

Digital Engineering

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NRIC Work Package Manager: Thomas Folk

04/01/2025

Agenda

- Digital Engineering Overview
- Live Demonstration: Digital Twin Model Viewer
- FY26+ Look Ahead

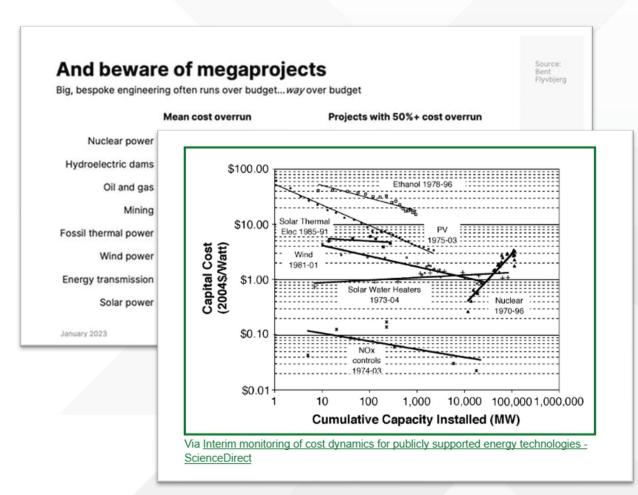


Digital Engineering Overview



The Need for Digital Engineering

- The nuclear industry has historically not done so well on project execution performance.
- Nuclear power has a historical mean cost overrun of 120%.
- Plants increased in cost, even as we built more.
- Vogtle 3/4 in Georgia:
 - Initial \$14B, final > \$30B (+\$17B).
 - Initial 2016, final 2024 (+8 yrs).
- How can we reverse this trend and accelerate nuclear plant deployment?





Model-Based Design



What

- Shifting engineering from documentbased to data-centric.
- START projects with this philosophy instead of retrofitting midflight.
- Reinforce systems engineering principles.

How

- Web-based, cloud-hosted, industry-leading software applications with broad access for collaboration.
- Model-Based System Engineering(MBSE) tools for functional analysis and concept of operations.
- Requirements Management (RM) tools for powerful RM functions above what MBSE tools offer.
- Building Information Modeling (BIM) and Model Based Definition (MBD).

Model-Based Requirements





Model Based Definition (MBD) & Building Information Modeling (BIM)



Model-Based Systems Engineering (MBSE)

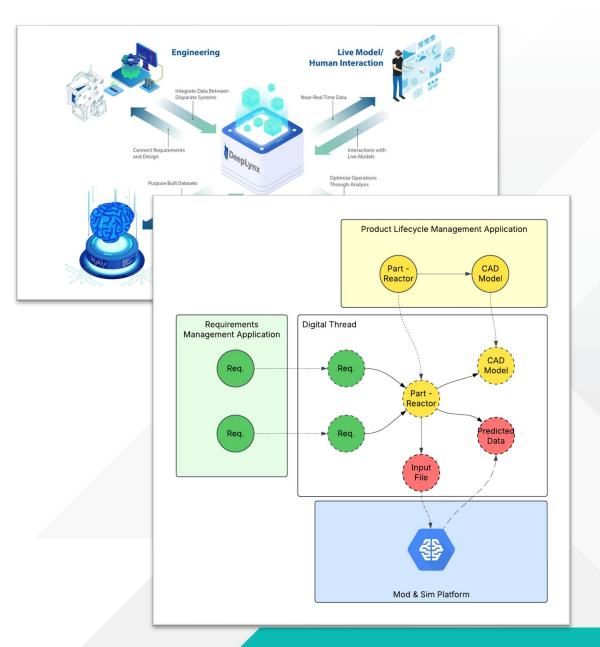


Product Lifecycle Management (PLM)



Digital Thread

- Interconnected data ecosystem.
- Connects data from different project domains in a single knowledge graph.
- Centralized, single source of truth.
- Why does this matter?
 - Change impact analysis.
 - o Dynamic workflows & automation.
 - Central repository in a single software solution.
 - o Powers digital twins & their applications.

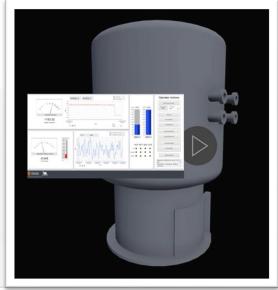




Digital Twin

- INL Definition: Digital Twins represent the merging of integrated and connected data, sensors and instrumentation, artificial intelligence, and online monitoring into a single cohesive unit.
- What is different than a traditional simulation?
 - 。 Integration of real-time data.
 - Dynamic model update (AI/ML integration).
 - Real-time operator visualization.
 - Accurate predictions with fused (integrated) data.
 - Ability to enable autonomous control.
 - Distributed across computing platforms.













