INL/MIS-24-76532-Revision-0

INL's Reactor Physics Capabilities

March 2024

Changing the World's Energy Future

Youssef A Shatilla

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INL’s Reactor Physics Capabilities

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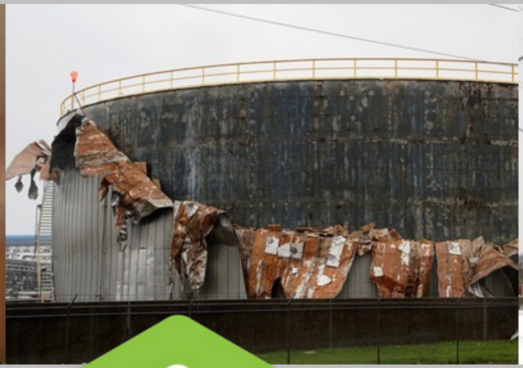
Reactor Physics Methods and Analysis (C110)

Addressing the world’s most pressing challenges through research, development, and demonstration


VISION

INL will change the world’s energy future and secure our critical infrastructure.

MISSION

Discover, demonstrate and secure innovative nuclear energy solutions, clean energy options and critical infrastructure.

VALUES

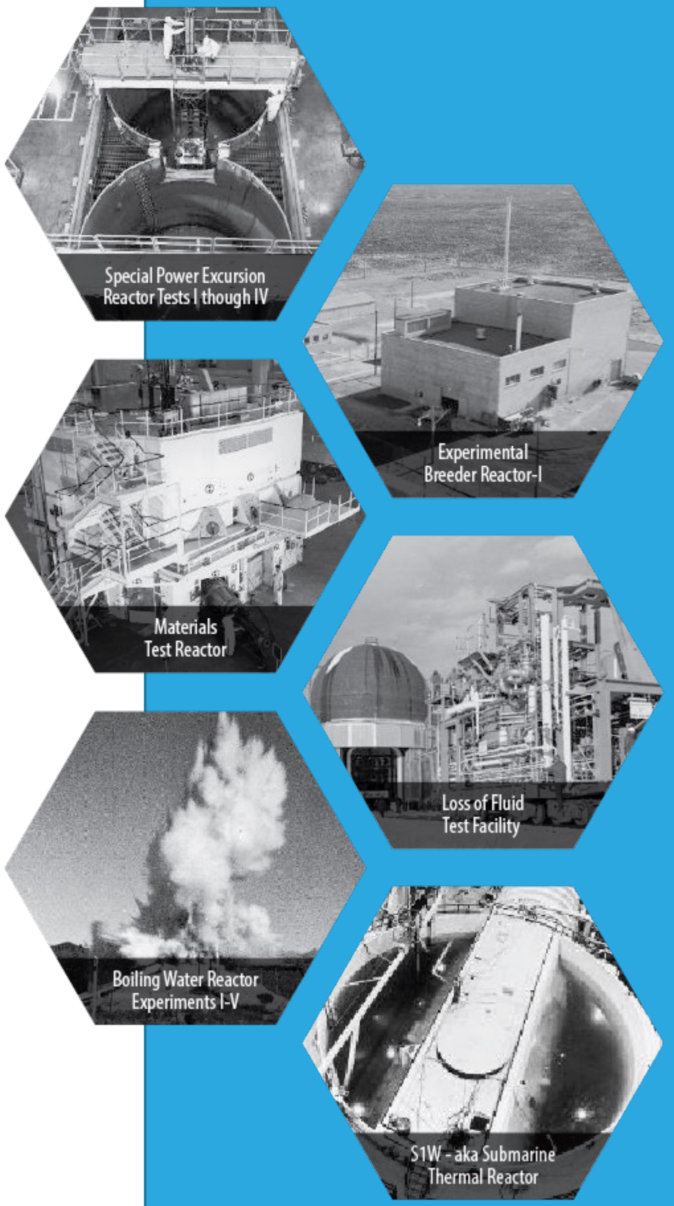
Excellence, Inclusivity, Integrity, Ownership, Teamwork, Safety.

Our Heritage: *The National Reactor Testing Station drove nuclear innovation in the U.S. and around the world*

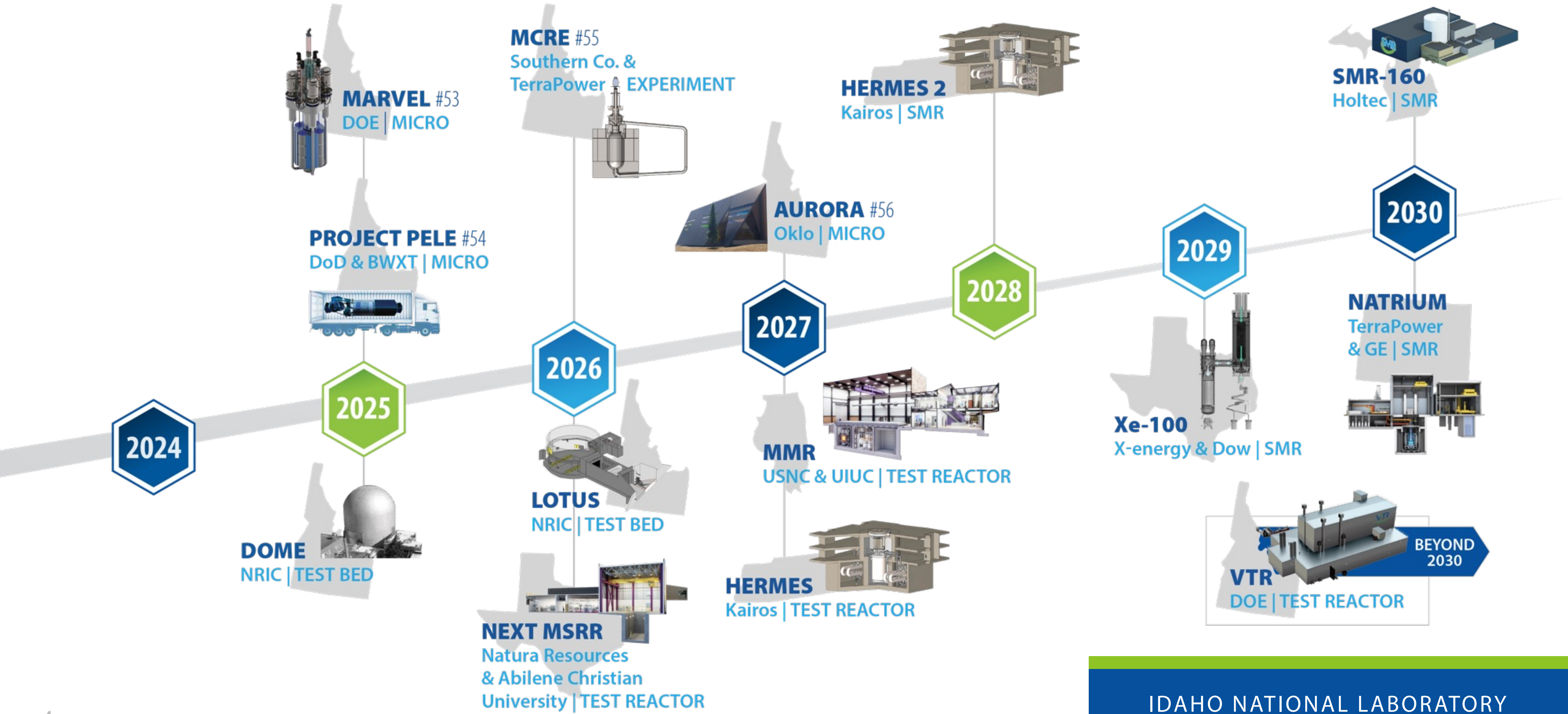
1st

- Nuclear power plant
- U.S. city to be powered by nuclear energy
- Submarine reactor tested; training of nearly 40,000 reactor operators until mid-1990s
- Mobile nuclear power plant for the army

Demonstration of self-sustaining fuel cycle	Basis for LWR reactor safety	Aircraft and aerospace reactor testing	Materials testing reactors

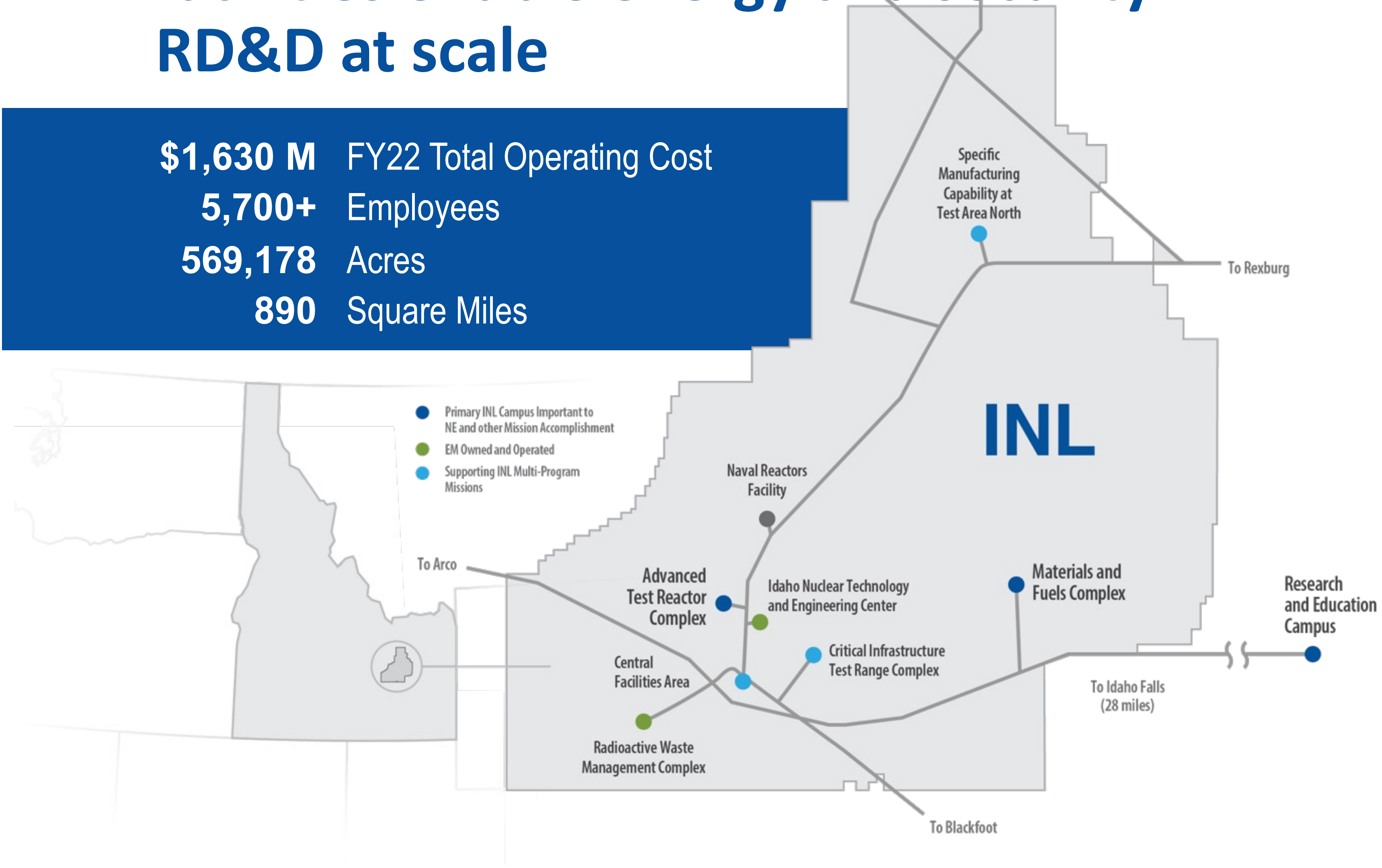


Accelerating advanced reactor demonstration & deployment



Unique INL site, infrastructure, and facilities enable energy and security RD&D at scale

$1,630 M	FY22 Total Operating Cost
5,700+	Employees
569,178	Acres
890	Square Miles

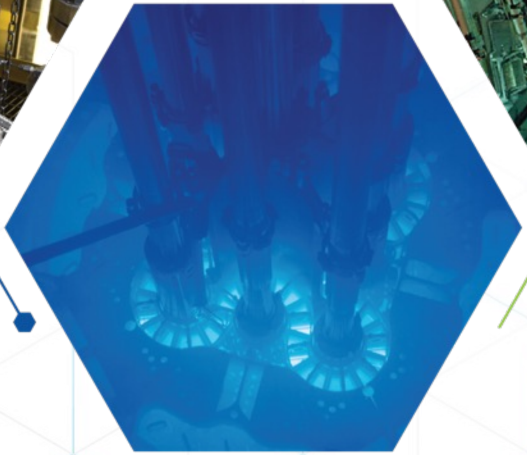


4	Operating reactors
12	Hazard Category II & III non-reactor facilities/ activities
50	Radiological facilities/activities
17.5	Miles railroad for shipping nuclear fuel
44	Miles primary roads (125 miles total)
9	Substations with interfaces to two power providers
126	Miles high-voltage transmission lines
3	Fire Stations

Creating a secure, resilient, clean energy future

Nuclear Science & Technology

Advanced Test Reactor Complex



Materials and Fuels Complex

Energy & Environment Science & Technology

National & Homeland Security Science & Technology

C110 – Reactor Physics Methods & Analysis

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Yaqi Wang
Holly Wrigley

C110 Vision

- “***To be the center of universe of multiphysics modelling and simulation of advanced nuclear reactors.***”

C110 Mission

- Provide reactor physics, analysis, and design expertise to enable the development of advanced nuclear reactors and fuel. Develop, verify, and validate MOOSE-based reactor physics capabilities and lead the integration of other MOOSE-based applications into multi-physics packages.

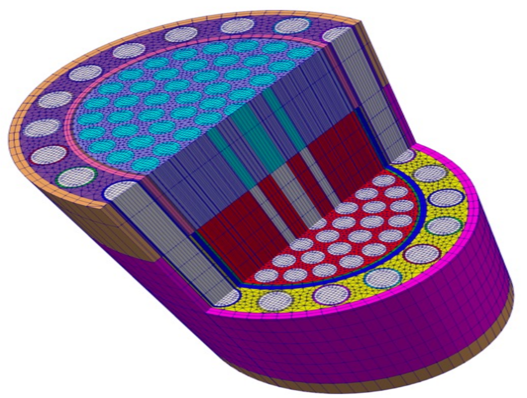
C110 Capabilities

- The available expertise ranges from basic nuclear data and radiation transport to core performance and overall fuel cycle issues; cradle-to-grave analysis for advanced reactor systems.

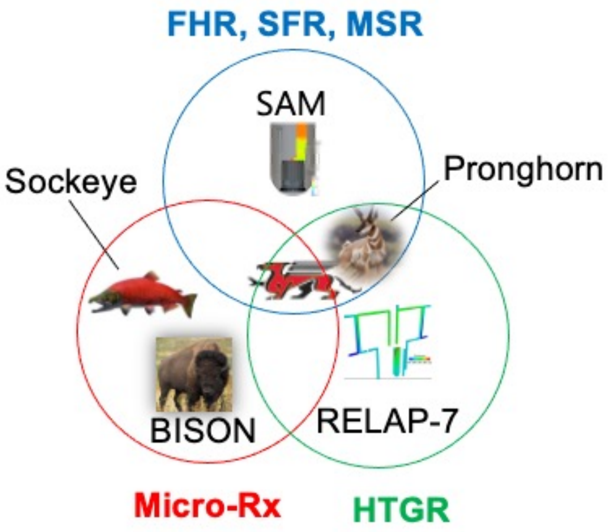
C110 – Reactor Physics Methods and Analysis

Current Project Portfolio: Griffin development (DOE-NEAMS, NASA, and NRC); advanced reactor model development and validation (NRC, DOE ART); nuclear thermal propulsion model development and support (NASA); validation and experiments support for SIRIUS fuel transients in TREAT (NASA); support micro-rector core design and safety analyses using MOOSE (DOD-Pele); Thermal Test Reactor Capabilities (INL-ATR/TTRC); Supporting industry with Griffin (Radiant, X-Energy, BWXT, Westinghouse)

