INL/CON-23-74349-Revision-0

Modeling and Simulation Techniques and Tools for the US Microreactor Program

August 2023

Changing the World's Energy Future

Jess C Gehin, Youssef A Shatilla

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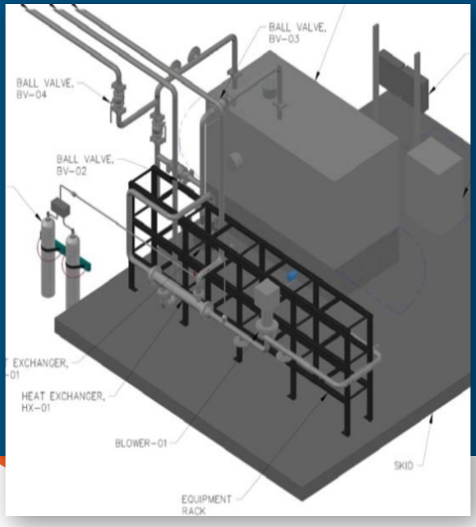

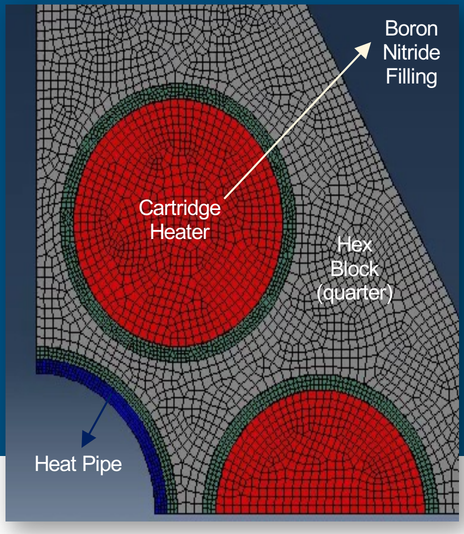

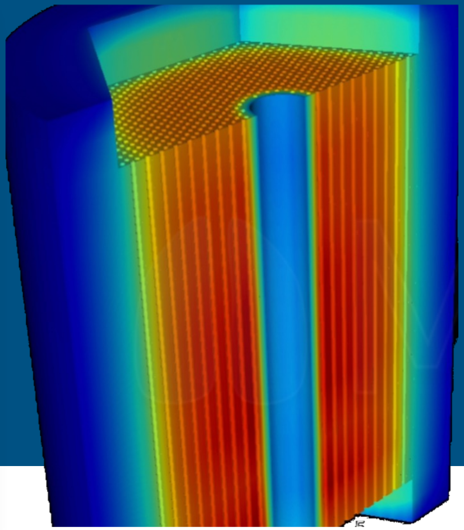

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August 17th 2023

INL Idaho National Laboratory

MRP Microreactor Program

DOE Microreactor Program – 2023

Program Vision

Through cross-cutting research and development and technology demonstration support, the Microreactor Program will enable broad deployment of microreactor technology by:

- Achieving technological breakthroughs for key features of microreactors
- Identifying and addressing technology solutions to improve the economic viability and licensing readiness of microreactors.
- Enabling successful demonstrations of multiple domestic commercial microreactors.

Program Objectives

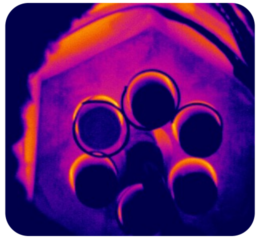
- Address critical cross-cutting R&D needs that require unique laboratory/university capability or expertise
- Develop R&D infrastructure to support design, demonstration, regulatory issue resolution, and M&S code validation
- Develop advanced technologies that enable improvements in microreactor viability

National Technical Director: John Jackson (INL)

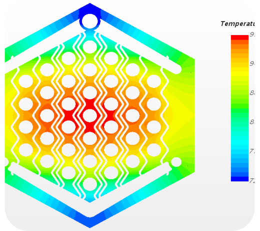
Technology Readiness Level

Microreactor Application
- Integrated Nuclear Testing
- Applied R&D

Demonstration Support Capabilities
- Non-nuclear Testing
- Test-beds for developers/regulators



Technology Maturation
- Matures fundamental microreactor enabling technologies and capabilities



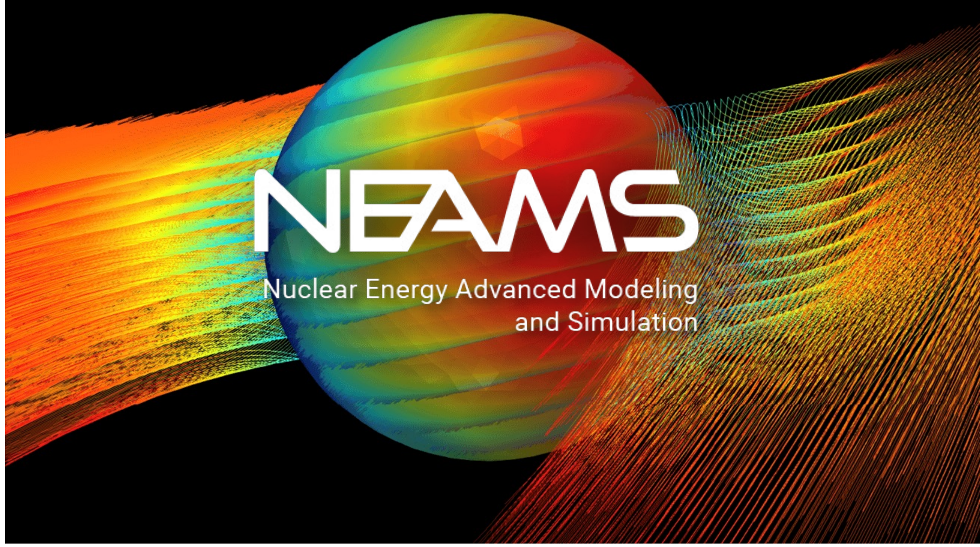
System Integration & Analyses
- Identification of technology and regulatory gaps for Microreactors

MRP Microreactor Program

NEAMS Program

www.neams.inl.gov

- Nuclear Energy Advanced Modeling & Simulation
- DOE-NE led program across several national labs: INL, ANL, ORNL, LANL
- Both LWR and non-LWR advanced reactor designs
- Divided into 5 technical areas:
  - Fuel Performance
  - Reactor Physics
  - Thermal Hydraulics
  - Structural Materials & Chemistry
  - Multiphysics Application
- Primarily leveraging MOOSE framework for Non-LWR software development



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INL Idaho National Laboratory

