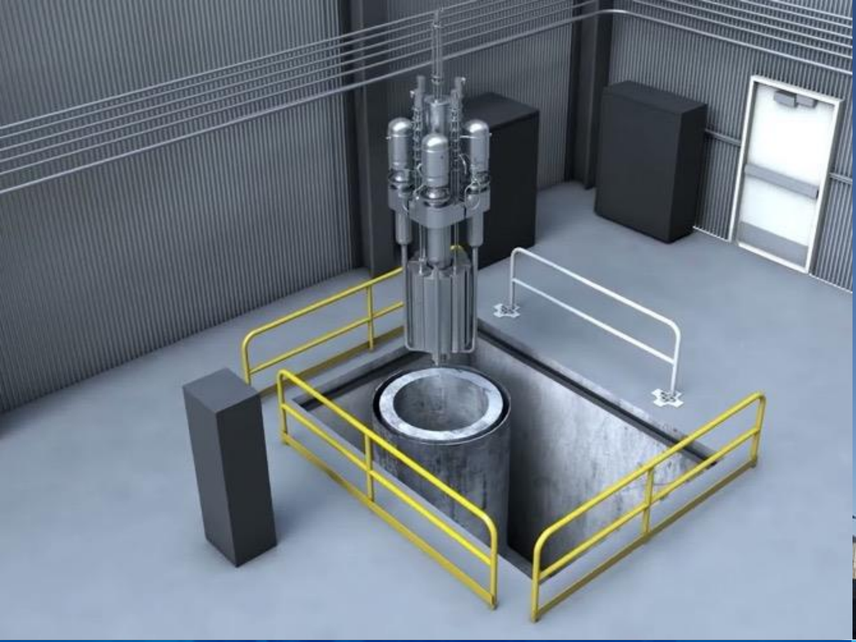


October 22, 2024

Paul Talbot

Modeling and Simulation lead, DOE-NE Integrated Energy Systems Program

Paul.Talbot@inl.gov

Power is the New Water: Nuclear Energy and Data Centers

Idaho National Laboratory

INL/CON-24-81352

Nuclear Data Centers: In the News

Amazon buys nuclear-powered data center from Talen

Thu, Mar 7, 2024, 6:01AM | Nuclear News

Susquehanna nuclear plant in Salem Township, Penn., along with the data center in foreground. (Photo: Talen Energy)

www.ans.org,March 2024

EIA

Data center owners turn to nuclear as potential electricity source

8 days ago

CNBC

Oracle is designing a data center that would be powered by three small nuclear reactors

Sep 10 • By Spencer Kimball

DatacenterDynamics

AWS hiring for data center 'principal nuclear engineer' to evaluate SMRs and nuclear fuel strategy roadmaps

Sep 20 • By Sebastian Moss

NBC NEWS

Three Mile Island nuclear plant to help power Microsoft's data-center needs

Sep 20 • By Rob Wile

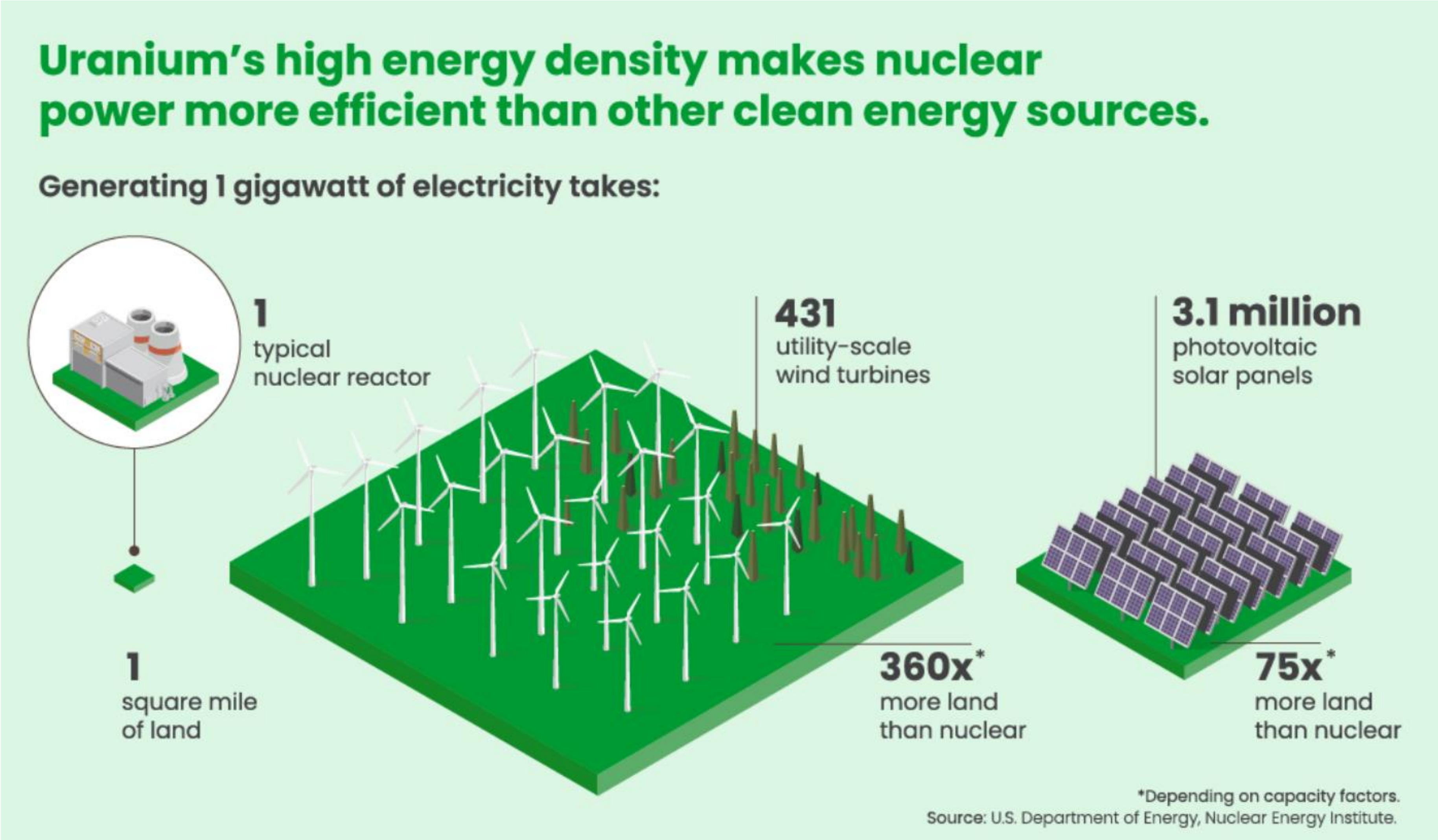
US Definition: Advanced Reactors

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” or “new” reactors. ***Improved safety*** is the focus.

Nuclear Energy Density Leads to Small Footprints

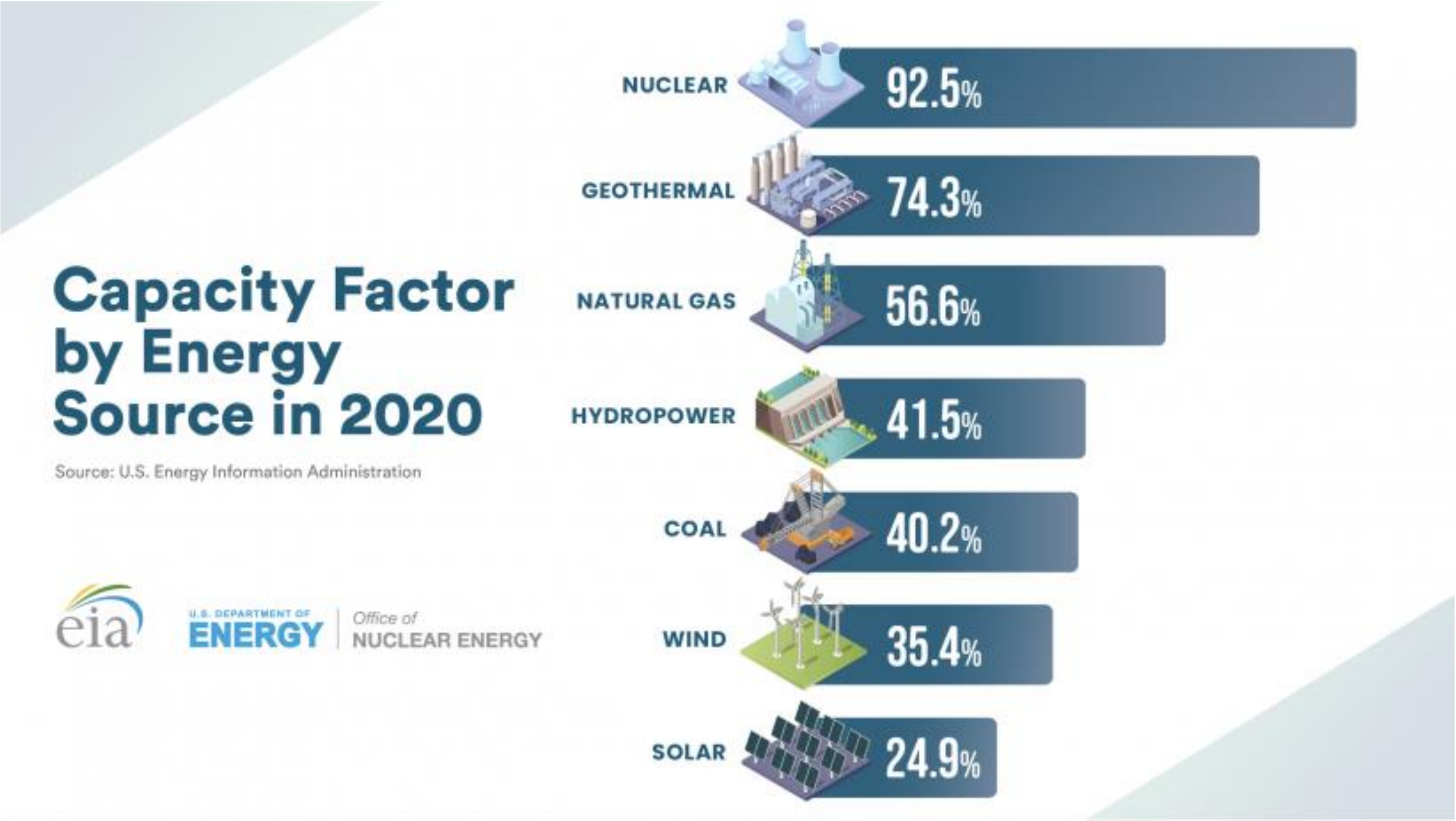


https://www.visualcapitalist.com/sp/smashing-atoms-the-history-of-uranium-and-nuclear-power/

