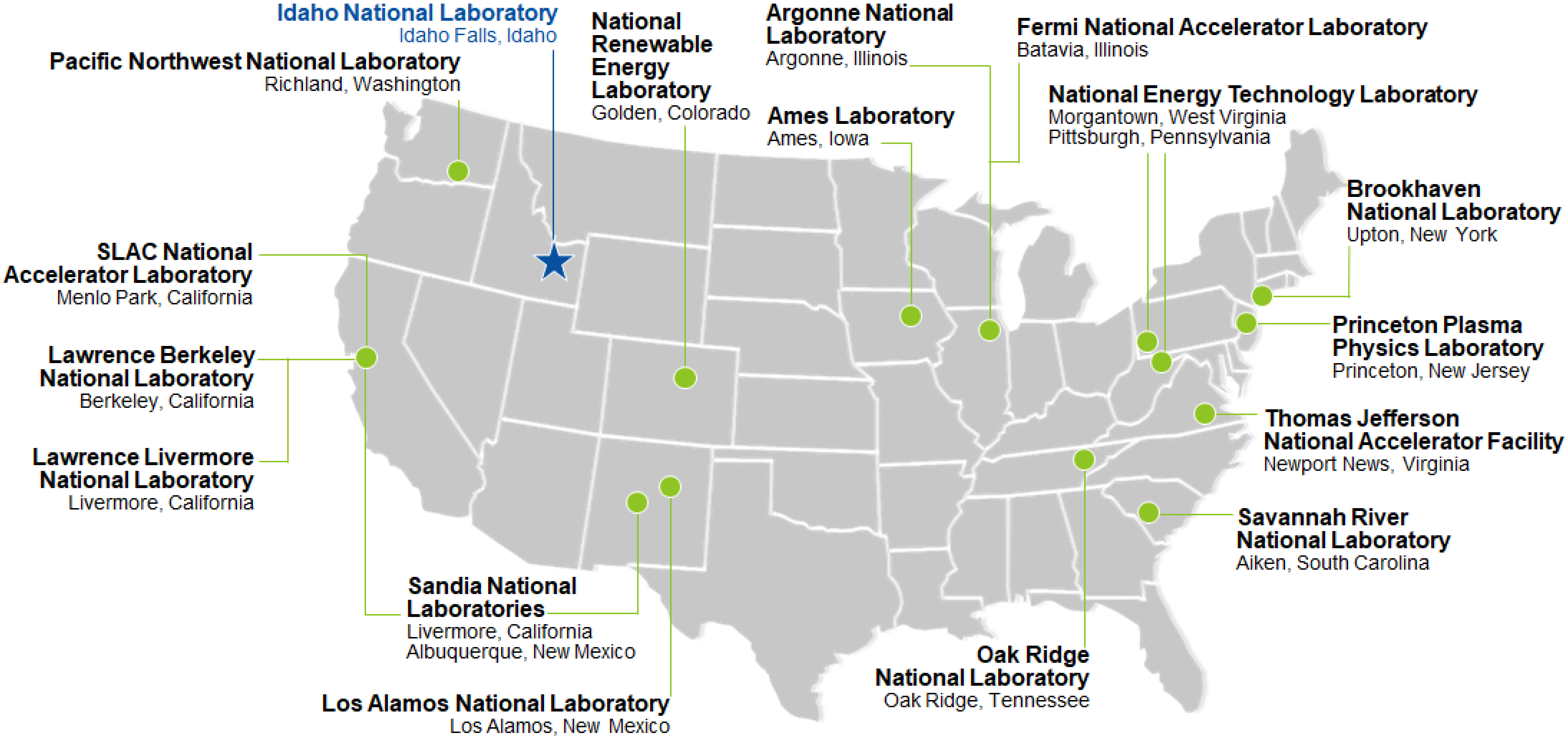
NE Modular Reactors and Sustainable Carbon Free Power

Ron Crone
Associate Laboratory Director
Materials and Fuels Complex
Idaho National Laboratory/Battelle Energy Alliance

DOE National Laboratories

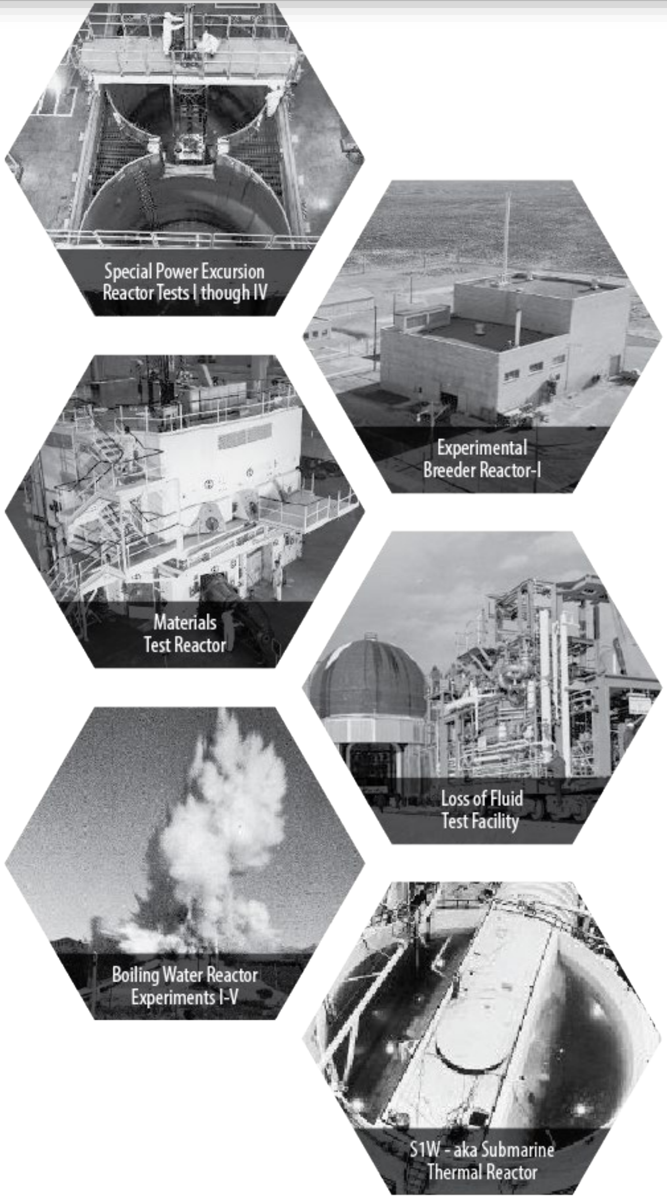


Our Heritage: *The National Reactor Testing Station drove nuclear innovation in the U.S. and around the world*

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

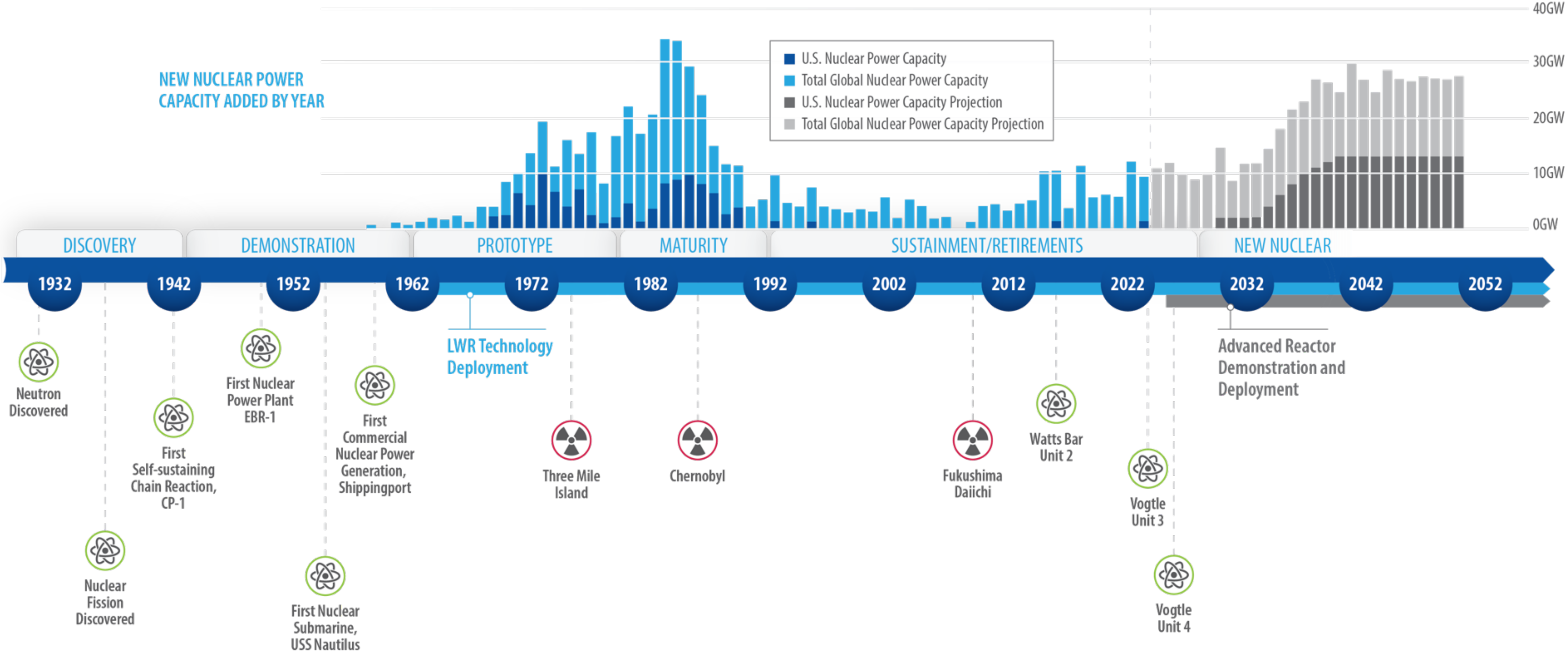


Unique INL Site, Infrastructure, and Facilities Enable Energy and Security RD&D at Scale

