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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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The Virtual Test Bed (VTB) Repository: A Library of Multiphysics Reference Reactor Models Using NEAMS Tools

G. Giudicelli[1], C. Permann[1], D. Gaston[1], B. Feng[2], and A. Abou-Jaoude[1]

[1]Idaho National Laboratory
2525 Fremont Ave., Idaho Falls, ID 83415

[2]Argonne National Laboratory
9700 S. Cass Ave., Lemont, IL 60439

guillaume.giudicelli@inl.gov

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ABSTRACT

With the next generation of nuclear reactors under development, modeling and simulation (M&S) tools are being developed by the Nuclear Energy Advanced Modeling and Simulation (NEAMS) program in order to support their design, licensing, and future operation. Mirroring the physical test beds currently under construction (i.e., EBR-II and ZPPR), the Virtual Test Bed (VTB) was launched by the National Reactor Innovation Center (NRIC) in collaboration with NEAMS to support the advanced reactor community. This collaborative effort, which involves multiple teams at both Idaho National Laboratory and Argonne National Laboratory aims to use NEAMS tools to model a wide range of reactor designs. Those models are automatically tested to ensure their continued functionality as the tools are further developed. Examples are extensively documented, each acting as a tutorial for applying the relevant NEAMS tools to that reactor design. Currently, five advanced reactor types (with a total of eight specific design variants) are simulated by a variety of different models. These models range from steady-state, core multiphysics simulations to integrated plant analysis during loss-of-flow transients.

KEYWORDS: multiphysics, reactor, repository

1. INTRODUCTION

The National Reactor Innovation Center (NRIC) was created to accelerate deployment of advanced reactor concepts. In addition to developing physical test beds to evaluate new components and systems, the Virtual Test Bed (VTB) [*] [1], is being developed in collaboration with the Department of Energy (DOE)'s Nuclear Energy Advanced Modeling and Simulation (NEAMS) program. The initiative supports the development advanced reactor models and provides an externally available repository to store them. This provides industry, regulators, and other institutions with reference models that can be used as starting points for evaluating proprietary models, in effect de-risking the development of NEAMS-based simulation for assessing demonstration concepts.

An overview of the VTB repository and its features is provided herein. The VTB consists of an online open-source repository exhibiting "challenge problems" relevant to potential reactor demonstrations. This repository utilizes GitHub to store NEAMS tools inputs and the MooseDocs system for documentation.

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[*] VTB webpage: https://mooseframework.inl.gov/vtb

No code executables are provided in the repository (these must be obtained via relevant channels such as the Nuclear Computational Resource Center due to their export controlled nature [†]). A testing framework embedded into the repository continuously checks new code updates against the stored models. This enables rapid non-regressive advancement of code capabilities while ensuring that the models stored in the repository continue to act as a reference for users.

The repository discussion is followed by an overview of the various simulation capabilities currently hosted on the VTB. This includes work sponsored directly by NRIC, as well as by other DOE Office of Nuclear Energy programs. A wide range of advanced reactor types are considered: molten-salt reactors (MSRs), sodium fast reactors (SFRs), fluoride high-temperature reactors (FHRs), heat-pipe microreactors (HP-MRs), and high-temperature gas-cooled reactors (HTGRs). Simulations cover neutronics, thermal hydraulics (high and medium fidelity), system level, thermomechanics, and fuel performance physics at different levels of multiphysics coupling. Both steady-state and transient examples are showcased.

2. BACKGROUND AND OVERVIEW

The VTB prioritizes models that support NRIC's mission of accelerating reactor demonstration efforts. Stakeholder engagement was conducted with industry, the Nuclear Regulatory Commission, and various DOE groups in order to help guide development activities. As highlighted in [2], over 20 concepts were submitted to the DOE Advanced Reactor Demonstration Program, representing nine different reactor types. Ten were selected for awards by the program, with multiple other concepts pursuing different funding avenues (e.g., the Department of Defense, NASA, etc.). As a result, the VTB must cater to a wide range of advanced reactor technologies and requirements. An overview of the capabilities of NEAMS M&S tools to address these needs is provided here (organized based on reactor type), along with some discussion on current gaps.

