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OVERVIEW OF THE VIRTUAL TEST BED (VTB)

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The Virtual Test Bed (VTB) was established to support the deployment of advanced reactors by facilitating the use of state-of-the-art modeling and simulation capabilities. These tools can solve previously prohibitive challenge problems with greater levels of fidelity and in a multiphysics framework. A VTB repository was recently set up to host models for a wide variety of reactor types and using a range of Nuclear Energy Advanced Modeling and Simulation-developed software. The repository currently includes models for High-Temperature Gas-Cooled Reactors, Sodium Fast Reactors, Fluoride-salt-cooled High-temperature Reactors, Molten Salt Reactors, and Heat-Pipe Microreactors. This article provides an overview of the capabilities currently in the VTB repository.

I. INTRODUCTION & BACKGROUND

The 2017 Nuclear Energy Innovation Capabilities Act established the National Reactor Innovation Center (NRIC) to accelerate the deployment of novel reactor concepts. This will be achieved by providing physical and virtual spaces for building and testing various components, systems, and complete pilot plants. The Virtual Test Bed (VTB) represents the virtual arm.[1] It is being developed in collaboration with the Department of Energy's (DOE) Nuclear Energy Advanced Modeling and Simulation (NEAMS) program.

The mission of the VTB is to accelerate the deployment of advanced reactors by facilitating the adoption of advanced modeling and simulation (M&S) tools developed by the DOE NEAMS program. This is achieved by two primary means: (1) storing example challenge problems in an externally available repository and (2) developing models to fill the M&S gaps needed by industry. The VTB repository consists of two sub-entities:

1. A documentation website detailing all of the models (https://mooseframework.inl.gov/virtual_test_bed)
2. A GitHub repository that hosts the corresponding files (https://github.com/idaholab/virtual_test_bed).

Summaries of the current VTB models are showcased here and in the following accompanying papers. A more detailed overview is provided in Ref. 1. The models encompass work sponsored directly by NRIC and other DOE-NE programs (namely NEAMS and Advanced Reactor Technologies [ART]). The models are hosted in an online, open-source repository to exhibit "challenge problems" relevant to potential reactor demonstrations.

The VTB prioritizes hosting models that are of interest to potential reactor demonstration efforts. As such, the models highlighted follow the recommendations of an internally conducted industry review. Advanced Reactor Demonstration Program (ARDP) awardees were divided into three tiers: demonstration, risk reduction, and advanced reactor concepts awards. Awards were nearly evenly split between each reactor type, with Sodium Fast Reactors (SFR) and High-Temperature Gas Reactors (HTGR) receiving slightly more awards. The application pool distribution was even more widespread, with a broader range of reactor types. Molten Salt Reactors (MSR) and Gas-Cooled Microreactors (GC-MR) applicants were slightly more common than others at this stage. Other concepts being pursued by reactor demonstrators include Fluoride High-temperature Reactors (FHRs), Heat-Pipe Microreactors (HP-MR), and Gas Fast Reactors (GFRs) as well as more traditional Pressurized and Boiling Water Reactors (PWRs and BWRs).

II. NEAMS CODES

A short overview of the NEAMS tools showcased in the VTB is provided here. Additional information on the various tools can be found on the website: https://inl.gov/neams.

MOOSE: MOOSE is the underlying framework for many of the advanced reactor NEAMS physics tools and the capability for connecting multiple physics applications. MOOSE aids application development by harnessing state-of-the-art fully coupled, fully implicit multiphysics solvers while providing automatic parallelization, mesh adaptivity,

[1] All input files and documentation developed are available via the VTB website: mooseframework.inl.gov/virtual_test_bed

simplified application coupling, and a growing set of physics modules [2].

Griffin: Griffin is a time-dependent reactor physics code built using the MOOSE framework with weak formulations for diffusion, P_N, and first- and second-order S_N transport, and various equivalence techniques with acceleration. It is specially designed to support multiphysics reactor analysis [3,4].

Pronghorn: Pronghorn is a multidimensional, coarse-mesh, thermal-hydraulics (TH) code for advanced reactors. It serves the intermediate fidelity realm between detailed computational fluid dynamics (CFD) analysis and lumped system models. Application development has focused on gas-cooled pebble bed (PBR) and prismatic reactors, FHRs, and open-pool molten salt reactors (MSRs) [5,6].

SAM: SAM is a fast-running, whole-plant transient analysis code with improved-fidelity capability for fast turnaround design scoping and safety analyses of advanced, non-light-water reactors. The system code capabilities include 1-D flow and multichannel representations of reactor coolant systems, point kinetics models, component models, species transport, control and trip systems, and reduced-order multidimensional models [7].

