U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Developing Software in a Shifting Landscape

How the Department of Energy, Office of Nuclear Energy is accelerating the growth of an industry that is in a constant state of change.

Dr. Derek Gaston
Senior Technical Advisor
Office of Nuclear Energy

My Journey

- Ozark: Small town in SW Missouri
  - Loved computers (games)
  - Wanted to go to MIT
  - Didn't even apply!
- 2000 - University of Missouri – Rolla
  - BS in Comp. Sci.
  - Wasn't interested in nuclear!
  - Saw the reactor once…
  - Lots of internships!
- 2005 - Sandia National Laboratory
  - Instantly sent to get my Master's…
- 2005 University of Texas – Austin
  - MS in Comp. Applied Math.
- 2007 – Sandia National Lab.
  - Sierra Framework

My Journey (2)

- 2008 - Idaho National Lab
  - Instantly started MOOSE
    - Multiphysics Object Oriented Simulation Environment
    - And BISON
- 2011
  PECASE: Presidential Early Career Award for Science and Engineering
- 2014
  - R&D100 award for MOOSE
  - Open-sourced MOOSE
  - Started my Ph.D. at MIT
- 2019
  - Finished my Ph.D.
  - Deputy director of NEAMS
- 2023
  - INL Chief Computational Scientist
  - R&D100 award for Cardinal
- 2024
  - Senior Technical Advisor for the Assistant Secretary for Nuclear Energy

Idaho National Laboratory

R&D 100 2014 Winner

2023 R&D 100 WINNER

MOOSE

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Clean. Reliable. Nuclear.

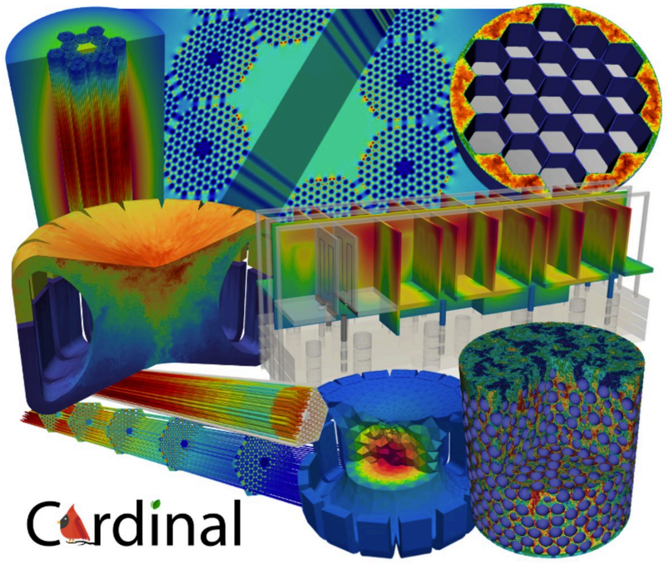


Photo #1: Cardinal Applications. *Top row*: neutron transport, fluid flow, and heat transfer in a gas-cooled microreactor; turbulent flow simulation in the core of a sodium fast reactor. *Middle row*: neutron transport and turbulent flow simulation in a molten salt reactor; coupled neutron-photon transport and heat conduction in a tritium breeder blanket module from the EU DEMO fusion plant. *Bottom row*: fluid flow and neutron transport in a high temperature gas reactor; fission heating simulated in a Computer Aided Design (CAD) geometry of a 16-leg liquid reactor; turbulent flow simulation in a pebble bed reactor with 1568 pebbles.

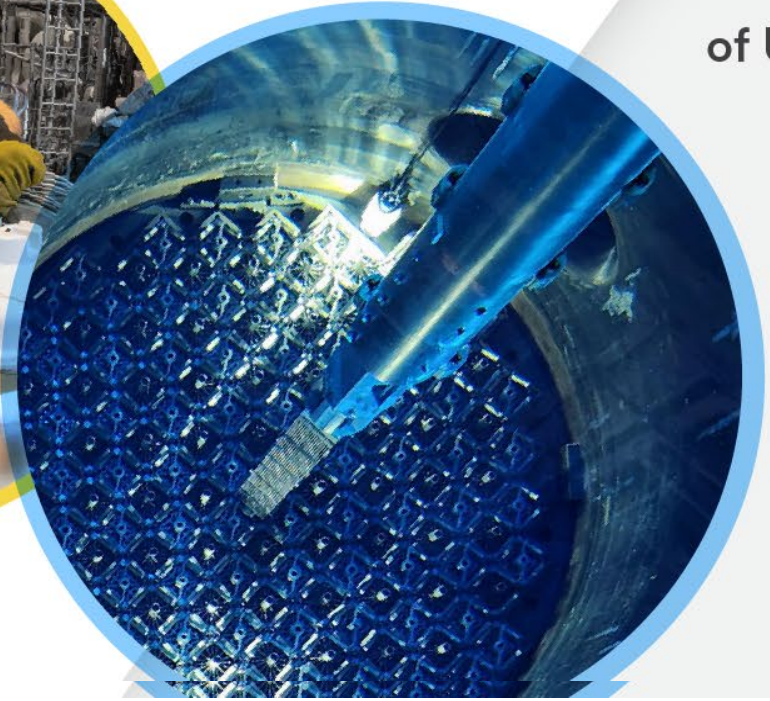
Department of Energy

Office of Nuclear Energy

Biden Administration's Aggressive Climate Goals

- **2035:** Carbon pollution-free power sector
- **2050:** Net zero emissions economy
- Nuclear energy is critical to meeting these goals!

STATE of NUCLEAR



93
commercial reactors

18%
of U.S. electricity generation

47%
of U.S. clean power production

475,000
U.S. jobs supported

1
SMR certified

1
reactor under construction

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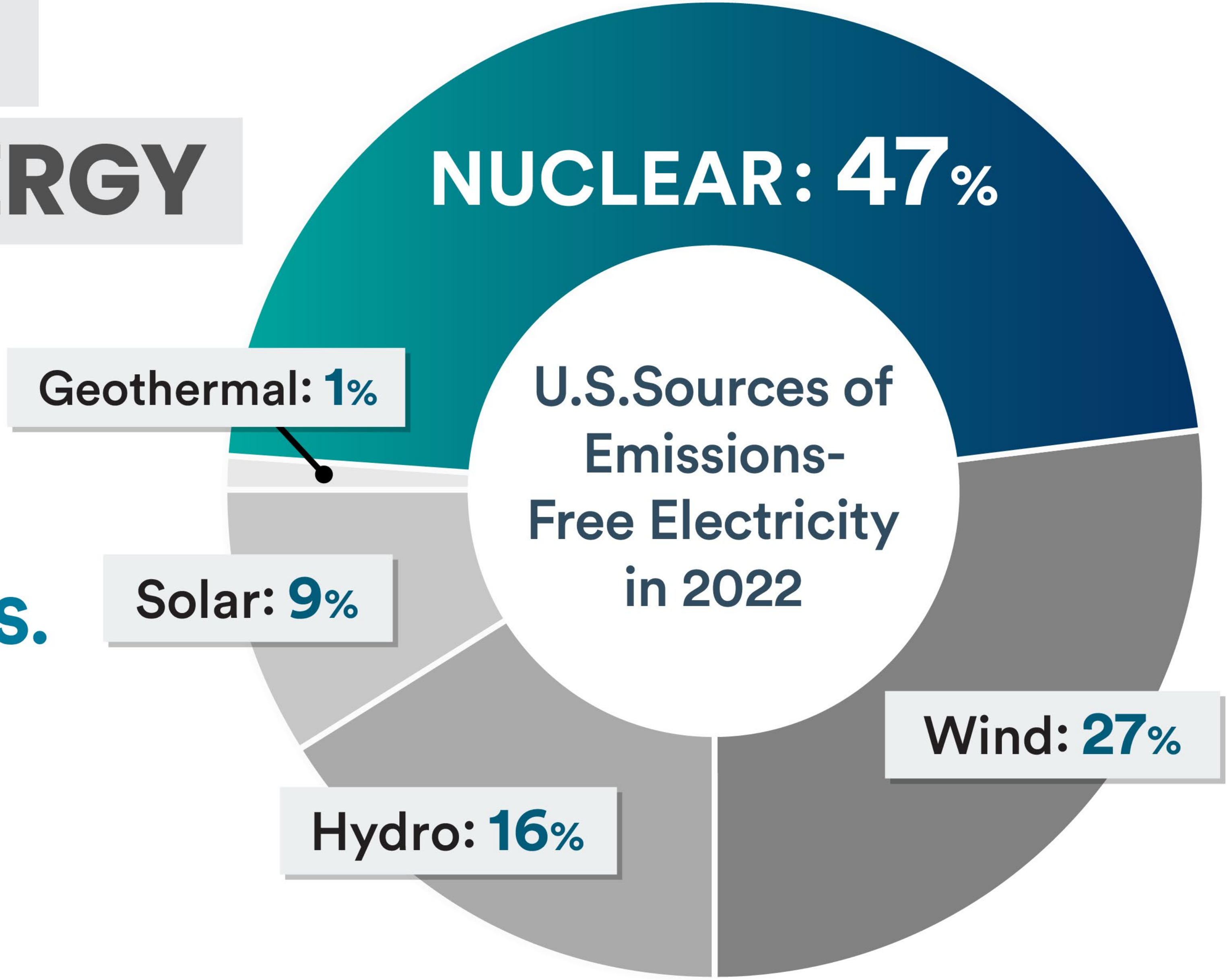
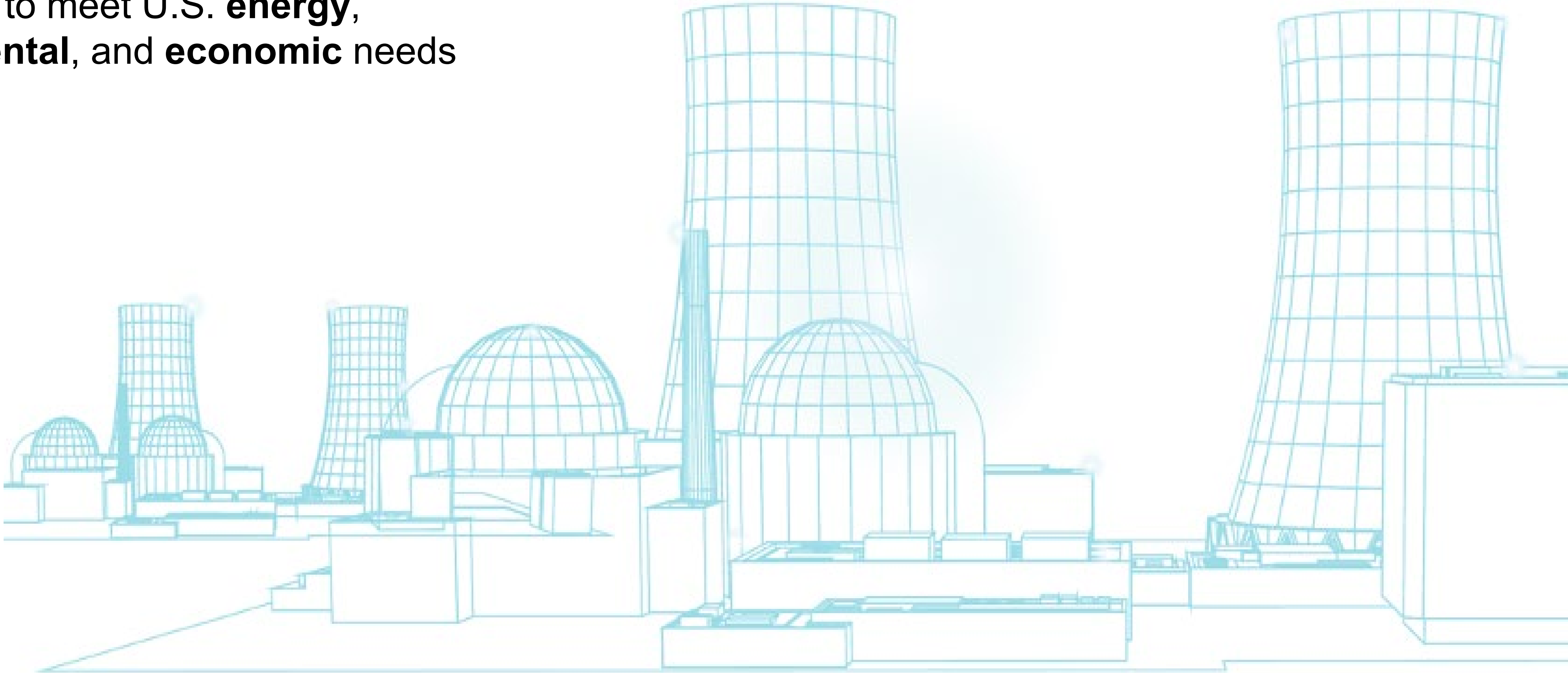
Fast Facts on NUCLEAR ENERGY

