INL/MIS-24-77148-Revision-0

Nuclear Science & Technology. Research and Development to Enable Advanced Reactor Demonstrations and Deployment

March 2024

Simon M Pimblott

Changing the World's Energy Future

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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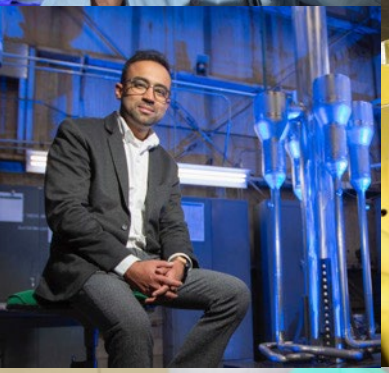


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Chief Science Officer
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Nuclear Science & Technology

Research and Development to Enable Advanced Reactor Demonstrations and Deployment

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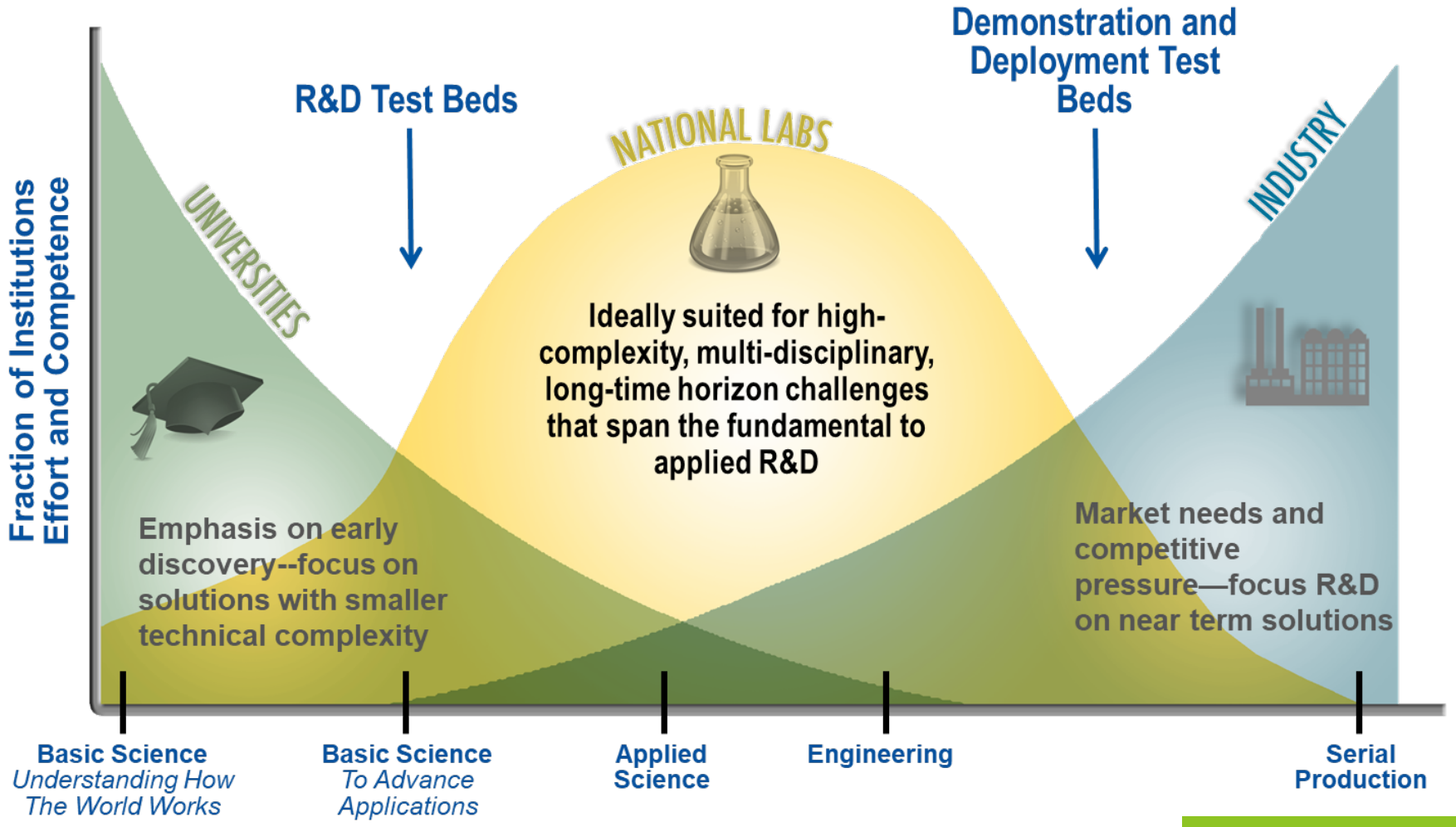
Idaho National Laboratory

“Spectrum” of DOE Laboratories

Advancing Technologies: Role of DOE Labs
Supporting the entire technology lifecycle




INL
Idaho National Laboratory
Changing the World's Energy Future
www.inl.gov
ENTERING

Today, INL is addressing the world's most pressing challenges





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

Unique site, infrastructure, and facilities that enable energy and security R&D at scale

$1,572 M	FY21 Total Operating Cost
5,400+	Employees
569,178	Acres
890	Square Miles

128	Miles high-voltage transmission lines
17.5	Miles railroad for shipping nuclear fuel
4	Operating reactors
12	Hazard Category II & III non-reactor facilities/activities
50	Radiological facilities/activities
3	Fire Stations

WE ARE ATR

Battelle Energy Alliance manages INL for the
U.S. Department of Energy's Office of Nuclear Energy

INL Idaho National Laboratory

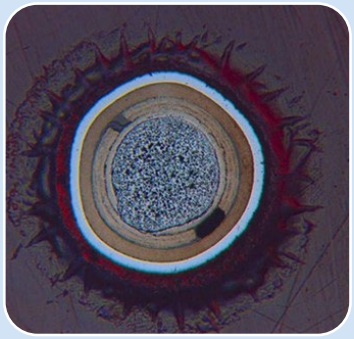
MFC

Idaho National Laboratory

MFC Nuclear Research, Development & Demonstration Capabilities (*with other connected INL capabilities*)

Fabrication

- Experimental Fuel Facilities
- Fuels & Applied Science Building
- Fuel Manufacturing Facility
- Zero Power Physics Reactor
- Analytical Laboratory
- Advanced Fuels Facility



Fresh Fuel Characterization

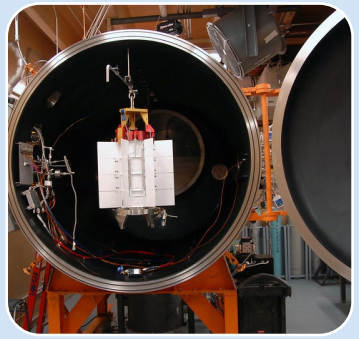
- Fuels & Applied Science Building
- Analytical Laboratory
- Experimental Fuel Facilities

Irradiation

- Transient Reactor Experiment & Testing (TREAT)
- NRAD
- Advanced Test Reactor (ATR)
- Offsite Reactors

Post-Irradiation Examination & Characterization

- Hot Fuel Examination Facility
- Irradiated Materials Characterization Lab
- Fuel Conditioning Facility
- Analytical Laboratory
- Fuels & Applied Science Building
- Electron Microscopy Lab
- NRAD



Space Nuclear Power and Isotope Technologies

- Space & Security Power Systems Facility
- Engineering Development Lab
- Idaho Nuclear Technology & Engineering Center

Advanced Reactor Demonstration Test Beds

- TREAT micro-Reactor Experiment Cell
- Laboratory for Operations and Testing in the US
- Demonstration of Microreactor Experiments