Nek: Nek5000 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 various turbulence models, including direct numerical simulation, large eddy simulation, and Reynolds-averaged Navier-Stokes (RANS). It has demonstrated impressive computational scalability, routinely running on leadership-class high-performance computing (HPC) facilities [8].

BISON: Built on top of MOOSE, which solves partial differential equations important to fuel performance via finite element (energy conservation, stress divergence, and species migration), BISON adds specific fuel behavior and material models designed to represent the response of fuel and cladding/structural layers in a variety of reactor types. The code has been applied to UO_2, TRISO, metallic, UN/UC, and U_3Si_2 fuel performance prediction [9].

Sockeye: Sockeye is a MOOSE-based heat-pipe simulator and analysis tool. Heat-pipe simulation offers the ability to accurately predict heat transfer for applications involving heat pipes, including heat-pipe-cooled microreactors. Additionally, it provides insight into heat-pipe performance; operational heat-pipe limits can be predicted in transient conditions and with greater flexibility than steady-state analyses can provide [10].

III. THE REPOSITORY

III.A. Website, Documentation, and GitHub

Comprehensive documentation on all the models included in the repository is hosted on an externally facing webpage. Fig. 1 shows a screenshot of the homepage of the public website. The landing page also links relevant resources, notably the NRIC website, the NEAMS website, the VTB GitHub repository, and the NCRC homepage for requesting the codes. All the additional sub-pages for the VTB are grouped between reactor types: Molten Salt Reactors (MSR), Fluoride High-Temperature Reactors (FHR), High-Temperature Gas-Cooled Reactors (HTGR), and Sodium Fast Reactors (SFR). Interested users can navigate through those links to obtain relevant documentation on each use case.

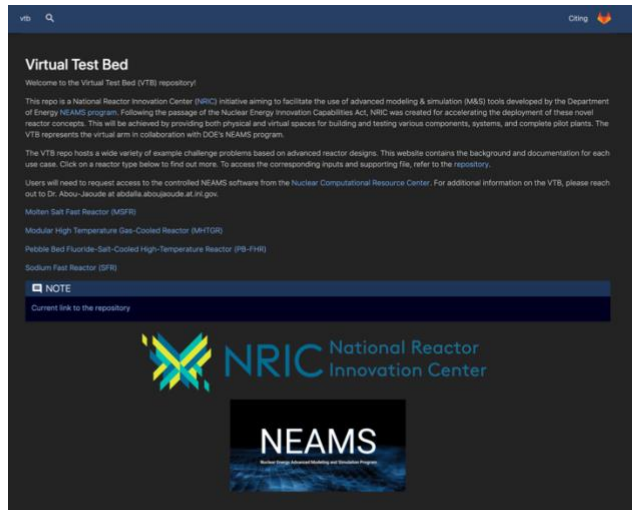

Fig. 1. Screenshot (dark mode) of the VTB Repository documentation homepage

Each reactor type can have different models in the future based on geometry (e.g., the HTGR category is divided between the MHTGR and the PBMR-400 specifications), codes employed (e.g., Pronghorn, SAM, or Nek), or the example application (e.g., reactivity transient or bypass flow analysis). The model documentation is then organized into three main subsections: reactor description, input description, and presentation of results.

Reactor descriptions are all based on the open literature with corresponding references included. The documentation then provides an overview of input specifications and physics used to define the problem. Whenever possible, the information is linked back to the corresponding code website (e.g., https://mooseframework.inl.gov), where a visitor can obtain additional information. Lastly, plots are generated and summarized separately to demonstrate how the models can be used for real applications.

A GitHub repository was set up to provide access to the inputs. It is placed under the already established ‘idaholab’ repository. A screenshot of the opening page is provided in Fig. 2. The ‘readme’ file includes a short description of the VTB and provides a link to the documentation site (see Section 2.1). Users can clone all or part of the VTB repo based on their interests and run the models on their local machine after obtaining access to the codes.

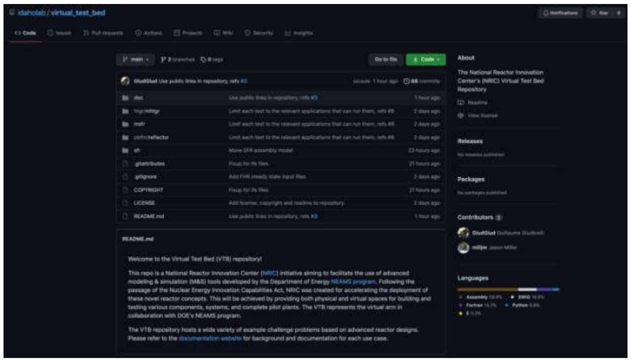

Fig. 2. Screenshot (dark mode) of the VTB Repository GitHub homepage.

