YH_2

Burnable poison absorber	B_4C particles, 25% packing fraction
Control rod	B_4C
Reflector	BeO
Coolant	
Inlet/outlet temperature (K)	873.15/ 1133.65
Pressure (MPa)	7
Velocity (m/s)	15
Dimensions	
Pin pitch (cm)	2.00
Total height (cm)	200
Active height (cm)	160
TRISO fuel compact radius (cm)	0.9
Burnable poison radius (cm)	0.25
Coolant hole radius (cm)	0.6
Control hole radius (cm)	0.99

In the expanded VTB-developed model for the modeling of inadvertent control rod ejection, NEAMS codes Griffin [5], SAM [6], and BISON [7] were employed to conduct time-dependent multi-physics simulations of the GC-MR model undergoing accidental scenarios. Griffin, a neutronics MOOSE-based application, offers a high degree of flexibility in representing intricate reactor configurations, allowing users to choose the desired level of detail. BISON, another MOOSE-based code, specializes in fuel performance and accommodates various fuel forms. In this study, BISON was utilized for heat-conduction computations. Additionally, SAM, a contemporary system analysis tool, is used to model coolant flow and conduction through the solid structures through a coupled SAM 1D Fluid – 3D solid simulation. As depicted in Figure 2, the MOOSE MultiApp hierarchy employed in this context designates Griffin as the parent application. Data seamlessly traverses between Griffin and its child application (BISON) and subsequently to its grandchild application (SAM), facilitating a closely interconnected simulation process.

A high-fidelity neutronic solver was used with Griffin which addressed the neutron transport equation using the discrete ordinates method (SN) for angular discretization, while spatial discretization was executed using the discontinuous finite element method (DFEM) and 11 energy-groups structure. Furthermore, on-the-fly coarse mesh generation was harnessed for acceleration, employing the coarse mesh finite element method (CMFD). The Griffin results were verified through a comparison with Monte Carlo Serpent-2 results [8]. Homogenized multi-group cross-sections were derived using Serpent-2, employing the ENDF/B-VII.1 data library, and then transformed into XML-format cross-section files. Griffin parsed the XML-format cross-section file, in conjunction with a mesh file detailing a 3D mesh mirroring the geometry employed in the cross-section generation process. The 3D mesh was generated using the intrinsic meshing tools within the MOOSE Reactor module [9]. To ensure the consistency between the geometric representations within the mesh file and the cross-section generation code, a direct comparison of the volumes of distinct blocks/universes was conducted.

Utilizing the multiphysics coupling approach illustrated in Figure 2, the power density distribution is computed by Griffin DFEM-SN simulation at each time-step of the transient. This data is then conveyed to BISON, enabling the performance of heat conduction calculations aimed at estimating fuel temperature. SAM is employed to model the coolant channels, to estimate the coolant temperature distributions within all the channels. To achieve a closely integrated simulation, the MOOSE Picard fixed-point iteration technique was adopted. This involves the iterative exchange of information among the three MOOSE-based applications, continuing until convergence of the power source distribution is achieved.

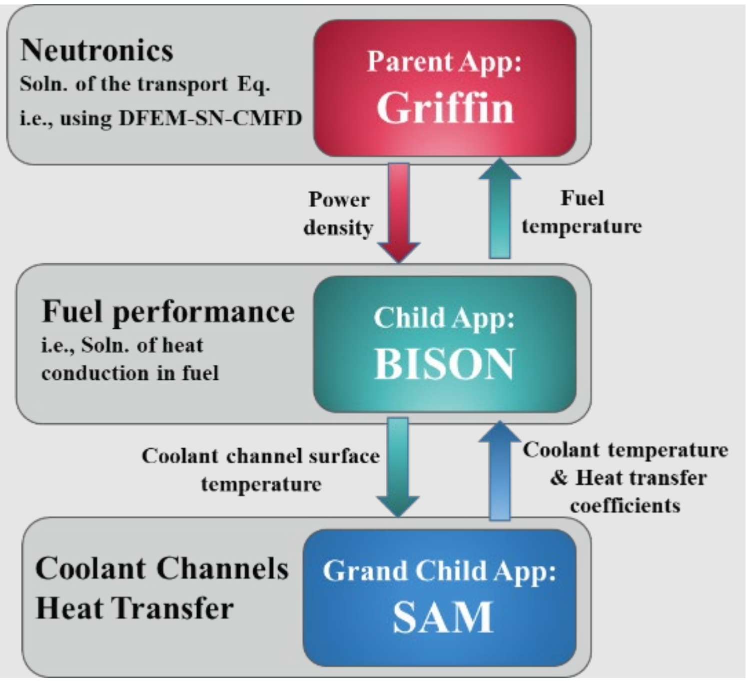

Figure 2. MOOSE MultiApp hierarchy of the gas-cooled microreactor assembly simulation

The NRIC VTB expands the previous work performed under NEAMS to examine dynamic multiphysics simulation of Reactivity Insertion Accident (RIA) within the GC-MR assembly. The RIA scenario entails a rapid and partial withdrawal of the control rod within 0.5s, causing a positive reactivity insertion of 1.03 dollars during the hot full power condition. The integrated power undergoes a swift escalation, as shown in Figure 3, culminating in a prominent peak, while the fuel temperature gradually rises over time. Around 0.65 seconds into the simulation, the system's negative thermal reactivity feedback takes precedence, primarily driven by the Doppler reactivity feedback, subsequently initiating a power reduction.