2.1. NEAMS Tools

This subsection briefly introduces the various NEAMS tools [‡] showcased in the VTB. Each tool is intended to cover a specific set of physics (e.g., fuel performance, reactor physics), level of fidelity (low/medium/high), and reactor systems (e.g., primary coolant loop, vessel, core). They are all designed to easily interface and be coupled with one another via the MOOSE framework. Applications built on MOOSE can harness state-of-the-art, fully coupled, fully implicit multiphysics solvers, as well as automatic parallelization, mesh adaptivity, simplified application coupling, and a growing set of physics modules [3].

The thermal-hydraulic (TH) suite comprises of four main codes. SAM is the system model solver built on the MOOSE framework. It is used for 1-D whole-plant transient analysis code with improved fidelity for fast-turnaround design scoping and safety analyses of advanced non-light-water reactors. [4]. Nek is a high-fidelity CFD code based on the spectral element method. It can simulate fluid flows and heat transfer at high spatial discretization order using direct numerical simulation and a variety of large eddy and Reynolds-averaged Navier-Stokes turbulence models. [5]. Pronghorn is a multidimensional, coarse-mesh, TH code built on the MOOSE framework. It serves the intermediate-fidelity realm situated between detailed computational fluid dynamics (CFD) analysis and lumped system models [6]. Lastly, Sockeye is a MOOSE-based heat-pipe simulator and analysis tool which is particularly relevant to microreactor concepts [7].

The NEAMS neutron transport code is Griffin. It is built on the MOOSE framework and is a reactor physics code with weak form formulations for diffusion, PN, and first- and second-order SN transport, with both

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[†] NCRC webpage for requesting different tiers of code access: https://inl.gov/ncrc

[‡] For more information, see https://inl.gov/neams.

steady and transient capabilities, in addition to a variety of equivalence techniques with acceleration [8]. *BISON*, is a MOOSE-based thermo-mechanical simulation tool. It can model material behavior to model the behavior of fuel, cladding and certain structures in a variety of reactor types. The code has been applied to predict UO_2, TRISO, metallic, UN, UC, and U_3Si_2 fuel performance [9].

2.2. Model Status and Gaps

A summary of the different models hosted on the VTB repository is provided in Table I. Building blocks for various different models have already been uploaded to the VTB repository, along with multiple code combinations. While the models are merely a starting point and many gaps remain to be addressed, the examples showcase the capabilities of the various tools in addressing challenging simulation problems.

Table I: Summary of the models hosted on the VTB repository

Reactor Type	Status in VTB	Codes Used	Gaps
Gas-cooled (HTGR)	Multiphysics neutronics + TH transient mode of pebble-bed reactor; 1-D system model of prismatic reactor	Griffin + Pronghon; SAM	Couple system with core model and fuel performance
Sodium Fast (SFR)	Assembly lattice model with coupled system code, neutronics, and fuel performance	Griffin + SAM + BISON	Expand model to 1/3 of core
Molten Salt (MSR)	Multiphysics neutronics + TH transient of pool-type reactor; high-fidelity CFD of pool-type model; 1-D system model of channel-type reactor	Griffin + Pronghorn; Nek; SAM	Coupled core + system physics in pool and channel type
Fluoride High-temperature (FHR)	Multiphysics neutronics + TH transient model of pebble-bed reactor; high-fidelity CFD of reflector bypass flow; 1-D system model of primary and secondary loop	Griffin + Pronghorn; Nek	Couple system with core model and fuel performance; low-fidelity bypass flow model
Microreactor (MR)	1/3 Core multiphysics heat-pipe and fuel thermo-mechanics model	Sockeye + BISON	Couple with neutronics feedback; expand to transient analysis

3. VTB REPOSITORY

3.1. GitHub Repository

The VTB repository hosting the inputs for the simulations is on Github[§]. The repository is open to the public without restrictions. It contains a README file describing the purpose of the project, with links to

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[§] VTB GitHub page: https://github.com/idaholab/virtual_test_bed the NRIC and NEAMS program pages in addition to the generated documentation pages for the repository.