$1,823 M	FY23 Total Operating Cost
6,000+	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

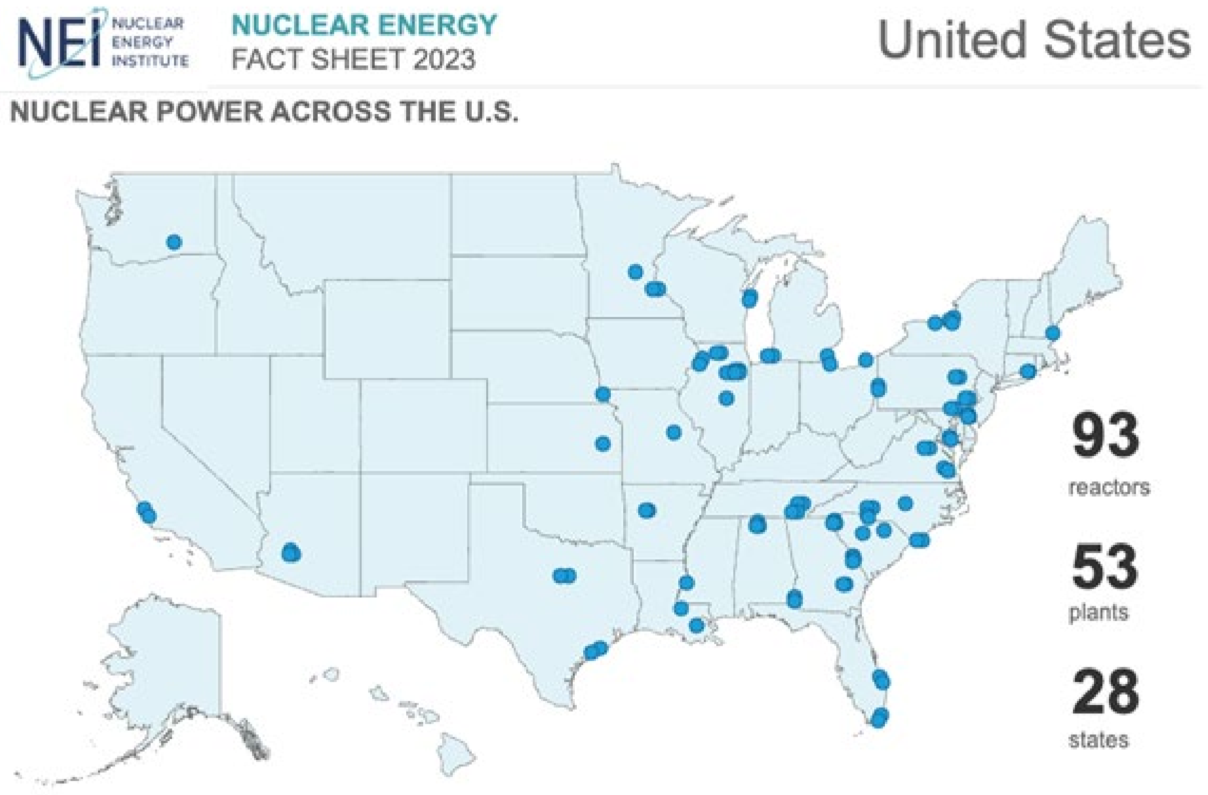
The Past and Future of Nuclear Power



U.S. Nuclear Industry Recognizes the Demand for New Nuclear Power Projects

Utilities recently identify the need to add **100 GIGAWATTS** of nuclear power by 2050, more than doubling current capacity.

Today, 93 reactors provide nearly 20% of the electricity produced for our power grid and more than half of our carbon-free electricity – more than solar, wind, hydro, and geothermal combined.



- Utilities are prepared to invest in nuclear energy because it is a proven non-carbon-emitting solution
- New reactor designs are simpler, more versatile, and more economical at scale
- Utilities are evaluating reusing retired coal plant sites to leverage existing infrastructure and workforce
- Emissions avoided by adding 100 gigawatts of nuclear power is equivalent to taking more than 100 million cars off the road.

U.S. Domestic Nuclear Capacity has the Potential to Scale from ~100 GW in 2023 to ~300 GW by 2050

New nuclear deployment starting in 2030
Annual deployment (GW/yr) built and Cumulative GW online

New nuclear deployment starting in 2035
Annual deployment (GW/yr) built and Cumulative GW online

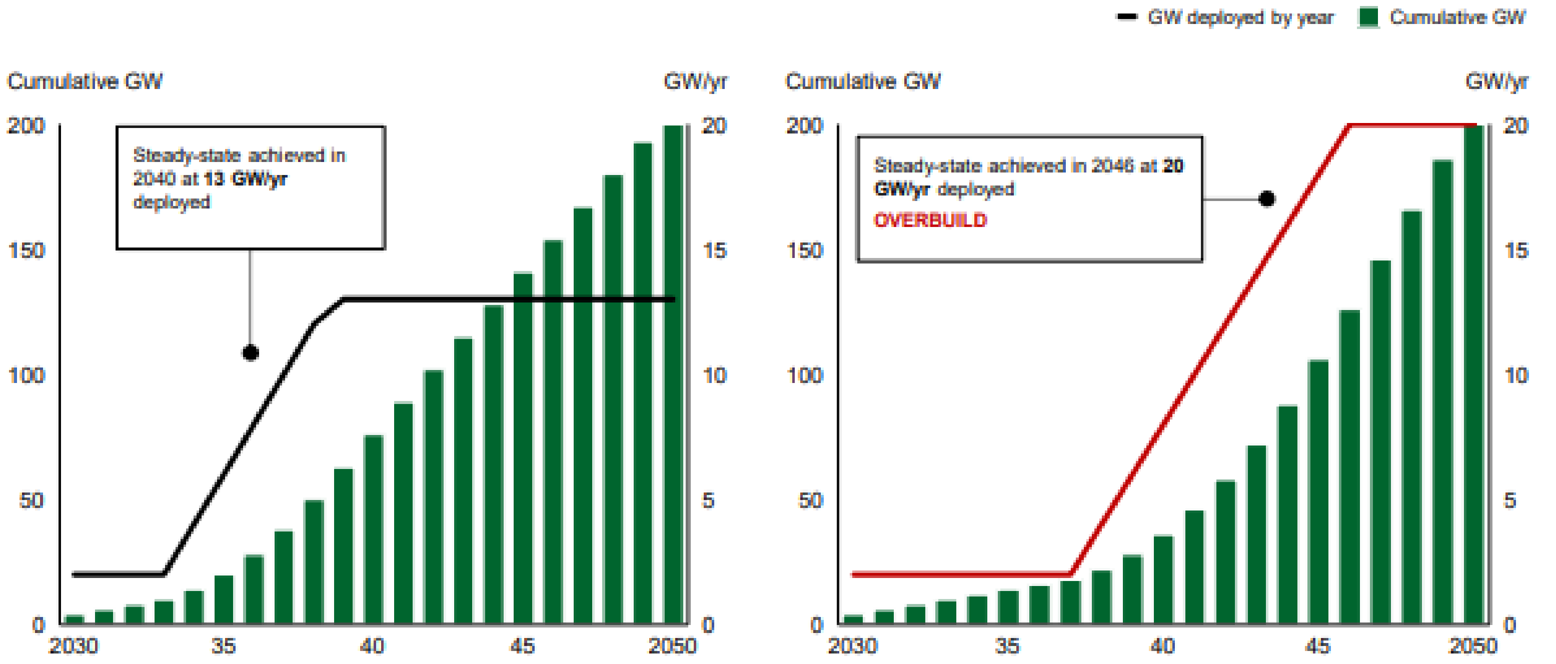
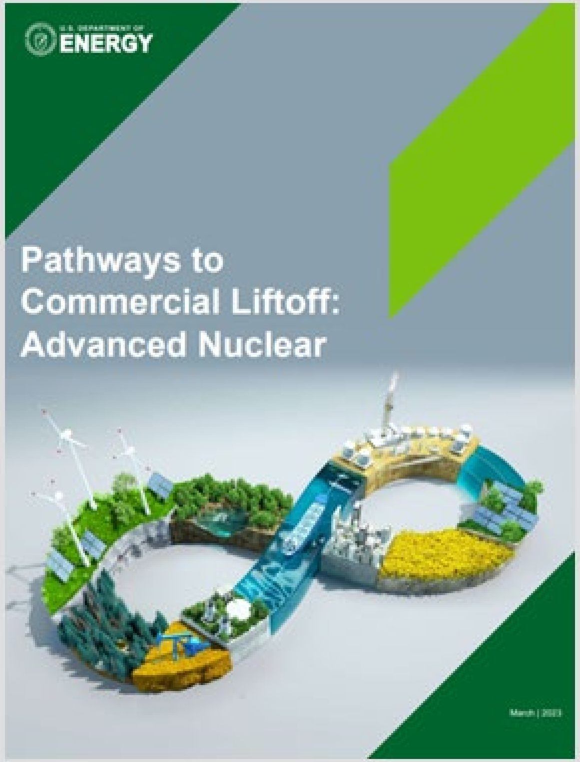


Figure 1: New nuclear build-out scenarios and implications for industrial base capacity requirements



"Power system decarbonization modeling, regardless of level of renewables deployment, suggests that the U.S. will need ~550–770 GW of additional clean, firm capacity to reach net-zero."