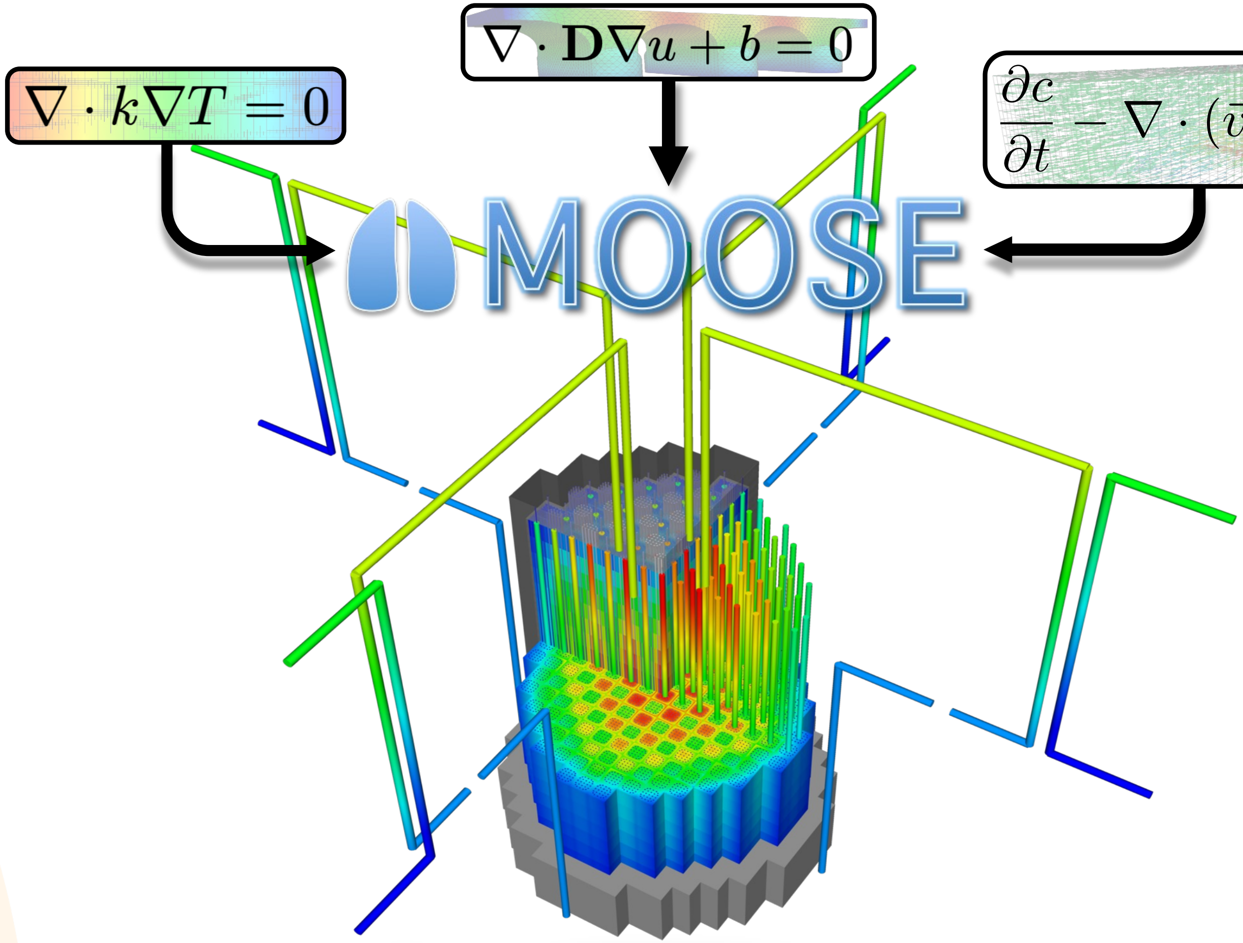
Argonne NATIONAL LABORATORY

OAK RIDGE National Laboratory

Los Alamos NATIONAL LABORATORY

MRP Microreactor Program

MOOSE – Multiphysics Object-Oriented Simulation Environment



What is MOOSE?

- Multiphysics
- Complete Platform
- Open-source
  - Equity, Inclusion
- Massively Parallel
- Flexible

mooseframework.org

Accelerates Development of High-Fidelity Modeling and Simulation Tools

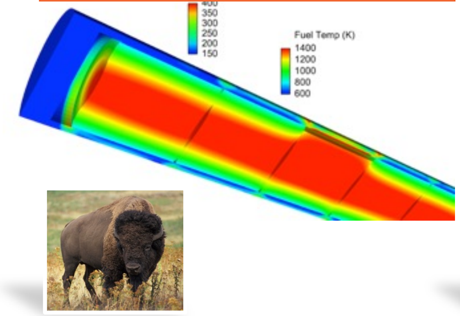
MRP Microreactor Program

Accelerating Microreactor Deployment

NEAMS

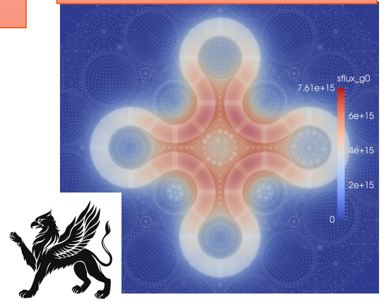
Selection of MOOSE-based Tools for Microreactor Simulation

Bison
Nuclear Fuel Performance

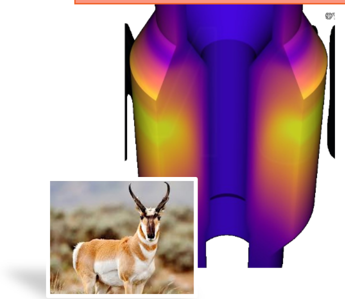


Grizzly
Structural Mechanics for Component Aging

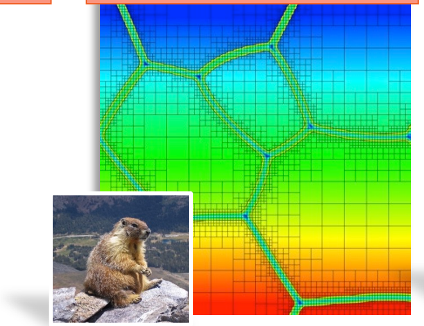
Griffin
Radiation Transport



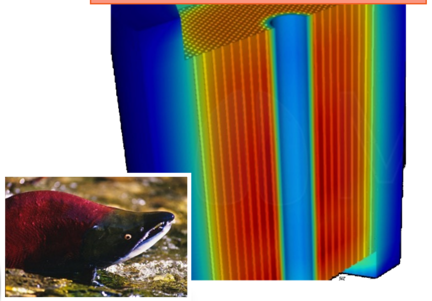
Pronghorn
Medium-fidelity CFD



Marmot
Mesoscale Materials



Sockeye
Heat pipe Simulation



Selection of Organizations Using NEAMS Tools For Microreactor Analysis

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Westinghouse

BWXT
Nuclear Energy Canada Inc.

RADIANT

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Heat Pipe Microreactor Modeling - Sockeye

- Engineering scale heat pipe application for the analysis of heat pipes in microreactors.
  - Focus is on high-temperature heat pipes.
- Based on the MOOSE framework.
  - Relatively simple coupling to other MOOSE-based applications.
- Funded by the Nuclear Energy Advanced Modeling and Simulation (NEAMS) program.

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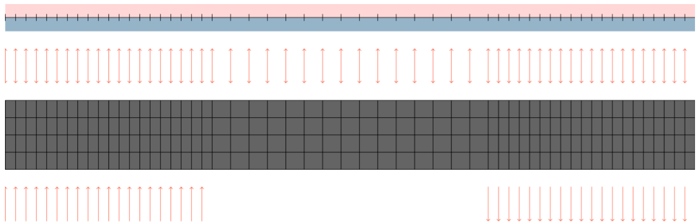
Sockeye Capabilities Overview

Two-Phase Flow Model

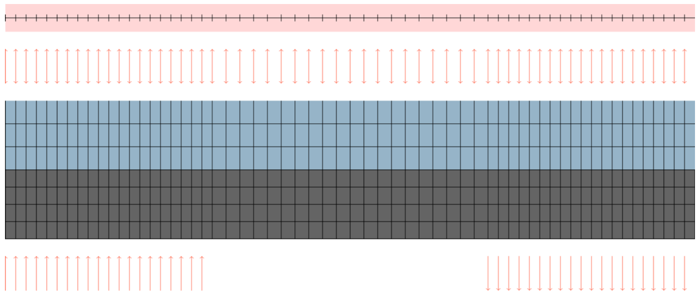
1D two-phase flow



- 1D two-phase flow
- 7 flow equations for liquid/vapor, coupled to 2D heat conduction in cladding.
- Most accurate, least robust.

Vapor-Only Flow Model

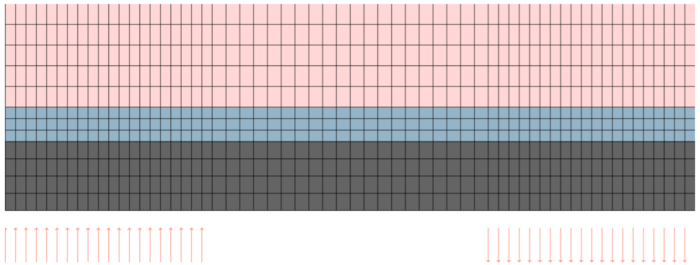
1D single-phase flow



- 1D single-phase flow
- 3 flow equations for vapor, coupled to 2D heat conduction in wick and cladding.
- Moderate accuracy and robustness.