Why Nuclear? Reliability

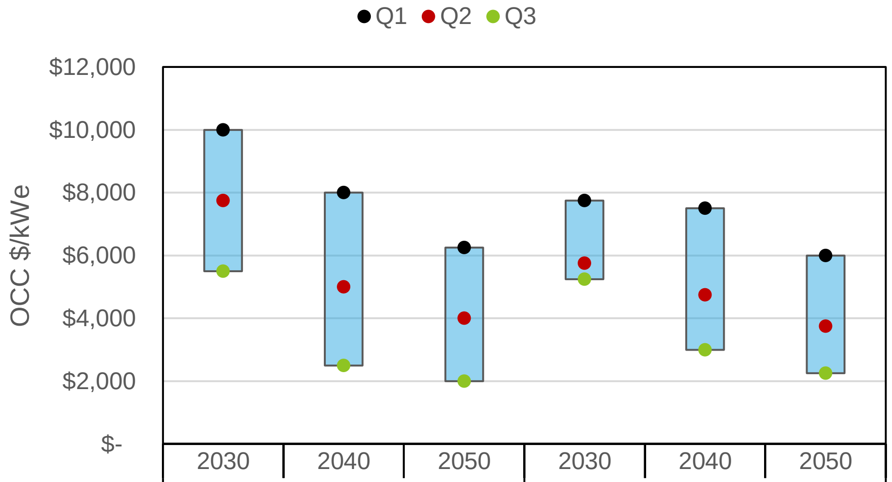
- Zero-carbon solutions for high-demand systems
- Reliable, 92+% uptime *per unit*
  - 99.99+% multiunit

- Nuclear Energy
  - Large Nuclear
  - Small Modular Reactors
  - Microreactors



Reference Cost Ranges for Large and Small Modular Reactors

- Meta-study of cost estimation reports for advanced reactors
- Focus on detailed bottom-up estimates to ensure cross-comparison
- Costs are given in conservative, moderate, advanced scenarios to highlight potential ranges of capital costs
- Costs are shown as Between-of-a-kind (BOAK) or costs after First-of-a-kind demonstrations have taken place, but before Nth-of-a-kind learning as materialized
- Additional data provided on broad range of other considerations, including:
  - Construction times, heat-only adjustments, multi-unit cost factors, ramp rates, subsidies, coal-to-nuclear, etc.



	Small Modular Reactor 2030	Small Modular Reactor 2040	Small Modular Reactor 2050	Large Reactor 2030	Large Reactor 2040	Large Reactor 2050
Q1	$10,000	$8,000	$6,250	$7,750	$7,500	$6,000
Q2	$7,750	$5,000	$4,000	$5,750	$4,750	$3,750
Q3	$5,500	$2,500	$2,000	$5,250	$3,000	$2,250

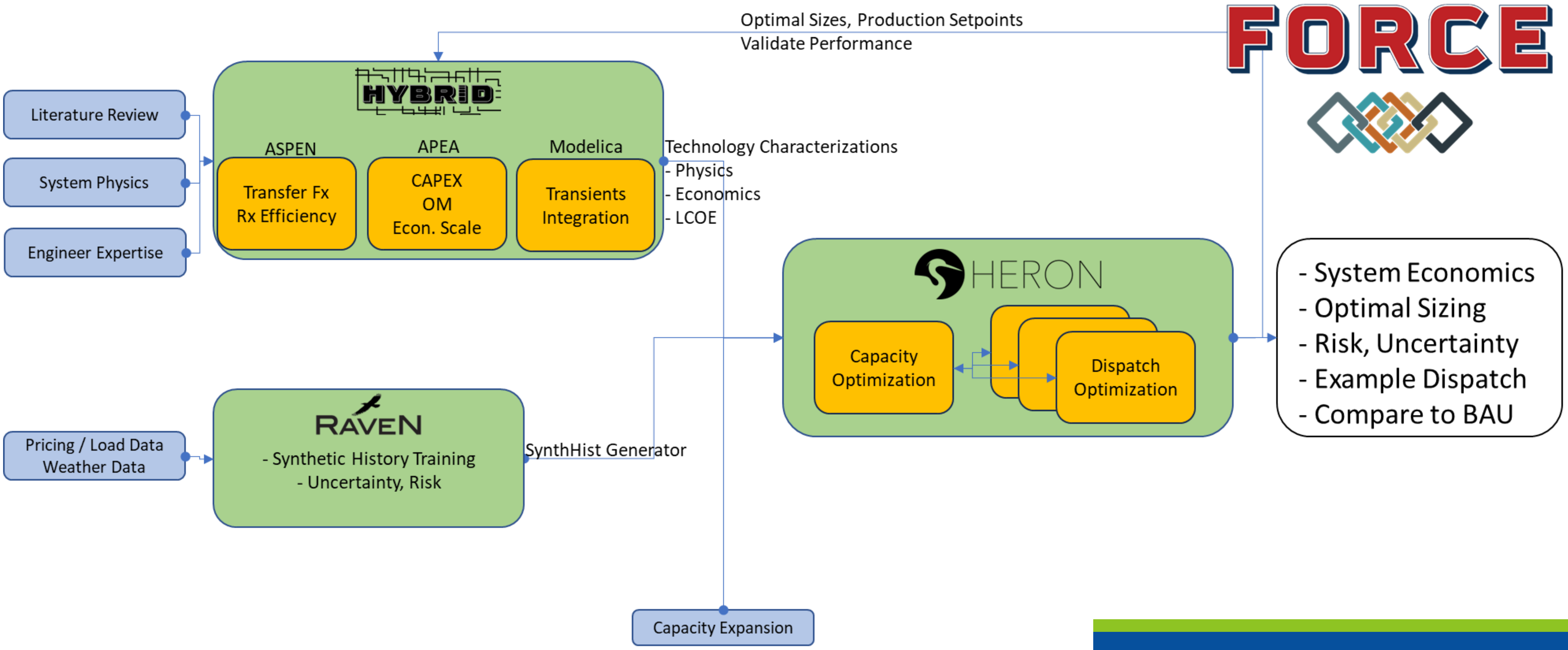
Reference Overnight Capital Costs (OCC) for large reactors and SMRs

Reference O&M costs for large reactors and SMRs

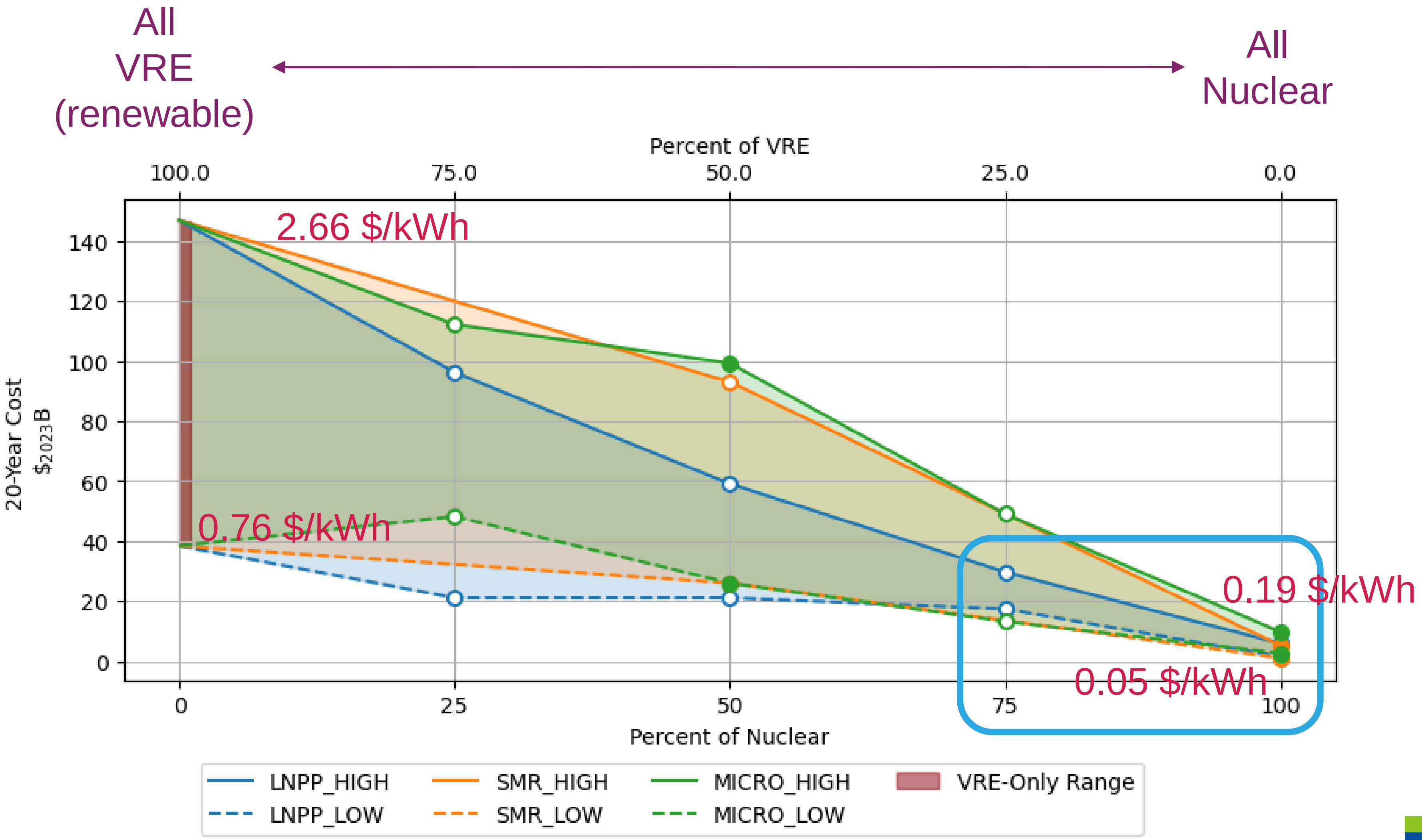
	Large Reactor			SMR		
	Advanced	Moderate	Conservative	Advanced	Moderate	Conservative
Nuclear Fuel Costs ($/MWh)	9.1	10.3	11.3	10.0	11.0	12.1
Nuclear Fuel Costs ($/MBTU)	0.88	0.99	1.09	0.97	1.06	1.17
Fixed non-fuel O&M ($/kWe-yr)	126	175	204	118	136	216
Fixed O&M ($/MWh) @ 93% capacity factor	15.5	21.5	25.1	14.5	16.6	26.5
Variable non-fuel O&M ($/MWh)	1.9	2.8	3.4	2.2	2.6	2.8
Total O&M ($/MWh)	26	35	40	27	30	41

