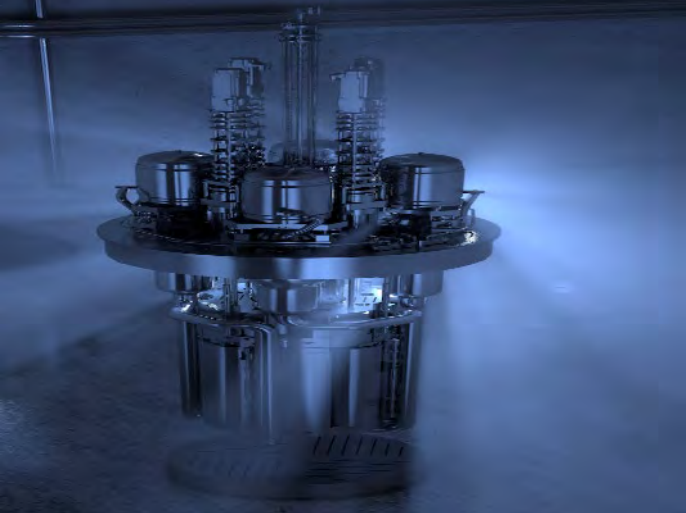
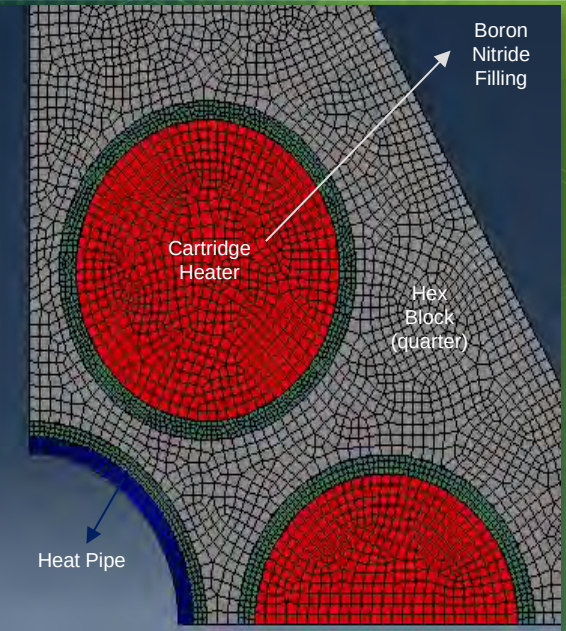
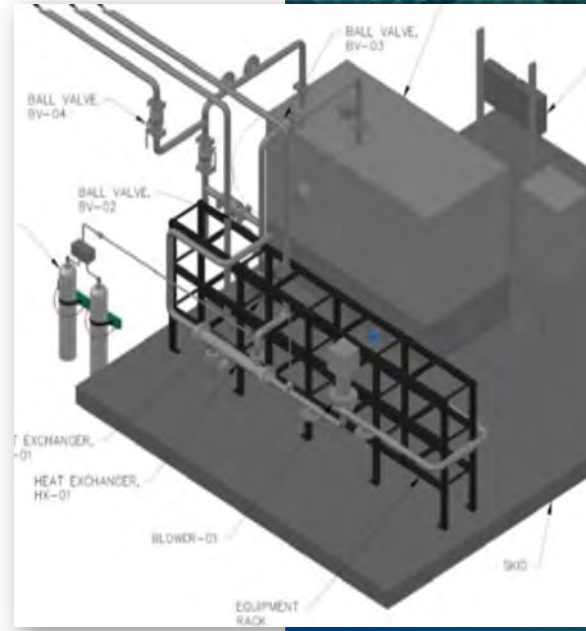
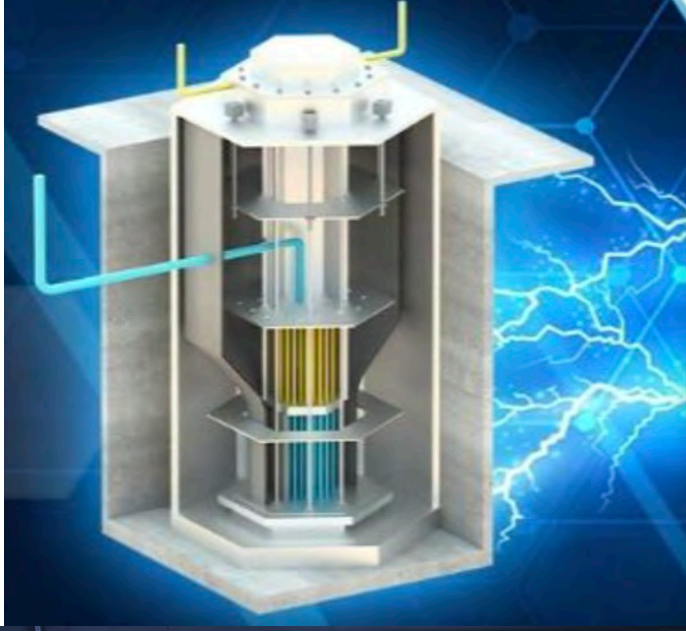




HI-TEST: Accelerating SMR Readiness with Comprehensive Effects Testing

INL/MIS-26-92276

May 20th, 2026

International RELAP5 User Group Meeting 2026

May 18–21, 2026 | Idaho Falls, Idaho



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Outline

- Reactor Evolution Map
- Active and Passive Safety
 - LWR's
 - Gen III & Gen III+ Reactors
 - Inherent/Passive Safety
- SET & ISET – Design and Development
- SET & ISET – Current Status
- Conclusions