Conduction Model

2D heat conduction



- 2D heat conduction for entire heat pipe domain.
- Least accurate, most robust.

Single Primary Heat Extraction and Removal Emulator

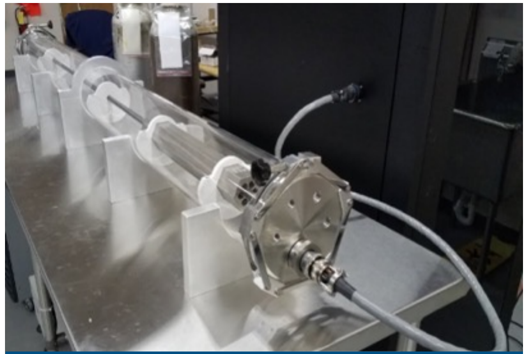
Provide capabilities to perform steady-state and transient testing of heat pipes and heat transfer:

- Wide range of heating values and operating temperatures
- Observe **heat pipe startup and transient operation**

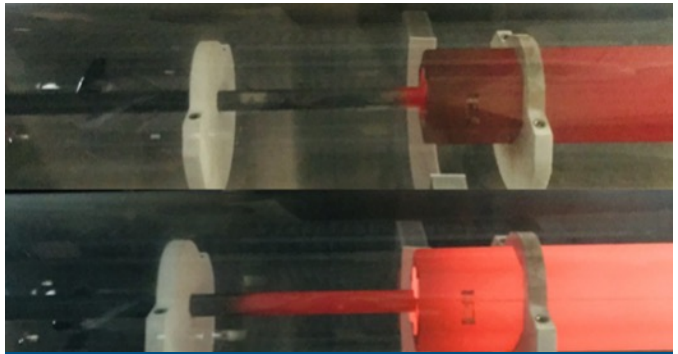
Develop effective thermal coupling methods between the heat pipe outer surface and core structures

Measure heat pipe axial temperature profiles during **startup, steady-state, and transient operation** using thermal imaging and surface measurements

Parameter	Value
Length	243 cm
Diameter	15 cm
Tube material	Quartz
Connections	Flanged for gas flow and instrumentation feedthrough
Maximum power	20 kW
Max temperature	750 C
Heat removal	Passive radiation or water-cooled gas gap calorimeter



SPHERE Test BED



Optical image of the block and heat pipe operations

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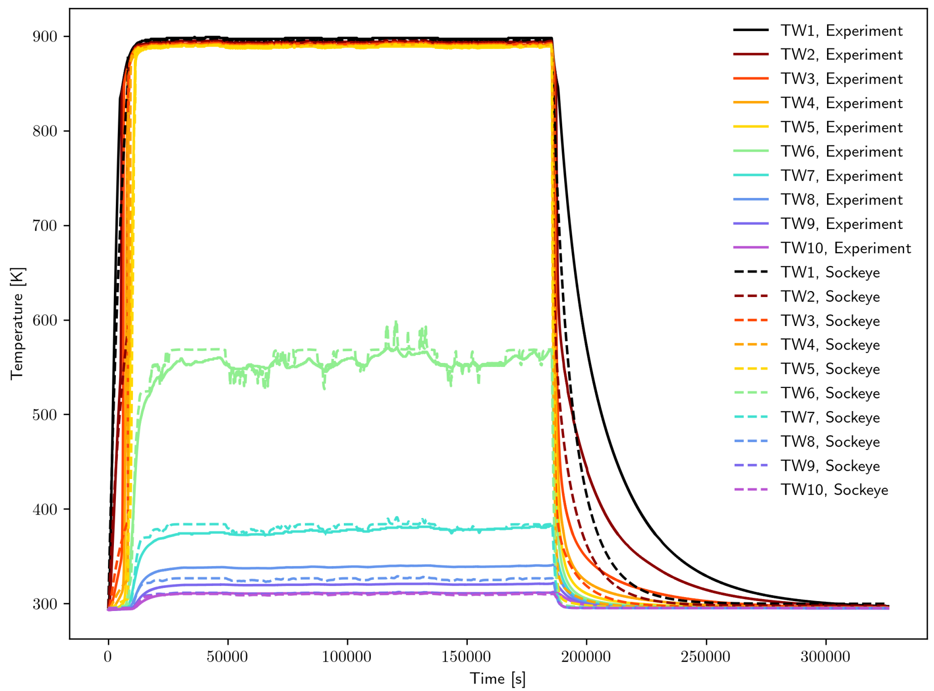
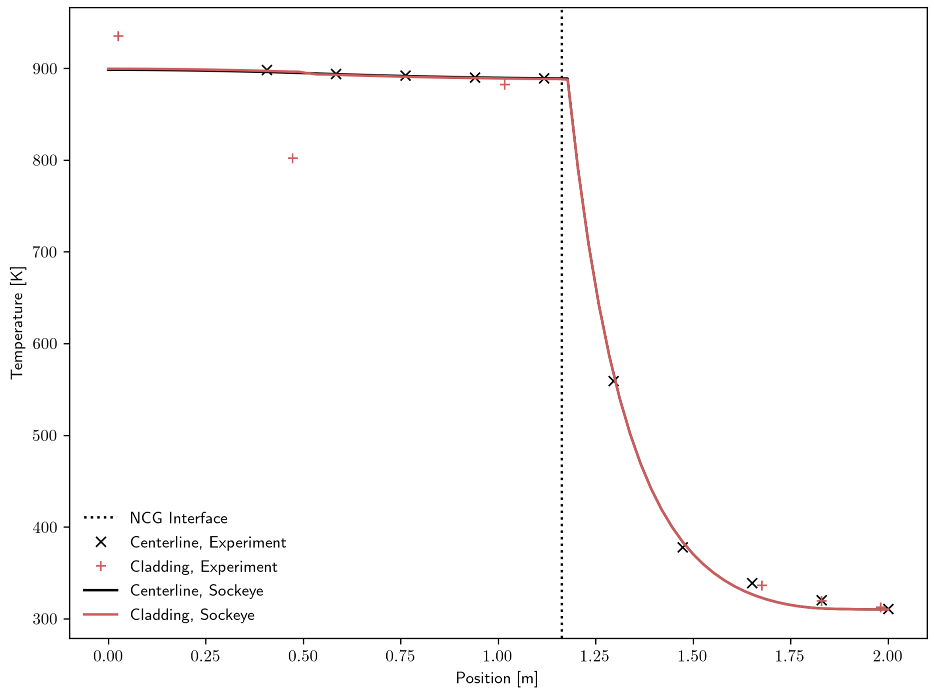
SPHERE Assessment

- Data produced in run performed Feb. 3, 2021.
- Sodium heat pipe manufactured with central thermowell for mounting 10 thermocouples to approximate vapor core temperature.
- Several externally mounted thermocouples.
- Frozen startup, steady operation, and shutdown.
- Used Sockeye's conduction heat pipe model.
  - Found non-condensable gases to be necessary to account for inactive length.
- Upper right: transient of vapor temperatures.
- Lower right: spatial temperature profile in steady portion of transient.