Nuclear power is the **largest source of clean energy in the U.S.**



Office of Nuclear Energy Mission

To advance nuclear energy science and technology to meet U.S. **energy**, **environmental**, and **economic** needs



Priorities

Keep Existing Plants Open

Build New Reactors

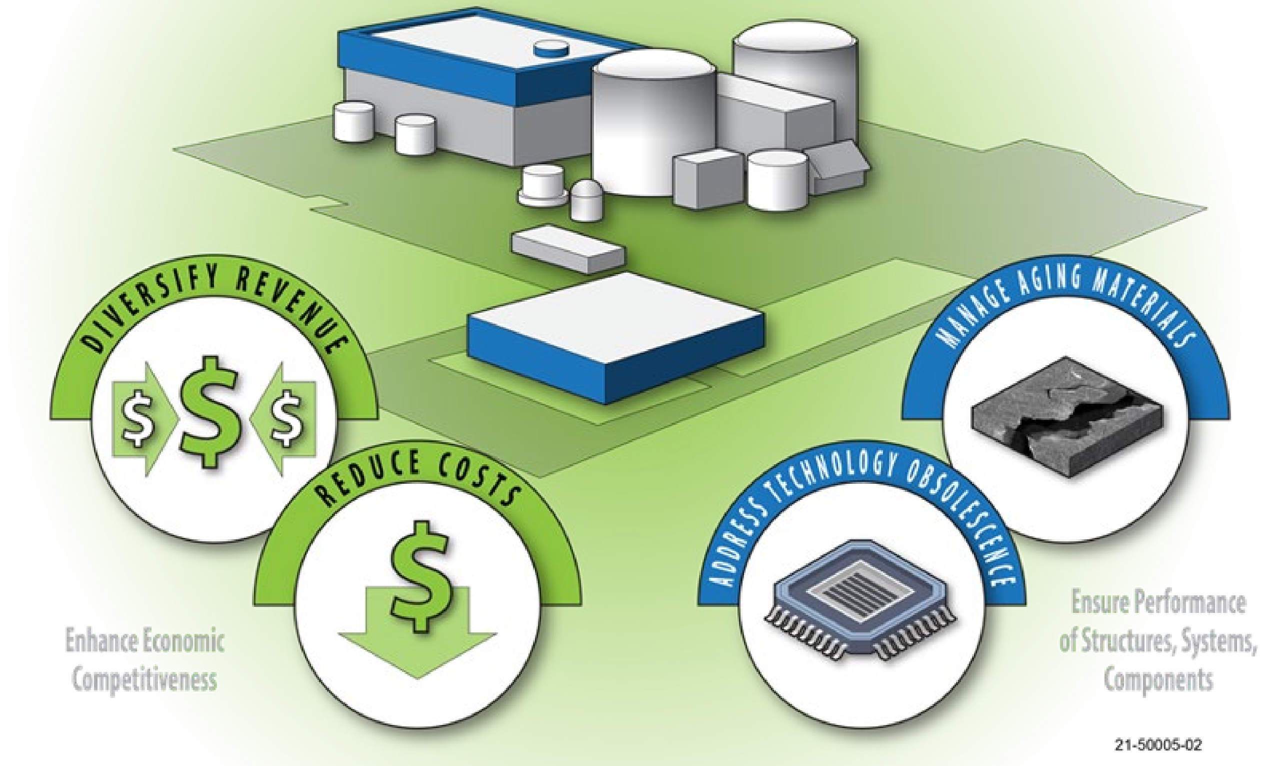
Secure and Sustain the Nuclear Fuel Cycle

Expand International Nuclear Energy Cooperation

Light-Water Sustainability Program

R&D Focus Areas:

- Plant Modernization
- Flexible Plant Operation and Generation
- Risk Informed System Analysis
- Materials Research
- Physical Security

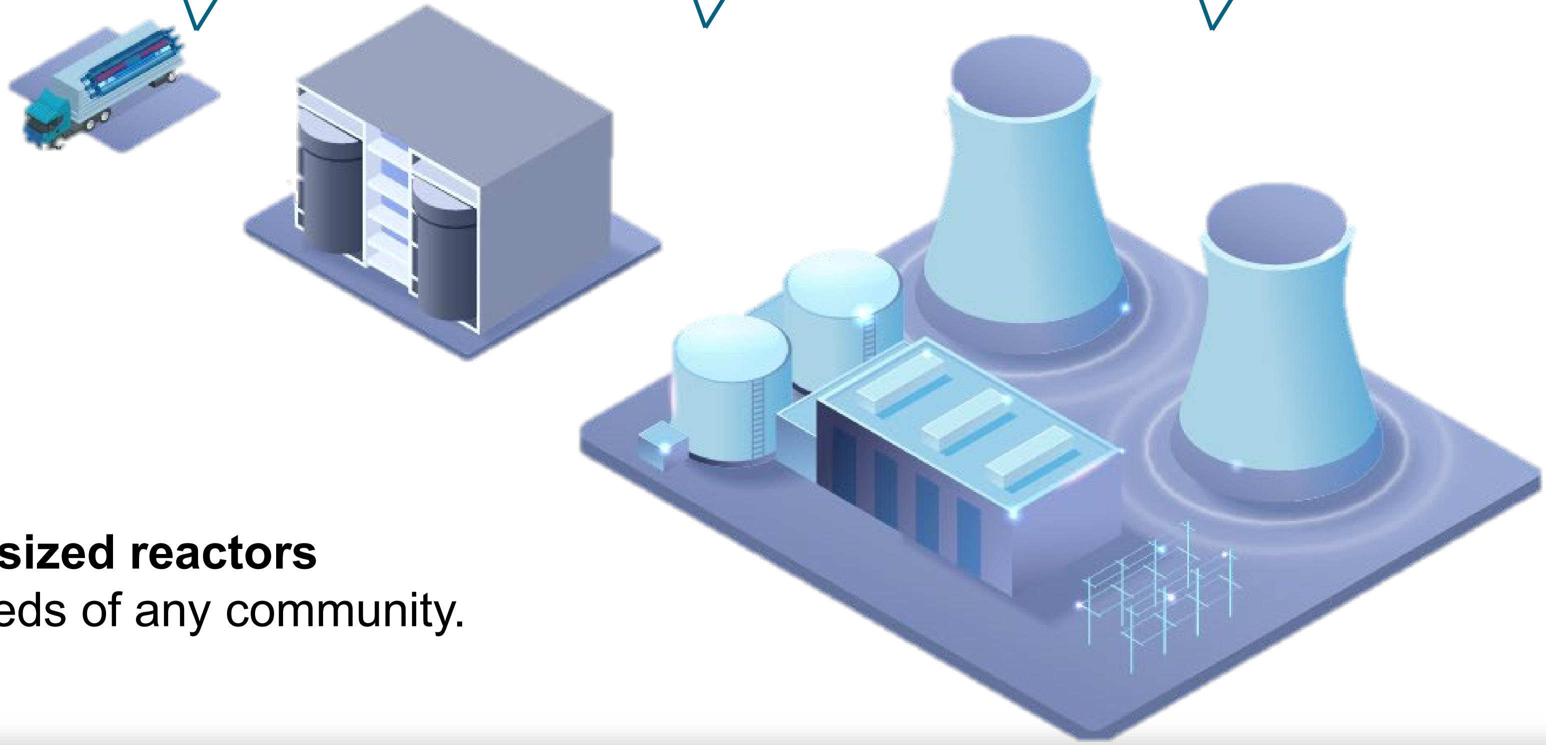


Advanced Reactor Options

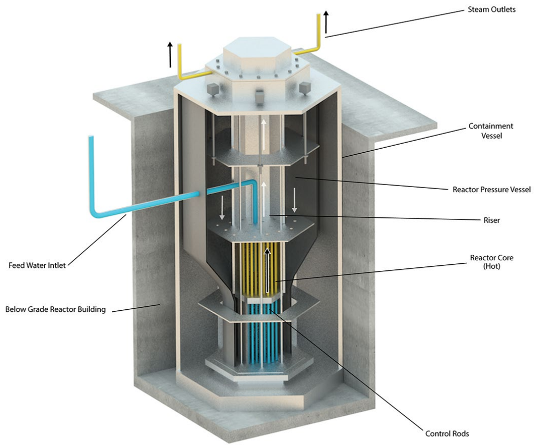
MICROREACTOR
(1 MW – 20 MW)

SMALL MODULAR REACTOR
(20 MW – 300 MW)

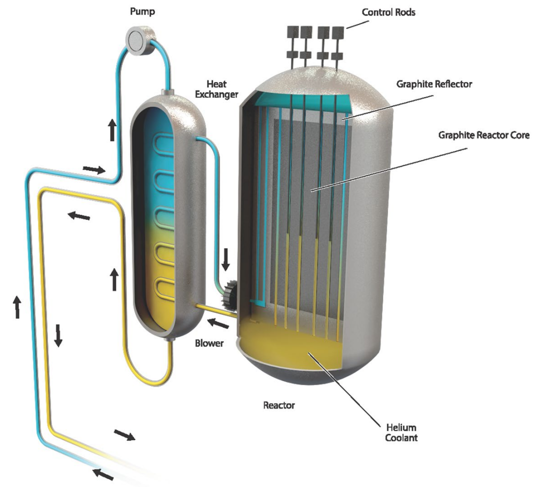
LARGE-SCALE REACTOR
(300 MW – 1,000 + MW)



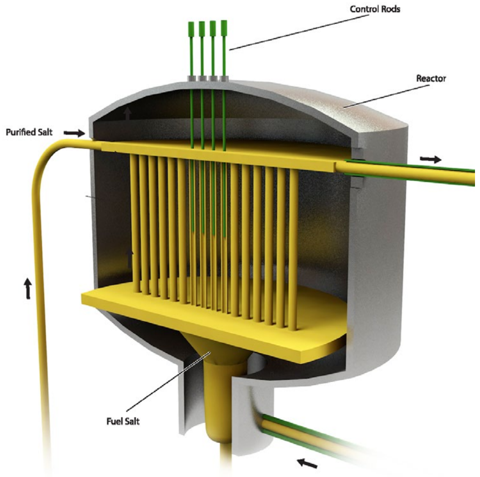
Nuclear has the **right-sized reactors**
to meet the energy needs of any community.