Nuclear 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

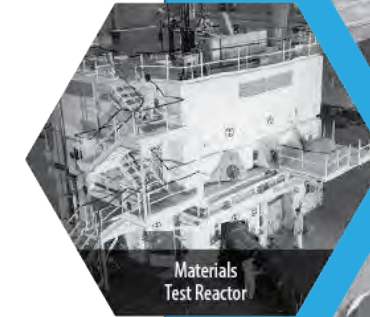
Mobile nuclear power plant for the army

Demonstration
of self-sustaining
fuel cycle

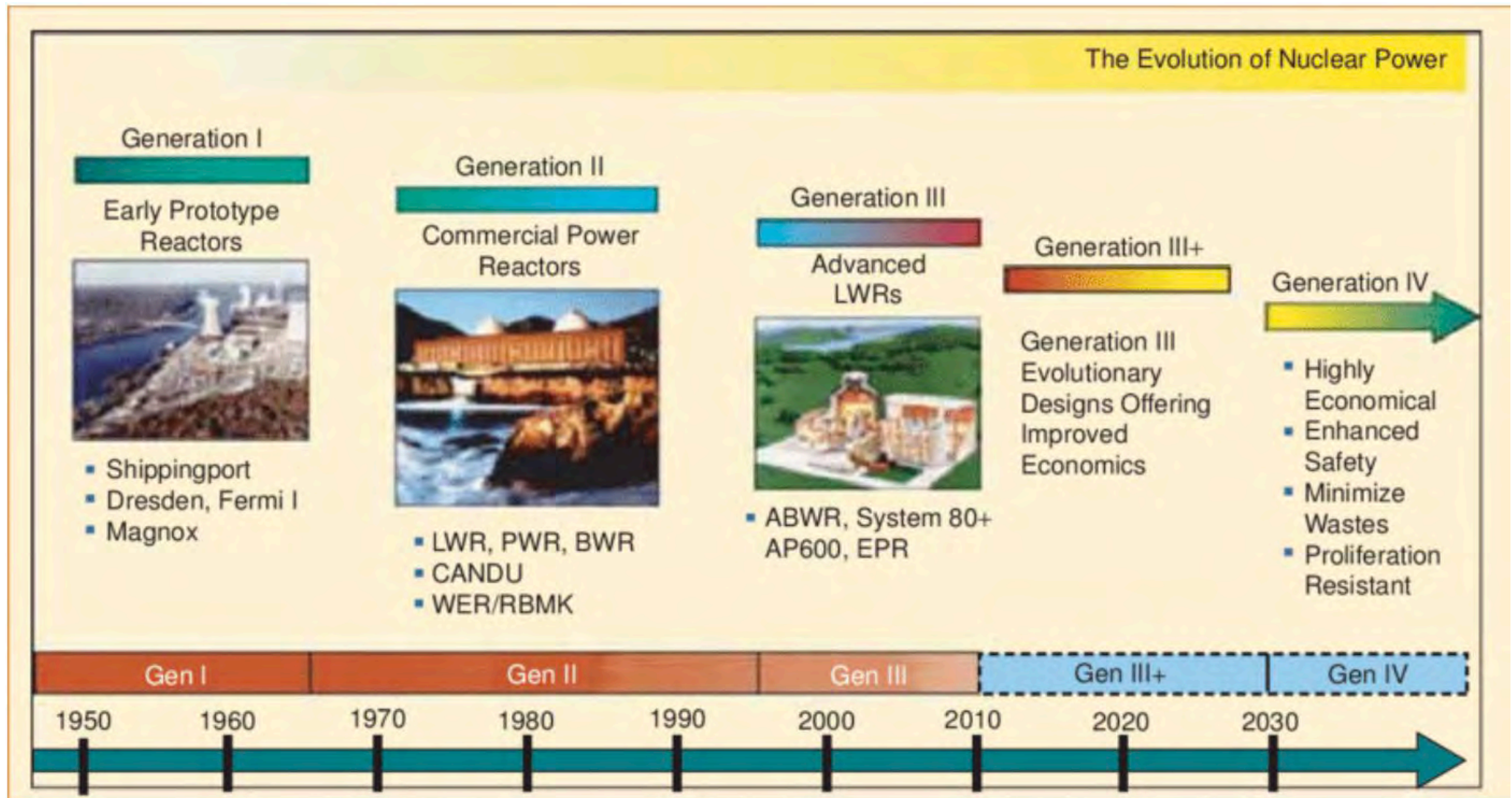
Basis for LWR
reactor safety

Aircraft and
aerospace
reactor testing

Materials
testing
reactors



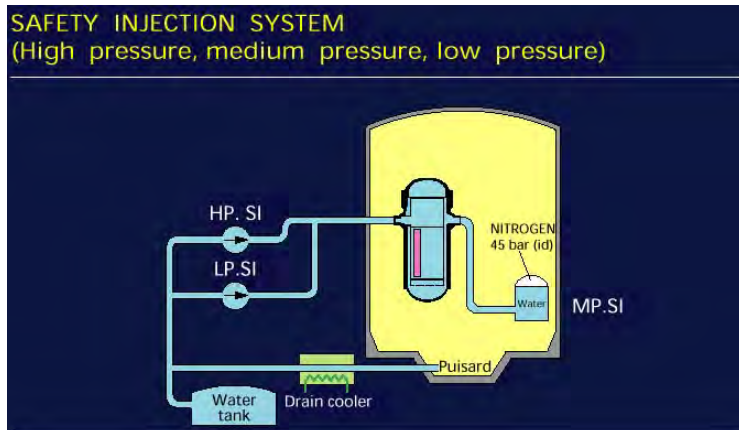
Reactor Evolution



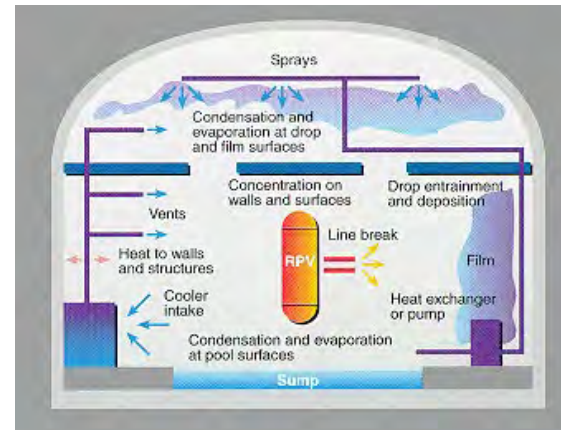
Active Safety Systems in Conventional LWRs

Various safety system acts to keep fuel covered all the time, carry decay heat away, and maintain containment barrier.

- **Reactor Protection System (RPS) – Control rod injection**
Instantly inserts control rods to stop the chain reaction
- **Emergency Core Cooling System (ECCS)**
High-Pressure & Low-Pressure Injection Pumps push borated water into the core
- **Containment Spray**
Motor driven pumps spray cool water to lower containment pressure



Emergency Core Cooling Systems (ECCS)
<https://www.nucleartourist.com/systems/eccs.htm>



Containment Pressure Control Methods
<https://www.nucleartourist.com/systems/cs.htm>

Passive Safety System (During Normal Operation)

- Passive safety implies that safety mechanisms can perform their duty **without** human intervention or the requirement of external work input
- Passive safety system ensures control over the reactor feedback behavior
- A quantitative feedback coefficient can be used to determine how the reactor power will change with respect to a certain parameter
 - Fuel Temperature Feedback Coefficient (α_T): how reactivity changes with fuel temperature
 - Void Coefficient (α_v): how reactivity changes if the ratio of vapor to liquid in the core changes
 - Moderator Temperature Feedback Coefficient (α_M): how reactivity changes with moderator temperature
 - Pressure Feedback Coefficient (α_p): how reactivity changes with reactor coolant system pressure
- In general, all feedback coefficients should be **negative**

Negative feedback generally promotes stability in a system by opposing changes in the output, preventing oscillations and runaway behavior.

Passive Safety System

Passive safety system is a nuclear safety feature that **works without electric power or operator actions** to bring the reactor to safe shutdown state, in event of a particular type of emergency

- Gen III + reactors uses passive mechanisms for core cooling and pressure control.
- **Active vs. Passive Safety System**
Both aim to control reactor safety under normal and non design basis conditions with three fundamental safety goals: keeping the fuel covered, removing decay heat, and maintaining the containment barrier.

