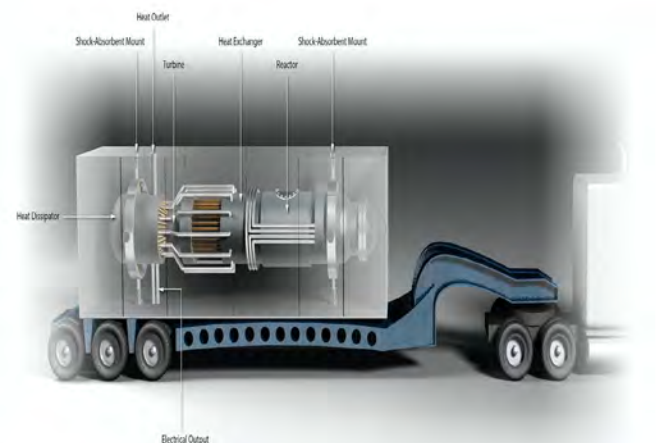
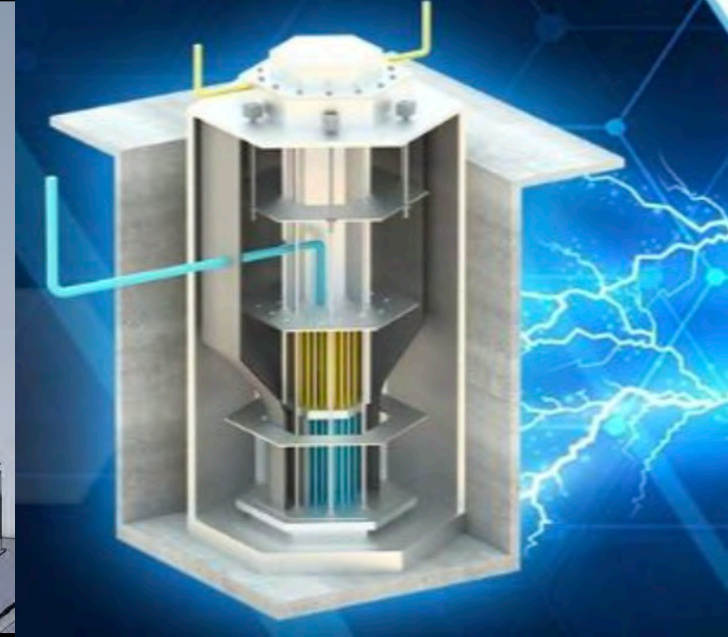
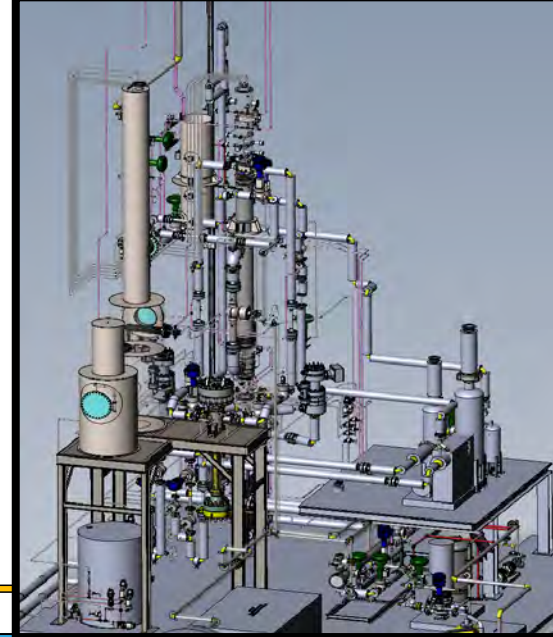
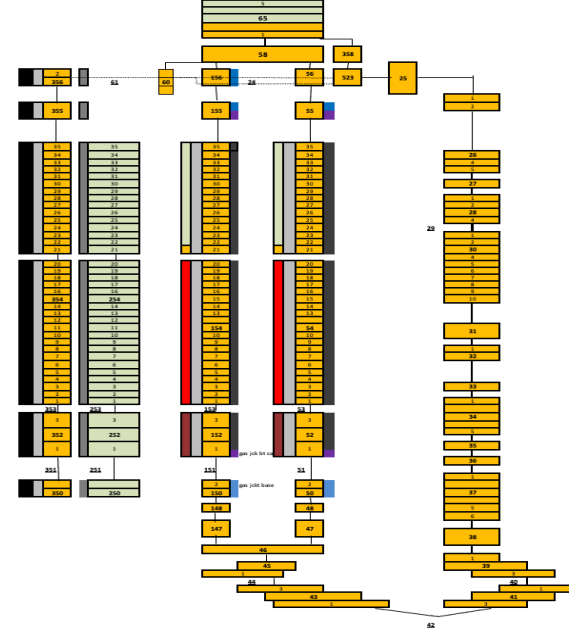