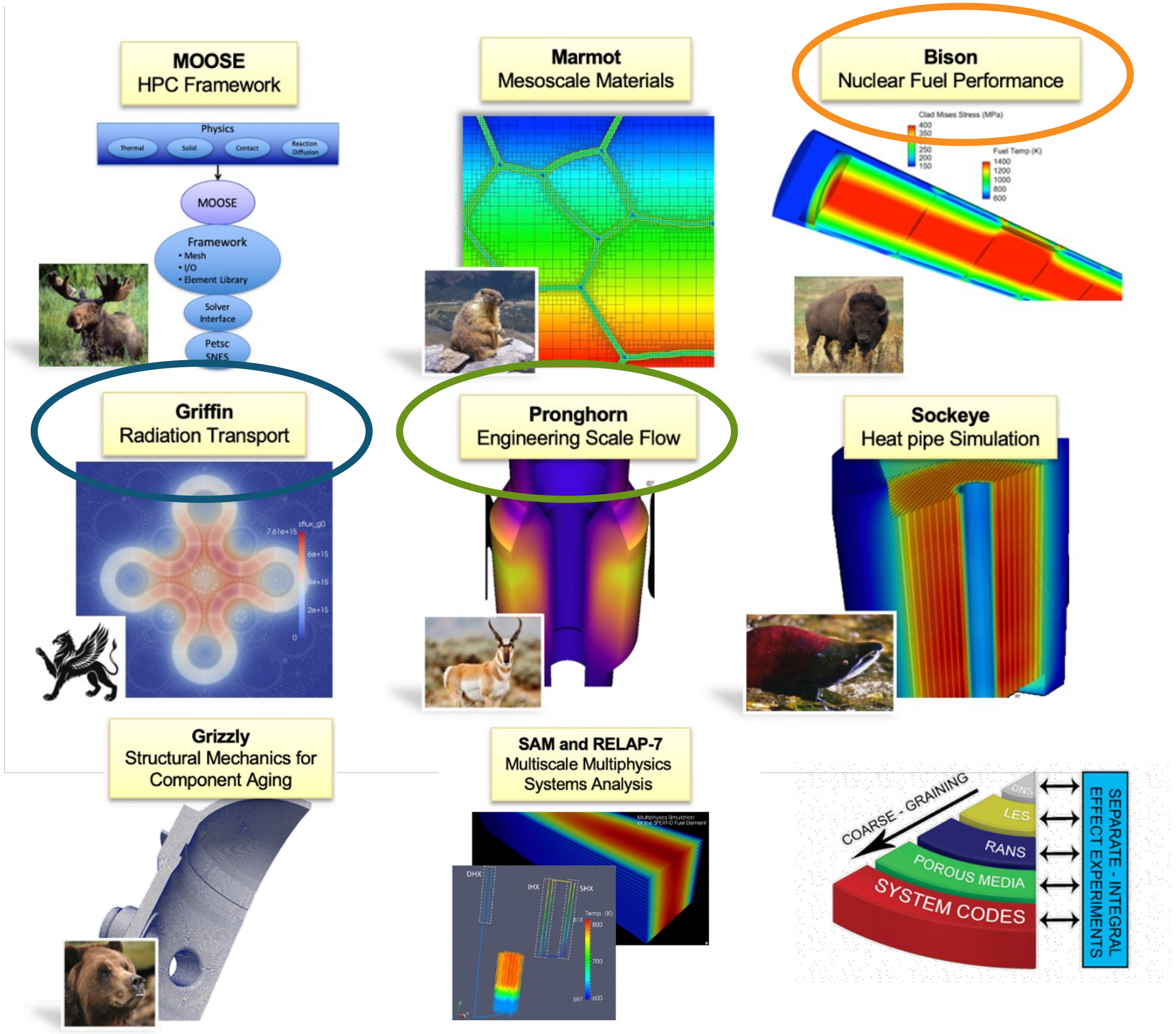
Tools: *Internal:* Griffin, Pronghorn, BISON, RELAP-5/7, MOOSE and MOOSE physics modules; *External:* MCNP, Serpent 2, OpenMC, SCALE, DRAGON



Core NTP



DOE NEAMS MOOSE Based Applications

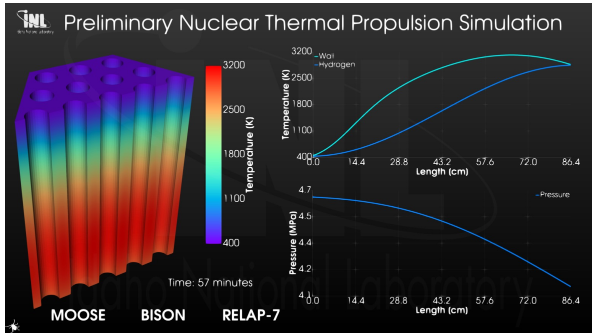


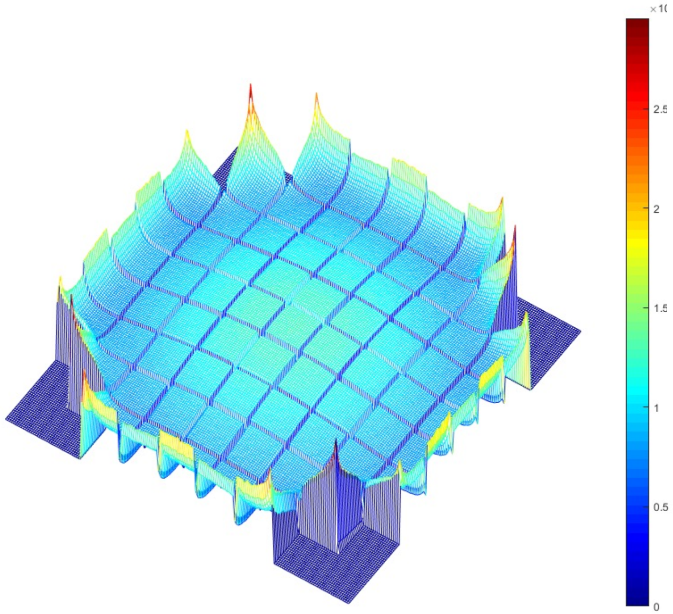
- **NEAMS**: The Nuclear Energy Advanced Modeling and Simulation Program
- **MOOSE**: Multiphysics Object Oriented Simulation Environment
- **Flexible**
  - 1D, 1DR, 2D, 2DRZ, 3D,
  - Huge variety of physics
  - Adaptive time stepping and sub cycling
  - Multiscale through Multiapp system
  - Easily Extendible to new physics and sales

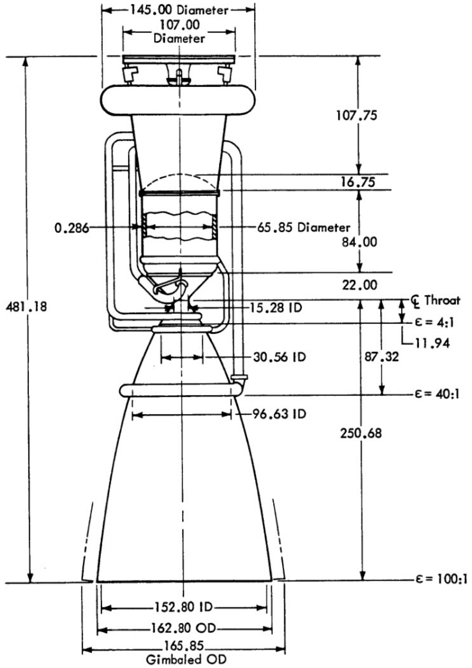
- **Tunable fidelity**
  - 0D scalar lumped parameters problem
  - 1D systems models
  - Multi D Intermediate “homogenized” geometry
  - High-fidelity “explicit” Geometry

- **Scalable**
  - MOOSE supports hybrid parallelism
  - Scales well on workstation and HPC
  - 2D/RZ models execute in minutes
  - High-fidelity 3D models execute on HPC

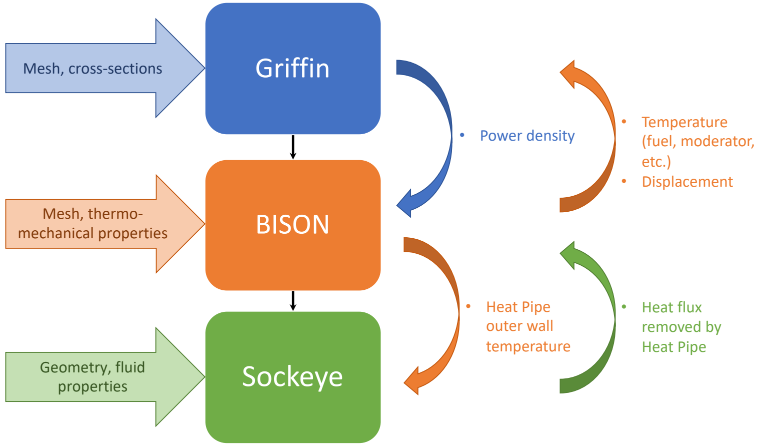
Flexibility is Key (Or "The Flexibility Factor"?)

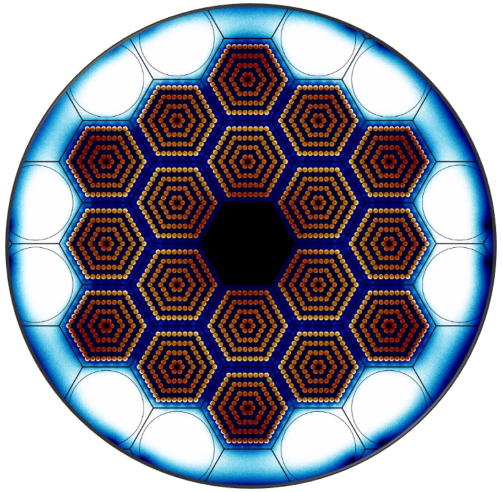


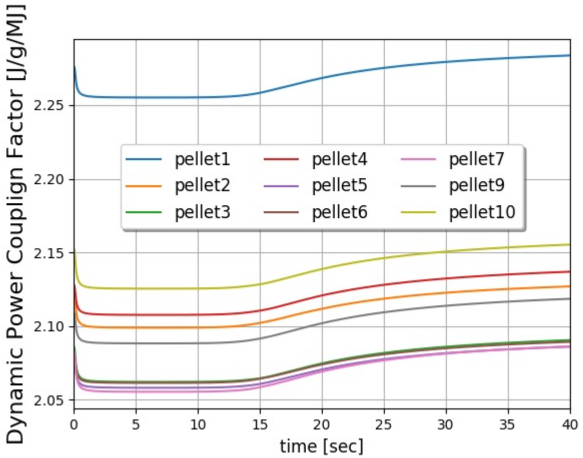


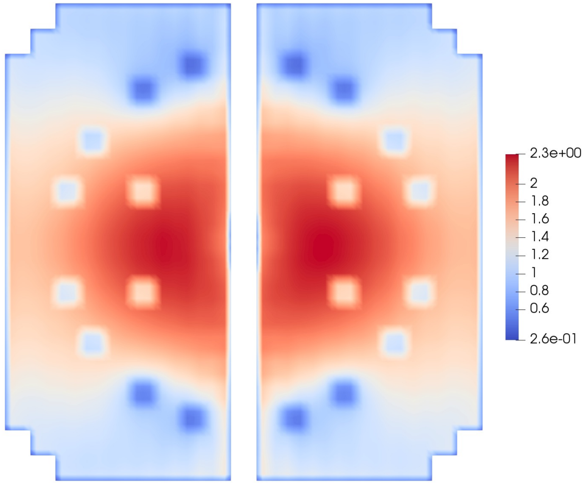


Nuclear Thermal Propulsion





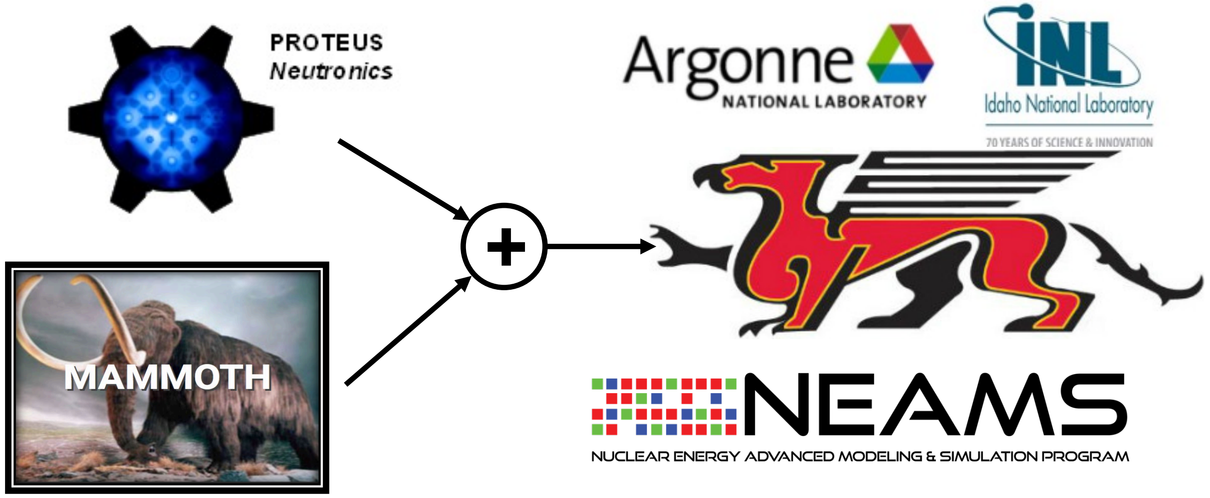




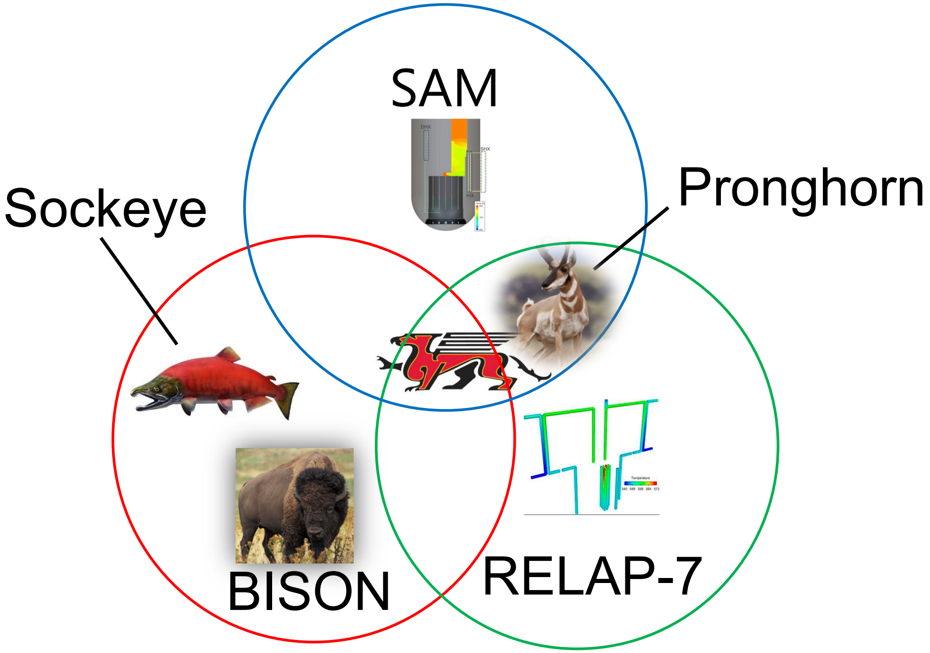
Transient Reactor Test Facility (TREAT)

Griffin Reactor Multiphysics

Griffin: NEAMS Advanced Reactor Physics Tool



FHR, SFR, MSR

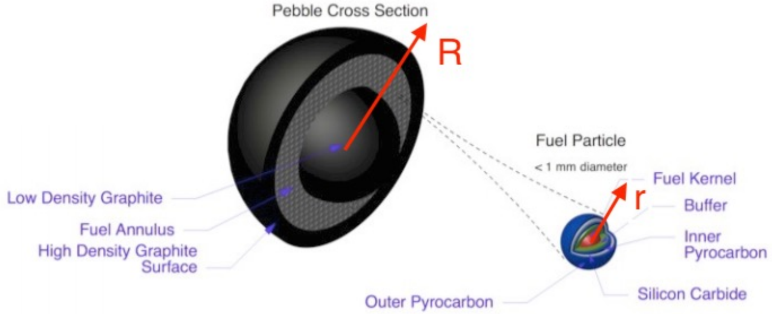


Micro-Rx

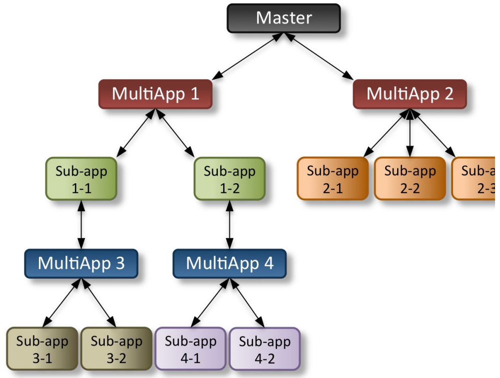
HTGR

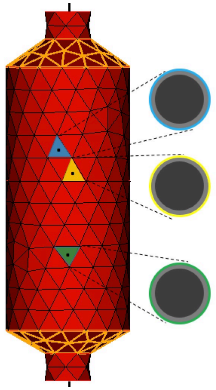
Coupling by Design

Strong Coupling



Multiapp





Griffin Capabilities

Cross Sections

- Serpent
- MC^2-3
- Online cross section

Transport Solver

- P_N, SAAF-S_N, Diffusion, S_N
- MOC, Nodal
- Multi-scheme, Hom. Equiv.
  Pebble Tracking Transport

Mesh generation

- CUBIT
- ANL mesh-kit
- MOOSE inline meshing,
  Python Meshing Tools

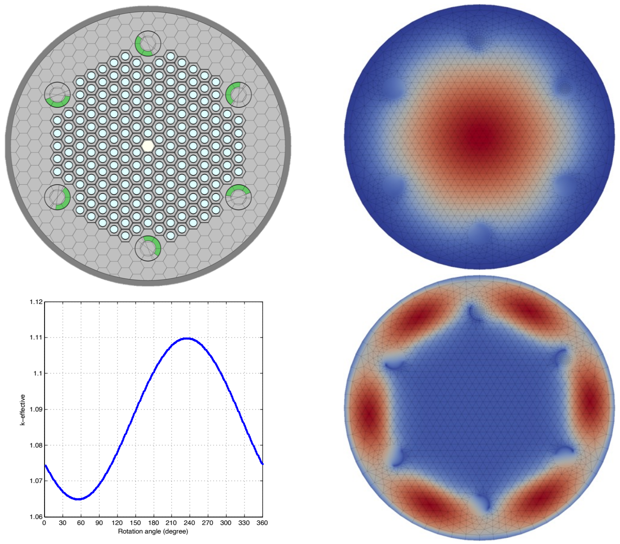
Physics

- Neutron
- Depletion: CRAM,
  ORIGEN data;
  Radiative transfer,
  Multiphysics coupling
- PBR equilibrium core
  Photon (X/gamma-ray)