DT Levels framework adapted from: Verdantix, Five Digital Twin Strategies For Industrial Facilities, 2019.



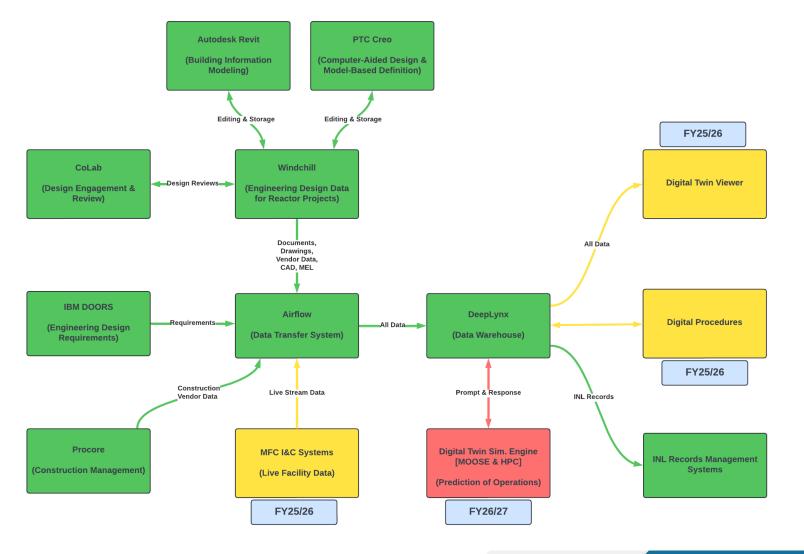
Live Demonstration: Digital Twin Model Viewer



Look Ahead



Digital Engineering Roadmap





NRIC Digital Engineering in Nuclear (DEN) Technology Transfer

- Open-source, project agnostic capabilities.
 - Available on INL's external Github repository.
- Publications:
 - Digital Engineering Implementation in Nuclear Demonstration and Nonproliferation Projects at Idaho National Laboratory
 - Digital Engineering Implementation in the Nuclear Energy Industry
- We're Here to Help Facilitate Technology Transfer!
- Looking for Requests from Industry.







Transforming DOE Authorization with Digital Tools

Enhancing Efficiency and Accuracy in DOE Authorization Process

Presenter: Jacob Rymer, NRIC Technical Program Manager

04/01/2025

Application of NRIC - Digital Engineering in Nuclear (DEN)

Current Challenge: Department of Energy (DOE) authorization process is complex, paper-intensive, and slow.

Result: project delays and increased costs.

Integration of NRIC-DEN and Artificial Intelligence (AI) to the DOE Authorization Process.

- Automating workflows and document development.
- Implementing user interface to validate data/sources.
- Streamlined digital authorization system can cut timelines by 30-50%.
 - Enhanced transparency.
 - Reduced administrative burden.
 - Supports rapid authorization needs for National Reactor Innovation Center (NRIC) test beds.



The Role of Safety Analysis in DOE Authorization

Purpose of Safety Analysis:

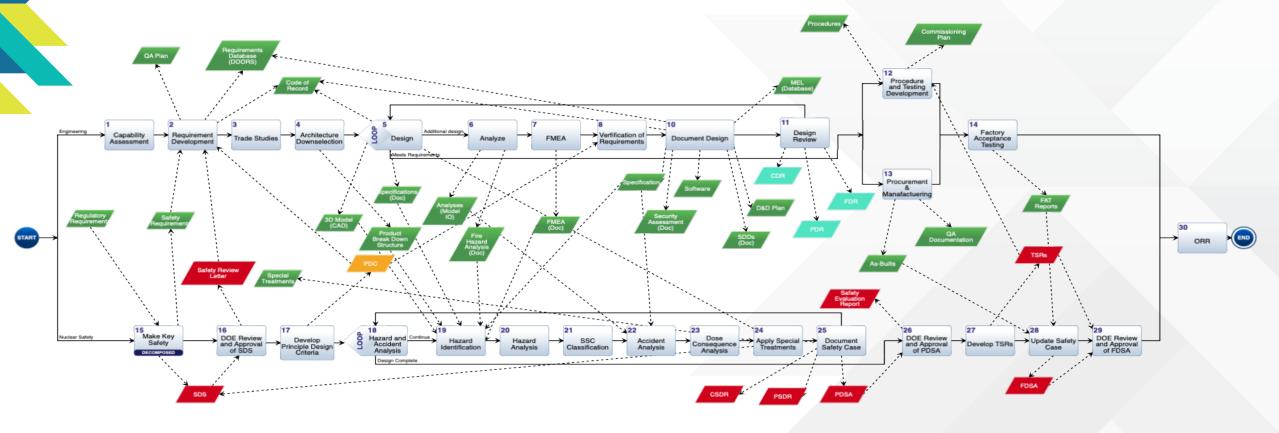
- · Ensures protection to workers, the public, and the environment.
- · Identifies potential hazards and evaluates risks.
- Provides a basis for safe design and operational decisions.

