

- High level waste management and geologic disposal
- Mixed Oxide Fuel (MOX) fabrication and reactor use
- Small Modular Reactors and Microreactors survey
- Nuclear reactor restarts in the US

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Commercial vs. Defense

- **Established policy in the US is to “separate” commercial nuclear power production and nuclear defense initiatives**
 - Commercial nuclear power plants are almost exclusively operated by private companies and are regulated by the Nuclear Regulatory Commission (NRC)
 - Defense nuclear initiatives are conducted by the Department of Energy (DOE) and National Nuclear Security Administration (NNSA) *

* **NNSA is a semi-autonomous agency within DOE**

NRC Radioactive Waste Definitions

- **Driven by 10CFR 61.55**
 - High-level waste
 - Spent nuclear fuel when it is accepted for disposal
 - Waste materials remaining after fuel reprocessing
 - Low-level waste
 - Class A, Class B, Class C, Greater than Class C
 - Classification depends on concentration of certain radionuclides
 - Packaging and disposal requirements increase as go from Class A to Class C
 - Currently no approved disposition path for GTCC
 - Disposition
 - EnergySolutions Barnwell Operations (South Carolina): Classes A, B and C
 - US Ecology (Washington): Classes A, B and C
 - EnergySolutions Clive Operations (Utah): Class A only
 - Waste Control Specialists (Texas): Classes A, B and C

Most other countries classify waste by hazard and/or risk!

Commercial Waste Types/Locations

- **Commercial Spent Fuel**
 - Over 250,000 spent fuel assemblies comprising over 70,000 metric tons of heavy metal (metric ton = 1000 kg)
 - Stored at 118 reactor sites
- **Low level waste**
 - Job control waste from nuclear facilities
 - Medical wastes
 - Laboratory wastes
 - Mill tailings
 - Represents about 90% of radioactive waste
 - Over 10 million cubic meters of waste stored in US