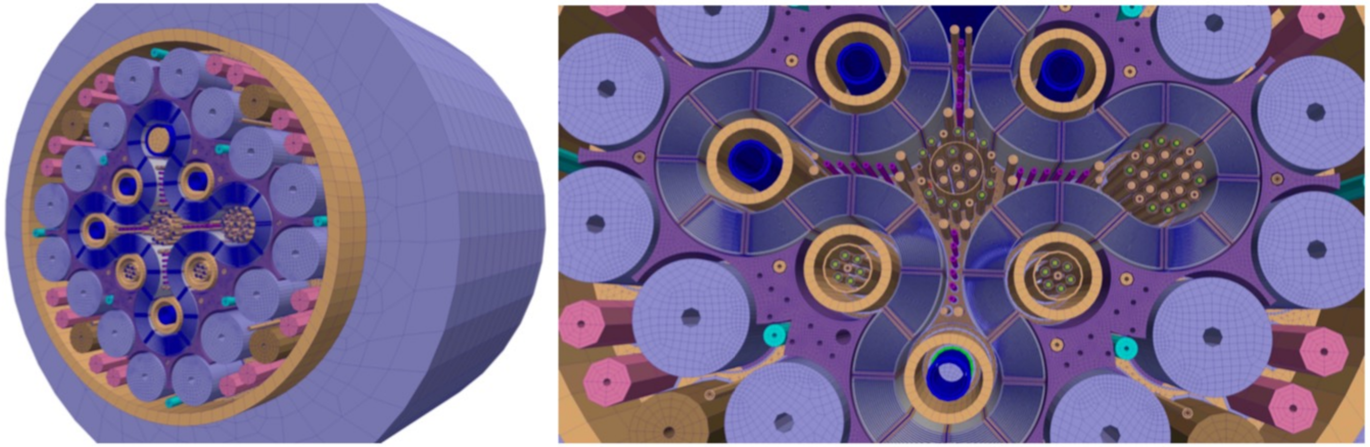
Legend:

- Ported from both
- Ported from PROTEUS
- Ported from MAMMOTH
- New development

Micro-reactors



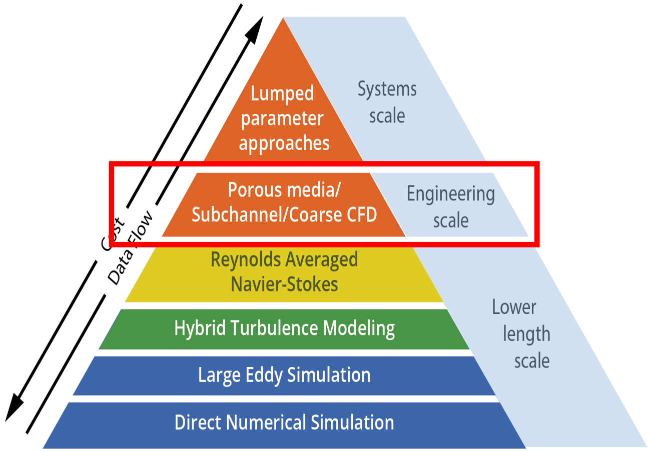
Advanced Test Reactor (ATR)

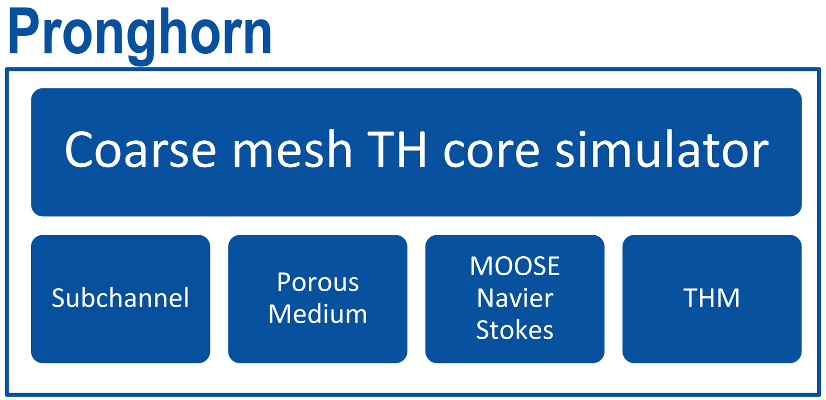


SQA-Compliant

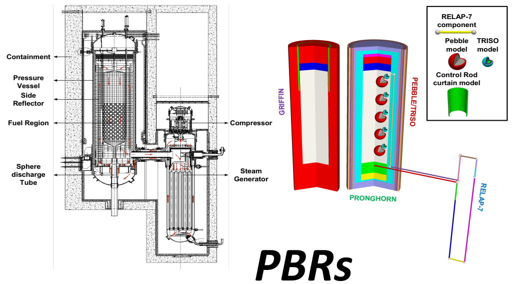
Coarse Mesh Thermal-hydraulics with Pronghorn

- Pronghorn is a flexible & fast thermal-hydraulics core modeling capability that can be natively coupled to other MOOSE tools for multiphysics
- Pronghorn includes:
  - subchannel capabilities (liquid metal fast reactors)
  - porous flow capabilities (for pebble bed reactors, prismatic GCR)Coarse-mesh CFD capabilities (for molten salt reactors)



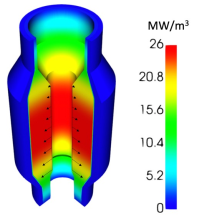


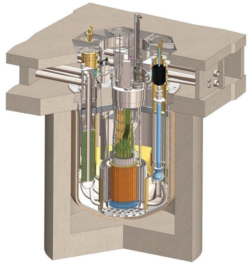
***Importance** of Pronghorn: Model multi-dimensional flow problems during long transients (50 h) in minutes on a laptop*



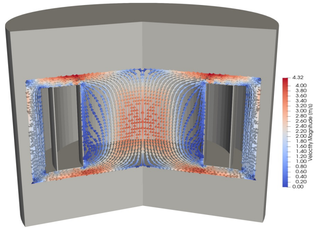
PBRs

FHRs

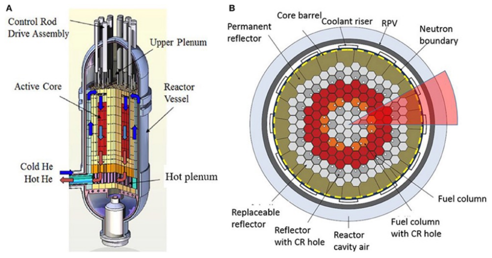




LMFR



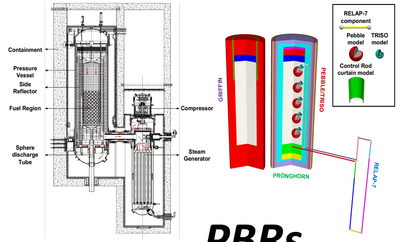
MSRs



Prismatic GCR

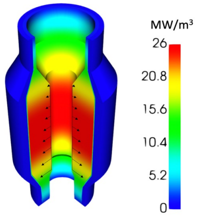
Pronghorn Capabilities

- Available and tested
- Under development or untested
- Future plan

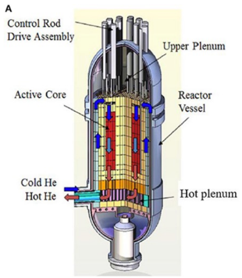


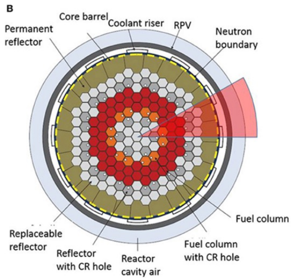
PBRs

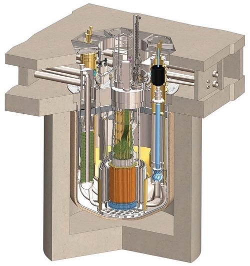
FHRs



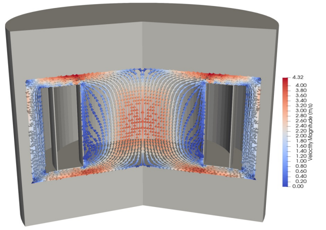
Prismatic GCR







LMFR



MSRs

PBRs / FHRs

- Efficient and accurate multi-dimensional flow model
- Coupling to pebble bed neutronics and depletion
- Multiphysics equilibrium core and running-in
- Most design basis transients (missing air/steam ingress & “secondary side upsets”)
- Verification of depletion method

Prismatic GCR

- Core wide flow distribution
- Vessel temperature temperature during transients
- Radiative heat transfer in complex geometries (upper dome)
- Effective thermal conductivities

LMFR

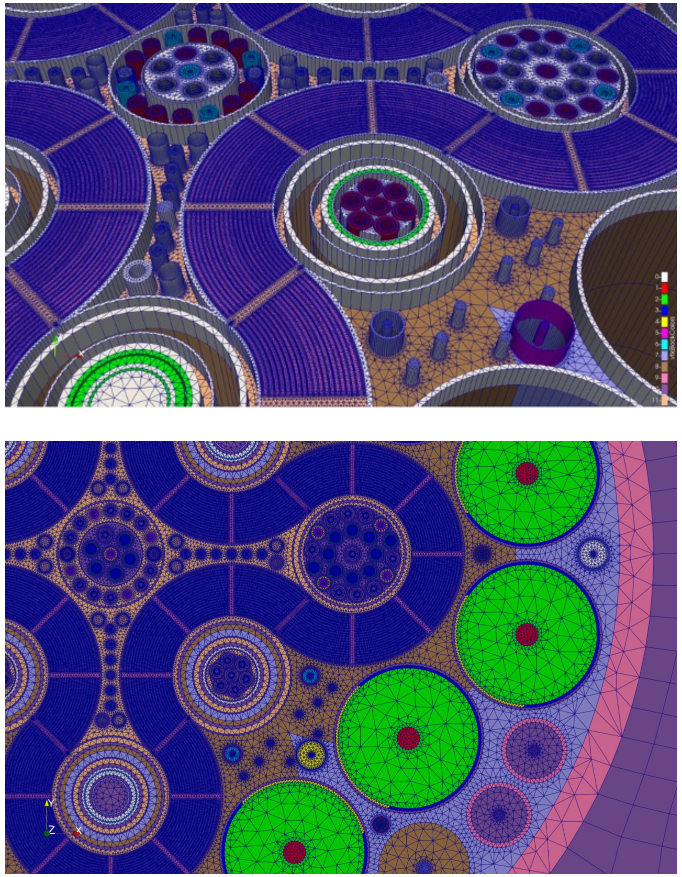
- Efficient and flexible subchannel code
- Flow blockage, Intra-element recirculation, core wide wrapper temperatures
- Ongoing validation
- Lead properties
- Stochastic clad failure for lead reactors

MSRs

- TH/neutronics coupled steady-state and transient (in 3D)
- Coarse-mesh turbulence modeling
- Solidification
- Thermo-chemistry and corrosion modeling
- Asymmetric transients

Benchmarked Griffin Model of the Advanced Test Reactor

- ***A First Complete Workflow for Simulation of the Advanced Test Reactor (ATR) has been developed.***
  - This workflow uses OpenMC for cross-section generation, Cubit scripts for mesh generation and Griffin for the eigenvalue calculation
  - The OpenMC model was validated against the International Handbook of Reactor Physics Experiment Evaluation Benchmark for data from the 1994 core-internals changeout (94CIC)
- ***Modeling Approach:***
  - The OpenMC Python API was used to generate the OpenMC model.
  - Cubit with its API was used to generate two-dimensional meshs for the core.
  - Two-dimensional mesh refinement studies were performed to find an appropriate mesh size
  - The MOOSE extruder function was used to generate three-dimensional meshes from the two-dimensional mesh with 23 axial regions.
  - Using the discontinuous finite element method and the Griffin discrete ordinates solver, Griffin calculates 0.99970 for the critical state, relative to 0.99934 for OpenMC
- ***Significance:***
  - This represents the first full mesh creation for ATR at INL and the ability to simulate the full core and validate against measured data
  - This work lays the foundation for future multiphysics analysis of ATR for
    - Experiment simulation
    - Safety analysis
    - Fuel performance



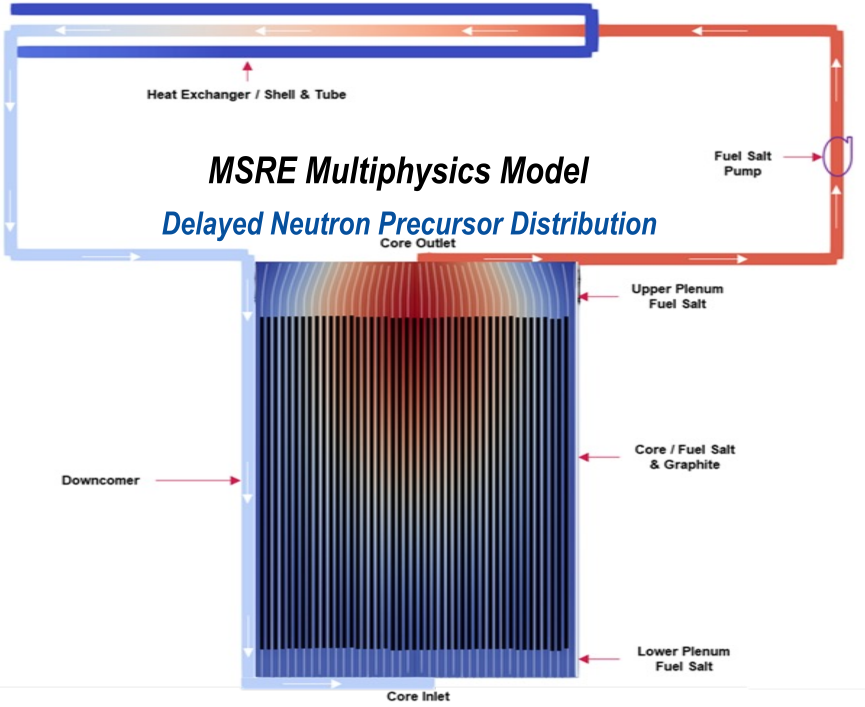
Examples of the ATR mesh used by Griffin

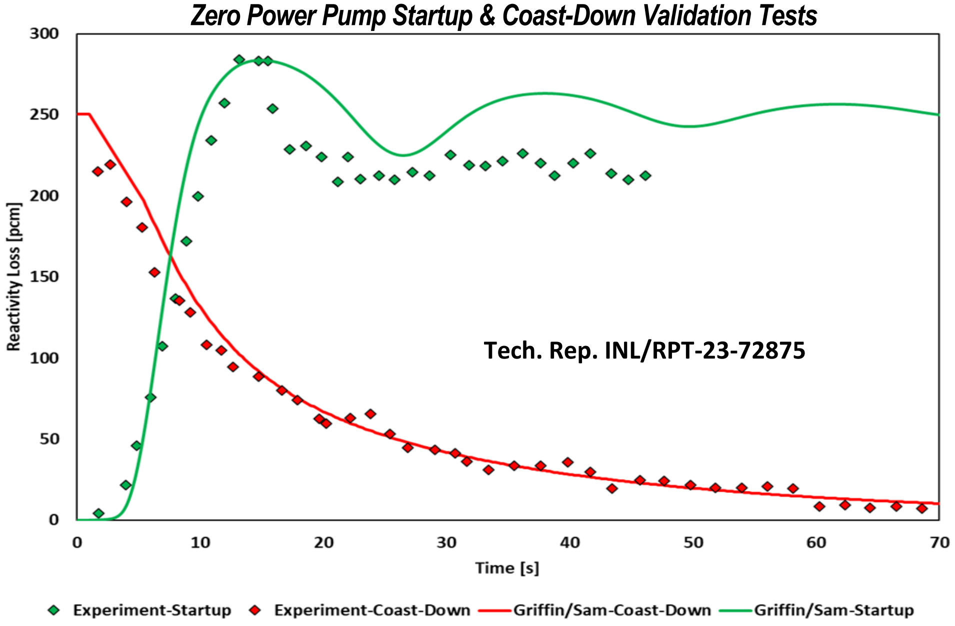
Research Highlight

Advanced Nuclear Reactor Modeling Project

Modeling the Molten Salt Reactor Experiment (MSRE) & Initial Validation Tests

- A full core model was developed for the MSRE experiment considering flowing liquid fuel in support of the U.S. Nuclear Regulatory Commission (NRC).
- The model couples the following codes to perform Multiphysics analysis:
  - **Griffin:** solves neutronics parameters with delayed neutron precursor drift.
  - **SAM Multi-D:** solves porous medium equations for the fluid regions and conduction in the solid regions.
  - **SAM 1-D:** solves 1-D thermal fluids equation of the outer loop.



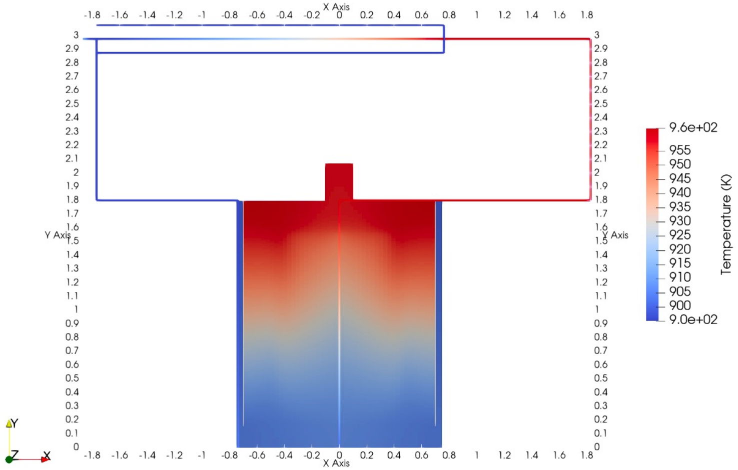


- We performed steady state and transient analysis considering several accidents:
  - The model was able to capture the effect of the delayed neutron precursor drift on steady state and transient solutions accurately
  - The model was validated against zero power pump transient tests
  - The model can capture the impact of the fluid (fuel) flow at different power levels (zero and full) for an unprotected loss of flow (ULOF) transient
  - Further validation tests and model improvements will be performed in the future
  - **The model was presented to the Nuclear Reactor Regulation (NRR) group**
- The model contributes to the NRC mission of licensing Molten Salt Reactors by providing an initial reference plant model in preparation for the development of the NRC evaluation models.