	Active System	Passive System
Driving Force	Electric pump and valves which requires AC electricity.	Natural forces such as gravity, natural circulation, pressure difference.
Strength	Easy to handle large reactors.	Reliable, low chance of human error.
Weakness	Complex design for redundancy and diversity.	Hard to scale for large output

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



SET & ISET Design Approach

- Reg Guide 1.203 used for evaluation model (EM) development
- Phenomena Identification and Ranking Tables (PIRTs)
 - LOCA and Non-LOCA PIRTs provide high ranking phenomena and identify experimental needs
 - Existing Integral and Separate Effects Test (ISET) facilities provide a knowledge base for many phenomena identified in PIRTs
- SMR-300 ISET facilities needed to support EM development
 - Supplements gaps from existing ISET facilities
 - Supports design basis testing
- Evaluate integral effects test (IET) distortions and separate effects test (SET) scaleup capability

HI-TEST – Holtec INL Thermal Effects Separate Test Facility

- Determine uncertainties in ISET facilities

SMR-300 ISET Facilities

- Idaho National Laboratory (INL) to construct and operate IET and SET facilities to support design and licensing needs for Holtec SMR 300
- IET Facility
 - Consists of reactor coolant system (RCS), OTSG, and passive safety systems
 - Will run several experiments to adequately assess safety system performance and important phenomena
- OTSG SET Facility
 - OTSG in IET not sufficient for all experimental objectives due to size
 - OTSG SET will support design basis performance and EM development

IET Scaling Approach

- Hierarchical Two-Tiered Scaling (H2TS) method used to develop similarity criteria to scale systems and processes
 - Top-down analysis identifies dominate processes and characteristic time ratios at the system level
 - Bottom-up analysis identifies key processes to obtain similarity criteria at the local levels
- Development of system scaling factors for ideal IET facility
 - Conservation of natural circulation is used for the balance equations
 - Assumptions and constraints are applied to derive the non-dimensional ratios
 - Geometrical ratios are derived to preserve the similarity between Model and Prototype
 - Maintain fluid property similitude

IET Scaling

- One-dimensional single-phase natural circulation momentum equation (Boussinesq Approximation)

$$\rho_0 \frac{du_0}{dt} \sum_{i=1}^n L_i \left(\frac{A_0}{A_i} \right) = \beta g \rho_0 (T_H - T_C) L_{TC} - \frac{\rho_0 u_0^2}{2} \sum_{i=1}^n \left(\frac{fL}{D_h} + k \right) \left(\frac{A_0}{A_i} \right)^2$$

- For steady-state, buoyancy force equals the friction force

- Richardson Number = $\Pi_{Ri} = \frac{\beta g (T_H - T_C) L_{TC}}{u_0^2} = \frac{\text{Bouyancy Force}}{\text{Inertia Force}}$

- Friction Number = $\Pi_{Fri} = \frac{1}{2} \sum_{i=1}^n \left(\frac{fL}{D_h} + k \right) \left(\frac{A_0}{A_i} \right)^2 = \frac{\text{Friction Force}}{\text{Inertia Force}}$

- Similarity Criteria = $\left(\frac{\Pi_{Ri}}{\Pi_{Fri}} \right)_R = 1$

- Power Relation = $(u_0^3)_R = \left(\frac{\beta g Q_{core} L_{TC}}{\rho A_0 c_p \Pi_{Fri}} \right)_R$

- Similarity criteria verified for two-phase natural circulation

OTSG SET Scaling Approach & Scaling Distortions

- Scaling of OTSG SET is based on power to volume scaling
 - OTSG SET is full height and uses prototypic tubes
 - SMR-300 primary side power to volume ratio is maintained
 - SMR-300 secondary side power to volume ratio is kept as close as possible to minimize distortions
- Distortions are a result of
 - Scaling
 - Differences between ideal and as-built facility
- Distortions will be calculated while performing H2TS methodology
- Distortion analysis will be performed based on the IET and prototype response to specific events
- Distortions may be accounted in the safety analysis or dispositioned based on magnitude and impact on the phenomena

Scaling Summary

- PIRT process provides the high-ranking phenomena, and existing experimental database is used to identify the gaps/needs for the IET/SET facility design and testing.
- Well established methodologies are used to perform scaling analysis for IET/SET.
- Geometrical scaling factors are calculated based on the natural circulation scaling method, time scale, fluid property similarity.
- Distortions will be calculated using H2TS methodology.
- Scaling distortions will be accounted for in the safety analysis methodology as appropriate

Holtec SMR-300 Test Loop

- Development split between DOE cost-share ARDP with \$4.5M, and Holtec direct funding at \$5.3M currently at INL
 - Large scale construction to support test loop deployment at IEDF (INL Building in Idaho Falls)
 - Development of the Integral and Separate Effects test loop to support RELAP5-3D validation.
- Additional \$5M of Holtec Funding and \$1.5M of FY25 DOE Funding
 - Fabricate and install piping, instruments, and support equipment.
 - Install Holtec provided vessels: Reactor Pressure Vessel, Steam Generator, Etc.
 - Testing
- High Level Schedule of Work at INL:
 - Years 1-3: Complete (FY23 – FY25)
 - Scaling analysis for integral and separate effects facility
 - Test Loop Design & Begin building and Infrastructure Modifications
 - Year 4: Fabrication and Installation of Test Loop (FY26)
 - Building Modifications complete
 - Test loop fabricated and installed
 - Years 5+Testing (FY27+)



