INL/MIS-23-72686-Revision-0

Advanced Reactors Development in USA

May 2023

Amy M Boll, William E Windes

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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Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Materials Department
May 2023

Advanced Reactors Development in USA

Small and micro-reactors

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Idaho National Laboratory
Directorate Fellow

Idaho National Laboratory

Why are you listening to me?

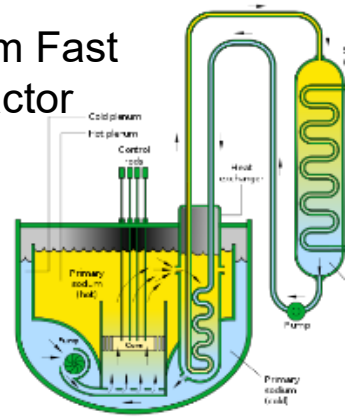
- A peek at the Advanced Reactor programs
  - Biggest news in NE since the 50s-60s
  - INL is the only DOE-NE lab
  - Huge impact on Nuclear Engineering worldwide

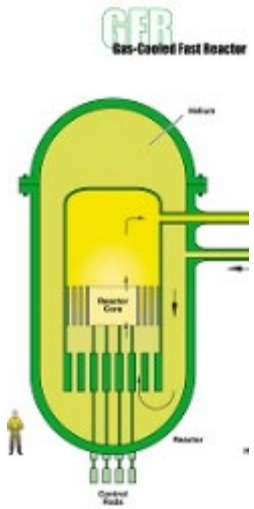
- Nuclear Renaissance
  - What are the GEN IV reactor designs?
  - SMRs and micro Rx designs
  - Multiple commercial reactor designs
  - New construction and operating code rules

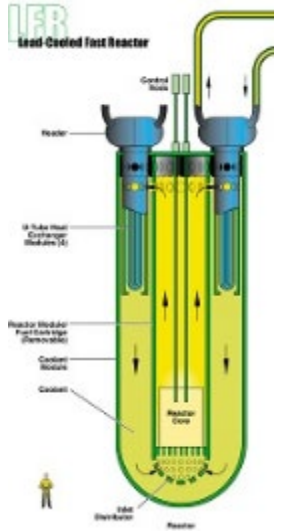
- INL as a test bed facility
  - What does this mean?
  - Who is taking advantage of this?

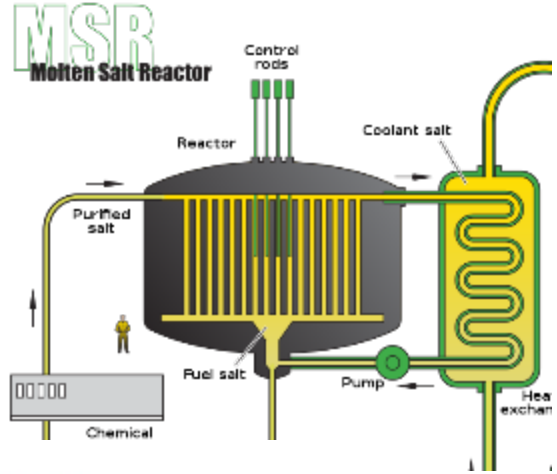
Generation IV Reactor Types

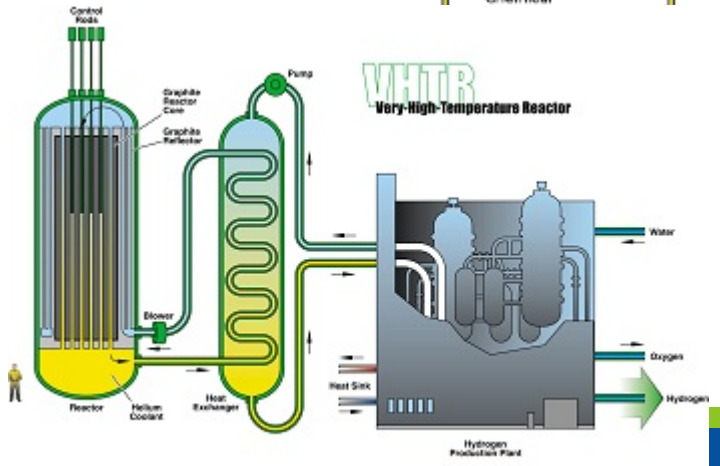
Sodium Fast Reactor







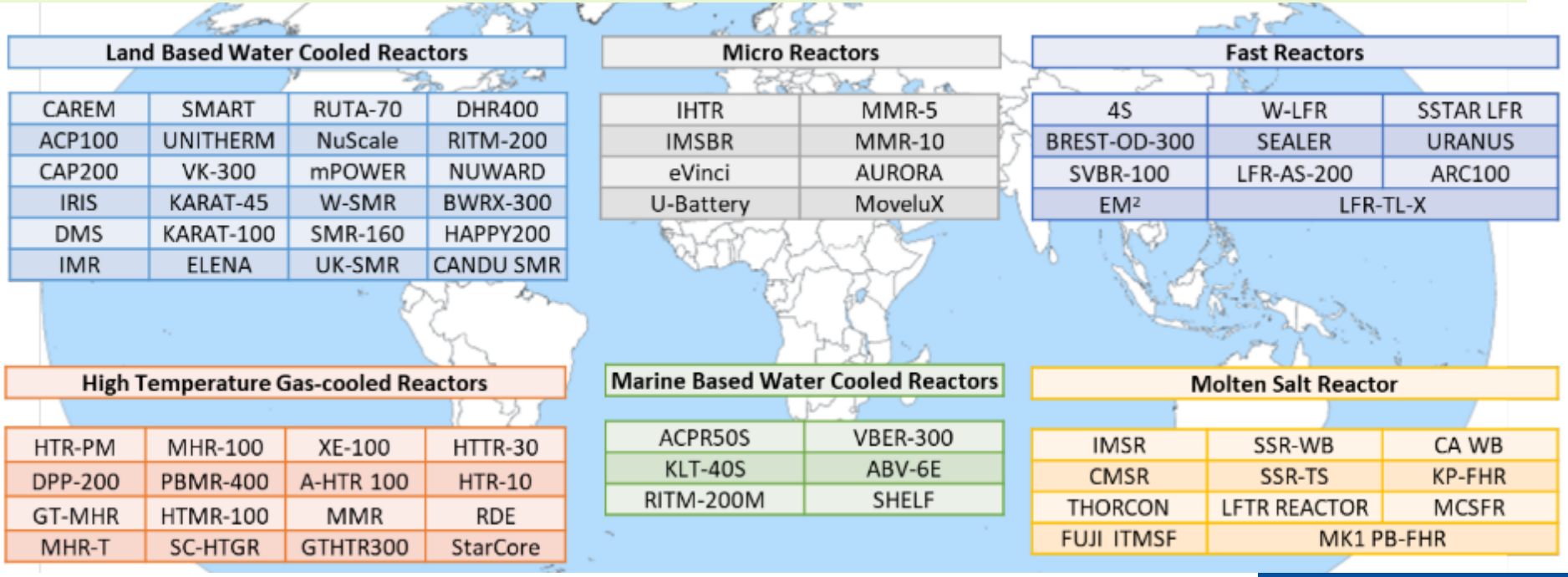




Nuclear Renaissance is here, now

- What started in 2000 as government funded R&D projects has evolved into numerous commercial enterprises
- **Things are moving fast!!**