U.S. Nuclear Innovation and Advanced System Analysis with RELAP5-3D

May 19th, 2026

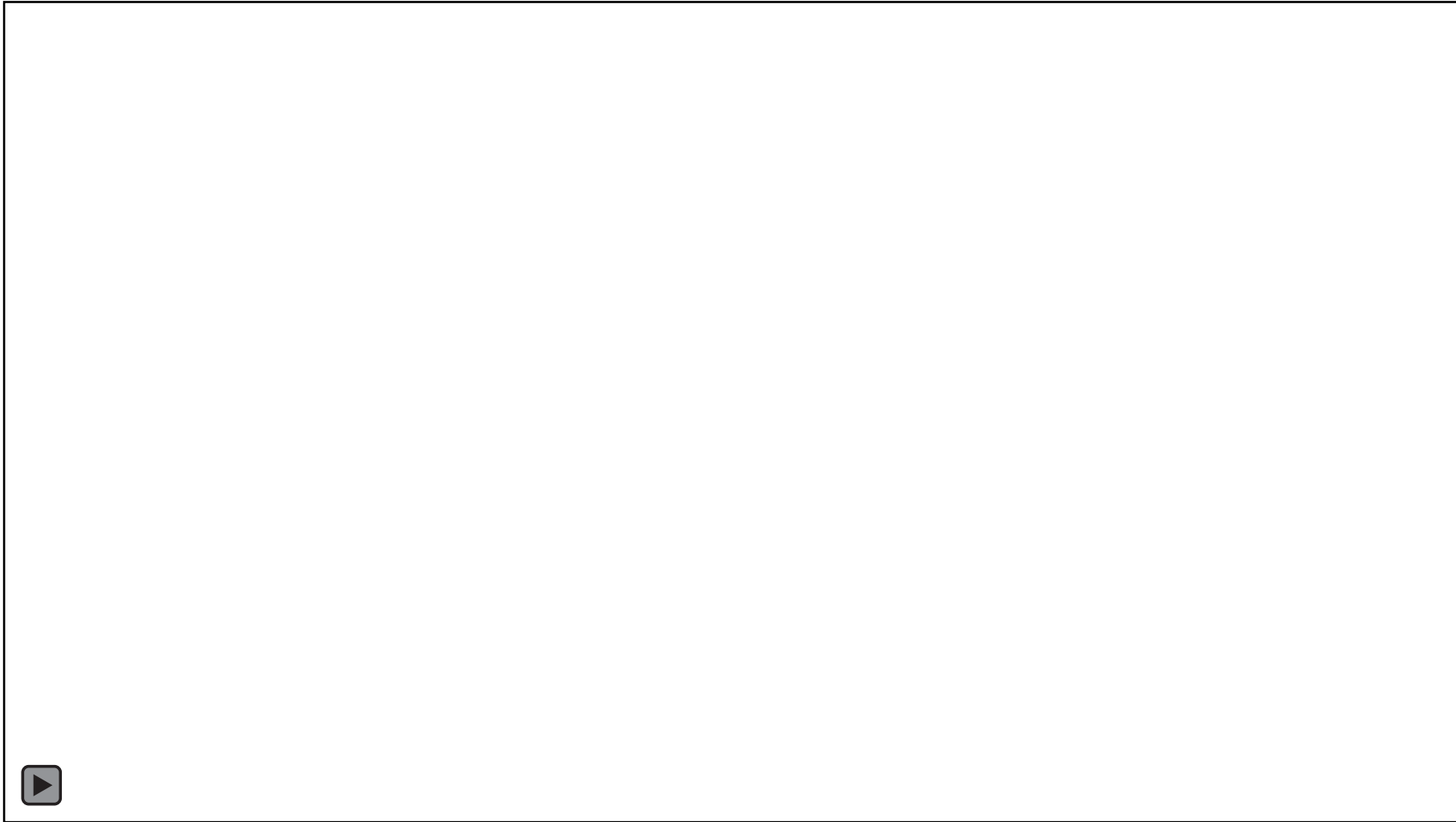
INL/MIS-26-9227

International RELAP5 User Group Meeting 2026
May 18–21, 2026 | Idaho Falls, Idaho

Piyush Sabharwall Ph.D. (Piyush.Sabharwall@inl.gov)
Distinguished Staff Scientist and DOE-NE MRP – Technical Area Lead
Reactor Systems and Heat Transport
Nuclear Science & Technology Directorate, Idaho National Laboratory

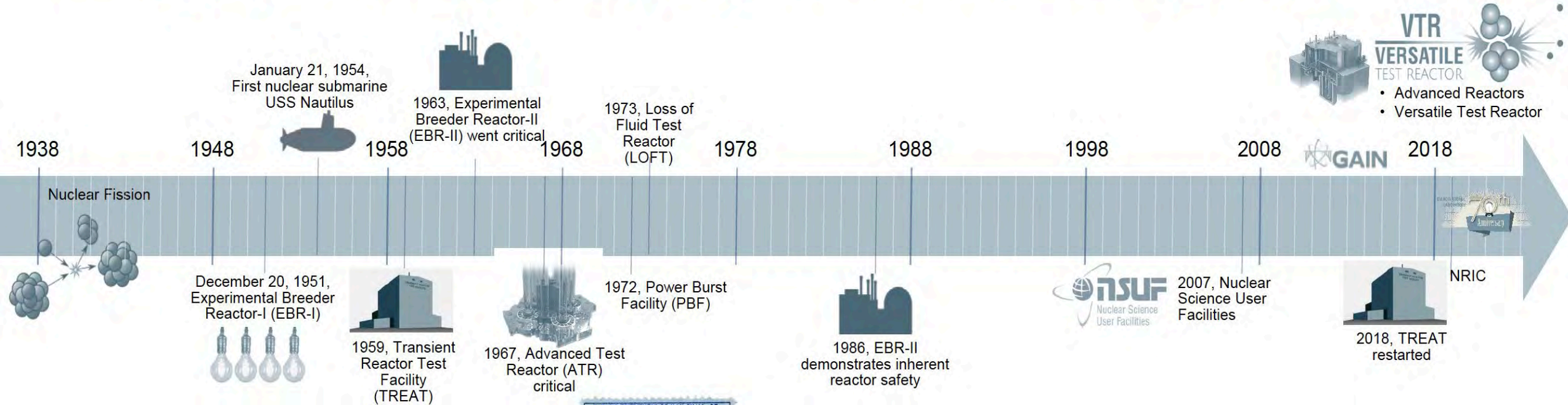


When you hear the word 'nuclear'...



Nuclear History

Our Eighty Year Past is Shaping the Nuclear Energy Future



Chicago Pile-1 the first human-made self-sustaining nuclear chain reaction - 1942