The models are sorted by reactor type, then design variant , then simulation type. For example, a CFD simulation of the Molten Salt Fast Reactor (MSFR)—using Nek5000—is located in the `msr/msfr/core_cfd` directory. Most models are composed of a set of input files and meshes. Large mesh files are stored using the Git Large File System. Mesh generation scripts are also stored within the repository, in the relevant mesh folders. The models each include a header indicating the type of simulations that the tools may be used to run, and the point of contact for that model is usually identified in this section as well.

3.2. Documentation Webpage

Documentation for the VTB repository is built and maintained using "MooseDocs", a markdown-based syntax that is rendered by a Python tool available with the Multiphysics Object Oriented Simulation Environment (MOOSE) framework [3,10]. This tool is used by all MOOSE-based applications to provide a common syntax for creating rich documentation that includes tables, figures, images, and animations useful for conveying capabilities and sharing information with the M&S community. The VTB documentation is automatically updated, since the markdown is updated and maintained within the source repository itself. Another notable feature of the MooseDocs system is that none of the webpages can be published in a non-functional state. With each change, automated integrity checks on the documentation are performed to ensure that it contains no rendering errors or broken links.

The documentation is organized by reactor type, but the various input models are cross referenced by application type as well. Once a user has selected a reactor type of interest, they will find information on the models available in the VTB repository. Some of these models will be for investigating individual reactor systems (typically monolithic multiphysics), while others may tie together multiple applications through MOOSE's MultiApp system [11] in more complex multiphysics simulations.

The documentation also provides several helpful resources, such as a tutorial on how to use the VTB and run its models, a link to the Frequently Asked Questions page and Discussions forums, and guidelines on how to contribute models to the VTB.

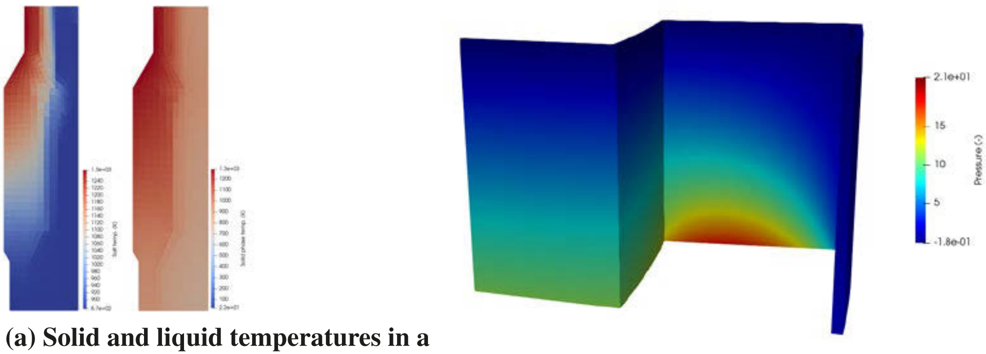
3.3. Model Testing

MOOSE-based application developers rely on the Continuous Integration, Verification, Enhancement, and Testing (CIVET) [10] tool to ensure that changes to individual applications do not adversely effect other applications in the ecosystem. CIVET is the advanced continuous integration system designed for complex dependency chains, high-throughput testing, and extendable customization. Multiple enhancements were developed specifically for testing the VTB repository.

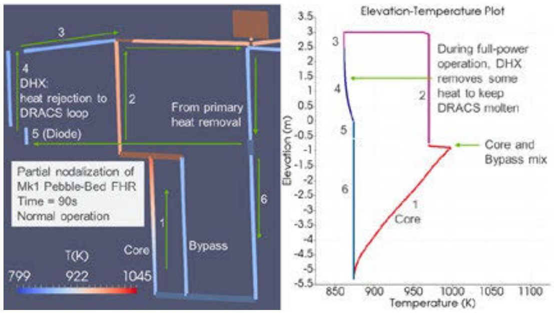
Unlike a typical MOOSE-based application, the VTB does not house applications. Instead, it is designed to store models and associated documentation. Existing capabilities within CIVET enable the testing of specific applications within each sub-directory of the repository. More specifically, the ability to search for tests outside of the standard directory structure was combined with the technique to filter out tests from being executed by an application, based on a pattern match of the executable name.