Evolution of Holtec Design

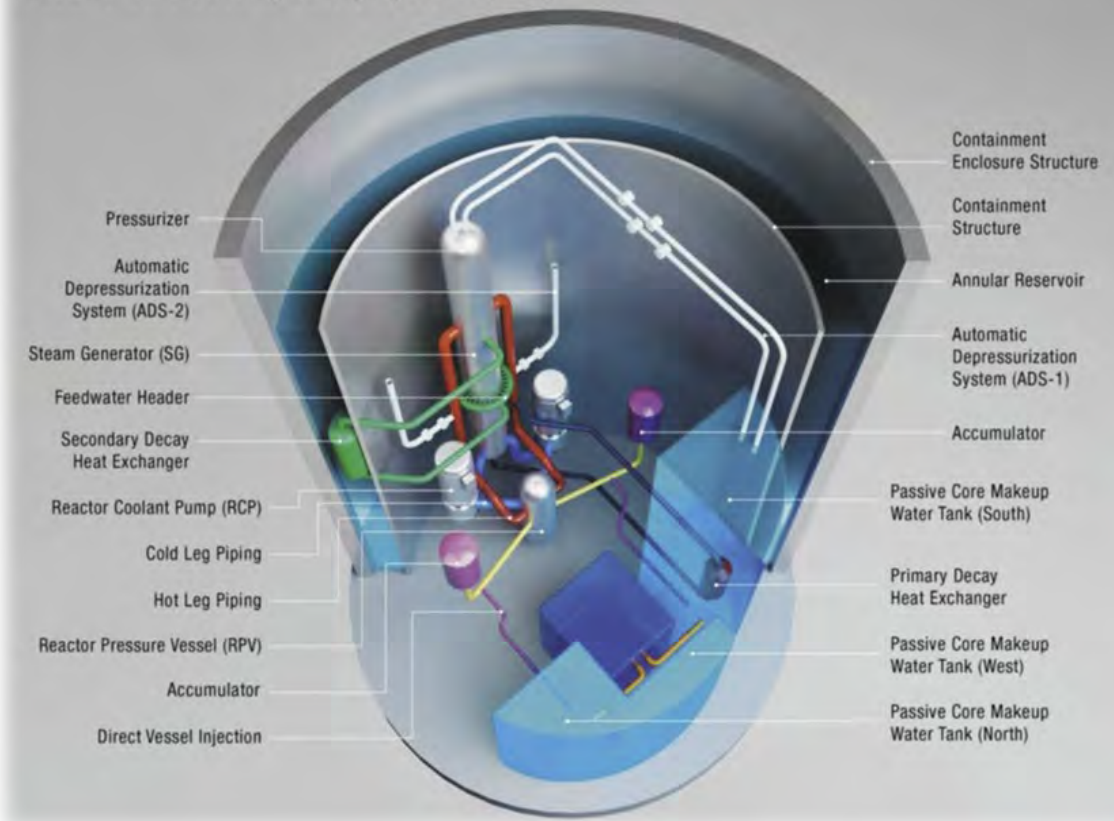
Evolution of Holtec Design

- Reduced design and licensing risk, improved schedule certainty, and increased regulator review speed
- Designed for 80 years of operation
- Primary Decay Heat (PDH) removal heat exchanger moved to pool inside containment

Power Upgraded: SMR - 300

- 300 MWe of electric power generation, with 1050 MWth power, upgraded from previous design to meet market demand
- Two-loop PWR with hot and cold leg piping between RPV and once-through steam generator (OTSG)
 - Removal of need for heavy forging between vessels
- RCS operation includes use of two Reactor Coolant Pumps (RCPs) for forced convection through core and steam generator
- OTSG replaces the Integral Economizer OTSG
 - This removes the central riser and aligns with Babcock & Wilcox standard design

Passive Core Cooling Safety Systems (PCC)



Gen III+ Passive Safety Systems

- Design approach for nuclear reactors to shut down the reactor without operator intervention
- Utilize physics principles to reduce reliance on active components
 - Allows for redundant and diverse methods of system activation without greatly increasing cost or complexity
- A common approach is positioning supplemental emergency coolant pools above the elevation of the fuel to allow gravity to assist in keeping the fuel covered
- Many designs also include direct containment structure cooling, to increase the safety margin on the allowed temperature and pressure bounds
- Key purpose of passive safety is lower core damage frequencies than the Gen I & II reactors which were deployed earlier
 - Integration of passive safety and reduced reliance on active components also has potential to reduce capital costs
- Experiments are often required for novel applications of passive principles to prove reliability in a variety of potential initiating accident conditions
 - Unique system or component geometries can also trigger this requirement for system testing, even when the phenomenon has been successfully applied previously

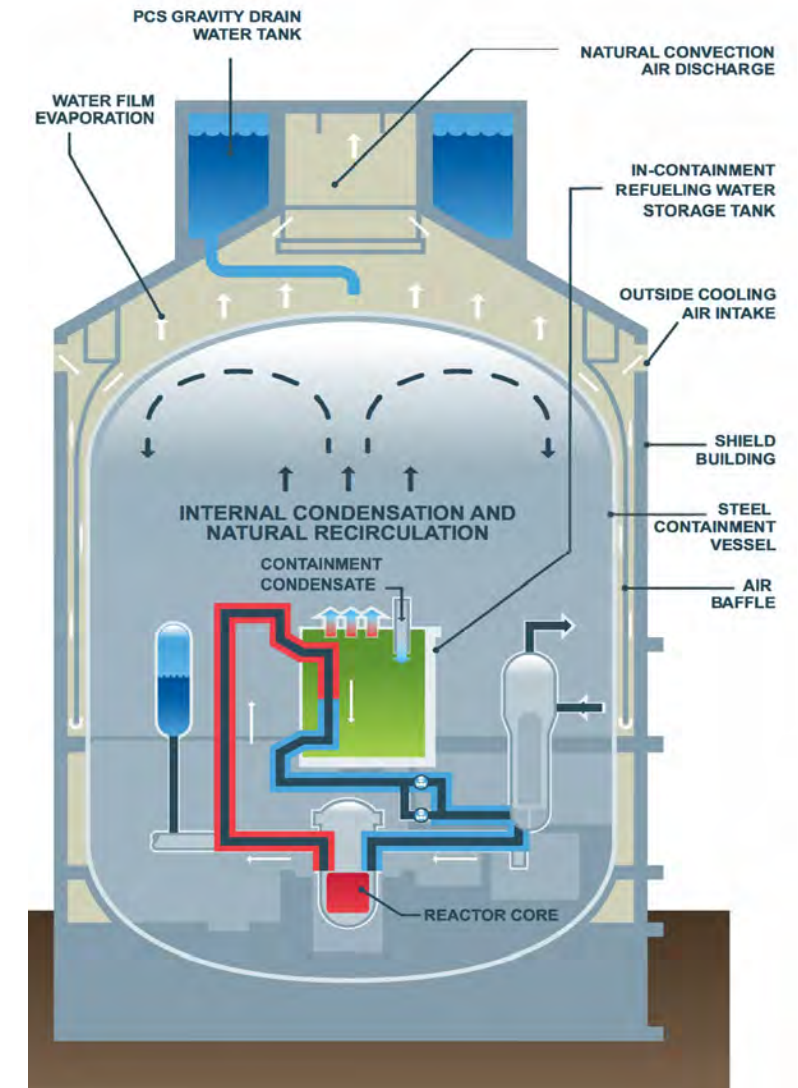


Figure. AP1000 decay heat removal and containment cooling strategy.

IET/SET Hardware Development

- Integral and Separate Effects Test (ISET) facility designed to validate RELAP5-3D model
 - Supporting design basis testing and system/component performance characterization
- Construction ongoing to upgrade supporting infrastructure for the facility:
 - Thickened concrete pad
 - Roof height greatly extended to accommodate full-height steam generator SET
 - Electrical switchgear, transformer, and transmission lines being upgraded to support multi-Megawatt operation
- IET loop to support design basis accident simulation is at temperature, pressure, and 1:1 time scale representation of the prototype
- ISET loops will include approximately 800 data collection instruments to support the evaluation model development and assessment process of Reg. Guide 1.203
- Robust safety culture integrated into facility design maintains operating personnel safety as paramount



Figure. IEDF during infrastructure upgrade.