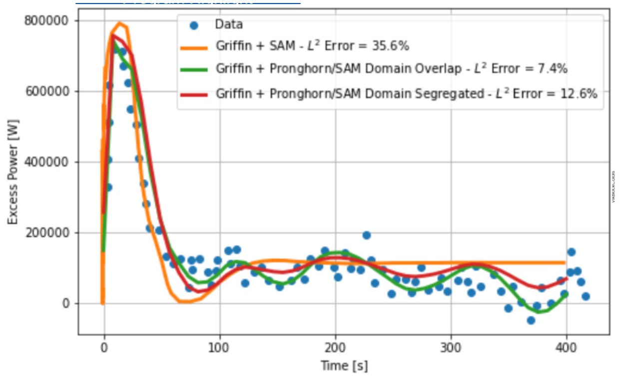
Program Highlight

New MOOSE Modeling Capability Uses Pronghorn and SAM for Molten Salt Reactor Analyses

- Liquid-fueled molten salt reactors (MSRs) require detailed multidimensional modeling of the flow, temperature, and delayed neutron precursors fields in the reactor core.
- Pronghorn is a MOOSE-based code that provides information on the ability of coolants to remove heat from nuclear fuel.
- The systems analysis method (SAM) is a whole-plant transient analysis code for design scoping of advanced non-light water reactors.
- Pronghorn and SAM were coupled to provide complete plant analyses of MSRs with high-fidelity core models.
- The coupling was validated for reactivity insertion transients in the Molten Salt Reactor Experiment.
- This new MOOSE-based modeling capability provides an additional analysis tool for small modular reactors using molten salt as the coolant.



Steady-state temperature profile for the Molten Salt Reactor Experiment predicted with the Pronghorn-SAM coupled model.



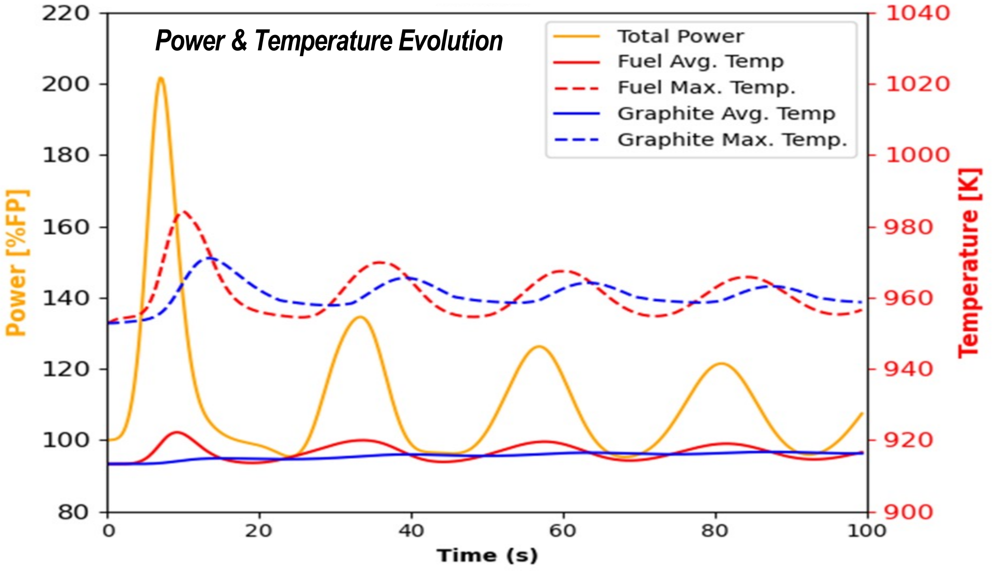
Excess Power for a Reactivity Insertion Transient in the Molten Salt Reactor Experiment.

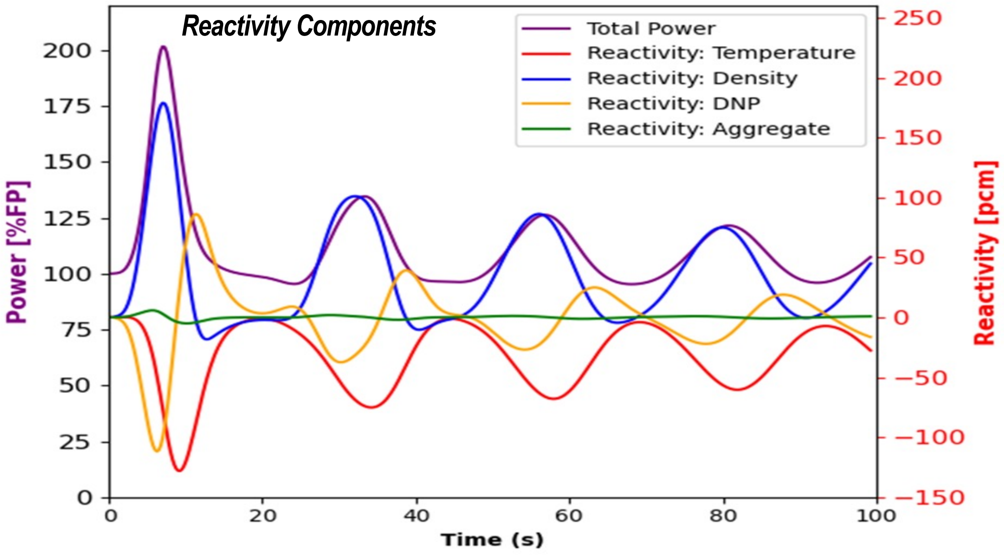
Reactor Systems Design & Analysis | Thermal Fluids Systems Methods & Analyses
Mauricio.TanoRetamales@inl.gov; Sebastian.Schunert@inl.gov

Advanced Nuclear Reactor Modeling Project

Modeling Fuel Salt Over Fueling in Molten Salt Reactors

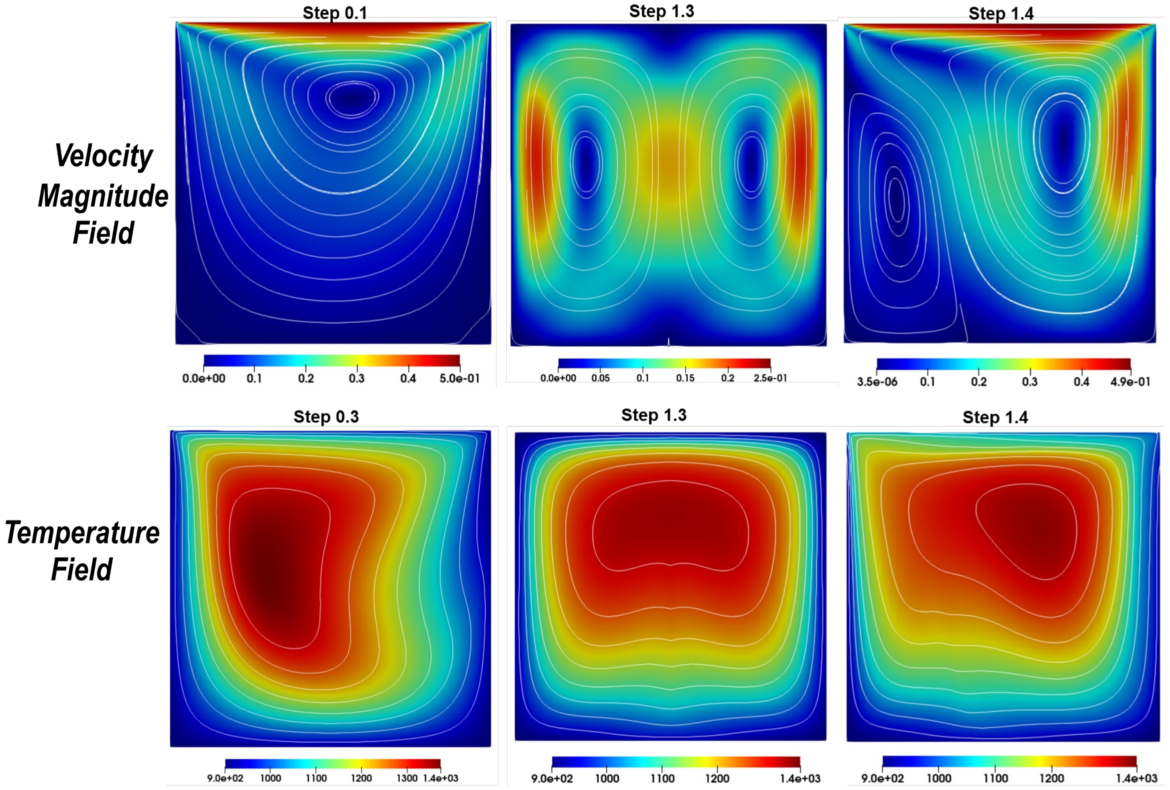
- Online refueling and reprocessing is a unique feature of Molten Salt Reactors (MSRs) with liquid fuel:
  - Fissile and fertile components are added continuously to maintain criticality
  - Injection rate depends on the demanded power and fuel consumption rate
  - Non-uniform distribution of salt nuclides results in reactivity perturbations
- A Multiphysics full core model developed with Griffin-SAM for the Molten Salt Reactor Experiment (MSRE) analysis was utilized to simulate Unprotected Fuel Salt Over Fueling (UFSOF) transient scenario:
  - The model was able to capture the localized effect of U-235 isotope addition
  - The drift of the injected U-235 results in wave power response with frequency equal to the circulation time of the salt in the system
  - The peak power depends on injection rate and amount of the U-235 isotope
- The model captured the main feedback components:
  - Temperature: Doppler and density changes on cross sections
  - Velocity: delayed neutron precursors, and salt nuclide distributions
- Modeling such phenomenon is important for safe operation and licensing mission of MSRs



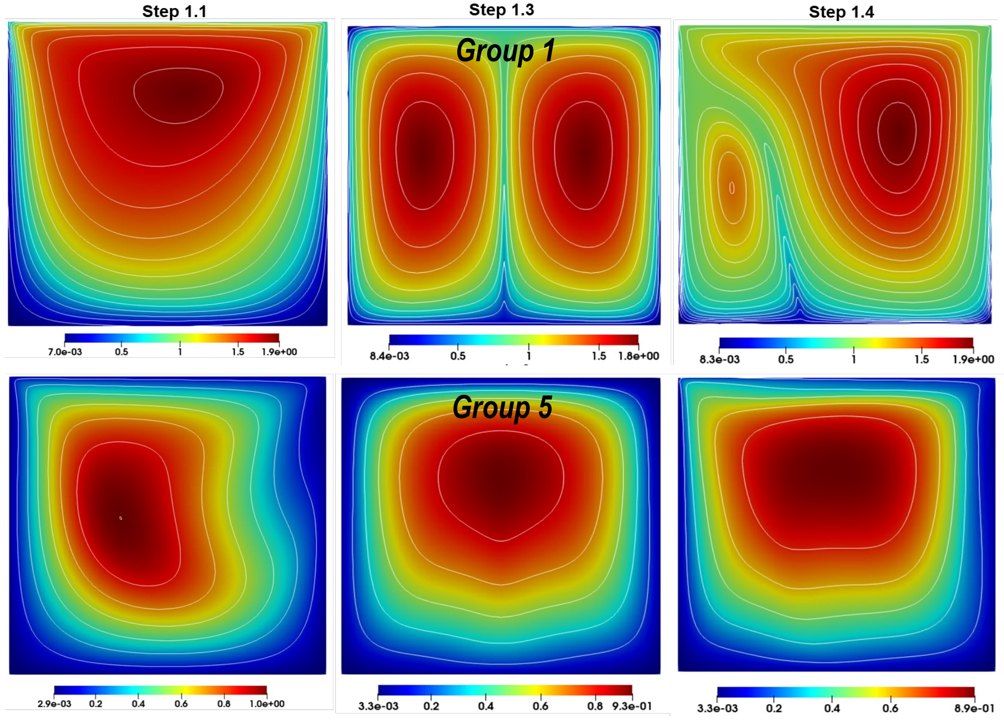


Verification of Molten Salt Reactor (MSR) Modeling Capabilities of Griffin-Pronghorn

- A fast spectrum MSR CNRS benchmark was simulated to verify the MSR modeling capabilities of the Griffin-Pronghorn coupled code system.
- Griffin provides the neutronics solution with the heat source to Pronghorn which solves the delayed neutron precursor distribution required for Griffin calculations along with the temperature field.



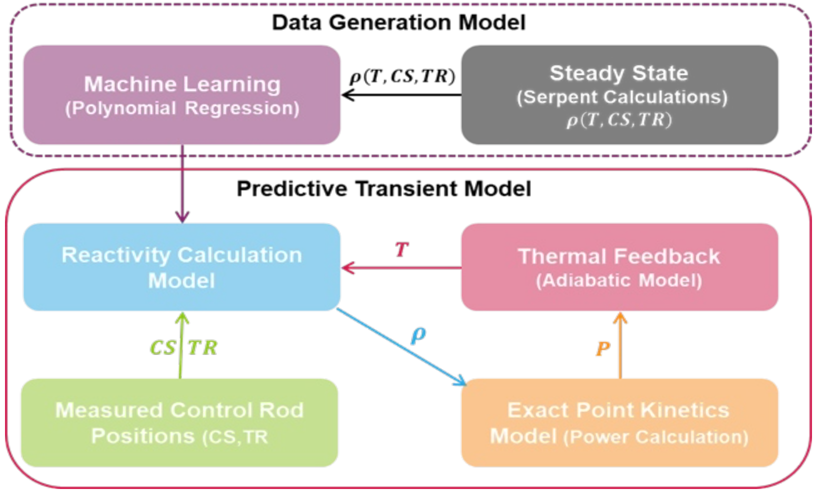
Distribution of Delayed Neutron Precursors



- The benchmark is divided into several steps to test the coupling between various physics phenomena
  - **Step 0: Steady-State Single Physics Benchmark**
  - **Step 1: Steady-State Multiphysics Coupling**
  - **Step 2: Time Dependent Multiphysics Coupling**
  - The solutions of Griffin-Pronghorn were consistent with reported benchmark results for all steps.
- This work was partially funded by ***Virtual Test Bed (VTB),*** and it will contribute to the INL mission of verifying and validating tools for MSR modeling and simulation.

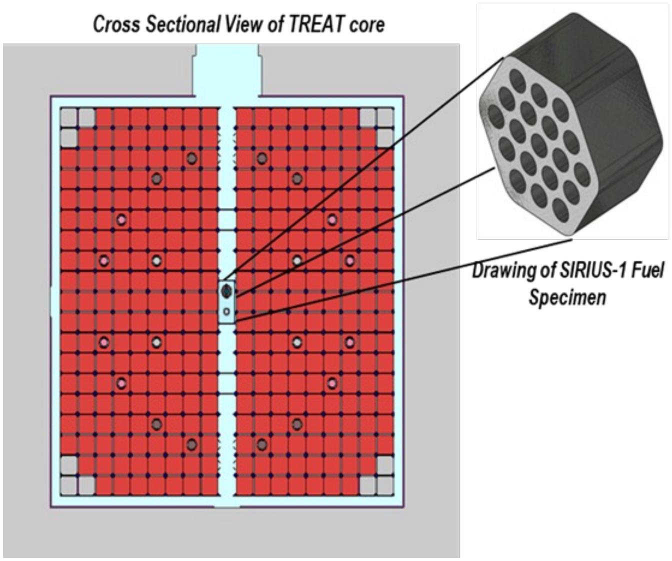
Predictive Transient Model of TREAT-SIRIUS Experiments (1)
Reactor Power

- To support experiment transient analysis for the NASA-sponsored SIRIUS experiments in the Transient Reactor Test Facility (TREAT), a **predictive** transient model of was developed leveraging
  - **Data Generation Model (Serpent):** for steady state analysis using Serpent code to generate reactivity data as a function of control rod positions and fuel temperature.
  - **Adiabatic Thermal Feedback Model:** to obtain average fuel temperature at each time point.
  - **Reactivity Insertion Surrogate Model (Moose Stochastic Tools Module):** to functionalize Serpent-generated data and predict the total reactivity of the core during the transient knowing control rod positions and fuel temperature.
  - **Exact Point Kinetics (EPK) Model (Griffin)**: to calculate the total reactor power with given reactivity and kinetics parameters during the transient.



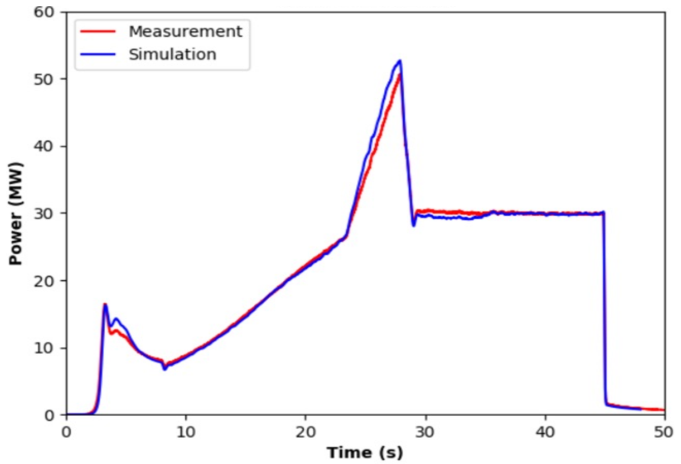
Predictive Transient Model: Power Prediction

Cross Sectional View of TREAT core



Drawing of SIRIUS-1 Fuel Specimen

- The **predictive** model was tested with SIRIUS-1 experiments, which were performed at three different power levels.
- Test results show a good agreement with the measured values for the three different power levels and the results were within uncertainty level of the reported power (5~10%).
- This **predictive** model will help in understanding the modeling requirements and details required for full dynamic analysis; it also will help in predicting the transient behavior of other experiments.