More than 70 SMR and microreactors projects worldwide under development



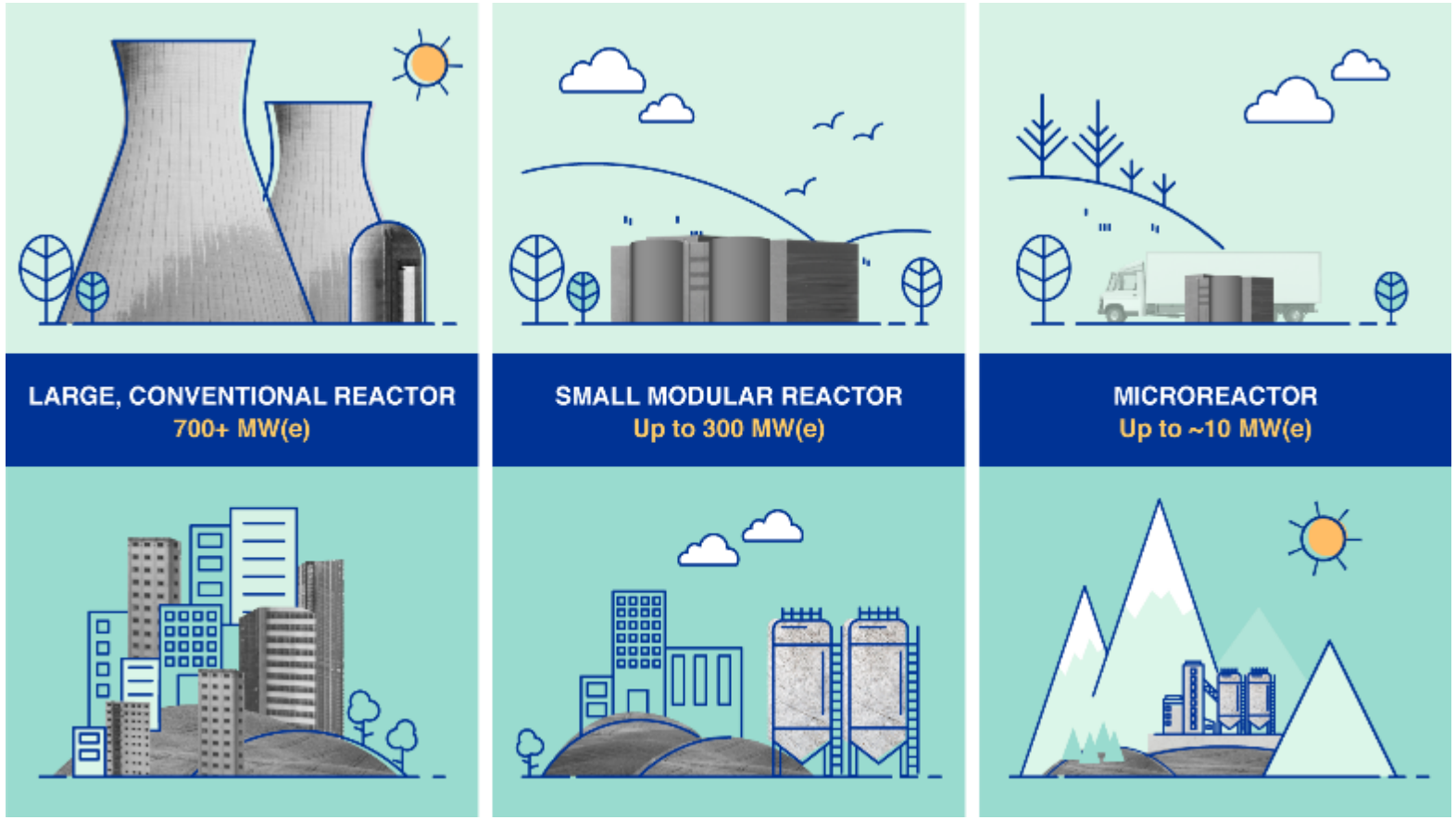
https://aris.iaea.org/

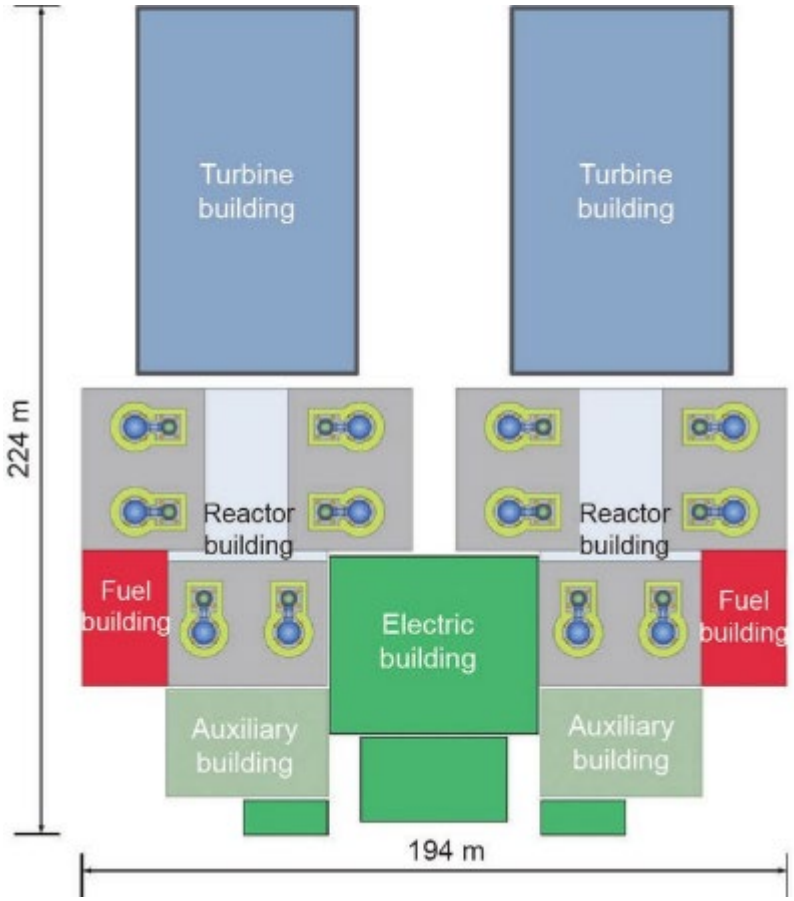
First: some definitions

- **Small Modular Reactors (SMR)**
  - *Just the size but also …*
- **Advanced SMRs (ASMR)**
  - *Size plus new technology*
  - *Inherently safe, natural cool down*
- **Advanced Non-LWR (ANLWR)**
  - *Advanced designs that aren't just down-sized LWR designs*
  - *NRC coined terminology*
- **High Temperature Reactor (HTR)**
  - *Thermal reactors with outlet >300C*
  - *Very high temperature reactors (VHTR)*
  - *Graphite core:*
    - *Gas, molten salt, heat pipe, etc.*
- ***Advanced Reactor Technologies (ART)***
  - *Gas-Cooled Reactor (GCR)*
  - *Molten-salt Reactor (MSR)*