Light-Water

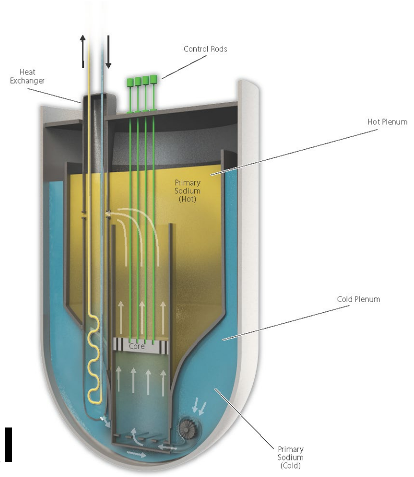


High Temperature Gas

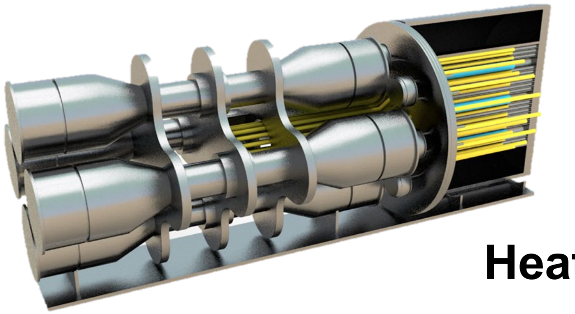


Molten Salt

Advanced Reactor Types

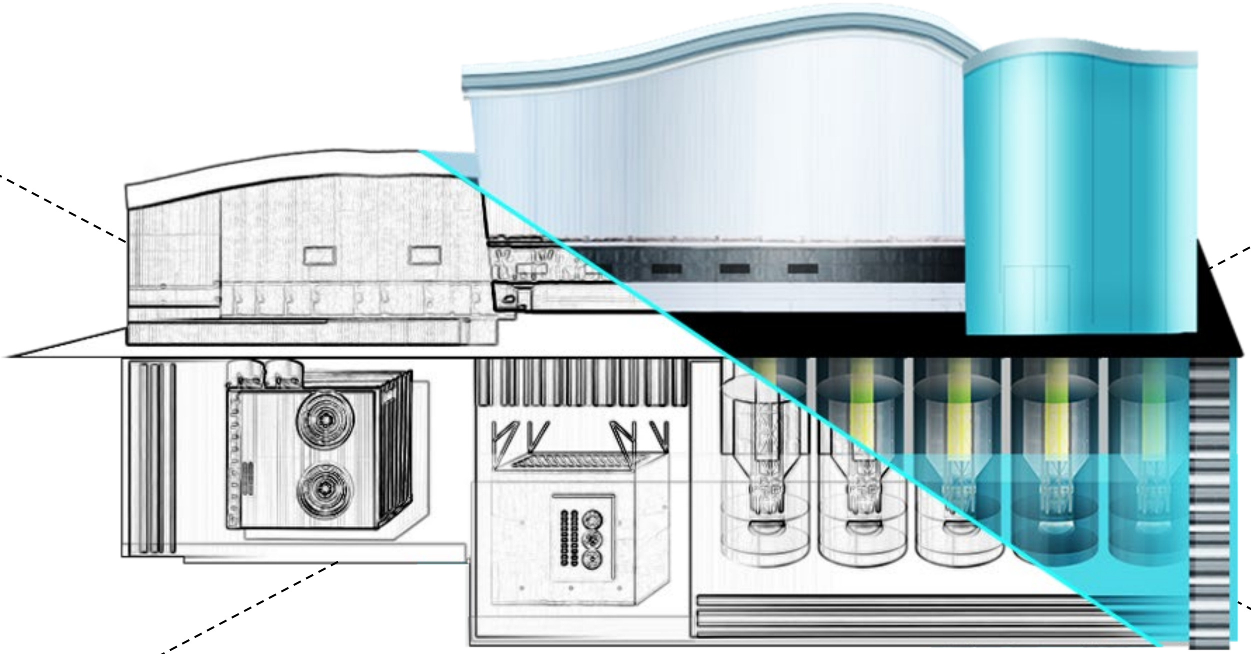


Liquid Metal



Heat pipe

Advanced Reactor Benefits



Enhanced Safety

Waste Management

Versatility

Affordability

COAL *to* NUCLEAR

Repowering coal plants with advanced nuclear reactors can help unlock **new job, economic, and environmental opportunities** for energy communities across the country as the United States shifts toward cleaner energy sources.

Here's how it works.

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Pilot Hydrogen Demonstration Projects

Constellation

Nine Mile Point Plant (2023)
- Low-temperature electrolysis

Vistra Energy

Davis-Besse Plant (2024)
- Low-temperature electrolysis

Xcel Energy

Prairie Island Plant (2024)
- High-temperature electrolysis

U.S. Uranium Production

BY THE NUMBERS

40.5 million pounds

uranium purchased in the U.S. in 2022.

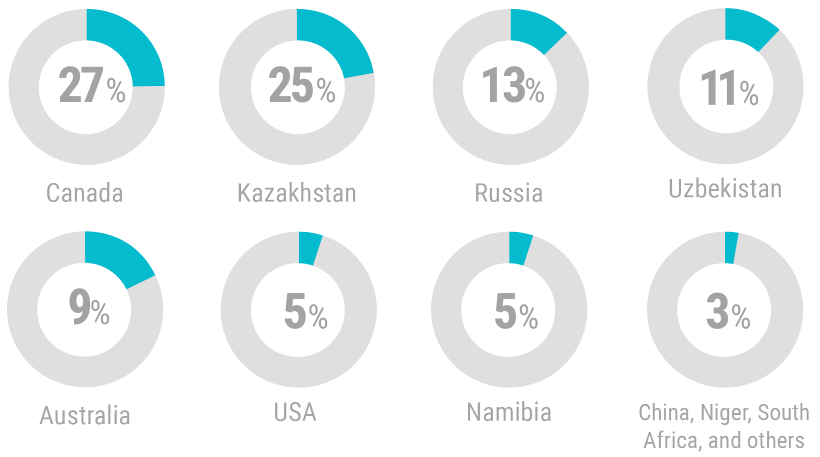
194,000

pounds of domestic uranium produced

95%

of uranium delivered to U.S. utilities was of foreign origin (2022)

Source: U.S. Energy Information Administration, 2022 data



U.S. HALEU Production

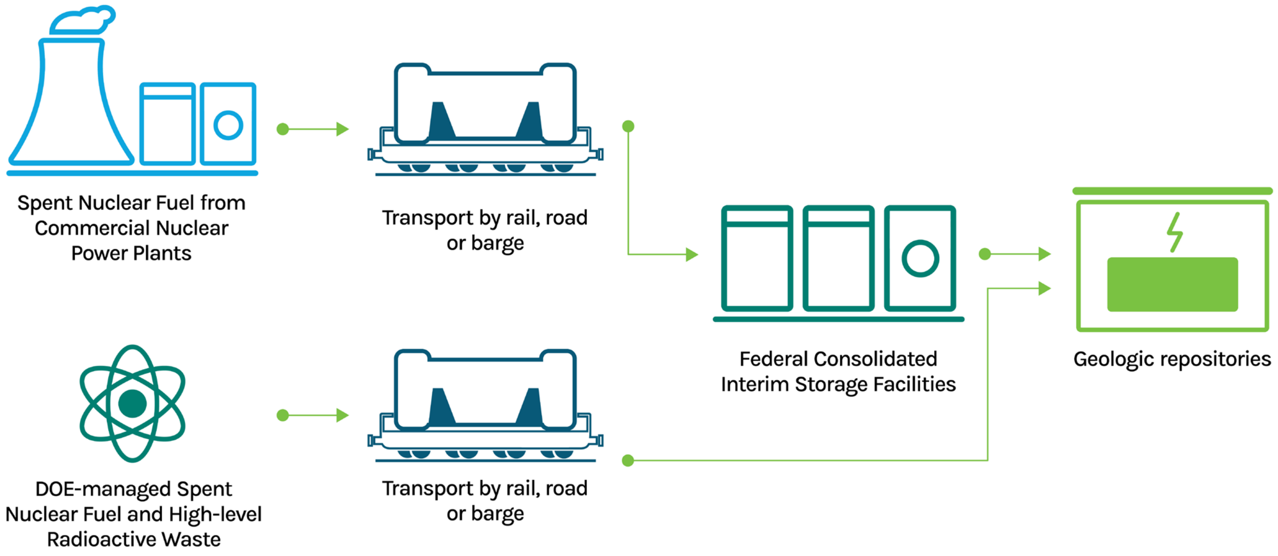
- American Centrifuge produced the target of 20 kilograms of HALEU for 2023 two months ahead of schedule.
  - 900 kilograms of HALEU targeted for 2024

- HALEU to support reactor demonstrations and fuel qualification testing

- Passage of the FY24 Energy and Water Bill
  - Provides up to $2.72B of Civil Nuclear Credit Program funds for domestic HALEU and LEU production.

Spent Nuclear Fuel Management

- Revamp DOE's overall integrated waste management strategy
- Implement consent-based approach for siting federal consolidated interim storage facilities
- Develop high-tech railcars to transport spent nuclear fuel
- Perform R&D on high-burnup fuel
- Integrate spent fuel management into international approach



Crosscutting Priorities

- **Improve diversity in nuclear energy**
  - Foster a culture of inclusion, transparency, and commitment to the nuclear energy mission
- **Advance environmental and energy justice**
  - Integrate energy and environmental justice into management of spent nuclear fuel through consent-based siting of interim storage
  - Embed justice in advanced reactor deployments at home and abroad to deliver benefits to historically underserved, marginalized, or over-burdened communities, including transitioning fossil communities
- **Increase jobs and strengthen the American workforce**
  - Work with communities, unions, industry groups, the educational sector, and others to support training and development of the next generation nuclear energy workforce.

FY2024 Spending Bill Fuels Historic Push for U.S. Advanced Reactors

- **$2.7B** from unobligated appropriations to build out our advanced fuel supply chain and **$100M** to continue ongoing HALEU Availability Program activities.
- **$800** million for DOE to demonstrate two advanced light-water reactor systems in the United States
- **$100 million** for competitive awards to support the advanced light-water reactor supply chain
- **$100 million** to help identify, develop, and implement new safety training programs at universities, trade schools, and 2-year colleges

DOE-NE has provided more than $1B in Support to U.S. Universities

- **FY25**
  - **$44M** for 25 university led R&D projects
  - **$9M** for Integrated Research Projects
  - **$6.6M** for Nuclear Science User Facilities

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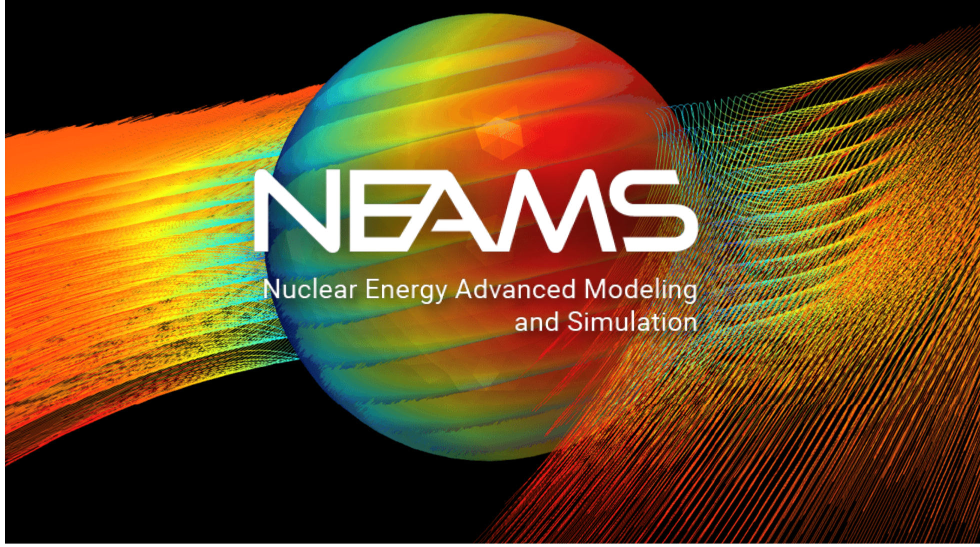
Modeling and Simulation of Nuclear Reactors

Managing complexity by design.