INL is addressing the world's most challenging problems

Nuclear Science & Technology

- Nuclear fuels and materials
- Reactor systems design and analysis
- Fuel cycle science and technology
- Nuclear safety and regulatory research
- Advanced scientific computing

Advanced Test Reactor Complex

- Steady-state neutron irradiation of materials and fuels
  - Naval Nuclear Propulsion Program
  - Industry
  - National laboratories and universities

Materials and Fuels Complex

- Transient testing
- Analytical laboratories
- Post-irradiation examination
- Advanced characterization
- Fuel fabrication
- Space nuclear power and isotope technologies

Energy & Environment Science & Technology

- Advanced transportation
- Environmental sustainability
- Clean energy
- Advanced manufacturing
- Biomass

National & Homeland Security Science & Technology

- Critical infrastructure protection and resiliency
- Nuclear nonproliferation
- Physical defense systems

Sustaining & Expanding Nuclear Energy

Sustaining: LWRS Program

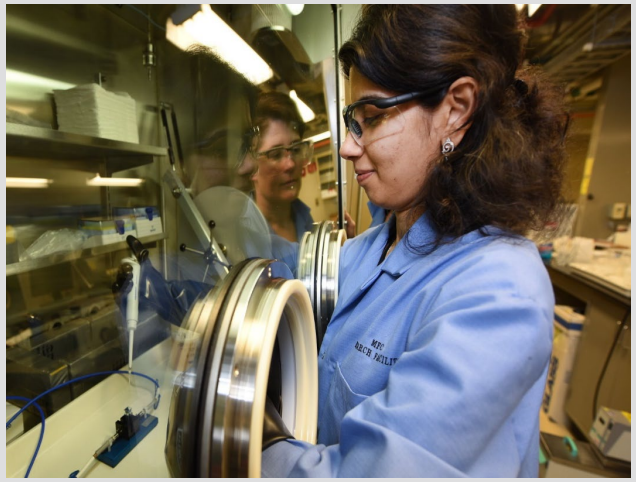
- #1 • Plant Modernization R&D
- #2 • Flexible Plant Operation and Generation
- #3 • Risk-Informed Systems Analysis
- #4 • Materials Research
- #5 • Physical Security

Expanding: Advanced Reactors

- #1 • Lead demonstration of advanced reactors
- #2 • Enable the success of the DOE-NE Advanced Reactor Demonstration Program (ARDP)
- #3 • Lead research and innovation in advanced reactors
- #4 • Deliver world-class research and development (R&D) assets to support advanced reactors

Nuclear S&T supports INL's vision, mission, and priorities

- Enable the success of advanced reactor demonstrations to deploy cost-competitive nuclear energy.
- Expand and deploy national nuclear energy strategic assets.
- Enable INL to achieve net-zero carbon emissions by 2031.
- Transform our work processes and work culture.



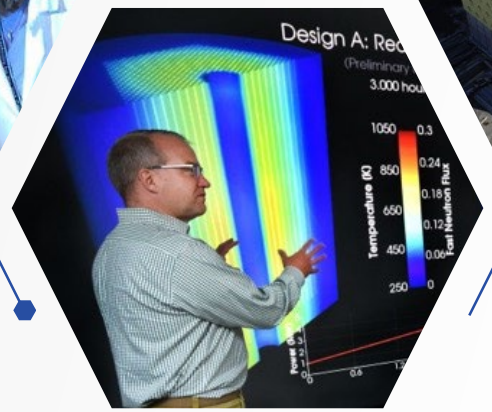
Strategic focus and key objectives

- Sustain and optimize the light-water reactor fleet for national energy security and low-carbon energy production
- Design, demonstrate, and rapidly deploy advanced reactors
- Accelerate the development and qualification of nuclear fuels and materials
- Design, demonstrate, and rapidly deploy innovative and sustainable integrated fuel cycle solutions
- Realize the Next-level INL and foster a high-performing research organization

Nuclear S&T leverages its unique capabilities to lead high-impact research

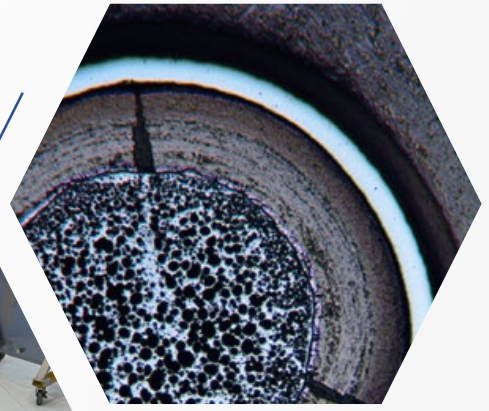
New nuclear materials and fuels

HPC for advance modeling and simulation



National nuclear energy strategic infrastructure

Powering space exploration



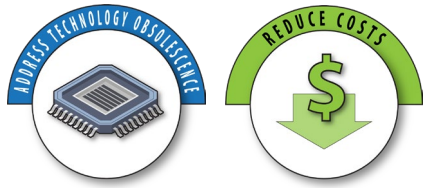
Next-generation fuels

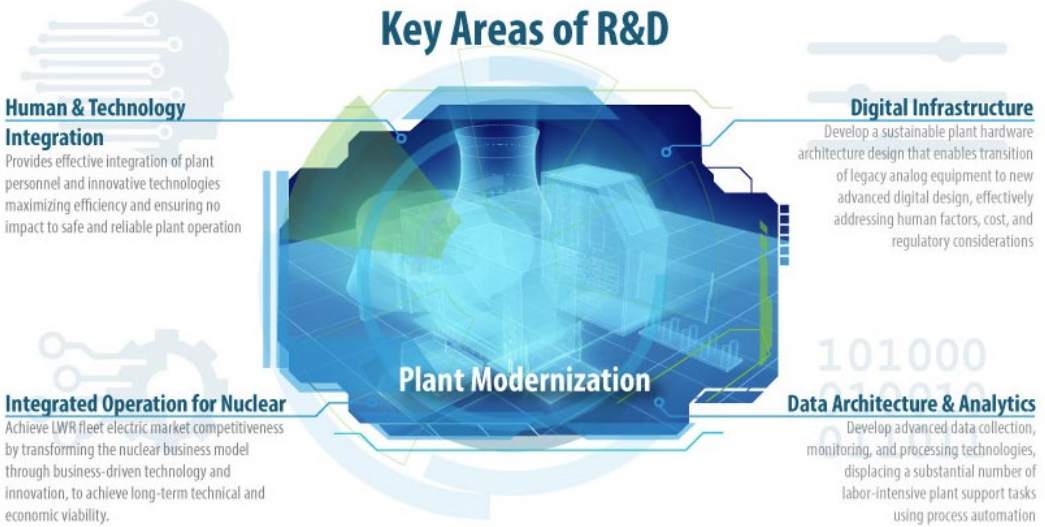
Light Water Reactor *Sustainment*

Modernize Fleet

- First echelon safety instrumentation and control systems on two units
- Conceptual Design Phase complete
- Detailed Design Phase in progress
- Multiple pre-submittal meetings with Nuclear Regulatory Commission
- Human Factors efforts well underway
  - Operating Experience Review (Q3–Q4 of 2021)
  - Function Analysis and Allocation Workshop (March 2022)
  - Task Analysis Workshop (May 2022)
- NRC has accepted Constellation's License Amendment Request (December 2022)
- Dynamic preliminary validation completed February 2023 at INL with NRC observation

INL Human Systems Simulation Laboratory Task A nalysis Workshop





Nuclear H_2 Demonstration Projects

2023

Constellation: Nine-Mile Point NPP (~1 MWe LTE)

2023–2024

Energy Harbor: Davis-Besse NPP (~1–2 MWe LTE)