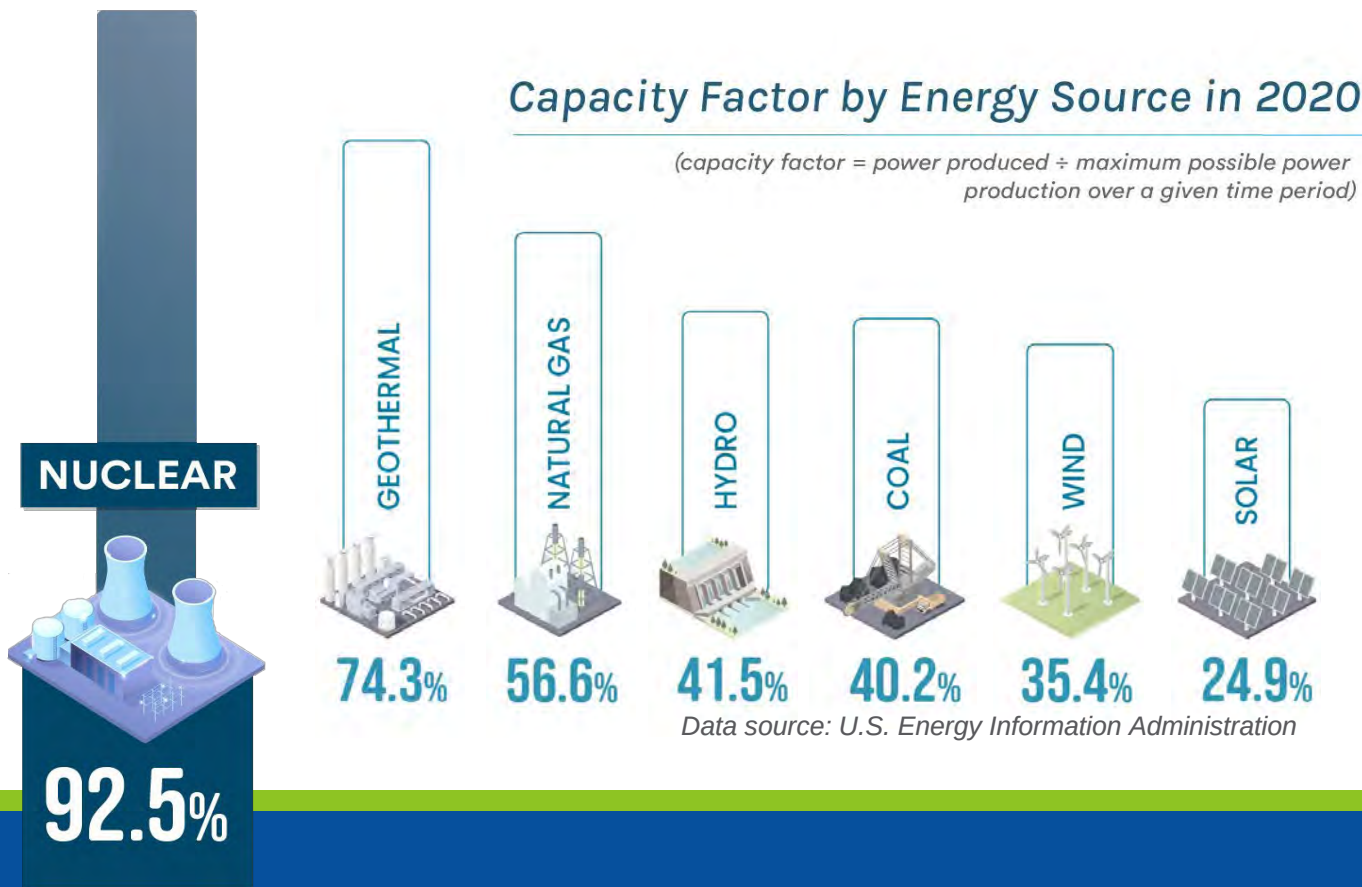
Atoms for Peace - 1953

Shippingport Atomic Power Station - 1957

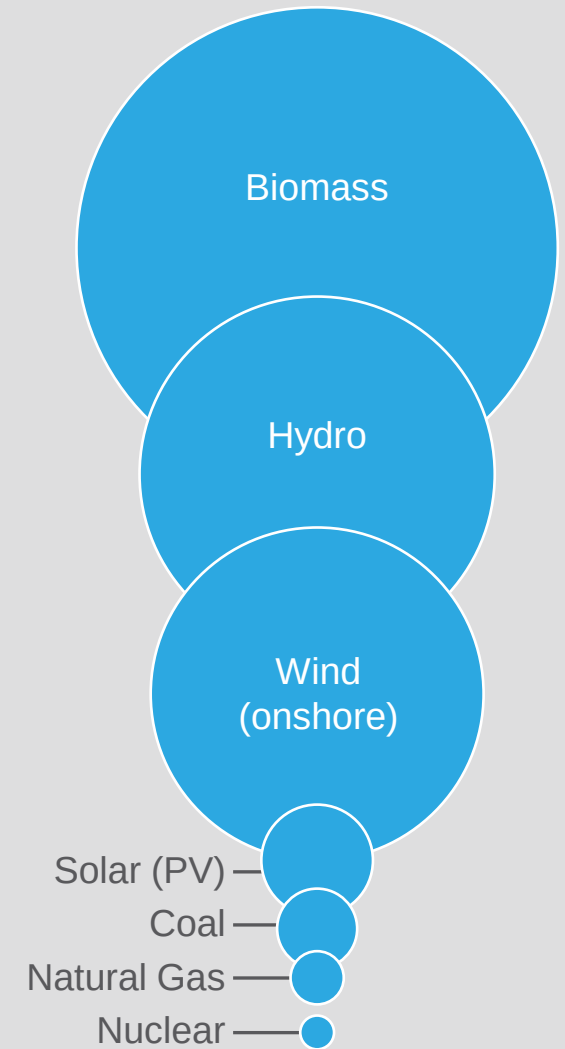
Nuclear Energy Reimagined

Courtesy of Third Way

Nuclear Provides Reliable, High-Density Energy with Comparatively Low Land Use

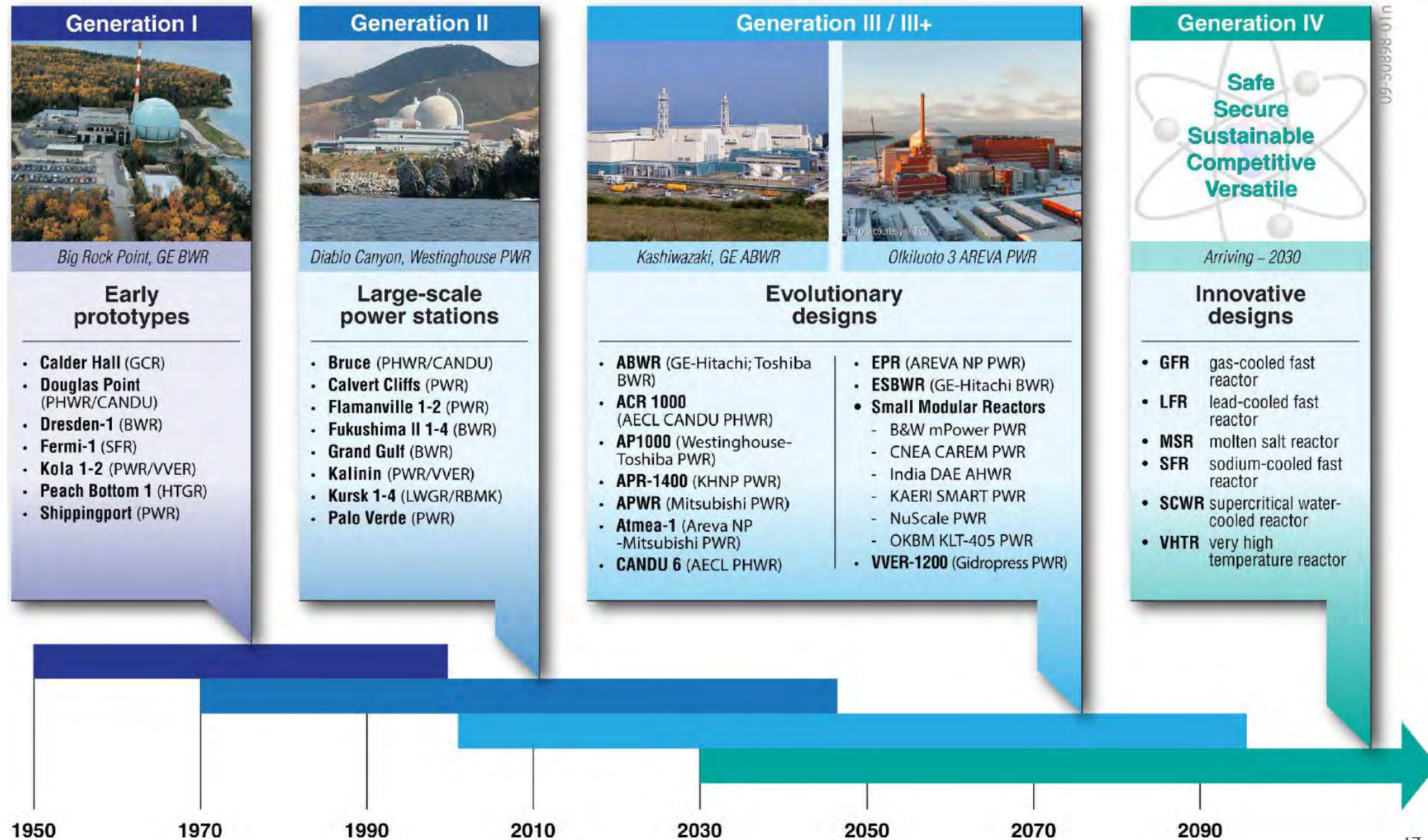


RELATIVE LAND FOOTPRINTS



Source: World Nuclear Association

Evolution of Nuclear Power



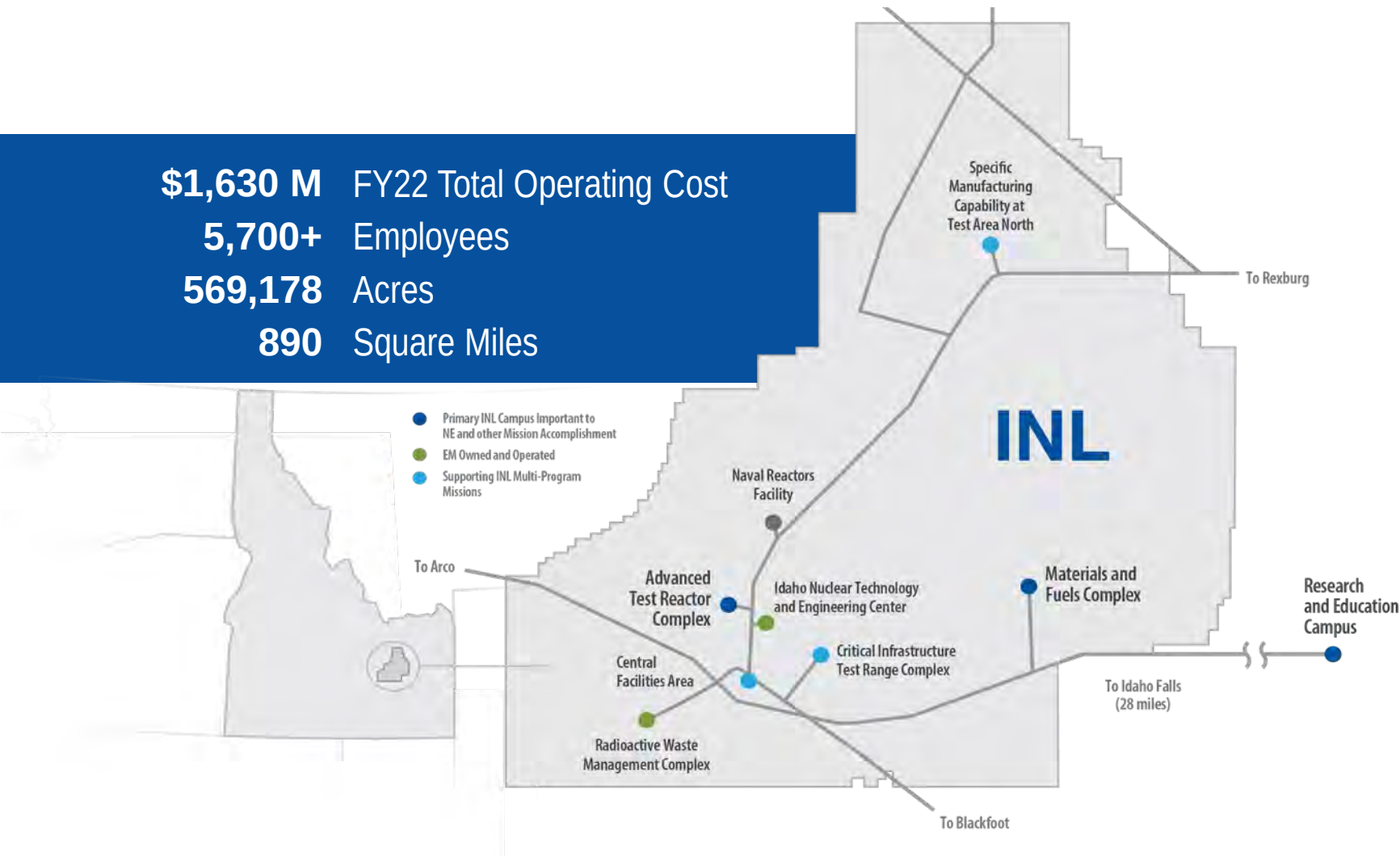
Advanced Reactor Future State: One Size Does Not Fit All

Researchers at Idaho National Laboratory are collaborating with industry and academia to develop nuclear reactor concepts of various sizes for various use cases.



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

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

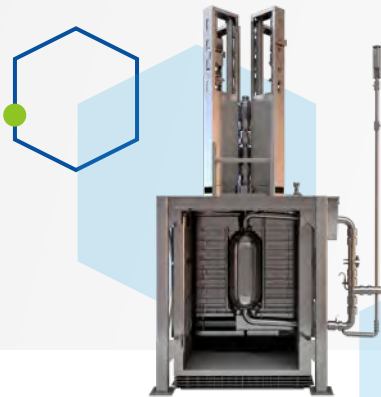
Enabling U.S. technological leadership

Accelerating advanced reactor demonstration

- MARVEL
- Pele
- MCRE

Revolutionizing space exploration

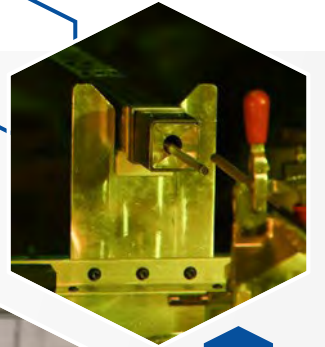
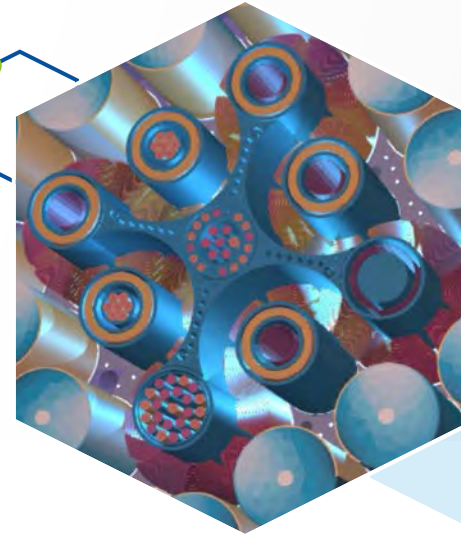
- NextGen radioisotope thermoelectric generator
- Increasing Pu-238 production
- Nuclear thermal propulsion
- Surface fission power



Strengthening the domestic nuclear enterprise

Strengthening the current fleet

- Reduce operating costs
- Automate operations with AI and ML
- Enhance advanced nuclear power plant design, licensing, and deployment life cycle through AI and digital engineering