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 software development**



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Idaho National Laboratory

Argonne NATIONAL LABORATORY

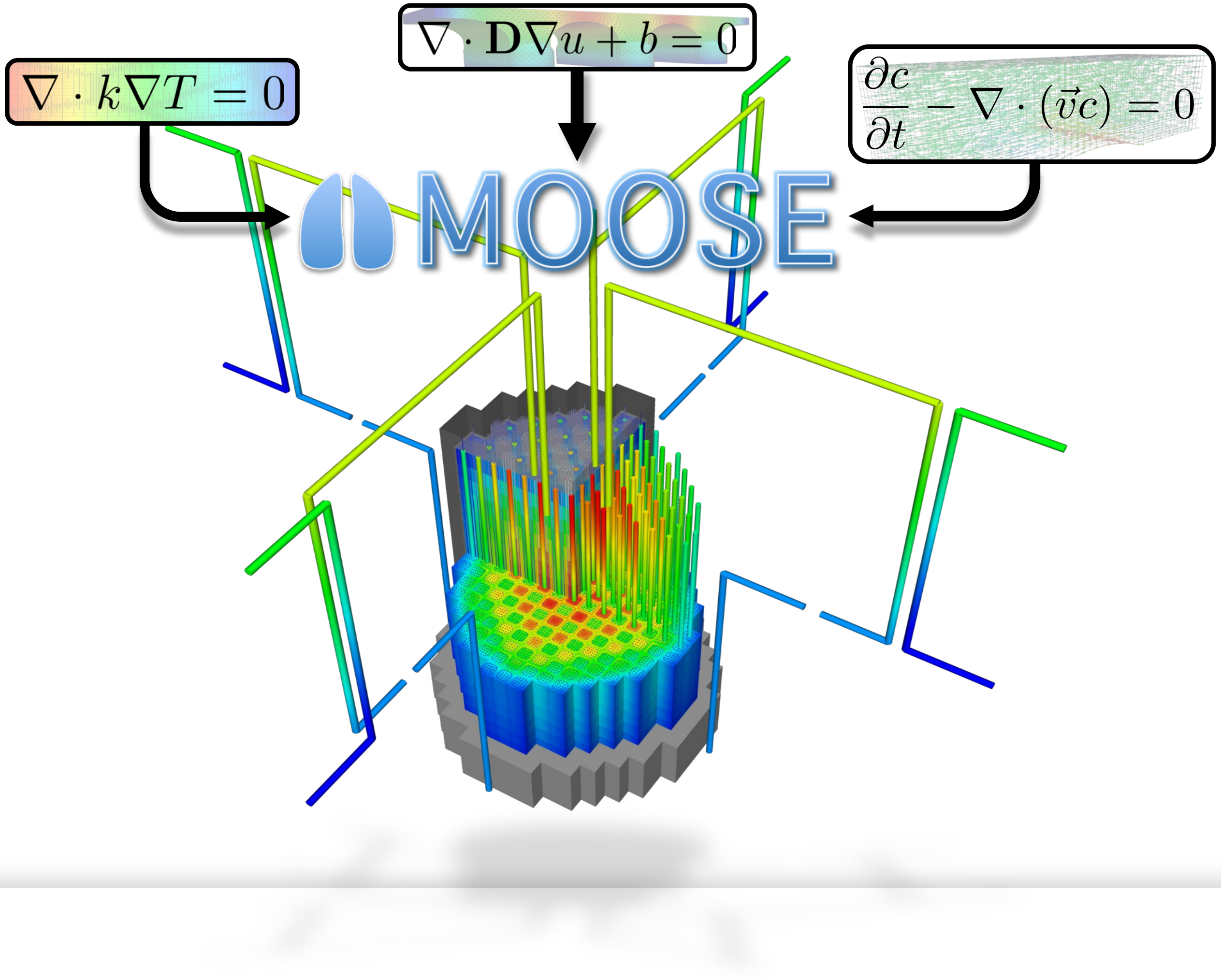
OAK RIDGE National Laboratory

Los Alamos NATIONAL LABORATORY

MOOSE Project

- **Multiphysics Object-Oriented Simulation Environment**
- **Started in May of 2008 (LDRD)**
- **MOOSE is an object-oriented FEM/FVM framework allowing rapid development of new simulation tools**
- **Code development focuses on implementing physics rather than numerical issues**
- **Meets NQA-1 requirements**
- **Ecosystem of diverse applications:**
  - Nuclear fuel, reactor physics, geomechanics, mining, chemistry, earthquake prediction, groundwater flow, fluid flow, microstructure evolution, etc.
- **Open sourced on March 19, 2014**
- **Numbers:**
  - 228 contributors
  - 50,000 commits
  - 3,000 citations for the MOOSE papers
  - 60M+ tests per week

MOOSE Accelerates Development of High-Fidelity Modeling and Simulation Tools



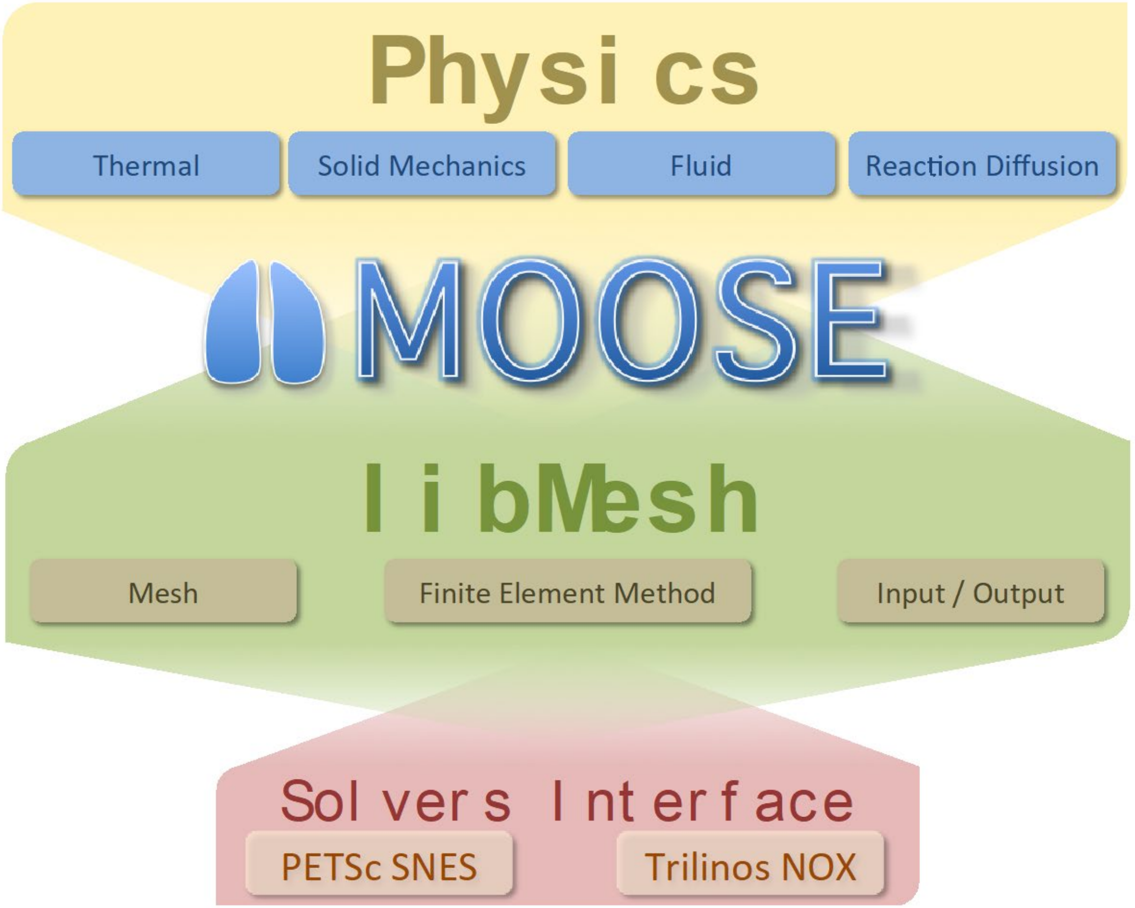
What is MOOSE?

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

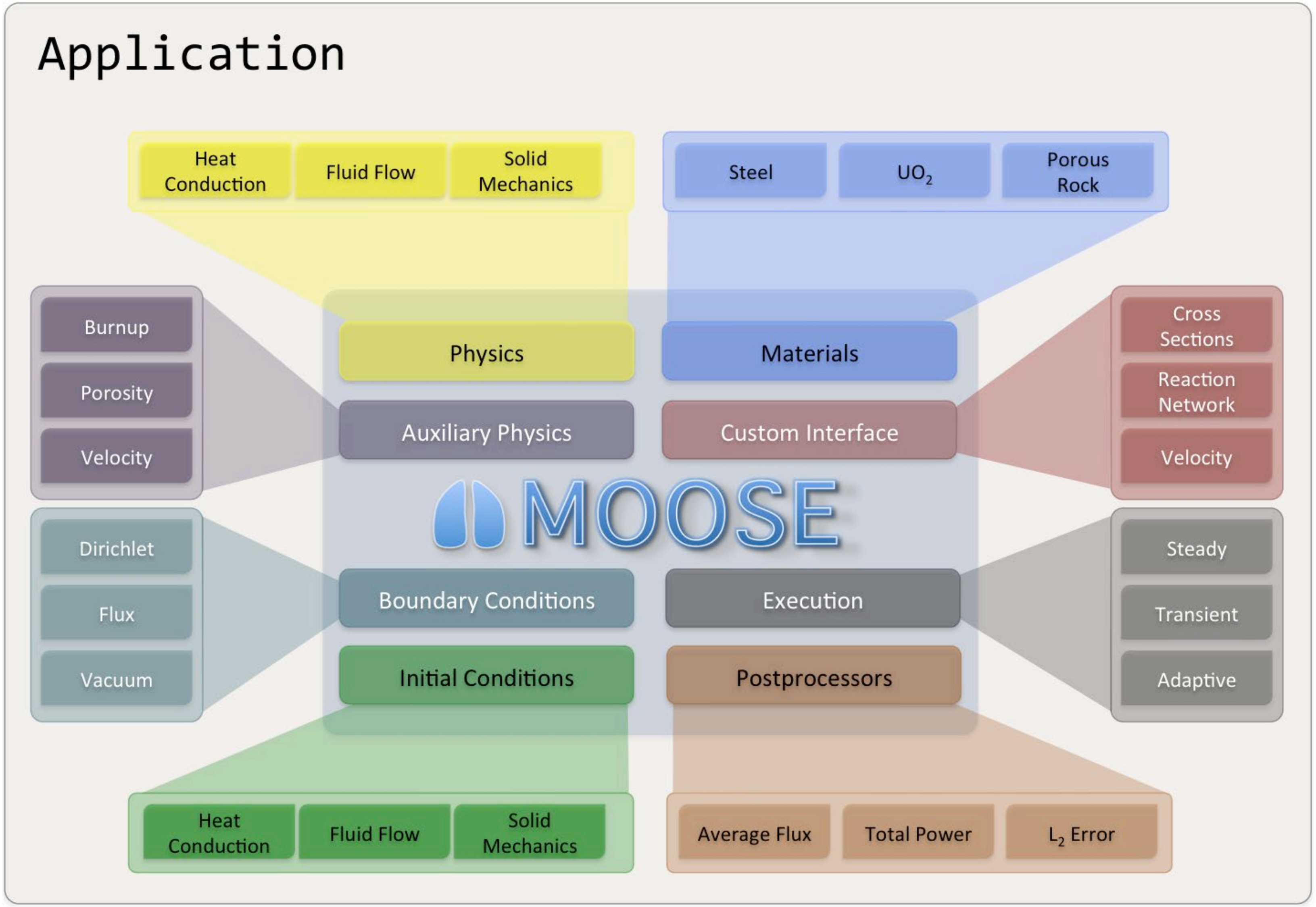
mooseframework.org

Code Platform

- **Provides an object-oriented, pluggable system for defining all aspects of a simulation tool.**
- **Leverages multiple DOE and university developed scientific computational tools**
- **Massively parallel:**
  - Hybrid (MPI + threading)
  - Used on 30k+ cores
- **Allows scientists and engineers to efficiently develop state of the art simulation capabilities.**
  - **Maximize Science/$**



Object-Oriented Pluggable Systems



MOOSE Code Example

Strong Form

$$\rho C p \frac{\partial T}{\partial t} - \nabla \cdot k(T, B) \nabla T = f$$

Weak Form

$$\int_{\Omega} \rho C p \frac{\partial T}{\partial t} \psi_i + \int_{\Omega} k \nabla T \cdot \nabla \psi_i - \int_{\partial\Omega} k \nabla T \cdot \mathbf{n} \psi_i - \int_{\Omega} f \psi_i = 0$$

Kernel | Kernel | BoundaryCondition | Kernel

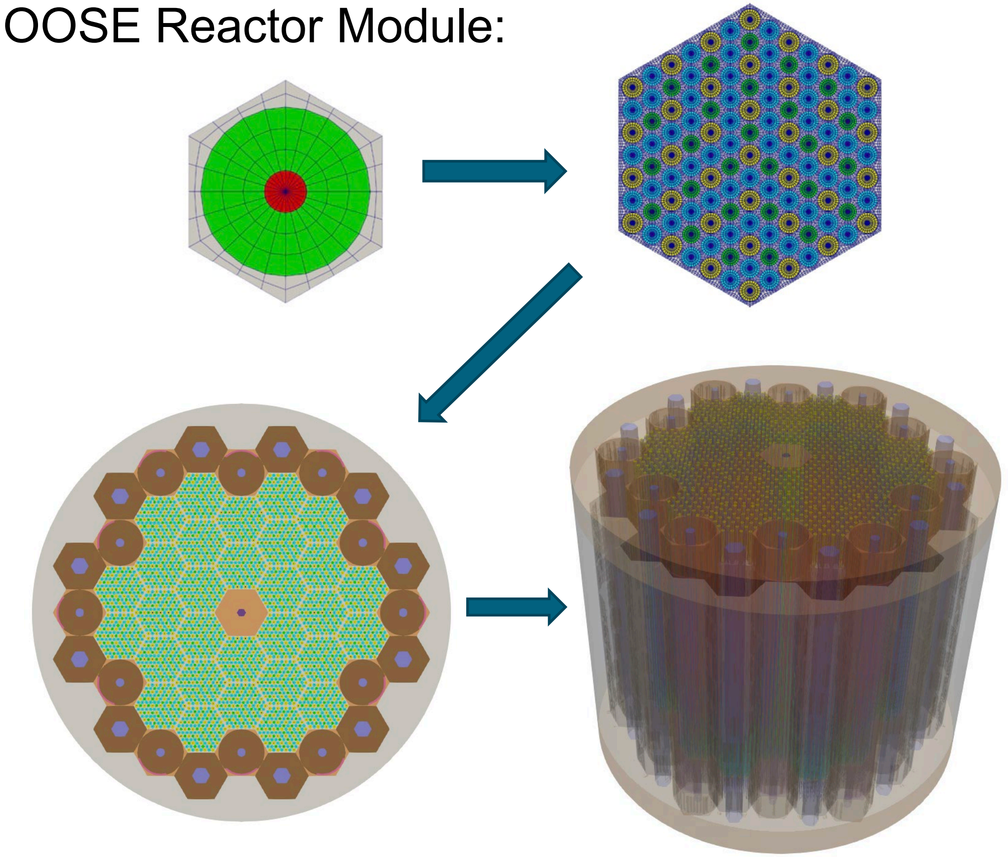
Actual Code

```
return _k[_qp]*_grad_u[_qp]*_grad_test[_i][_qp];
```

MOOSE Physics Modules – All Open Source!