~2024

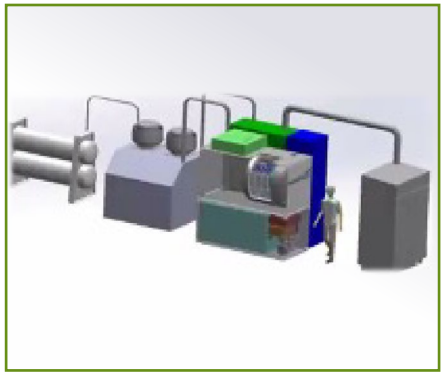
Xcel Energy: Prairie Island NPP ~150 kWe steam

*Thermal & Electrical Integration (*High-temperature steam electrolysis/ Solid oxide electrolysis (SOEC))

~2024

APS/Pinnacle West Hydrogen: Palo Verde Generating Station (~15–20 MWe LTE)

H_2 Production for Combustion and Synthetic Fuels

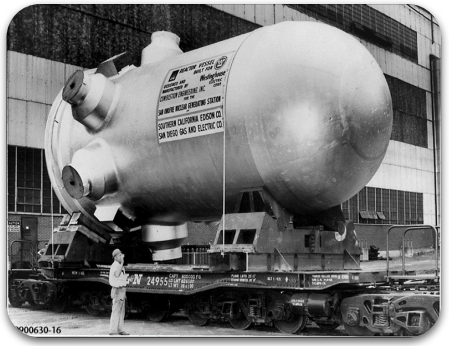


FuelCell Energy: Demonstration at INL (250 kW)

Nuclear energy and SOEC

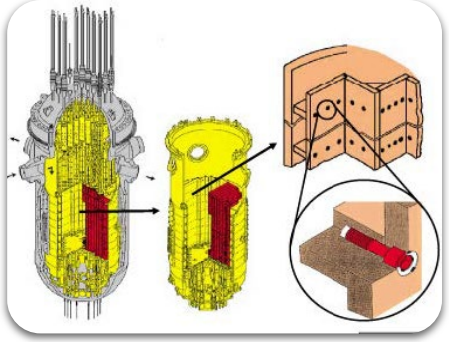
Materials Research

Reactor Pressure Vessel (RPV)



1. Harvest high fluence A-60 Palisades surveillance capsule (FY23)
2. Embrittlement trend curve development (FY25)

Core internal and pressure boundary

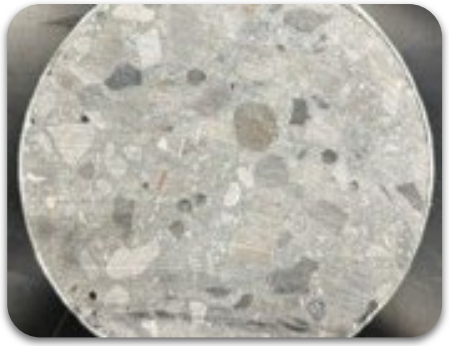


1. Long-term thermal aging on Alloy 690 and its weldment (FY23)
2. Replace LiOH with KOH (FY23)
3. Long-term SCC initiation testing of alloy 690 (FY25)
4. Long-term SCC initiation testing on blunt notch high Cr Ni-based weld metals (FY25)

Mitigation

1. Develop advanced welding technology, including laser and friction stir welding (FY25)
2. Complete timeline/roadmap for ASME code development in collaboration with EPRI (FY25)

Concrete



1. Develop code to improve Microstructure Oriented Scientific Analysis of Irradiated Concrete (MOSAIC) parallelization capabilities to enable large 3D simulations (FY23)
2. Develop methodological guidelines to be used by industry for experimental and predictive assessment of irradiated concrete (FY23)

Cable

1. Consolidate the status of the Cable Expanded Materials Degradation Assessment (FY23)
2. Extend Spread Spectrum Time Domain Reflectometry (SSTDR) bandwidth and test, and use the ARENA test bed, for thermal aging, ground fault, and water detection (FY23)

Improving LWR Fuels

- Evaluations of accident-tolerant fuel with High Burnup
  - Objectives
    - Economic gains via extended refueling cycle, lower volume of new and spent fuel
- Plant Reload Optimization
  - Objectives
    - All-inclusive integrated framework for fuel reload analyses
    - Optimization of core configuration to minimize new fuel volume
  - Benefits of Risk-Informed Approach
    - Allows enhanced optimization of core configuration and further reduction of new fuel volume

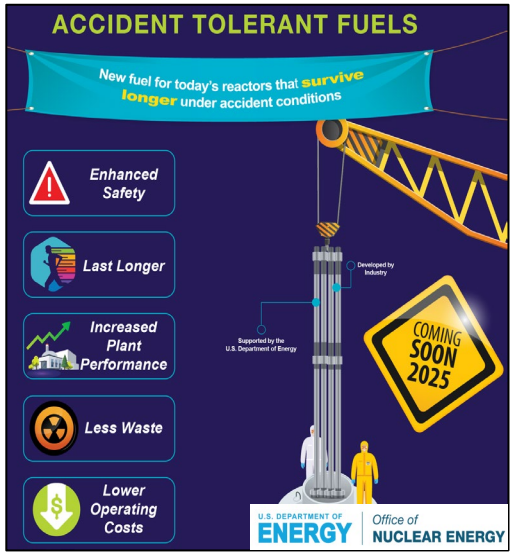
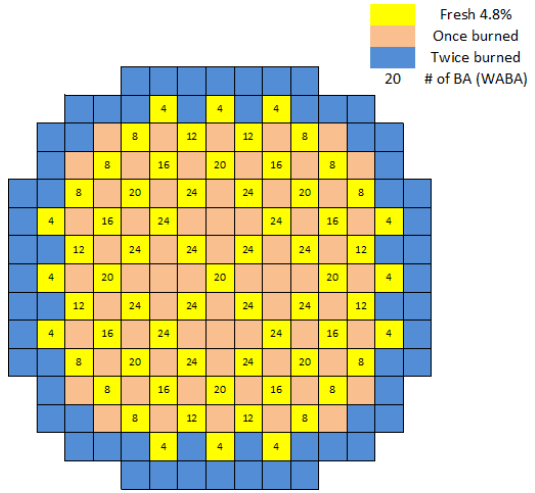


Image Credit: U.S. Department of Energy (link)



Configuration of Reactor Core

Advanced Reactor *Expansion*

US Definition: Advanced Reactors

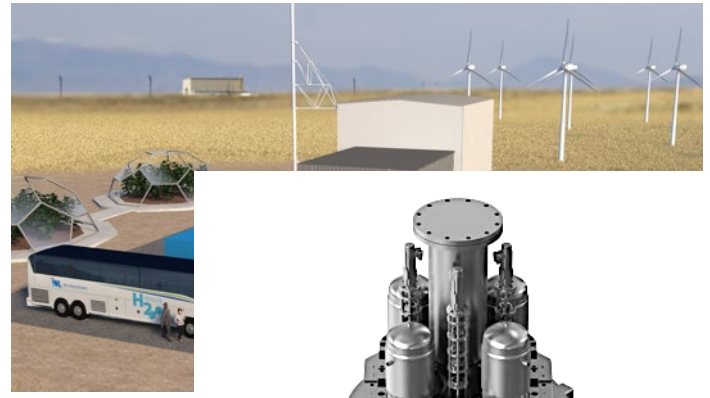
The term "advanced nuclear reactor" means a nuclear fission reactor with significant improvements, including additional inherent safety features, compared to reactors operating on December 27, 2020, in the U.S.