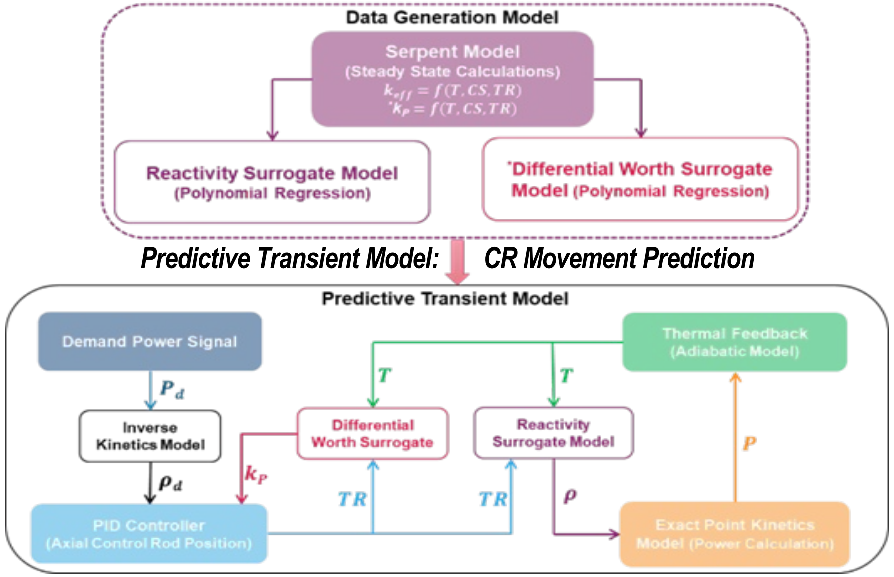


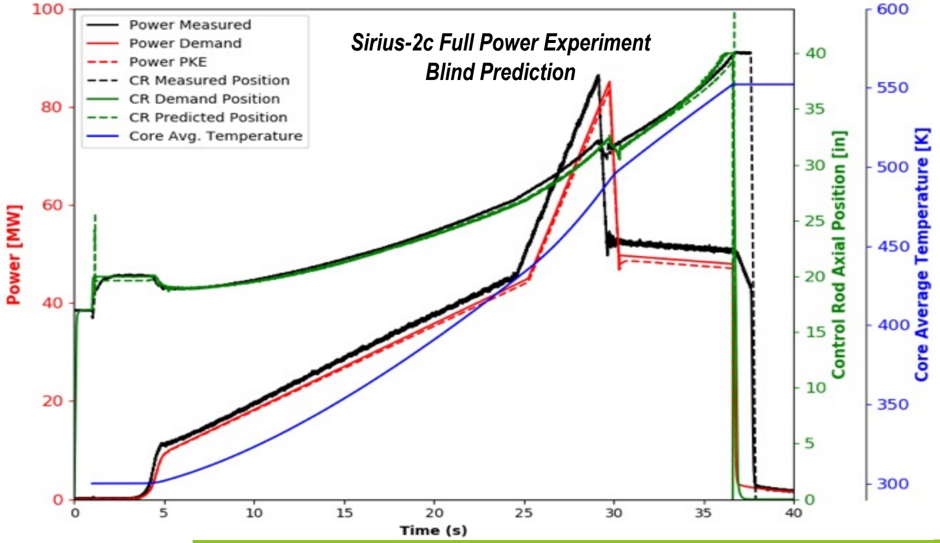
Power Evolution During SIRIUS-1 Full Power Experiment

Predictive Transient Model of TREAT-SIRIUS Experiments (2)

Control Rod Movement

- An improved predictive transient model was developed to support analysis for the NASA-sponsored Sirius experiments in the Transient Reactor Test Facility (TREAT).
- The model relies on two surrogate models based on MOOSE stochastic tools and steady state Serpent calculations to predict the **control rod axial position and its corresponding reactivity during a transient.**
- The model has the following components:
  - **Data Generation (Serpent):** perform steady state analysis using Serpent code to generate reactivity data points and differential worth coefficients as a function of control rod axial positions and fuel average temperature.
  - **Inverse Kinetics**: converts the demand power signal into a reactivity signal.
  - **Differential Worth Surrogate (Moose Stochastic Tools Module)**: predicts the differential rod worth coefficients based on Serpent calculations.
  - **Proportional Controller:** determines the equivalent-reactivity control rod axial position.
  - **Power Predictive Model (Griffin):** Reactivity Insertion Surrogate, Adiabatic Thermal Feedback, and Exact Point Kinetics models.
  - The model was validated against Sirius-1 experimental data, and it was utilized to perform Sirius-2c blind prediction.
- The model contributes to the long distance nuclear thermal propulsion (NTP) mission by providing a critical capability for NTP modeling.

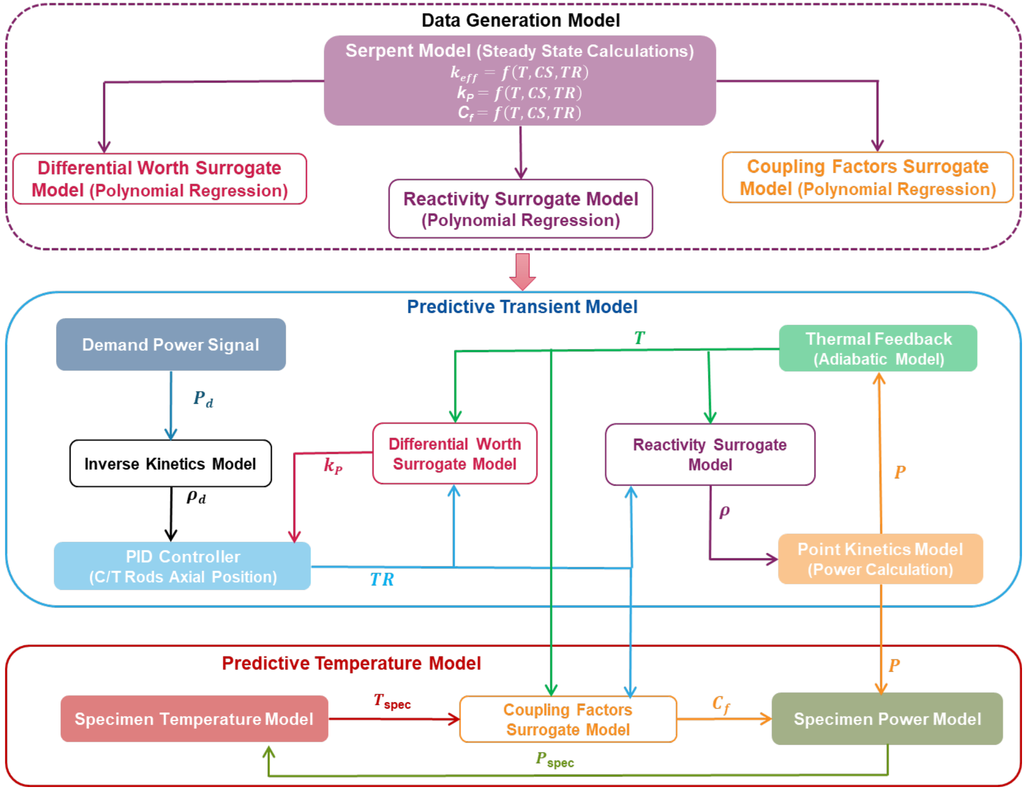


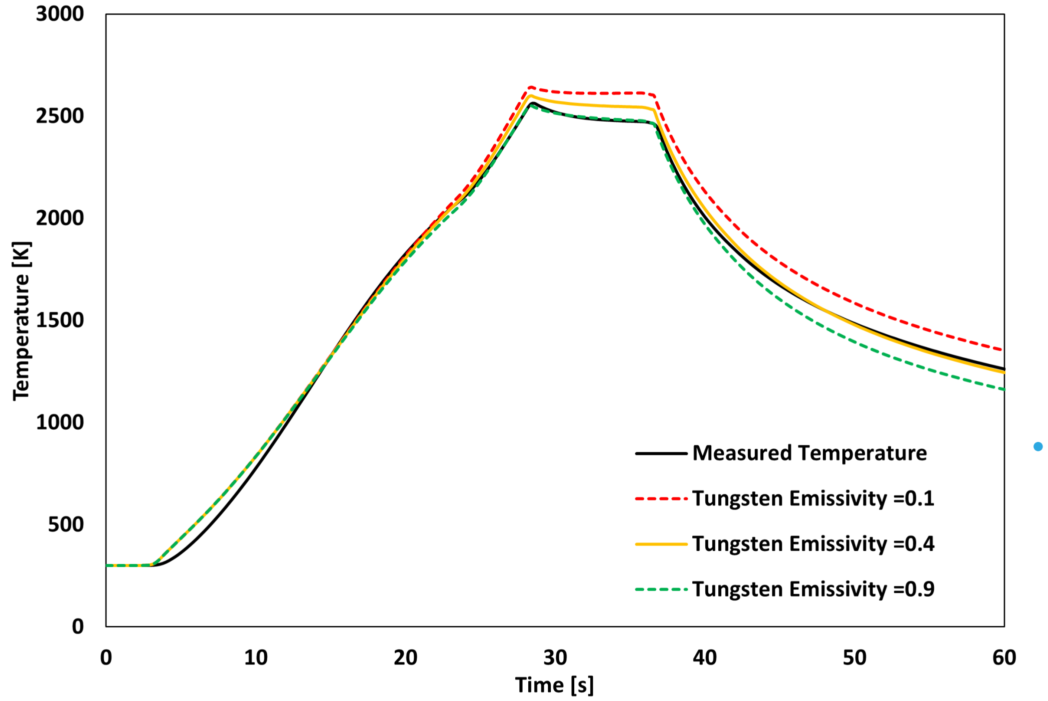


Predictive Transient Model of TREAT-SIRIUS Experiments (3)

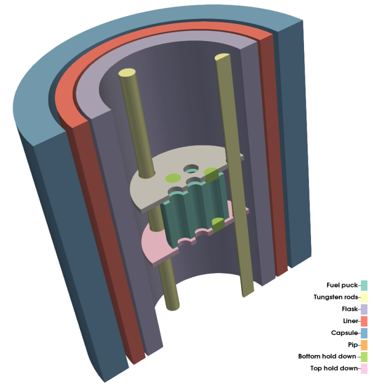
Experiment Temperature

- Further improvements were made to the predictive transient model to support analysis for the NASA-sponsored Sirius experiments in the TREAT Facility.
- A thermal predictive model was added by coupling Griffin, Moose Stochastic Tools Module, and Bison codes to predict the **Sirius experiment temperature evolution**.
- These tests will determine whether operational temperature conditions will result in detrimental performance phenomena.





Predicted and measured temperature profile of Sirius-2c full power experiment.

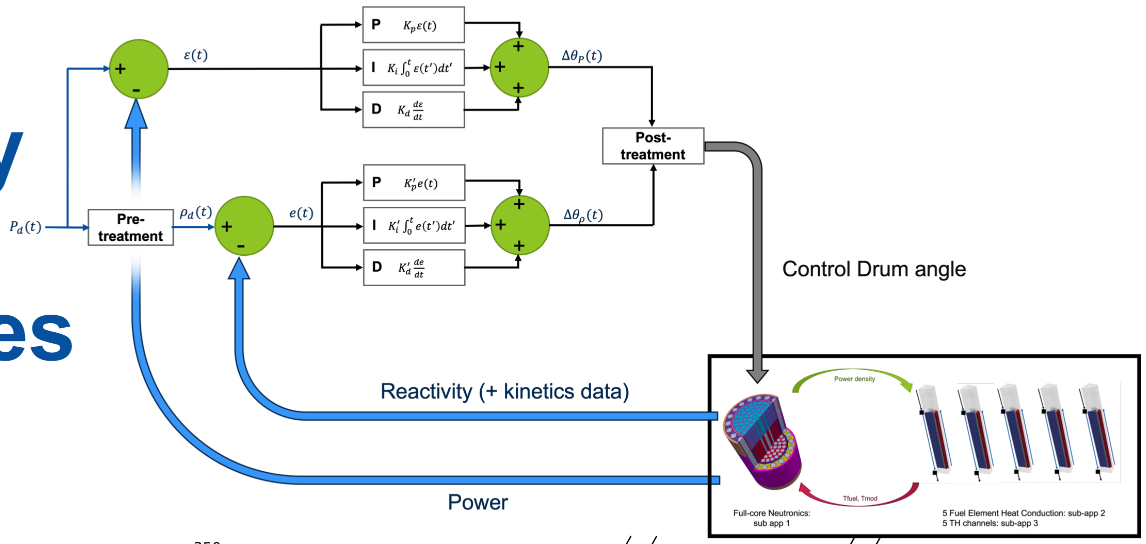


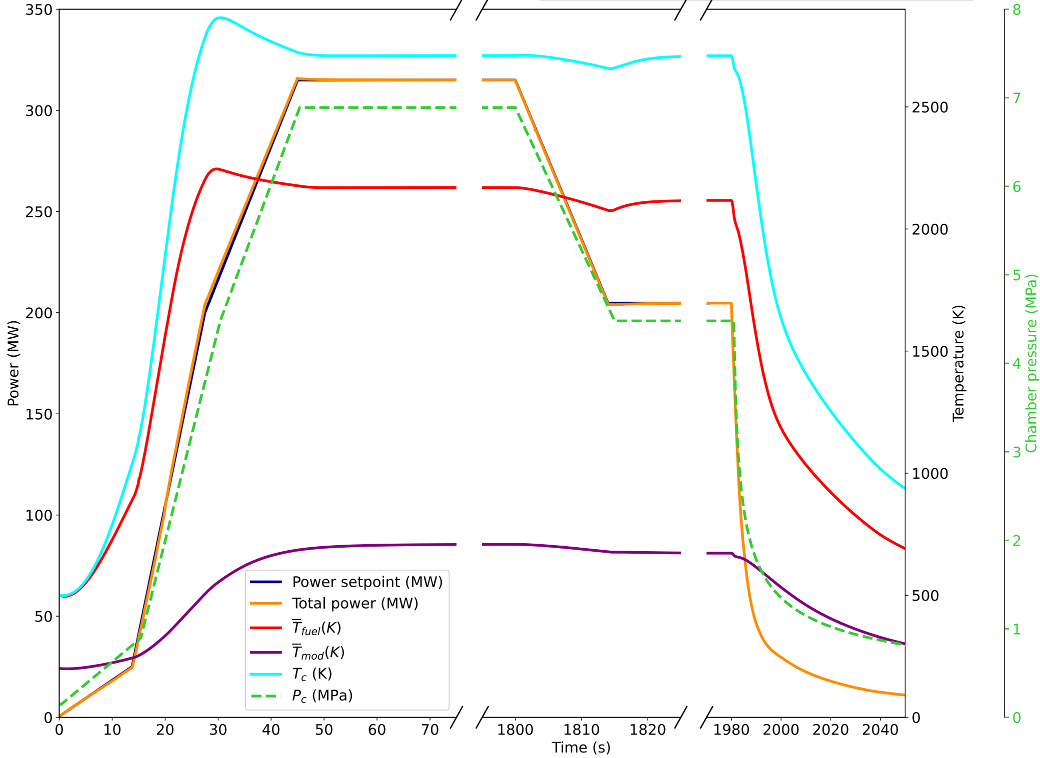
Sirius-2c model

- The Sirius-2c test specimen were irradiated in the Transient Reactor Test Facility (TREAT) with irradiation startup ramp rates that are prototypical of a potential reactor's ramp rate.
  - A blind prediction of the SIRIUS-2C was preformed with the Comprehensive Reactor Analysis Bundle (BlueCRAB) MOOSE suite of tools.
  - The prediction demonstrates that the BlueCRAB MOOSE tools can do predictive and bounding analysis for experiments inside TREAT.

New Hybrid Power-Reactivity Controller Proposed for NTP Startup and Shutdown Phases

- Nuclear Thermal Propulsion (NTP) systems for interplanetary travel (such as manned missions to Mars) need to reach full power in less than a minute. This is challenging to achieve without significant power overshoots and delays.
- Typical automated control (e.g., PID controllers) require a lot of manual adjustment and do not anticipate sudden changes in power demand.
- New controller proposed to use a power and reactivity signals to control the reactor without overshoots or delays much like state-of-the-art controllers.
- Successfully implemented in MOOSE to drive a coupled Griffin-MOOSE-RELAP7 multiphysics calculation.
- Power multiplied by 630 in 45s with only 0.4% power overshoot.