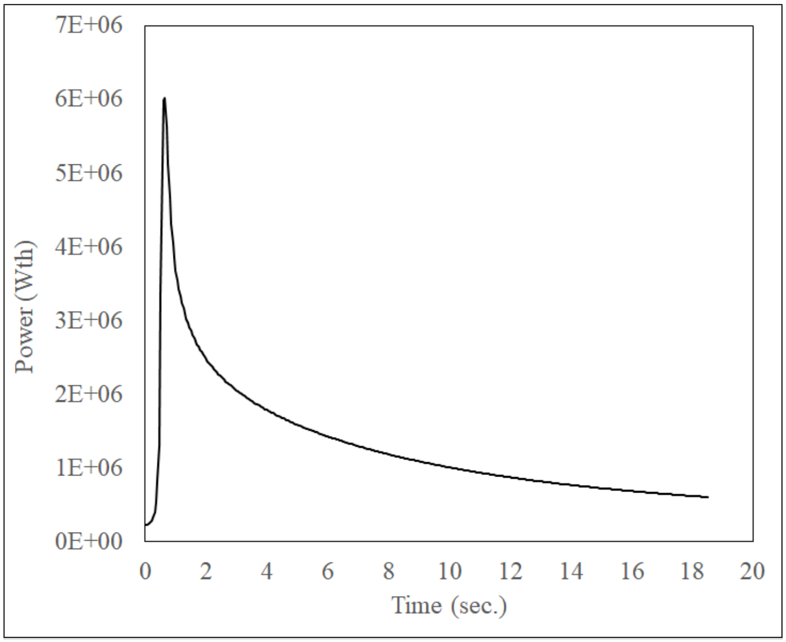

Figure 3. Variation of the assembly power during the RIA

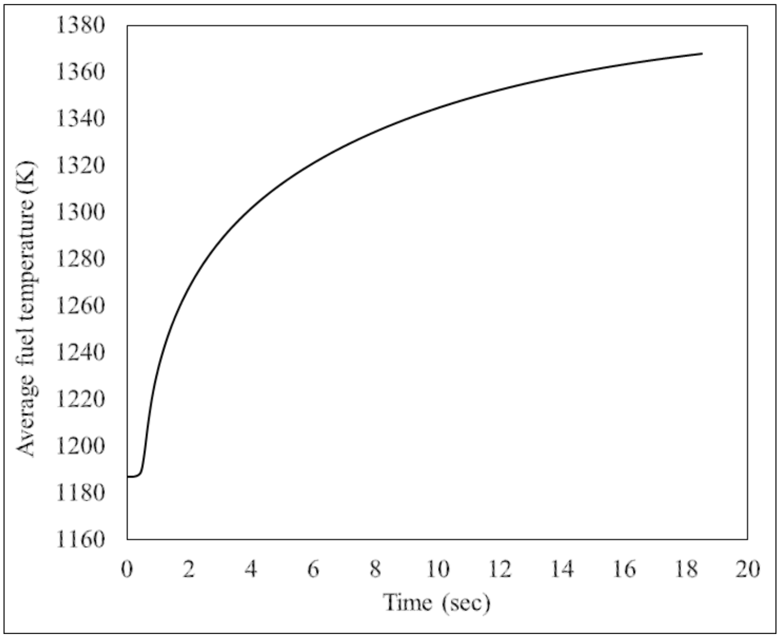

Figure 4. Variation of the average fuel temperature during the RIA

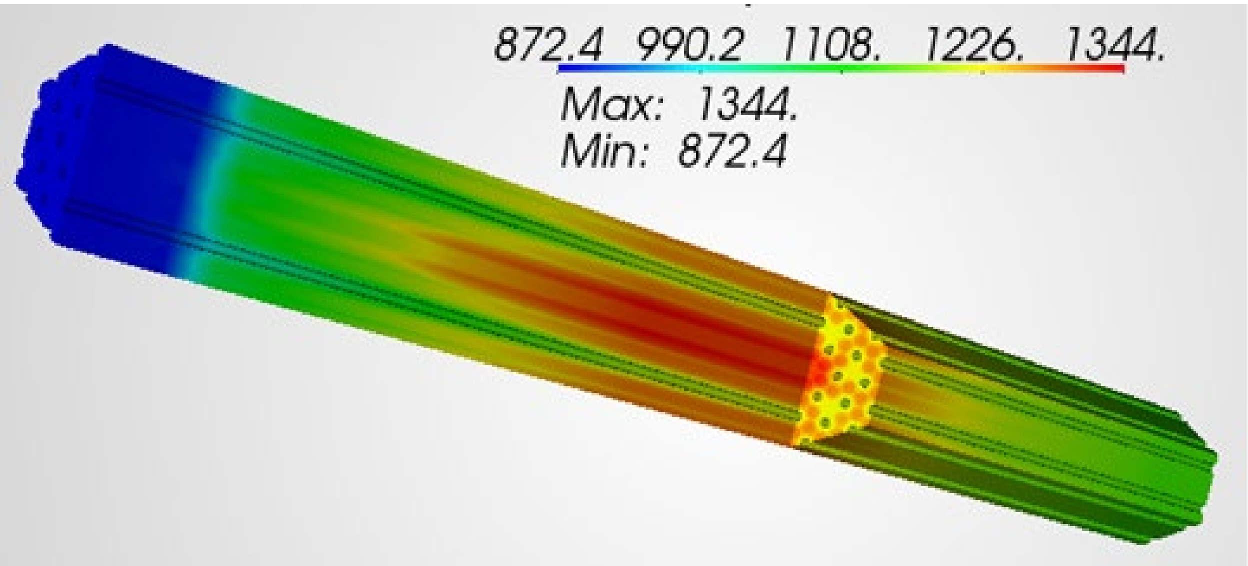

Figure 5. Assembly temperature distribution (K) during RIA at t=0.65 sec

Even though the reactor power diminishes quickly after about 0.65 seconds, the fuel temperature keeps rising because the power level remains above the nominal threshold. Nevertheless, the fuel temperature increase slows over time because the negative Doppler reactivity feedback becomes more pronounced as the fuel temperature rises. As a result, the gas-cooled system's inherent safety is demonstrated through the overall negative reactivity feedback observed in the RIA simulation. In this situation, the negative reactivity feedback causes a rapid reduction in reactor power, effectively limiting the extent to which the fuel temperature rises due to the RIA event. The temperature distribution in three dimensions at the 0.65-second mark is presented in Figure 5, displaying a highest local temperature of 1344 K at this time snapshot.