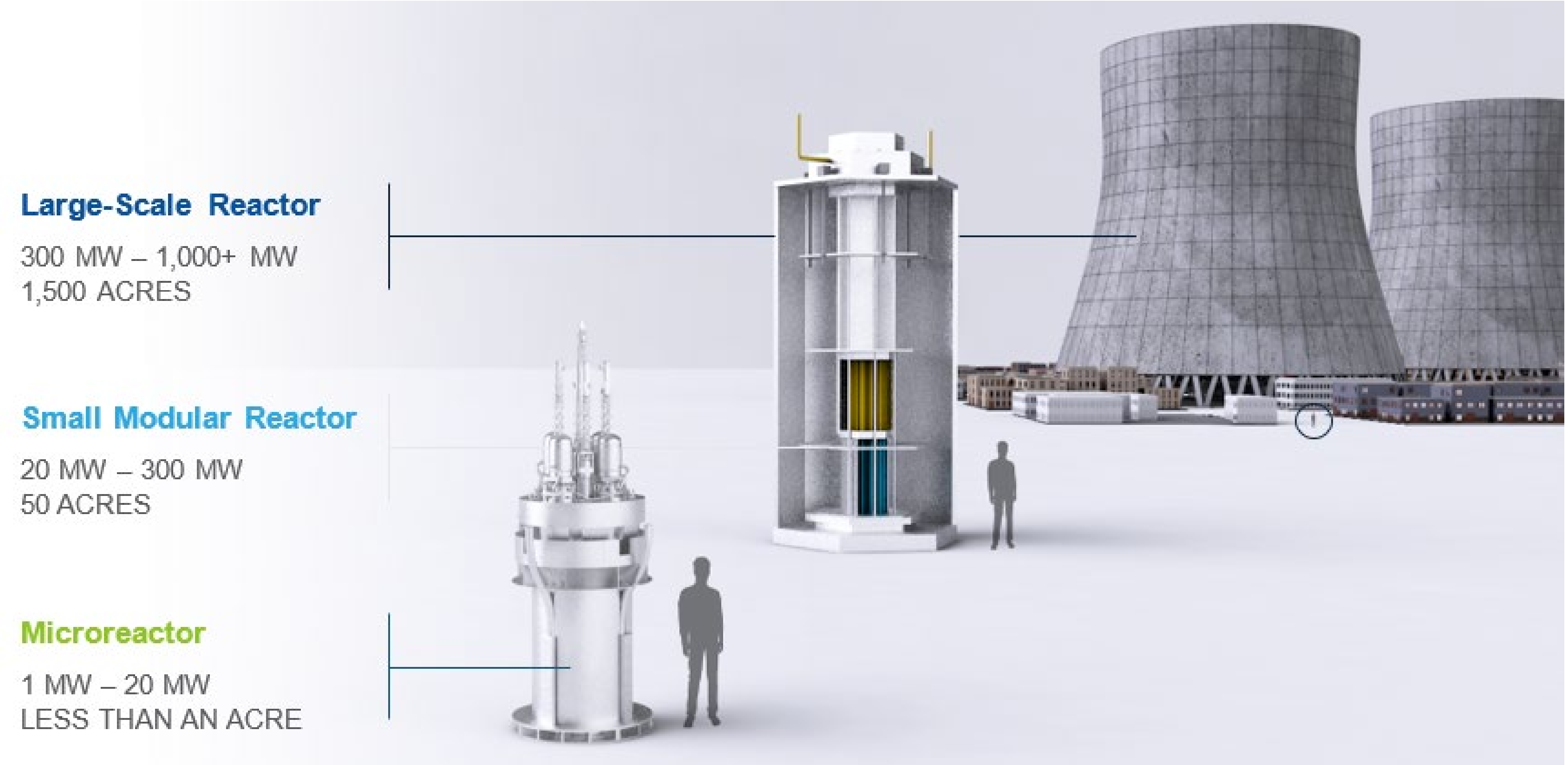
Nuclear in the News

- 20+ countries launched the Declaration to Triple Nuclear Energy at COP28
- Vogtle unit 3 operating, Unit 4 to begin operations soon
- Rep. John Curtis (3rd District Utah) *"Nuclear power is a critical component of our clean energy future"*
- Due to strong market conditions, three new uranium mines opened in Arizona and Utah in 2023.
- Michigan lawmakers support Palisades restart
- Illinois lifts nuclear construction moratorium
- Canada announces ambitious nuclear construction plans
- Great British Nuclear drives UK nuclear revival
- Wave of international agreements and contracts *(U.S.-India; U.S. Philippines; Poland)*

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.

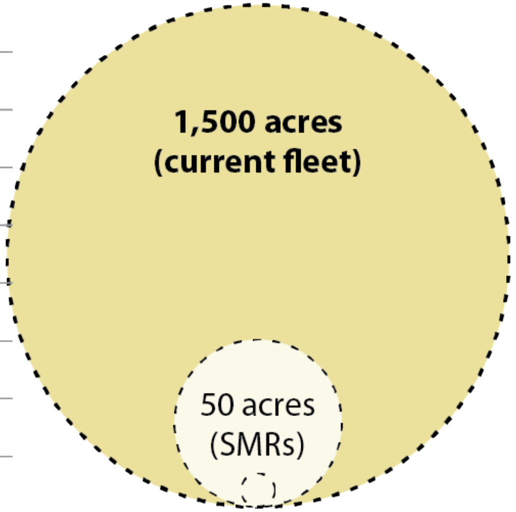
Advanced Reactor Size Comparison



Existing and Large Nuclear Reactors

Number in operation:	**95 in U.S.**
Timeframe:	**Built in the 1950s-1980s**
Products:	**Electricity**
Megawatts:	**1,000+ megawatts**
Customers:	**Large utilities**
Emergency zone:	**10 miles**
Construction:	**Custom built on site**
Scalability:	**Difficult due to size and cost**

Footprint



Less than an Acre
(Micro Reactors)

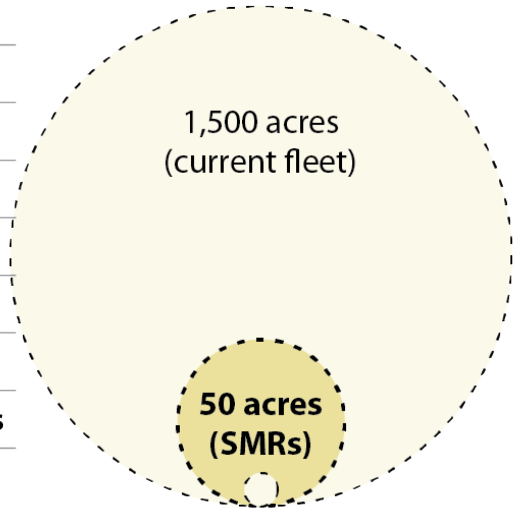
Applications:
Baseload electricity; 24/7

Did you know? In November 2018, the Union of Concerned Scientist recommended that federal and state governments adopt policies to preserve the low-carbon electricity the current fleet of nuclear reactors provides.

Small Modular Reactors

Number in operation:	**None***
Timeframe:	**First reactors expected by 2029**
Products:	**Electricity, heat, and steam**
Megawatts:	**60-300 megawatts per module**
Customers:	**Large utilities; municipalities; industry**
Emergency zone:	**.19 miles**
Construction:	**Factory built; assembled on site**
Scalability:	**Reactor modules added as demand increases**

Footprint



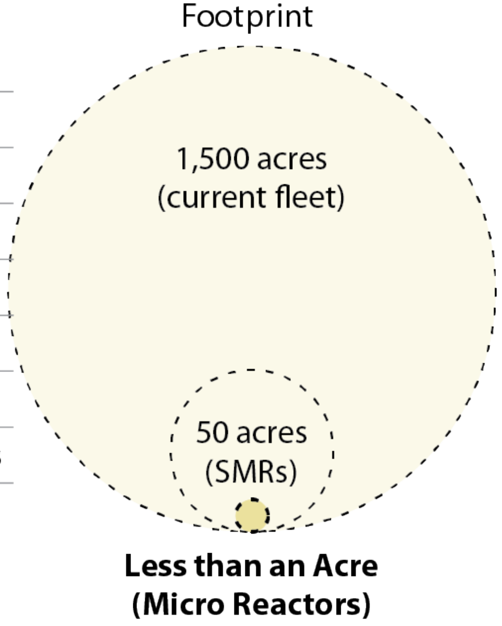
Less than an Acre
(Micro Reactors)

Applications:
Baseload electricity, industrial heat, industrial processes such as hydrogen production

**First SMR in U.S. is currently going through regulatory approval and siting process. UAMPS is proposing a 12-module SMR in Idaho using NuScale technology, which has now received design safety approval from the NRC.*

Microreactors

Number in operation:	**None**
Timeframe:	**First reactors expected by 2025**
Products:	**Electricity, heat, and steam**
Megawatts:	**20 megawatts or less**
Customers:	**Military; municipalities; industry**
Emergency zone:	**Less than 1 acre**
Construction:	**Factory built; assembled on site**
Scalability:	**Reactor modules added as demand increases**