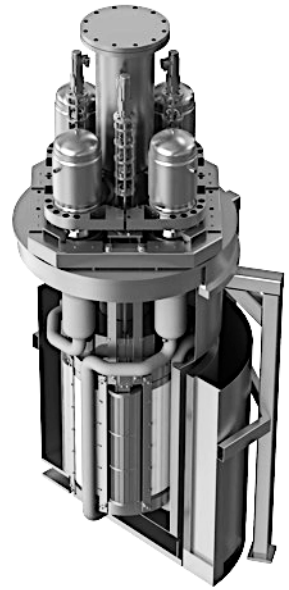
- [42 U.S. Code of Federal Regulations (USC) 16271].

It does not mean “better”, “new” reactors, reactors not using water as coolant, or even “modular”. ***Improved safety*** is the main focus.

Design, Demonstrate, and Rapidly Deploy Advanced Reactors

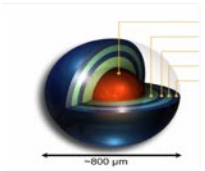
- INL is at the forefront in the development of advanced reactor technologies that will deliver net-zero emissions energy.
- INL will demonstrate advanced reactor technologies, including:
  - Microreactor Applications Research, Validation, and Evaluation (MARVEL)
  - First-of-a -kind molten salt fast reactor, Molten Chloride Reactor Experiment (MCRE),
  - Support microreactor technology for U.S. Department of Defense (PELE).
- INL plays a critical role in the demonstration of other advanced reactors.





MARVEL

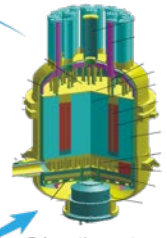
PELE



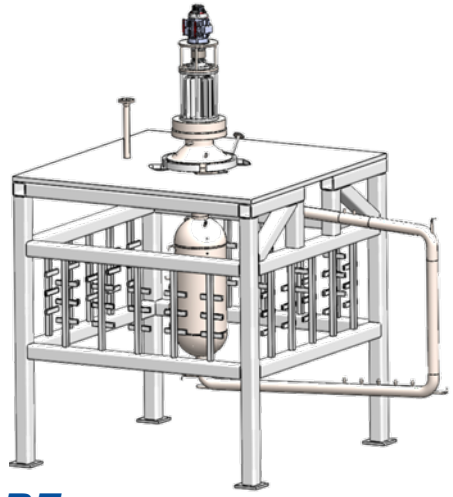
Tristructural isotropic (TRISO) particles