To prevent applications from attempting to run all the input files found within the VTB tree—some of which are not designed for that application—the `executable_pattern` key is used within every relevant test specification to match only specific applications. An example that would run only when the SAM or BlueCRAB binaries were being used as the executable would resemble the following:

```
executable_pattern = ’sam*|blue_crab*’
```



(a) Solid and liquid temperatures in a Griffin-Pronghorn model [12]. **(b) Pressure in bypass flow, using Nek [13].**



(c) Temperature distribution in the FHR primary loop, using SAM [14].

Figure 1: NEAMS-based FHR simulation results hosted in the VTB repository.

Model testing is performed mostly through regression and syntax checking tests. Syntax checks only verify that the syntax of the input file is not deprecated. Regression testing in MOOSE and many NEAMS tools is often performed using full-dimensional solutions files, which include all variable values on the mesh. For the VTB, this would often incur too high a memory cost to store the model results. Therefore, postprocessors, which output key metrics such as an eigenvalue or a maximum temperature, are compared against a pre-computed reference. The memory cost of the reference files is thus made negligible.

4. MODELS AVAILABLE ON THE VTB

The VTB currently hosts 14 distinct simulation examples representing five different reactor types. A brief overview of these models showcased is provided below. Additional information on their specifications can be found in INL/EXT-21-63162 [2] and on the VTB webpage.

4.1. Fluoride High-Temperature Reactors (FHRs)

The VTB currently hosts three distinct FHR models (see below), all based on the open-source Mk1-FHR, which was published by a consortium led by UC Berkeley [¶].

- **Steady-State Core Multiphysics:** Griffin is used for neutronics and Pronghorn for coarse mesh thermal hydraulics. Both physics are solved using an intermediate-fidelity method to achieve fast simula-

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[¶] Additional information on the Mk1-FHR design: https://fhr.nuc.berkeley.edu/

tion times—namely, diffusion (for neutronics) and a multiscale approach with porous media flow at the macroscale, 1-D pebble heat conduction at the mesoscale, and 1-D particulate heat conduction at the microscale (for thermal hydraulics) [15,12]. Figure 1a showcases the resulting converged temperatures within the core model. Transient versions of this model, with a rod ejection transient and pump flow reduction, are also planned for released on the VTB [16].

- **Reflector Bypass Flow:** The graphite reflectors around the pebble bed in an FHR are usually made of stacked blocks of graphite, allowing for thermal expansion and thus salt flow through them. This bypass flow significantly influences the core temperature and can be challenging for Pronghorn to model. Therefore, Nek was used instead, and is also planned to be used in developing informed anisotropic friction loss coefficients in Pronghorn models [13]. Figure 1b displays the estimating pressure gradient within that bypass region of the FHR.
- **Integrated Plant Analysis:** Both steady-state and loss-of-forced-flow models using SAM are included in the repository. These models include 1-D components for the core, pumps, heat exchangers, and Direct Reactor Auxiliary Cooling System (DRACS) loops [14]. The resulting temperature distribution throughout the primary loop is shown in Figure 1c.

4.2. Molten Salt Reactors (MSRs)

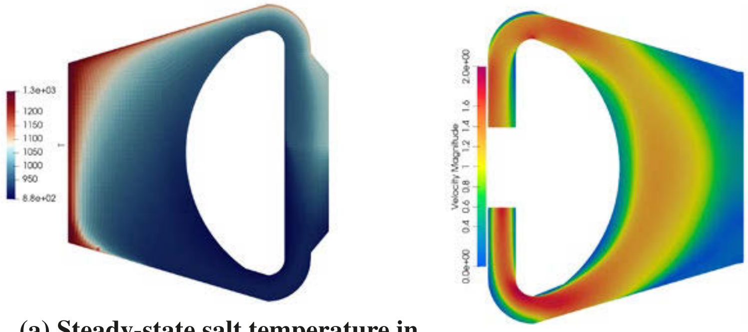
In the VTB, the fast and thermal MSR variants are represented by the European Molten Salt Fast Reactor (MSFR) [17] and Molten Salt Reactor Experiment (MSRE) [18], respectively. Three distinct models are showcased below.