Importance in DOE Authorization:

- Supports the approval process for facility operation.
- Ensure alignment with DOE safety standards and requirements.
- Facilitates informed decision-making by DOE officials.



Navigating Complexity: Engineering and Authorization Interwoven





Modernizing DOE Authorizations: Progress in Action

FY24: Developed Architecture for Leveraging Digital Tools:

- Built on NRIC-DEN to manage data structure
- Mapped semi-autonomous DOE Authorization Documents
- NRIC digital engineering tools: DOORS, DeepLynx, Windchill
- Single source of truth using the digital thread
- At large language models for document creation
- Graphical user interface (GUI) to accelerate reviews

FY25: Pilot Project Demonstration:

- Enhanced digital thread for Al integration.
- Pilot project is Hight Temperature Gas Reactor (HTGR) in NRIC-DOME.
- Create input documents Aug 2025.
- Al generated nuclear safety document – Dec 2025.

Challenges:

 Government cloud limits Al capabilities; Investigating opportunities.



Roadmap to Digital Transformation for **DOE** Authorization

Phase 1: Integration of Digital **Engineering Tools**

- ·Requirements.
- ·3D Models.
- · Product Lifecycle Manager.

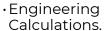
Established

Actively Working

Future Actions

Phase 2: Create Safety Analysis Workflows





- •Failure Mode and Effects Analysis (FMEA).
- · Hazard Identification.
- Determination of Safety Structures. Systems, or Components (SSCs) and Special Treatments.
- ·Evaluation for Defense In Depth (DID).

Phase 3: Automatic Document Generation

- Engineering Calculations.
- ·System Design Description.
- Documented Safety Analysis.
- ·Technical Safety Requirement.

Phase 4: Data Pipelines



- ·3D Model → Analyses
- Analyses → Analyses
- FMEA → Probabilistic Risk Analysis (PRA)
- PRA → Accident
- Analyses → Accident
- ·Accident → Dose

Phase 5: Digital **DSA GUI**



Phase 6: Regulator Approval

- Update Regulations.
- ·Training.
- ·Build Confidence in Tools
- ·Implementation.

- Validation.
- Interface Design. ·User/Regulator

Database

Integration.

Configuration

Management.

·Human Machine

Engagement.

Requirements

Development.

Verification &



Empowering Reviewers: Next-Gen GUI for Streamlined Decisions

User-friendly GUI that Interconnects a Digital Twin & Engineering Tools:

• Dynamic environment for hazard and accident analyses, 3D plant navigation, and SSC exploration.

Dashboard-like Home Page:

• Quick access to modules via clear, descriptive icons or tiles allow access to 3D model visualization, hazard & accident analysis, safety requirements, validation matrices, analyses.

3D Model Navigation Module:

- · Responsive and detailed viewer with zooming, panning, rotating, and isolation tools.
- ·Clickable elements for linked metadata, source documents, and related analyses.
- •Interactive timeline or version history feature for design change evolution.

User-centric Design:

- ·Onboarding tutorial, tooltips, and contextual help for quick learning and ease of use.
- ·Search bar with predictive text and NLP capabilities for swift information location.

Adaptive HMI for Different User Roles:

- · Customized views highlighting relevant data and tools tailored to job functions.
- Example: Regulators' view with V&V matrix, SSCs, component specs, P&IDs, analyses, and quality reports.

Streamlined Review Process for Analysts:

· Workflow for USQ/50.59 change review process with guided steps and dynamic engineering information.



Securing DOE Regulatory Acceptance and Approvals

Key Areas for DOE Alignment:

- Al Generated Documents:
 - Ensure transparency, traceability, and validation of Al-assisted outputs.
- Graphical User Interface (GUI):
 - o Demonstrate usability, security, and efficiency improvement for reviewers.
- Reviewer Training:
 - Equip DOE staff with tools and knowledge to adapt to digital workflows.
- Regulatory Updates:
 - o Collaborate with DOE to refine policies supporting digital transformation.