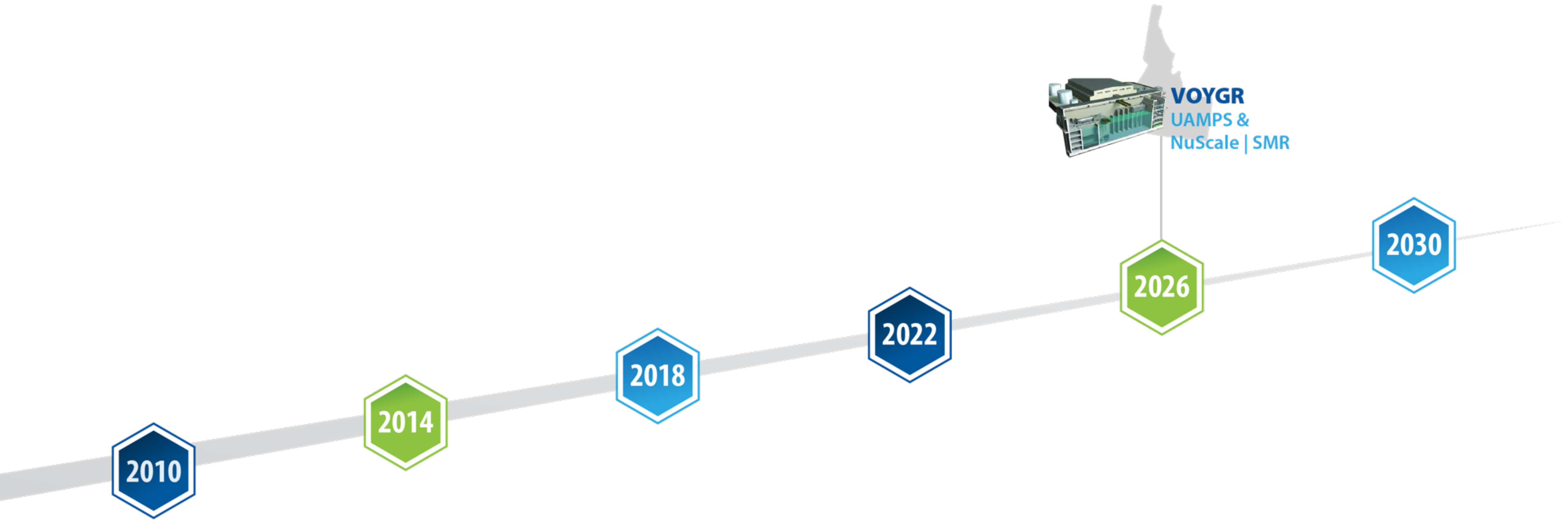


Applications:
Power for remote locations, maritime shipping, military installations, mining, space missions, desalination, disaster relief

Sen. Lisa Murkowski, R-Alaska, April 4, 2019 Op-Ed in the Anchorage Daily News.

Improvements in nuclear technology "are enabling the emergence of so-called "microreactors" that could be a perfect fit throughout our state. As the name suggests, these smaller reactors can be right-sized for dozens of Alaska communities and will have off-grid capability that could solve the challenge of providing clean, affordable energy in our remote areas."

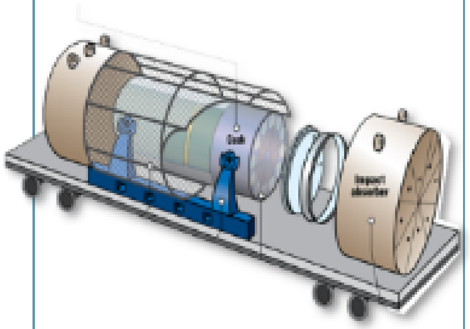
10 Years Ago the Advanced Reactor Ecosystem Was Bleak



In 2018 the Advanced Reactor Landscape had Improved but Was Still Very Uncertain

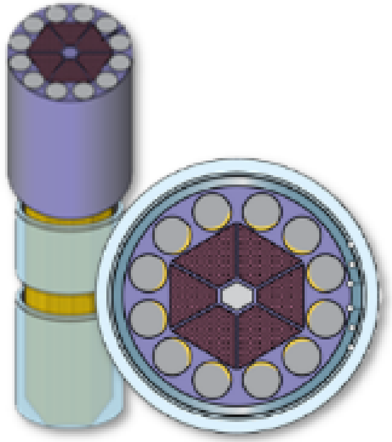
Microreactor (<10MW) demonstration by early 2020s

- Advanced reactor designs
- New markets for nuclear energy



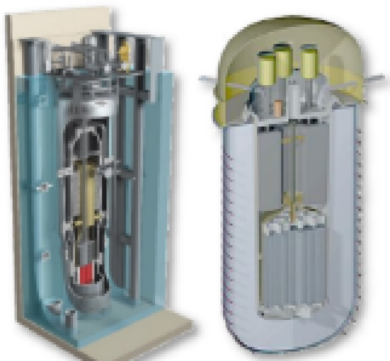
Commercial microreactors deployed

- Remote site power and process heat customers



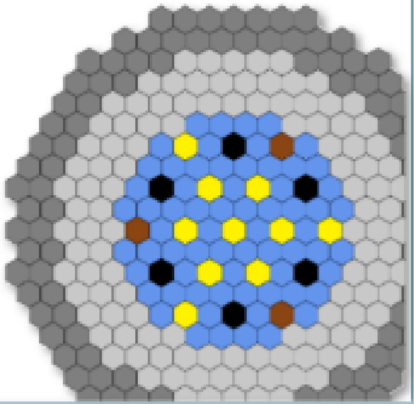
SMR(s) operating by 2026

- SMR siting and technical support
- Joint Use Modular Plant (JUMP)



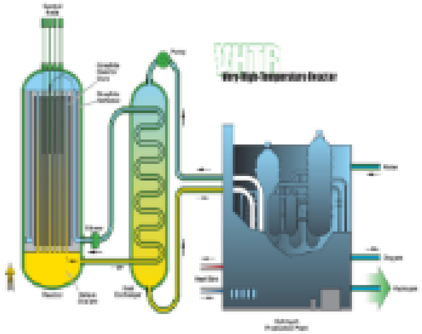
Versatile Test Reactor (VTR) operating by 2026

- Fast-spectrum testing and fuel development capability



Non-LWR advanced demonstration reactors by 2030

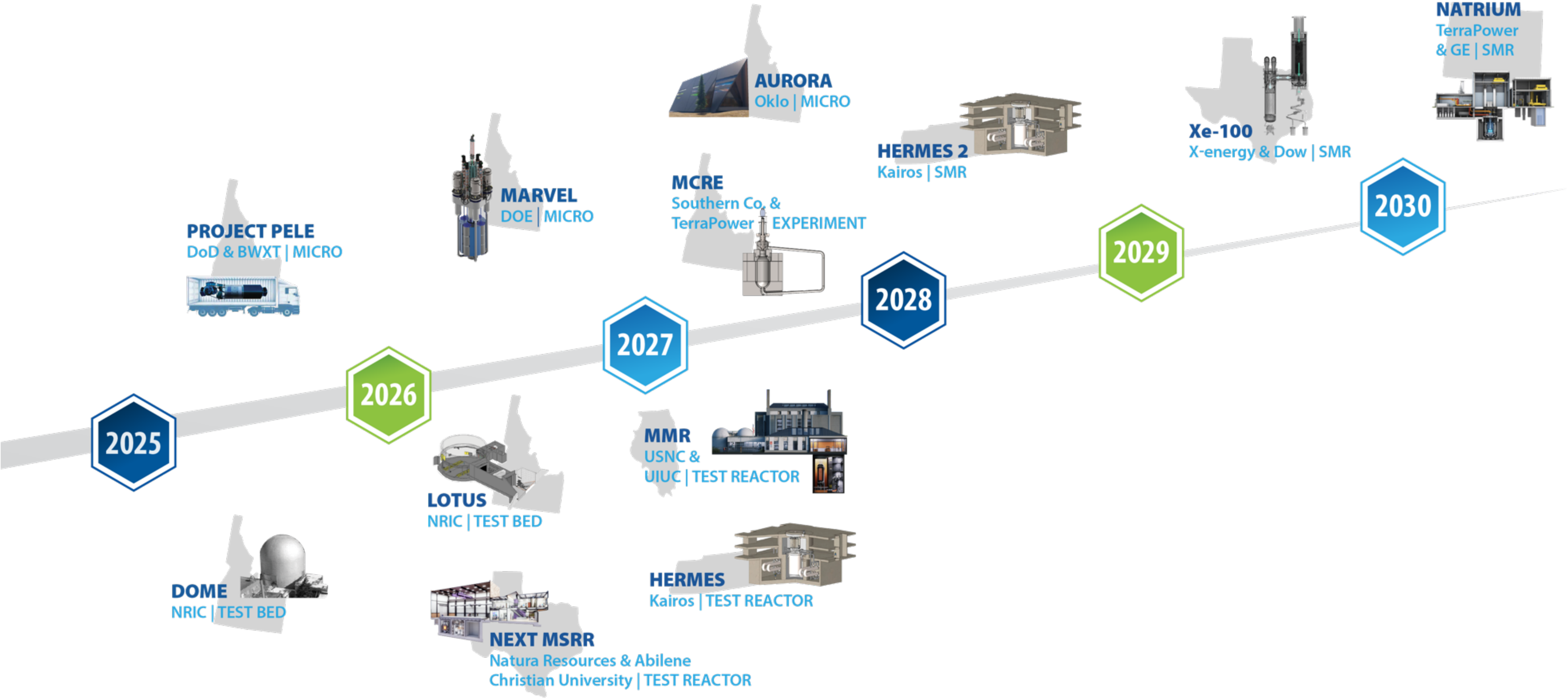
- Replacement of U.S. baseload clean power capacity