Report: link
Data: link
ATB nuclear page: link

Modeling: Technoeconomic Analysis



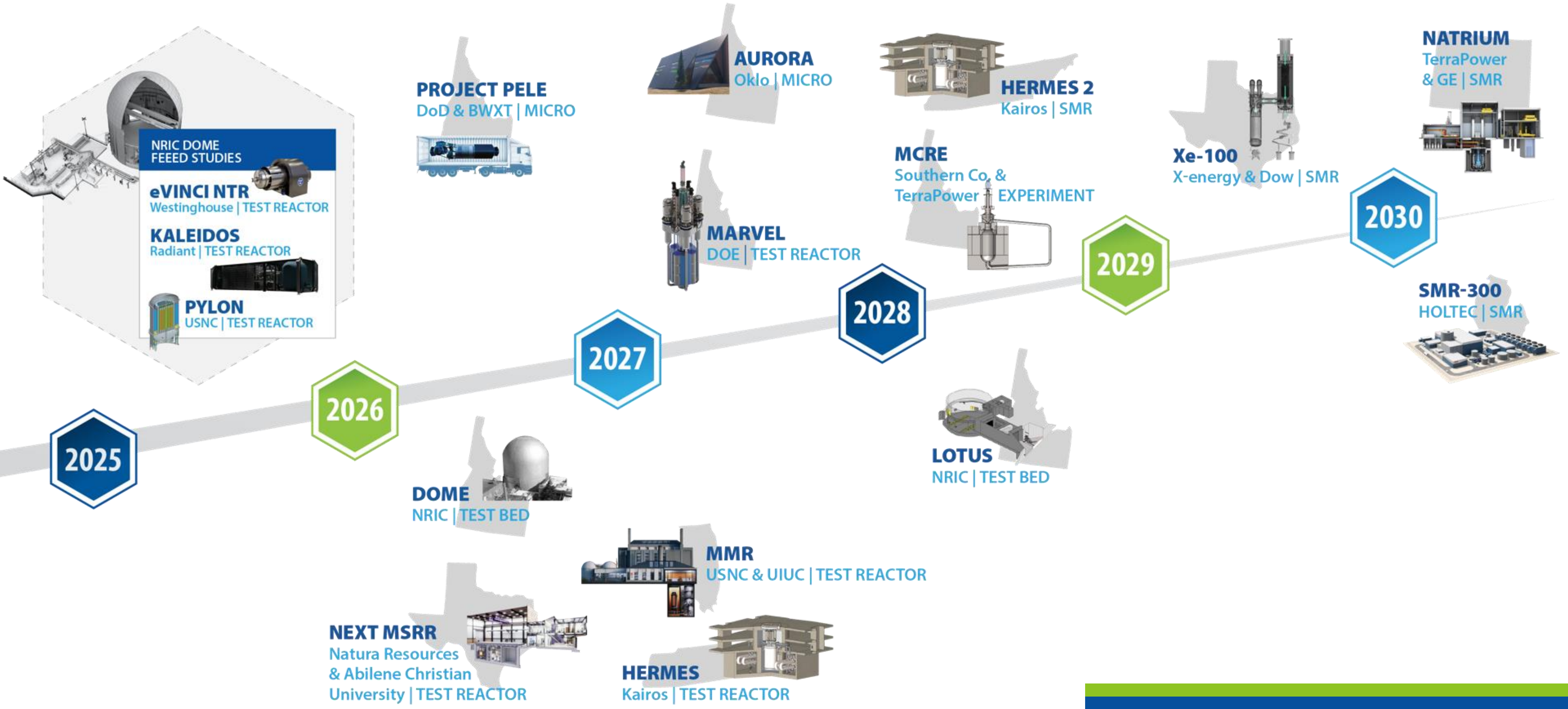
Analysis Results: Carbon-Free Options



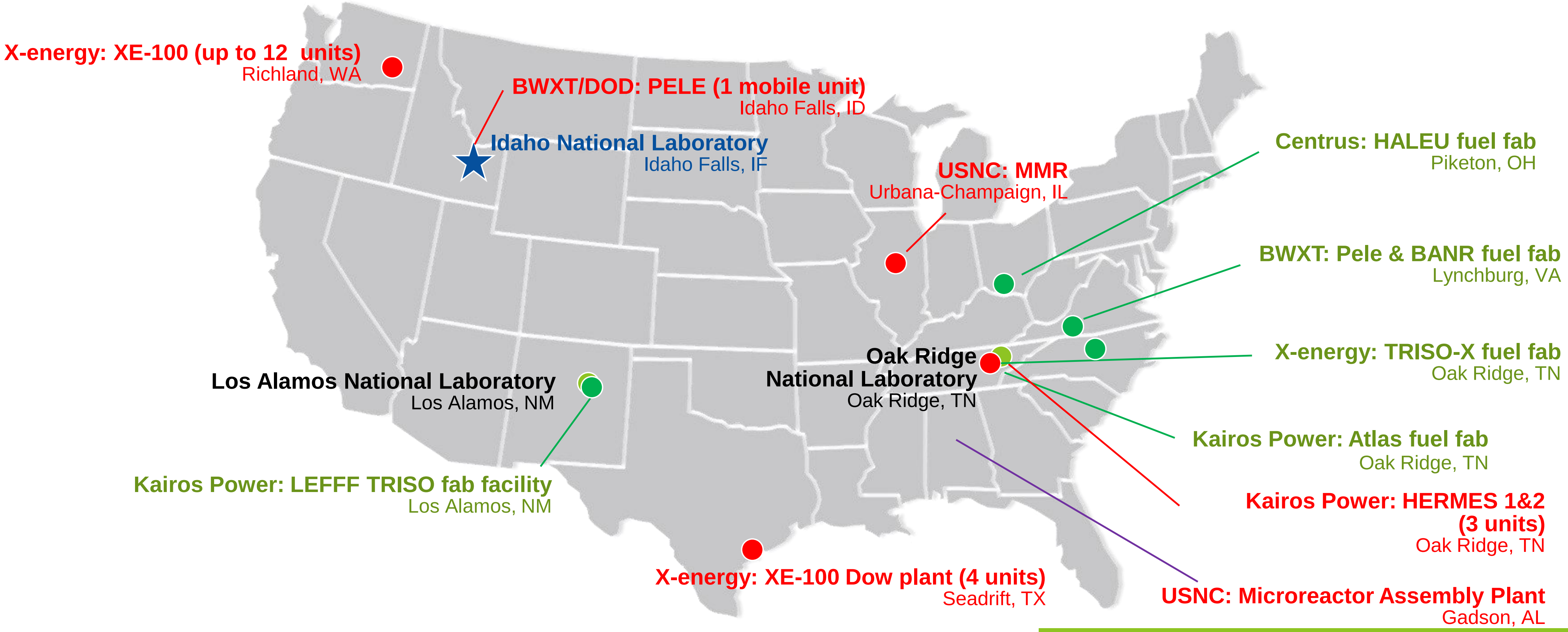
Notes

- Cost: 20-year build-and-operate discounted cost (NPV)
- High all-nuclear cost still lower than all-VRE
- Wide range of uncertainty
- Very large costs for VRE
  - Battery requirement
  - Capacity factors

Accelerating Advanced Reactor Demonstration & Deployment



Commercial and Demonstration Projects: Planned Reactor and Fuel Fabrication Facilities



GAS-COOLED REACTOR
ADVANCED REACTOR TECHNOLOGIES PROGRAM

Advanced Reactor Licensing Status

Small Modular Light Water Reactors

- NuScale US600
- NuScale US460
- Holtec SMR-300 *
- Westinghouse AP300*

Pressurized Water Reactors

- GEH BWRX-300*

Boiling Water Reactor

Liquid Metal Cooled Fast Reactors (LMFR)

- TerraPower/GEH (Natrium)*
- GEH PRISM (VTR)
- ARC Clean Technology *

Sodium-Cooled

- Westinghouse
- Columbia Basin
- Hydromine

Lead-Cooled

High-Temperature Gas-Cooled Reactors (HTGR)

- X-energy (Xe-100)*
- Framatome
- StarCore
- MIT

TRISO Fuel

- General Atomics (EM2) *
- General Atomics*

Molten Salt Reactors (MSR)

- Kairos *
- Kairos (Hermes | RTR)

Liquid Salt Cooled

- Terrestrial *
- TerraPower (MCFR)
- Southern (TP MCRE) | RTR
- ACU | RTR
- Elysium
- ThorCon
- Muons
- Flibe
- Alpha Tech

Liquid Salt Fueled

Micro Reactors

- Westinghouse (eVinci) *
- BWX Technologies
- X-energy
- Radiant *
- Ultra Safe Nuclear
- Alpha Tech
- Nano Nuclear Energy

Transportable

- UIUC / Ultra Safe | RTR*
- Oklo *

Stationary

LEGEND

ARDP Awardees
- Demo Reactors
- Risk Reduction
- ARC-20

(bold box)	In Licensing Review
*	Preapplication
RTR	Research/Test Reactor

Connecting with Advanced Nuclear

Gateway for Accelerated Innovation in Nuclear

@GAINnuclear | gain.inl.gov

- Gateway for Accelerated Innovation in Nuclear (GAIN)
  - Technoeconomic Assessments
    - What about wind, solar, and nuclear in my region?
    - Vouchers for DOE Lab Complex to partner with you for analysis
  - Community Engagement and Outreach

- Data Center Workshop Group
  - Lori Braase, lori.braase@inl.gov
- Learn more about advanced reactors
  - Gerhard Strydom, gerhard.strydom@inl.gov
- Integrated Energy System Modeling and Simulation
  - Paul Talbot, paul.talbot@inl.gov