Future Applications and NRC Licensing

Pilot Project:

- Streamlines authorizations for NRIC test bed or other experiments.
- Establishes precedents for AI-driven regulatory document generation.

NRC Licensing:

- Leverage lessons learned to inform NRC regulatory modernization.
- Actively collaborating with NRC through phases.

Results:

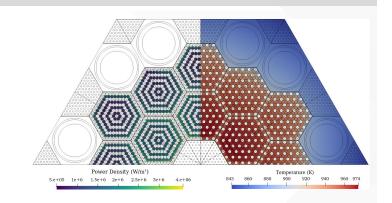
• Transformation is beyond DOE Authorization, it's about setting the stage for a more agile, technology driven regulatory future across the nuclear sector.

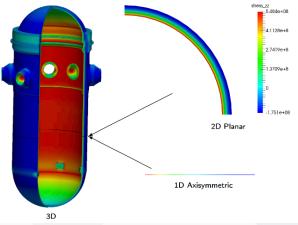






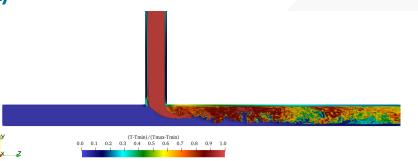
NRIC Virtual Test Bed (VTB)

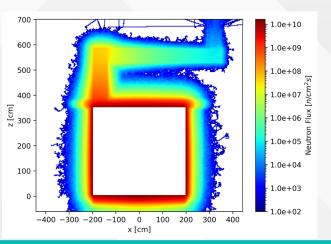




Lise Charlot (INL), Emily Shemon (ANL)

04/01/2025





NEAMS





Mission Statement

NRIC: Deliver successful demonstration and deployment of advanced nuclear energy.

- EBR-II Test Bed (NRIC-DOME)
- ZPPR Test Bed (LOTUS)
- Virtual Test Bed (VTB): Accelerate deployment of advanced reactors by leveraging state-of-the-art ModSim tools to evaluate performance and safety.

Virtual Test Bed:

- <u>Library of Reference Model</u>: database of advanced multiphysics advanced reactor models that users can download, edit, and re-run.
- <u>Continuous Software Quality Assurance (QA)</u>: linking repository to software development to avoid legacy issues while enabling rapid code development.
- <u>Virtual models of the test bed</u>: developing demonstration-relevant models (e.g., candidates for NRIC-DOME/LOTUS) to accelerate safety evaluations.

Reactor Demonstrations

Accelerate Licensing Evaluation (NRC) Accelerate Authorization Evaluation (DOE) Accelerate
Design
Maturation
(industry)

Targeted Model Generation Library of Reference Testing for Agile Software QA



VTB Team

INL Team

- Lise Charlot: VTB Work Package Manager
- Thomas Folk: NRIC Technical Point of Contact
- Cody Permann: VTB Department Support
- Guillaume Giudecilli: VTB Infrastructure Lead
- Patrick Behne: Repository Maintenance
- Khaldoon Al Dawood: VTB External Model integration
- Paul Ferney: VTB DOME Model Developer
- Mohamed Elkamash: VTB NRIC-DOME Model Developer
- Mustafa Jaradat: VTB NRIC-DOME Model Developer

ANL Team

- Emily Shemon: VTB Work Package Manager
- Jun Fang: VTB Model Developer
- Joffrey Dorville: VTB NRIC-DOME Developer
- Paul Romano: VTB NRIC-DOME Developer
- Shikhar Kumar: VTB NRIC-DOME Developer

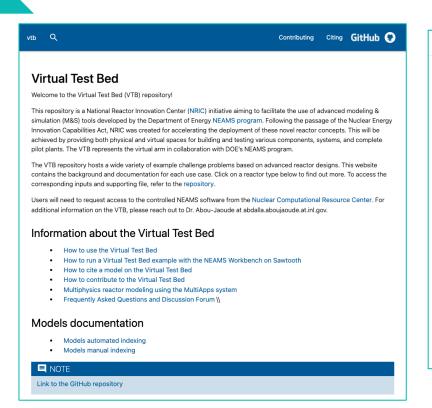
Additional Contributors:

Nicolas Martin, Jason Miller, Logan Harbour, Paolo Balestra, Nicolas Stauff, Dillon Shaver, Rui Hu, Ling Zou, Thanh Hua, Yinbin Miao, Ahmed Abdelhameed, Ting Fei, Zhiee Jhia Ooi, Nick Wozniak, Hansol Park, Marco Delchini, April Novak, Derek Gaston, Mauricio Tano, Stefano Terlizzi, Vincent Laboure, Namjae Choi, Sebastian Schunert, Javi Ortensi, Vasileios Kryiakopoulos, Yan Cao, Joshua Hansel, Zach Prince, Pierre-Clément Simon, Ben Spencer, Kylee Swanson, Andres Fierro Lopez, Isaac Naupa, Ramiro Freile, Liam Martinez, Samuel Walker, Shikhar Kumar, Masashi Shimada, Aaron Oaks, Shipeng Shu, Abdellatif Yacout and others.



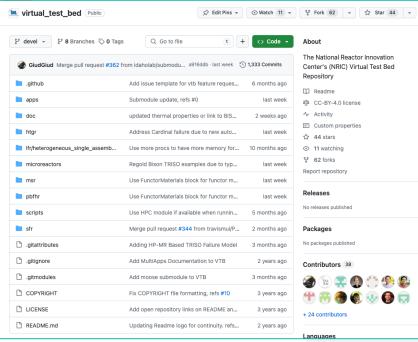
1. Documentation

Detailed explanation of models.



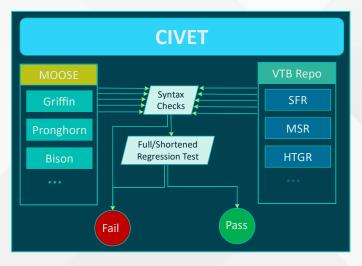
2. GitHub Repo

Ability to clone and contribute to models.



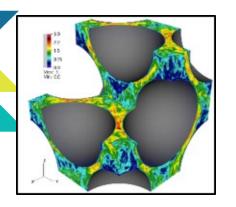
3. Integration with Code Development

Continuous testing of models against codes using CIVET.