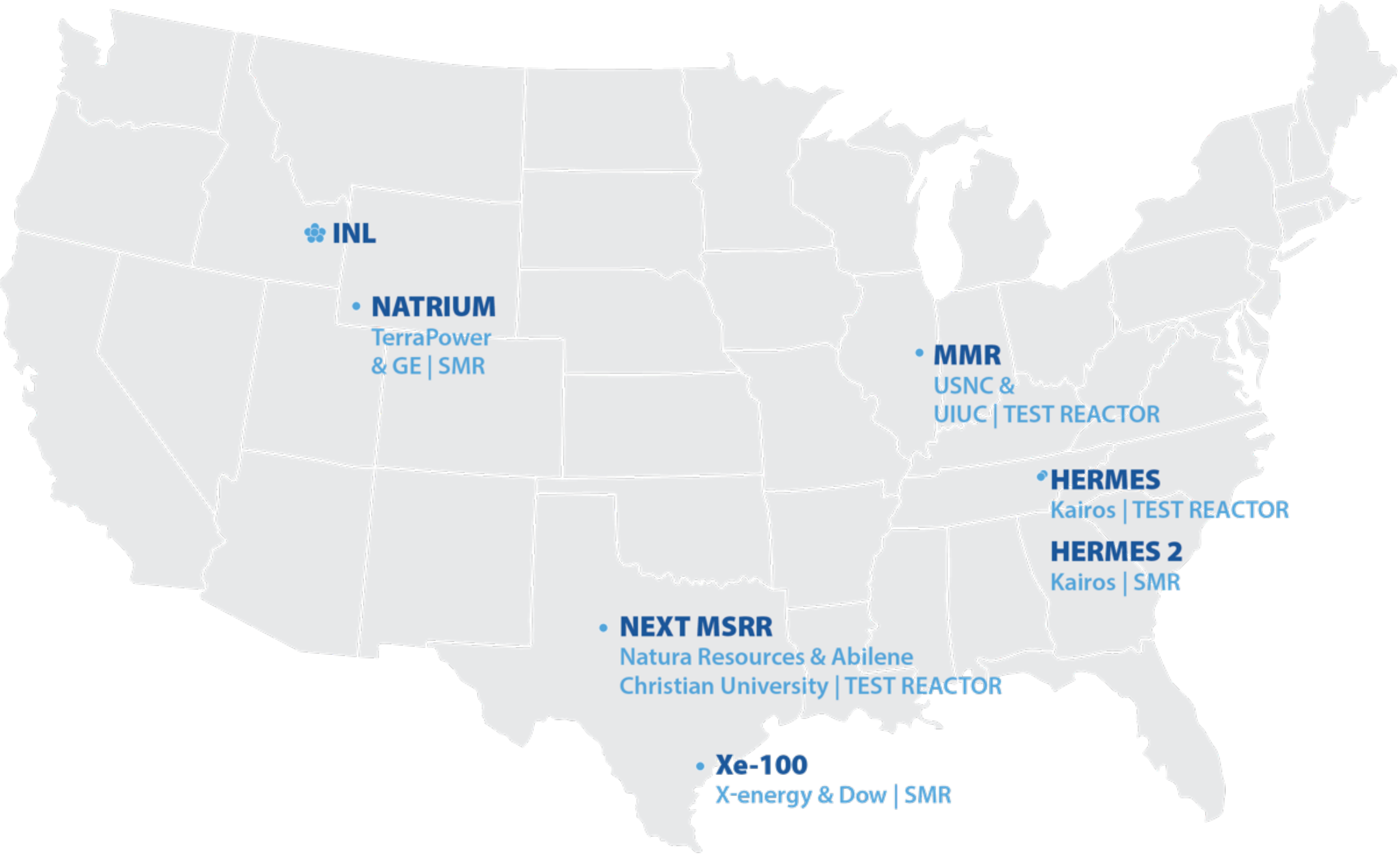
2023

2030

Accelerating Advanced Reactor Demonstration & Deployment



Advanced Reactor Demonstrations and Deployments are Planned Nation-wide



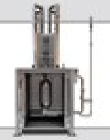
INL

Reactor Demonstrations & Experiments


MARVEL
DOE | MICRO

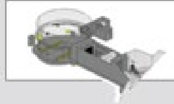

PROJECT PELE
DoD & BWXT | MICRO


AURORA
Oklo | MICRO

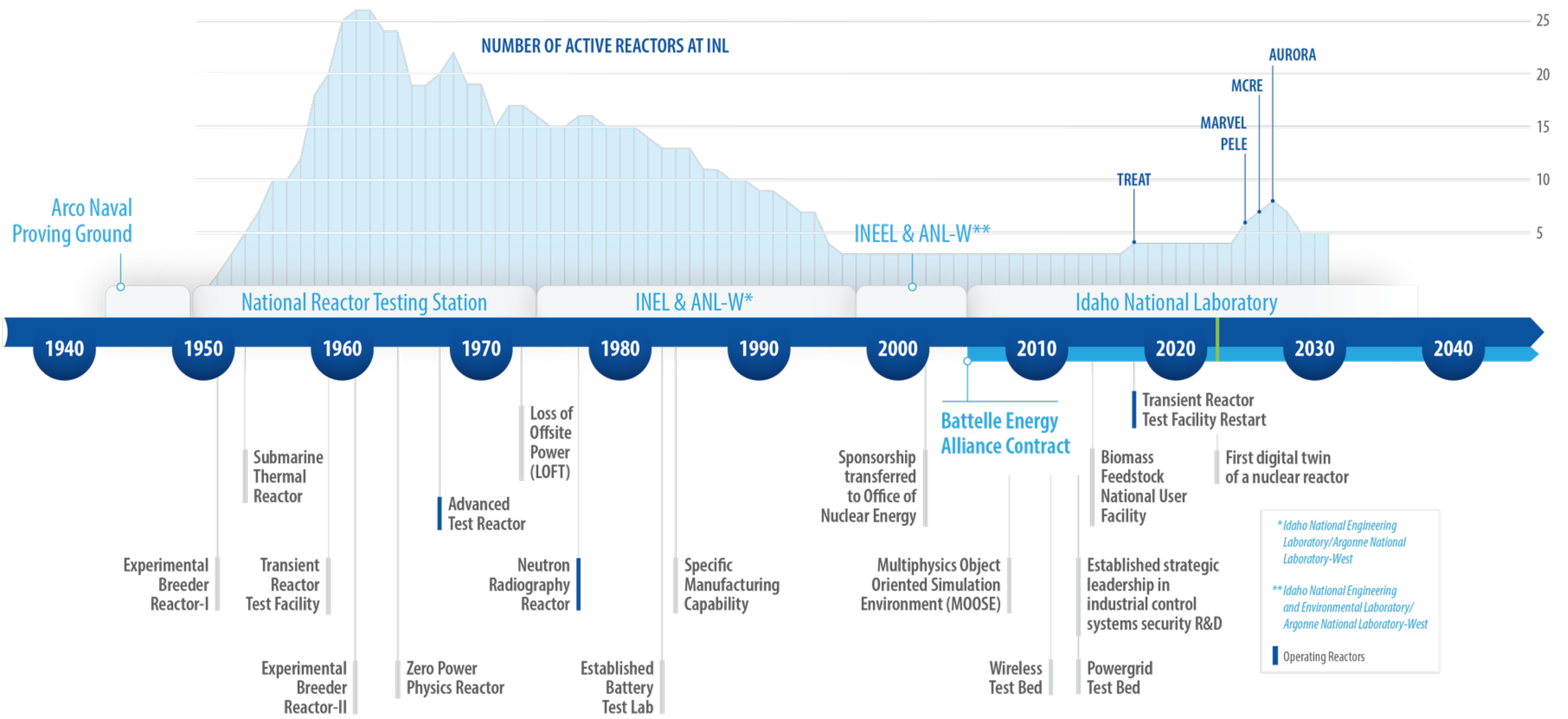

MCRE
Southern Co. & TerraPower EXPERIMENT

Test Beds


DOME
NRIC | TEST BED

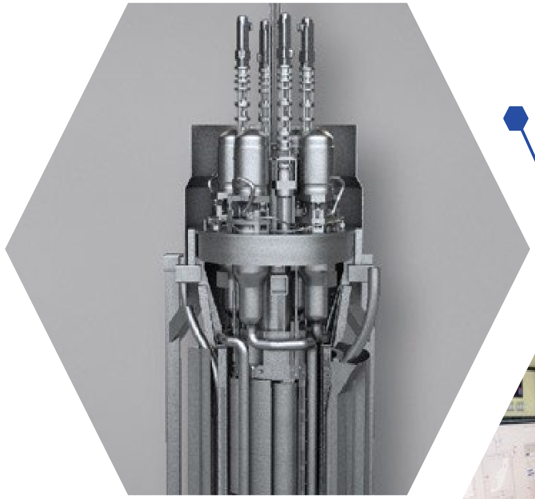

LOTUS
NRIC | TEST BED

The Past and Future of Idaho National Laboratory

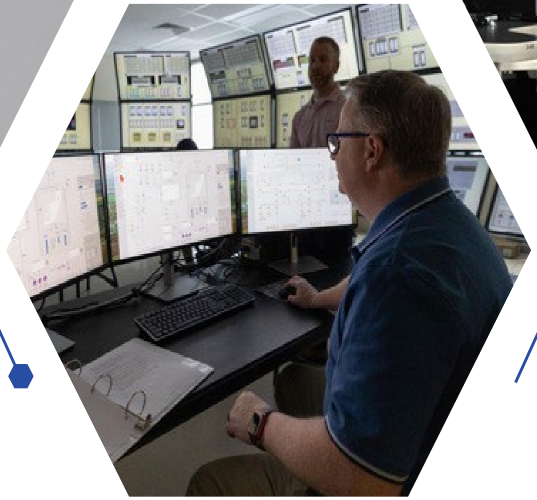


Significant Reactor Deployment Faces Technical, Geopolitical, Policy, and Economic Challenges