- Increase safety and enhance performance of nuclear fuels and materials
- Enable LWR fuel burnup extension through new capability development



 MOOSE


Lightbridge

Expanding R&D infrastructure

Existing irradiation and post irradiation capabilities

- Advanced Test Reactor
- Transient Reactor Test Facility
- Neutron Radiography Reactor
- MFC characterization facilities

Under development

- Sample Preparation Laboratory
- Expanded irradiation capabilities in existing facilities
- DOME and LOTUS test beds
- Expanded computing capabilities

Infrastructure needs

- Advanced Nuclear Fuels Fabrication Laboratory
- Long term need for fast spectrum testing capabilities

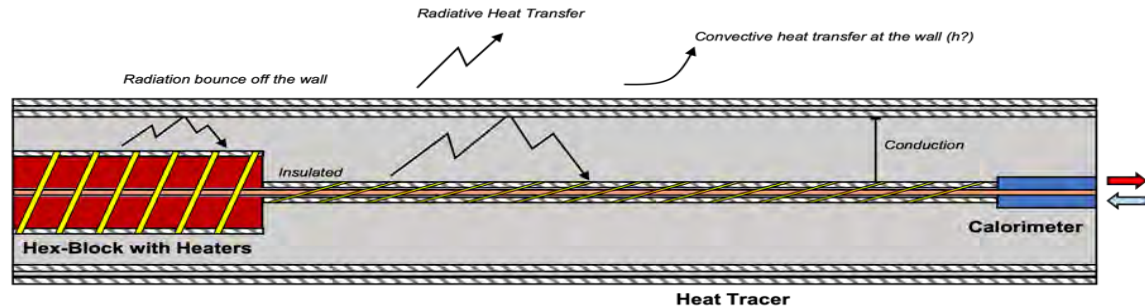


Experimental Test Beds

Single Primary Heat Extraction and Removal Emulator (SPHERE)

SPHERE Test Bed

- **SPHERE Facility Capabilities:** Controlled testing of heat pipe heat-rejection using electrical heaters to simulate nuclear fission, with monitoring of axial temperature profiles and heat rejection quantification.
- **Advanced Instrumentation:** Includes infrared thermal imaging, surface thermocouples, fiber-optic sensors, electrical power meters, and gas-gap calorimeter; operates under vacuum and inert-gas conditions.
- **Recent Enhancements:** In-operando heat pipe operation with x-ray imaging added for better understanding of heat pipe dynamics.