The ‘doc’ folder contains all of the ‘markdown’ files used to build the documentation shown on the VTB website (Figure 1). This allows the documentation to evolve simultaneously with the input files and geometries. As for the documentation, the examples are grouped by reactor type, then model. Each case would contain a mesh along with any additional pre-computed data (e.g., cross-section library). The VTB repo mainly includes the inputs needed for multiphysics calculations. Users interested in the pre-computation steps would contact the model developers.

III.B. Continuous Model Integration

The NEAMS program is utilizing a continuous integration strategy for rapid code development. This fast development pace can lead to legacy models becoming incompatible with the latest code versions. The VTB intends to address this concern by integrating all the models stored on its repository with the MOOSE Continuous Integration, Verification, Enhancement, and Testing (CIVET) system.

As shown in Fig. 3, each time an edit is performed to some of the underlying codes (e.g., MOOSE, Pronghorn) the CIVET tools conduct a series of tests based on the models within the VTB repo. This includes both simple syntax checks and regression checks. If a test fails, the developers performing an edit to the code are notified, and the modification is blocked. This framework ensures that models shared on the VTB remain relevant and usable as the underlying codes are rapidly improved. Figure 4 shows a screenshot of the CIVET summary page for the VTB.

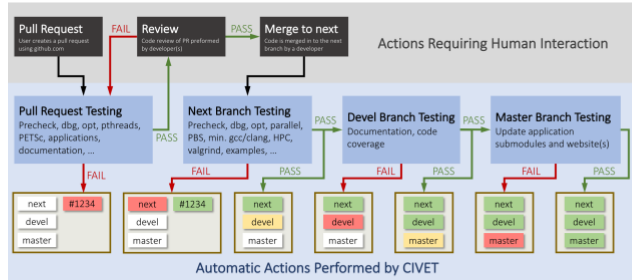

Fig. 3. Overview of the CIVET testing & integration tool. Taken from Ref. 11.

IV. OVERVIEW OF HOSTED MODELS

A summary of the different capabilities already available in the repository is provided in Table I. The capabilities are divided between currently available, near/long term, and currently unavailable. Note that the level of maturity of each model can vary significantly from case to case. Additional information on each example problem can be found in the accompanying sister articles to this publication.

TABLE I. Status of models in the VTB repository based on examples being available (A), coming in near (N) long-term (L), not applicable (N/A), and not under current development (U). Taken from Ref. 1.

	Griff.	Prong.	SAM	Nek	Sock.	BISON
HTGR	A	A	A	L	N/A	N
SFR	A	L	A	L	N/A	A
HP-MR	N	N/A	N	U	A	A
FHR	A	N	A	A	N/A	N
MSR	A	N	N	A	N/A	
GFR	U	U	U	U	NA	U

Two HTGR models are included in the repository: one SAM-based [12] and another Griffin+Pronghorn-based [13]. The SAM-based example of a prismatic HTGR consists of all components, including fuel, reflectors, coolant channels, core barrel, reactor pressure vessel, and reactor cavity cooling system as concentric cylindrical rings. The active core consists of three fuel rings: inner, middle, and outer ring. Each fuel ring is represented by 11 coolant channels and 22 heat structures. The second model is for a pebble-bed type HTGR. The two-dimensional flux and power density profiles are computed by Griffin, while Pronghorn computes the helium pressure, temperature, and velocity streamlines. Both steady-state and transient simulation examples are provided.

Three FHR-based models are showcased in the VTB: one SAM-based, another Nek-based, and a third using Griffin+Pronghorn. All cases are for an open-source pebble-bed FHR concept [14]. The coupled Griffin+Pronghorn model leverages a similar approach to the HTGR use case. The Nek example consists of a reflector bypass flow simulation. The SAM-based model simulates the FHR primary loop in a transient condition.

The MSR-based simulation in the VTB consists of a coupled Griffin+Pronghorn simulation and Nek core flow model. The examples are for fast, open pool-type MSRs. Precursor drifting is accounted for in the Griffin+Pronghorn simulation, and some initial turbulence modeling capability is included. The Nek simulation can resolve the fuel flow in greater detail within the reactor and is expected to ultimately be leveraged for closure relations in Pronghorn.

A lattice-based use case for SFRs is also showcased in the VTB. Griffin, Sam, and BISON are all coupled to capture the feedback mechanisms, notably core-bowing, that are important for this type of reactor.

Lastly, an HP-MR model is also included in the VTB. The simulation couples BISON and Sockeye with a placeholder power distribution (instead of Griffin, which will be incorporated as part of future work). The 1/6th core model provides an example steady-state simulation for that type of system.

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