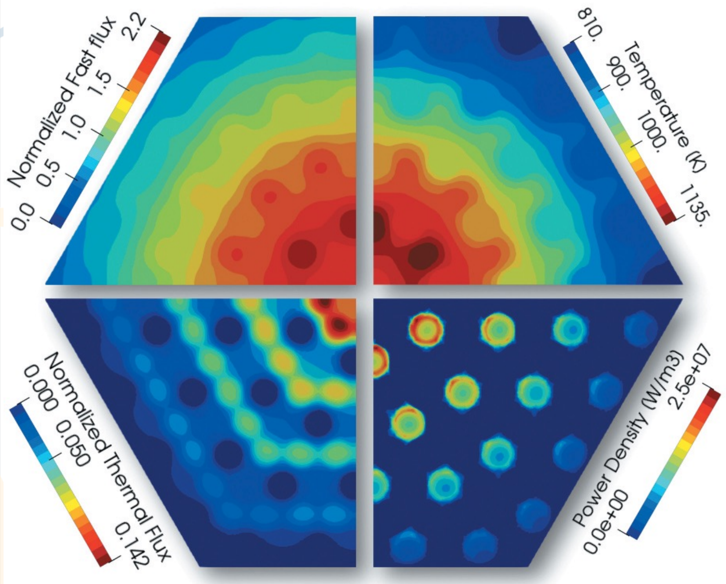


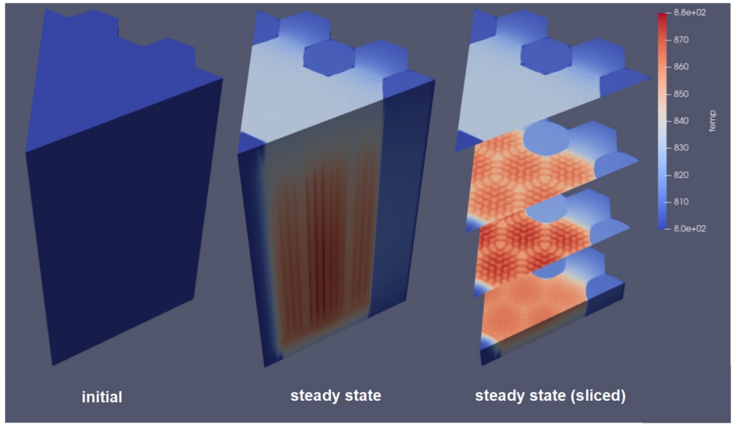


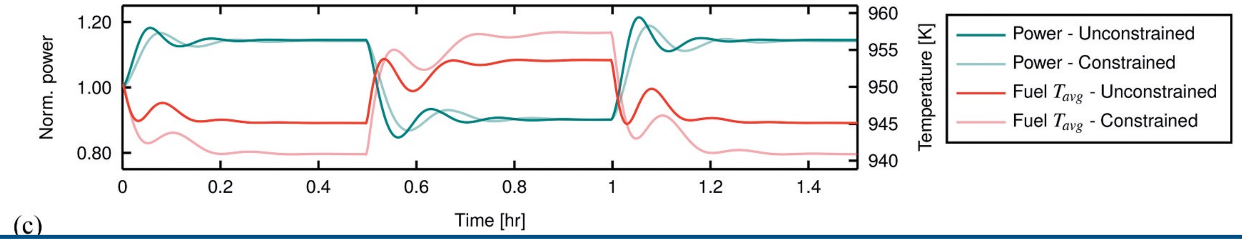
MOOSE-based Microreactor Models

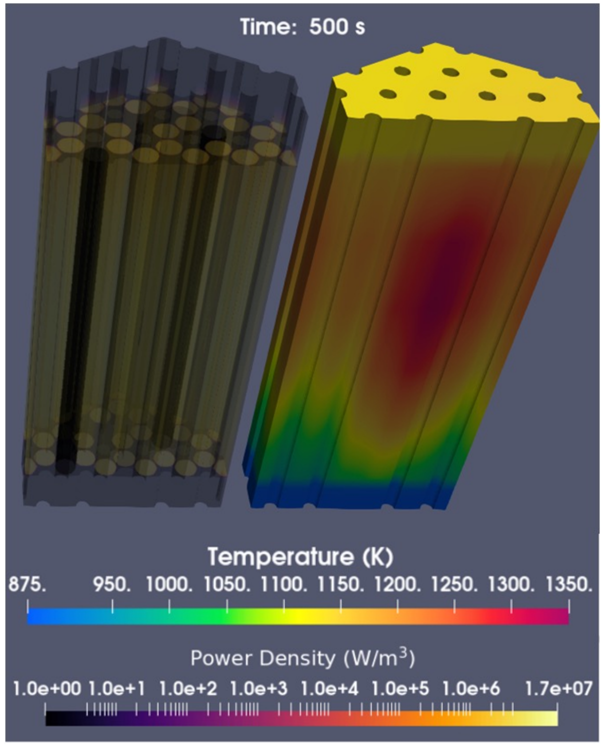
Empire Design

- Coupled core neutronics (Griffin), heat pipe (Sockeye), and thermomechanics (Bison)
- Steady-state and transient simulations
- POC: Javier Ortensi(INL), Nicolas Stauff (ANL)









Generic Gas-cooled Microreactor (GC-MR)

- Neutronics (Griffin) coupled with system hydraulics (SAM) and thermomechanics (Bison)
- Steady state and transient capabilities
- POC: Nicolas Stauff (ANL)

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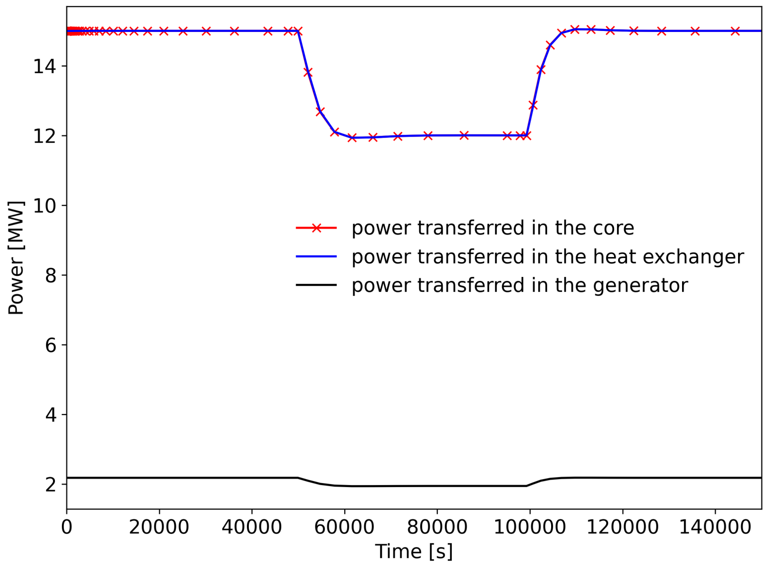
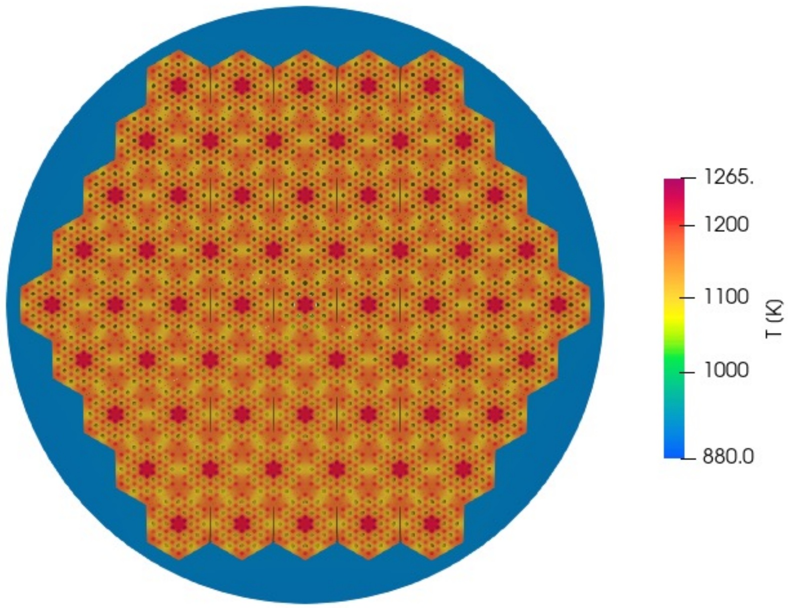
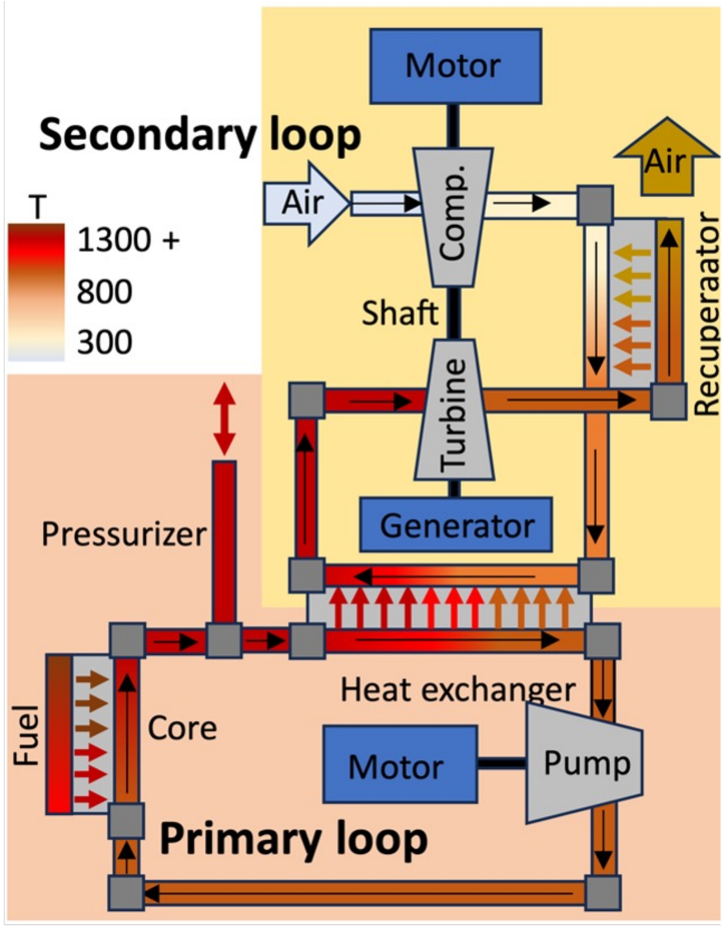
MOOSE-based Balance of Plant for Gas Cooled Microreactor