Schematic of SPHERE Test Bed

Parameter	Value
Length	10 ft
Diameter	12 in
Tube material	Stainless steel
Connections	Flanged for gas flow and instrumentation feedthrough
Maximum power	20 kW
Max temperature	900 C
Heat removal	Passive radiation or water-cooled gas gap calorimeter

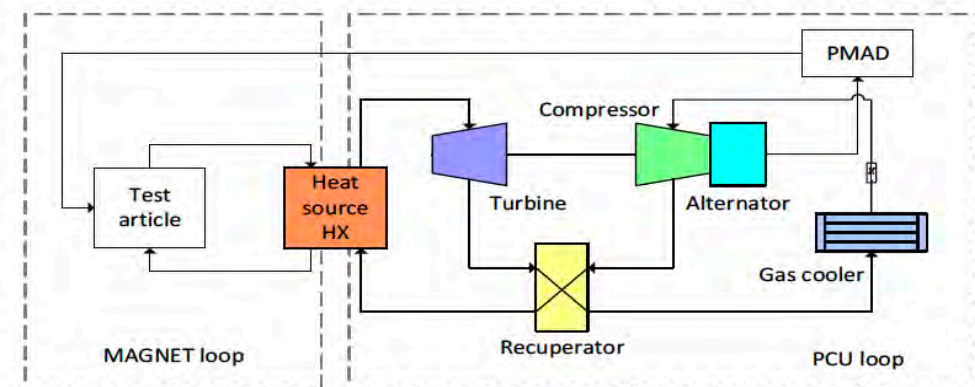
SPHERE Vacuum Chamber

- 2' x 3' x 13' aluminum vacuum chamber
 - 10^{-5} torr capability
 - 8 flanges for power and instrumentation feedthroughs
 - Windows for Xray
- Large door for experiment loading
- Small side doors for adjustments



MAGNET Test Bed

Layout of PCU loop connected to the MAGNET



MAGNET Environmental Enclosure



- **MAGNET Facility Functions:** A 250-kW electrically-heated micro reactor test bed for non-nuclear evaluation of microreactor concepts, including heat-rejection systems, thermal-hydraulic and structural phenomena, and interface-coupling with power conversion units and energy storage systems.
- **Goals:** Supports technology maturation, reduces design and operational uncertainty, and provides broad applicability for multiple reactor concepts. Partnered with Idaho, Los Alamos, and Oak Ridge National Laboratories for development and testing.

Parameter	Value
Chamber size	5 ft x 5 ft x 10 ft
Heat removal	Liquid-cooled chamber walls, gas flow
Coolants	Air, inert gas (He, N ₂)
Gas flow rates	Up to 43.7 ACFM at 290 psig
Design pressure	22 barg
Maximum power	250 kW
Max temperature	750 C
Heat removal	Passive radiation or water-cooled gas gap calorimeter

Dynamic Energy Transport and Integration Laboratory (DETAIL)

Vehicles
Wireless charging

Power plant operations
HSSL - Human Systems Simulations Lab
Energy storage
Battery testing
(out of picture)

Hydrogen
High-temperature electrolysis

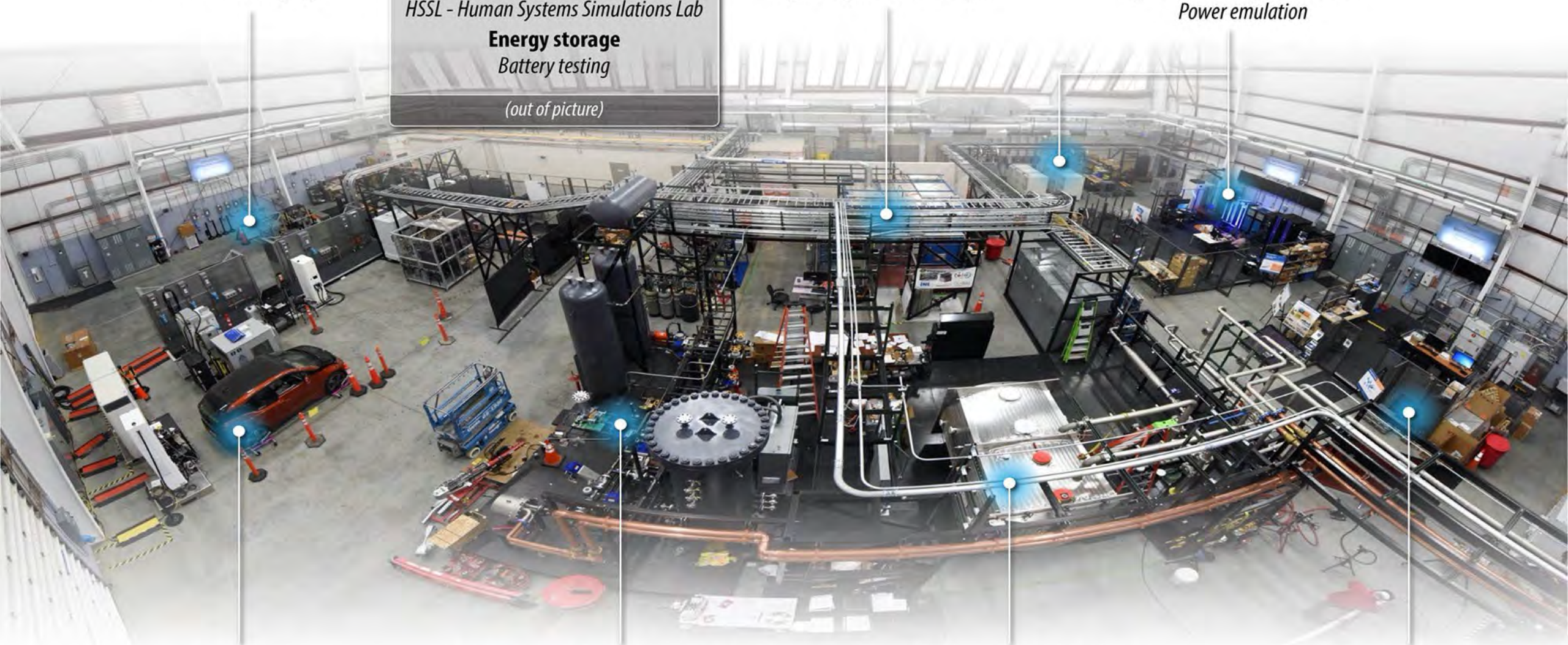
Power systems
Digital, real-time grid simulation
Power emulation

Fast charging

TEDS - Thermal Energy Distribution System
(includes thermal energy storage)