GAS-COOLED REACTOR
ADVANCED REACTOR TECHNOLOGIES PROGRAM

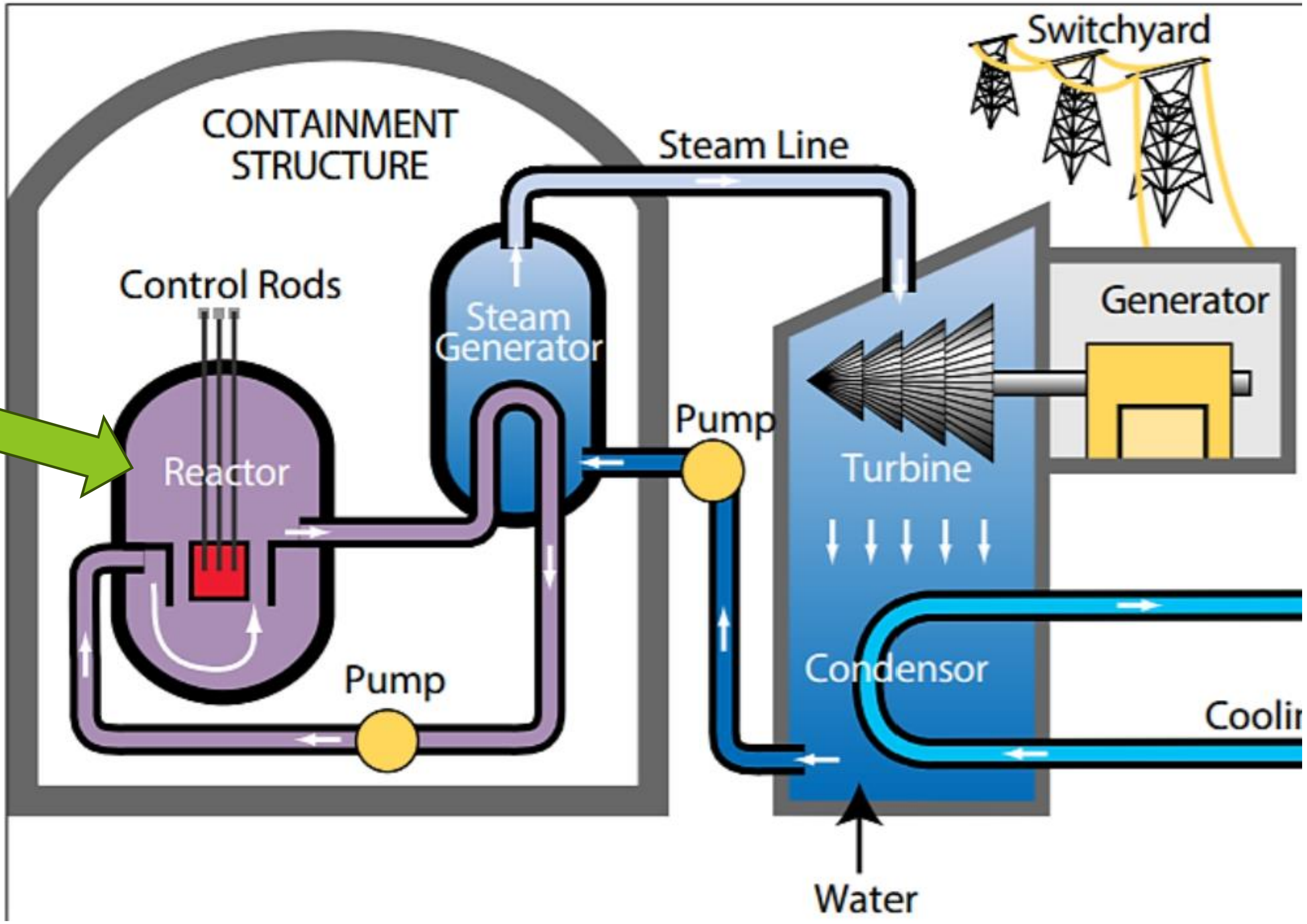
IES
Integrated Energy Systems

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.

Additional Materials

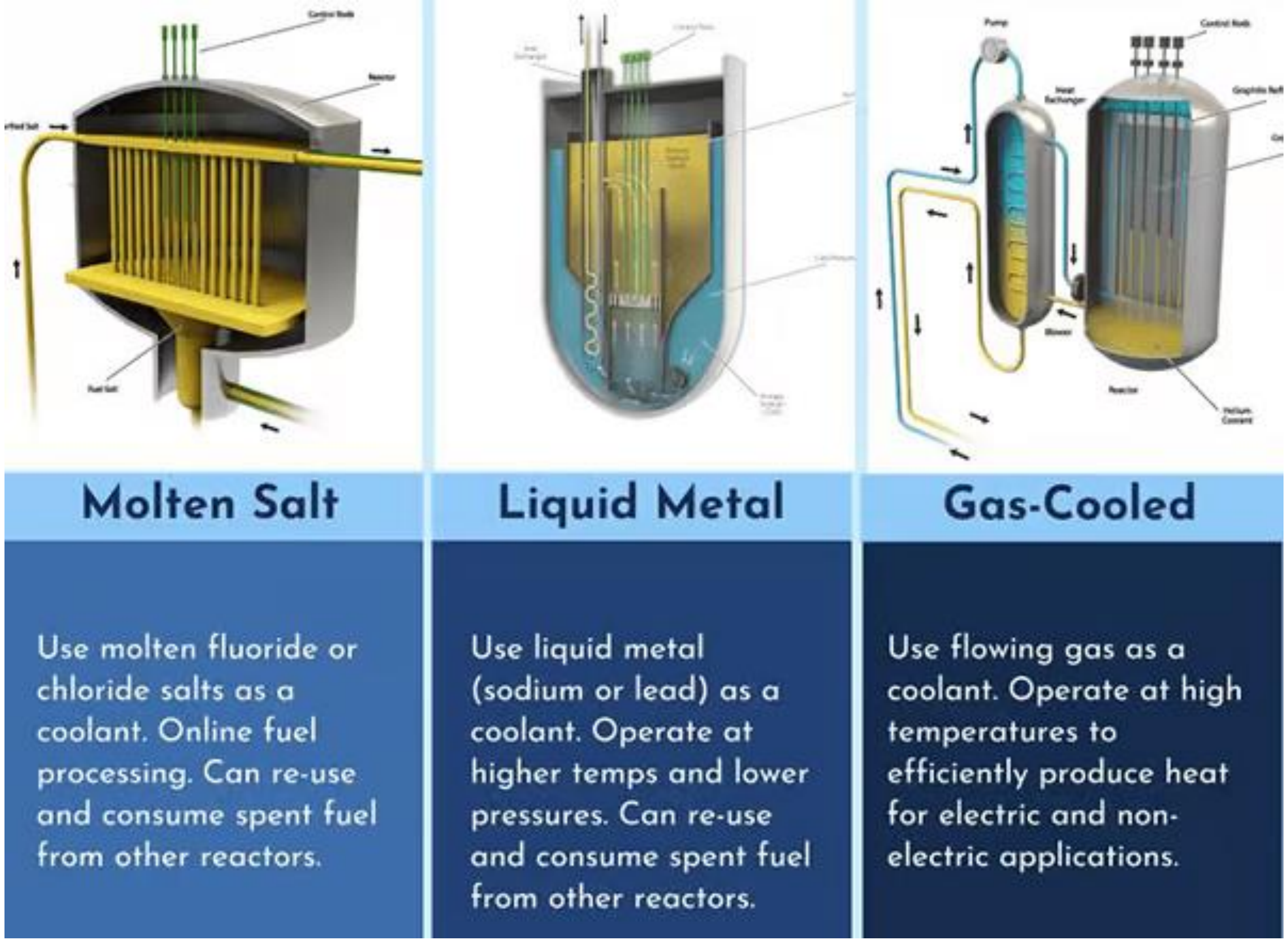
Nuclear Reactors 101

Light Water Reactor: Primary system coolant is water



https://www.linquip.com/blog/nuclear-power-plant-guide/

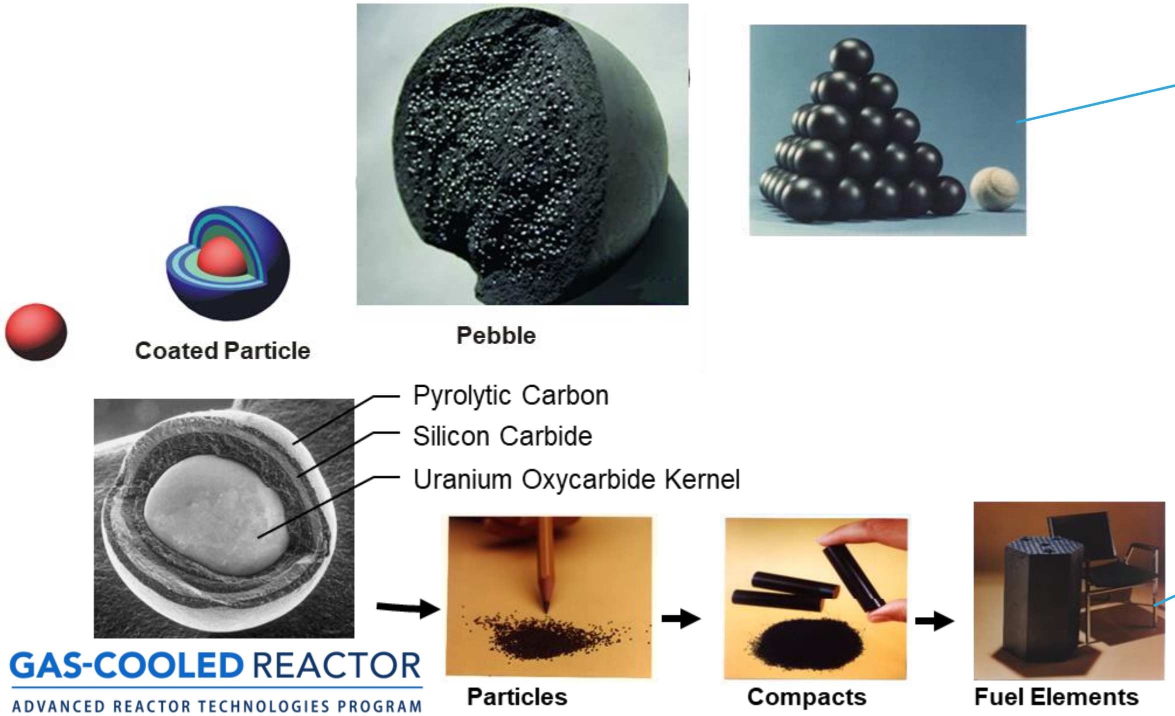
Advanced Reactors (non-water systems)