- Open-source thermal-hydraulic model including:
  - Detailed 3D heat conduction model of the core
  - Primary loop with circulator
  - Heat exchanger
  - Open-air Bryton cycle
- Start-up and load-follow transients







Credit: Sixte de Boisset(INL), Lise Charlot(INL), Thomas Freyman(INL), Joshua Hansel(INL).

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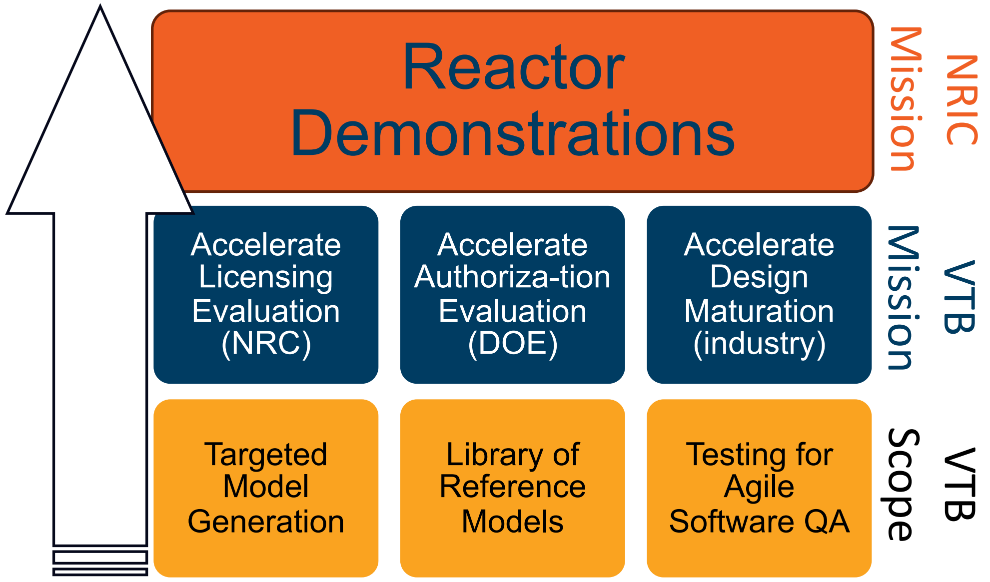
Contact: abdalla.aboujaoude@inl.gov

NRIC Virtual Test Bed (VTB)

mooseframework.org/virtual_test_bed



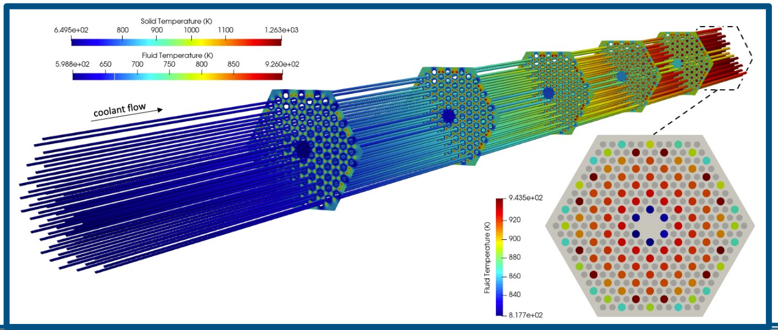
- The VTB supports the National Reactor Innovation Center (NRIC) mission of delivering successful demonstration and deployment of advanced nuclear energy

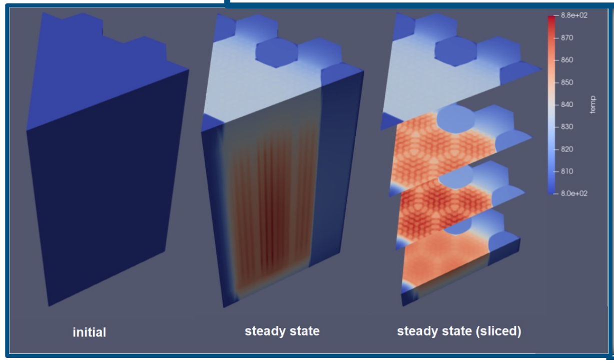
How?

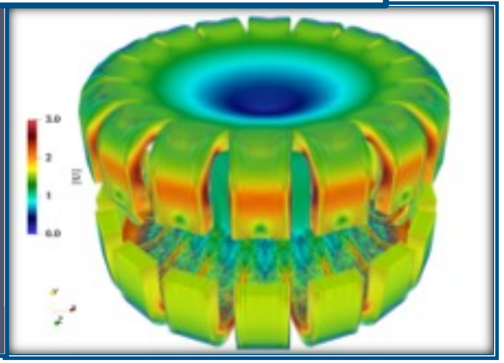
- **Library of Reference Model**: database of advanced multiphysics advanced reactor models that users can download, edit, and re-run
- **Targeted Model Generation**: developing demonstration-relevant models (e.g., candidates for DOME/LOTUS) to accelerate safety evaluations
- **Continuous Software QA**: linking repository to software development to avoid legacy issues while enabling rapid code development

VTB So Far

- 30+ models hosted (and counting): 14 reactor designs, and 7 codes showcased
- Collaboration with NEAMS, industry, NRC, and academia
- Help accelerate timelines for DOE/NRC confirmatory analysis
- Accelerate development cycle for industry and academia