MAGNET - Microreactor Agile
Non nuclear Experimental Testbed

Distributed energy
and microgrid



MAGNET Facility



- MAGNET Deployment in the INL Energy Systems Laboratory (ESL) building, Systems Integration Laboratory
- Co-located with the Thermal Energy Distribution System (TEDS) and the High-Temperature Steam Electrolysis (HTSE) System

Nuclear Test Bed

MARVEL Enables a New Class of Nuclear Reactors

(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

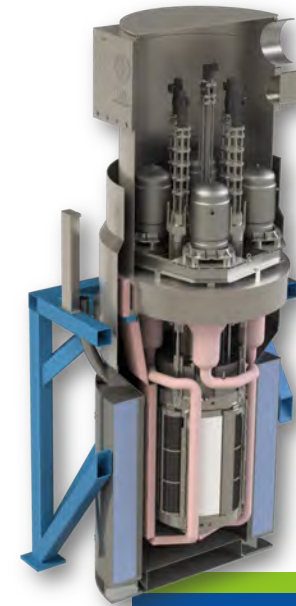
Primary Objectives:

- 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

U.S. DOE



Create momentum,
Champion rapid technology maturation to de-risk industry
Collaborate and engage microreactor end-user companies



- 85 kW-thermal
- 20 kW-electric
- ~15 feet tall
- < 8 tons
- 2 operators
- Self-regulating

MARVEL - Test Microreactor

Novel Design

- 85 KW-th Liquid metal thermal reactor
- Five natural circulation loops
- No containment needed

Integrated Fuel-Moderator

- Low Uranium mass needed
- Strong reactivity feedback
 - Doppler
 - $S(\alpha, \beta)$ effect
- Research reactor fuel; NRC licensed

Key Safety Features

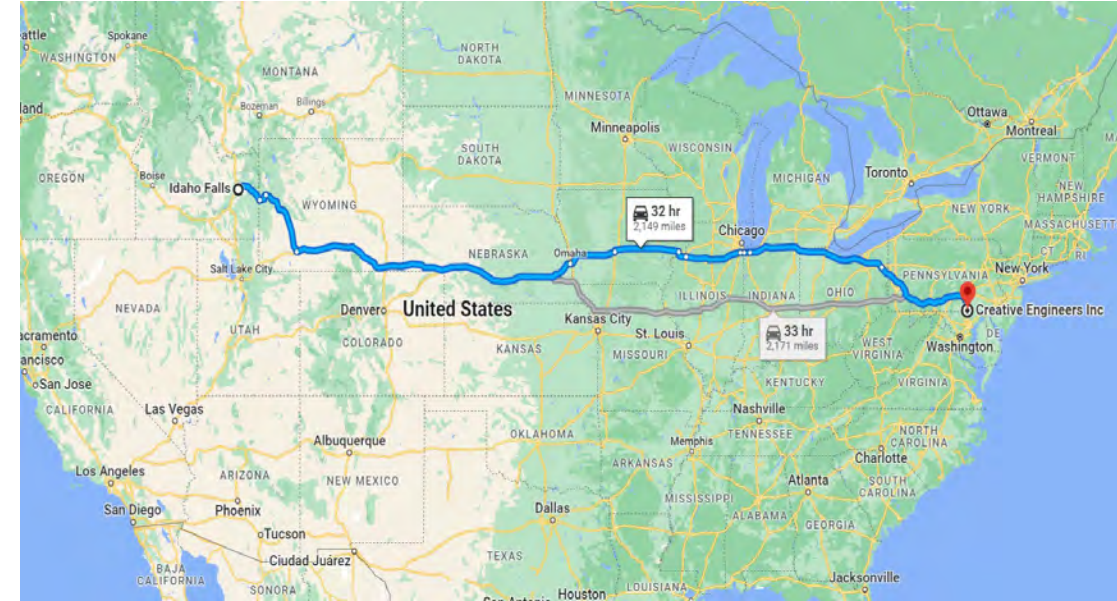
- Inherently safe fuel (UZrH)
- Passive primary coolant circulation
- Natural decay heat removal
- Air-cooled heat rejection

Compact

- ~7.5 metric tons
- <15 feet tall



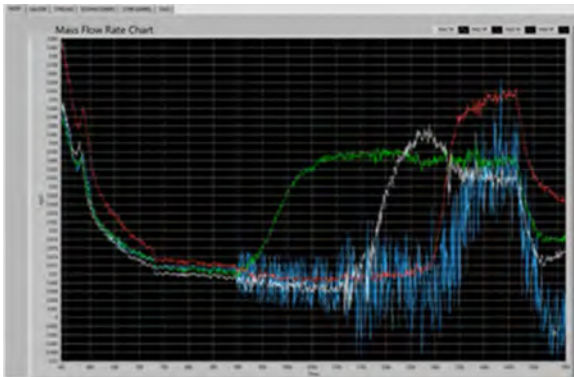
Integral Effects Test – Primary Coolant Apparatus Test (PCAT)





MARVEL Thermal Hydraulic Prototype

- Thermophysical twin of MARVEL
- Full-scale, electrically heated
- Data used to validate models, per NQA-1
- Initial startup on September 19th, 2023 with demonstration of natural circulation and power generation



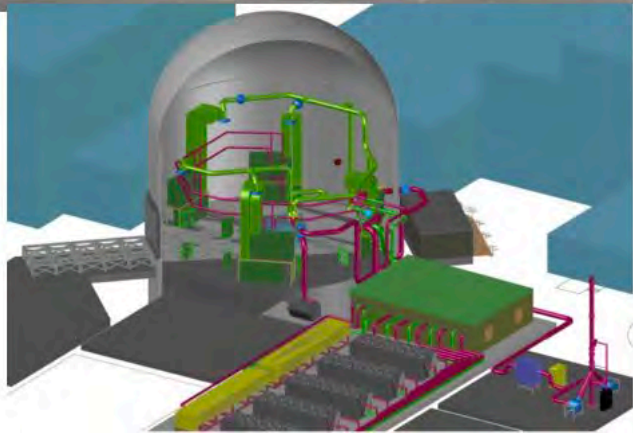
NaK flow measurements through 4 loops



NRIC-DOME Test Bed

(Demonstration of Operational Microreactor Experiments)

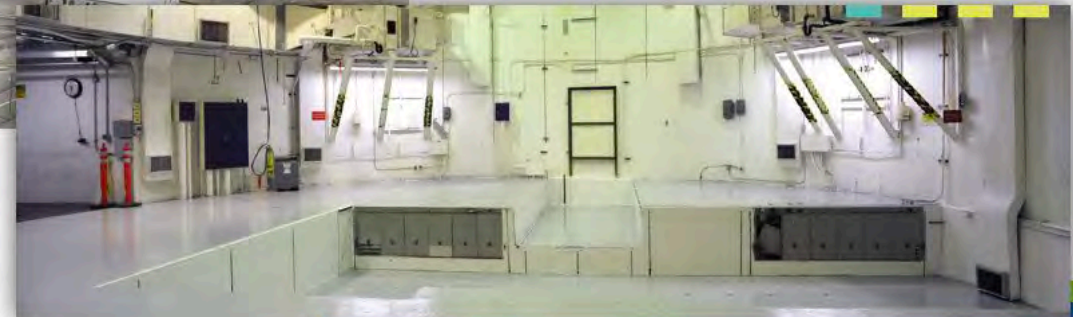
- Test bed for microreactors less than 20 MWt
- Reestablish capabilities of existing infrastructure