- **GAIN: Gateway for Accelerated Innovation in Nuclear**
  - *It's a portal into the DOE*
    - *Data, Material Test Reactors, Test-bed capabilities, etc.*
  - *GAIN Vouchers: Way to pay for the help*
  - *Run by INL but encompasses whole DOE complex*
    - *INL Test Bed, ORNL test bed, LANL Facilities, PNNL Site*
- **ARDA: Advanced Reactor Demonstration Program**
  - *DOE program to accelerate deployment of ASMRs*
  - *First Technologies:*
    - *Terra Power and X-Energy*
  - *Fast Followers:*
    - *Kairos, BWXT, Westinghouse (eVinci), Holtec, others*
- ***NRIC: National Reactor Innovation Center***
  - *End-to-end assistance (Experience & Data)*
- ***ARPA-E: Advanced Research Projects Agency-Energy***
  - *DOE Program to advance early technologies*

Small Modular Reactors (SMRs)





2 × 600 MWe HTR-PM multi-modules plant:
Same physical size as 1,200 MWe LWR

Left: https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs
Right: "The Shandong Shidao Bay 200 MWe High-Temperature Gas-Cooled Reactor Pebble-Bed Module (HTR-PM) Demonstration Power Plant: An Engineering and Technological Innovation"

Features of Small Modular Reactors (SMRs)

Simplification by Modularization and System Integration

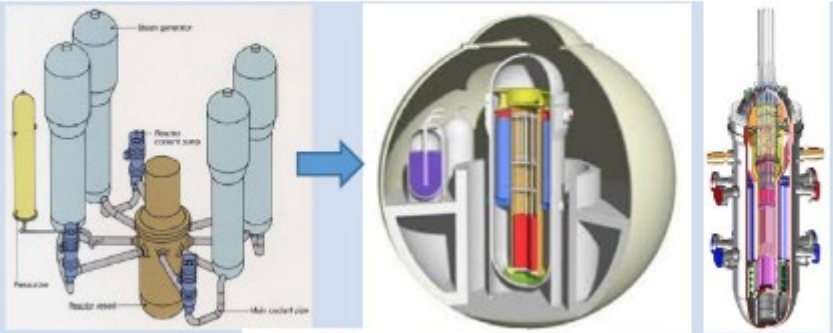


Image courtesy of IRIS 7 .

Multi-module Plant Layout Configuration

Image courtesy of NuScale Power Inc.

Underground construction for enhanced security and seismic

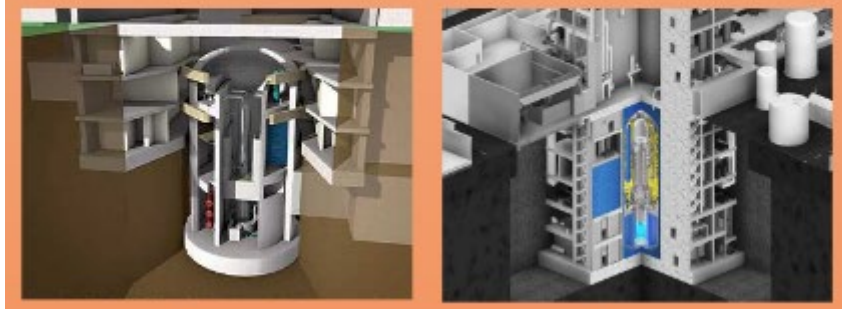


Image courtesy of BWX Technology, Inc.

Enhanced Safety Performance through Passive System

- Enhanced severe accident features
- Passive containment cooling system
- Pressure suppression containment

Image courtesy of BWX Technology, Inc.

Slide credit: Frederik Reitsma (GIF Webinar: Overview of SMR Technology Development, July 2020)

The big boys and girls are now in the game

Companies at CARD 2023

- **Framatome**
- **B&W (BWXT)**
- **Westinghouse**
- **GE / Hitachi**
- **Bechtel**

- And most of the smaller ones were there too …
  - X-Energy
  - Terra Power
  - X-Energy
  - Ultra Safe Nuclear
  - OKLO
  - Radiant
  - BWXT

- **Plenaries by:**
  - **Directors of INL, Westinghouse, Kairos**
  - **Principal Deputy Assistant Secretary, DOE**
- **Reactor Technologies**
  - **3 Sessions over 2 days**
- **Code Development + Harmonization**
- **Modular Construction Panel**
- *Navigating the Nuclear Narrative with Huff Post*

Two main branches of ANLWR development

Thermal HTR

HolosGen™


Ultra Safe Nuclear

Fast Reactor

Some recent developments

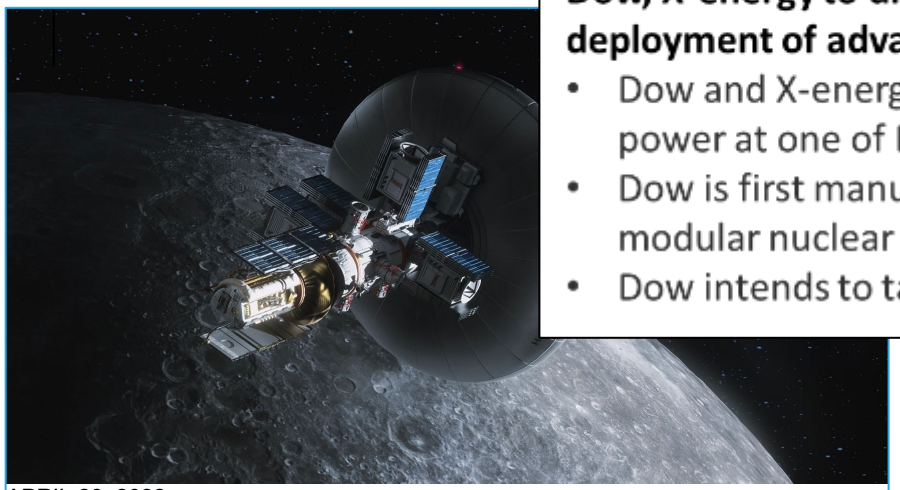
Kairos Power, Los Alamos collaborate to make TRISO fuel 08/12/2022

TRISO fuel pebbles for the Hermes demonstration reactor will be produced at the New Mexico lab's Low Enriched Fuel Fabrication Facility (LEFFF) under a newly announced agreement. This is the first nuclear iteration in Kairos Power's "rapid iterative approach" to nuclear fuel development as well as the first nuclear fuel development campaign for LEFFF.

energy | DOW

Dow, X-energy to drive carbon emissions reductions through deployment of advanced small modular nuclear power