Furthermore, in the GC-MR system, the net thermal reactivity feedback is consistently negative. Consequently, whenever temperatures surpass their designated nominal values, this negative net thermal reactivity feedback comes into play. Consequently, this feedback mechanism induces a decline in power output. Even if the power output declines but remains above the nominal power value, the outcome is a slower pace of temperature increase. However, as long as temperatures persist above their nominal values, the negative net thermal reactivity persists, ensuring a continuous reduction in power output. This decline will continue until temperatures align with their nominal values. This holds true unless there is a substantial impact from Xe, altering the asymptotic values of both power and temperatures. Nonetheless, it is plausible that another steady-state will be reached due to the persistent negative feedback.

2.2 Gas-cooled microreactor air jacket model

POC: Anshuman Chaube (ANL)

Code(s): Nek5000

NRIC VTB supported the development of a gas-cooled microreactor air jacket cooling system model that passively removes decay heat (Figure 6). The complex geometry and natural circulation-driven flow may be challenging to capture with systems-level codes without calibration from experiments or higher-fidelity thermal-fluid modeling. However, Computational Fluid Dynamics (CFD) is particularly well-suited to the task of modeling microreactor air jackets due to its ability to capture the effects of the geometry on the flow with resolved boundary layers. Nek5000 [10] was used to simulate flow through an air-jacket geometry and predict heat transfer and flow characteristics. From these CFD simulations, it is possible to evaluate available models for bulk heat and momentum transfer that can be used in systems-level codes, and to develop modifications to those models specific to the proposed design. Using the pressure balance for natural circulation, we derive the correct mass flow rate for a given geometry, along with demonstrating the application of CFD in deriving the friction factor, Nusselt number, heat flux, bulk temperature, and mean outlet temperature for a prototypical concept. This also adds a natural circulation model to the VTB repository, which until now has had limited coverage on the VTB website.

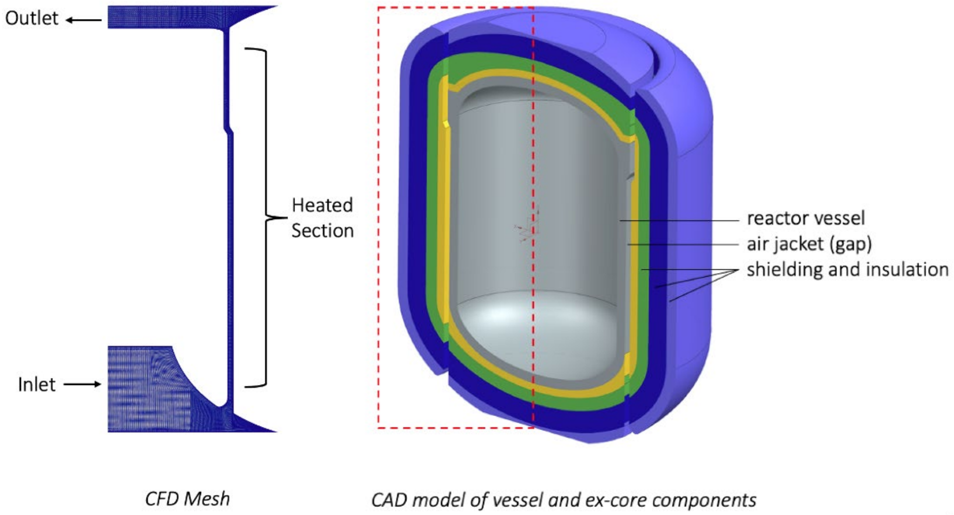

Figure 6. Air jacket (right) and mesh of a 2D slice of the air jacket (left)

The design is inspired by a commercial vendor's concept (but contains no proprietary information), and the problem is representative of a reactor in early stages of design. While it is customary to simulate natural circulation in a closed loop, this geometry represents a state of the design when such information is not available. The inlet temperature is known, and the maximum operational temperature of the hot wall is given. It is desired to derive the mass flow rate, friction factors, and Nusselt numbers at this limiting operating condition. We use pressure balance for natural convection and an initial guess from canonical correlations to iteratively derive the mass flow rate (Figure 7), and other subsequent quantities of interest. This model illustrates how it is possible to employ CFD to fill in gaps related to a novel design's operational parameters and generate data that can subsequently be used in systems analysis or reduced order modeling.

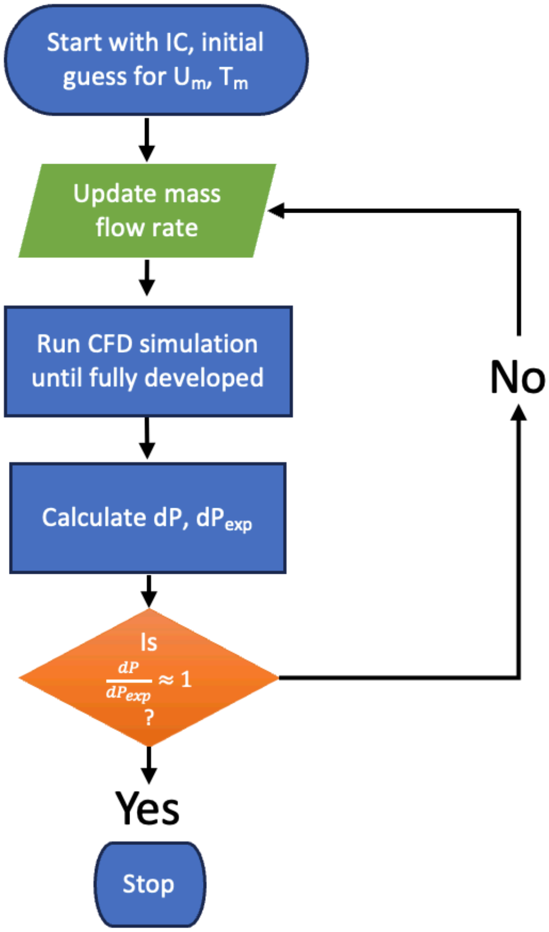

Figure 7. Iterative procedure used to derive mass flow rate for natural convection problems