NRIC-LOTUS Test Bed

(Laboratory for Operations and Testing in the United States)

- Experimental test bed with 500kW heat rejection system



IDAHO NATIONAL LABORATORY

SMR-300 Overview

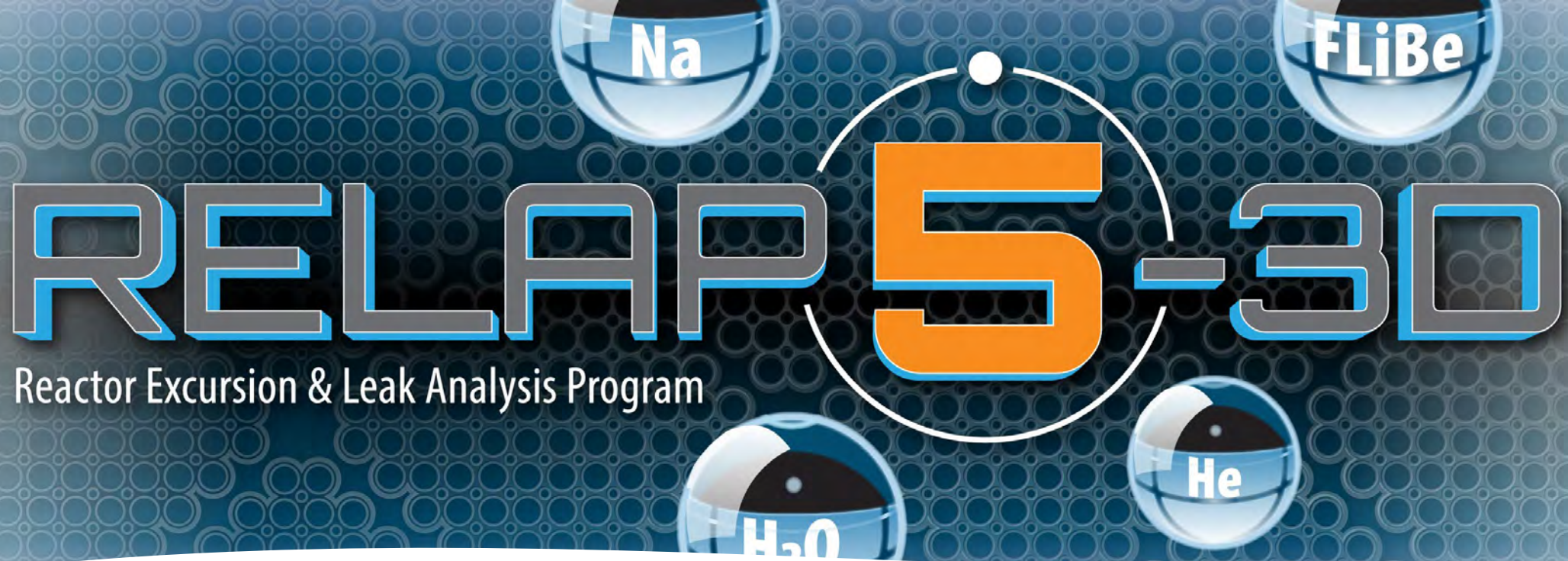


- Produces 1050 MWth
- Reactor pressure vessel (RPV) consists of:
 - Standard 17x17 PWR fuel assemblies and control rods
 - Typical PWR RPV internals
- Once-through steam generator (OTSG) with integral PZR
- Two centrifugal reactor coolant pumps (RCPs)
- Two cold legs and two hot legs connect RPV to OTSG
- Passive safety systems used for emergency core cooling and decay heat removal





Thermal Hydraulic Analysis for Current Nuclear Technologies and Enabling Deployment of Advanced Reactors.



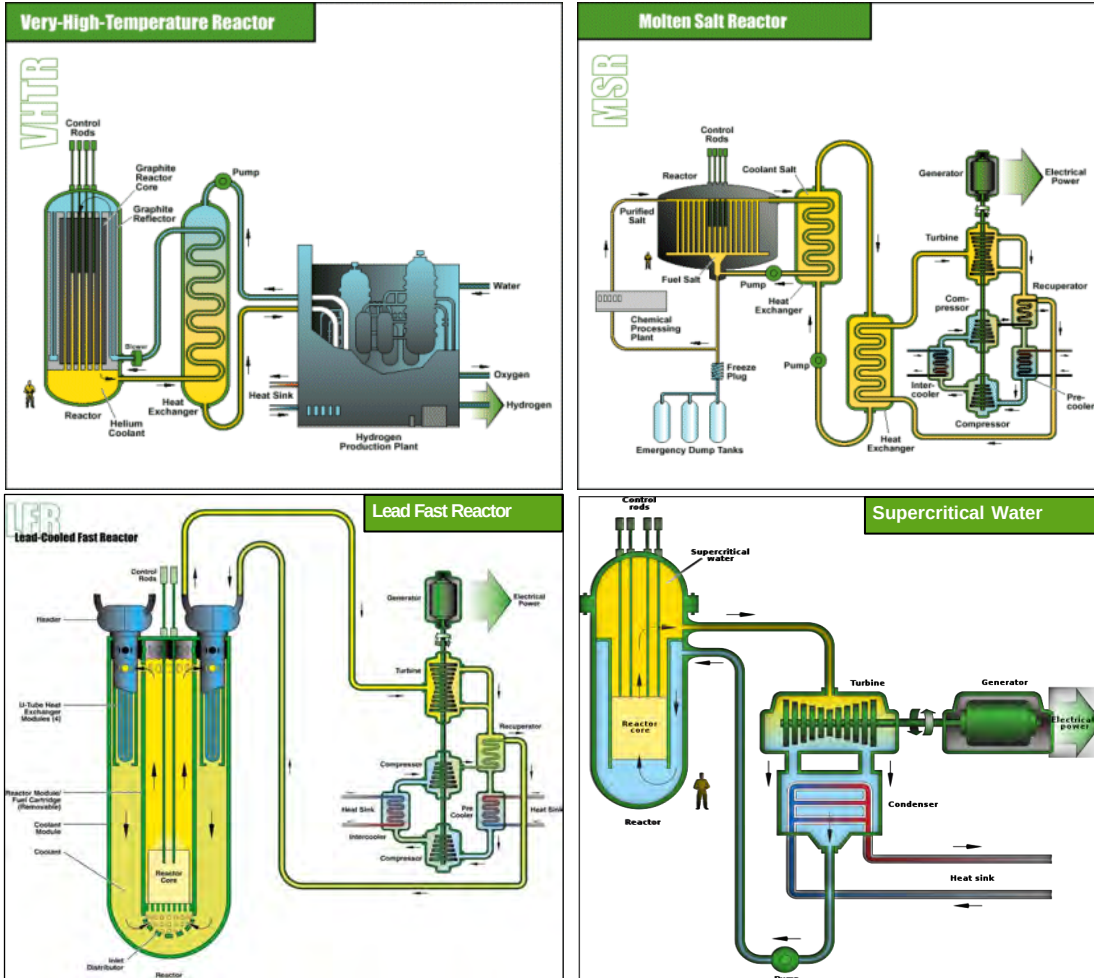
Primary purpose of RELAP5-3D is to model entire nuclear reactor systems

A system analysis code for modeling the behavior of reactor systems during normal and off-normal conditions