R&D for Sustaining the Existing Commercial Reactor Fleet and Expanding Deployment of Future Reactors

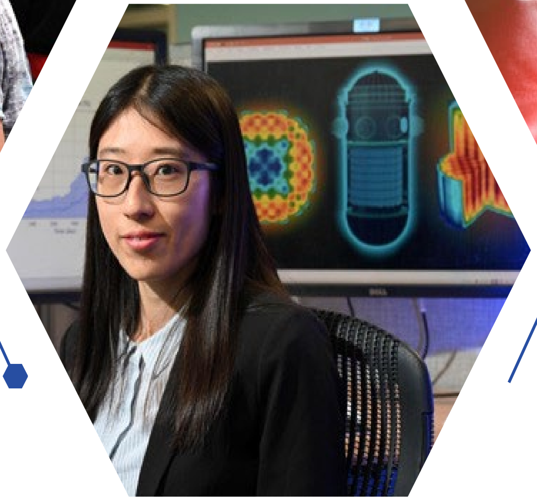


Advanced
reactor technologies



Regulatory
and safety
research

Fuel cycle
and separations

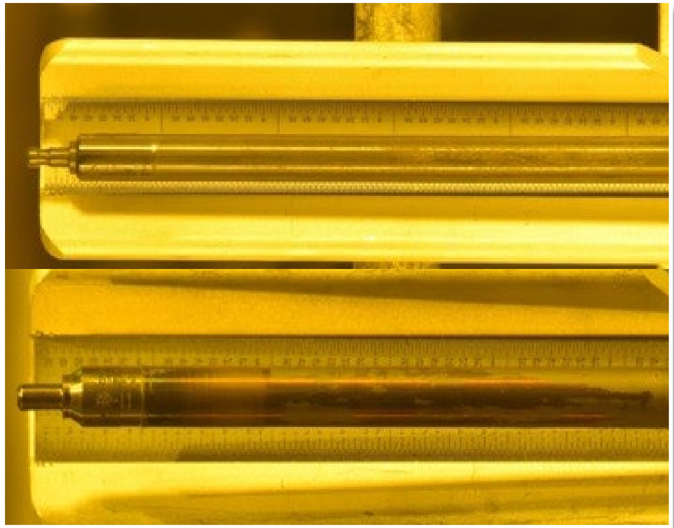


Advanced
modeling and simulation

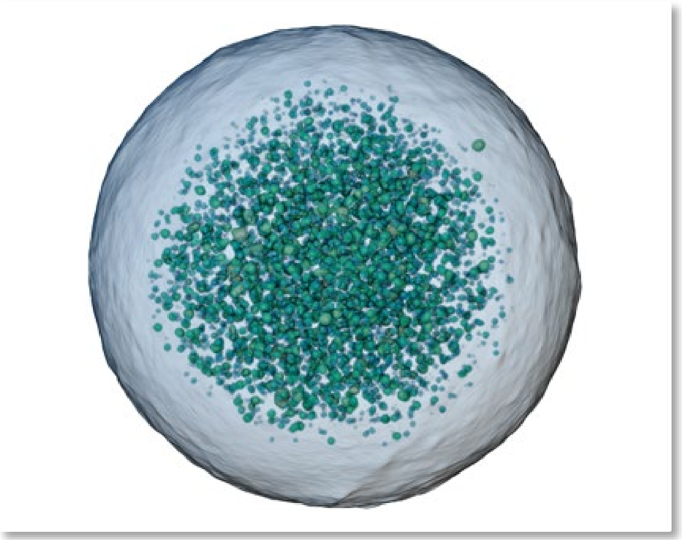
Nuclear fuels and
materials

Strengthening the Domestic Commercial Nuclear Energy Enterprise

Piloting Integrated Operations concepts for light water reactors

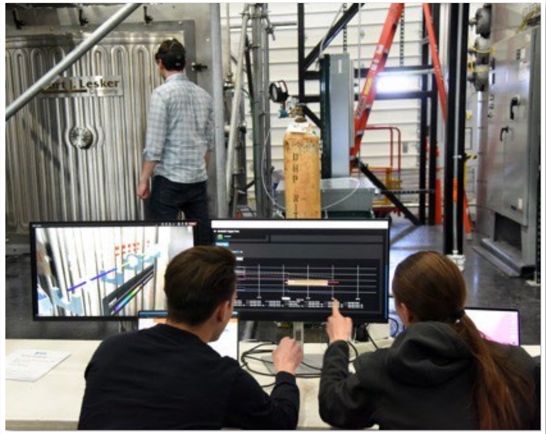


Developing and testing accident tolerant fuel concepts

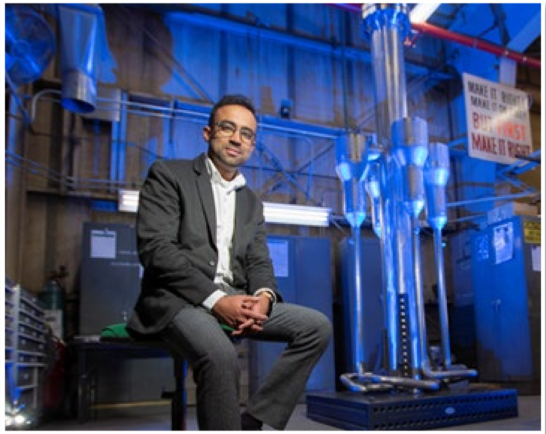


Enabling the TRISO fuel commercial supply chain

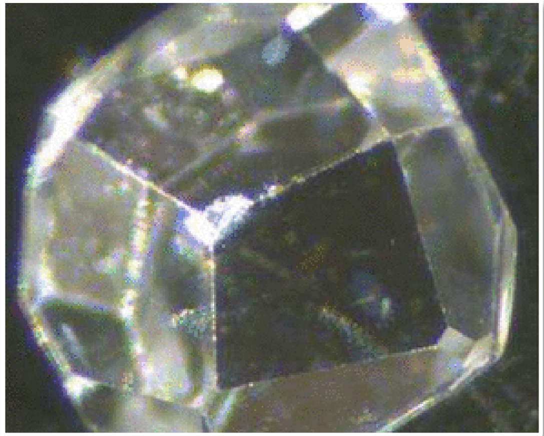
Enabling the Future of Nuclear Energy Through Innovation



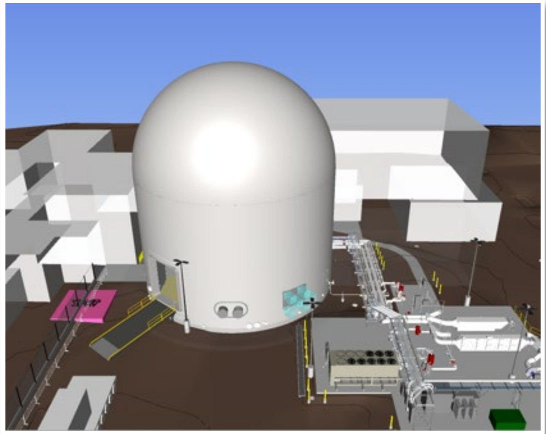
Achieving battery-like functionality for nuclear systems



Advanced Reactors



Advancing technology through fundamental science

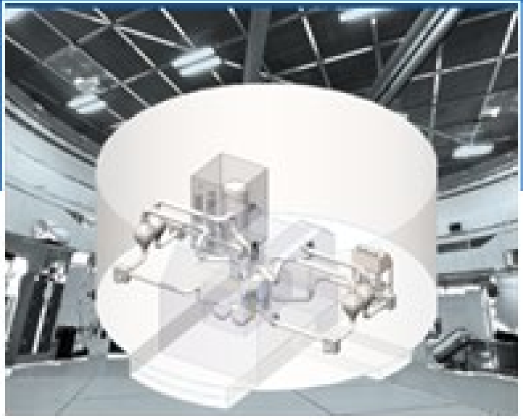


Digital Engineering

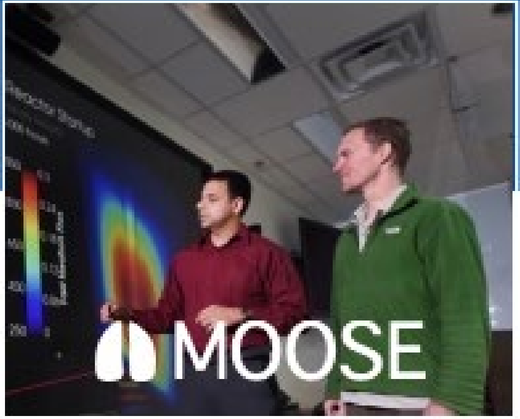
Expanding and Deploying National Nuclear Energy Strategic Infrastructure