DOE Waste Types/Locations

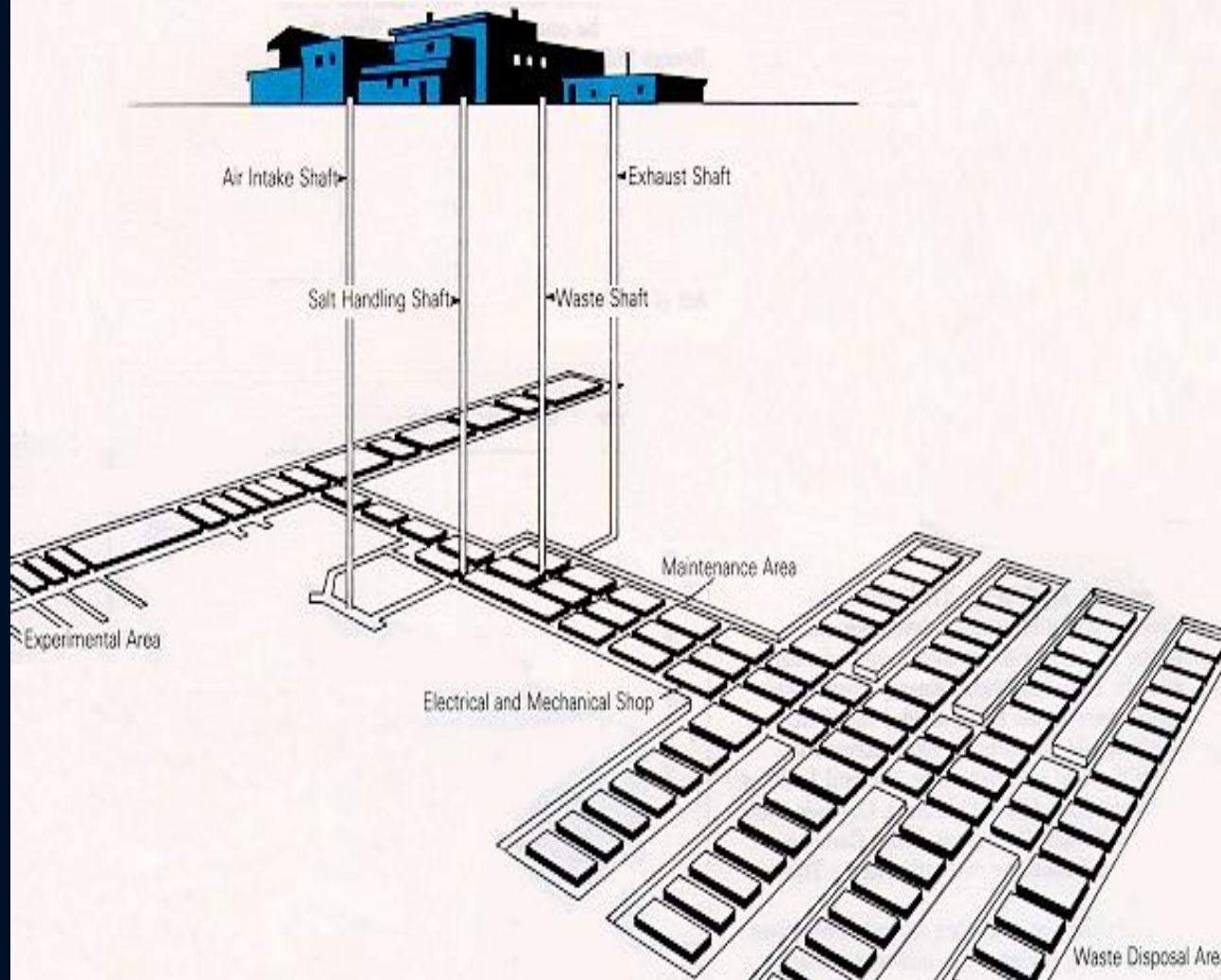
- DOE managed spent nuclear fuel: 2400 MT heavy metal (~7000 m³) primarily located at Idaho National Laboratory (INL) and Savannah River Site (SRS)
- High level waste
 - Liquid tank waste:
 - ~53 million gallons (~200 million L) in 177 underground tanks at Hanford
 - ~36 million gallons (~135 million L) in 51 underground tanks (8 tanks emptied and closed) at SRS
 - Sodium bearing waste: ~850,000 gallons (~3.2 million L) located at INL
 - Calcined waste: 4400 m³ stored in 6 bin sets at INL
 - Demonstration project vitrified waste: 275 canisters (~500,000 kg) located at West Valley Demonstration Project (WVDP)
 - Other miscellaneous waste (e.g. Cs capsules at Hanford)

DOE Waste Types/Locations (cont.)