- Chemical Reactions
- Contact
- Electromagnetics
- Fluid Properties
- Fluid Structure Interaction (FSI)
- Function Expansion Tools
- Geochemistry
- Heat Conduction
- Level Set
- Navier Stokes
- Peridynamics
- Phase Field
- Porous Flow
- Ray Tracing/Particle Tracking
- rDG
- Reactor
- Stochastic Tools
- Tensor (solid) Mechanics
- Thermal Hydraulics
- XFEM

MOOSE Reactor Module:



Building a mesh with the Reactor module [1]

1. Shemon, Emily, Yinbin Miao, Shikhar Kumar, Kun Mo, Yeon Sang Jung, Aaron Oaks, Scott Richards, Guillaume Giudicelli, Logan Harbour, and Roy Stogner. "MOOSE Reactor Module: An Open-Source Capability for Meshing Nuclear Reactor Geometries." *Nuclear Science and Engineering* (2023): 1-25.

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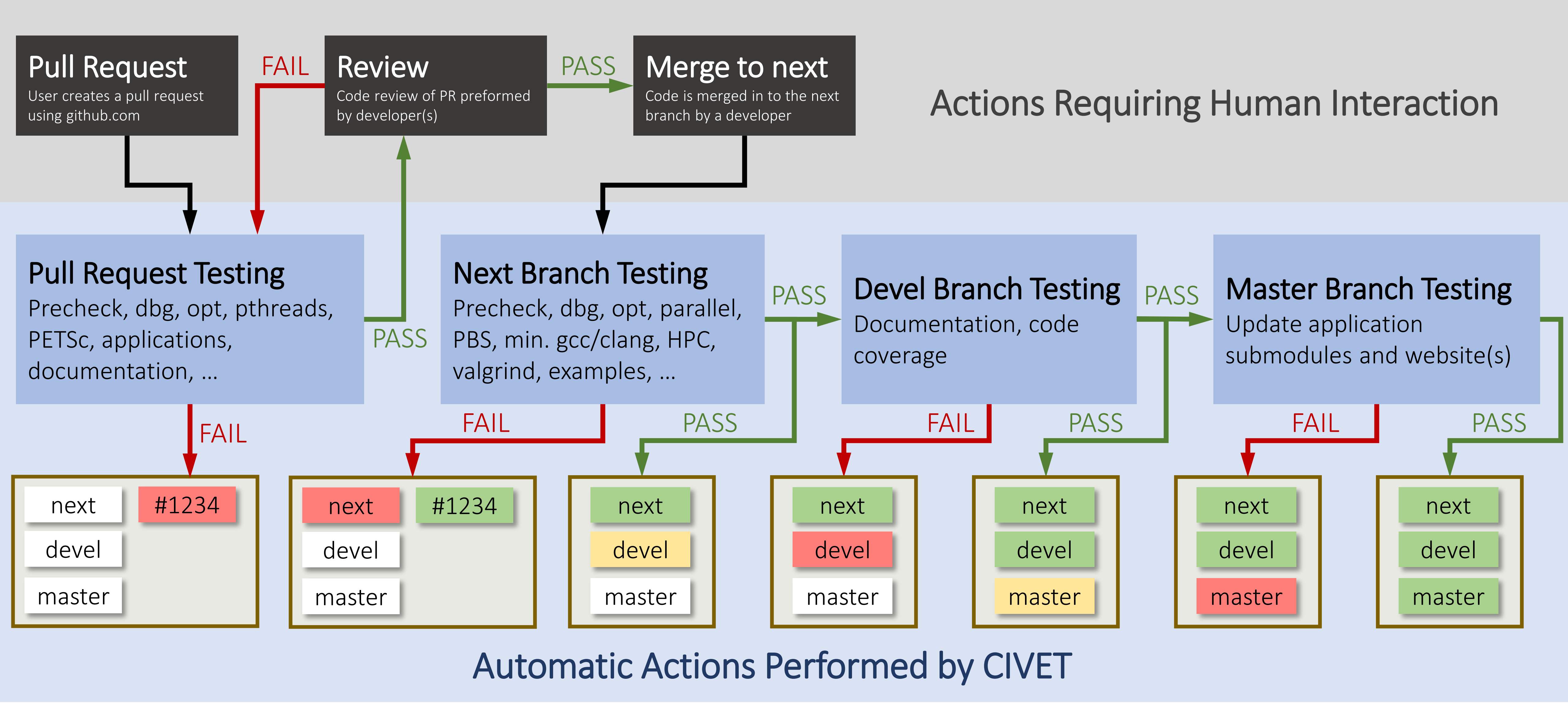
The MOOSE Platform (SQA for Engineers)

- **MOOSE Docs**
  - Extendable markdown documentation system
  - “Single source” rich document generator
  - Contained within the repository (automatic revisions)
  - SQA Document Generation (SRS, SDD, RTM, STP)
- **MOOSE TestHarness System**
  - Extendable regression test system
  - Multithreaded Scheduling for workstations and clusters
- **CIVET (Continuous Integration, Verification, Enhancement, Testing)**
  - Extendable continuous integration system
  - Repository backed recipe system
  - Meetings SQA Configuration Management Reqs.
- **Peacock (lightweight input generation and PP tool)**
- **MOOSE Build system (Modular and straightforward)**

Consistent Interface

Continuous Integration for Scientific Computing



Metrics

- **Several metrics are automatically collected for every change to MOOSE and the applications.**
- **Code Coverage:**
  - Uses GCOV/LCOV
  - Detailed breakdowns
- **Syntax Checking**
  - Strict coding guidelines enforced
  - Certain violations cause rejection of commit.
- **Timing Data**
  - Tests are scaled up and solve time is tracked for every commit
  - Timing plots linked with commits

LCOV - MOOSE Test Cover

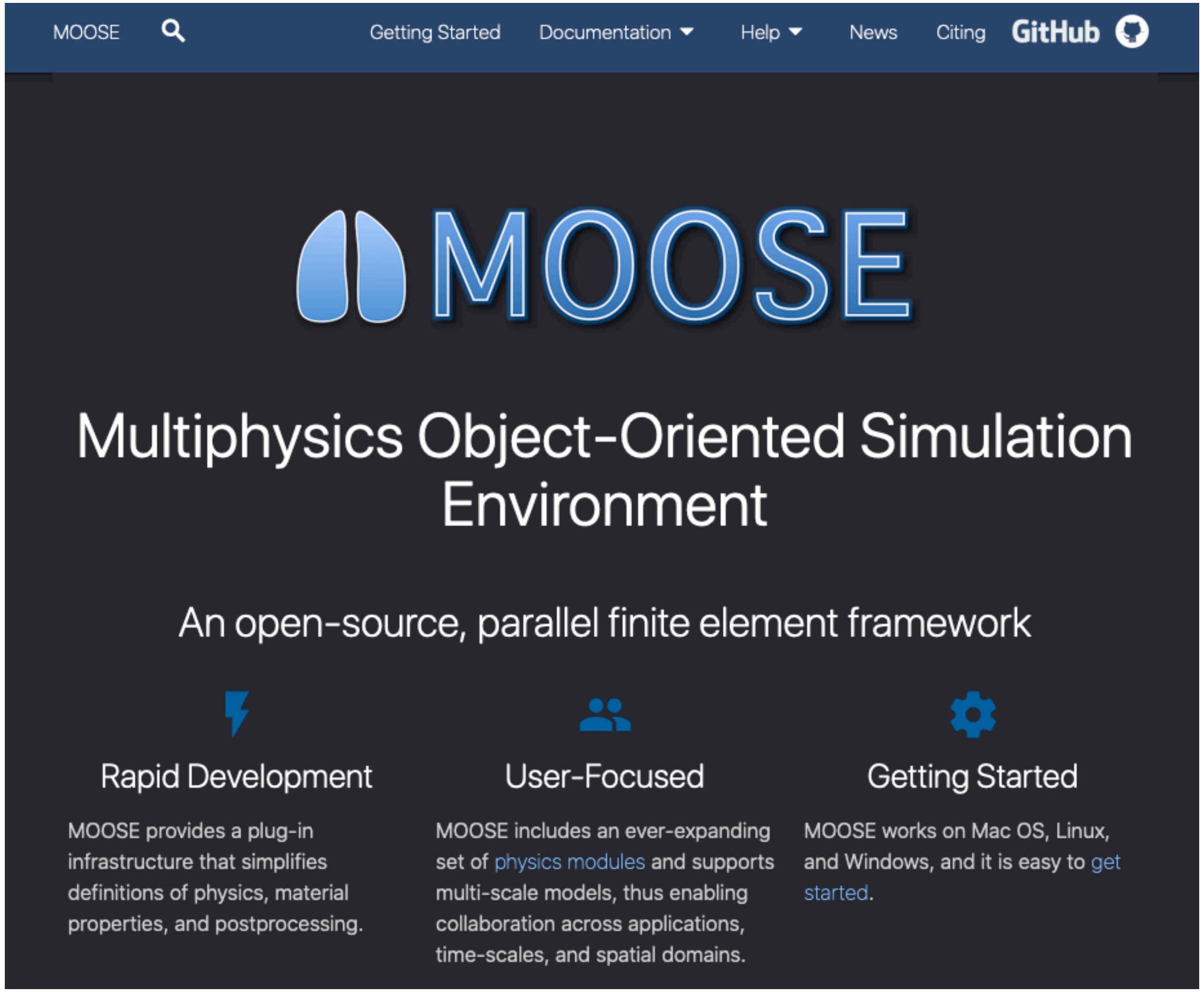
https://hpcsc/ssl/MOOSE/coverage/index.html