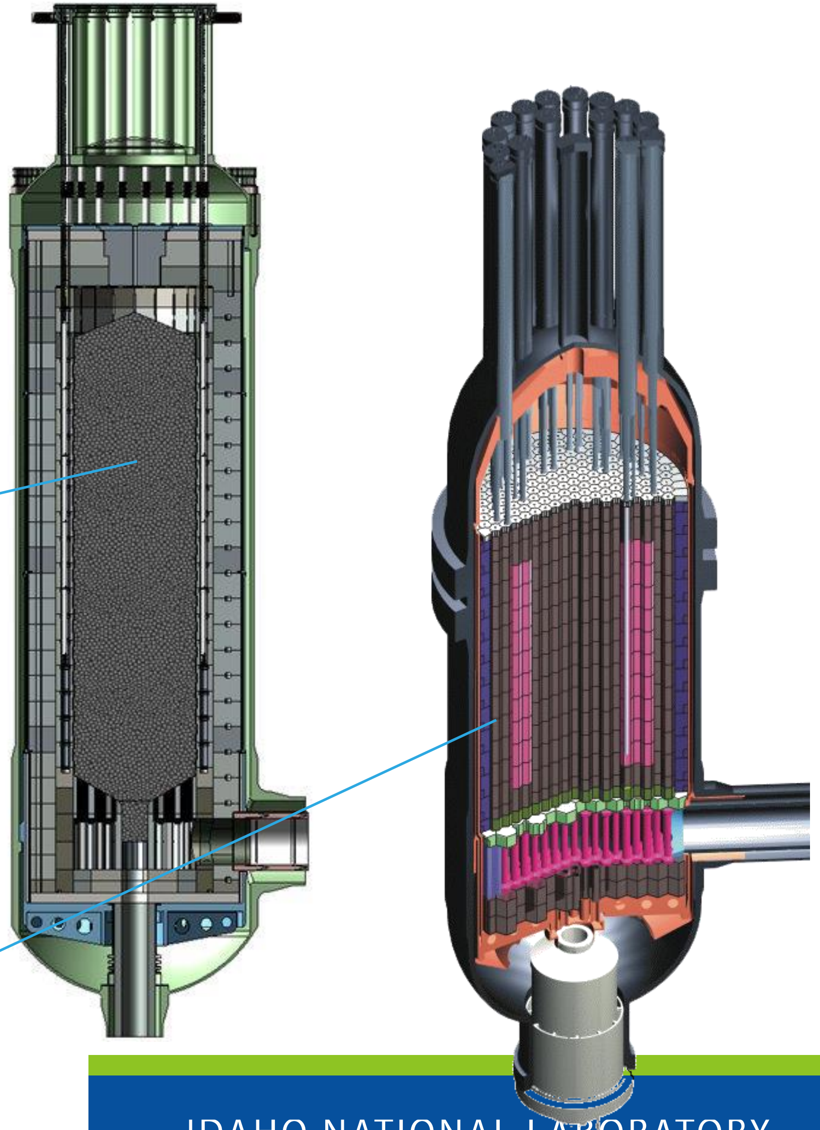


https://www.bluewaveailabs.com/3-advanced-reactor-systems-to-watch-by-2030/

Modular High-Temperature Gas-Cooled Reactors (HTGRs)

- UO2 or UCO TRISO {*Tristructural isotropic}:* inner pyrolytic carbon (PyC), SiC, outer (PyC).
- Pressed into semi-graphitic matrix and shaped into either ‘compacts’ or pebbles.
- Cylindrical or annular cores (with central graphite reflector)





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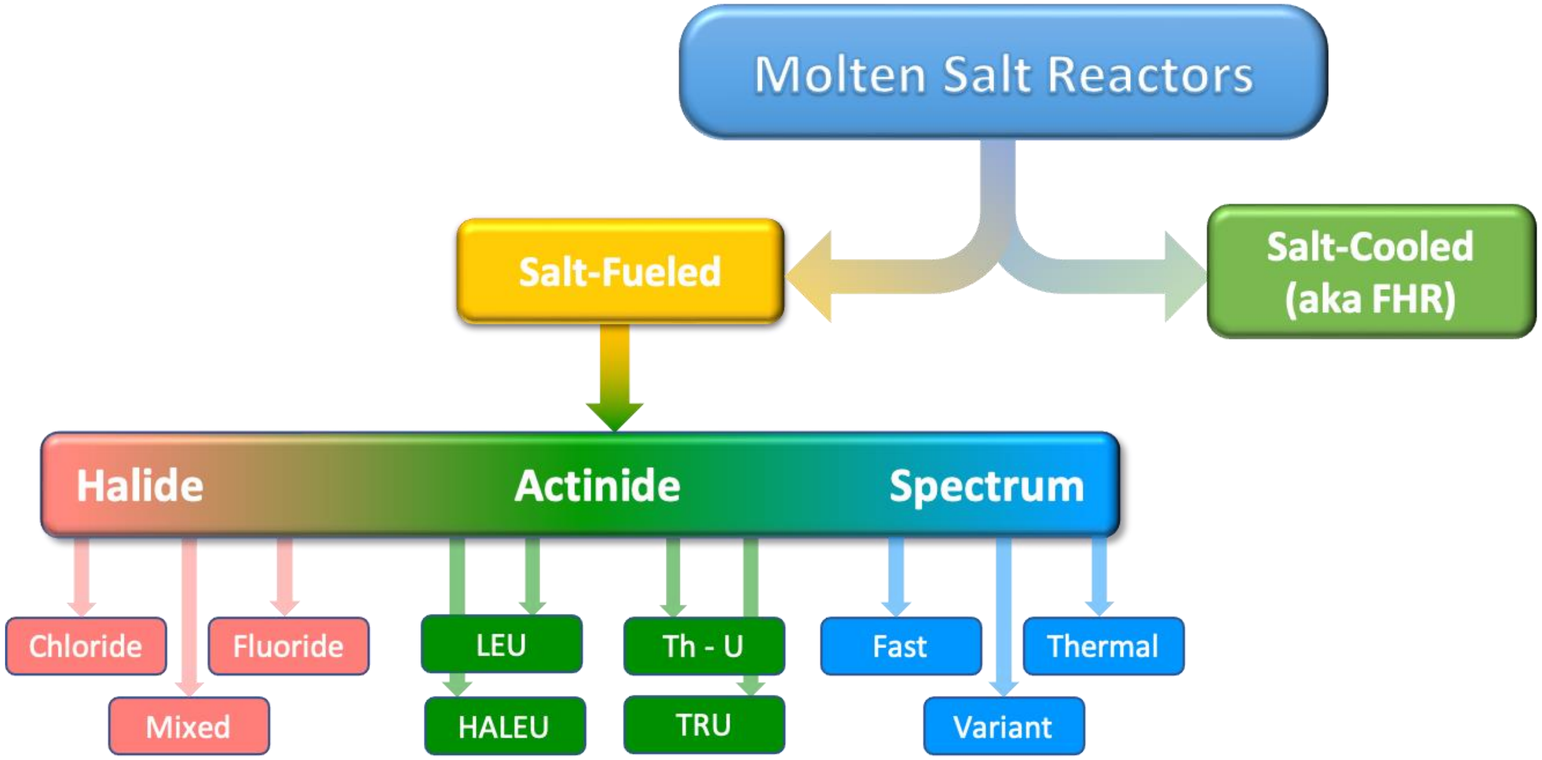
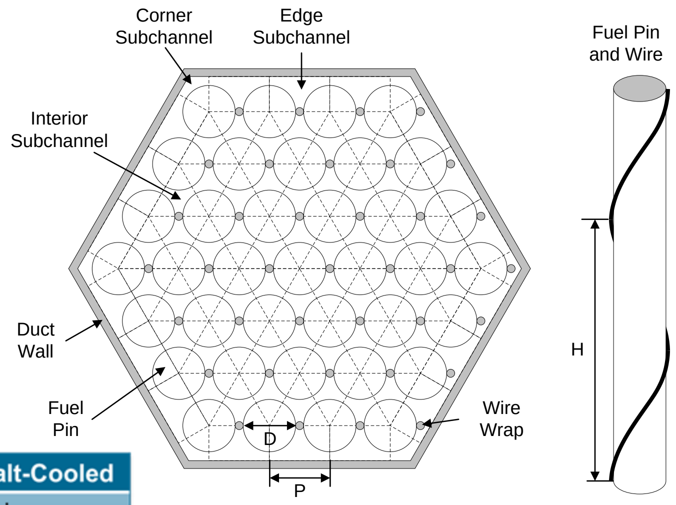
Molten Salt Reactors (MSRs)

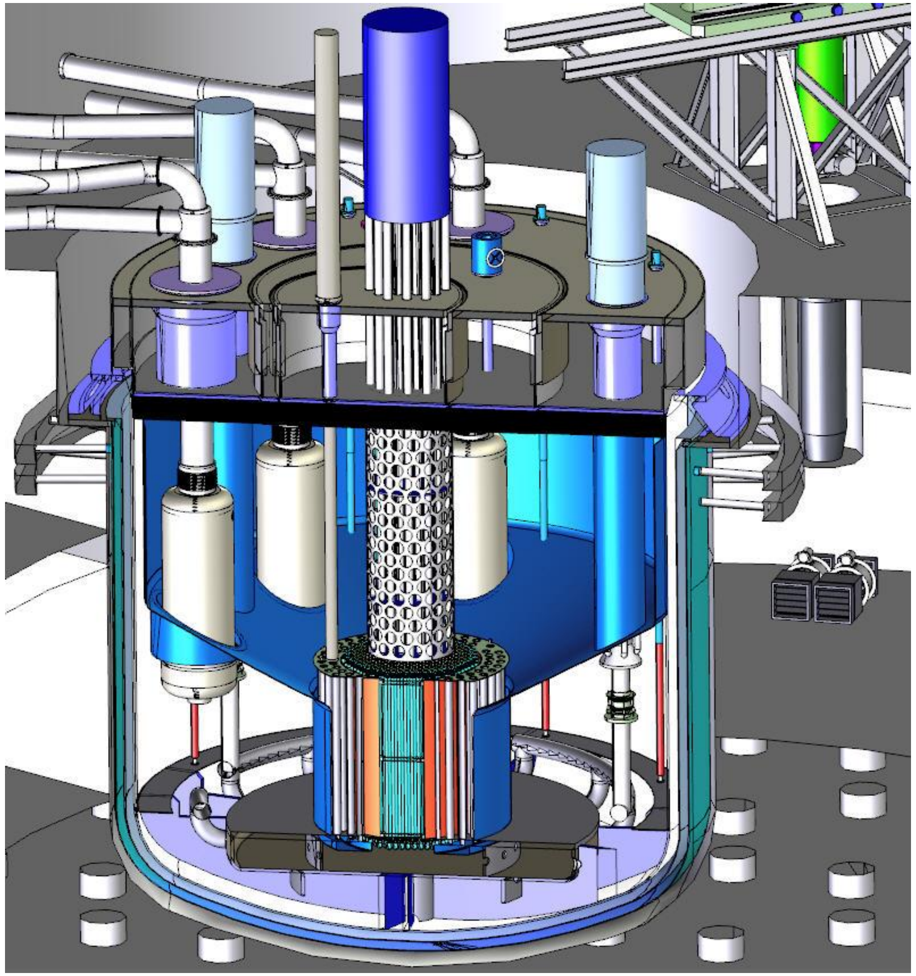


- Liquid- and solid-fueled variants
- Chloride-, fluoride-, and mixed halide-based fuel salts
- Salt and liquid-metal coolants
- Thermal, fast, time-variant, and spatially variant neutron spectra
- Wide range of power scales
- Intensive, minimal, or inherent fuel processing
- Multiple different primary system configurations
- Nearly all fuel cycles

Fast Reactors (FRs)