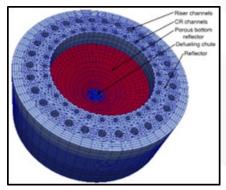


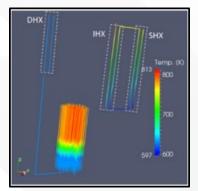


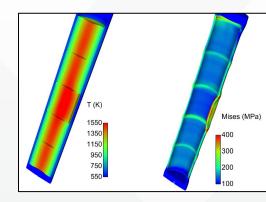
Advanced Reactor ModSim Suite











NEKRS/NEK-5000



GRIFFIN



PRONGHORN



SAM



Fuel Performance/ Thermochemistry

High Fidelity

2D/3D Multiphysics Transients

System-level Simulation

Depletion & Fuel Performance



Overview of Models

Туре	Reacto	or Simulation	Codes Used	HTGR	PBMR	Core neutronics and hydraulics, steady state +	Griffin; Pronghor	LMFR	Lattice	Assembly neutronics, hydraulics, and fuel	Griffin; SAM; Bison	
		Core neutronics and hydraulics, steady state + transient	Griffin; Pronghorn			transient 67 pebble high-fidelity conjugate heat transfer	n Cardinal			Subchannel hydraulics benchmarks, steady-state and transient	Subchann el	
		Core + system neutronics and hydraulics, steady state +	Griffin; Pronghorn;			Primary loop steady-state and transient	SAM			Lead-cooled reactor assembly heterogeneous neutronics	Griffin	
	MSFF		SAM		MHTGR	Primary loop steady-state	SAM			Duct bowing	MOOSE	
		Core depletion with species removal	Griffin			Assembly high-fidelity neutronics and thermal	Cardinal			Multiphysics 7 pin demonstration	Griffin, Cardinal	
		Core high-fidelity CFD (LES and RANS)	Nek5000			hydraulics TRISO fuel performance	Bison		VTR	3D Core neutronics, hydraulics, and fuel; steady-state	Griffin; SAM; Bison	
		Primary loop Transient	SAM			Core neutronics steady-state	Griffin		ABTR	Primary loop Transient	SAM	
MSR		Primary loop steady-state and	SAM			3D full core mesh	MOOSE			Cross section generation and	Griffin	
	2	transient Core coarse mesh steady-state	Pronghorn;			Hydraulics and structure transient	MOOSE- THM			full core eigenvalue calculation		
	MSRE	and transient Thermal striping in piping system	Griffin Cardinal		HTTF	Hydraulics system steady- state and transient benchmark	SAM		Uset	Core hydraulics and structure, steady-state	Sockeye; Bison	
		CFD model of MSRE lower plenum	NekRS			High-fidelity CFD of lower plenum	Nek5000			3D Core neutronics, hydraulics, and fuel; steady- state and transient	Griffin; Sockeye; Bison	
	LOTUS	Molten salt reactor core	Griffin;		HTR10	Core neutronics steady-state	Griffin			3D Core neutronics,		
	MSR	hydrauliec and etrueture	Pronghorn; Bison			TREAT- like	Core pulsed transient	Griffin; Bison		Heat pipe	hydraulics, and fuel with hydride migration; steady-	Griffin; Sockeye;
	Gener	Seismic analysis CNRS benchmark	Mastodon Griffin-		HTR-PM	System level steady state and transient	SAM	Micro		state and transient, control drum rotation	Bison	
		Core neutronics and hydraulics,	Pronghorn Griffin;		HTTR	Multiphysics core steady state	Griifin, Bison,			KRUSTY steady state	Griffin, Bison	
FHR		steady state	Pronghorn				Pronghor			3D mesh	MOOSE	
		Reactor bypass high-fidelity conjugate heat transfer	Cardinal	Fusion	Generic	Coarse mesh porous media	n Pronghor		Gas cooled	Neutronics, hydraulics, and structure; steady-state and	Griffin;	
	Mk1	Primary loop steady-state and transient	SAM			Divertor Monoblock During Pulsed Operation	TMAP8			transient assembly, steady state full core neutronics	SAM; Bison	
		Core + system neutronics and hydraulics, steady state	Griffin; Pronghorn; SAM		MCF					System steady-state and transient balance of plant	MOOSE- THM	
				Research	AGN-201	3D full core mesh	MOOSE		SNAP8	2D Core neutronics and	Griffin;	
	gFHR	Multiphysics equilibrium pebble core with neutronics and hydraulics	Griffin; Pronghorn						SIVAFO	structure; steady-state	Bison	

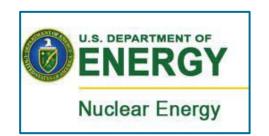


VTB Benefits to Stakeholder

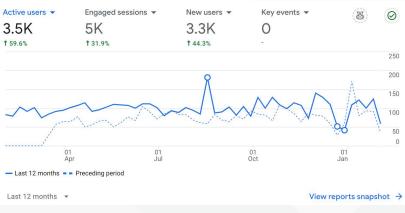
- Maintain models that can be downloaded and repurposed for specific need/designs.
- Host reference problem that can be used for code-to-code comparison.
- Showcase challenge problems.
- Enable coordination of teams working on similar reactor type.
- Share models and new capabilities developed through Department of Energy (DOE) programs.
- Industry relevant through active collaborations.
- Model used for student training.

Success stories:

- VTB models referenced in a Nuclear Regulatory Commission (NRC) report on verification and validation of Nuclear Energy Advanced Modeling and Simulation (NEAMS) tools.
- Very positive feedback from industry and university partners.







3,300+ Distinct Users (2,500 last year)







Output of Radiant SBIR was released on the VTB





Quick Overview: NRC/VTB Collaboration

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United States Nuclear Regulatory Commission
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April 1, 2025



- NRC, in collaboration with INL and ANL, is using the BlueCRAB suite of codes to develop reference plant models for a number of advanced non-LWR technologies, including:
 - gas-cooled pebble bed reactors,
 - molten salt cooled pebble bed reactors,
 - sodium cooled fast spectrum reactors,
 - heat pipe cooled microreactors,
 - molten salt fueled thermal spectrum reactors, and
 - molten salt fueled fast spectrum reactors.
- NRC plans to update these reference plant models with actual design information, as needed, in support of its licensing review needs and priorities.



- Throughout the process of reference plant model development, the NRC staff as well as the INL and ANL teams benefited greatly from the information that was readily available in VTB.
 - > VTB included some example problems that were used, in part, as a staring point in developing the NRC reference plant models, or that provided insights and guidance into the model development and the setup of the multi-physics coupled simulations.
 - DOE provided a number of training workshops to NRC staff on the NEAMS codes. The learning curve was somewhat steep for NRC staff, but VTB was helpful as the staff used it as a complimentary source of information to overcome the challenge.
 - VTB is also very helpful to NRC staff as they are in the process of developing their own model in support of the HTTR LOFC project.