Cylindrical fuel compacts

Prismatic fuel block

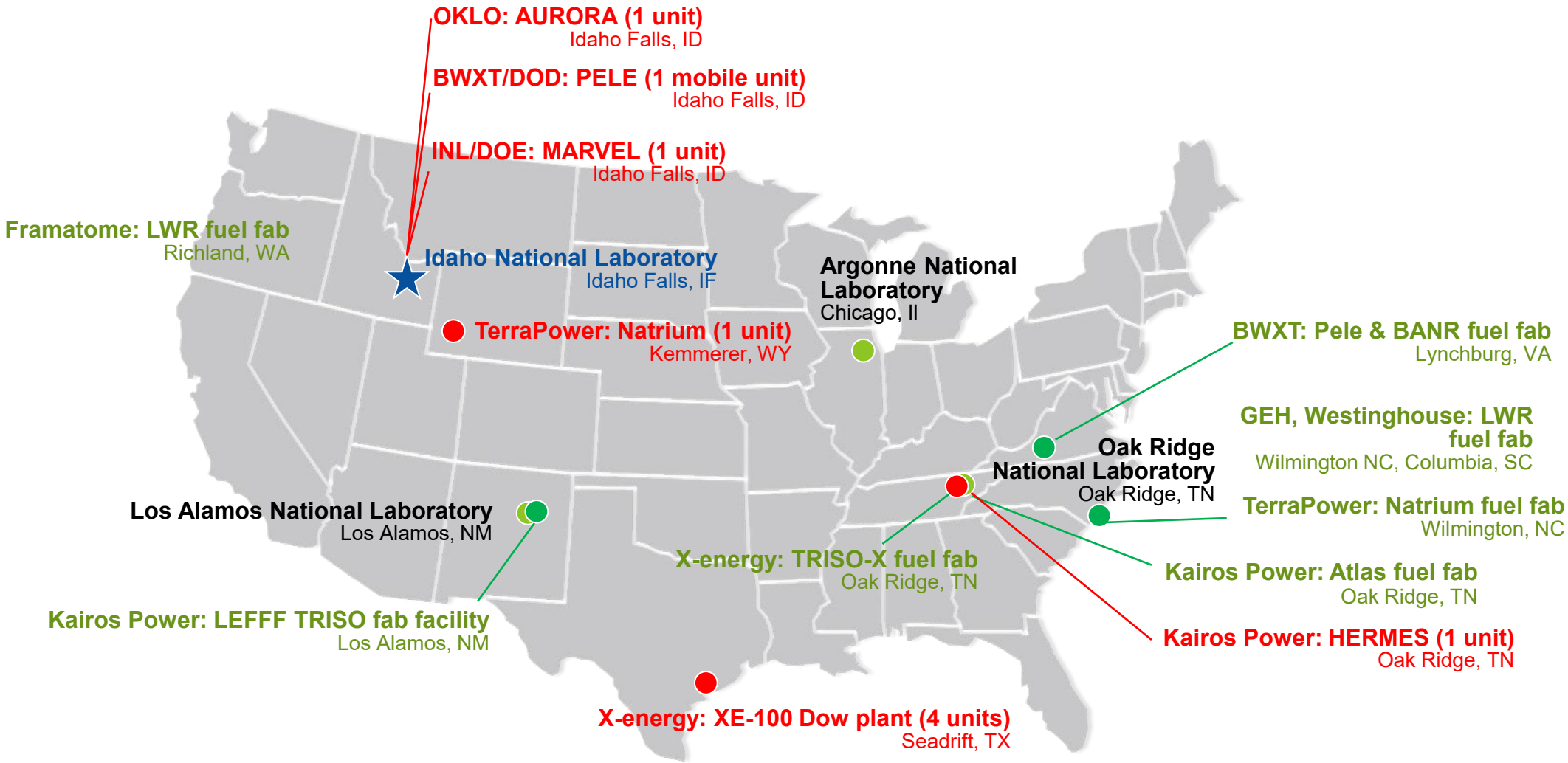


Prismatic reactor

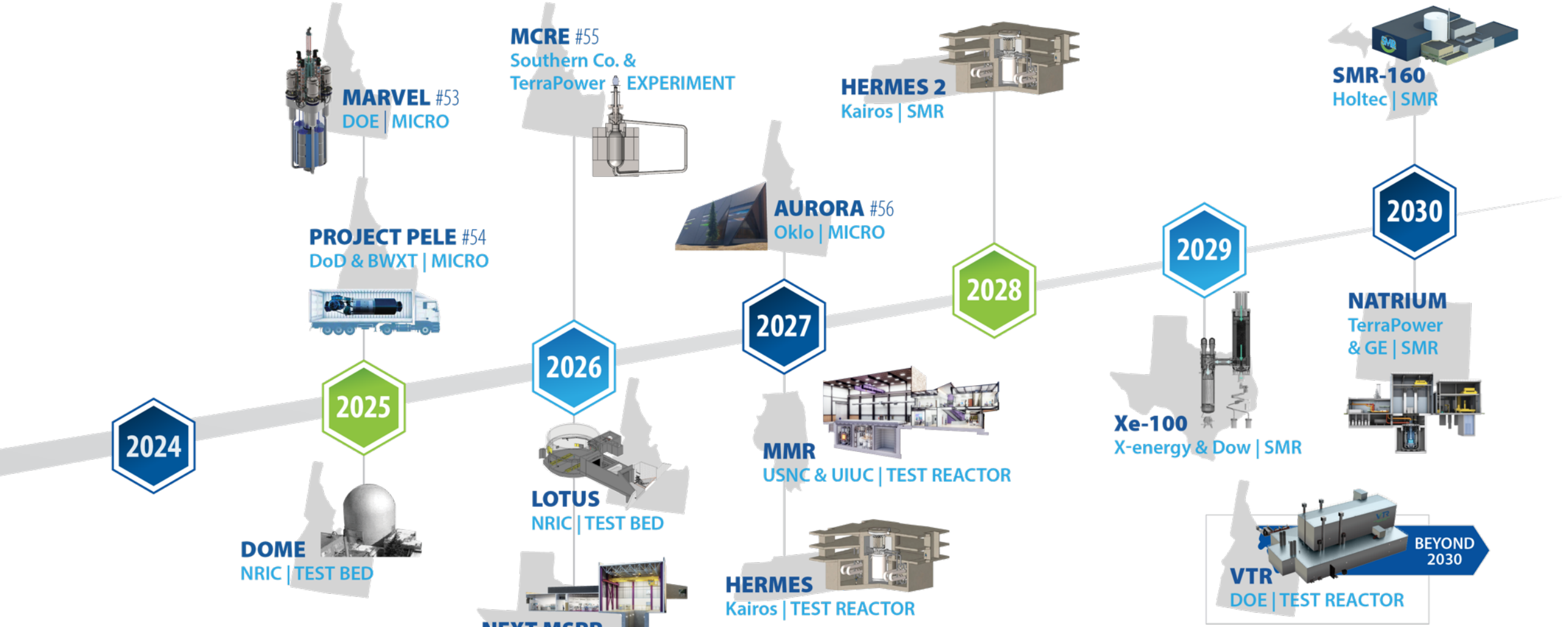


MCRE

AR Projects: Reactors and Fuel Fabrication Facilities



Accelerating advanced reactor demonstration & deployment



National Reactor Innovation Center
Enabling Reactor Demonstrations

- Established in 2019 with the purpose to provide the capabilities to support development and demonstration of advanced reactors
- Objective 1: Enable demonstration of two advanced reactors by the end of 2025
  - Make available infrastructure, sites, materials, expertise
  - Provide regulatory support
  - Best practices in public engagement
- Objective 2: Prepare DOE/labs for continuing innovation and demonstration
  - Develop best practices for planning/construction/demonstration of nuclear projects
  - Develop enduring infrastructure and expertise
  - Establish methods for efficient coordination among laboratories

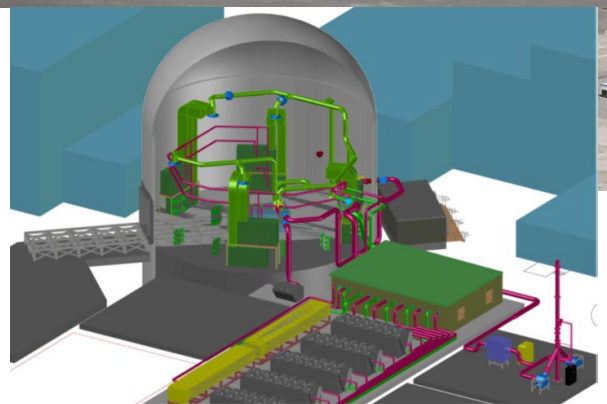
For more information: https://nric.inl.gov

NRIC-DOME Test Bed
(Demonstration of Operational Microreactor Experiments)

- Test bed for microreactors less than 20 MWt
- Reestablish capabilities of existing infrastructure

NRIC-LOTUS Test Bed
(Laboratory for Operations and Testing in the United States)

- Experimental test bed with 500kW heat rejection system



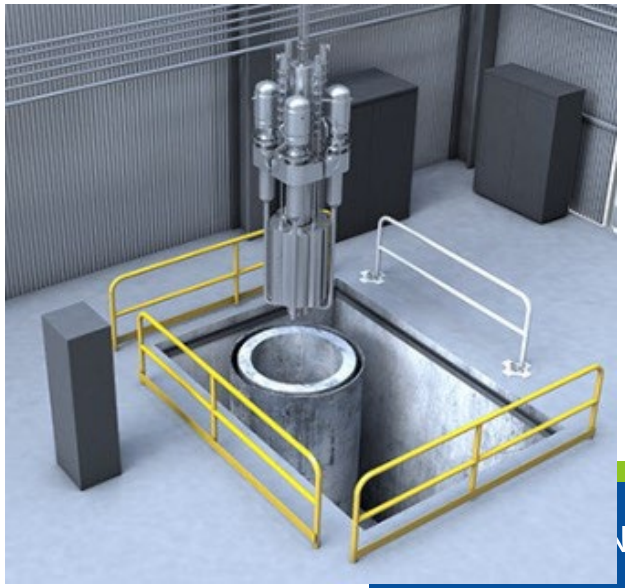
Microreactor Applications Research, Validation & EvaLuation

Project Goals:

- Rapid development of a small-scale microreactor that provides a platform to test unique operational aspects and applications of microreactors

Primary Objectives:

- Operational microreactor in the most **accelerated timeline** possible
- Produce **combined heat and power (CHP)** to a functional **microgrid**
- **Share lessons learned** with commercial developers
- **Train** future operators



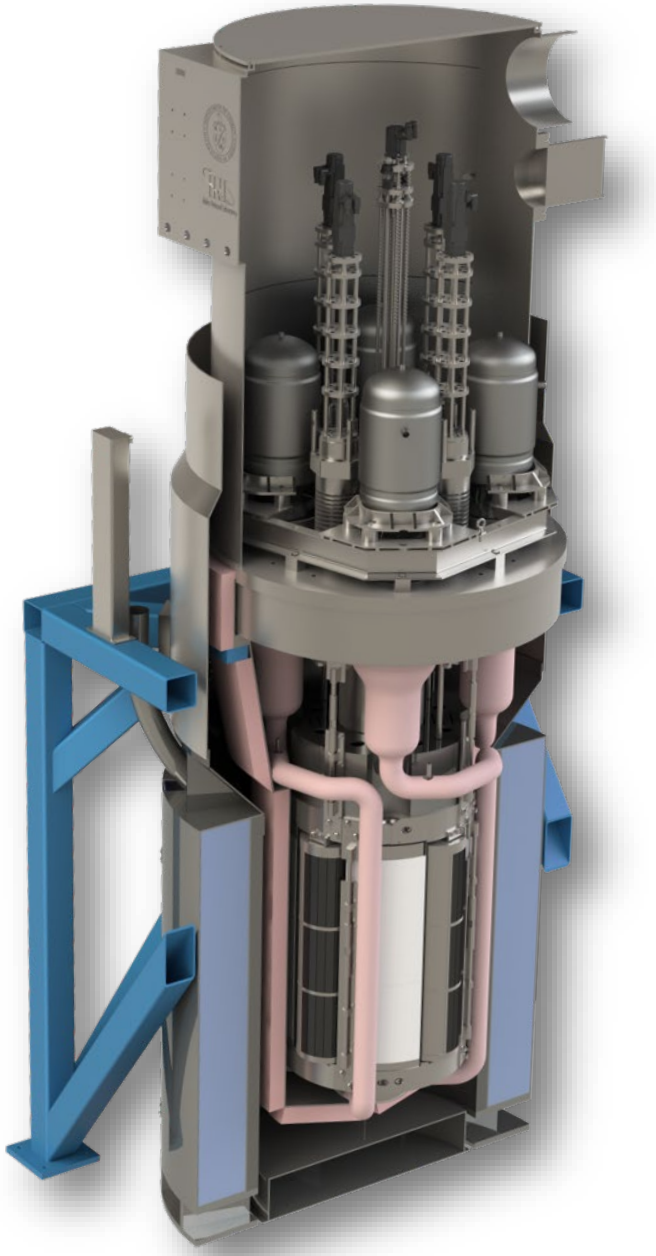
MARVEL critical by end of

MRP Microreactor Program

NATIONAL LABORATORY

MARVEL - Test Microreactor

Key Design Features	
Thermal Power	100 kW (85 kW nominal)
Electrical Power	20 kWe (QB80 Stirling Engines)
Weight	< 12 US ton
Primary Coolant	Sodium-Potassium eutectic
Intermediate Coolant	Lead
Coolant Driver	Natural Convection, single phase
Fuel	HALE(UZrH), 304SS clad, end caps
Moderator	Hydrogen
Neutron Reflector	Graphite, Beryllium (S200), Beryllium oxide
Reactivity Control	Radial Control Drums, Central Absorber
Primary Coolant Boundary	SS316H