INL GMail · Nucleus · MOOSE · libMesh · Doxygen · libMesh Builds · GMail · Forwarded · SIAM: Program and

include/transfers	83.3 %	15 / 18	77.4 %	24 / 31
include/userobject	84.3 %	43 / 51	71.2 %	52 / 73
include/utils	92.1 %	340 / 369	73.6 %	293 / 398
src/actions	95.4 %	1233 / 1293	98.7 %	300 / 304
src/auxkernels	82.9 %	605 / 730	95.9 %	140 / 146
src/base	82.5 %	5999 / 7273	76.6 %	727 / 949
src/bcs	91.6 %	434 / 474	91.2 %	125 / 137
src/constraints	95.6 %	239 / 250	92.7 %	38 / 41
src/dampers	86.2 %	50 / 58	78.3 %	18 / 23
src/dgkernels	83.9 %	151 / 180	86.2 %	25 / 29
src/diracKernels	91.1 %	133 / 146	77.8 %	35 / 45
src/executioners	95.1 %	469 / 493	85.3 %	64 / 75
src/functions	87.0 %	407 / 468	90.6 %	77 / 85
src/geomsearch	76.9 %	816 / 1061	82.5 %	66 / 80
src/ics	100.0 %	112 / 112	94.7 %	36 / 38
src/indicators	90.3 %	186 / 206	89.7 %	52 / 58
src/kernels	81.8 %	455 / 556	81.9 %	118 / 144
src/markers	95.6 %	240 / 251	98.4 %	61 / 62
src/materials	89.8 %	531 / 591	86.8 %	79 / 91
src/mesh	86.5 %	647 / 748	91.1 %	82 / 90
src/meshmodifiers	97.4 %	264 / 271	96.8 %	61 / 63
src/multiapps	84.4 %	379 / 449	91.5 %	43 / 47
src/output	78.9 %	341 / 432	77.1 %	84 / 109
src/output/syntax	98.8 %	159 / 161	100.0 %	21 / 21
src/parser	87.5 %	539 / 616	80.4 %	82 / 102
src/postprocessors	85.6 %	722 / 843	90.8 %	295 / 325
src/preconditioners	91.6 %	229 / 250	91.4 %	32 / 35
src/timeintegrators	100.0 %	223 / 223	98.4 %	61 / 62
src/timesteppers	49.4 %	133 / 269	78.2 %	43 / 55
src/transfers	90.3 %	1020 / 1129	86.3 %	88 / 102
src/userobject	86.6 %	638 / 737	82.7 %	148 / 179
src/utils	66.6 %	1336 / 2006	77.6 %	177 / 228

Auto-Generated Documentation

- Every time MOOSE or any of the applications change documentation is automatically regenerated:
- API documentation
- Input file syntax
- Tutorials
- Website itself

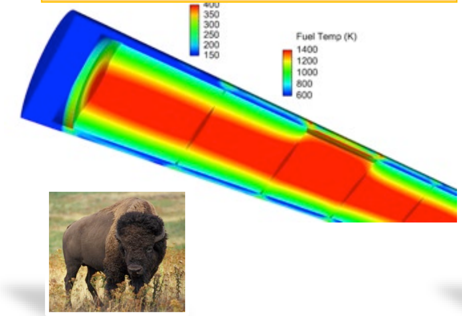


Handling Shifting Reactor Designs Through Modularity

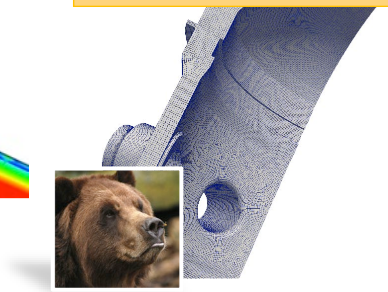
NEAMS

Accelerating Advanced Fission Reactor Deployment

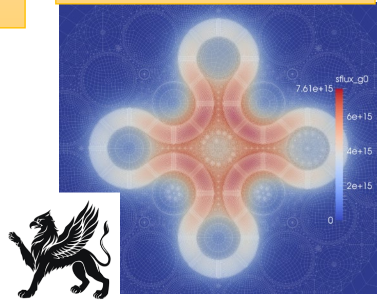
Bison
Nuclear Fuel Performance



Grizzly
Structural Mechanics for Component Aging

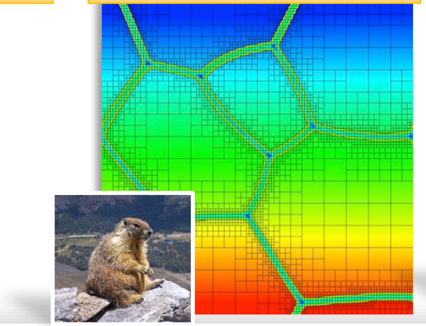


Griffin
Radiation Transport

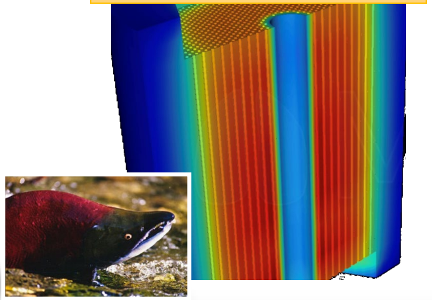


Pronghorn
Medium-fidelity CFD

Marmot
Mesoscale Materials



Sockeye
Heat pipe Simulation



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

Kairos Power

RADIANT

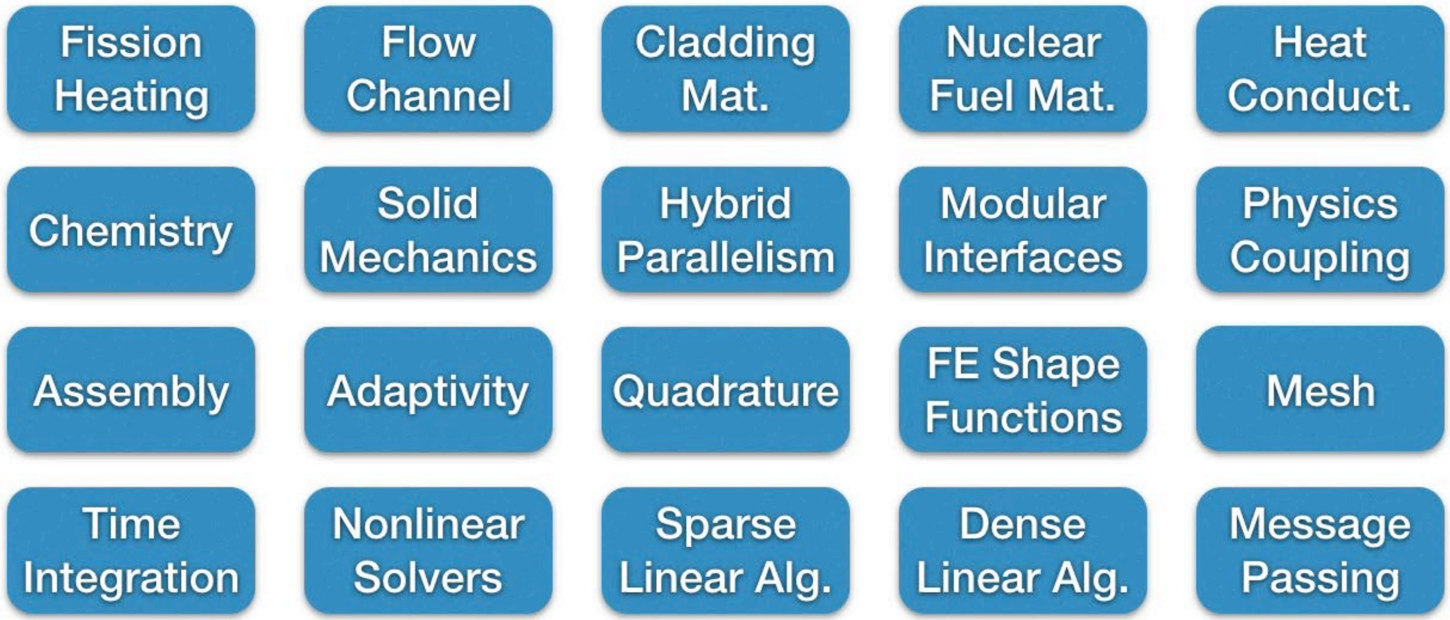
Westinghouse

BWXT
Nuclear Energy Canada Inc.

Structural Integrity Associates, Inc.®

EPRI

Modular Software Accelerates Development



MSR Case Studies

Equilibrium Isotope Transport

Griffin

Mole

NekRS

Pronghorn

SAM

Stochastic Tools

Phase-field

MOOSE Framework Ecosystem for Non-LWR Analysis

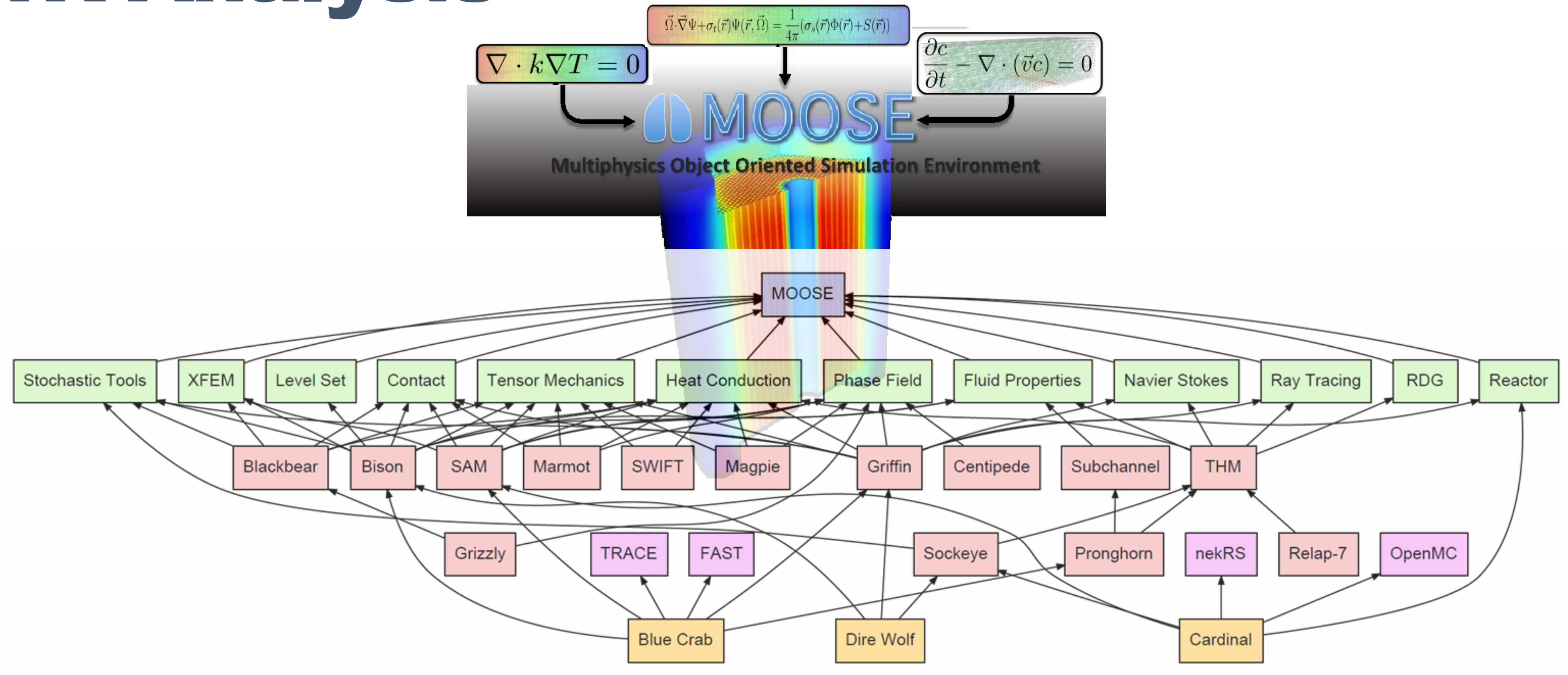
MOOSE Framework

MOOSE Modules

MOOSE-Based Applications

MOOSE-Wrapped Applications

MOOSE-Coupling Applications



HTGR

FHR

MSR

Microreactor

LMFR

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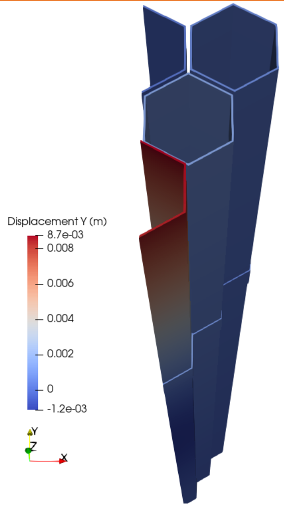
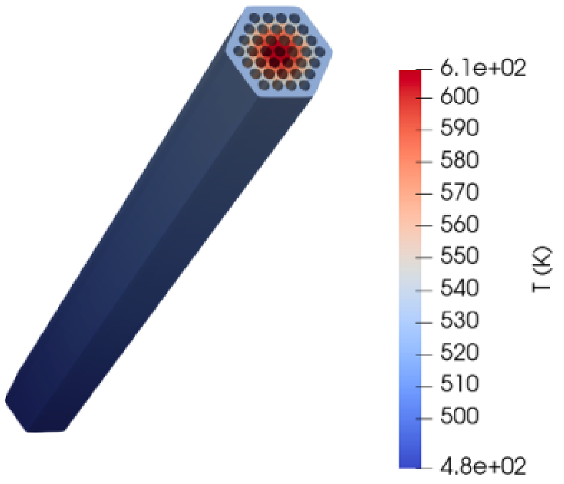
Putting It All Together