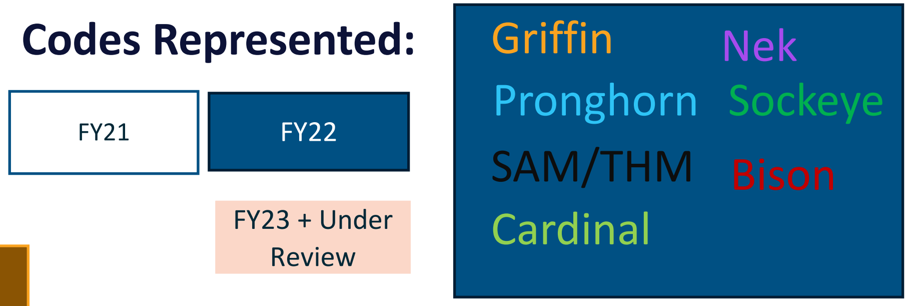


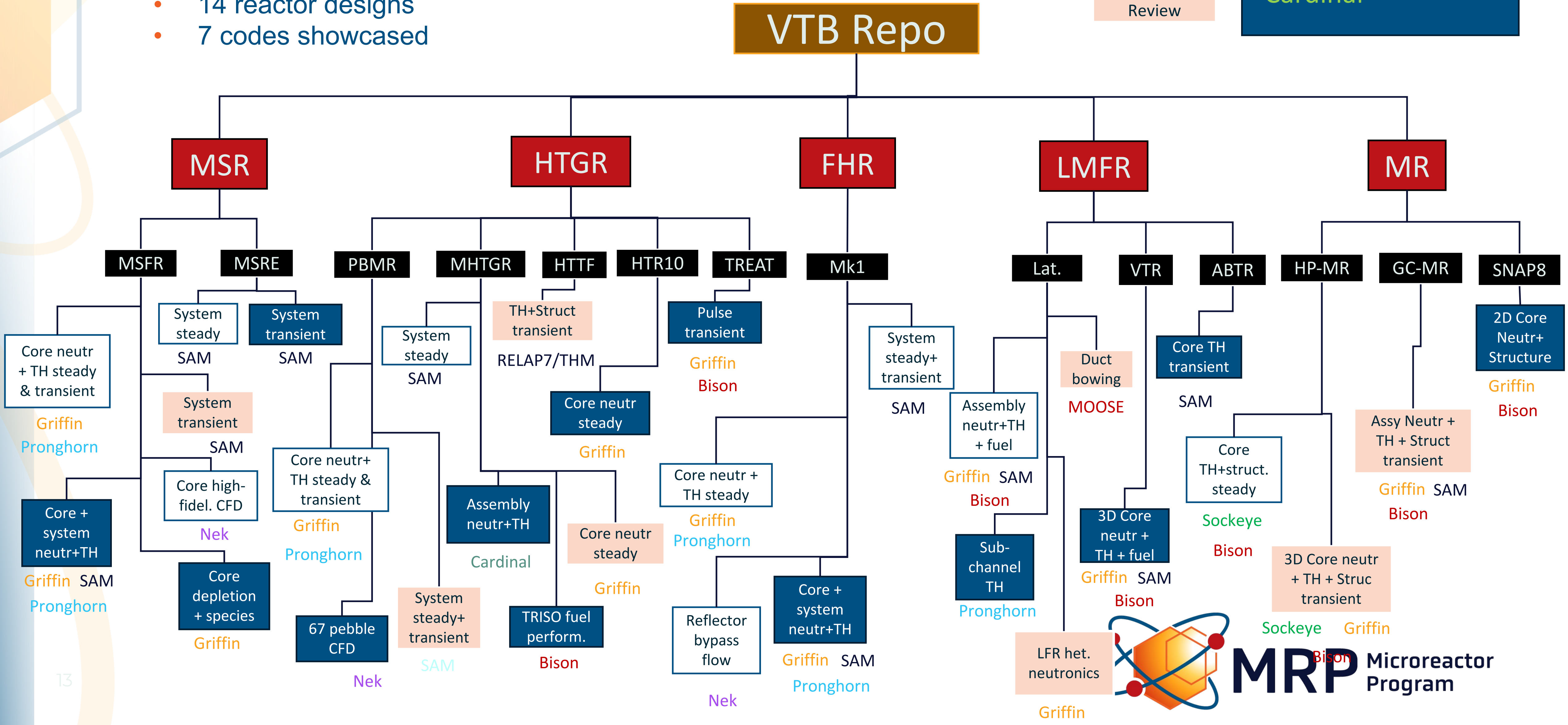




VTB Model Tree

- 30+ distinct simulations
- 14 reactor designs
- 7 codes showcased





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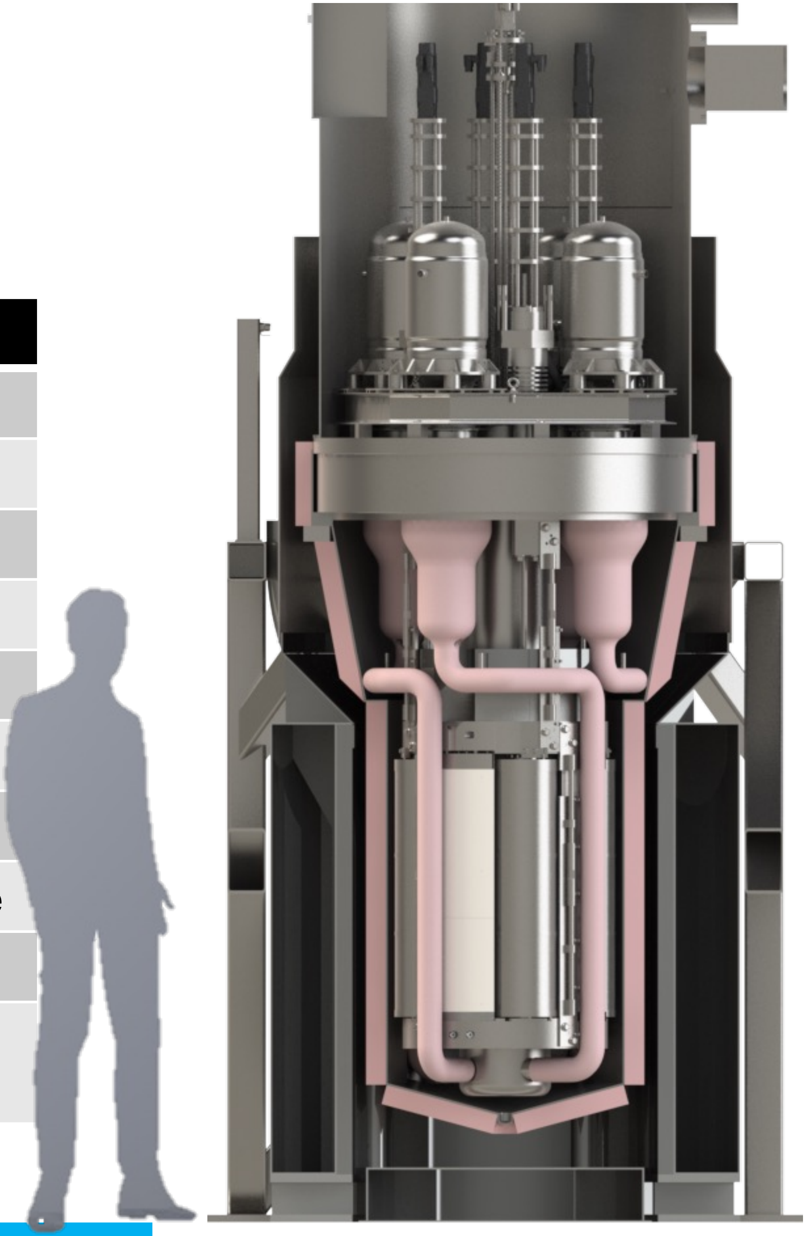
MARVEL - Test Microreactor

Microreactor Application Research, Validation and EvaLuation Project

Key Design Features	
Thermal Power	100 kW (85kW nominal)
Electrical Power	~20 kWe (QB80 Stirling Engines)
Weight	~7.5 metric ton
Primary Coolant	Sodium-Potassium eutectic
Coolant Driver	Natural Convection, single phase
Fuel	HALE(UZrH), 304SS clad, end caps
Moderator	Hydrogen
Core Reflector	Graphite, Beryllium (S200), Beryllium oxide
Reactivity Control	Radial Control Drums, Central Absorber
Primary Coolant Boundary	SS316H