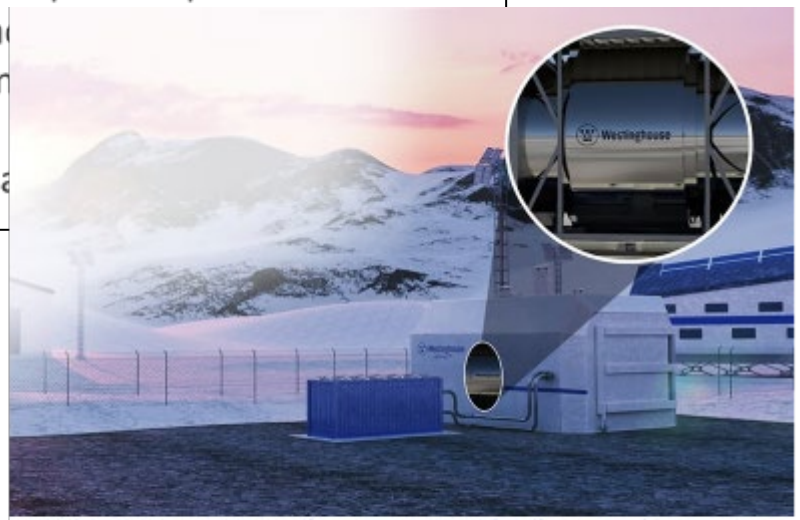
- Dow and X-energy collaborate on intent to provide process heat and power at one of Dow's U.S. Gulf Coast fa
- Dow is first manufacturer to announce in modular nuclear technology options
- Dow intends to take a minority equity sta



APRIL 28, 2022

NASA Selects USNC Advanced Technologies for Ultra-High Temperature Component Testing Facility

Proposed Infrastructure First to Combine Mechanical and Ultra-High Temperature Evaluations



eVinci™ Microreactor Team Closes Out 2022 with Milestone Achievement

January 27, 2023

The microreactor team last month submitted two important topical reports to the Nuclear Regulatory Commission, and 24 white papers during 2022, on critical aspects of the technology and design

INL Site & Infrastructure

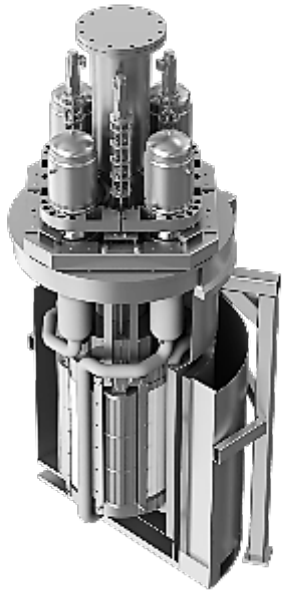
$1,630 M	FY22 Total Operating Cost
5,500+	Employees
569,178	Acres
890	Square Miles

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

Design, Demonstrate, and Deploy Advanced Reactors

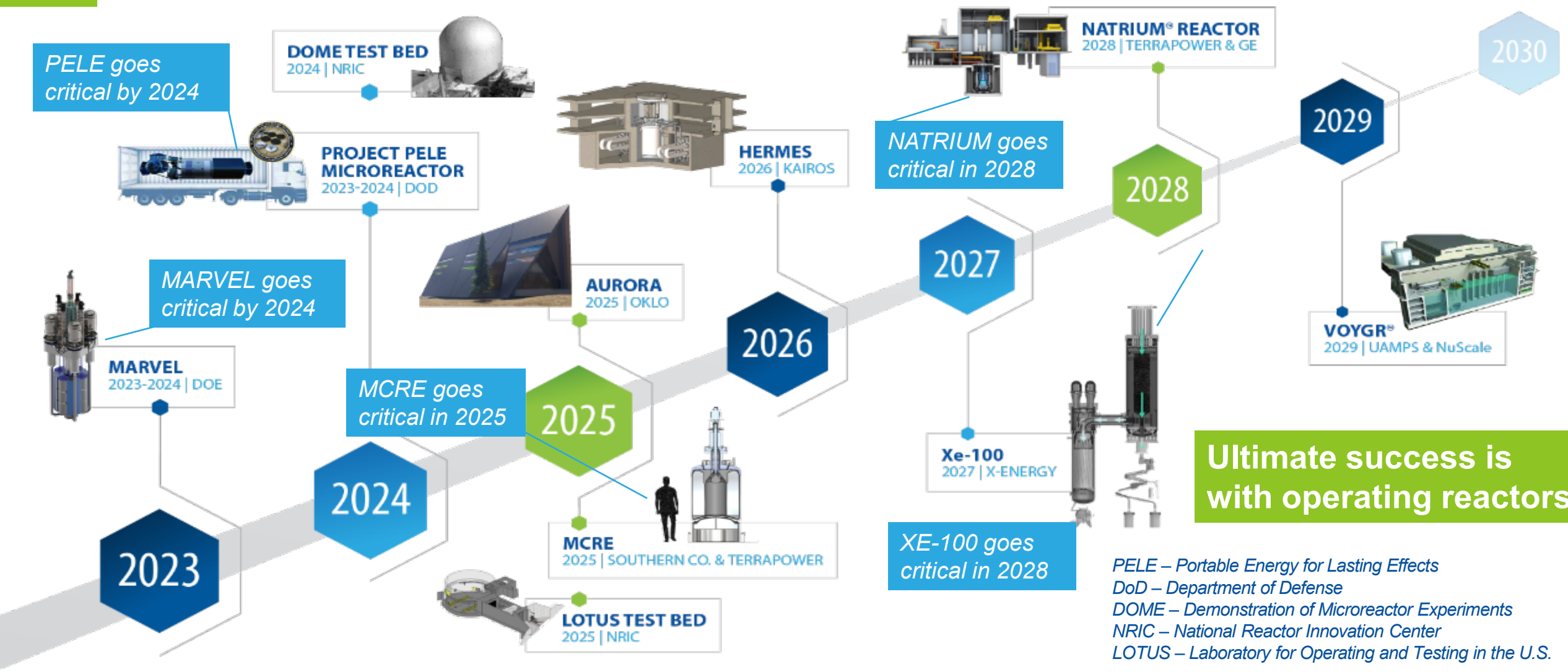
- INL is at the forefront in the development of advanced reactor technologies that will deliver net-zero emissions energy.
- INL will demonstrate advanced reactor technologies, including:
  - Microreactor Applications Research, Validation, and Evaluation (MARVEL)
  - Support microreactor technology for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