- NRC ensures that advanced reactor work it funds, in full or in part, is made available to the public, provided that all security and proprietary-related requirements are met. NRC also encourages uploading its reference plant models, as they are being developed and updated, onto VTB. So far, the following models have been uploaded onto VTB:
 - HTR-10 3D Griffin model
 - MSRE 2D-RZ coupled Griffin- Pronghorn (neutronics funded by NRC)
 - gFHR 2D-RZ coupled Griffin- Pronghorn
 - Generic Heat Pipe Microreactor 3D coupled Assembly BISON-Sockeye
 - HTR-PM SAM model
 - ABTR SAM 5-channel model (primarily based on NEAMS work)



- NRC also plans to make the following reference plant models available to the public once they are developed and to have them uploaded onto VTB as well, provided that all security and proprietary-related requirements are met:
 - ABTR 3D coupled Griffin-Bison-SAM (61 channel model)
 - PB-FHR 2D-RZ coupled Griffin-Pronghorn-BISON-SAM
 - HTR-PM 2D-RZ coupled Griffin-Pronghorn-BISON-SAM
 - PB-FHR 3D coupled Griffin-Pronghorn-BISON
 - HTR-PM 3D coupled Griffin-Pronghorn-BISON
 - PB-FHR 2D-RZ coupled Griffin-SAM
 - HTR-PM 2D-RZ coupled Griffin-SAM
 - Generic Heat Pipe Microreactor 3D coupled Griffin-BISON-Sockeye
 - Additional new or updated reference plant models once they are developed and approved





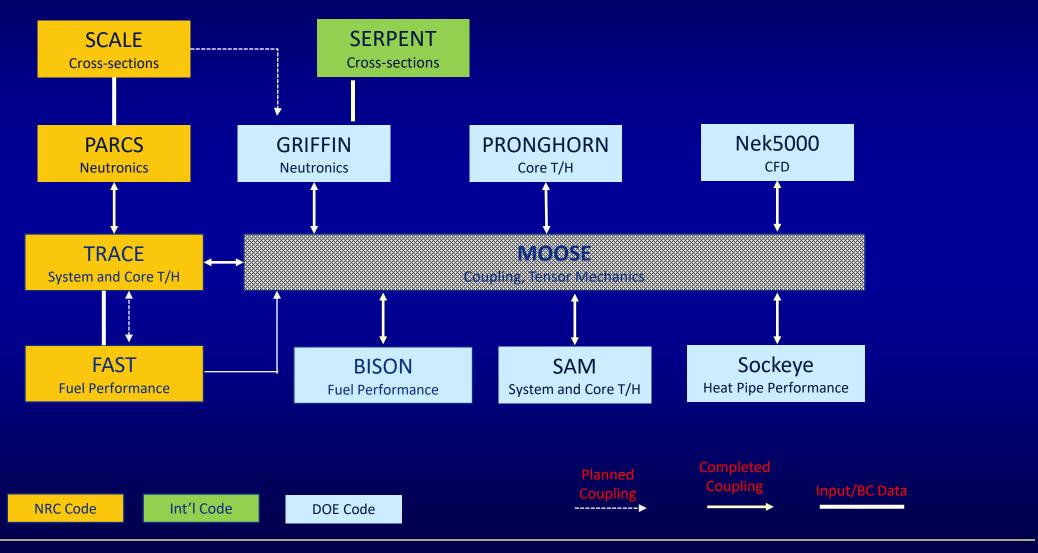


Backup Slide

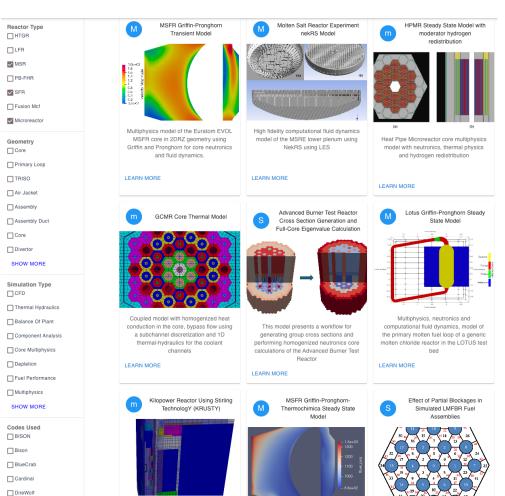


Comprehensive Reactor Analysis Bundle "BlueCRAB"





VTB Repository Improvements



Coupled multiphysics model of the MSFR

core with neutronics, fluid dynamics and

salt thermochemistry using

fast reactor assemblies using a

subchannel discretization of the thermal

hydraulics. The new flow distribution is

the core of the Kilopower Reactor Using

Stirling TechnologY using NEAMS tools

- Search engine with filters:
 - User friendly interface to find models faster.
 - Filter model by reactor type, physics, code used, model size, simulation type, Verifcation and Validation (V&V) status etc.
- New models uploaded and maintenance of existing models.
- Deployment of High-Performance Computing (HPC) testing of the models:
 - Large memory and several compute nodes to be fully tested.
 - HPC testing enabled by containerized applications and test scheduler.
 - Contributes to root out model deprecation and breakage.