The model uses wall-resolved Reynolds-Averaged Navier-Stokes (RANS) to keep the model's computational costs accessible to a wide range of users. Due to Reynolds-averaging, the problem essentially has a 2D character due to averaging of the solution in the azimuthal direction. We have run the problem in the axisymmetric mode to capture the cylindrical nature of the air jacket with respect to the 2D slice we have meshed. The effect of buoyancy is captured through the Boussinesq approximation and ideal gas behavior.

The results at the mass flow rate computed through natural circulation-based pressure balance equations are shown in Figure 8. The systems-level quantities derived from this simulation are summarized in Table 2. There are some differences between the CFD-derived quantities and the correlation-based estimates (as to be expected), especially in the Reynolds number (mass flow rate) and Darcy friction factor. We were also able to derive quantities which are not straightforward to estimate using correlations or systems-level codes alone, such as the average hot wall heat flux at the limiting condition, the heat removal, bulk temperature, and average outlet temperature. This highlights the utility of CFD as a vital tool in reactor design.

Table 2. Summary of air jacket simulation results

Parameter	**Correlation-based estimate**	**CFD-based result**
Reynolds number	3153	3580
Friction factor	0.0409	0.028403
Nusselt number	13.98	13.53
Bulk temperature	-	352.46 K
Outlet Temperature	-	383.39 K
Heat flux	-	3.01×10^3 W m^{-2}
Heat removal	-	2.072×10^4 W

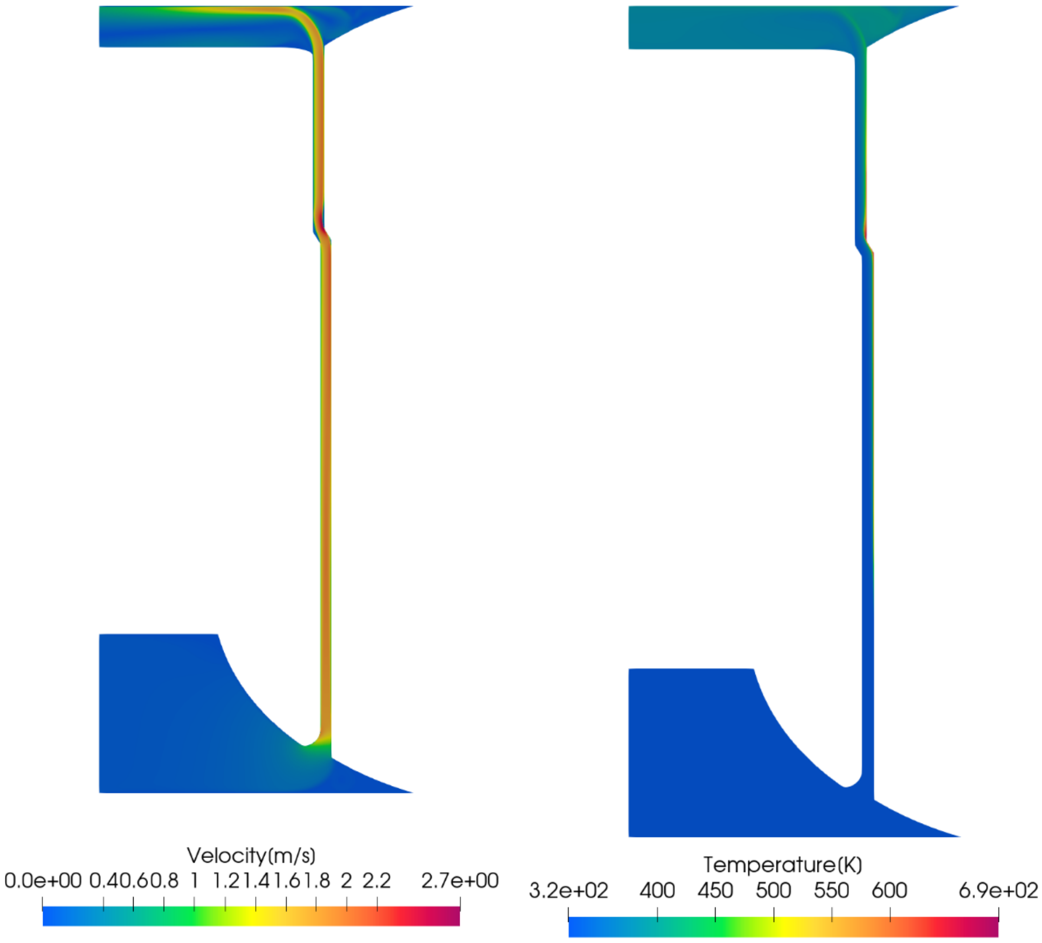

Figure 8. Air jacket fluid velocity in m/s (left) and temperature (K)

2.3 Multigroup cross section generation for a molten chloride salt fast reactor multiphysics model

POC: Changho Lee (ANL)

Code(s): MC^2-3

The Molten Chloride Reactor Experiment (MCRE) being developed by TerraPower is a fast spectrum molten salt system that will be sited at INL in the Laboratory for Operation and Testing in the U.S. (LOTUS) Test Bed. The primary objective of MCRE is to measure key reactor physics phenomena and test hypotheses about molten chloride salt fast reactor (MCFR) behavior to reduce uncertainty and provide foundational knowledge to support the development of the MCFR Demonstration Reactor.