ISSET Facility Capabilities

- Large non-nuclear thermal hydraulic test facility capable of producing PWR conditions, including:
 - 900-psia steam superheated to ~596°F during normal operation
 - Primary loop of subcooled water at a normal operating pressure of 2250 psia and average temperature of 578°F across the 2-MW electrically-heated core bundle
- Automatic operation of standard PWR engineered safety features, including:
 - 2 stages of Automatic Depressurization Systems, condensed in vessels of water for constant safe operation
 - A Decay Heat Removal system for both the primary and secondary loops
 - Large water volumes with integral cooling supply to simulate injection of makeup water during accidents, as well as provide control of water conditions for test scenarios
 - High-capacity redundant pressure safety valves directed through a manifold to the building roof, protecting operating personnel and facility components from fluid release
- Water chemistry and system durability is maintained using chemical injection and sampling skids, as well as vacuum pumps and deionizer/demineralizer cartridges to minimize dissolved oxygen and impurities, improving system lifespan
- Data Acquisition System includes interface with remote instrumentation cabinets to reduce total loop uncertainty of data collection
 - Remote cabinets are positioned near instrumentation locations to collect sensor signal output. These are then passed to the main instrumentation cabinet with an ethernet cable, narrowing uncertainty bands resulting from long instrument extension wires

SMR Test Loop Building Modifications Underway

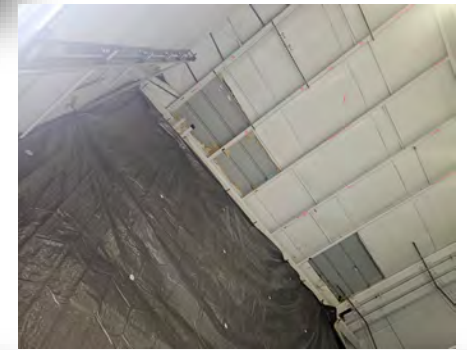
- INL is supporting Holtec's SMR-300 design, safety analysis and building integrated and separate effect test facilities.

(Part of the U.S. Department of Energy (DOE) Advanced Reactor Demonstration project "INL Support for the Holtec ARDP SMR 300")

- Test loop operation considered critical path for SMR-300 deployment
- Significant progress has been achieved for the Holtec SMR Test Loop Building modifications:
- New thickened floor poured.
- Roof penetration to accommodate 40 ft tall components for testing is complete
- Construction is planned to be complete by early Fall of 2025



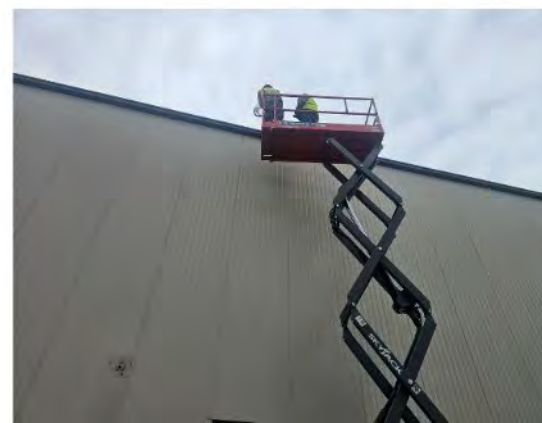
Building Progress: Roof Penetrations in progress to support Holtec SMR Test Loop



Preparing the new floor to meet floor weight requirements

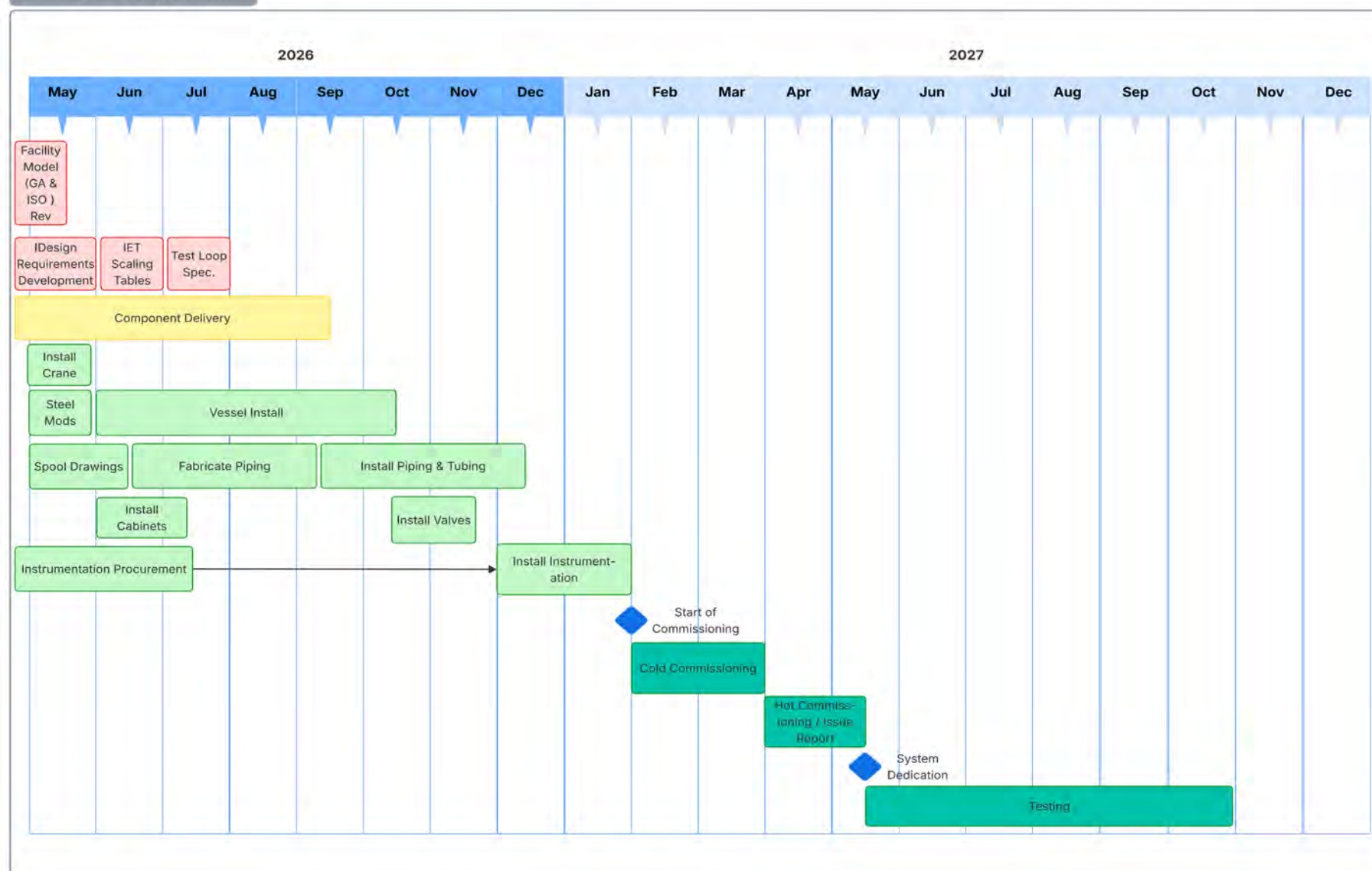
IET and SET Facility Knowledge Gain

- The IET facility will enable design basis testing coupled with the evaluation model (RELAP5-3D) validation process.
 - The RELAP5-3D model will enhance testing performance through pre-test predictive calculations to identify the salient features of the tests
- The SET Steam Generator will primarily focus on performance characterization on the component, utilizing the full height and primary/secondary flow rates scaled to match the number of steam generator tubes for consistency with the prototype design