MARVEL's Thermal Hydraulic Design is Novel

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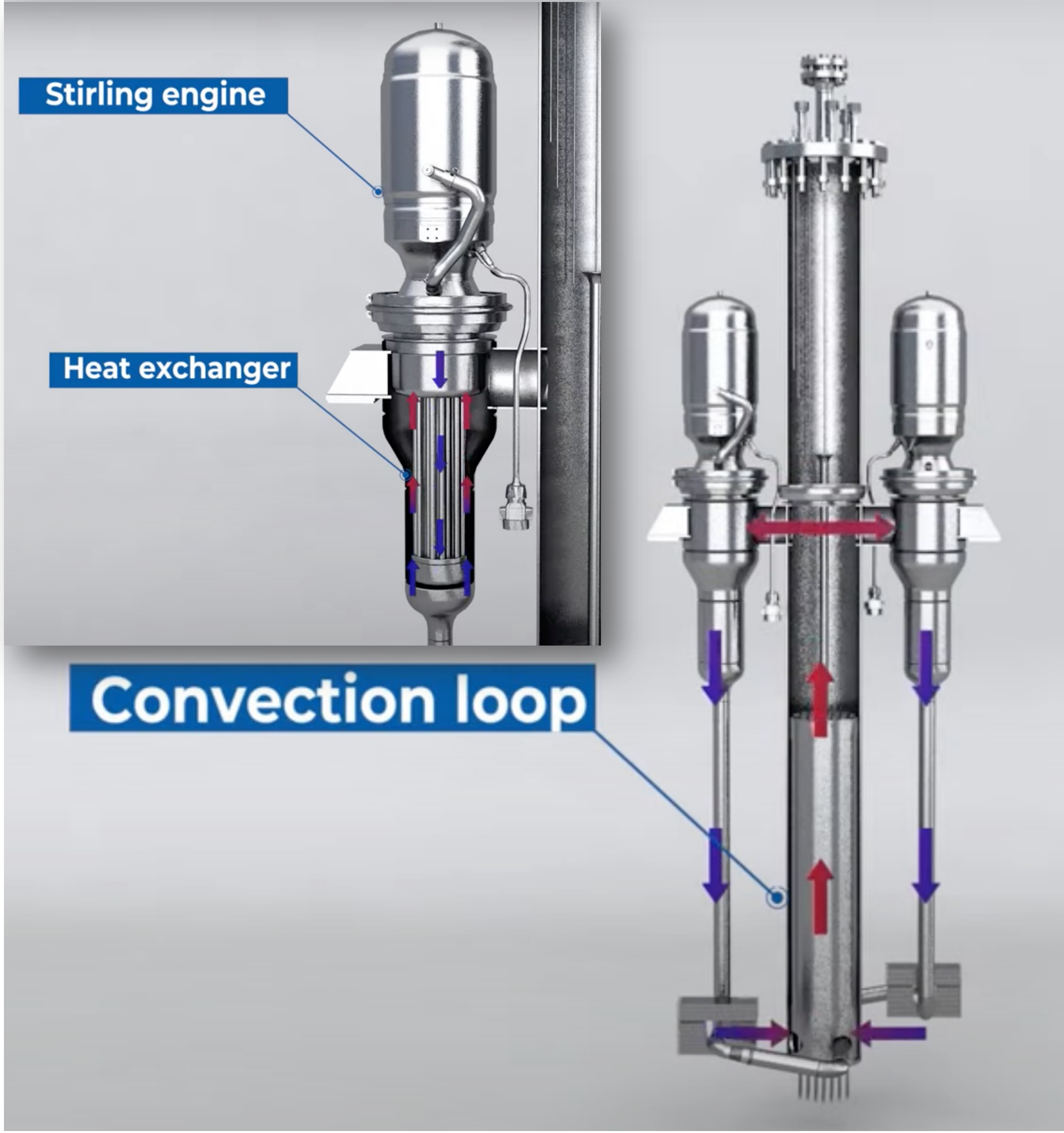
MARVEL Thermal Hydraulics

- Primary Coolant is driven by natural circulation
  - Reynold’s Number < 6000
  - P/D <1.1
- Four intermediate lead loops- also natural circulation
- Vibrating Stirling engine in lead

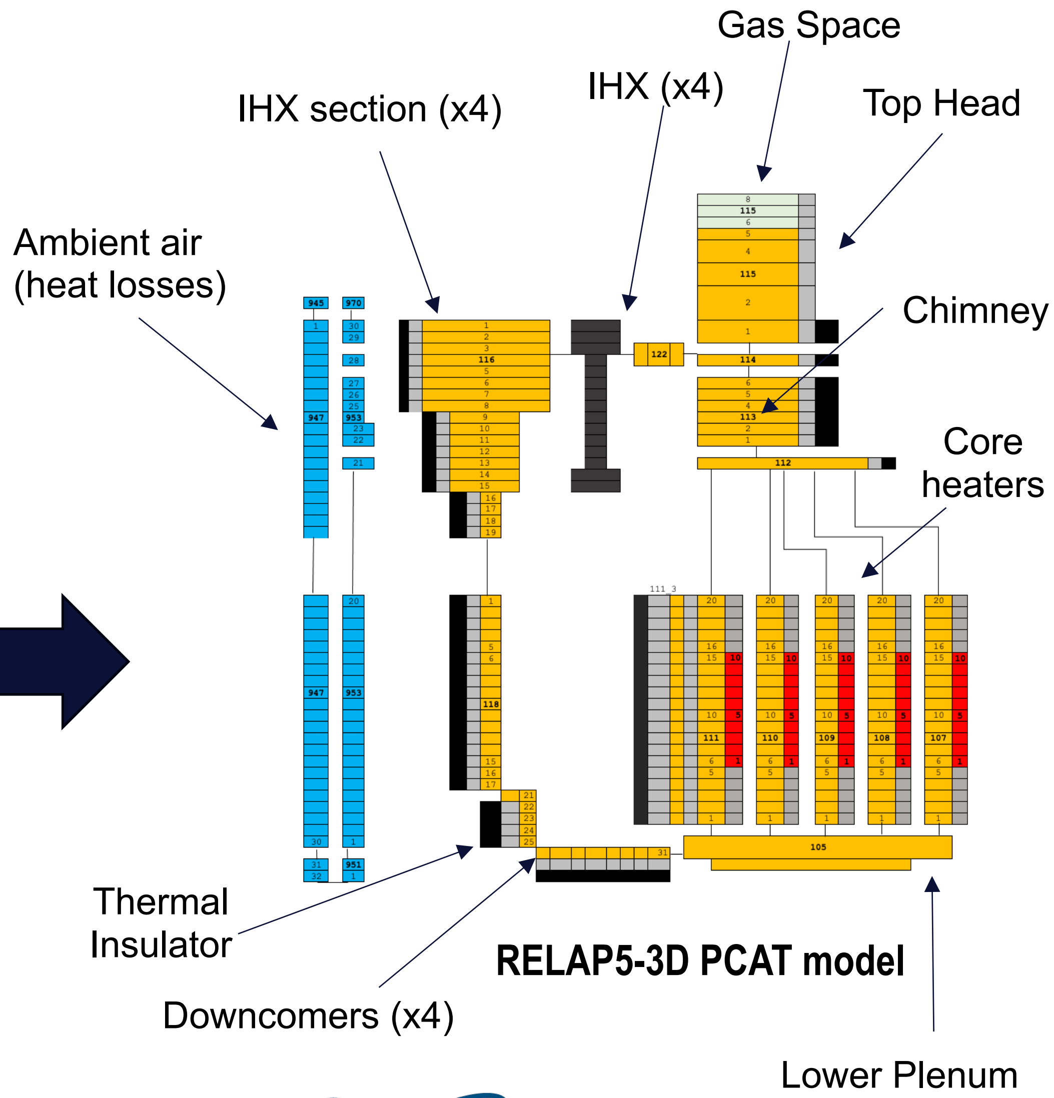
Parameters - Primary & secondary side	SS Values
NaK inlet core temperature, ºC	465
NaK outlet core temperature, ºC	532
NaK core temperature rise, ºC	67
Total mass flow, kg/s	1.55
IHX Pb minimum temperature, ºC	386
IHX Pb maximum temperature, ºC	411
Pb temperature rise, ºC	25
IHX Pb mass flow, kg/s	5.2



PCAT & RELAP5-3D Thermal-hydraulic Modeling

- The **Primary Coolant Apparatus Test** (PCAT) is the electrically-heated integral test loop of MARVEL
- **INL RELAP5-3D** is the reference thermal-hydraulic system code for MARVEL design and analysis
  - Validation to be performed using PCAT experimental data
  - PCAT RELAP5-3D model developed for pre-test and post-test analyses
  - Parallel activity code-to-code comparison RELAP5-3D/SAM being also performed

MARVEL PCAT



RELAP5-3D PCAT model

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Multiphysics Modeling of MARVEL with NEAMS tools

- A 3D full-core model of the MARVEL reactor is currently under development.
- The model includes (1) neutronic transport through DFEM-S_N, (2) heat conduction, and (3) hydrogen redistribution in the $UZrH_x$.