A molten salt reactor design was explored in this study to support future LOTUS MSR concepts. The LOTUS MSR reactor studied here is based on technical specifications in [11] and illustrated in Figure 9. The geometry of the model involves a primary open core cavity, a pump, and interconnected piping facilitating the flow of the liquid nuclear fuel between the reactor and the pump. The main core cavity is encased by a reflector. The fuel salt composition employed in this reactor design is based on the eutectic point of the UCl3-NaCl system. A higher fuel enrichment (93.2 wt% U^{235}) is used to ensure a substantial reactivity margin above criticality during operation. A brief specification of the LOTUS MSR model is listed in Table 3.

A comprehensive three-dimensional (3D) multiphysics model was established by INL [12] in a companion Virtual Test Bed activity, utilizing three physics tools: Griffin for neutronics simulation, Pronghorn for thermal-hydraulics simulation, and BISON for thermo-mechanics simulation. The multiphysics simulation of the LOTUS MSR was conducted for both steady-state and transient reactor operations. The primary objective of the Argonne activity was to generate multigroup cross sections and provide them to INL for use in multiphysics simulations.

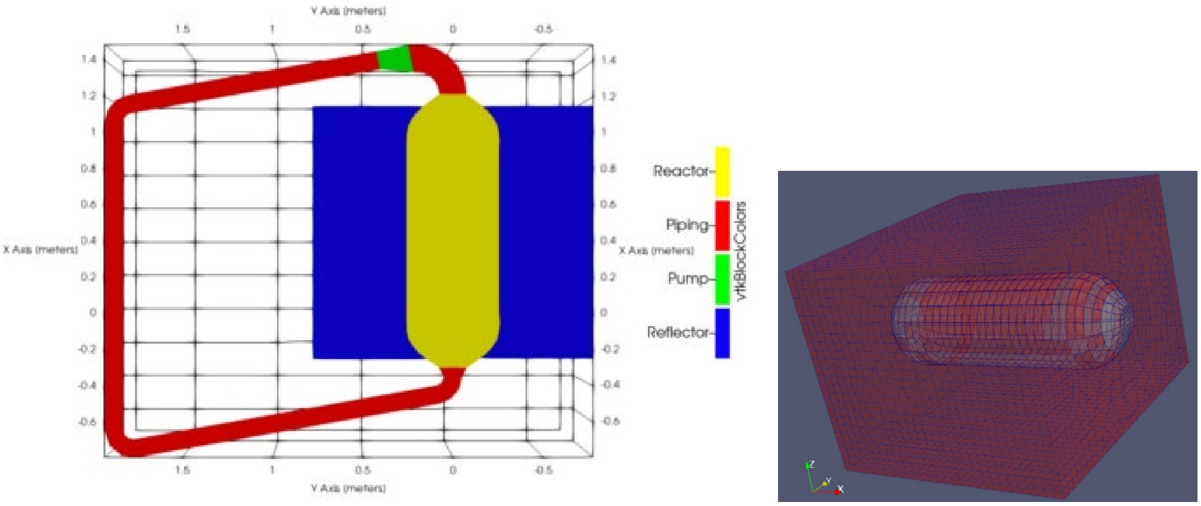

Figure 9. Primary loop model (left) and core model/mesh (right) of the LOTUS MSR core

Table 3. Key specifications of the LOTUS MSR model

Parameter	Unit	Value
Core Power	MWt	10
Operation Temperature	K	900
Fuel Salt Composition	mol%	UCI3(33.3%) – NaCl (66.7%)
Fuel Enrichment (U-235)	wt%	93.2

Figure 10 shows the neutron spectra in both the fuel and reflector regions of the LOTUS MSR model. In the fuel region, the spectrum exhibits the characteristics of a typical fast spectrum reactor, while in the reflector region neutrons are significantly thermalized. While MC^2-3 [13] can be applied to the fuel region, it is important to note that thermal cross sections should be updated with the thermal library for the reflector region and the fuel region adjacent to reflector in order to accurately simulate the neutron transport behavior of the core.

For cross-section generation using MC^2-3, typically a two-step process is conducted. In the first step, ultrafine group cross sections are generated using MC^2-3, which are subsequently used for a 2D (R-Z) whole-core calculation to obtain region-wise ultrafine group spectrum solution. In the second step, the ultrafine group cross sections from MC^2-3 are condensed to broad groups, typically 9 or 33 groups, using the region-wise ultrafine group spectrum solution. In this study, we generated 9-group cross sections to achieve reasonable performance of Griffin with the DFEM-SN solver [5] in multiphysics simulation with other physics tools.