Advanced Post Irradiation Examination Capabilities

ATR retrofit to expand irradiation capabilities

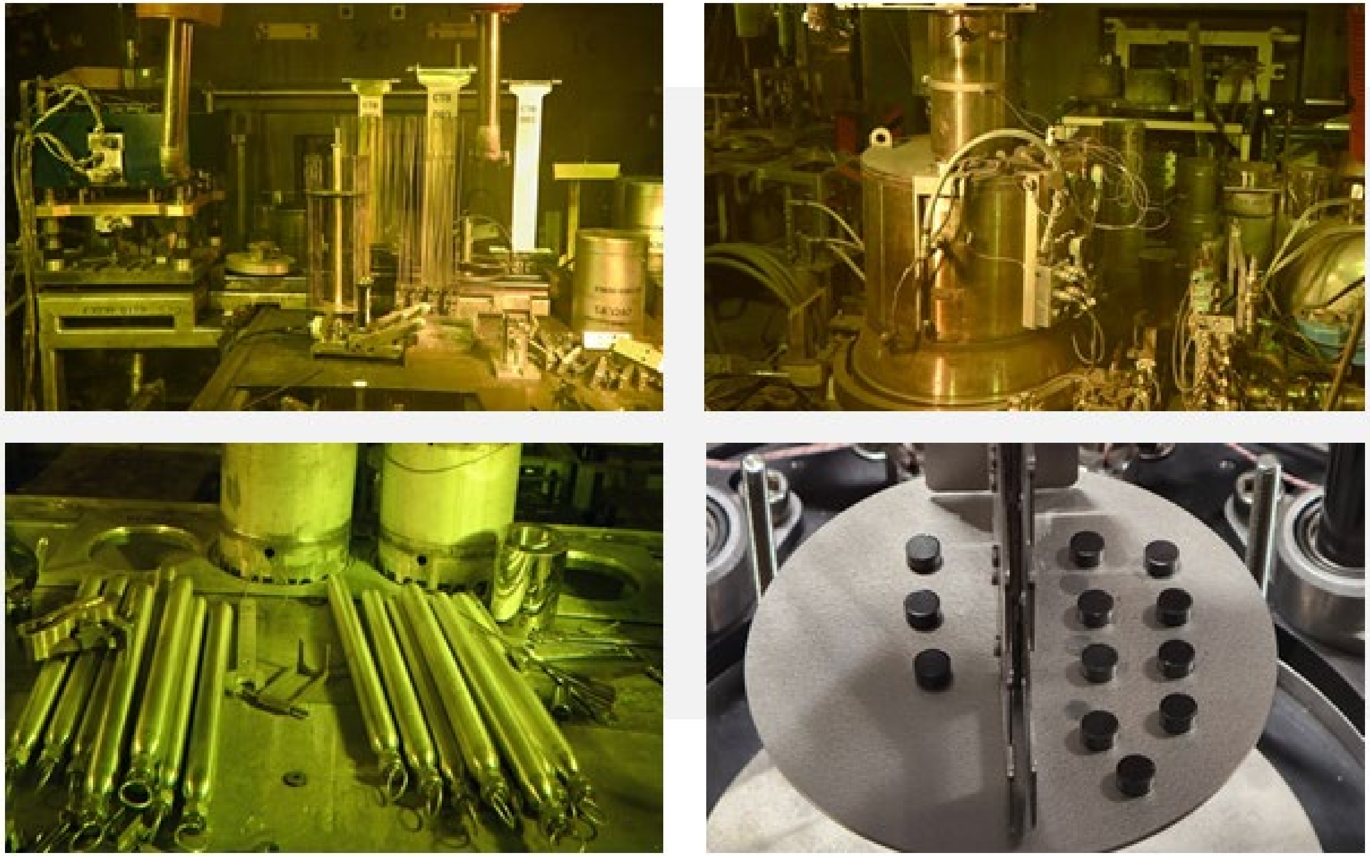


Establishing Testbeds for reactor demonstrations



High performance computing and advanced modeling and simulation capabilities

Working with DOE and Industry to Advance Fuel Recycling RD&D



High-assay low-enriched uranium (HALEU) from recovered stocks, like Experimental Breeder Reactor-II fuel, supports near-term needs of advanced reactor developers and a future domestic fuel cycle capability.

Up-blended UO_2 powder.

Partnering to fabricate lead test rods of up to 6% enrichment for Vogtle Electric Generating Plant, Unit 2

Up-blended 5% enriched Westinghouse UO_2 powder with legacy INL HEU UO_2 powder to 9% effective enrichment

Westinghouse Southern Nuclear

Need HALEU Feedstock and Fuel Fabrication

- Recovery of material from irradiated EBR-II and other high-enriched uranium (HEU) spent fuels
- DOE working to reestablish domestic enrichment
- Initiate operations to support advanced reactor start-up cores

What more needs to be done?

Cost and Schedule Challenges for First of a Kind Systems

- Vogtle units cost and schedule overruns, Olkiluoto in Finland
- Inflation and supply chain issues increasing costs and schedules
- Approaches to Address
  - **Size nuclear to meet specific needs to reduce capital costs (micro, SMR, large)**
  - **Order and build multiple units to reduce costs through learning and shared infrastructure**
  - **AP1000 has 6+ orders and interest expressed by US Utilities**
  - **Strong interest also in Canada, Poland, Romania, UK, emerging interest in many countries**
- Government stimulating nuclear deployment to levelized support for nuclear:
  - **Advanced Reactor Demonstration Program**
  - **BIL – Civil nuclear credit program to address plant shutdowns**
  - **IRA – Production Tax Credits and Investment Tax Credits**
  - **IRA – Hydrogen hubs – 3 of 8 hubs involve nuclear.**
  - **Loan Programs Office has authority to support reactor and facilities for nuclear energy**

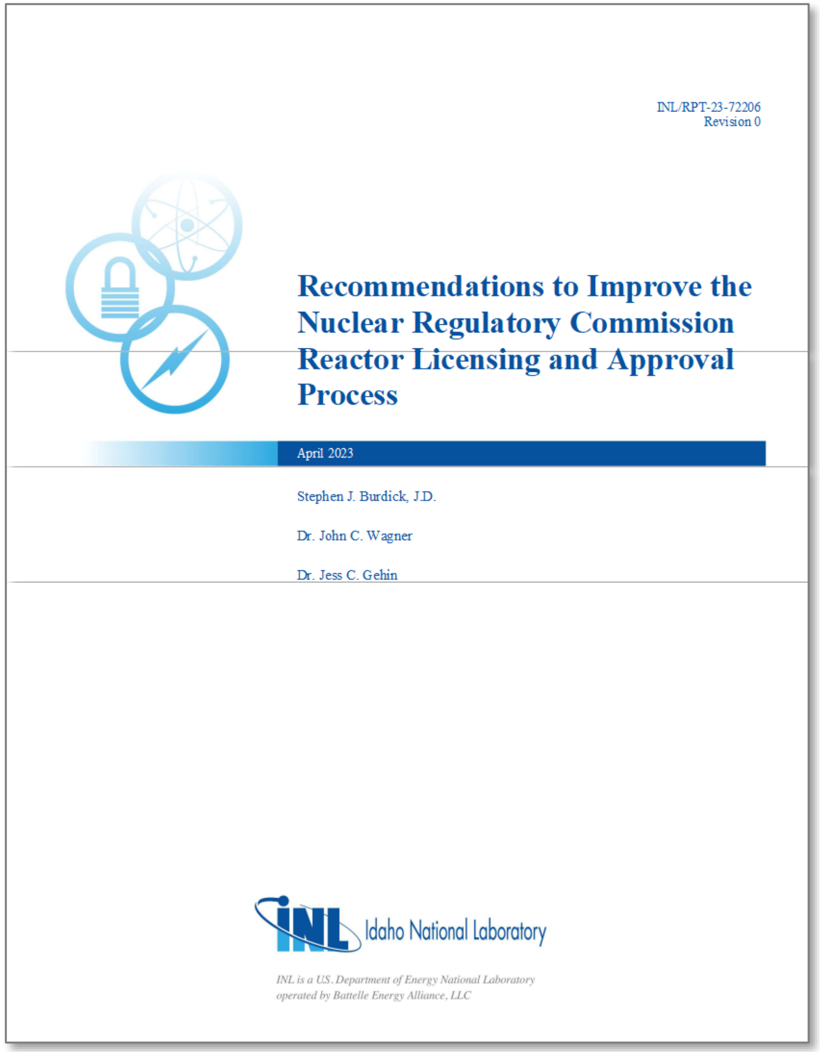
Example: United Arab Emirates – Barakah Plant

Regulatory Certainty

- Concerns about long regulatory review and burdens periods could impact schedule
- NuScale 50 MWe design first SMR design certification
- Kairos Power test reactor construction license approved
- Developers engaging in pre-licensing activities with NRC and in Canada with CSNC

Approaches to Address:

- NRC working on new rule “Part 53” to create technology-neutral licensing framework
- ADVANCE Act being pursued in Congress to increase regulatory certainty
- INL recommendations to improve regulatory process


INL/RPT-23-72206
Revision 0

Recommendations to Improve the Nuclear Regulatory Commission Reactor Licensing and Approval Process

April 2023

Stephen J. Burdick, J.D.

Dr. John C. Wagner

Dr. Jess C. Gehin

Idaho National Laboratory

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

Transforming our Energy System Provides an Opportunity for a Secure and Resilient Clean Energy Future

IDAHO NATIONAL LABORATORY 75TH ANNIVERSARY

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.