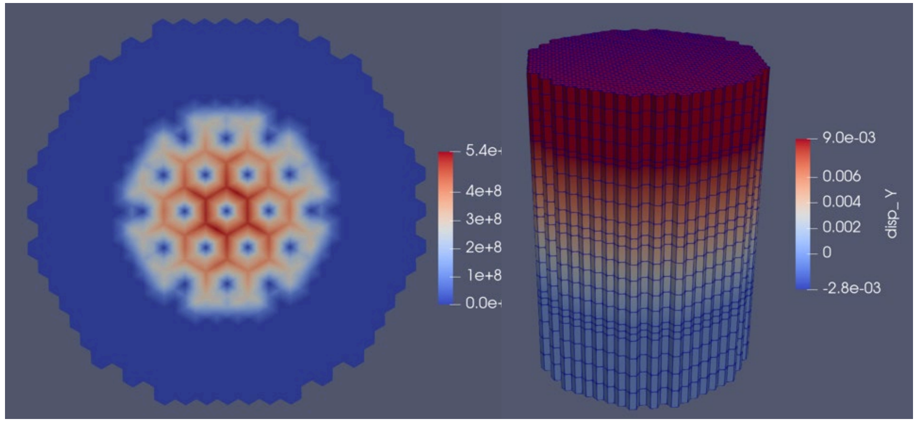
Reactor Use Case: SFR





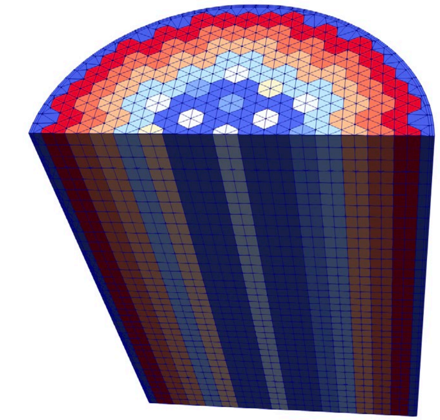
Hexagonal Assembly

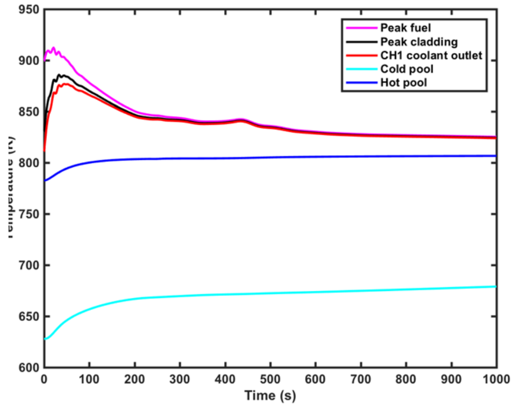
- Duct bowing simulation due to temperature gradient (IAEA benchmark) – POC: Nicolas Wozniak (ANL)
- Subchannel liquid metal flow simulation (Toshiba 37-pin benchmark) – POC: Mauricio Tano (INL)



Versatile Test Reactor (VTR)

- Fully-coupled feedback model between neutronics, conduction, hydraulics, and structural expansion
- Codes coupled: Griffin, Bison, and SAM
- POC: Nicolas Martin (INL)



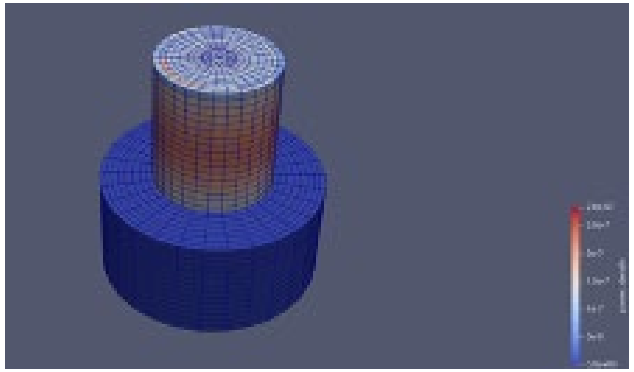


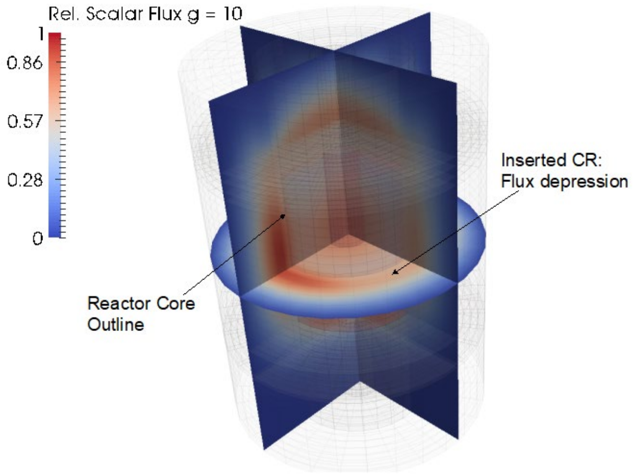
Advanced Burner Test Reactor (ABTR)

- Neutronics (Griffin) coupled with structural thermomechancis – POC: Javier Ortensi (INL)
- System code hydraulic (SAM) simulation coupled with point kinetics model – POC: Rui Hu (ANL)

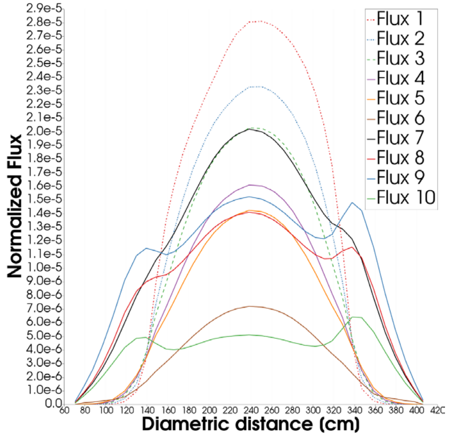
Reactor Use Case: HTGR

High-Temperature Reactor (HTR-10)

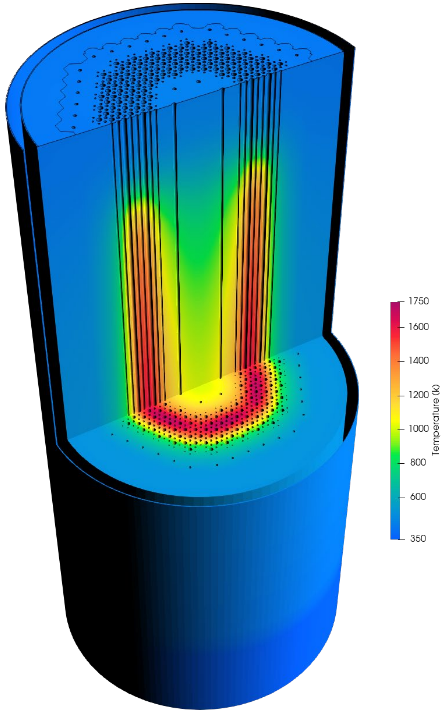




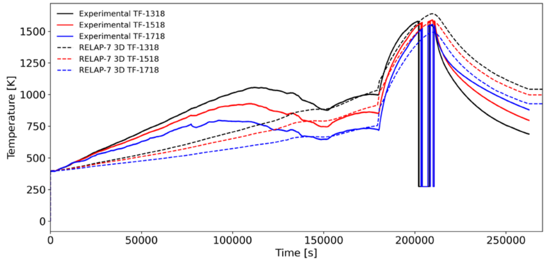
- Steady-state benchmarks with different control rod positions
- Neutronics (Griffin) with heat conduction (MOOSE)
- POC: Javier Ortensi (INL)



High-Temperature Test Facility (HTTF)

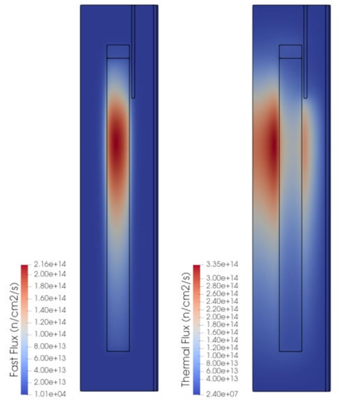


- Coupled heat conduction with system hydraulics
- Steady-state and transient simulations
- POC: Lise Charlot (INL)



Pebble-Bed Modular Reactor (PBMR400)

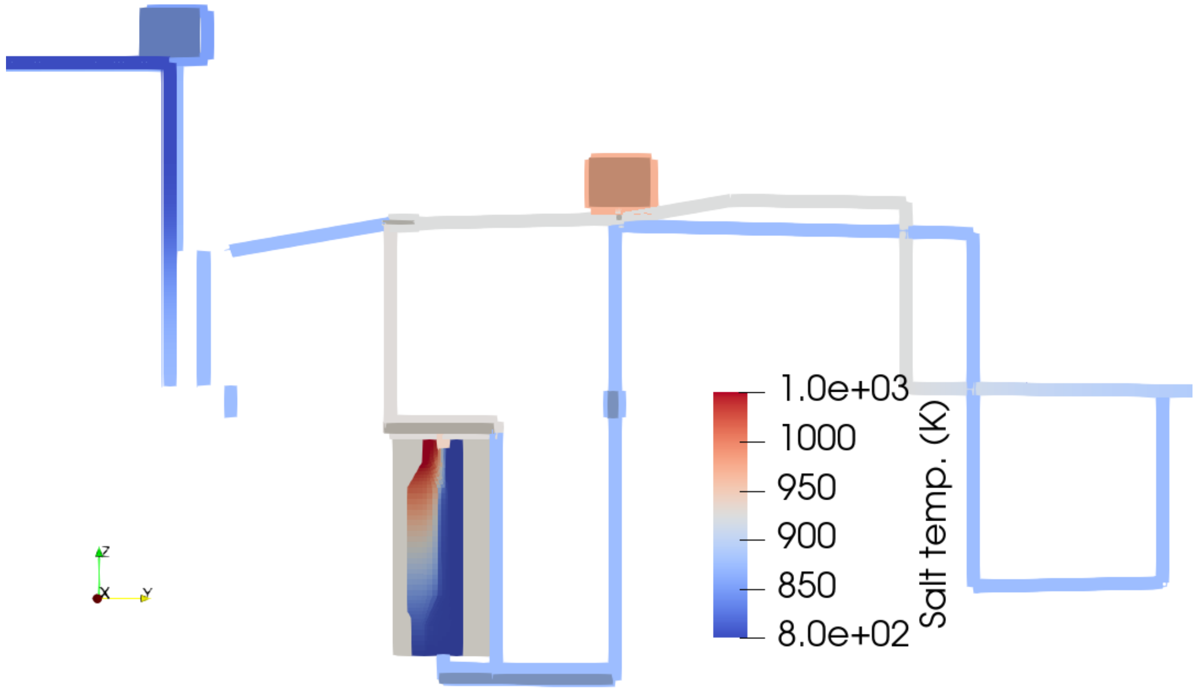
- Coupled neutronics (Griffin) with thermal hydraulics (Pronghorn)
- Multiscale modeling: core-pebble-particle
- Steady-state and transient simulations
- POC: Paolo Balestra (INL)