Source: V. Labouré, S. Schunert, S. Terlizzi, Z. Prince, J. Ortensi, C-S Lin, L. Charlot, and M. DeHart, "Automated Power-following Control for Nuclear Thermal Propulsion Startup and Shutdown Using MOOSE-based Applications", Progress in Nuclear Energy, Volume 161, 2023, 104710, ISSN 0149-1970, https://doi.org/10.1016/j.pnucene.2023.104710

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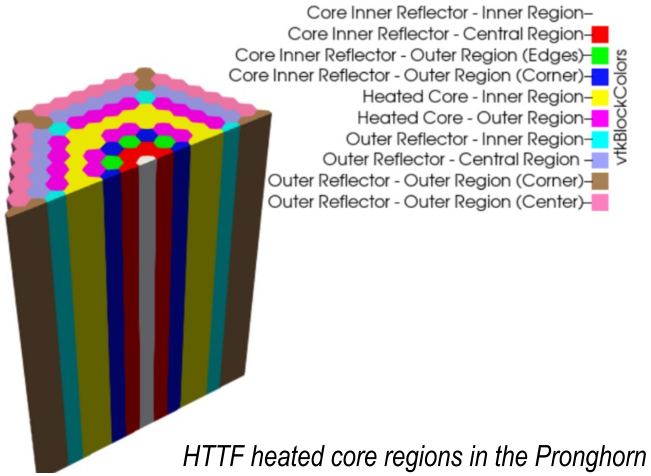
Program Highlight

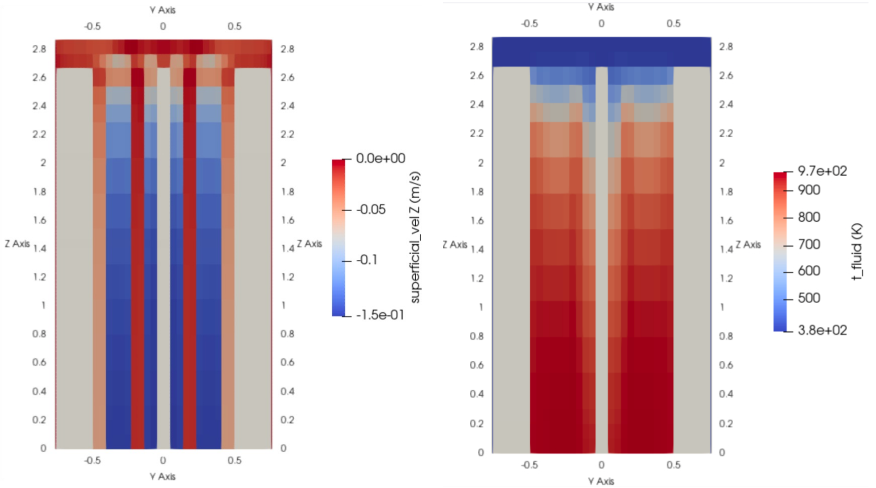
DOE-NEAMS

Verification Completed for Pronghorn Modeling of Gas Cooled Reactors

- High temperature gas-cooled reactors (GCR) have radial and azimuthal temperature gradients due to differential heating and cooling of the graphite core.
- Pronghorn is a MOOSE-based code that provides information on the ability of coolants to remove heat from nuclear fuel.
- Novel approaches for solid conductivity homogenization, radiation heat transfer, and heat exchanges in developing flow were implemented in Pronghorn's 3D porous-media modeling.
- Validation of the Pronghorn modeling for both steady-state and transient conditions was completed against experiment data from the Oregon State University High-Temperature Test Facility were used for the validation.
- This expansion of Pronghorn's capabilities provides an additional analysis tool for GCR designs and the Generation IV International Forum.



HTTF heated core regions in the Pronghorn model.



Superficial velocity (left) and coolant temperature (right) predicted by the Pronghorn model during transient PG-26.

Reactor Systems Design & Analysis | Thermal Fluids Systems Methods & Analyses
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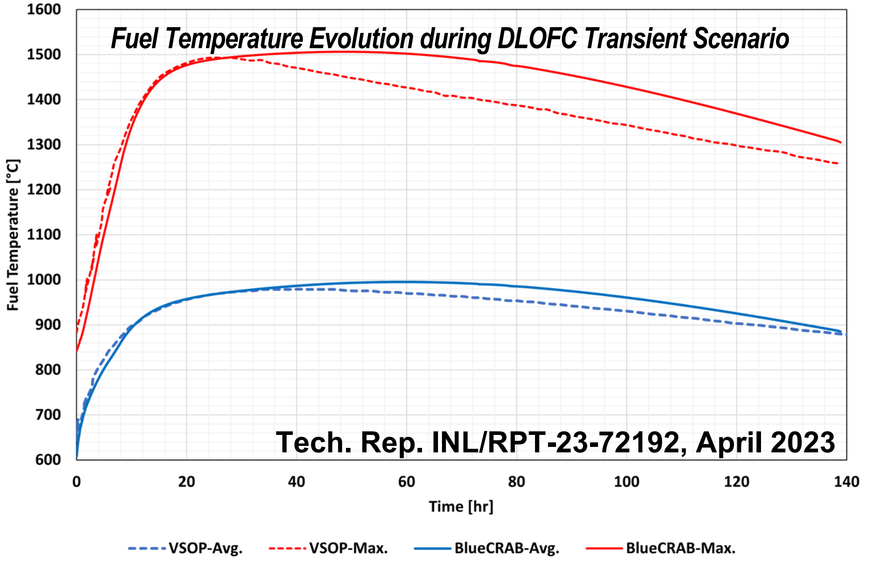
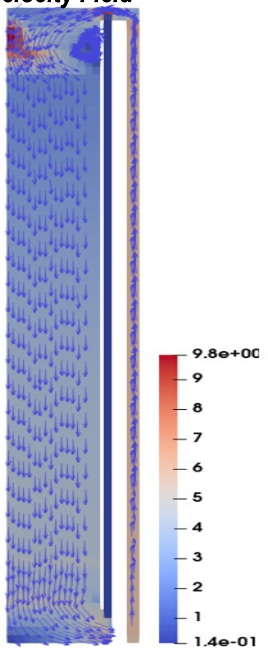
Research Highlight

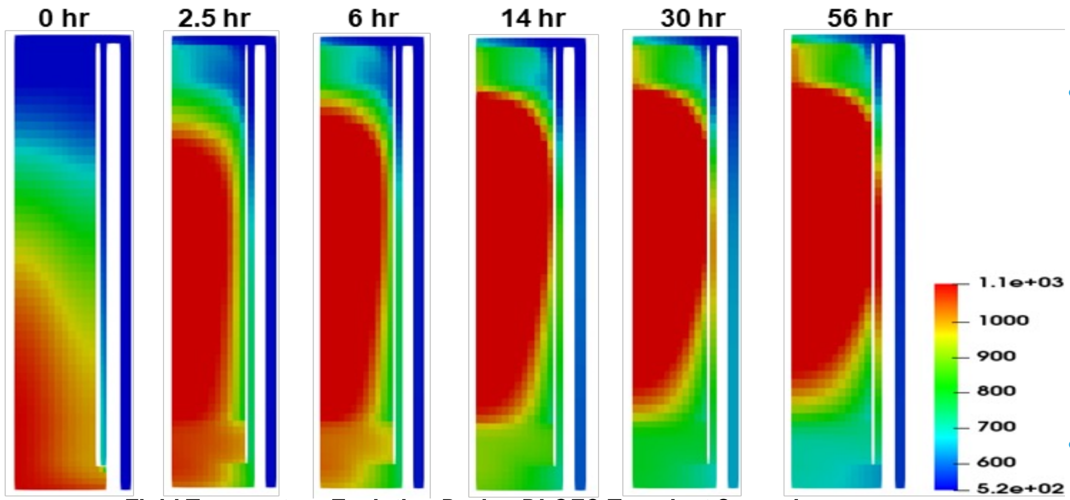
Advanced Nuclear Reactor Modeling Project

Modeling Depressurized Loss-Of-Forced-Cooling Event of High Temperature Gas Cooled Reactor - Pebble-Bed Module (HTR-PM)

- To support Nuclear Regulatory Commission (NRC) efforts for development and modeling support for advanced non-light water reactors, an equilibrium full core model was developed for the reference HTR-PM reactor.
- The model couples the following codes to perform Multiphysics analysis:
  - **Griffin:** solves reactor physics parameters including equilibrium core depletion and transient solutions.
  - **Pronghorn:** solves porous medium equations for the fluid regions and conduction in the solid regions.
  - **BISON:** solves thermal conduction problems for pebbles in the pebble-bed core to provide fuel and moderator spatial temperature fields.





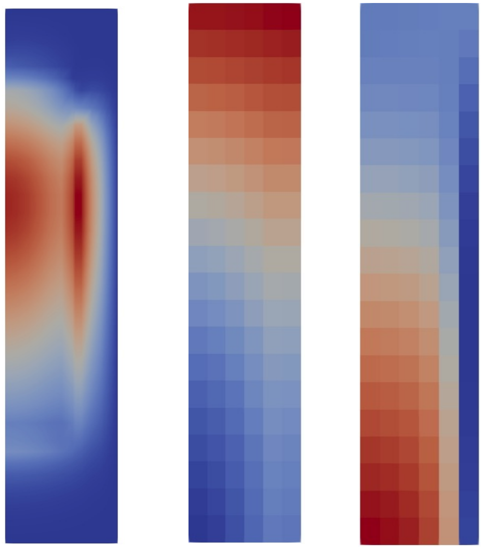


Fluid Temperature Evolution During DLOFC Transient Scenario

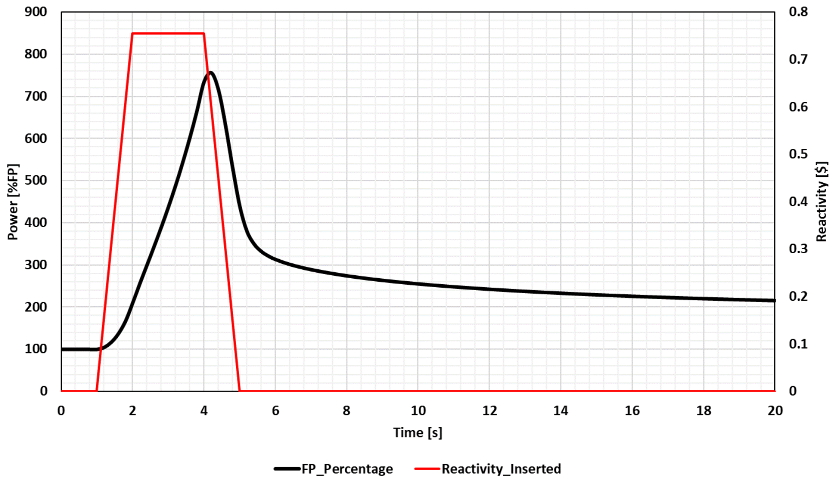
- The developed model of the HTR-PM was used to perform equilibrium core steady state calculations and depressurized loss of forced cooling accidents (DLOFC).
  - Numerical test results show very good agreement with published Very Superior Old Programs (VSOP) results.
  - Steady state solution: eigenvalue to within 150 pcm, power peaking factor within 0.2%
  - Transient solution: average and maximum temperatures are within 1%.
- The model contributes to the NRC mission of licensing Pebble-Bed Reactors by providing the necessary capabilities for Multiphysics modeling and simulation.

NRC Workshop for Gas-Cooled PBR Analysis

- ***INL team conducted a Griffin workshop for the Nuclear Regulatory Commission on 12/11/2023***
  - *Main purpose was on the use of the Griffin application for PBR analysis using the INL HTR-PM reference plant model*
  - The training covered meshing as well as the calculation of the equilibrium core, temperature coefficients of reactivity, adjoint, PKE parameters, and a control rod withdrawal transient event
  - 21 staff members from NRC attended the training as well as ANL staff to learn how to model PBRs with Griffin
- ***Impact***
  - Strengthen collaboration between NRC and the INL team
  - Increase trust in the Griffin application
  - Increase NRC staff familiarization with the HTR-PM model
  - Has led to plans for additional workshops for coupled Griffin-Pronghorn-SAM calculations next calendar year
  - Additional future work is expected leveraging this reference model to develop NRCs evaluation model for Xe-100™



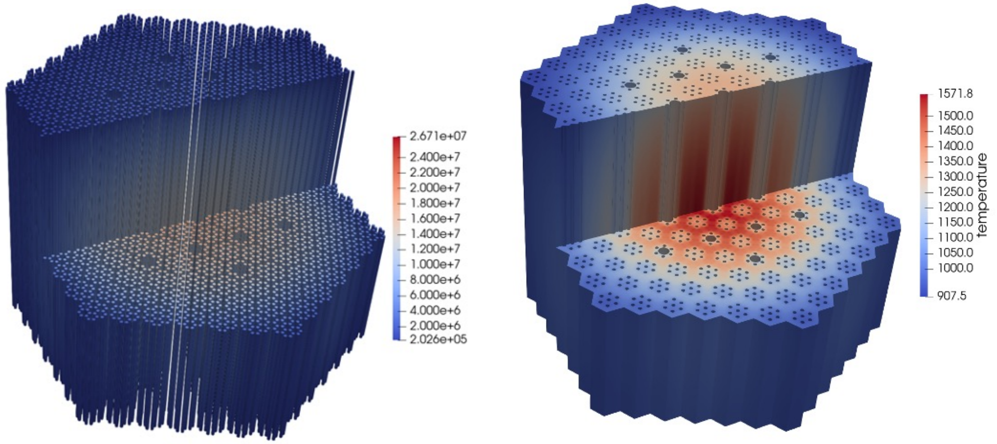
Thermal flux, U235 and Pu239 distributions in the equilibrium core



Control rod withdrawal transient for the HTR-PM using Griffin

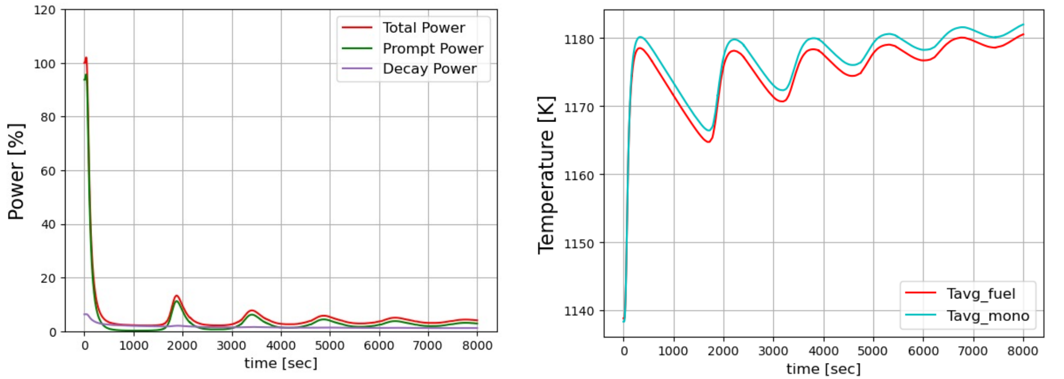
NRC Presentation of a Monolithic Micro Reactor Transient

- ***INL team presented the results of the monolithic micro reactor reference plant model to the Nuclear Regulatory Commission on 12/12/2023***
  - Fully heterogeneous SN transport and core conduction coupling Griffin, Bison, and Sockeye
  - Each heat pipe is included explicitly with the Sockeye vapor-only model
  - Model specification are based on open literature information



SN Transport Pin Power and Temperature distribution at steady state

- ***Impact***
  - Increase the level of readiness of the various MOOSE-based applications
  - Determine needs for the NRC reference plant
  - Additional work is expected in the future leveraging this reference plant model to develop the NRCs evaluation model for eVinci™



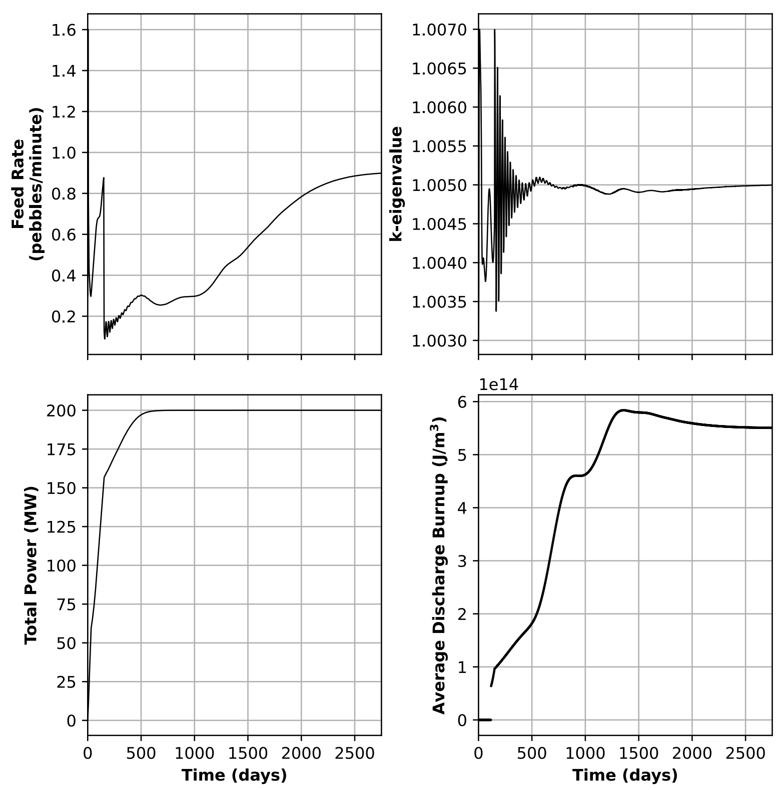
Loss of heat sink transient (based on initial diffusion calculations, SN transport under deployment)

Contact: javier.ortensi@inl.gov, Mustafa.Jaradat@inl.gov, joshua.hansel@inl.gov, Stefano.Terlizzi@inl.gov

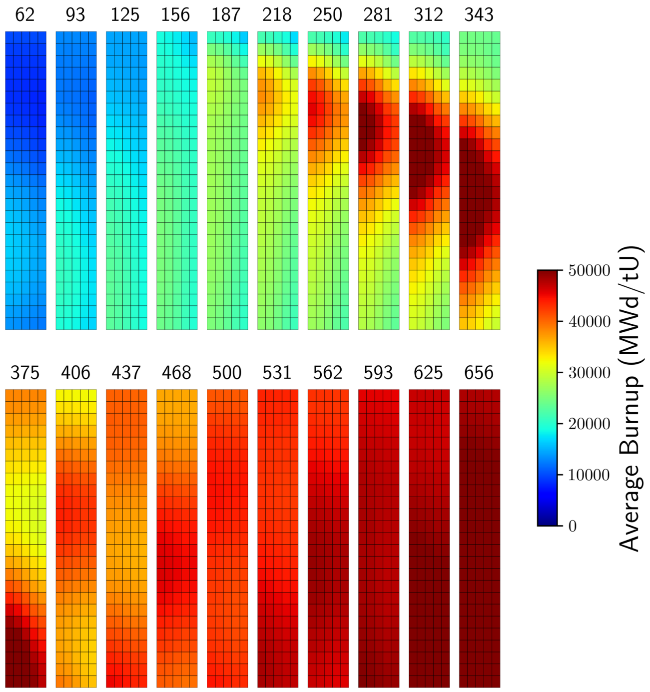
Nuclear Energy Advance Modelling and Simulation

Simulating the Running-In Phase of Pebble-Bed Reactor Operation with Griffin

- Pebble-Bed Reactors (PBRs) are initially filled with graphite pebbles and brought to criticality as these initial graphite pebbles exit the reactor and are replaced with fuel pebbles.
- The power of the reactor is increased over time as more fuel is added and graphite pebbles removed, the burnup of the fuel increases as power is produced.
- Simulating the running-in phase is critical:
  - Economic incentive to reach rated operating power levels as quickly as allowable
  - Safety related calculations depend on accurately simulating core configuration during this phase where the core changes with time



Important quantities plotted for the first 2750 days of simulated PBR operation



Average burnup in core, numbers on top of the plots are the time in days.