INL Idaho National Laboratory | www.inl.gov

Backup Slides

Lead Demonstration of Advanced Reactors: MARVEL

Microreactor Application Research, Validation and EvaLuation Project

MARVEL is the first DOE reactor to achieve 90% Final Design

MAJOR MILESTONES ACHIEVED

- 90% Final Design completed September 2023
- Demonstrated natural circulation and power conversion in thermal hydraulic twin (Primary Coolant Apparatus Test- PCAT)
- Fuel fabrication contract with TRIGA International signed

FY24 DELIVERABLES

- Complete Final design – remaining 10%
- Complete PCAT testing, Submit Preliminary Documented System Analyses (PDSA) to DOE-ID
- Fuel fabrication starts in March 2024, fuel delivery estimated May 2024
- Fabricate reactivity control system

MARVEL goes critical in 2025

Lead Demonstration of Advanced Reactors: Pele

MAJOR MILESTONES ACHIEVED

- Delivered draft Preliminary Safety Analysis Report (PSAR) to DOE-ID (FY 2023 Notable Outcome). Represents a trailblazing effort for the first advanced reactor system PSAR to DOE-ID.
- 18 Equipment Long Lead Procurements (LLP) approved ($64M). The process allows Pele to purchase reactor hardware prior to PSAR approval.
- INL purchased a Mack Defense 86BT Tractor to pull the reactor.
- Important operations staff training completed.
- TRISO Fuel - BWXT-NOG Subcontract: ~50kg of TRISO coated particles fabricated for Pele.

FY24 DELIVERABLES

- Addendum to TREAT SAR allowing fueling of Pele.
- Start site preparation at CITRC Pad A.
- Procure support office building to house operational and reactor engineering staff.
- Support fabrication of Pele, and start DOE design authority approval process.

Lead Demonstration of Advanced Reactors: *MCRE*

Molten Chloride Reactor Experiment

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

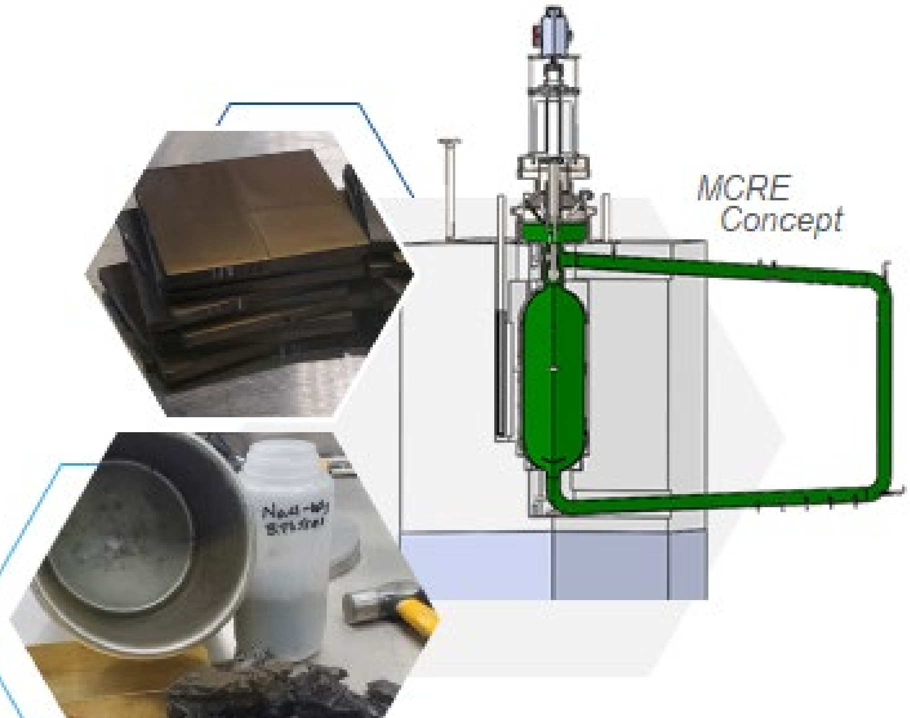
MAJOR MILESTONES ACHIEVED

- Scaled up fuel synthesis process.
- Experiments started at 10g U scale and have progressed to 9kg U (full scale).
- Completed thermophysical property measurements.
- Completed final design of Fuel Salt Synthesis Line (FSSL).
- Placed FSSL Hardware Procurements.
- FSSL furnaces, furnace well/retort, and prototype equipment.

KEY FY24 DELIVERABLES

- Complete final fuel salt scale up demonstrations.
- Begin installation of FSSL.
- Complete final design of Fuel Handling Glovebox (FH

INL is leveraging unique capabilities at MFC to synthesize fuel salt and operate MCRE



MCRE plans to go critical by the end of 2027

Advanced Reactors by Coolant

Advanced Reactors by Coolant

Includes only companies that are engaged in formal licensing or pre-licensing activities with the Nuclear Regulatory Commission for power-producing reactors.

- 🟢 HALEU (High-assay low-enriched uranium is 5-20% U-235)
- 🟣 Fast neutron reactor

GAS: Gas is used to transfer heat from the core. Helium is favored because it is inert and does not react with other materials or deteriorate components.

Micro Modular Reactor (3.5-15 MWe)
- Fuel: TRISO 🟢
- Company: Ultra Safe Nuclear Corp.

Fast Modular Reactor (44 MWe) 🟣
- Fuel: Uranium oxide 🟢
- Company: General Atomics

Xe-100 (80 MWe per module)
- Fuel: TRISO 🟢
- Company: X-energy

Energy Multiplier Module (265 MWe) 🟣
- Fuel: Uranium carbide 🟢
- Company: General Atomics

WATER: Highly purified water carries heat from the reactor core.

VOYGR (77 MWe per module)
- Fuel: Uranium oxide
- Company: NuScale Power

SMR-160 (160 MWe)
- Fuel: Uranium oxide
- Company: Holtec International

BWRX-300 (300 MWe)
- Fuel: Uranium oxide
- Company: GE-Hitachi

AP300 (300 MWe)
- Fuel: Uranium oxide
- Company: Westinghouse

MOLTEN SALT: Melted (or molten) salt transfers the heat, which has a high boiling point, so the reactors can run at higher temperatures and lower pressures. Fuel can be in the salt or in solid form.

Fluoride Salt-Cooled High-Temperature Reactor (140 MWe)
- Fuel: TRISO (solid fuel) 🟢
- Company: Kairos Power

Integral Molten Salt Reactor (195 MWe)
- Fuel: Uranium molten fluoride
- Company: Terrestrial Energy

Molten Chloride Fast Reactor (310 MWe) 🟣
- Fuel: Molten salt 🟢
- Company: TerraPower

LIQUID METAL: Liquid metal, often sodium or lead, transfers the heat in these reactors. Liquid metals do not slow down neutrons and are typically used for fast neutron reactors.

Aurora (15 MWe) 🟣
- Fuel: Uranium metal alloy 🟢
- Company: Oklo

ARC-100 (100 MWe) 🟣
- Fuel: Uranium metal alloy 🟢
- Company: ARC Clean Technology

Natrium (345 MWe) 🟣
- Fuel: Uranium metal alloy 🟢
- Company: TerraPower

HEAT PIPES: Heat pipes made from steel alloys transfer heat away from the reactor core with no moving parts.

eVinci (5 MWe)
- Fuel: TRISO 🟢
- Company: Westinghouse

Advanced Reactors by Size

Advanced Reactors by Size

Includes only companies that are engaged in formal licensing or pre-licensing activities with the Nuclear Regulatory Commission for power-producing reactors.

🟢 HALEU (High-assay low-enriched uranium is 5-20% U-235)
🟣 Fast neutron reactor

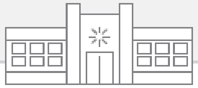
Up to ~50 MWe

Micro Modular Reactor (3.5-15 MWe)
- Company: Ultra Safe Nuclear Corp.
- Coolant: Gas (helium)
- Fuel: TRISO 🟢

eVinci (5 MWe)
- Company: Westinghouse
- Coolant: Heat pipes
- Fuel: TRISO 🟢

Aurora (15 MWe) 🟣
- Company: Oklo
- Coolant: Metal (sodium)
- Fuel: Uranium metal alloy 🟢

Fast Modular Reactor (44 MWe) 🟣
- Company: General Atomics
- Coolant: Gas (helium)
- Fuel: Uranium oxide 🟢



MICROREACTORS

- 1 MWe can power a big-box superstore
- Factory fabricated, readily transportable
- Minimal on-site staffing

10s to mid-100s of MWe

VOYGR (77 MWe per module)
- Company: NuScale Power
- Coolant: Water
- Fuel: Uranium oxide

Xe-100 (80 MWe per module)
- Company: X-energy
- Coolant: Gas (helium)
- Fuel: TRISO 🟢

ARC-100 (100 MWe) 🟣
- Company: ARC Clean Technology
- Coolant: Metal (sodium)
- Fuel: Uranium metal alloy 🟢

Fluoride Salt-Cooled High Temperature Reactor (140 MWe)
- Company: Kairos Power
- Coolant: Salt (fluoride)
- Fuel: TRISO 🟢

SMR-160 (160 MWe)
- Company: Holtec International
- Coolant: Water
- Fuel: Uranium oxide

Integral Molten Salt Reactor (195 MWe)
- Company: Terrestrial Energy
- Coolant: Salt (fluoride)
- Fuel: Uranium molten salt

Energy Multiplier Module (265 MWe) 🟣
- Company: General Atomics
- Coolant: Gas
- Fuel: Uranium carbide 🟢

BWRX-300 (300 MWe)
- Company: GE-Hitachi
- Coolant: Water
- Fuel: Uranium oxide

AP300 (300 MWe)
- Company: Westinghouse
- Coolant: Water
- Fuel: Uranium oxide

Natrium (345 MWe) 🟣
- Company: TerraPower
- Coolant: Metal (sodium)
- Fuel: Uranium metal alloy 🟢

Molten Chloride Fast Reactor (310 MWe) 🟣
- Company: TerraPower
- Coolant: Salt (chloride)
- Fuel: Molten salt 🟢

SMALL AND MEDIUM ADVANCED REACTORS

- 100 MWe can power about 100,000 U.S. homes
- Flexible operation to meet demand
- Major components factory fabricated
- Can add modules as demand increases
- Reduced construction times