Innovation- MARVEL used an inherently safe research reactor fuel and designed a high-temperature advanced reactor

Department of Defense Strategic Capabilities Office Project Pele

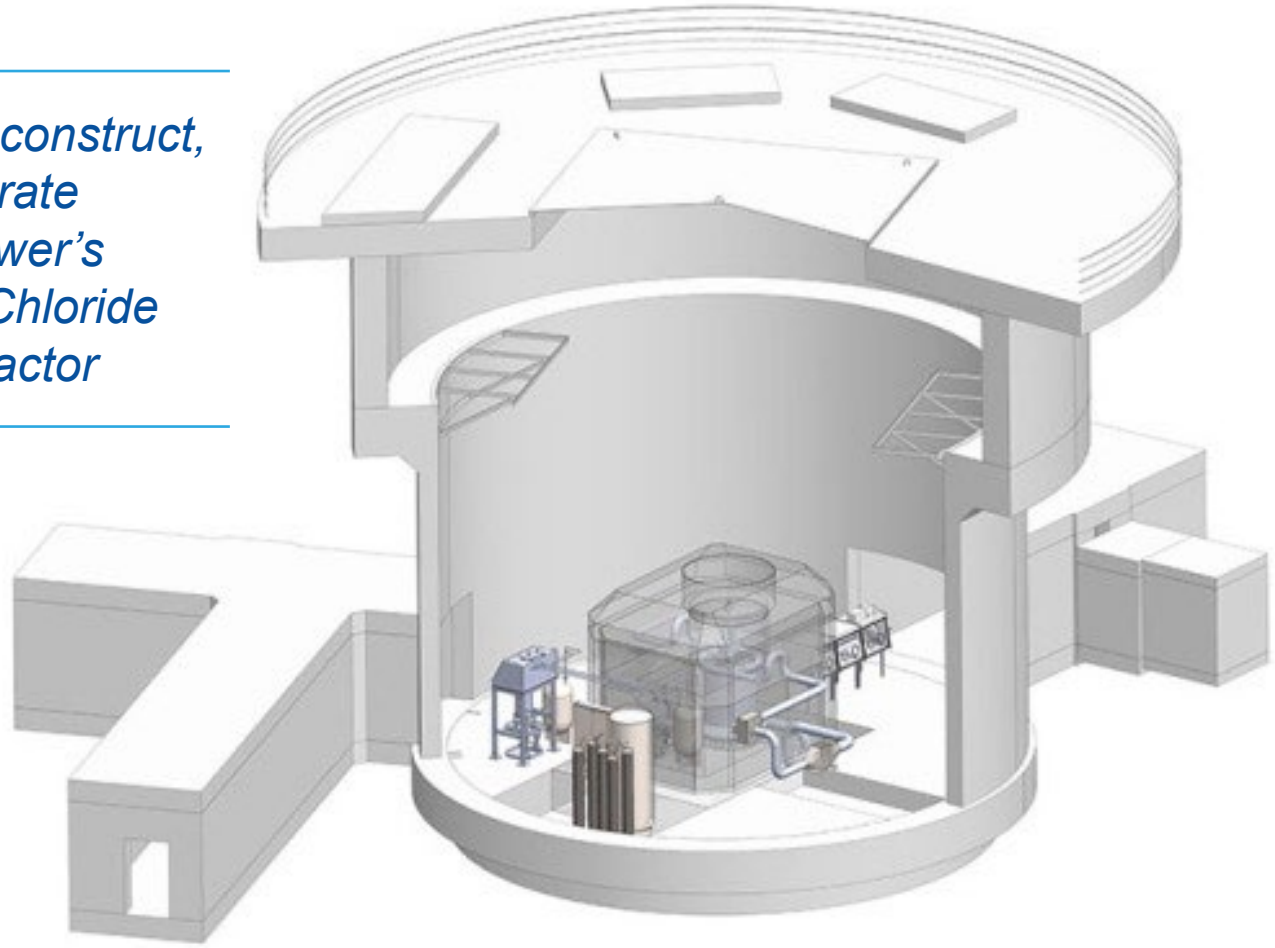
US Army Corps of Engineers ®

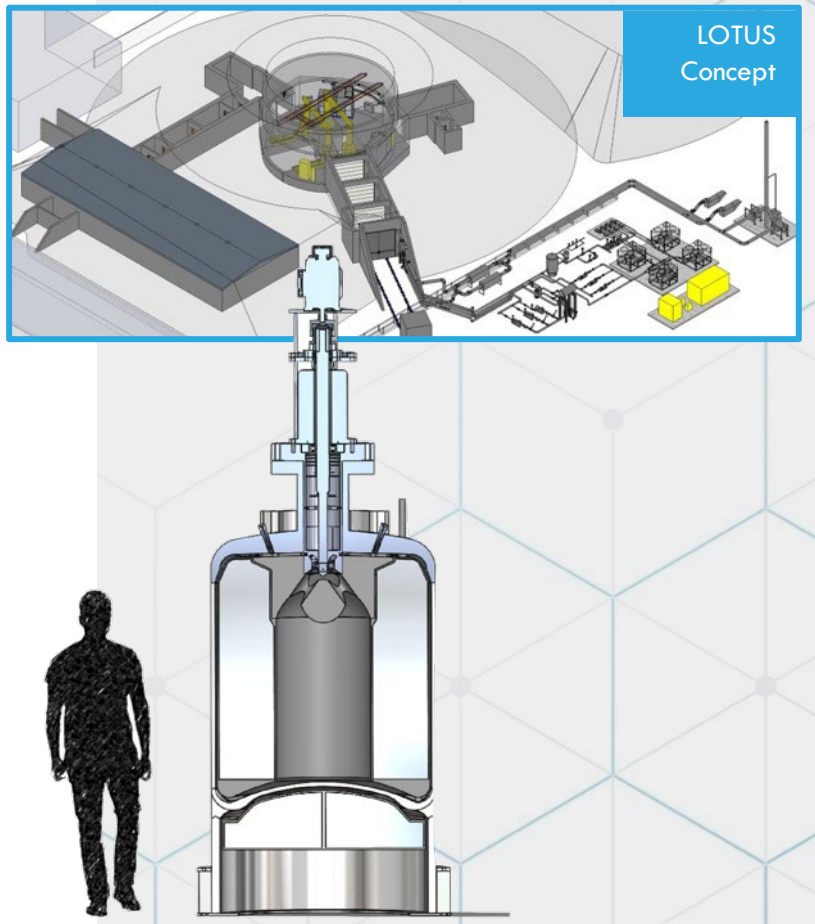
National Nuclear Security Administration