HI-TEST Project Status

HI-TEST Loop Install

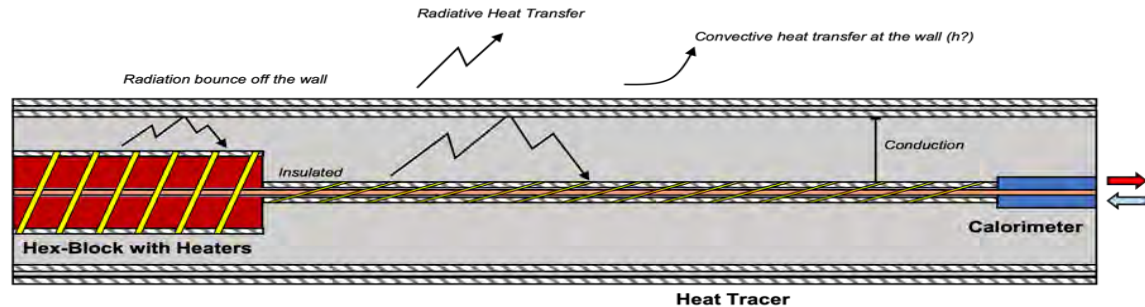


Experimental Test Beds

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

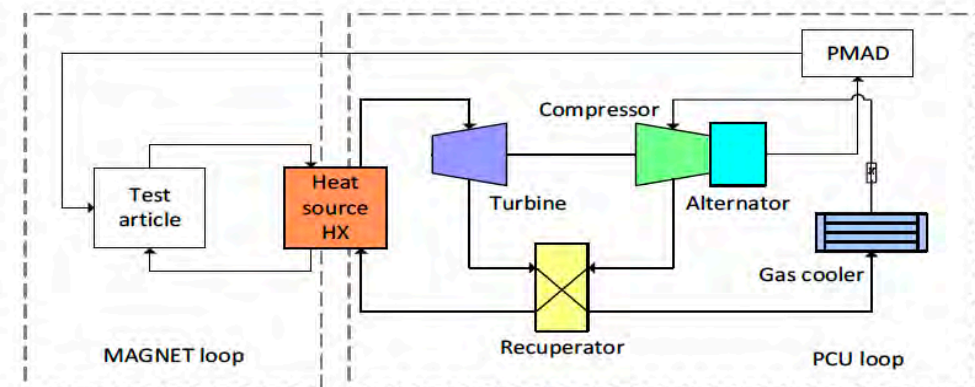
SPHERE Vacuum Chamber

- 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 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

MAGNET Environmental Enclosure



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

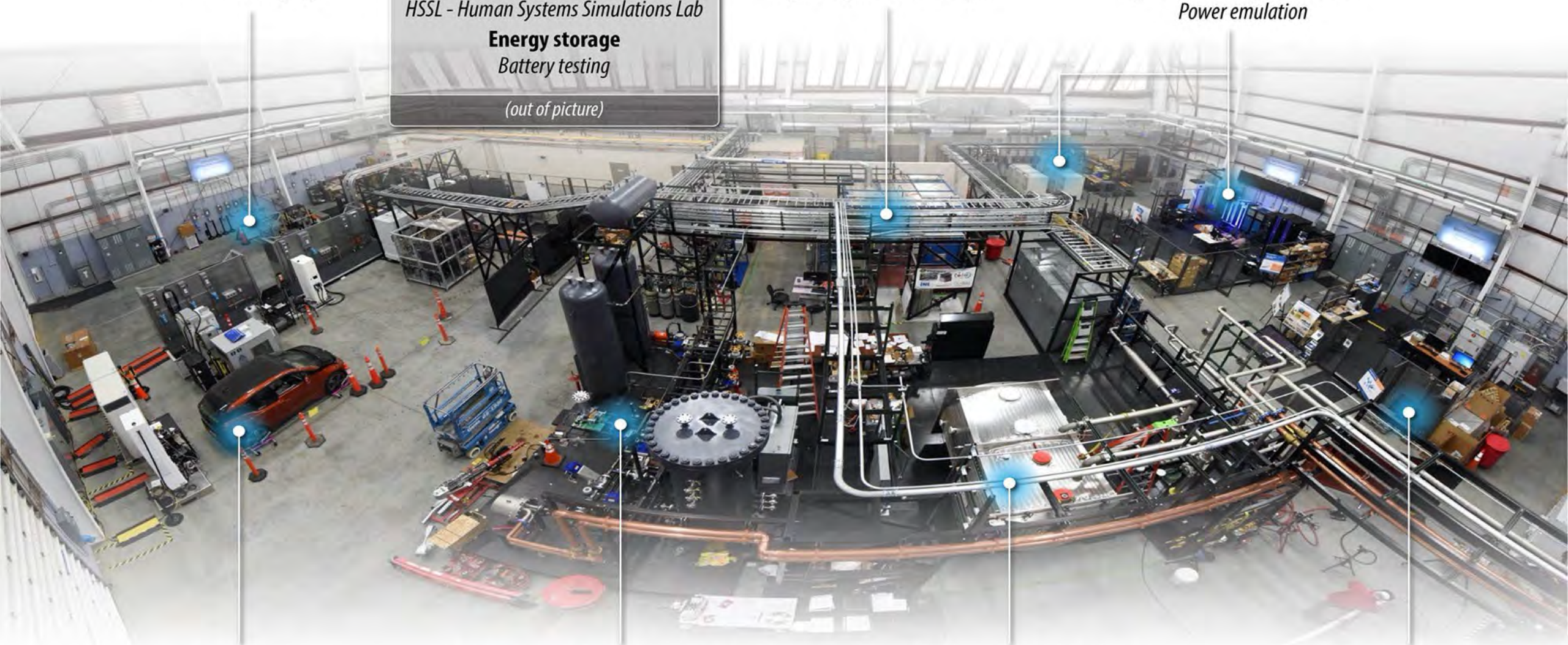
Power systems
Digital, real-time grid simulation
Power emulation

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

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

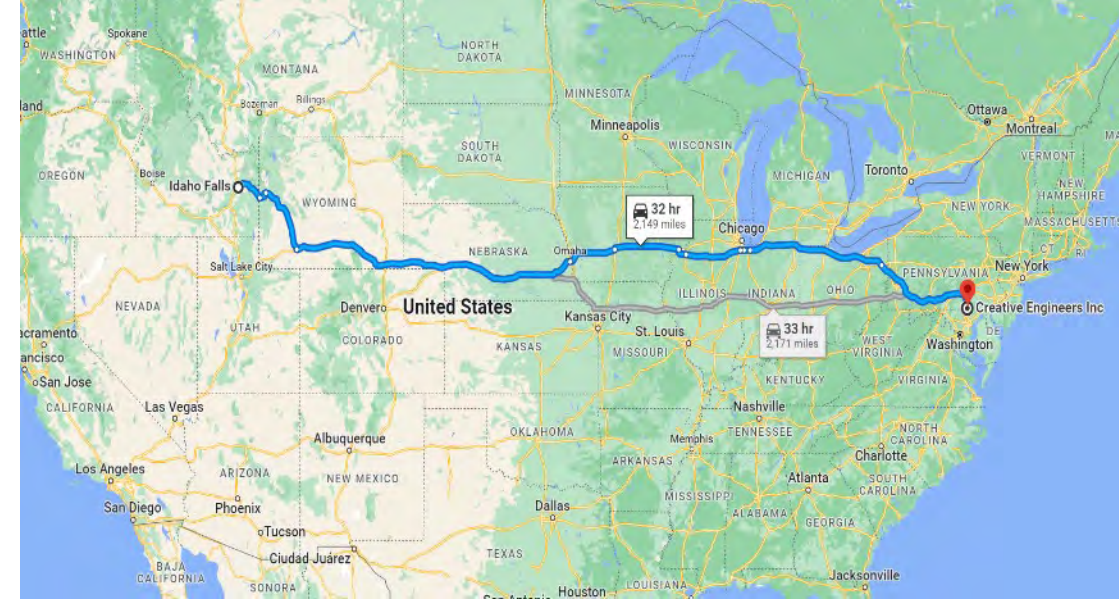
- Inherently safe fuel (UZrH)
- Passive primary coolant circulation
- Natural decay heat removal
- Air-cooled heat rejection