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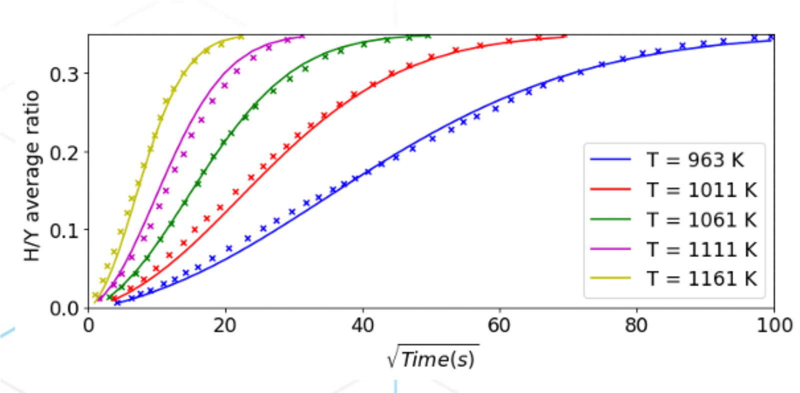
Hydrogen migration in microreactors

- LDRD-funded project to analyze the effect of hydrogen migration on microreactor performance.
- The DireWolf multiphysics software driver was used to solve the coupled radiation transport, heat transfer, heat pipe two-phase flow, and hydrogen migration equations.



Models for hydrogen dissociation of hydrogen at the yttrium hydride surface, including adsorption and desorption, were implemented in Bison and the results obtained were compared to the experimental values.

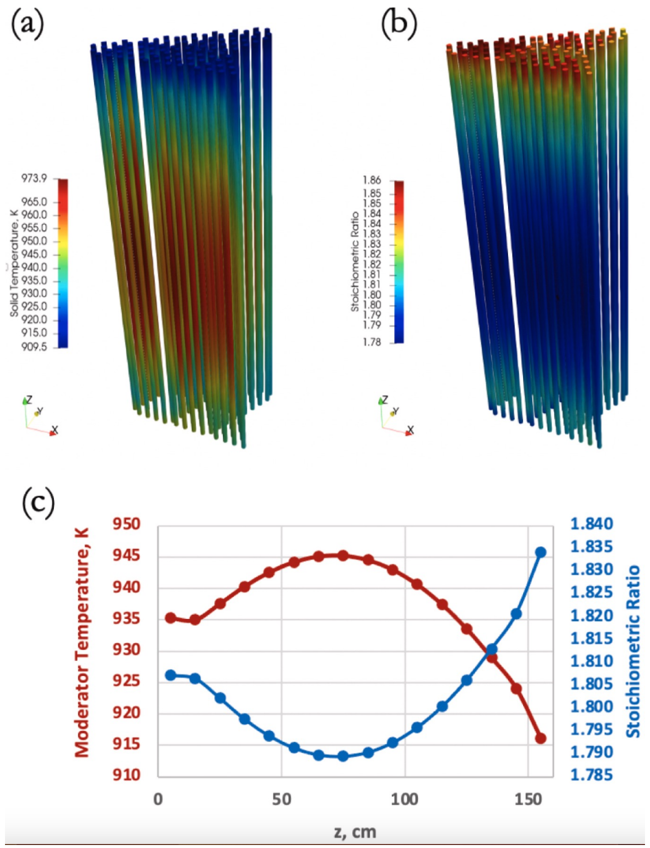


Fig. 3. (a) Three-dimensional temperature spatial distribution in the moderator pins, (b) 3-D hydrogen stoichiometric ratio spatial distribution, and (c) radially averaged moderator temperature and hydrogen stoichiometric ratio for 16 10-cm-high axial levels as a function of the distance from the bottom of the YH_x moderator pins

S. Terlizzi, V. Labouré, (2023). Asymptotic hydrogen redistribution analysis in yttrium-hydride-moderated heat-pipe-cooled microreactors using DireWolf, Annals of Nuclear Energy, Volume 186, 109735.

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**

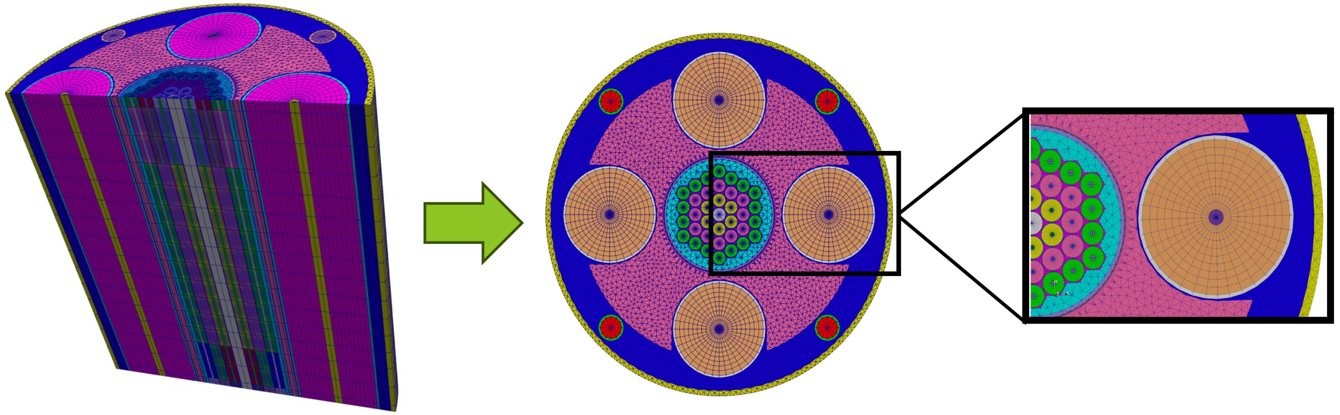
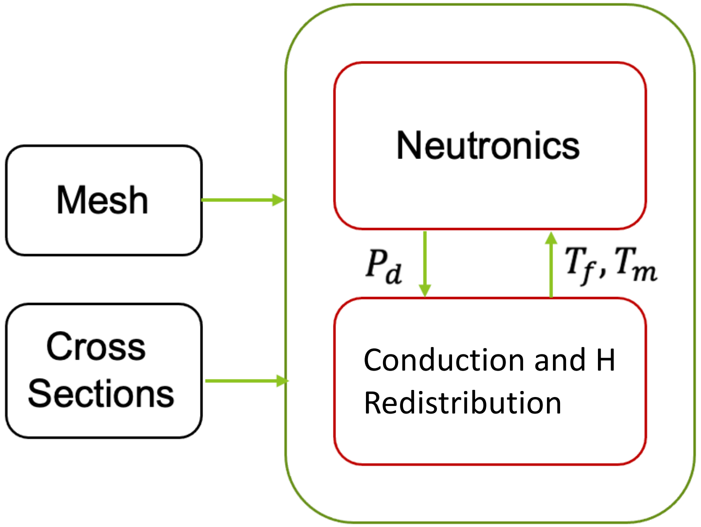


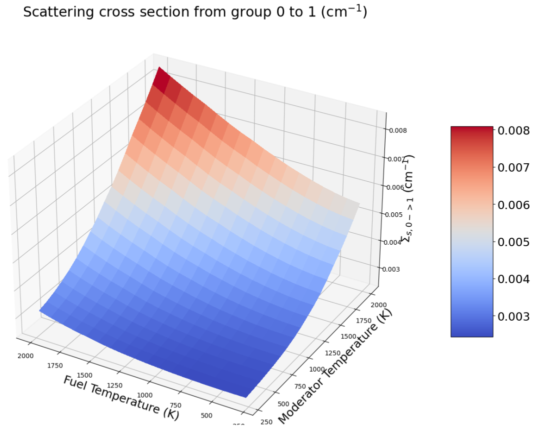
Fig. 1: MOOSE-generated 3D mesh and mid-plane

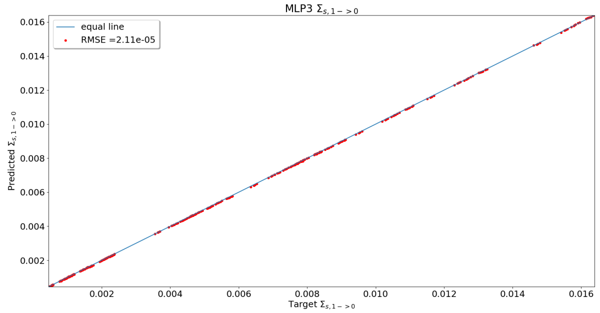


S. Terlizzi, I. Trivedi, (In preparation, 2024). Towards a high-fidelity NEAMS-based model of the MARVEL reactor, International Conference on Physics of Reactors (PHYSOR 2024).

DOE-NE Nuclear Energy Advanced Modeling and Simulation Program

Machine Learning Shows Potential for Improving Accuracy and Speed of Multiphysics Core Analyses





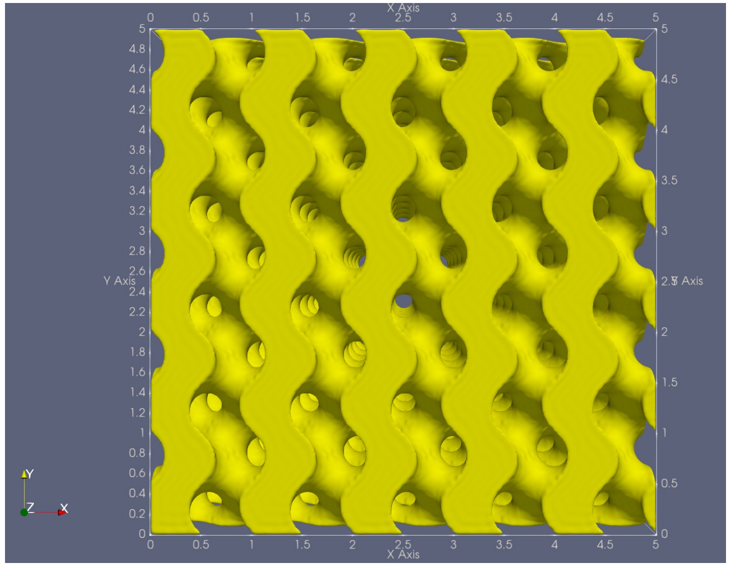
- ***Multiphysics core simulations in the Griffin reactor physics code traditionally rely on pre-generated parametrized multigroup cross-sections, which are interpolated during simulation using local conditions.***
  - *Generating these cross-sections is computationally costly since current interpolation model is linear, and number of calculations exponentially increase as a function of the number of feedback parameters (curse of dimensionality)*
- ***Multigroup cross-sections were represented using Fully-Connected Artificial Neural Networks (ANN) in the MOOSE-based Griffin reactor physics code.***
  - The ANN-based cross-section model is trained using PyTorch, an open-source Deep Learning Environment, and then used in Griffin via an optimized binary format termed torchscript, used for Deep Learning model deployment in production environments (servers, phones, etc.)
  - This work was made possible thanks to the coupling of the MOOSE framework with libtorch, the C++ Application Programming Interface used within PyTorch
  - Applicability of the method was demonstrated on both a High-Temperature Gas Reactor as well as a Sodium-Cooled Fast Reactor fuel assembly case
- **This new capability provides shorter simulation time with a lower cross-section reconstruction error, which is crucial when scoping many time-dependent, multiphysics simulations of advanced reactors.**

Title: Deep Learning for Multigroup Cross-Section Representation in Two-Step Core Calculations
Authors: Nicolas Martin, Zachary Prince, Vincent Labouré, Mauricio Tano-Retamales
Journal: Nuclear Science and Engineering
Link: https://doi.org/10.1080/00295639.2022.2159220

LDRD: Unlocking the Power of Microreactors with Biomimicry and Additively Manufactured Nuclear Fuel

First Study Characterizing Potential Benefits from Additively Manufactured Nuclear Fuel Lattices

- Additive manufacturing (AM) unlocks new types of innovative structures and designs.
- Triply Periodic Minimal Surface (TPMS) lattices are periodic structures found in nature that are being investigated for heat exchangers/heat sink applications.
- TPMS lattices offer increased convective heat transfer relative to traditional geometries thanks to high surface area-to-volume ratios, smooth curvatures, and labyrinth-like flow paths.
- This study is the first to characterize the neutronics behavior of TPMS lattices and identify geometric parameters that can be tailored for either fast or thermal nuclear core designs.
- TPMS nuclear fuel could reach much larger power densities than with traditional fuel designs, thereby allowing extremely compact core designs.
- Future work includes testing of TPMS fuel lattice in TREAT.



Example of Gyroid lattice

Title: Reactor physics characterization of triply periodic minimal nuclear fuel lattices
Authors: Nicolas Martin, Seokbin Seo, Silvino Balderrama Prieto, Casey Jesse, Nicolas Woolstenhulme
Journal: Progress in Nuclear Energy
Link: https://doi.org/10.1016/j.pnucene.2023.104895

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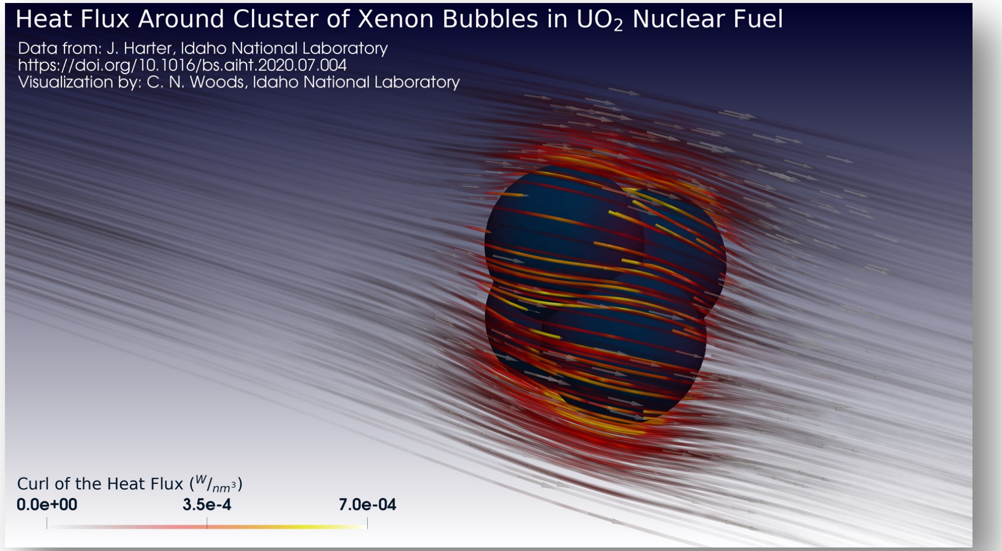
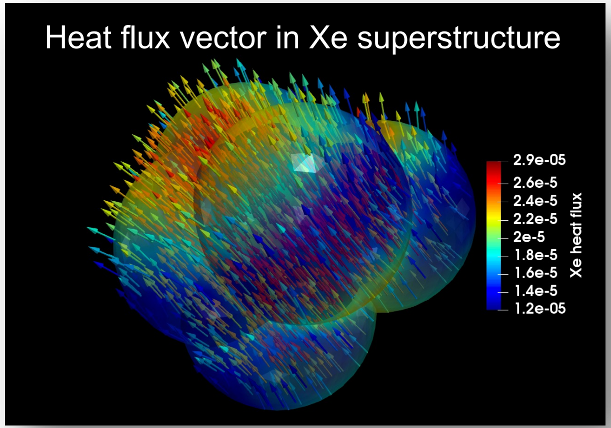
Advanced Nuclear Reactor Modeling Project

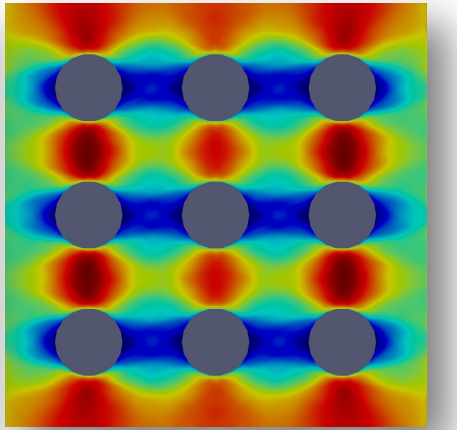
Multigroup Phonon and Electron Transport