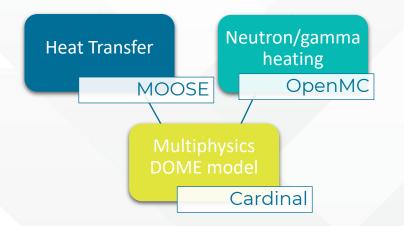
Griffin

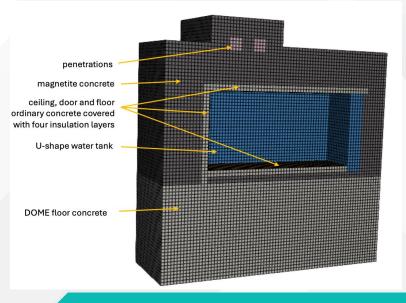
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MASTODON

NRIC-DOME Shield Virtual Model

- **Goal:** Accelerate confirmatory analysis by providing a model of the NRIC-DOME shield that can interface with a NRIC-DOME user reactor model.
- Model requirements:
 - Coupling with any reactor design.
 - Evaluation of the maximum concrete temperature in the shield for both steady state operation and transient scenarios.
 - Evaluation of the doses in the NRIC-DOME facility.
 - Use open-source codes.
 - Model should be easy to modify to accommodate shield configuration changes.

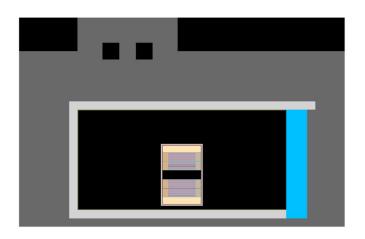




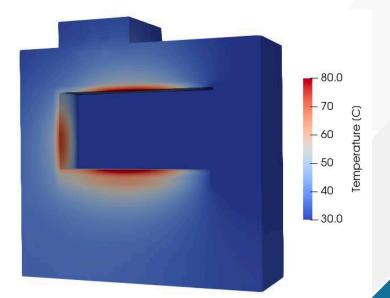


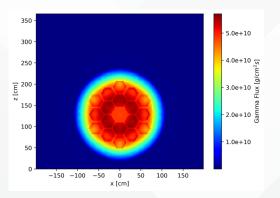
NRIC-DOME Shield Multiphysics Model

- Evaluation of the neutron/gamma heating in OpenMC:
 - Generate a physical source term problem with the goal of 2 reactor types (heat pipe and gas cooled [ongoing]).
 - Develop a model for shield with a fixed source.
 - Extensive verification and testing of the model.
- Coupling with thermal model in Cardinal:
 - Max concrete temperature of 84C.
 - Verification of Multiphysics approach.

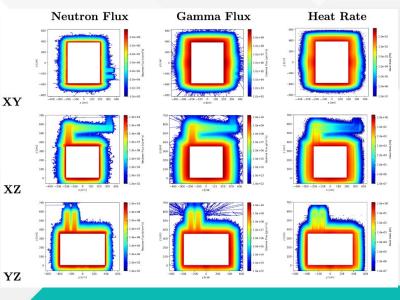


OpenMC model of the NRIC-DOME shield





OpenMC model of a heat pipe micro reactor





Summary

- VTB Goal: Support deployment of advanced reactor by building a database of models & simulations integrated with software QA.
- VTB Benefits: Accelerate timeline for Nuclear Regulatory Commission (NRC)/Department of Energy (DOE) review of candidate demos, support maturation of industry designs.
- VTB Stakeholder engagements: Government (DOE, NRC), Industry, Academia, other DOE programs (ART, MRP).
- FY25 Tasks: (1) repo improvements, (2) hosting external models, (3) generating models for NRIC-DOME Shield.
- Future Scopes: Expand NRIC-DOME models, Linking with Digital Engineering, Support Commercial Grade Dedication.



Questions?

https://mooseframework.inl.gov/virtual test bed