IDAHO NATIONAL LABORATORY

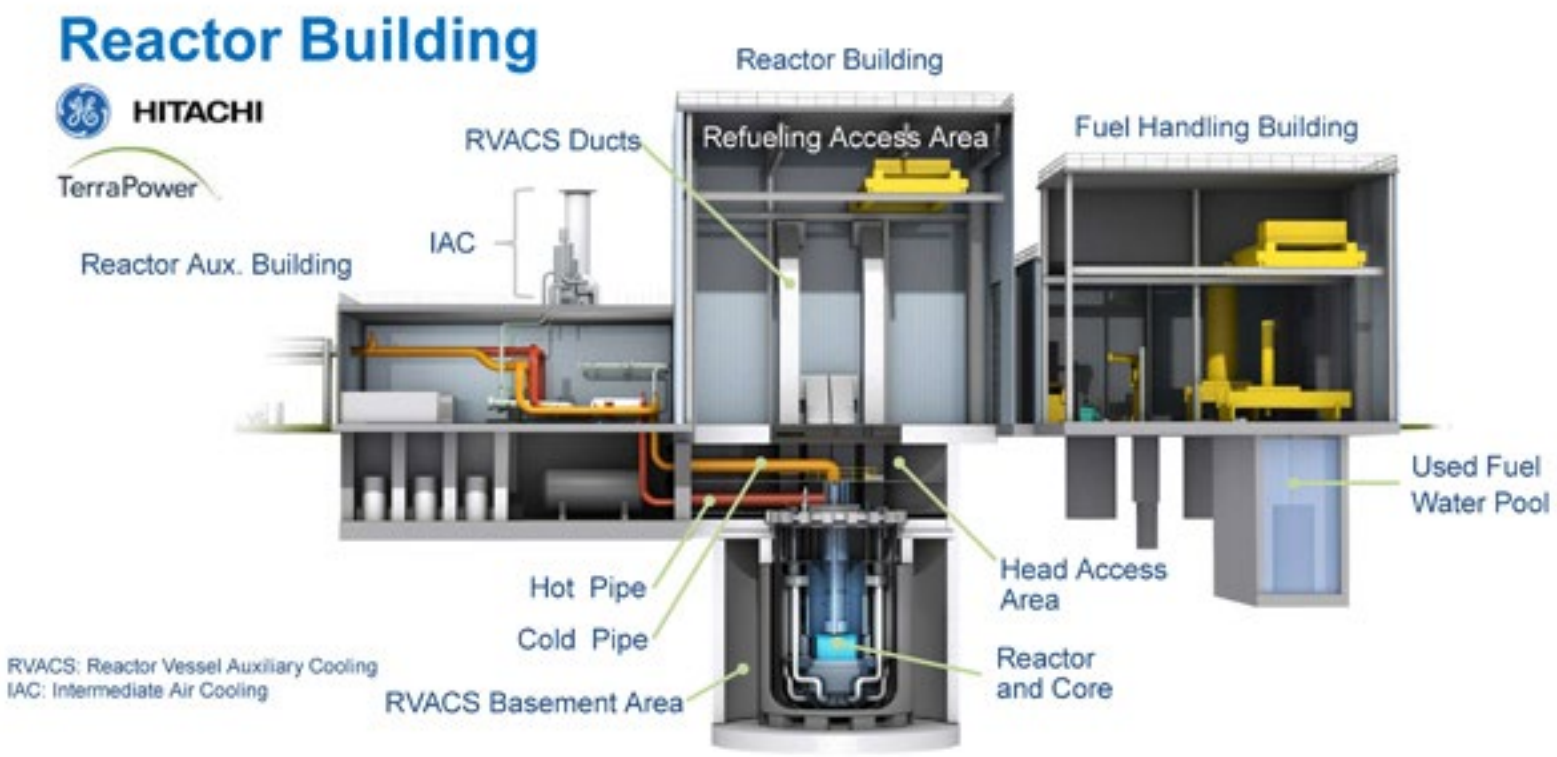
Molten Chloride Fast Reactor Experiment (MCRE)

Design, construct, and operate TerraPower's Molten Chloride Fast Reactor





Natrium



- Natrium design combines features from previous General Electric Hitachi (GEH) PRISM and TerraPower Traveling Wave designs.
- Reactor is a 345 MWe pool-type sodium fast reactor using High-Assay Low-Enriched Uranium (HALEU) metal fuel.
- TerraPower formally selected Kemmerer, Wyoming as the site of its Natrium demonstration reactor in November 2021.

INL Support Scope

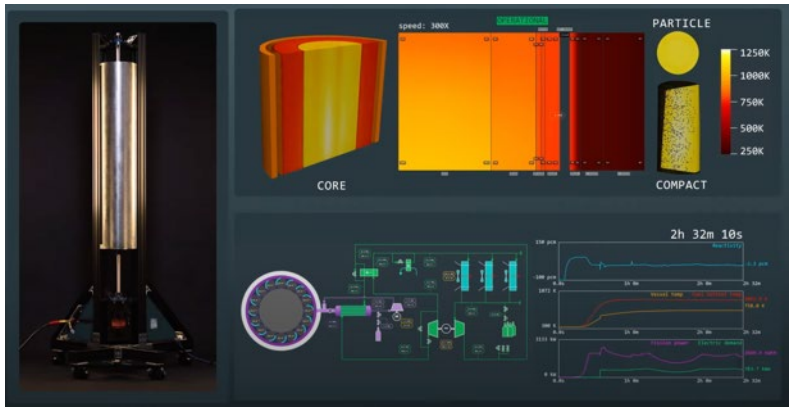
- Fuel fabrication R&D and performance testing
- Post-irradiation examination
- Digital engineering
- Technical support

https://www.terrapower.com/natrium-demo-kemmerer-wyoming/

Simulation Tools

Impact of INL MOOSE-Based Simulation Tools

- Citations for Multiphysics Object Oriented Simulation Environment (MOOSE): 1,240
- Citations of INL papers using MOOSE: ~3,000
- 5,000+ unique visitors a month to the MOOSE website
- Supported by DOE NEAMS program



Radiant is utilizing MOOSE-based applications in a digital twin for real-time reactor simulation

Source: https://www.youtube.com/watch?v=9cc1j-MbVVA&t=21s

NEAMS

Nuclear Entities Using INL MOOSE-Based Applications:

U.S.NRC United States Nuclear Regulatory Commission *Protecting People and the Environment* · RADIANT · BWXT Nuclear Energy Canada Inc. · Structural Integrity Associates, Inc.® · Kairos Power · EPRI · Westinghouse

Oregon State University · Texas A&M University · Idaho State University

Collaboration with universities:

National University Consortium, Texas A&M, Oregon State University, Idaho State University