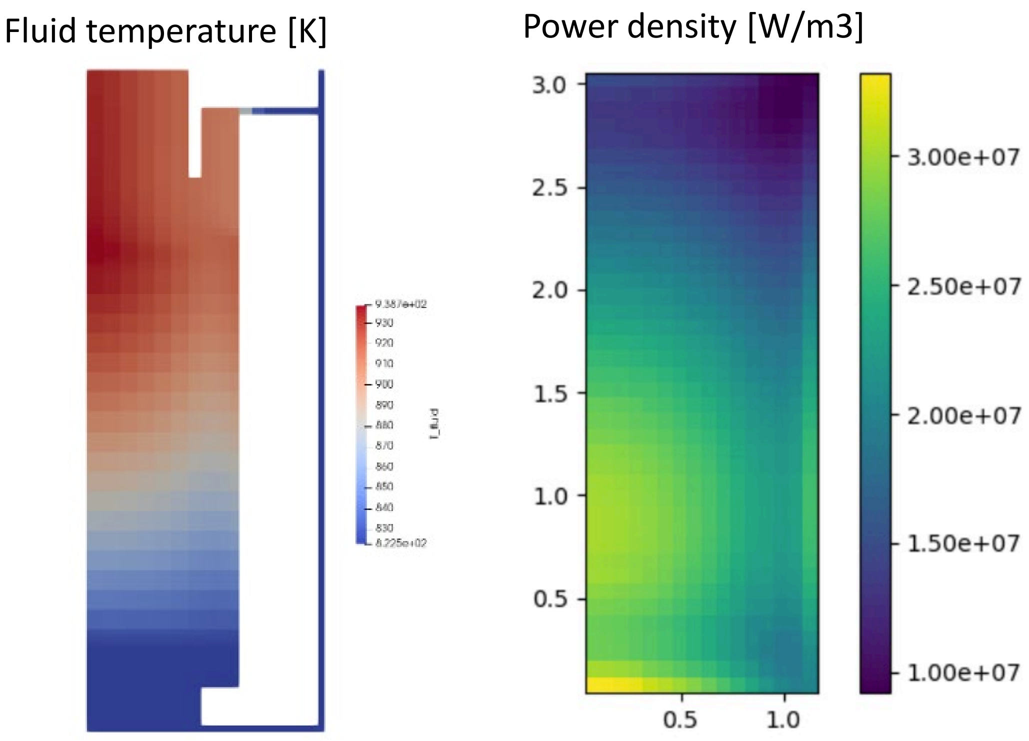


Reactor Use Case: FHR

Mk-I FHR

- Coupled core neutronics (Griffin) with core thermal hydraulics (Pronghorn) with plant hydraulics (SAM)
- Steady-state and transient simulations
- POC: Guillaume Giudicelli (INL)





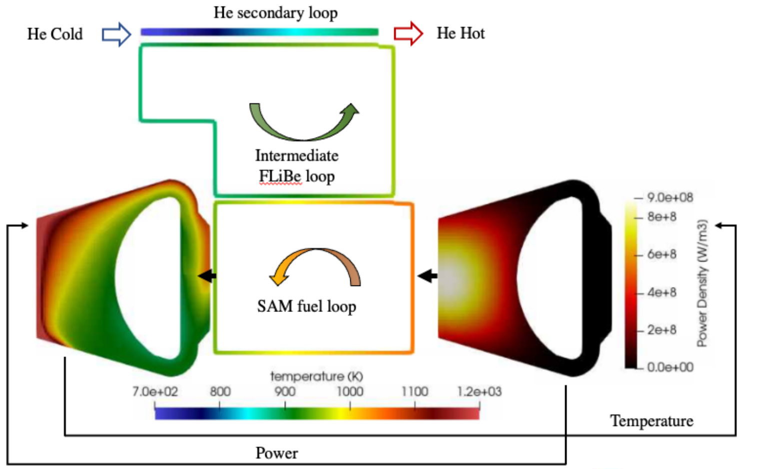
Generic Fluoride High-Temperature Reactor (gFHR)

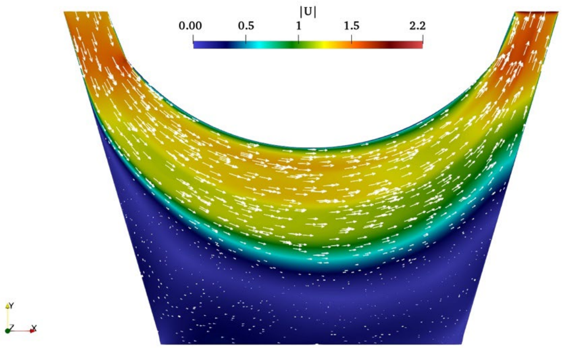
- Equilibrium core calculation with pebble tracking
- Coupled neutronics (Griffin) with thermal hydraulics (Pronghorn)
- Steady-state and transient simulations
- POC: Sebastien Schunert and Javier Ortensi (INL)

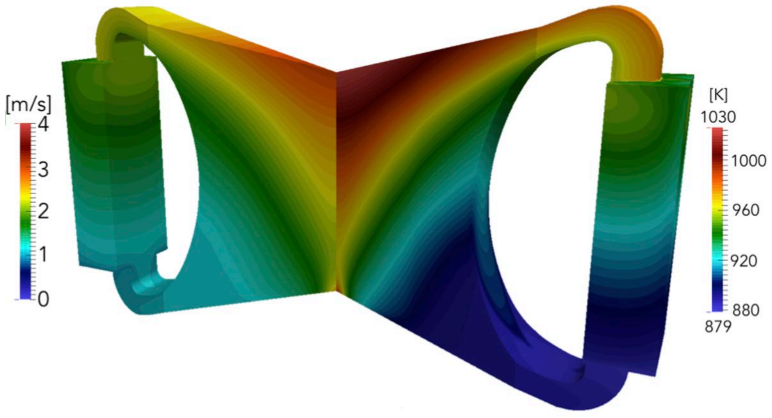
Reactor Use Case: MSR

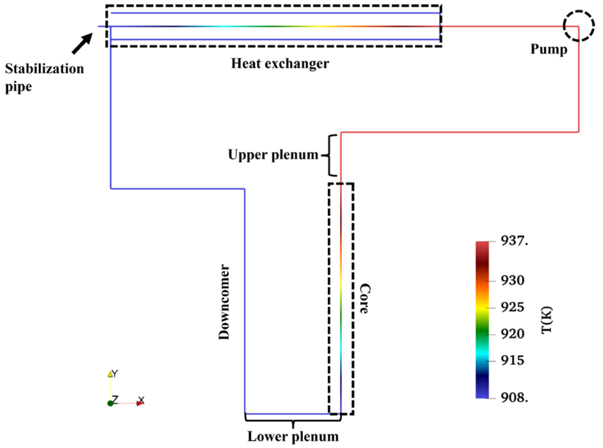
Molten Salt Fast Reactor (MSFR)

- Coupled core neutronics (Griffin) with core thermal hydraulics (Pronghorn) with plant hydraulics (SAM)
- Steady-state and transient simulations
- POC: Mauricio Tano (INL)



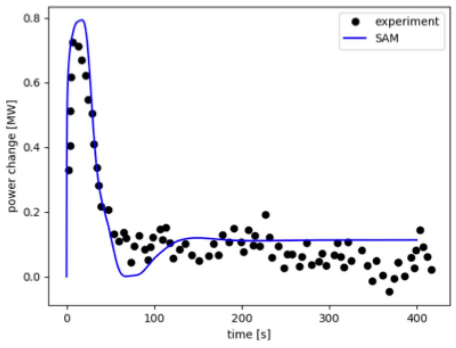






Molten Salt Reactor Experiment (MSRE)

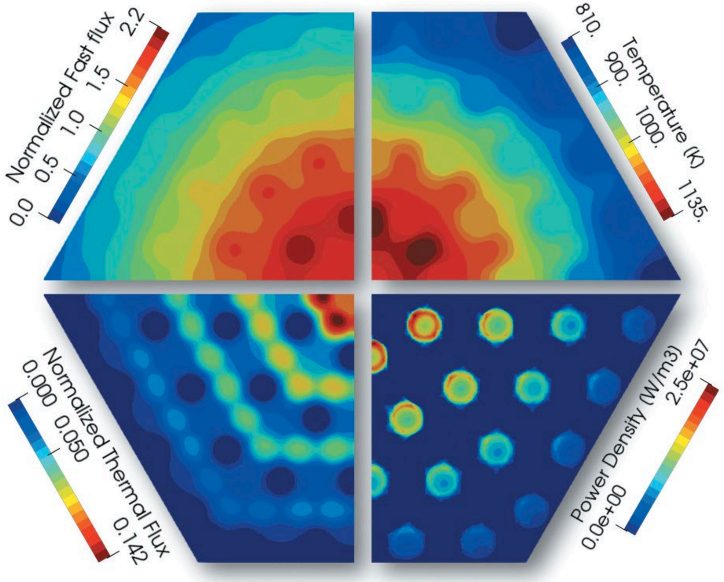
- Coupled systems hydraulics with point kinetics model (SAM)
- Steady-state and transient simulations
- Benchmarked against MSRE data
- POC: Rui Hu (INL)



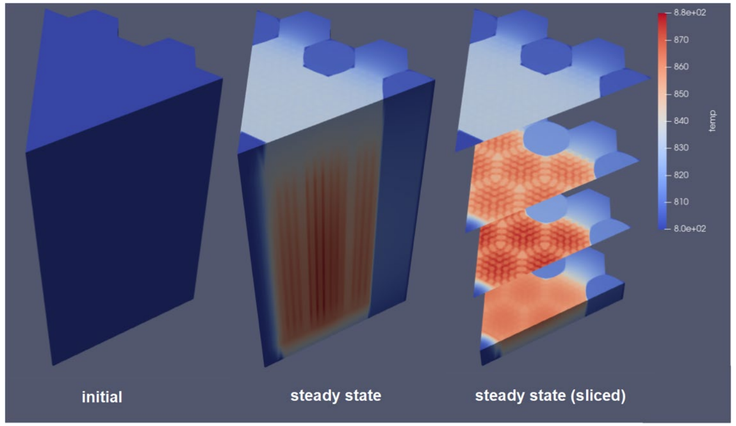
Reactor Use Case: Microreactor

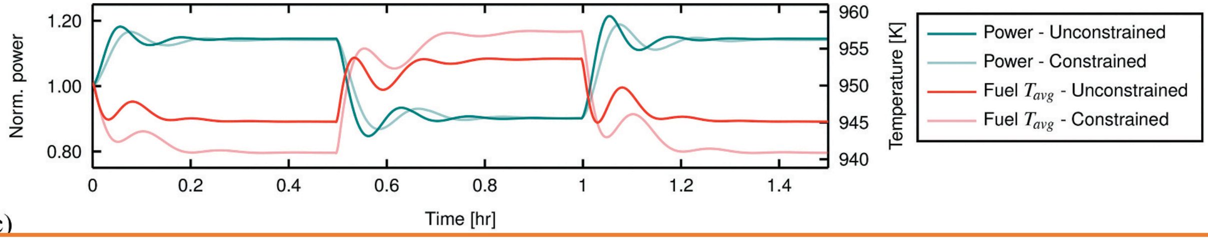
Empire Design

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

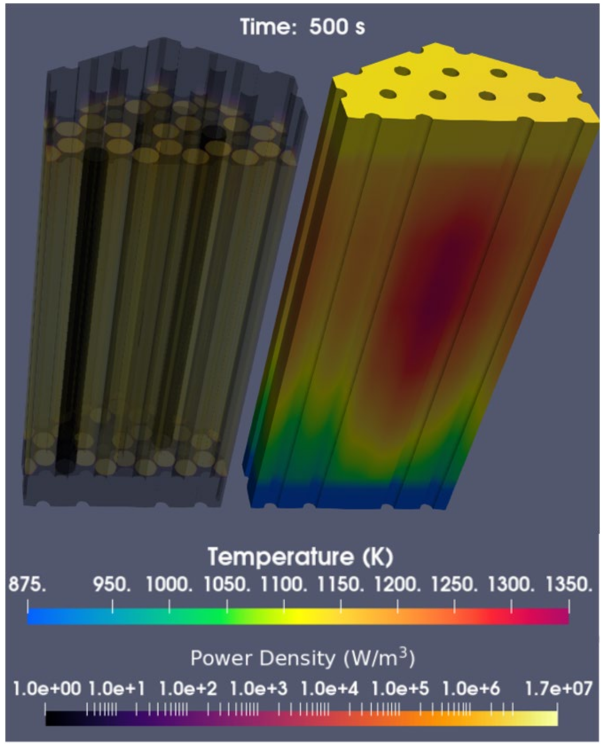


Power [kW]





(c)



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)

Takeaways

- The Biden Administration is making historic investments in solving the climate crisis
- Nuclear must be a part of the solution
- DOE-NE is working to enable that
- NEAMS accelerates advanced reactor deployment by providing predictive simulation tools
- The MOOSE platform's modularity/flexibility and robust software development processes enable the NRC and advanced reactor vendors to model a wide variety of designs and scenarios

Thank You!

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