PELE



MARVEL

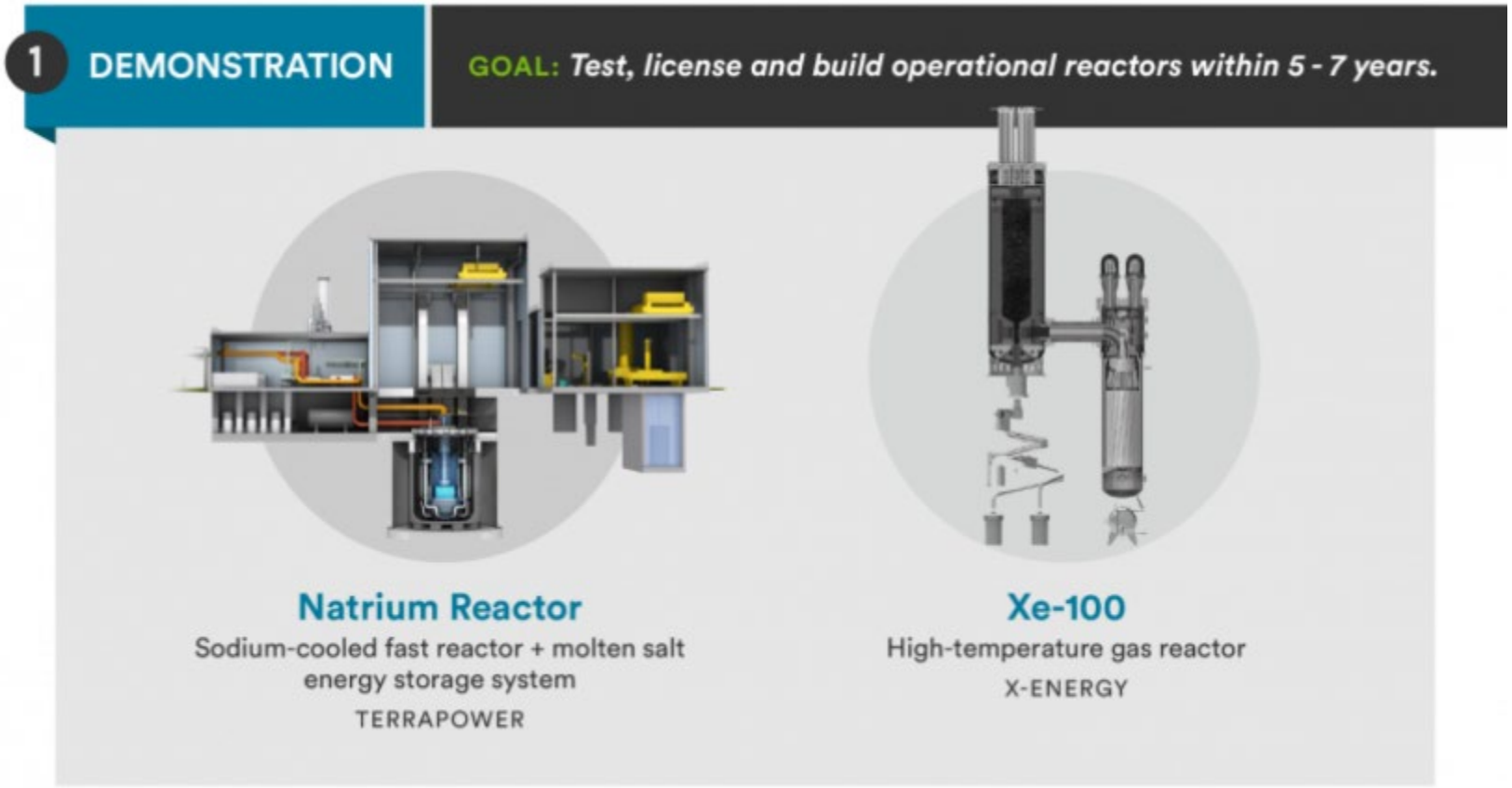
Measures of Success



Ultimate success is with operating reactors

PELE – Portable Energy for Lasting Effects
DoD – Department of Defense
DOME – Demonstration of Microreactor Experiments
NRIC – National Reactor Innovation Center
LOTUS – Laboratory for Operating and Testing in the U.S.

DOE Support of SMRs: Demonstration



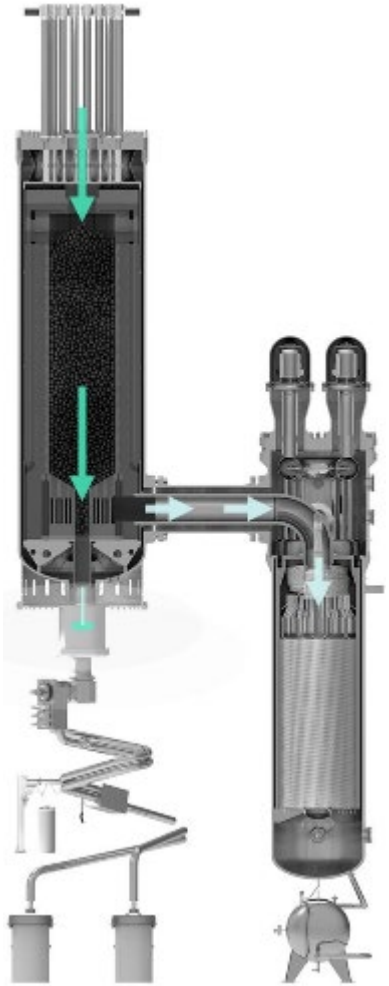
- The US DOE Advanced Reactor Demonstration program (ARDP) was established in 2020 to accelerate demonstration of advanced reactors through cost-shared partnerships with U.S. industry.
- Two Demonstration awards were made to high-TRL SFR and HTGR designs to test, license and build operational reactors in 5-7 years.

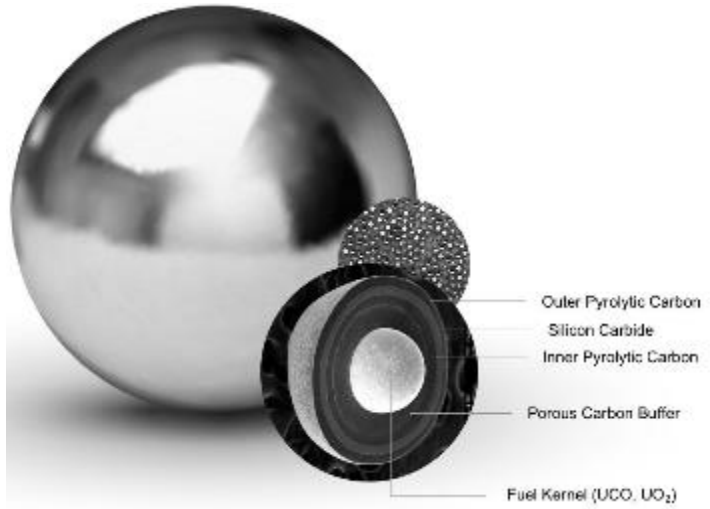
- https://www.energy.gov/ne/advanced-reactor-demonstration-program

DOE Support of Advanced Reactors: X-energy

X-Energy:

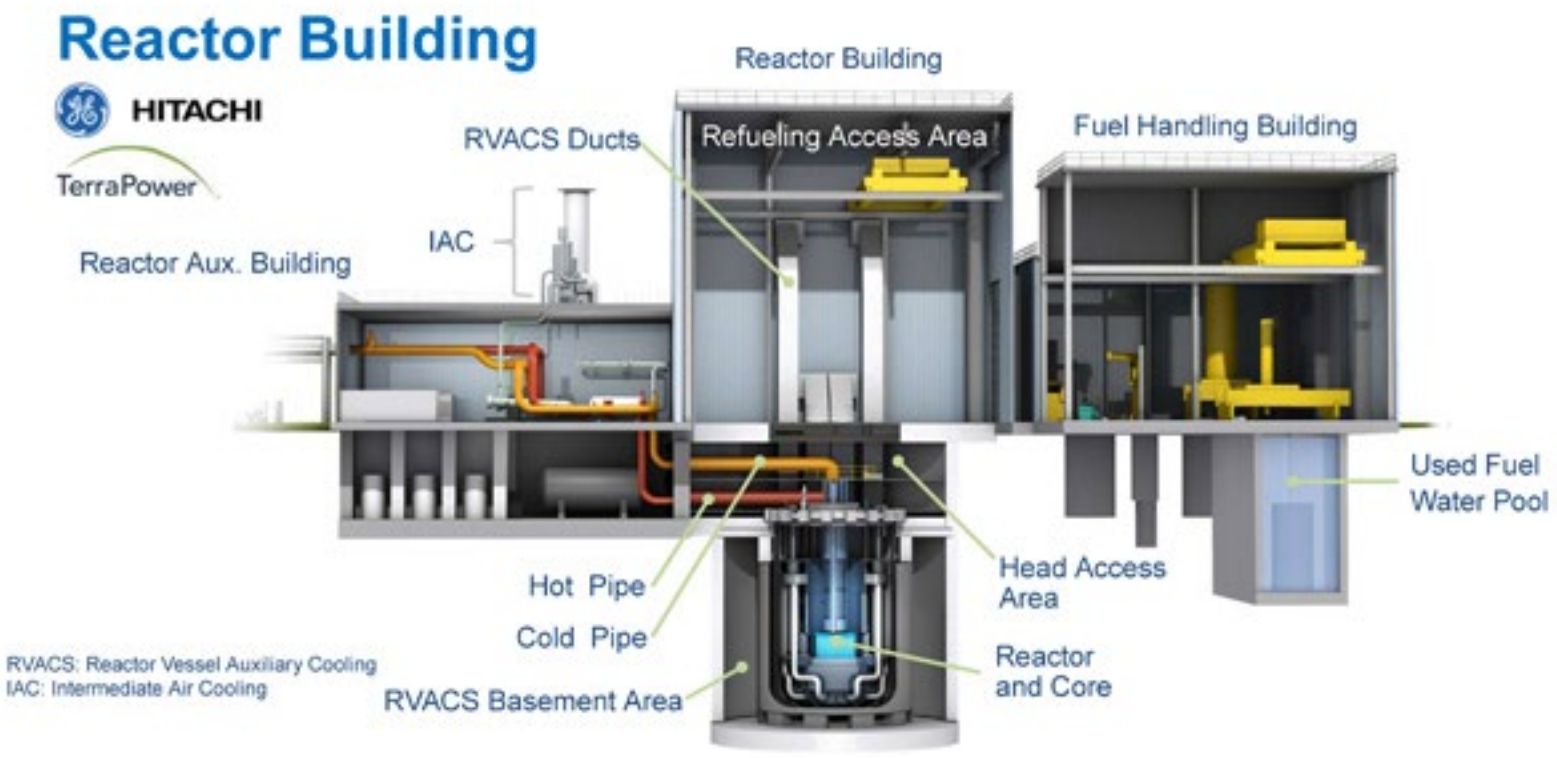
- Funded by DOE with $1.23 billion over 7 years to build a 2-unit XE-100 demonstration plant.
- Chose Energy Northwest and Grant County Public Utility District as utility partners
- Will be located in **Washington state**, close to Pacific Northwest National Laboratory (**PNNL**).
- Planned operation by 2027.





- https://www.energy.gov/ne/advanced-reactor-demonstration-program
- Figure (left) and pebble: https://x-energy.com/fuel/triso-x

DOE Support of Advanced Reactors: 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 site of Natrium demonstration reactor in November 2021.

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

Microreactors: Megawatt-scale Nuclear Reactors

BENEFITS:

Small Size

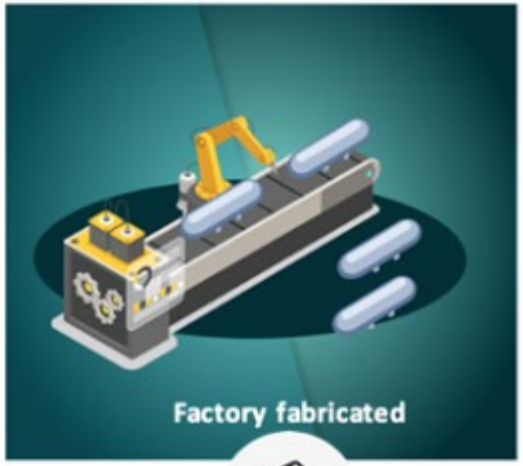
Fits on the back of a semi-truck and can be deployed to remote locations and military bases for reliable heat and power.

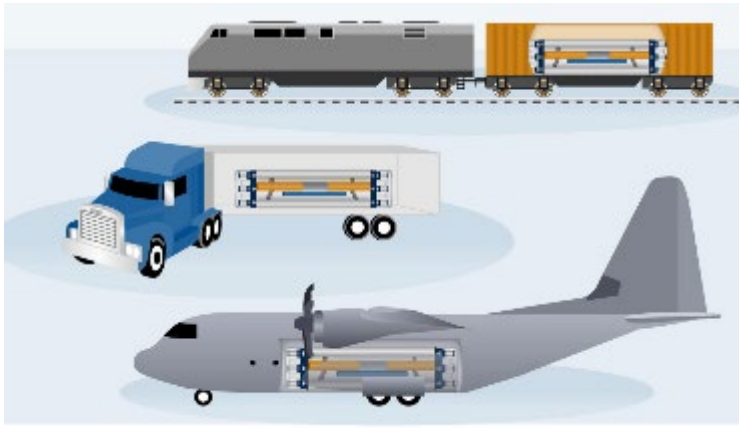
Simple Design

Fail-safe and self-regulating designs that require fewer components, maintenance and operators.

Fast On-site Installation

Can be connected and generating power within a week of arriving on site.





Source: GAO. | GAO-20-380SP

https://www.energy.gov/ne/downloads/infographic-what-nuclear-microreactor-0

Demonstration of Advanced Reactors: PELE Project

DoD (Army): Nuclear power could offer resilient, reliable energy for remote, strategically important, and key mission assurance installations within the United States

- Record of Decision made: BWXT awarded Phase 2 – April 2022
- Prototype testing at INL in 2024+


U.S. Department of Defense

Release

IMMEDIATE RELEASE

DoD to Build Project Pele Mobile Microreactor and Perform Demonstration at Idaho National Laboratory