MOOSE · BISON · Blackbear

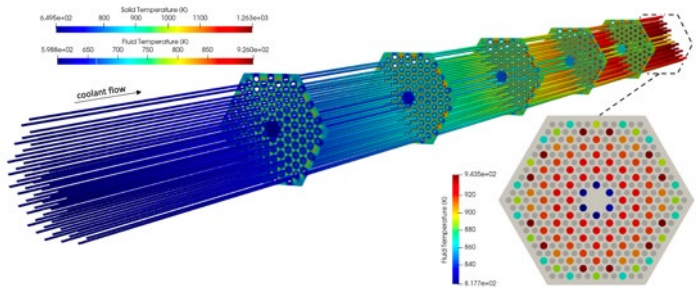
Falcon · Griffin · Grizzly

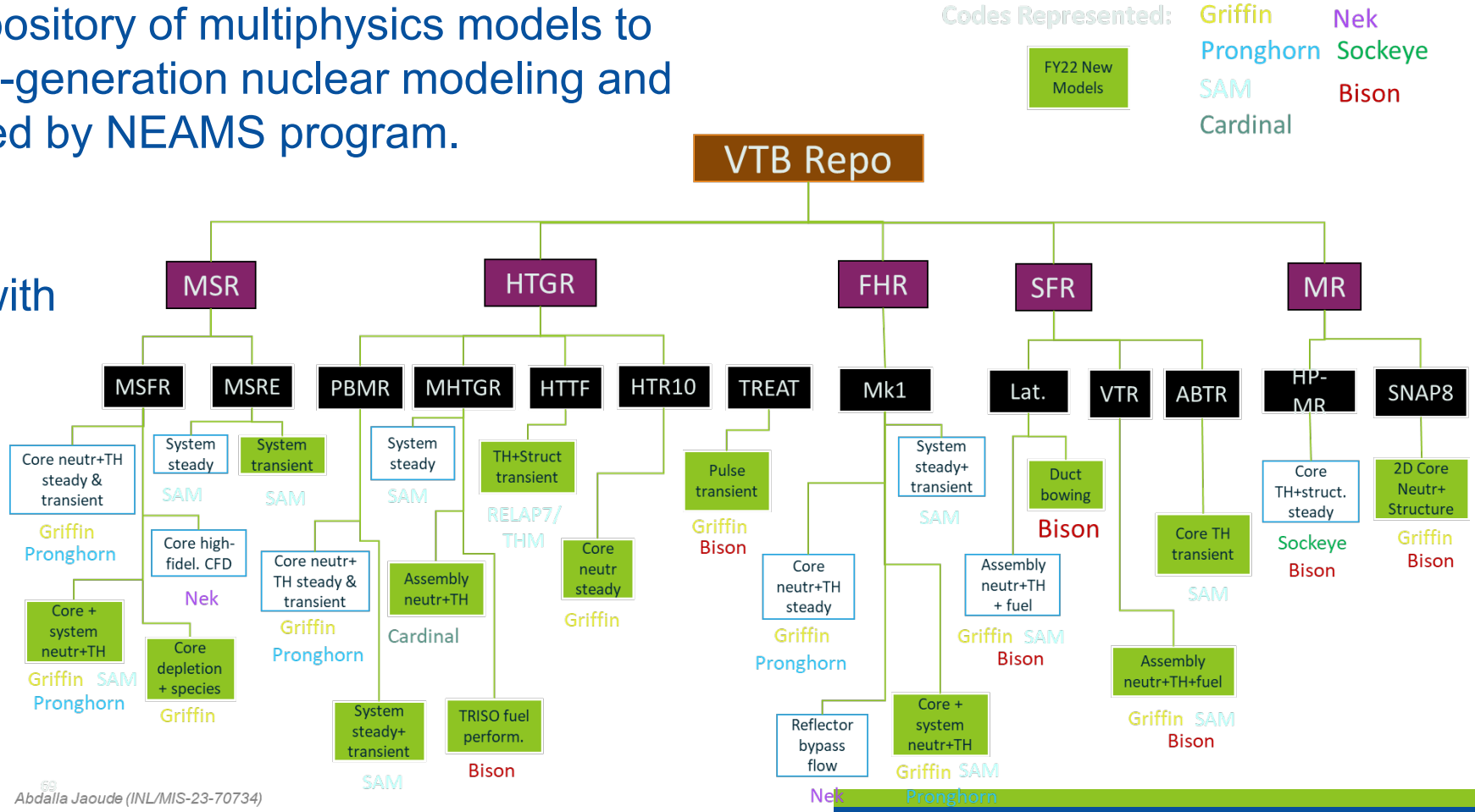
Magpie · Marmot · Mastodon

RELAP-7 · Sockeye · Pronghorn

Virtual Test Bed (VTB): Modeling Simulation Repository for Advanced Reactors

- Public-facing website/repository of multiphysics models to facilitate adoption of next-generation nuclear modeling and simulation tools developed by NEAMS program.
- Supported by NRIC.
- Database of 30+ models, continuously integrated with software QA process





Abdalla Jaoude (INL/MIS-23-70734)

Integrated Energy System - Shifting the energy paradigm

Nuclear Energy Generation

(Light water reactors, small modular reactors, microreactors, etc.)

Other Energy Generation

(Variable renewables, municipal waste, etc.)

Biofuel

New chemical processes

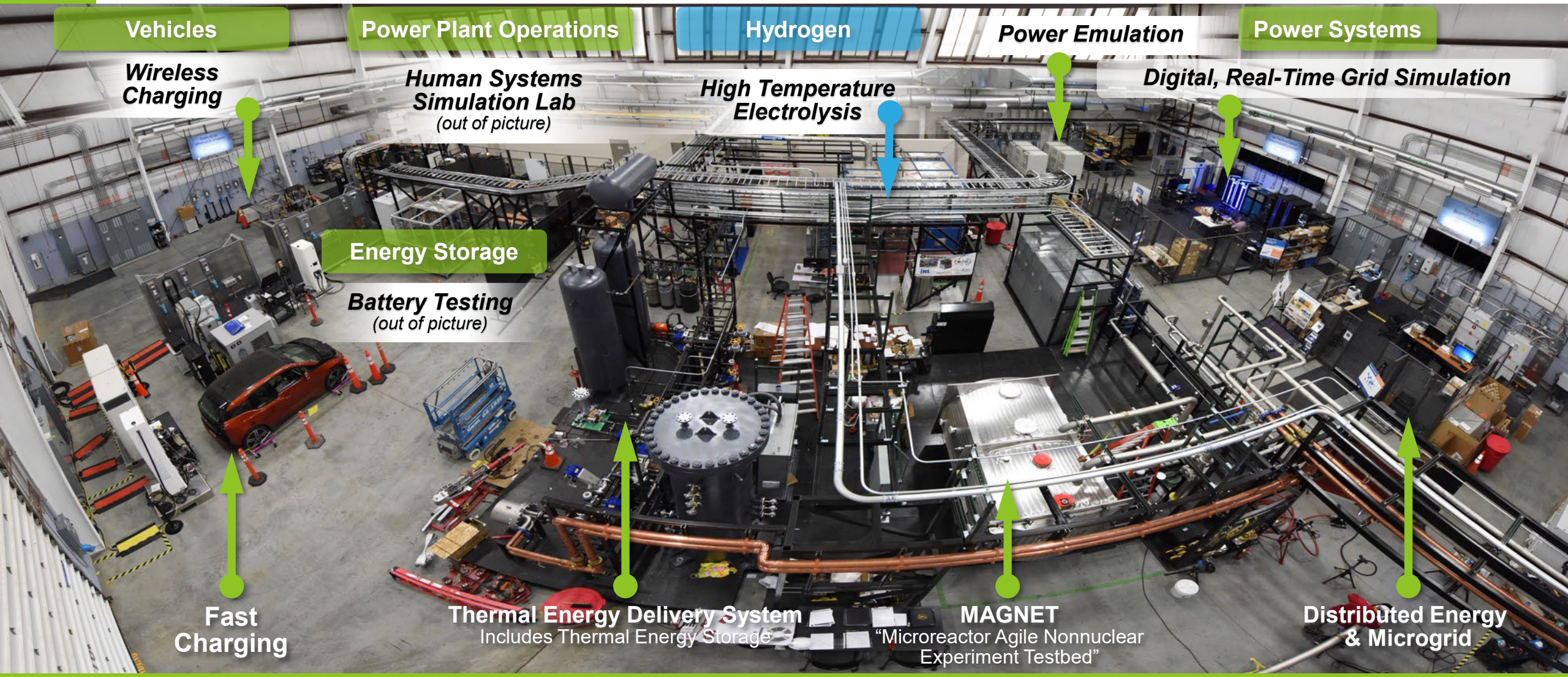
Clean water

Industry

Electricity

Hydrogen for vehicles and industry

INL Energy Systems Laboratory IES Capability



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.