- **Core Multiphysics:** The MSFR primary loop, with homogenized pump and heat exchangers, is modeled using Griffin and Pronghorn [19]. This is another intermediate-fidelity model, with diffusion for neutronics and coarse-mesh CFD for fluid flow. A capped mixing length model is used to model turbulence and the resutling temperature profile is shown in Figure 2a. The neutron precursor source is passed from the neutronics application to the TH solver. A transient model, an unprotected loss of 50% of primary flow, is also provided in the repository.
- **High-Fidelity CFD:** To validate the fluid flow simulation in the previous model—and most notably in the simplified turbulence models—CFD Reynolds-averaged Navier-Stokes simulations of the MSFR core were performed using Nek5000 [20]. The resulting high-fidelity velocity profile is shown in Figure 2b and was found to agree well with the pronghorn intermediate-fidelity model [21] once the mixing length model was appropriately capped.
- **Integrated Plant Analysis:** With ongoing efforts to validate the NEAMS simulation tools using MSRE data, an integrated plant analysis of the MSRE was performed using SAM [22]. This model is shared as an example of how SAM can be used to track delayed neutron precursors flowing through the primary loop outside of the core. The temperature distribution inside the primary MSRE loop is displayed in Figure 2c.

4.3. High-Temperature Gas-Cooled Reactors (HTGRs)

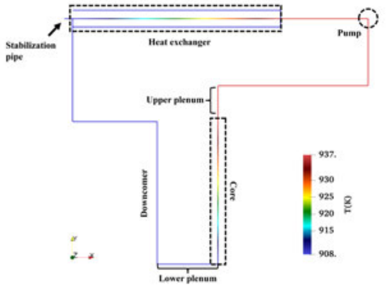
The two main types of HTGR, the prismatic MHTGR [23] and the pebble-bed PBMR-400 [24] are showcased in the VTB. A simulation for each design variant is discussed below.

- **Transient Core Multiphysics:** A 2-D model of the PBMR-400 benchmark was simulated using Griffin and Pronghorn. The solvers used were similar to those in the MSR and FHR models, with the exception of a finite element solver used in Pronghorn. Both a steady-state and pressurized loss of forced cooling were simulated. Figure 3a shows the resulting pressure drop across the core under steady-state operation along with the coolant and fuel temperatures.



(a) Steady-state salt temperature in the MSFR reactor core, using Griffin and Pronghorn [21].

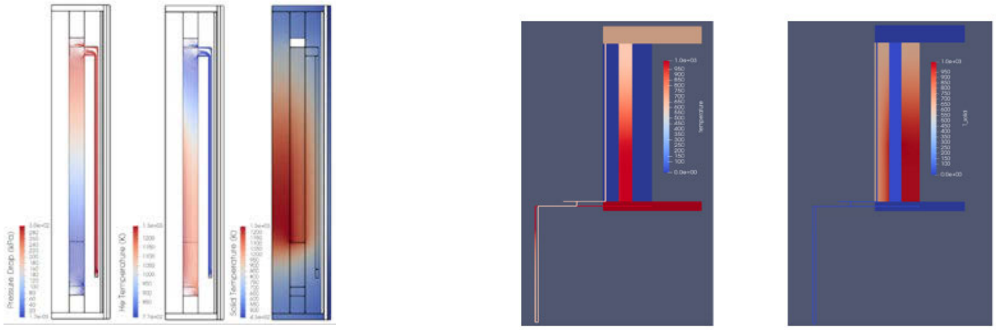
(b) Fluid velocity simulation in the MSFR reactor core, using Nek.



(c) Integrated plant analysis of the MSRE, using SAM [22].