Block	Code
Cross Sections	**Serpent**
Mesh	**MOOSE**
Neutronics	**Griffin**
Conduction/H redistribution	**Bison**

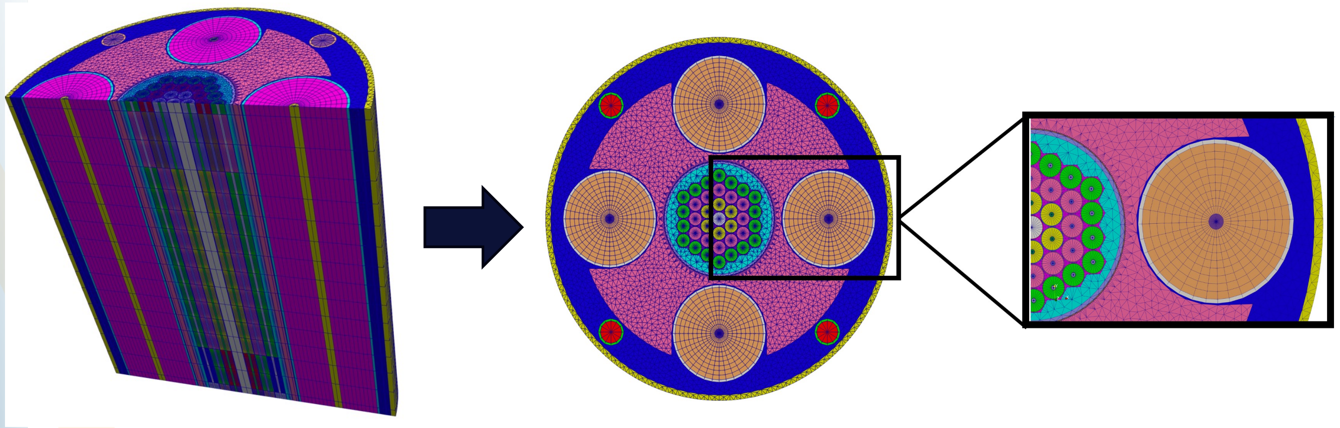
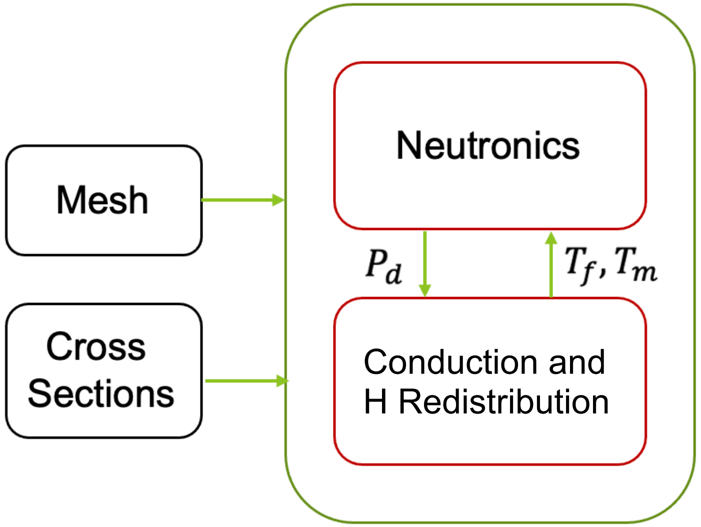


Fig. 1: MOOSE-generated 3D mesh and mid-plane



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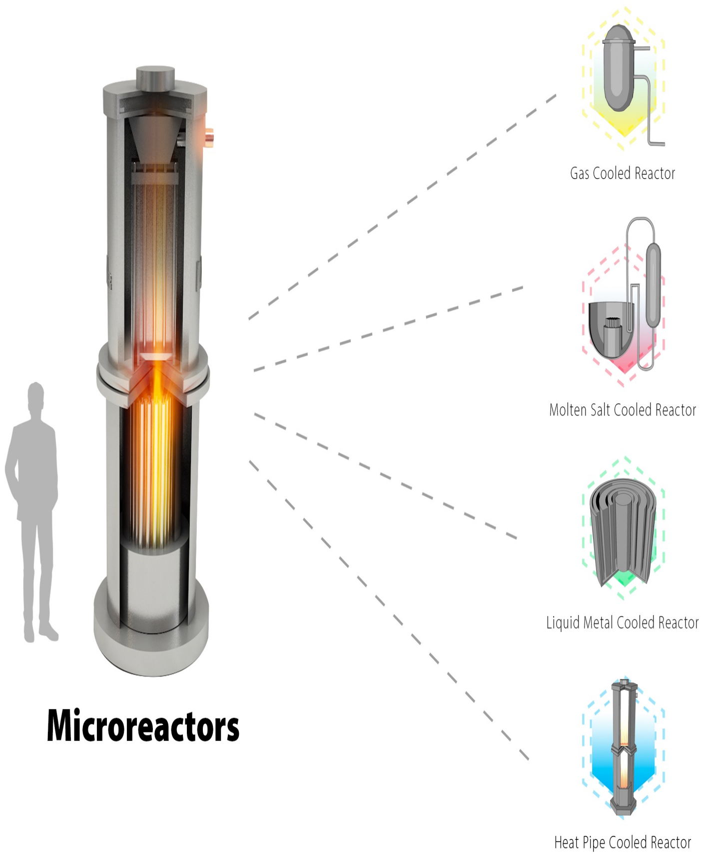
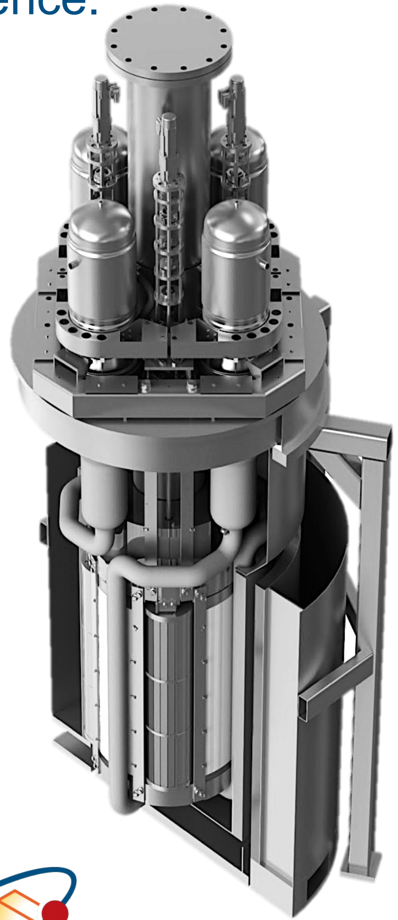
Main Conclusions

- Working closely with other DOE Programs to leverage and support joint efforts
- Regular interaction with industry through programs such as NRIC (ARDP funded projects)
- Interaction with Academia through DOE-NEUP program
- Successful demonstration are needed to gain utility, regulator, and public confidence.





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