Industry standard for thermal-hydraulic simulation

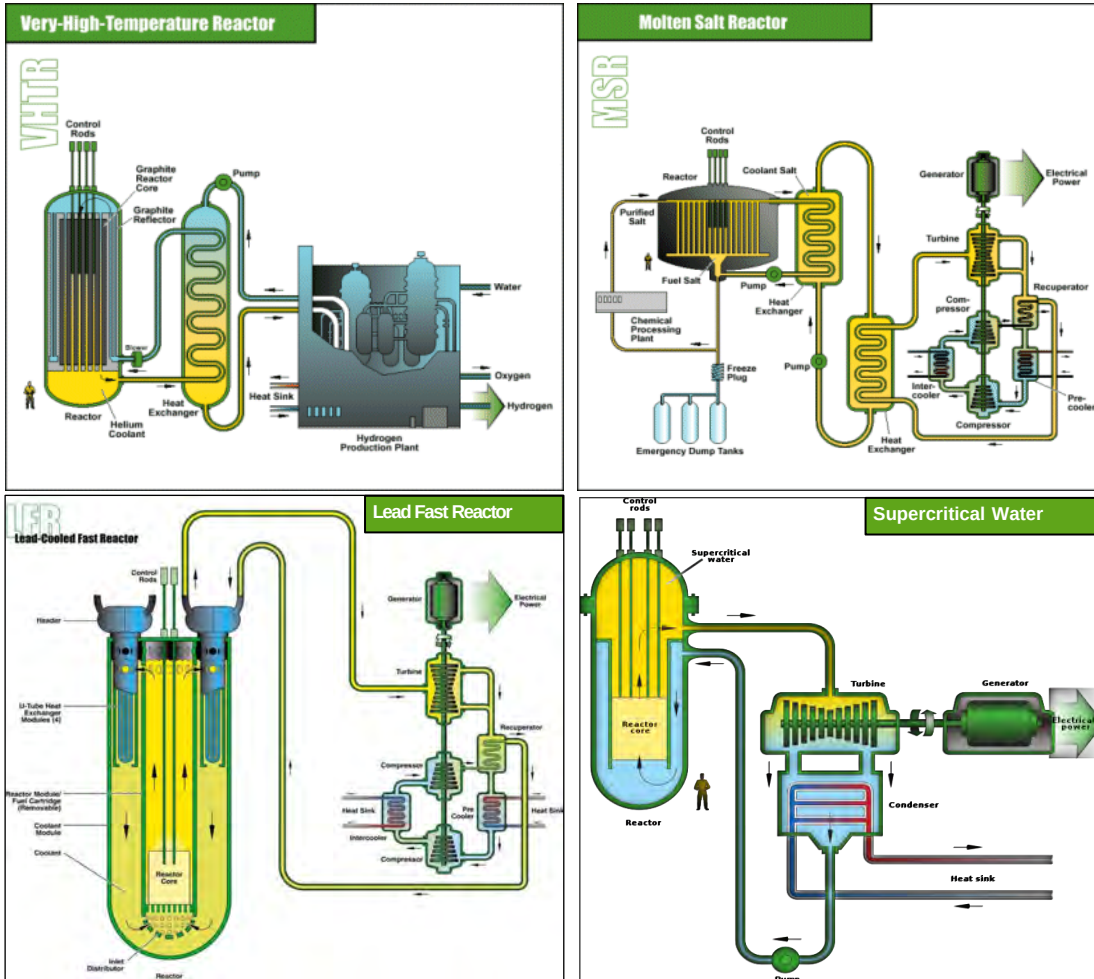
Supports SMRs, Gen-IV, and advanced reactor concepts

Primary purpose of RELAP5-3D is to model entire nuclear reactor systems



- Types of reactors by fluids:
 - Light Water Reactor (LWR)
 - Pressurized Water Reactor (PWR)
 - Boiling Water Reactor (BWR)
 - Heavy Water Reactor (HWR) such as CANDU
 - High Temperature Gas-cooled Reactor (HTGR)
 - Supercritical Water and Supercritical CO₂
 - Liquid Metal Reactor (LMR)
 - Molten Salt Reactor (MSR)
- RELAP5-3D/Version 4.5.2 has 31 fluids available

Primary purpose of RELAP5-3D is to model entire nuclear reactor systems



- Types of reactors by size/function:
 - Generation I, II, III, and IV reactors
 - Small Modular Reactors (SMR)
 - Microreactors
- Recent Examples
 - mPower, another DoD reactor (BWXT)
 - NuScale
 - Sodium (TerraPower)
 - SMR-300 (Holtec)
 - MARVEL and PCAT (DOE)
 - ATR

RELAP5-3D Success Stories (few examples..)

NuScale used RELAP5-3D extensively to model the VOYGR module's integral primary system

- Natural Circulation: Demonstrated passive decay heat removal without any pumps or active systems
- **Key Result**: NRC Design Certification Approval (2022) — first SMR certified in the US

Westinghouse AP1000 & AP300: Key Results

RELAP5-3D was the primary tool for **AP1000 passive safety system qualification** and is being used for AP300 SMR design.

Space Nuclear Applications

The Kilowatt Reactor Using Stirling Technology (KRUSTY) test (2018) provided the first space fission reactor test in the USA since SNAP-10A (1965). **RELAP5-3D predictions matched experimental data.**

Simulation of thermal-hydraulic systems in microgravity and analysis of space reactor designs for power and propulsion.

Why is RELAP5-3D Industry Standard

-  30+ Years of Continuous Development to further enhance V&V database
-  Validated against 50+ separate-effects and integral-effects facilities worldwide
-  Regulatory acceptance in the USA (NRC), Europe (IAEA endorsed), and Asia

Advancing Nuclear Technology Across Industries

Our Group Currently Supports (To name a few..)

- SMR 300 Holtec Project (DOE ARDP Program) – R5 CGD
 - Small Modular Reactor integral and separate effects test for Holtec
- DOE Microreactor Program
 - Thermal Hydraulic test on MARVEL integral test facility PCAT
- Simulation support to Irradiation Experiment (NaCl- UCl_3) fuel salt capsule
- Engineering support for MCRE
- Supporting engineering design for MITRX(MITR) and National Bureau of Standard Reactor (NBSR) conversion fuel
- TCF with EPRI on RELAP5-3D coupling with MOOSE (last FY)
- RELAP5 analysis work (supporting tasks for Holtec, Terra Power (MCRE & Natrium) & BWXT)
- Advanced Test Reactor operations and irradiation experiment engineering that combines RELAP5-3D and CFD
- TREAT sodium loop experiment for TerraPower
- Light Water Reactor Sustainability project to extend the life of existing light water plants.
- Thermal Analysis for Lightbridge (supporting the new fuel design concept)
- Working closely with our colleagues at Naval Nuclear Labs
- Working closely with other national laboratories and research organizations

In Summary..

- INL is playing a vital role in supporting conventional fleet and development and deployment of advanced reactor technologies.
- In nut-shell why RELAP ?
 - Comprehensive thermal-hydraulics capabilities
 - High-fidelity transient and accident analysis
 - Broad adoption by reactor vendors and other industries
 - Strong validation and credibility
 - Extensive experimental benchmark comparisons
 - International collaboration validation suites
 - Expanding applications in space nuclear systems
- Call to Action:
 - **Learn more about RELAP5-3D and how it can support your respective projects.**

Accelerating advanced reactor demonstration and deployment





INL

Idaho National Laboratory