Figure 2: Results from NEAMS-based MSR models hosted in the VTB repository.

- **Integrated Plant Analysis:** A reactor and primary system model of a prismatic HTGR were simulated using SAM under steady-state conditions. The core model was developed via a ring approach based on a specified coolant channel pitch of fuel assembly. The active core was simulated using 99 circular rings: 66 for homogenized fuel heat structure and 33 for gas coolant. Each coolant ring was sandwiched between two heat structure rings. Figure 3 showcases the resolved coolant and solid temperature distribution across the model.



(a) Steady-state pressure and temperature profiles in the PBMR-400 model [2].

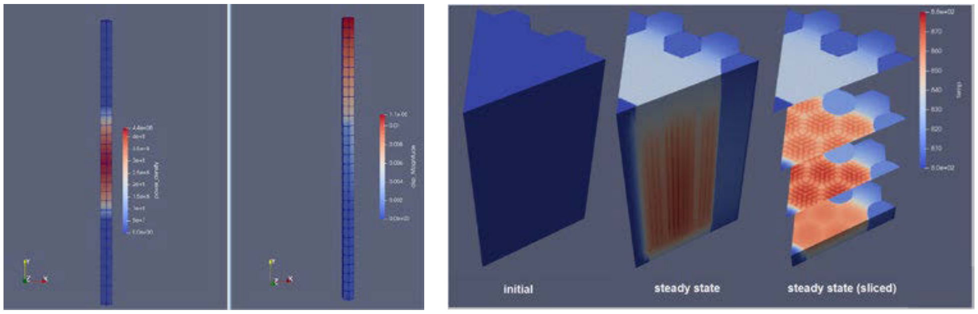
(b) HTGR system model using SAM [25].

Figure 3: Results from NEAMS-based HTGR models hosted in the VTB repository.

4.4. Sodium Fast Reactor (SFR) and Heat-Pipe Microreactor (HP-MR)

The VTB also hosts generic SFR and HP-MR simulation examples, as detailed below.

- **Multiphysics Lattice Feedback:** The SFR model consists of a single assembly lattice modeled in Griffin, SAM, and BISON. A 2-D axisymmetric fuel rod was modeled using BISON, with the power density obtained from Griffin. BISON provides both the fuel temperature and axial expansion feedbacks to the neutronics model. The coolant channel was modeled via a 1-D model in SAM and takes the wall temperature profile from BISON. Finally, a simple 2-D core support plate model relying on the MOOSE tensor mechanics model provides the radial expansion feedback corresponding to the inlet temperature. This example provides all the functionalities required for scaling up to a full-core SFR model for both steady-state and transient conditions. The converged power density and displacement within the assembly are illustrated in Figure 4a.
- **Steady-State Multiphyics:** $1/6^{th}$ core of the HP-MR was modeled in MOOSE, with a constant power distribution assumed at this stage (this will be updated later with a Griffin model). The simulation leverages the heat conduction module in MOOSE and BISON to estimate the surface temperature and conditions within the monolithic block. Sockeye was then employed for steady-state heat removal via the heat pipes, using the equivalent thermal conductivity model. The temperature distribution across core slices are shown in Figure 4b



(a) Power density and axial displacement in the SFR lattice [2].

(b) Thermomechanics model of an HP-MR. From [2].

Figure 4: Results from NEAMS-based SFR and HP-MR models hosted in the VTB repository.

5. SUMMARY

The VTB repository was recently set up to host models for a wide variety of reactor types—models using a range of NEAMS-developed software. These tools can conduct challenging simulations of advanced reactor reactor, thanks to greater levels of fidelity and the multiphysics framework. The repository currently hosts models for a variety of reactor types such as HTGRs, SFRs, FHRs, MSRs, and HP-MRs. Crucial building blocks have been established for a wide variety of these models in terms of neutronics, CFD, and system analysis. Future work will expand the coupling/interfacing of different codes in order to develop comprehensive multiphsyics transient models of each reactor type in 3-D. This will be expanded to also include fuel performance and structural material degradation effects.

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