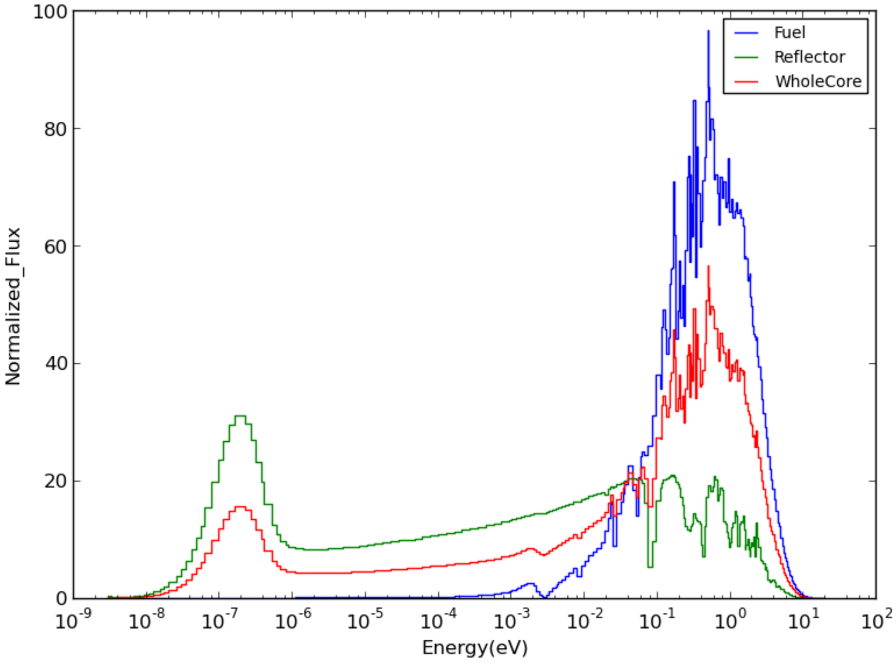

Figure 10. Neutron spectra of the LOTUS MSR model

First, an R-Z core configuration equivalent to the actual core was determined, which was used for the two-step calculation with MC^2-3 (ultrafine and broad group cross section generation) and TWODANT (R-Z core calculation with ultra group cross sections). To ensure the usefulness of the cross section data for multiphysics calculations, cross sections were tabulated to accommodate varying fuel and reflector temperatures, ranging from 700 to 1100 K. Macroscopic cross sections were generated using ENDF/B-VII.0 data. Moreover, the cross-section file was supplemented with delayed neutron data to enable transient calculations as well.

For the verification test, fuel and reflector temperatures of 900 K were applied for both Serpent2 and MC^2-3/Griffin calculations. In Griffin, the DFEM-SN transport solver was used with

48 angles and P_2 anisotropic scattering. The results of the eigenvalue solutions exhibited good agreement within 174 pcm Δk between the two codes, as listed in Table 4.

In the future, for more accurate simulation as previously mentioned, thermal cross sections will be assessed and updated for the fuel region adjacent to the reflector as well as the reflector region. Those generated cross sections are to be used for rigorous testing with multiphysics simulations of Griffin, Pronghorn, and BISON under steady-state and transient conditions.

Table 4. Eigenvalue comparison between Serpent2 and Griffin for the LOTUS MSR model

Code	Serpent2	MC^2-3 / Griffin	Δk, pcm
Eigenvalue	1.14564 ±0.00011	1.14738	174

3 Model Porting Activities

The NEAMS program develops computational models for various reactor types to perform validation exercises, demonstrate NEAMS software and challenge problems, and assess current software gaps. Several NEAMS-developed advanced reactor models (input files, model description, and discussion of results) were contributed to the NRIC VTB in FY23. The open sharing of these models benefits the reactor community by providing "best practice" examples using NEAMS tools for advanced reactor physics problems. This report summarizes and provides links to these new models. Details of individual work done by the modeling teams is published in separate reports.

Model contributions which are available on both the VTB documentation site and the Github repository are reported as "*Available*" with an included hyperlink to the model documentation. Model contributions which are pending review are categorized as "*In Review*" with an included hyperlink to the associated Github pull request (PR). These models will be fully merged to the main repository following peer review and testing setup.

Table 5 summarizes models contributed to the VTB by Argonne during FY23. The models are categorized by reactor type: liquid metal-cooled fast reactor (LMFR), molten salt reactor (MSR), fluoride salt-cooled high temperature reactor (FHR), high temperature gas-cooled reactor (HTGR), and microreactor (MR). As evident in the chart, the new examples demonstrate a variety of NEAMS applications and physics phenomena: MOOSE (open source physics modules and framework), Griffin [5] (reactor physics), MC^2-3 (multigroup cross section generation for reactor physics tools) [13], SAM [6] (systems scale fluids), Nek5000 [10] (computational fluid dynamics), Sockeye [14] (heat pipe analysis), Bison [7] (fuel performance and heat conduction), and Cardinal [15] (multiphysics application coupling the NekRS CFD solver [16] to MOOSE).

Table 5. Summary of models from NEAMS ported to the VTB in FY23

Reactor Type	Description	Contact	Status
LMFR	**MOOSE** thermo-mechanical model of IAEA VP1 predicting displacement in an isolated hexagonal duct due to linear thermal gradient.	N. Wozniak (ANL)	Available
LMFR	**MOOSE** thermo-mechanical model of IAEA VP3A predicting displacement and contact in a symmetric core sector of hexagonal assemblies due to a linear thermal gradient.	N. Wozniak (ANL)	Available

LMFR	Lead-cooled fast reactor assembly with pin heterogeneity neutronics model including cross section processing procedure with **MC^2-3** and **Griffin**	H. Park (ANL)	Available
MSR	MSFR **Nek5000** CFD models	J. Fang (ANL)	Available
MSR	MSFR **SAM** system model transient updates	J. Fang (ANL)	Available
FHR	Conjugate heat transfer simulation of a helium-cooled 67-pebble bed core using **Cardinal (NekRS)** and **MOOSE**	D. Shaver (ANL)	Available
HTGR	System-level **SAM** model for the steady state simulation of a generic pebble bed HTGR followed by transient event	Z. Ooi (ANL)	Available
HTGR	**SAM** model of the High Temperature Test Facility (HTTF) for full power (2.2 MW) steady-state operation	T. Hua (ANL)	In Review
HTGR	CFD model of High Temperature Test Facility (HTTF) lower plenum flow mixing problem using **Nek5000** and **NekRS.**	Jun Fang (ANL)	Available (Nek5000) In Review (NekRS)
MR	Updated existing heat pipe-cooled 1/6th core microreactor model to include **Griffin** (new), **Bison and Sockeye**. Extended model to accidental heat pipe cascading failure with overpower. Load following transient.	N. Stauff (ANL)	Available
MR	Gas-cooled microreactor assembly flow blockage and reactivity insertion transients simulation with **Griffin, Bison and SAM**	N. Stauff (ANL)	Available

The following sections briefly describe the contributed models. References are given to specify the origin of the benchmark (if applicable). All other references related to setting up the model, performing the analysis, and discussion results are located at the Virtual Test Bed site on each model's documentation page. The development of these models was fully or at least partially funded by the NEAMS program and is the result of multiple contributors' efforts, whereas NRIC supported the development of documentation and the sharing of this model with the reactor community via the VTB. Each model has a designated point of contact.