- FRs typically operates at near atmospheric pressure
- Fast neutron energy spectrum (no moderation)
- Significant US experience (EBR-I, EBR-II, FFTF, SEFOR, FERMI, etc.)
- System Configuration
  - Metal Alloy or Oxide Fuel
  - Pool or Loop Configuration
  - High Power Density Core

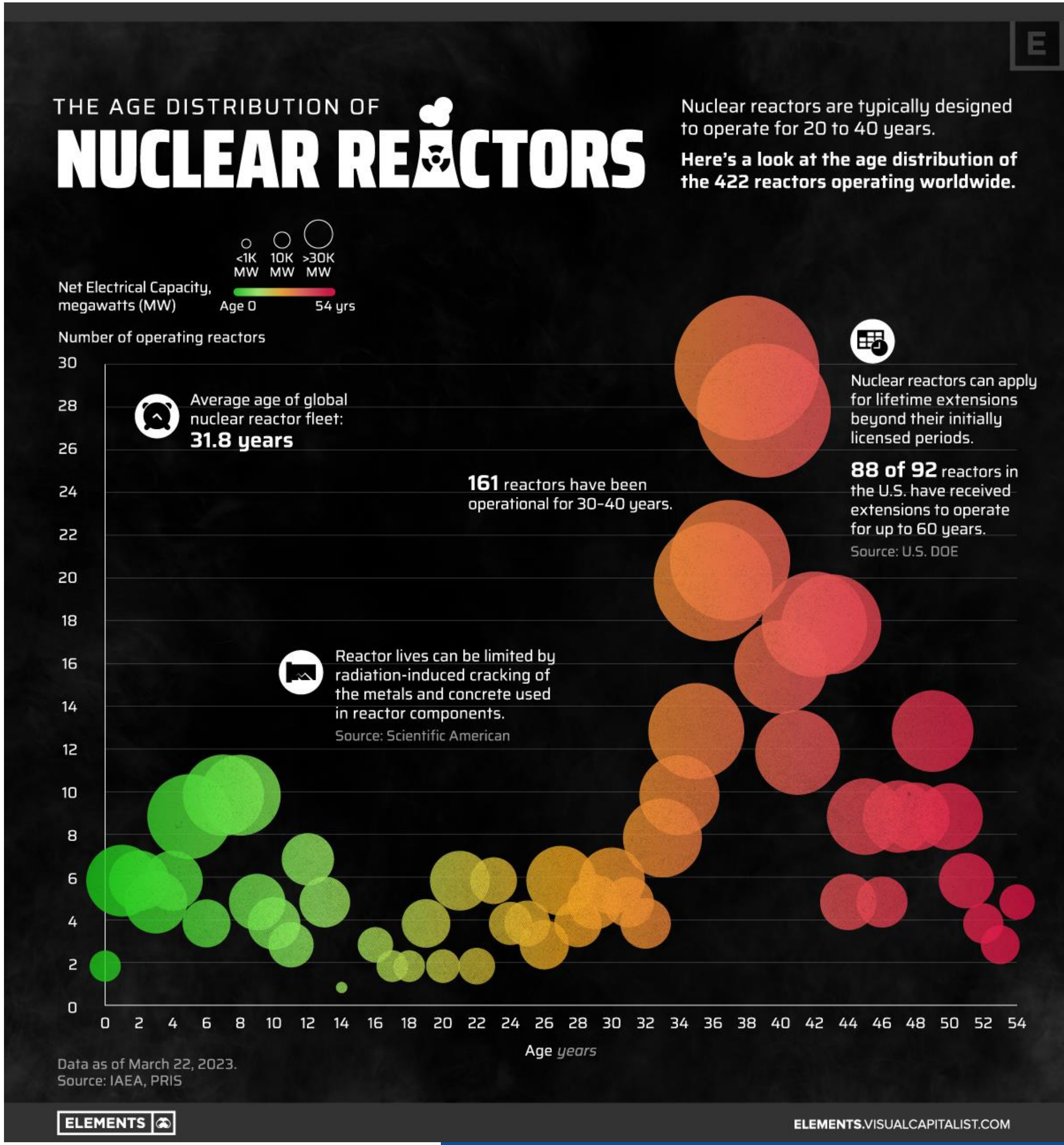




Sodium-Cooled	Lead-Cooled	Gas-Cooled	Molten Salt-Cooled
Oklo	Westinghouse	General Atomics	Elysium
General Electric	Columbia Basin Consulting Group		Southern/TerraPower
TerraPower			Flibe Energy
Advanced Reactor Concepts			

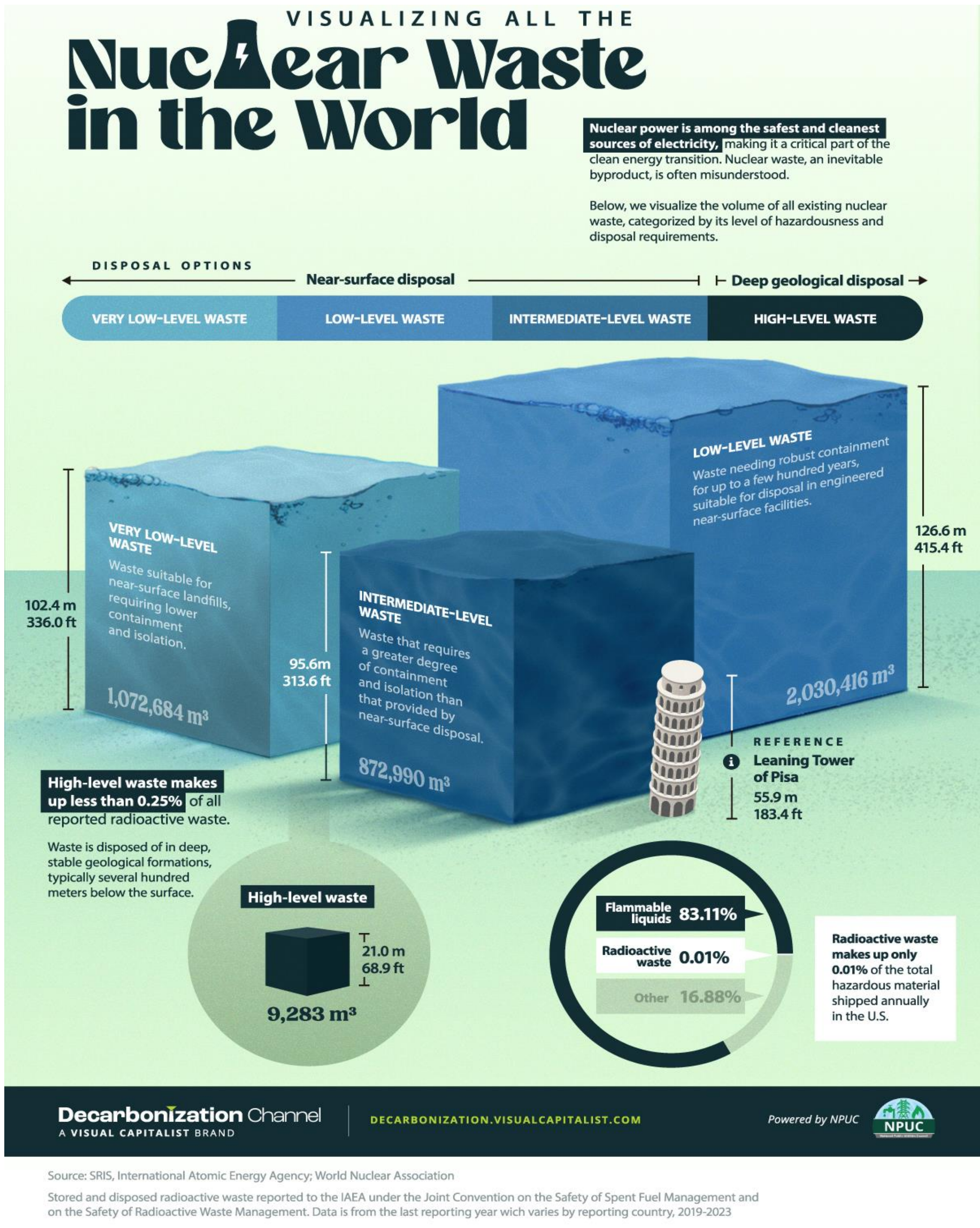
Nuclear Reactor Fleet Age

- Average age of 422 nuclear reactors operating in 2023 is 32 years.
- If today's nuclear plants retire after 60 years of operation, the US would need 22 GWe of new nuclear capacity by 2030 and 55 GWe by 2035 to maintain a 20% nuclear share.
- That is equal to building 25 Vogtle plants by 2035.



Nuclear Waste

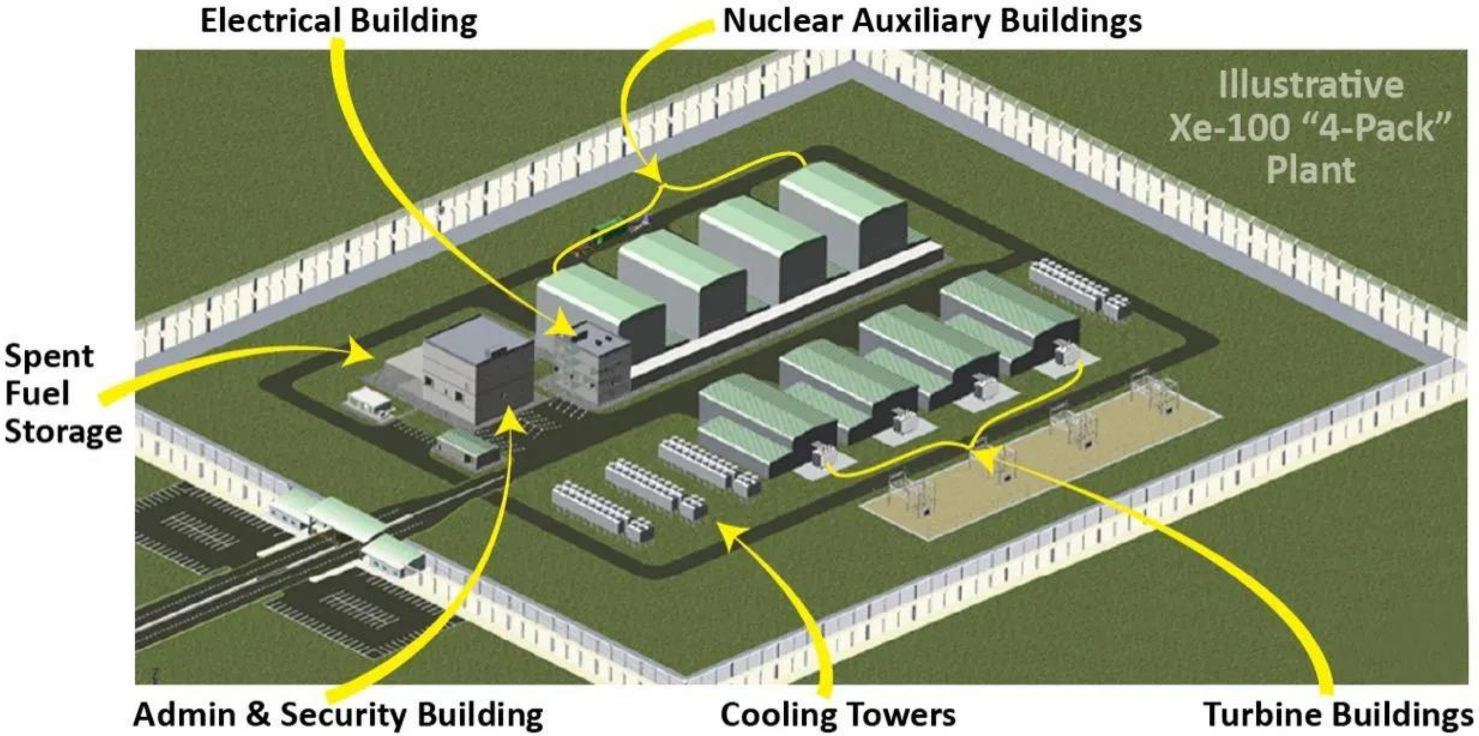
- ***All*** nuclear waste produced so far by ***all*** nuclear reactors in the world fit in two football field lengths; or a 700 x 700 x 700 ft cube (0.13 mi on each side).
- High-level (deep geological disposal) waste requires only 70 x 70 x 70 ft.