APRIL 13, 2022

PELE critical by end of 2024

Demonstration of Microreactor Potential @ INL: MARVEL

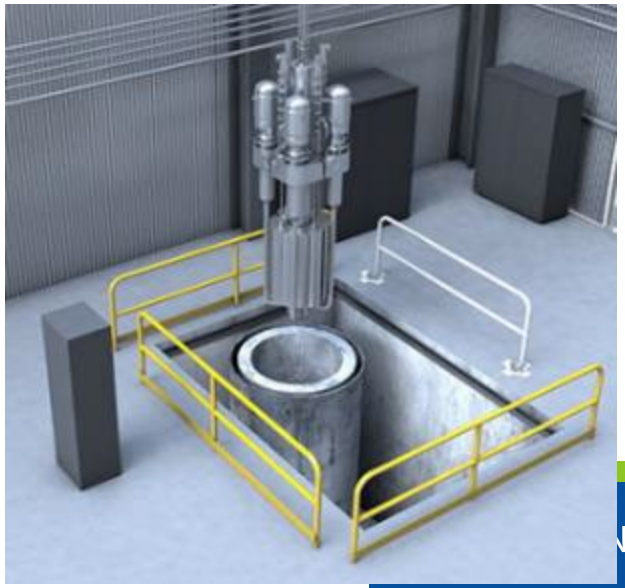
(Microreactor Applications Research, Validation & EvaLuation)

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



- 100 kW-thermal
- 20 kW-electric
- ~10 feet tall
- < 12 tons
- 2 operators
- Self-regulating

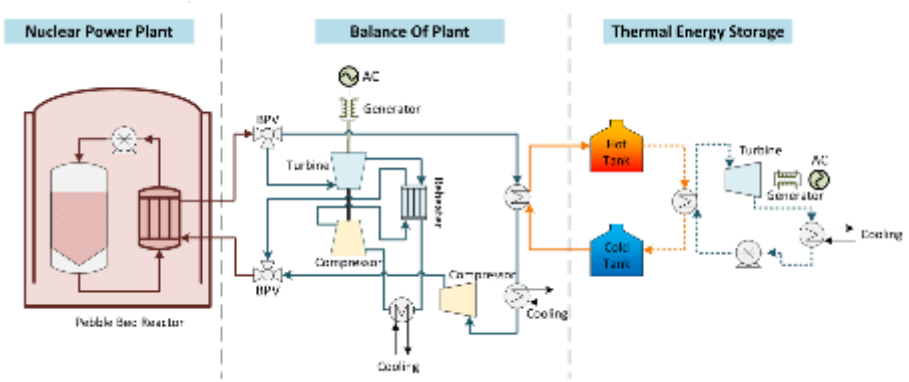
MRP Microreactor Program

National Reactor Innovation Center (NRIC) advanced reactor testing infrastructure

NRIC
National Reactor Innovation Center

- NRIC Goal: Demonstrate two advanced reactors by 2025
- NRIC Strategy
  - Repurpose two facilities at INL and establish two test beds to provide confinement for reactors to go critical for the first time
  - Build/establish testing infrastructure for fuels and components
- NRIC DOME (Demonstration of Microreactor Experiments)
  - Advanced Microreactors up to 20 MWth
  - High-Assay Low-Enriched Uranium (HALEU) fuels < 20%
- NRIC-IES demonstration platform
  - Design and construct a highly flexible advanced reactor integrated energy system (AR-IES) demonstration platform
  - **Goal:** Demonstrate how advanced reactors can be coupled to various thermal energy users, and how thermal energy storage can enable coupled operation of various thermal loads/users.

Anticipate initial reactor testing in ~2024. Flexible testbed to support testing of multiple reactor concepts using the same infrastructure ~annually.



For more information on NRIC and to download resources, see https://nric.inl.gov/.

IES
Integrated Energy Systems

Nuclear-H_2 demonstration projects

Multiple projects have been selected for demonstration of hydrogen production at U.S. nuclear power plants (NPP)

- H_2 production using direct electrical power offtake
- Develop monitoring and controls procedures for scaleup to large commercial-scale H_2 plants
- Evaluate power offtake dynamics on NPP power transmission stations to avoid NPP flexible operations
- Produce H_2 for captive use by NPPs and clean hydrogen markets

Projects

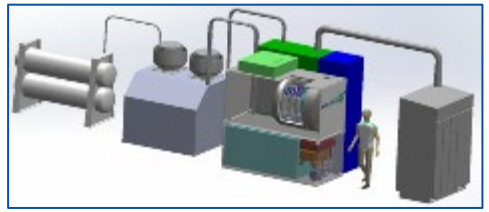
- Constellation: Nine-Mile Point NPP (~1 MWe LTE/PEM)
- Energy Harbor: Davis-Besse NPP (~1-2 MWe LTE/PEM)
- Xcel Energy: Prairie Island NPP (~150 kWe HTSE)
- FuelCell Energy: Demonstration at INL (250 kWe)

Nine Mile Point NPP LTE/PEM

Davis-Besse NPP LTE-PEM

Thermal & Electrical Integration at Prairie Island NPP HTSE/SOEC

FuelCell Energy at INL, SOEC at increasing scale



~2024

Current work with CAES (1/2)

- Work with CAES's TEM.:
  - Dual aberration-corrected high resolution Scanning Transmission Electron Microscopy (STEM) in High-angle annular dark-field imaging (HAADF) and Integrated Differential Phase Contrast imaging (iDPC).

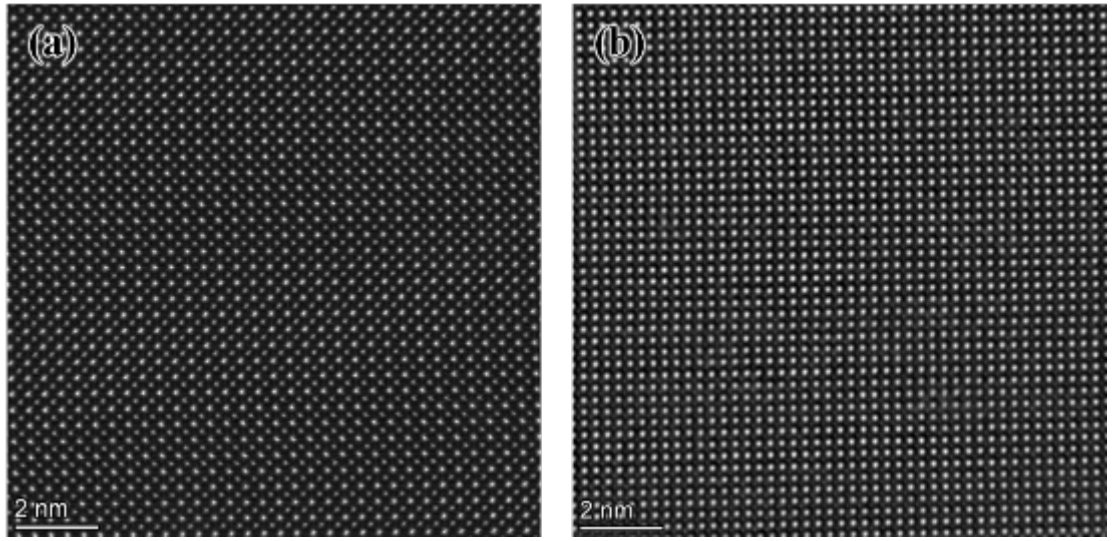
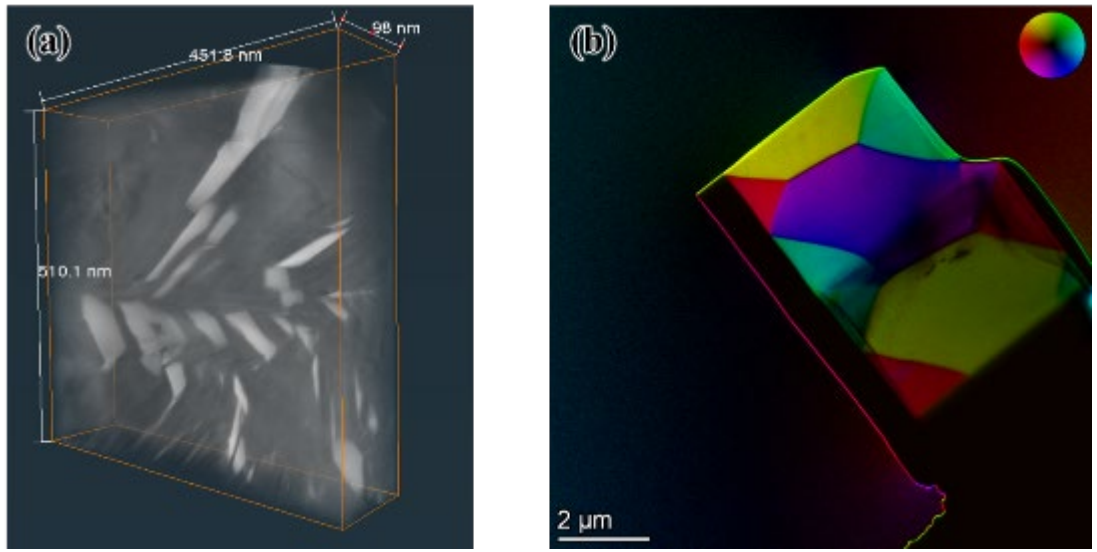