3.1 LMFR: Thermo-mechanical bowing in IAEA VP1

POC: Nick Wozniak (ANL)

Code(s): MOOSE (Tensor Mechanics Module)

Description: This model examines the restrained thermal bowed deformation of a 3D hexagonal assembly (duct) which is subject to thermal gradients along the axial and radial directions bowing into a sector of a reactor core. The ducts are mechanically fixed at the bottom. The model specification is based on Verification Problem 3A (VP3A) in the series of benchmark problems published [17] to support the verification and validation of Liquid Metal Fast Breeder Reactor (LMFBR) analysis codes organized by The International Atomic Energy Agency (IAEA)'s International Working Group on Fast Reactors (IWGFR). This model employs the MOOSE Tensor Mechanics Module to model the thermo-mechanical deformation response due to the thermal gradients in the duct, and the Contact Module to model the inter-assembly contact at specific locations along the ducts. This type of deformation is present in liquid-metal cooled fast reactors and serves as an important reactivity feedback effect. The results obtained from this fully open source MOOSE-based model demonstrate proper set up of a single assembly thermal duct bowing problem which can be used to build larger and more complex models.

3.2 LMFR: Thermo-mechanical bowing in IAEA VP3A

POC: Nick Wozniak (ANL)

Code(s): MOOSE (Tensor Mechanics and Contact Modules)

Description: IAEA Verification Problem 3A (VP3A) builds on VP1 (described in the previous section) by examining a symmetric sector of ducts in which one assembly bows into the others along the vertex direction due to the thermal gradient from described in VP1. This problem introduces contact between assemblies at the above core load pad. No restraint ring or top load pad structures are present. The MOOSE-based model of IAEA VP3A is fully open source as it requires only the open source MOOSE modules (Tensor Mechanics, Contact) to predict the resulting duct displacement.

3.3 LMFR: Lead-cooled fast reactor assembly neutronics model

POC: Hansol Park (ANL)

Code(s): MC^2-3, Griffin

Description: This model of a lead-cooled fast reactor assembly with MOX fuel is based on an early prototype provided by Westinghouse Electric Company, LLC [18]. The model demonstrates the setup of a pin-by-pin heterogeneous assembly neutron transport simulation using the MC^2-3 fast reactor multigroup generation code with a two-step approach to account for heterogeneity effects as well as pin-by-pin representation in Griffin. This model will later be updated to include coupling with heat conduction and computational fluid dynamics models to calculate the impact of uncertainties in manufacturing tolerance or physical parameters on local temperature distributions. For now, the neutronics model is available and fully described. This is the only current example describing multigroup cross section generation techniques for heterogeneous fast spectrum systems.

3.4 MSR: MSFR CFD models

POC: Jun Fang (ANL)

Code(s): Nek5000

Description: These models contain CFD examples for modeling the coolant flow in the Molten Salt Fast Reactor (MSFR) [19,20] core cavity. The models range from relatively low-cost 2-D Reynolds-Averaged Navier Stokes (RANS) simulations to more accurate 3-D Large Eddy Simulations (LES) using Nek5000. The various CFD modeling approaches and case studies are used to seek an in-depth understanding of how the internal velocity distribution can be influenced by the MSFR core cavity shape, the Reynolds number, turbulence modeling options and the inlet boundary conditions. The related CFD examples can be readily customized to simulate other advanced reactor concepts that share similar geometric features or flow conditions.

3.5 MSR: MSFR systems model transient updates

POC: Jun Fang (ANL)

Code(s): SAM

Description: This model builds upon the initial SAM steady state model for the MSFR design developed under the Euratom EVOL project [19,20]. The reference MSFR is a 3000 MW fast-spectrum reactor with three different circuits: the fuel circuit, the intermediate circuit, and the power conversion circuit. Based upon the design specifications of EVOL MSFR, representative 1-D system models were created using the NEAMS system modeling code, SAM. The system modeling covers both the fuel and intermediate circuit, whereas only the heat exchanger is modeled for the energy conversion circuit. The 16 ex-core loops are lumped together, which means only one loop is considered for both fuel and intermediate circuit. In addition to the steady-state modeling, transient scenarios that involve pump head changes were also simulated to study the MSFR system responses under possible accident conditions including the influence of possible head changes of the primary pump.

3.6 FHR: Conjugate heat transfer simulation of a helium-cooled 67-pebble core

POC: Dillon Shaver (ANL)

Code(s): Cardinal (NekRS), MOOSE

Description: This model simulates a simple conjugate heat transfer (CHT) model of a helium (Pr=0.71) cooled 67-pebble bed. This case was developed from an example case provided with NekRS and couples to MOOSE's Heat Conduction Module using Cardinal as a wrapper. More information about Cardinal can be found on github, or on the Cardinal website. In each time step MOOSE solves the energy equation in the solid subdomain and passes the solution to NekRS, which in-turn solves both the Navier-Stokes and energy equations in the fluid subdomain. NekRS then passes its temperature solve back to MOOSE in the next time step. This transfer of information occurs at the boundary between solid and fluid subdomains, which are the pebble surfaces in this case.