https://www.visualcapitalist.com/visualizing-all-the-nuclear-waste-in-the-world/

Small Modular Reactors (SMRs) vs Large Reactors

Vogtle PWR (USA): 2,430 MWe
- *Plant footprint: ~600 acres*
- *EPZ boundary: 10 miles*



- **Secure:** underground reactor layout is possible
- **Scalable:** allows for build-out based on power demand
- **Small:** can be built on 10 acres of land and allows for grid independence
- **Safe:** smaller EPZ allows for building close to existing infrastructure

X-energy: 4x80 = 320 *MWe*
- *Plant footprint: 10 acres*
- *EPZ boundary: < 1 mile*

https://www.southernnuclear.com/our-plants/plant-vogtle.html
https://x-energy.com/

Features of Small Modular Reactors (SMRs)

Simplification by Modularization and System Integration

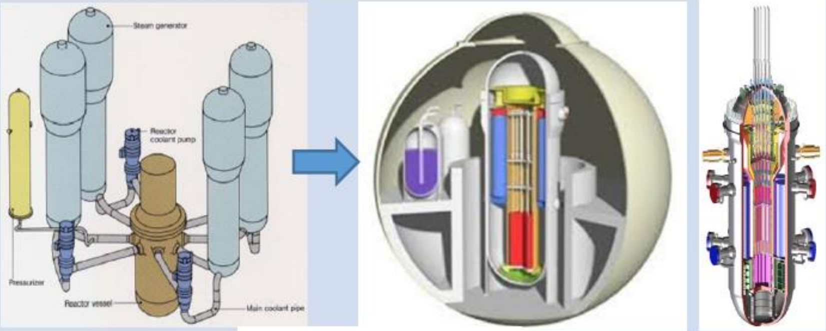


Image courtesy of IRIS 7 .

Multi-module Plant Layout Configuration

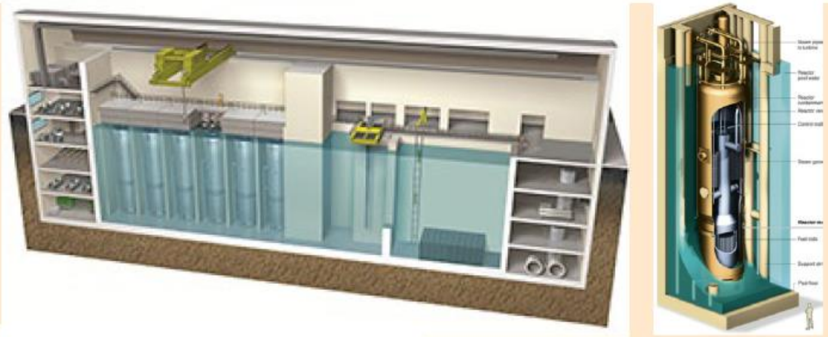


Image courtesy of NuScale Power Inc.

Underground construction for enhanced security and seismic

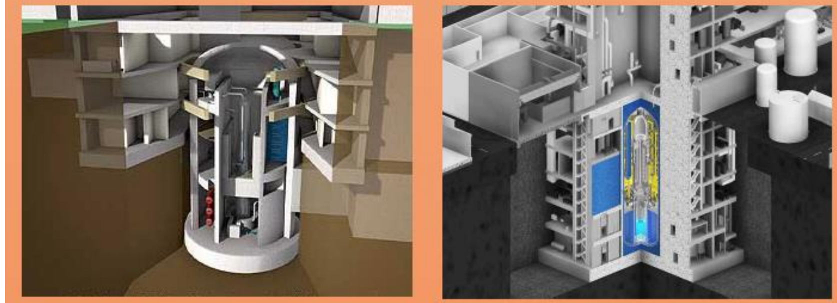


Image courtesy of BWX Technology, Inc.

Enhanced Safety Performance through Passive System

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

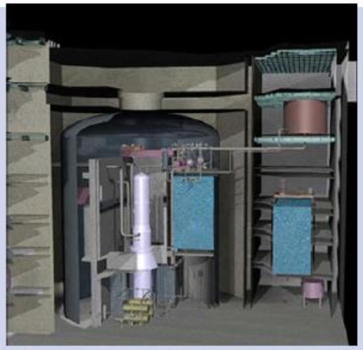


Image courtesy of BWX Technology, Inc.

GAS-COOLED REACTOR
ADVANCED REACTOR TECHNOLOGIES PROGRAM

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

IDAHO NATIONAL LABORATORY

Microreactors: Megawatt-scale Nuclear Reactors

BENEFITS:

Small Size

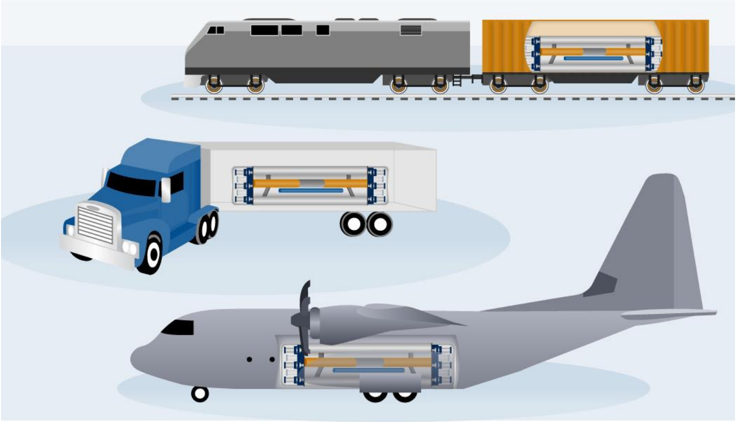
Fits on the back of a semi-truck and can be deployed to remote locations and military bases for reliable heat and power.

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

GAS-COOLED REACTOR
ADVANCED REACTOR TECHNOLOGIES PROGRAM

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

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

Kaleidos (1.2 MWe)
- Fuel: TRISO 🟢
- Company: Radiant

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

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

SMR-300 (300 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

Aalo-1 Microreactor (10 MWe)
- Fuel: Uranium Zironium Hydride
- Company: Aalo Atomics

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

DOE Support of Advanced Reactors: X-energy XE-100

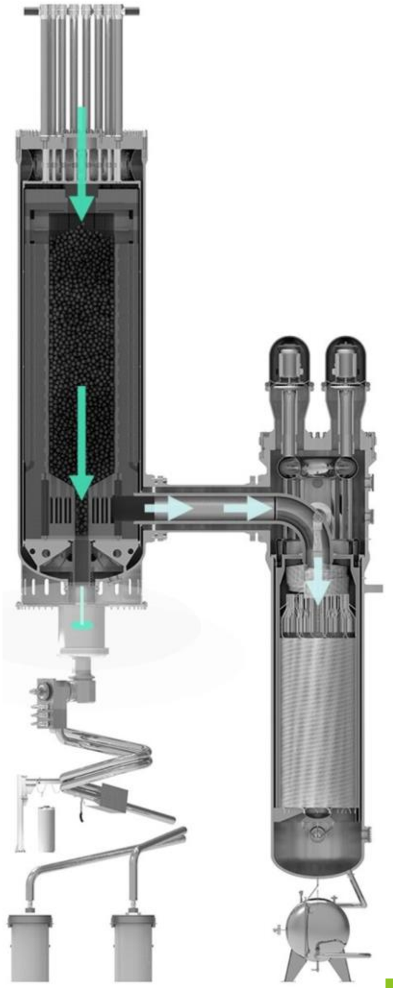
- Funded by DOE Advanced Reactor Demonstration program (ARDP) with $1.23 billion over 7 years through cost-shared partnership to build a 2-unit XE-100 demonstration plant.

- Announced in March 2023 a joint venture with Dow Chemicals to site their first 4 units at/inside Dow's chemical facility at Seadrift, Texas. Planned operation by 2029. Four Xe-100 rectors will act as a drop-in replacement for three natural gas boilers to ensure reliable steam generation for Dow, which will then sell any excess power to the grid.

- Utility Energy Northwest and X-Energy plan to deploy up to 12 units in central Washington State, with first unit online by 2030.

- X-energy and Cavendish Nuclear were granted $4.2 million in funding from the UK government to assess a 12-reactor plant deployment at Hartlepool.