Figure 1. (a) HAADF image showing atomic columns Sr (brightest contrast) and Ti (weaker contrast) in a sample of $SrTiO_3$; note the oxygen columns cannot be resolved using HAADF. (b) iDPC image of the same $SrTiO_3$ with the oxygen atomic columns resolved.

- In addition, training was conducted on electron tomography techniques and magnetic domain imaging.

Figure 2. (a) electron tomography of poco-grade nuclear graphite. (b) magnetic domain imaging of FeSi.



CAES (Electron Energy Loss Spectroscopy (ELLS) – 2/2

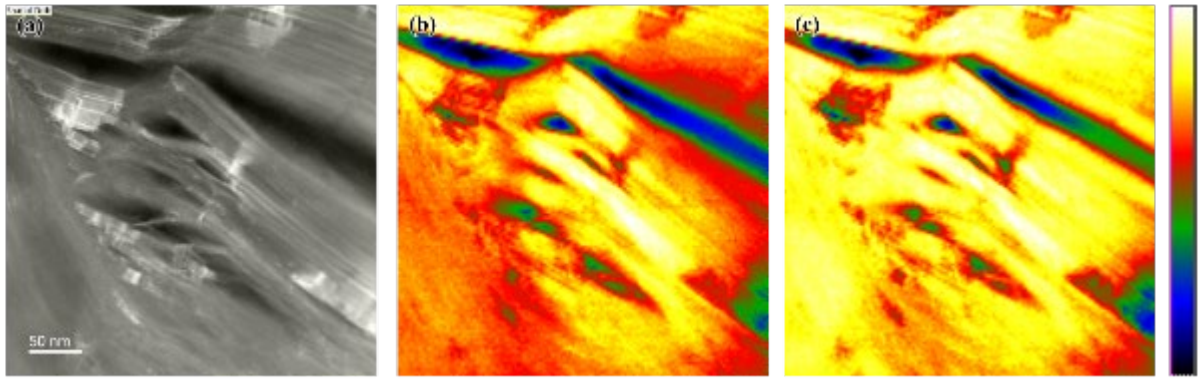
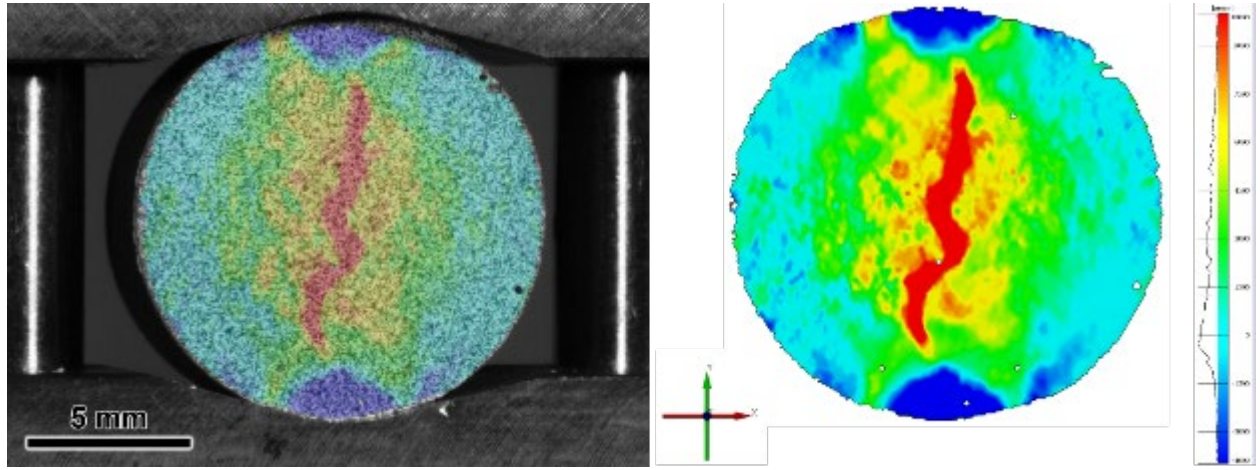


Figure 3. (a) ADF spectra map of poco-grade nuclear graphite. (b) EFTEM image shows the relative amount of sp2 bonding, and (c) shows the relative amount of sp3 bonded carbon.

- Analytical TEM has been initiated for heavy-ion irradiated nuclear graphite IG-110 under the Penn State Neup “Multi-scale Effects of Irradiation Damage on Nuclear Graphite Properties (CFA 21-24247)”. The analysis will include simultaneous Energy Dispersive Spectroscopy (EDS) & ELLS and HRTEM. Thinned TEM lamellas are with the INL co-collaborator Dr. Johns who is awaiting maintenance on the Spectra STEM to be finished so that analysis may be conducted.
- Installation of new 3D Digital Image Correlation equipment.

Figure 4. PCEA Nuclear graphite with Brazilian split disc mechanical testing and DIC analysis. Shown is the horizontal strain (εxx) of the pseudo-tensile test one frame before fracture. Acquired at 43 Hz.

- Installation and pic of the in-situ heating TEM holder on the Spectra S/TEM at CAES.
- Development of universal degradation model for nuclear graphites.
- Facilitated shipping of irradiated nuclear graphites for international collaborators conducting C-14 disposal studies.



A few references

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- https://event.asme.org/CARD-2023
- https://nric.inl.gov/

Idaho National Laboratory

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