3.7 HTGR: Systems level model of generic pebble bed HTGR steady state and transient

POC: Zhiee Jhia Ooi (ANL)

Code(s): SAM

Description: This generic helium-cooled pebble-bed high temperature gas-cooled reactor model utilizes geometry and design information from [21]. The reactor has a capacity of 200 MWth during steady-state operation and contains 223,000 6-cm wide fuel pebbles. Steady-state and transient load-following simulations are performed to demonstrate the thermal-hydraulics (TH) and neutronics behaviors of the reactor using SAM. TH is modeled with SAM at the system-level where the fluid is modeled in 1-D and the solids are modeled in 2-D. The neutronics are modeled with SAM's PKE model where only the temperature reactivity feedbacks from the fuels, moderators, and reflectors are considered.

3.8 HTGR: Systems level model of the High Temperature Test Facility (HTTF) for full power steady state

POC: Thanh Hua (ANL)

Code(s): SAM

Description: The HTTF is an integral effects test facility which was operated at Oregon State University in 2019 to investigate thermal fluids behavior of interest to high-temperature gas-cooled nuclear reactors with prismatic fuel and reflector blocks. The vast amount of data obtained from the tests are available for benchmarking both system level and CFD codes. The SAM model for the HTTF is based on the so-called 2D ring model approach by which all structural components are modeled as concentric cylindrical rings. The steady-state model assumes full power (2.2 MW) operation although this operating condition was not carried out experimentally. The model is utilized in the OECD/NEA HTTF Benchmark for code-to-code comparison with other system level codes. This steady-state model is a prerequisite to two transients selected for the benchmark: Depressurized Conduction Cooldown (DCC) and Pressurized Conduction Cooldown (PCC). The SAM 2D ring model approach was submitted to the VTB and is in review here at time of publication.

3.9 HTGR: CFD model of High Temperature Test Facility (HTTF) lower plenum flow mixing problem

POC: Jun Fang (ANL)

Code(s): Nek5000 and NekRS

Description: The HTTF, a specialized test facility exploring thermal fluid behavior in high-temperature gas-cooled nuclear reactors (HTGR), yielded crucial data for benchmarking codes. With the need for accurate simulation in HTGR development, a significant knowledge gap was identified in understanding lower plenum flow distribution. This study employs advanced CFD modeling focusing on the HTTF's lower plenum, where heated coolant gas from the core region mixes and interacts. The coolant jets into the lower plenum have a non-uniform temperature and risk yielding high cycling thermal stresses, negative pressure gradients opposing the flow ingress, and hot streaking. These phenomena cannot be accurately captured by 1-D system codes. Utilizing high-fidelity turbulence modeling offered by NEAMS CFD codes Nek5000/NekRS, the simulation scrutinizes velocity and temperature patterns to enhance comprehension of thermal-fluid dynamics. These findings, pivotal for gas-cooled reactor research, will support code-to-code and code-to-data comparisons under the OECD/NEA international benchmark campaign, propelling the application of CFD in reactor innovation. The Nek5000 model is available here, and the NekRS model contribution is in review here.

3.10 MR: Heat pipe-cooled microreactor core multiphysics steady state and transient models including heat pipe failure and load-following

POC: Nicolas Stauff (ANL)

Code(s): Griffin, Bison, Sockeye

Description: This heat pipe microreactor model (HP-MR) is based on the microreactor design under analysis by the NEAMS Multiphysics Applications microreactor team at Argonne National Laboratory [22] to gather some of the most pressing modeling challenges faced by the microreactor industry: a) the use of heat pipe technologies to remove the thermal energy; b) the use of TRi-structural ISOtropic (TRISO) fuel to enable operations at very high temperatures; c) the use of rotating control drums in the radial reflectors. This model of a 1/6 full-core HP-MR concept demonstrates multiphysics transient simulations performed through MultiApp coupling of the Griffin DFEM-SN neutronic solver with CMFD acceleration, BISON for thermal physics, and Sockeye for heat transfer and operational limits within each heat-pipe. Two different scenarios are modelled including a load following transient and a scenario initiated by the forced failure of a single heat-pipe.

3.11 MR: Gas-cooled microreactor assembly flow blockage transient simulation

POC: Nicolas Stauff (ANL)

Code(s): Griffin, Bison, SAM

Description: The gas-cooled microreactor assembly model (GC-MR) is based on the microreactor design under analysis by the NEAMS Multiphysics Applications microreactor analysis team [4]. The horizontal GC-MR concept was designed at Argonne National Laboratory as a modeling exercise. It uses TRISO fuel in a graphite matrix, hydride metal blocks, a central shut-down rod, burnable poison blocks, and coolant channels. Pressurized helium at high temperature is employed as flowing coolant. This assembly model demonstrates multiphysics transient simulations performed through MultiApp coupling of the Griffin DFEM-SN neutronic solver (with CMFD acceleration), BISON for thermal physics, and SAM for heat transfer within all coolant channels. This example models 1) an accident scenario considering total blockage of one channel at the center of the assembly, and 2) an accident scenario considering postulated reactivity insertion from rapid partial withdrawal of the central control rod (this portion developed under NRIC funding as described in an early section of this document).

4 Summary

Three model development activities were completed as part of this activity: multiphysics reactivity insertion accident in a gas-cooled microreactor assembly, air jacket thermal fluid modeling in a gas-cooled microreactor and multigroup cross section generation for a molten chloride salt reactor. In addition, documentation and porting of 11 NEAMS-developed models was completed as part of this activity. The contributed models span all advanced (non-light water) reactor types including LMFR, MSR, FHR, HTGR, and MR. The contributed models demonstrate the use of a wide range of codes for the study of different phenomena. This document summarizes these recent model contributions and provides hyperlinks to models as applicable.

The open sharing of models with the reactor community accelerates users in the setup of new reactor models, promotes best practices for specific physics coupling scenarios, and cultivates opportunities for collaboration including code-to-code verification.

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