Compact

- ~7.5 metric tons
- <15 feet tall



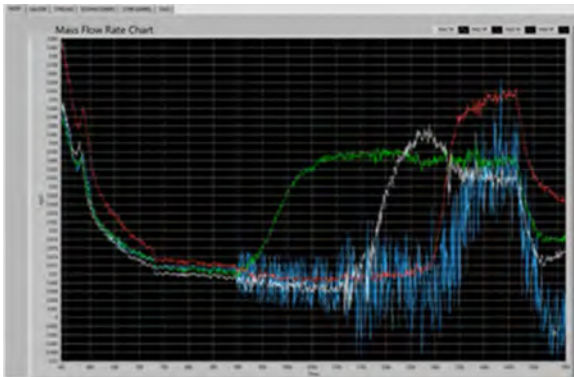
Integral Effects Test – Primary Coolant Apparatus Test (PCAT)





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



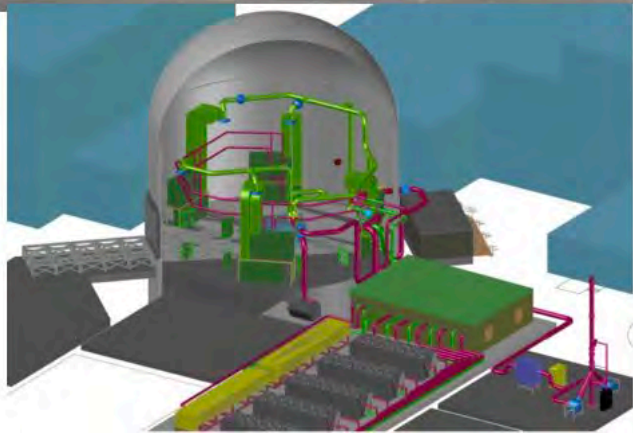
NaK flow measurements through 4 loops



NRIC-DOME Test Bed

(Demonstration of Operational Microreactor Experiments)

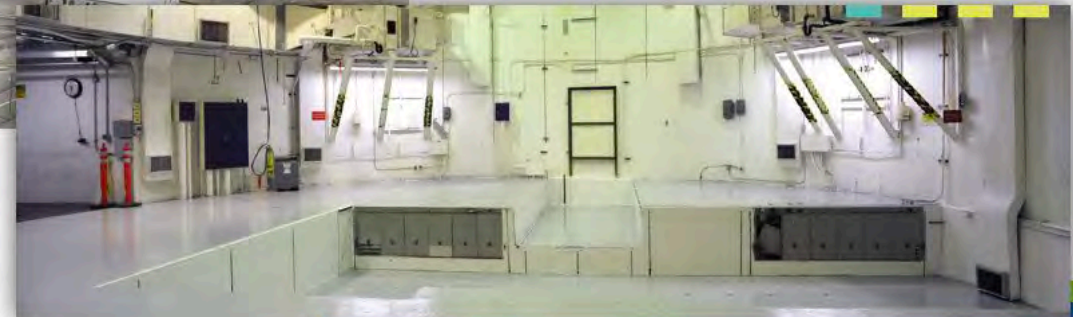
- Test bed for microreactors less than 20 MWt
- Reestablish capabilities of existing infrastructure



NRIC-LOTUS Test Bed

(Laboratory for Operations and Testing in the United States)

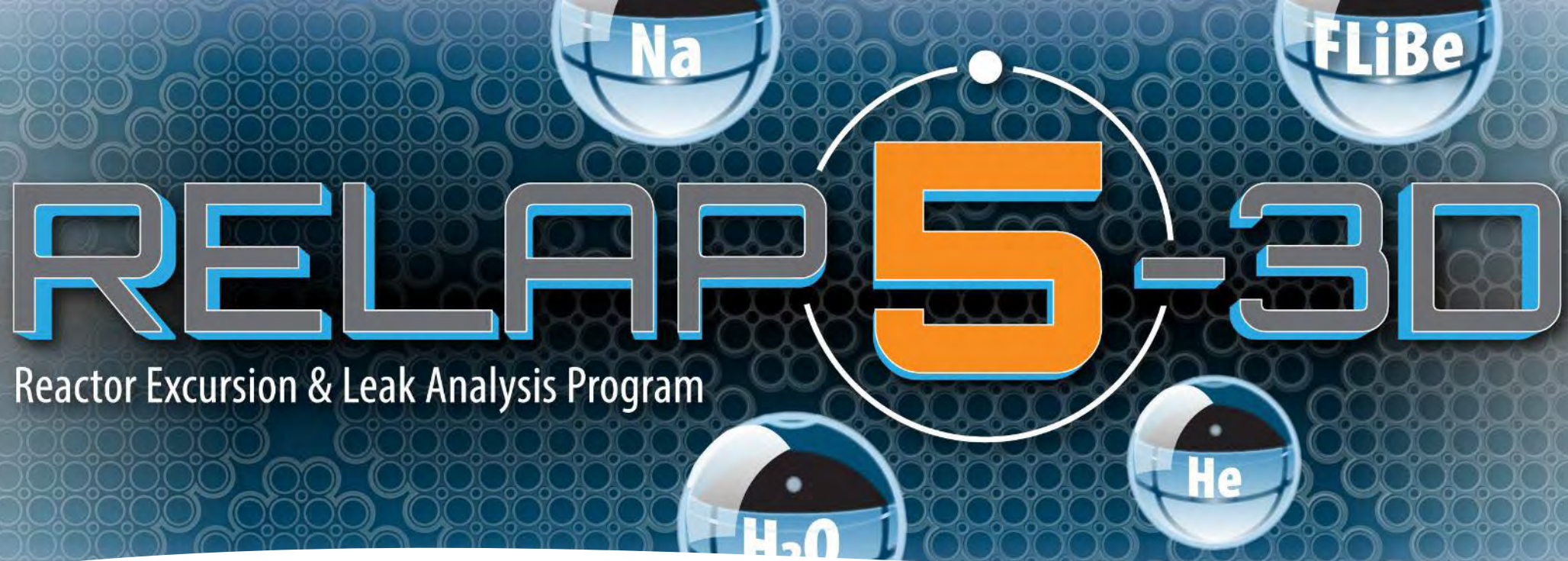
- Experimental test bed with 500kW heat rejection system