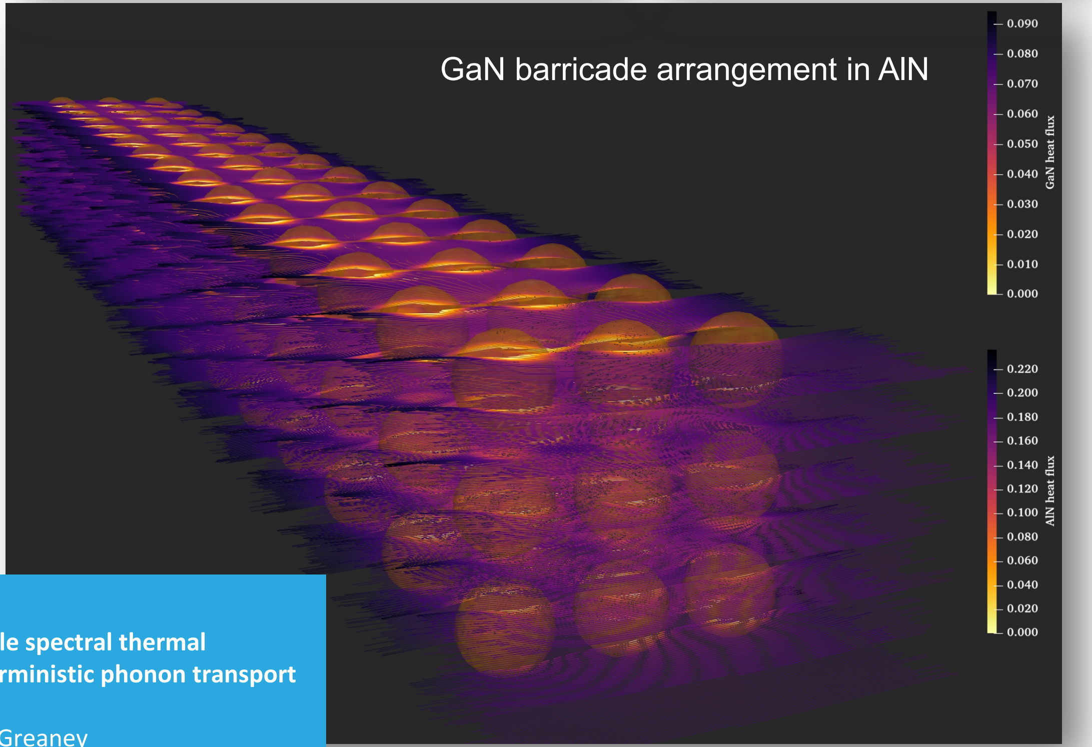
- Efficient phonon and electron transport capability in *Griffin*
- Implicitly coupled in temperature, using DFT-based material properties
- Sophisticated thermal interface model (temperature dependent transmission and reflection of phonons)
- Explicit defect or pore modeling, i.e., Xe in UO_2, GaN-doped AlN
- Applied to simulations for nuclear materials, thermoelectrics, semiconductors





Heat flux in porous Si





References:

Chapter Five - Predicting mesoscale spectral thermal conductivity using advanced deterministic phonon transport techniques

Authors: J. Harter, T. Palmer, P.A. Greaney

Journal: Advances in Heat Transfer

DOI: https://doi.org/10.1016/bs.aiht.2020.07.004

(Additional publications authored by J. Harter exist, some are pending)

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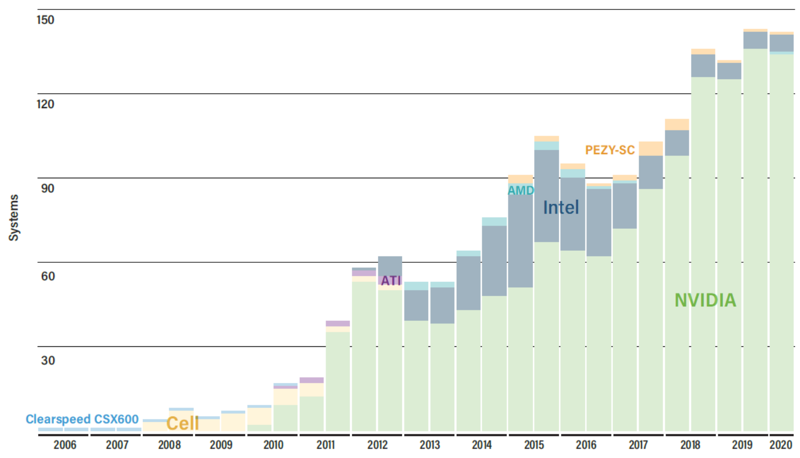
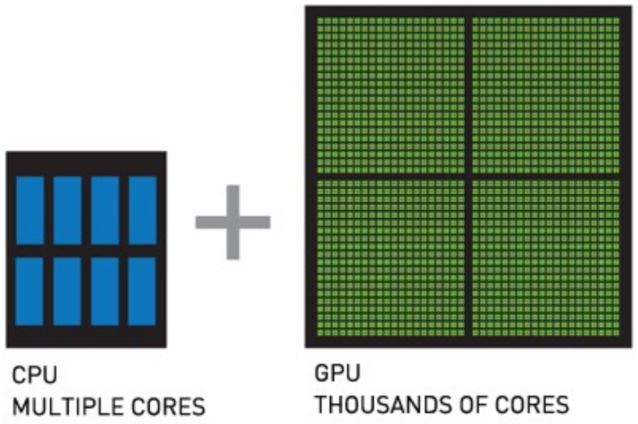
Advanced Nuclear Reactor Modeling Project

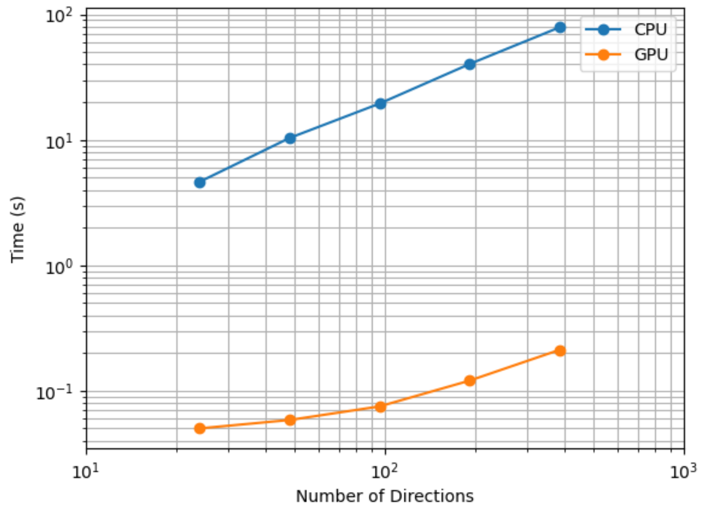
GPU Acceleration of Griffin

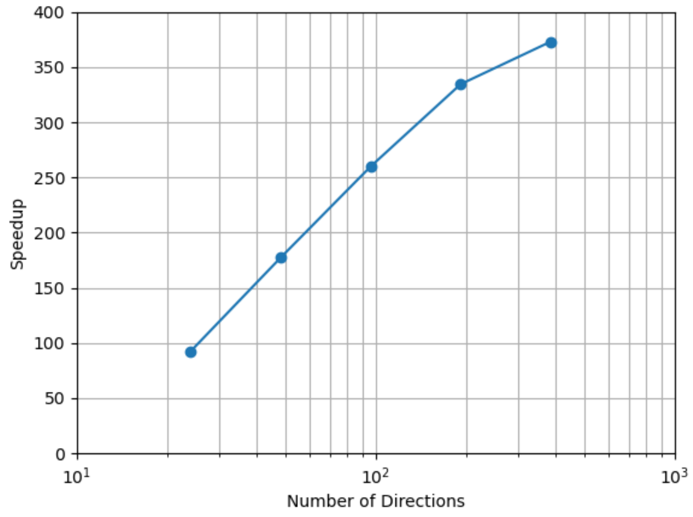
- GPUs have become the megatrend of modern supercomputing.
- Explosion of computing power driven by GPU technologies and AI industries opens up an opportunity for radiation transport fields to break the computational barrier.
- Massive parallelization of DFEM-S_N sweeper on GPU has been achieved in Griffin, which requires a fundamental algorithmic and code architectural changes.
- Griffin will be able to leverage the exponentially growing GPU computing powers to solve previously prohibited problems and remain competitive under the technological shift in today's computing arena.





Sweeper Performance (CPU vs GPU)





Application of Advanced Modeling and Simulation to Gas Cooled Microreactor Design and Licensing

- MOOSE-based model including 3D kinetics (Griffin), 3D heat transfer (BISON), and 1D thermal-hydraulics model (THM) developed in support of proprietary design
- Solves for the power distribution, temperature fields across the core, primary/secondary loop modeled using RELAP-7
  - Core physics performance: radial/axial peakings, flux distribution, rod worth, etc.
  - Transient and accident analyses: pressured /depressurized loss of forced flow, reactivity insertion accidents, etc.
  - Scoping studies for placement of instrumentations
- Another MOOSE-based model developed for mechanistic source term
  - Predicts TRISO failure rates using BISON
  - Tracks the diffusion of released fission products from TRISO particles to coolant pressure loop
- **INL-developed codes and methods can be applied to real-life engineering problems**

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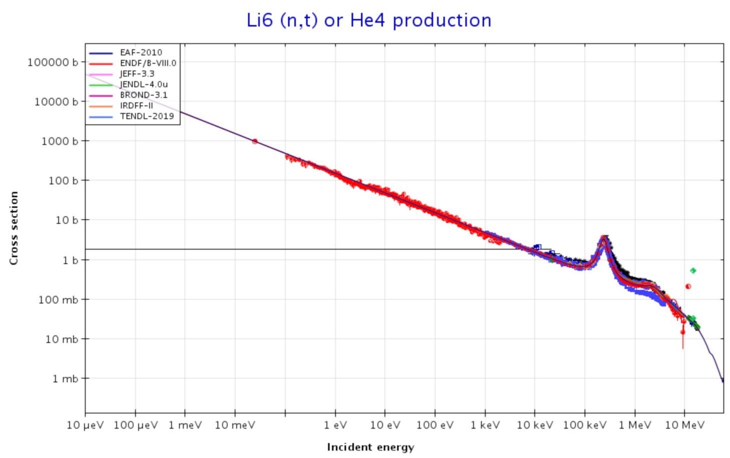
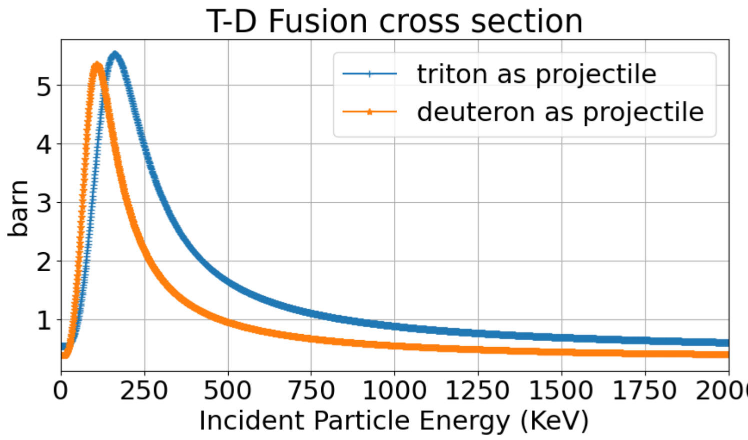
Design of a thermal to fast neutron converter for use in ATR

- High energy neutrons (> 14 MeV) can be generated from Tritium+Deuterium as well as from Tritium+Lithium reactions
- Relies on a sequence of reactions occurring in a breeder material such as Lithium Deuteride (LiD)
  - Neutron is absorbed by Lithium and generates a triton
  - Triton is slowed down and fuses with Deuterium
- A computational scheme relying on the GEANT4 high energy physics Monte Carlo code has been proposed, which internally models the sequence of reaction
  - GEANT4 perform neutron transport similarly to MCNP/Serpent for < 20 MeV neutrons with similar cross section libraries
  - GEANT4 performs light ion transport and model D-T fusion reactions
- **Purpose is to convert thermal neutrons into high energy neutrons for material testing prototypical of fusion reactors**





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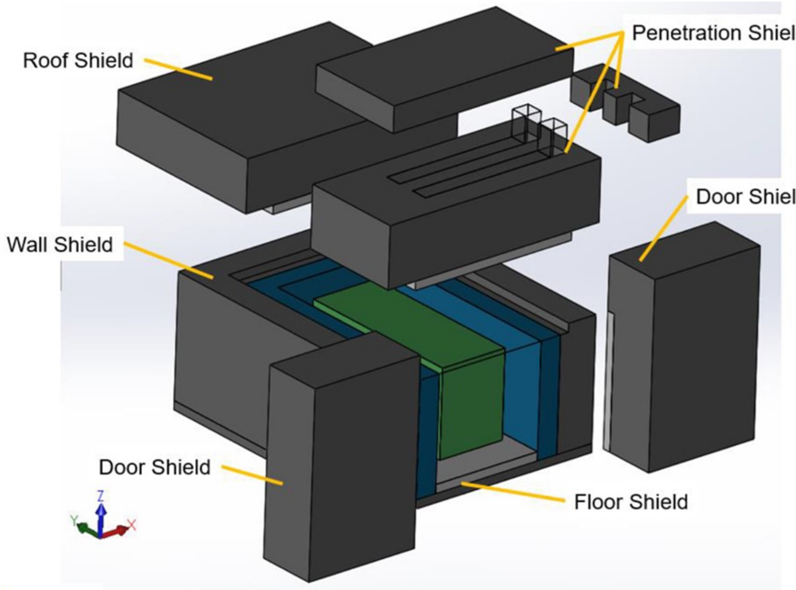
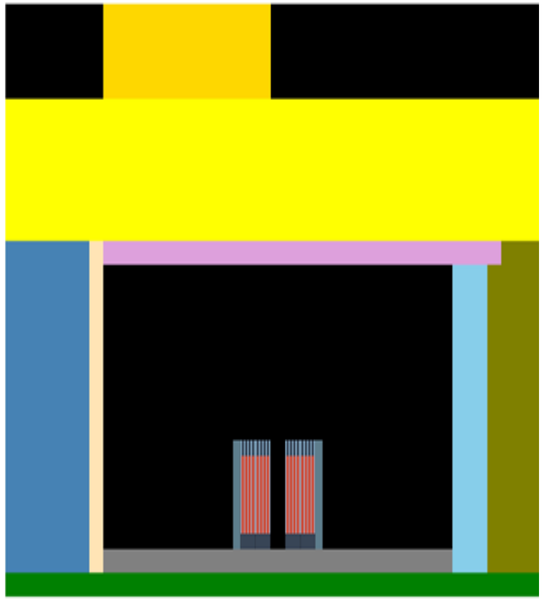
Demonstration of Micro-reactor Experiments
Reactor Supplemental Shielding

- National Reactor Innovation Center (NRIC) is developing the Demonstration of Micro-reactor Experiments (DOME) test bed at the Idaho National Lab (INL), Materials and Fuels Complex (MFC).
- The purpose of DOME is to support testing of advanced reactors to support reactor developer's licensing and commercialization activities for their reactor concepts.

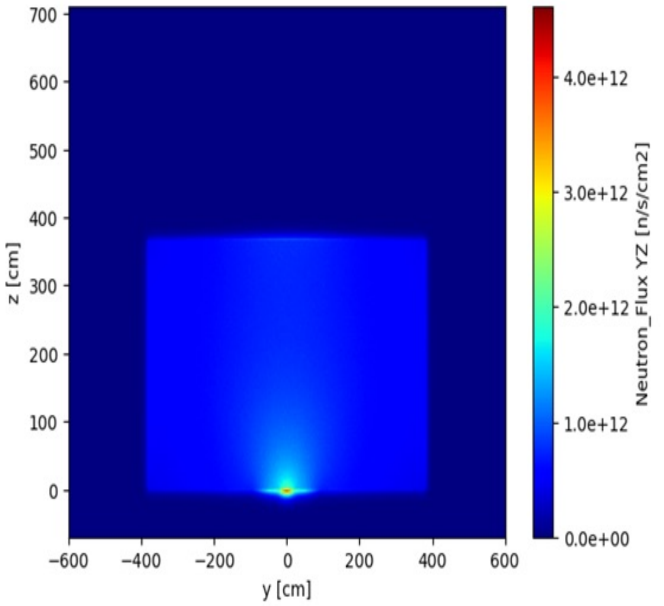
Reactor Supplemental Shielding (RSS)



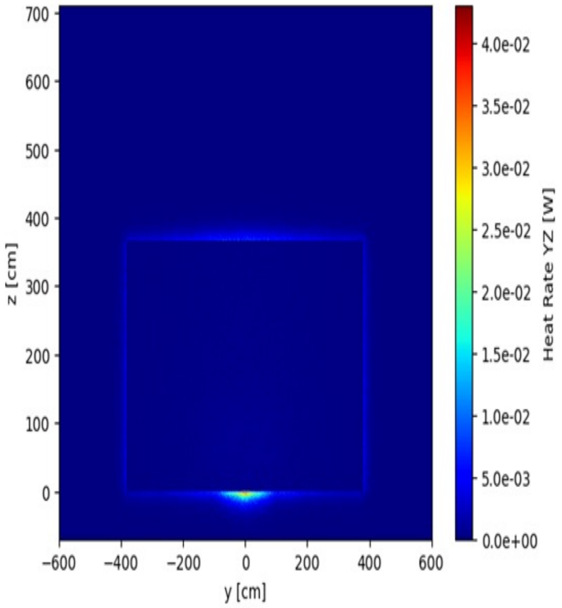
OpenMC RSS Model



Neutron Flux



Heat Deposited



- The key differences from LWRs :
  - The absence of large quantities of water within the reactors
  - The absence of large quantities of structural materials (concrete and steel) surrounding the reactors.
  - The result is a significant reduction in inherent radiation shielding.
- The objective of this work is to develop a conceptual design of the DOME Reactor Supplemental Shielding (RSS) using OpenMC code.
- The model will be used by vendor to test their designs.

Idaho National Laboratory

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy. INL is the nation's center for nuclear energy research and development, and also performs research in each of DOE's strategic goal areas: energy, national security, science and the environment.