- April 2024: X-Energy and Canadian power producer TransAlta Corporation will study feasibility of deploying Xe-100 at a repurposed fossil fuel power plant in Alberta.



https://x-energy.com/seadrift
https://www.world-nuclear-news.org/Articles/Multiple-Xe-100-SMRs-planned-for-Washington-State

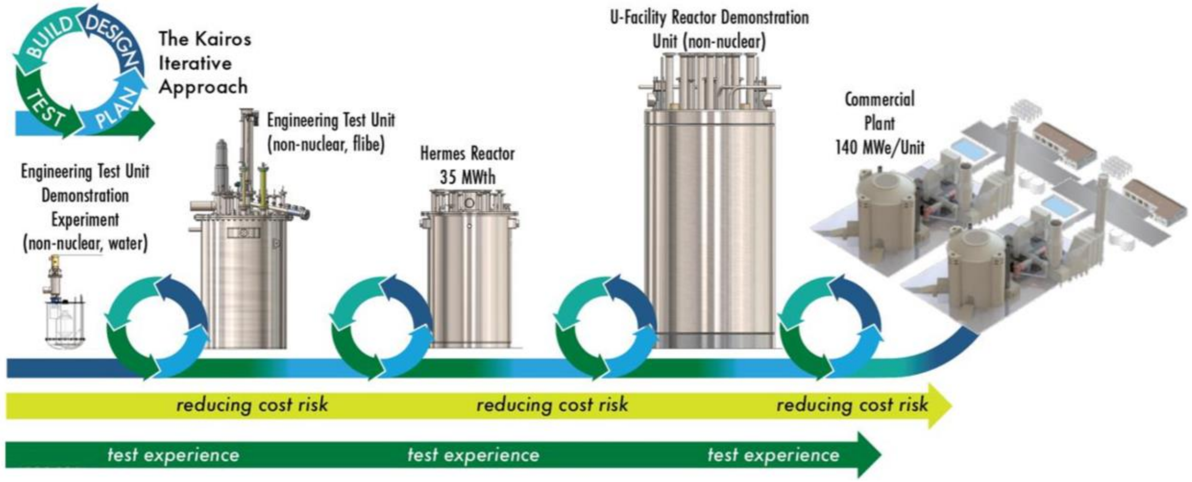
DOE Support of Advanced Reactors: Kairos Power HERMES

- Funded by DOE with $629 million over 7 years for Hermes Reduced-Scale Test Reactor at the East Tennessee Technology Park in Oak Ridge, TN.

- Hermes is a 35 MWth test reactor supporting the development of Kairos Power's 320 MWth commercial KP-FHR technology.

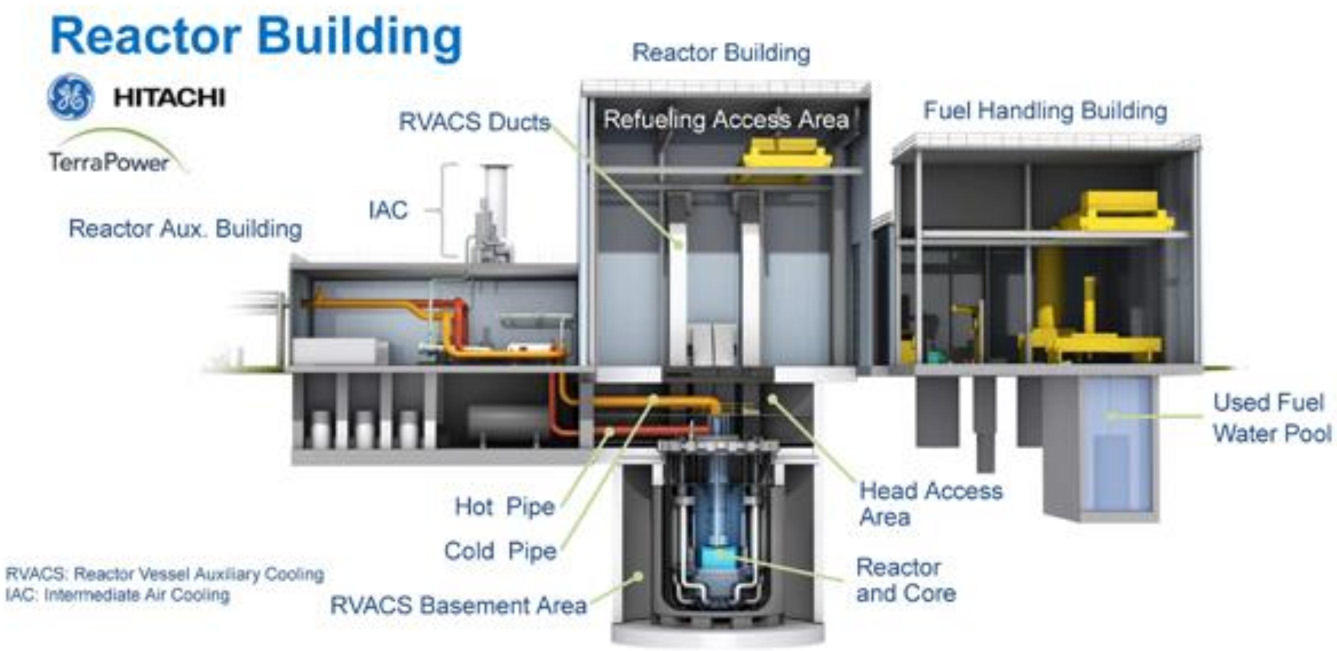
- In December, 2023, NRC approved Hermes construction permit. It is the first non-water cooled reactor approved for construction in the USA in more than 50 years. *Hermes started construction on July 17th!*

- Kairos also filed a construction permit application with the NRC for the Hermes 2 reactor facility, located at the same site. Hermes 2 facility will contain two 35MWt FHR units, intermediate salt loops, and a common power conversion unit. An 11-year core life and commercial electricity generation is planned, requiring a separate license from Hermes.



https://www.nrc.gov/docs/ML2210/ML22105A581.pdf
https://world-nuclear-news.org/Articles/Kairos-seeks-construction-licence-for-two-unit-Her
https://www.einpresswire.com/article/731550092/kairos-power-begins-construction-on-hermes-low-power-demonstration-

DOE Support of Advanced Reactors: Natrium



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

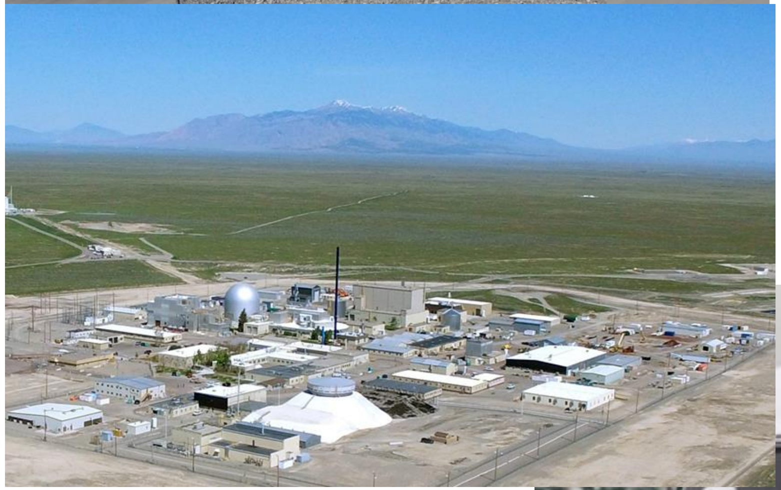
- Natrium is a 345 MWe pool-type sodium fast reactor using High-Assay Low-Enriched Uranium (HALEU) metal fuel.

- TerraPower selected Kemmerer, Wyoming as demonstration reactor site in November 2021.

- Utility PacifiCorp added two further units to its Wyoming plans in April 2023, in addition to the demonstration unit

- New MoU in July 2023 between Centrus and TerraPower will ensure HALEU availability to meet 2030 operation date at Centrus' HALEU production facility in Piketon, Ohio

Demonstration of Micro HTGRs in DOME



- **TRISO-fueled** Radiant, Ultra Safe Nuclear Corporation and Westinghouse microreactors have been awarded DOE funding for front-end engineering and experimental design.
- Will be housed in the Demonstration of Microreactor Experiments (*DOME*) facility at INL.

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- Westinghouse AP300*

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Stationary

LEGEND

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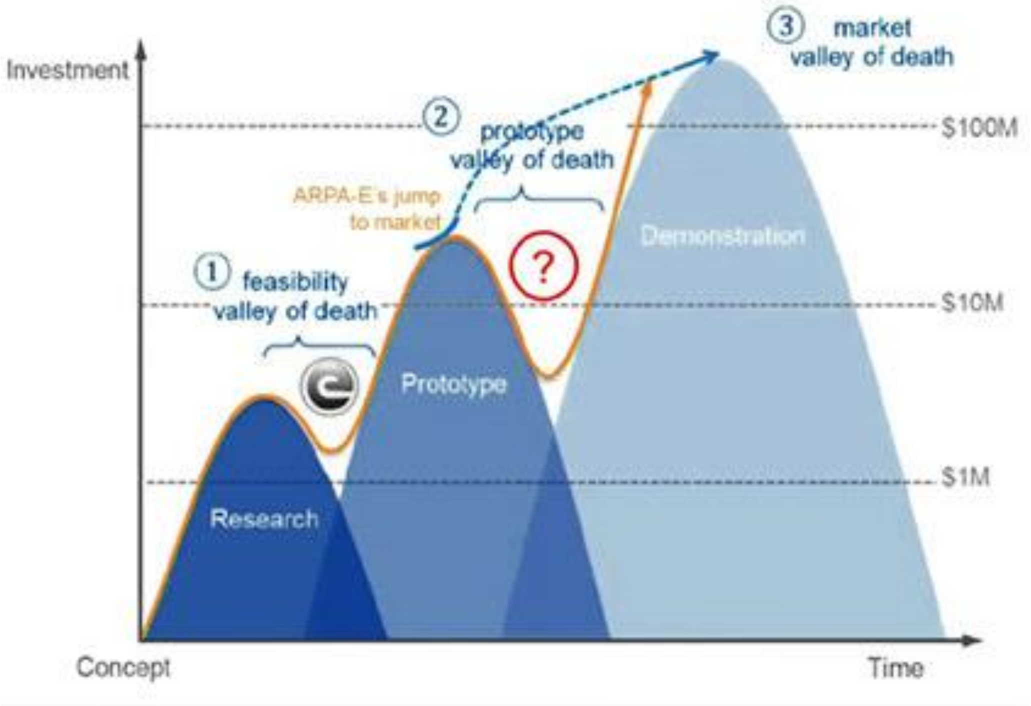
- Risk Reduction
- ARC-20

(thick border)	In Licensing Review
*	Preapplication
RTR	Research/Test Reactor

GAS-COOLED REACTOR
ADVANCED REACTOR TECHNOLOGIES PROGRAM

Slide credit: Kim Webber (NRC) - Kimberly.Webber@nrc.gov

SMR Deployment Challenges



Bridging the Valley of Death: Transitioning from Public to Private Sector Financing

Market/Economics: Business cases for First-of-a-Kind (FOAK) and Nth-of-a-Kind

Supply chain: Reactor vessel, graphite, helium, salts, instrumentation? How mature?

Fuel: HALEU availability, qualified fuel? (fabrication, irradiation, PIE)

Licensing: NRC, international or DOE authorization?

Siting: Permits, community interactions, transmission lines, transport (microreactors)?

Workforce: Enough people? Certified reactor operators, welders, support staff, etc.

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