IDAHO NATIONAL LABORATORY



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



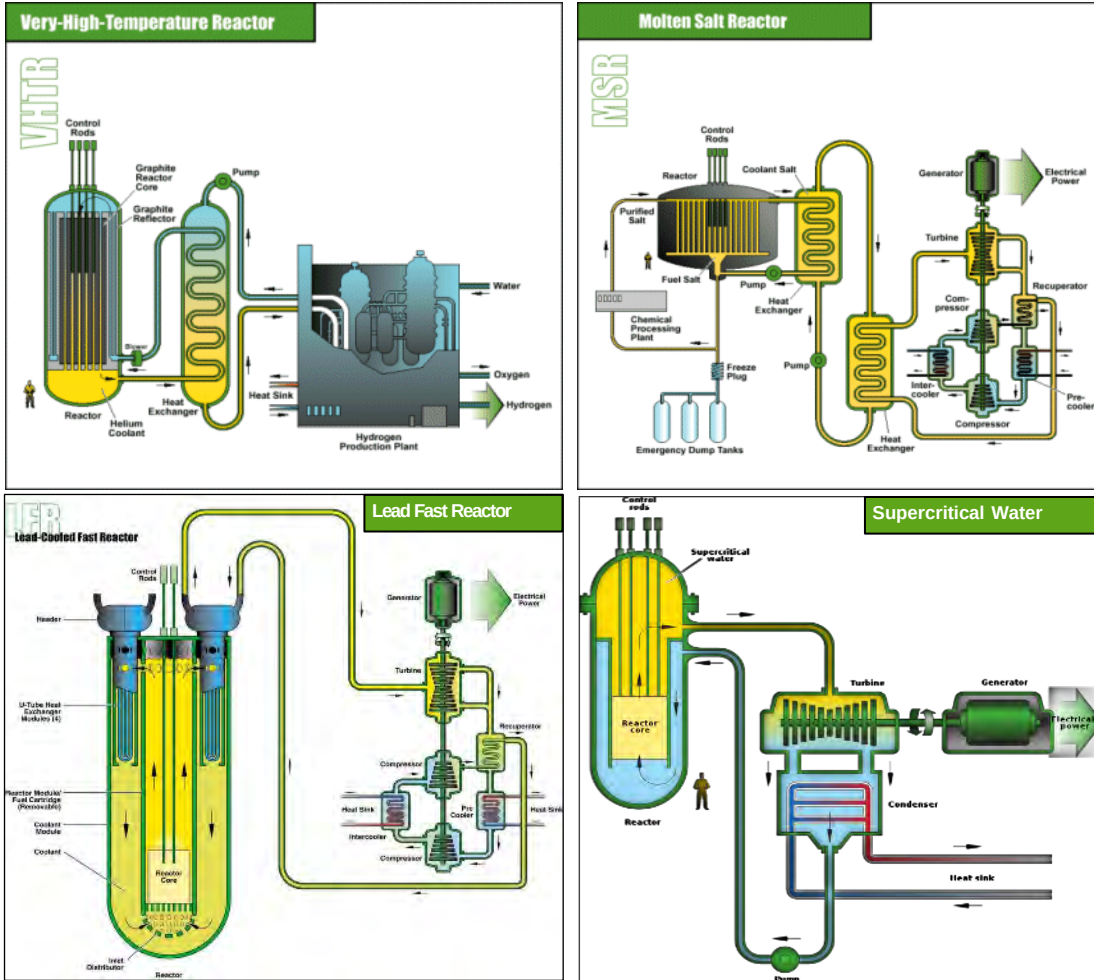
Primary purpose of RELAP5-3D is to model entire nuclear reactor systems

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

Industry standard for thermal-hydraulic simulation

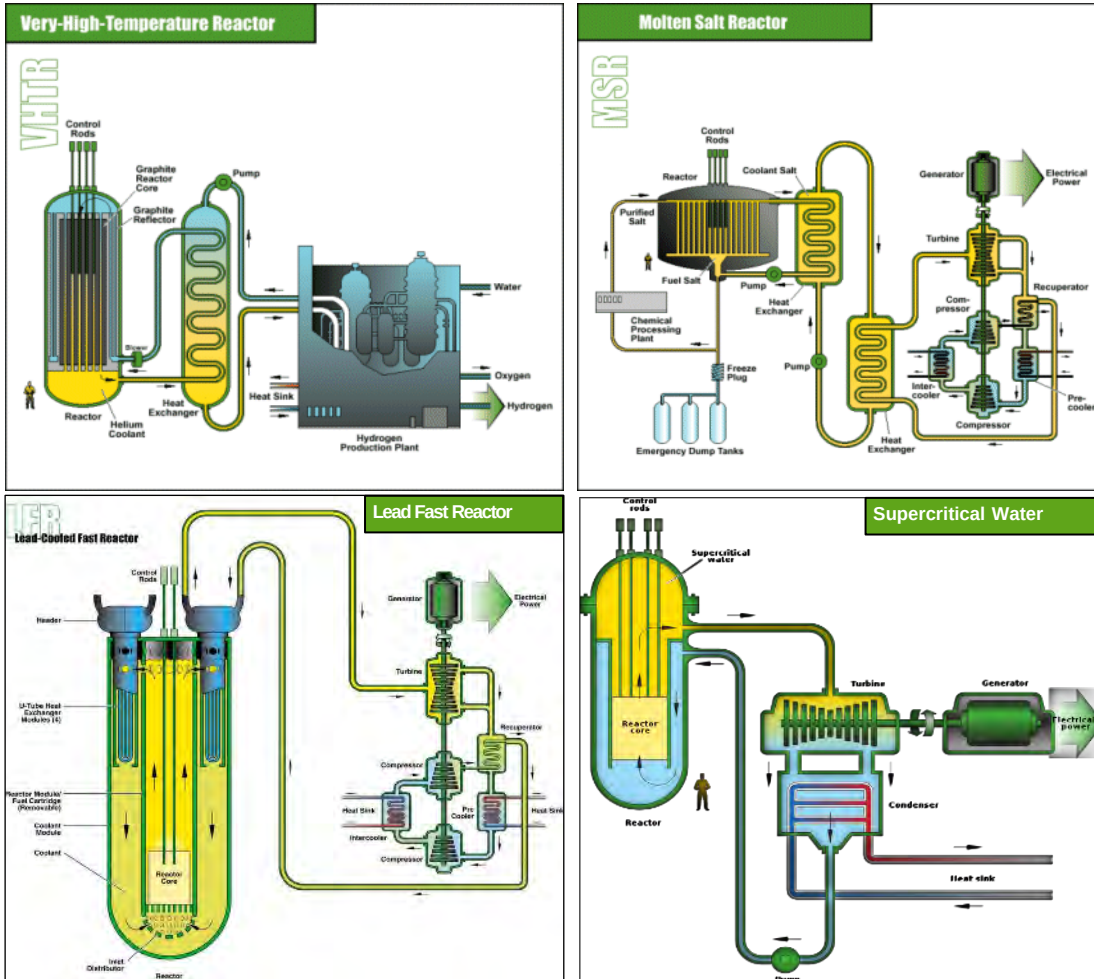
Supports SMRs, Gen-IV, and advanced reactor concepts

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

Accelerating advanced reactor demonstration and deployment





INL

Idaho National Laboratory