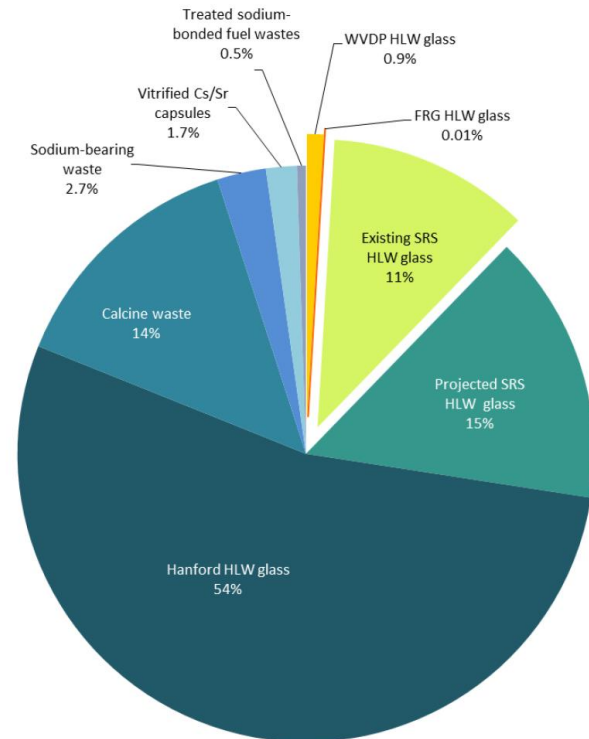
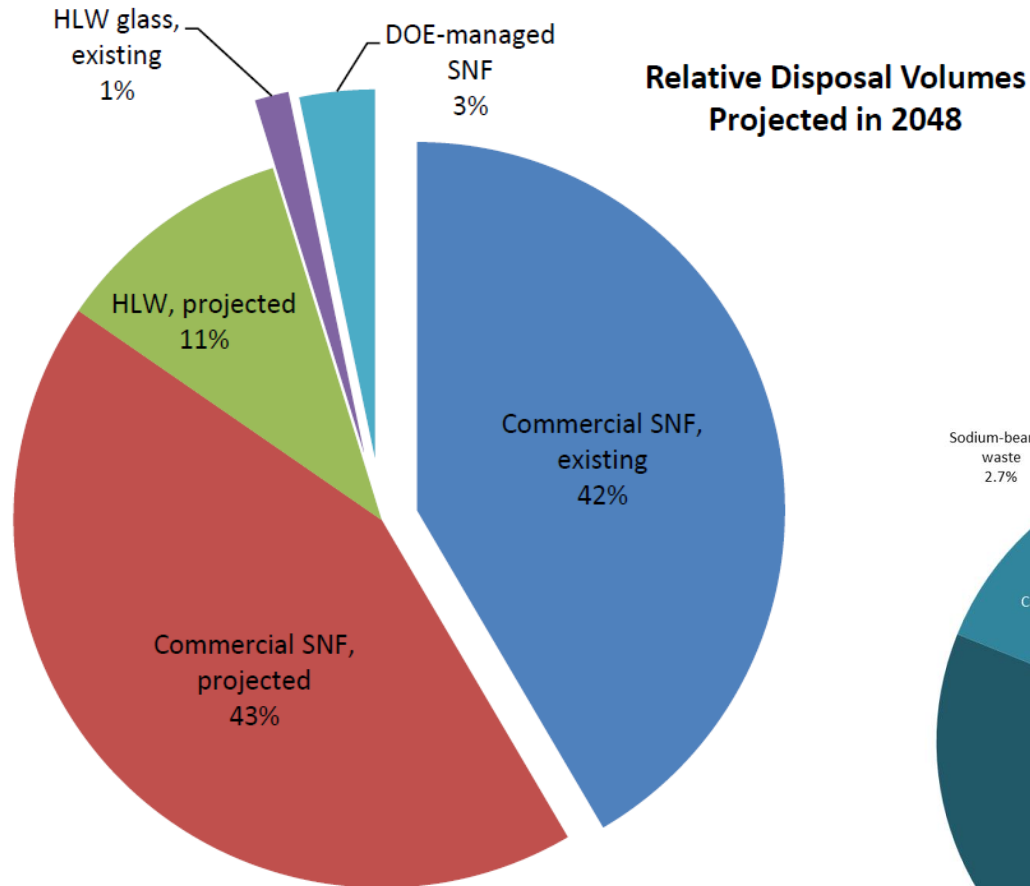
- **TRU Waste**
 - ~12,000 m³ disposed to date in the Waste Isolation Pilot Plant (WIPP) in New Mexico
 - TRU wastes being managed at 12 sites but majority of waste at SRS, Oak Ridge National Laboratory (ORNL), Los Alamos National Laboratory (LANL), INL and Hanford
- **Low level radioactive waste**
 - Currently being managed at 29 different sites across DOE complex
- **“Challenging Waste”**
 - Wastes with no clear disposition path (e.g. used HLW glass melters, activated metals, SNM wastes, etc.)

Schematic Diagram of WIPP

Figure 5
Schematic of the WIPP Repository



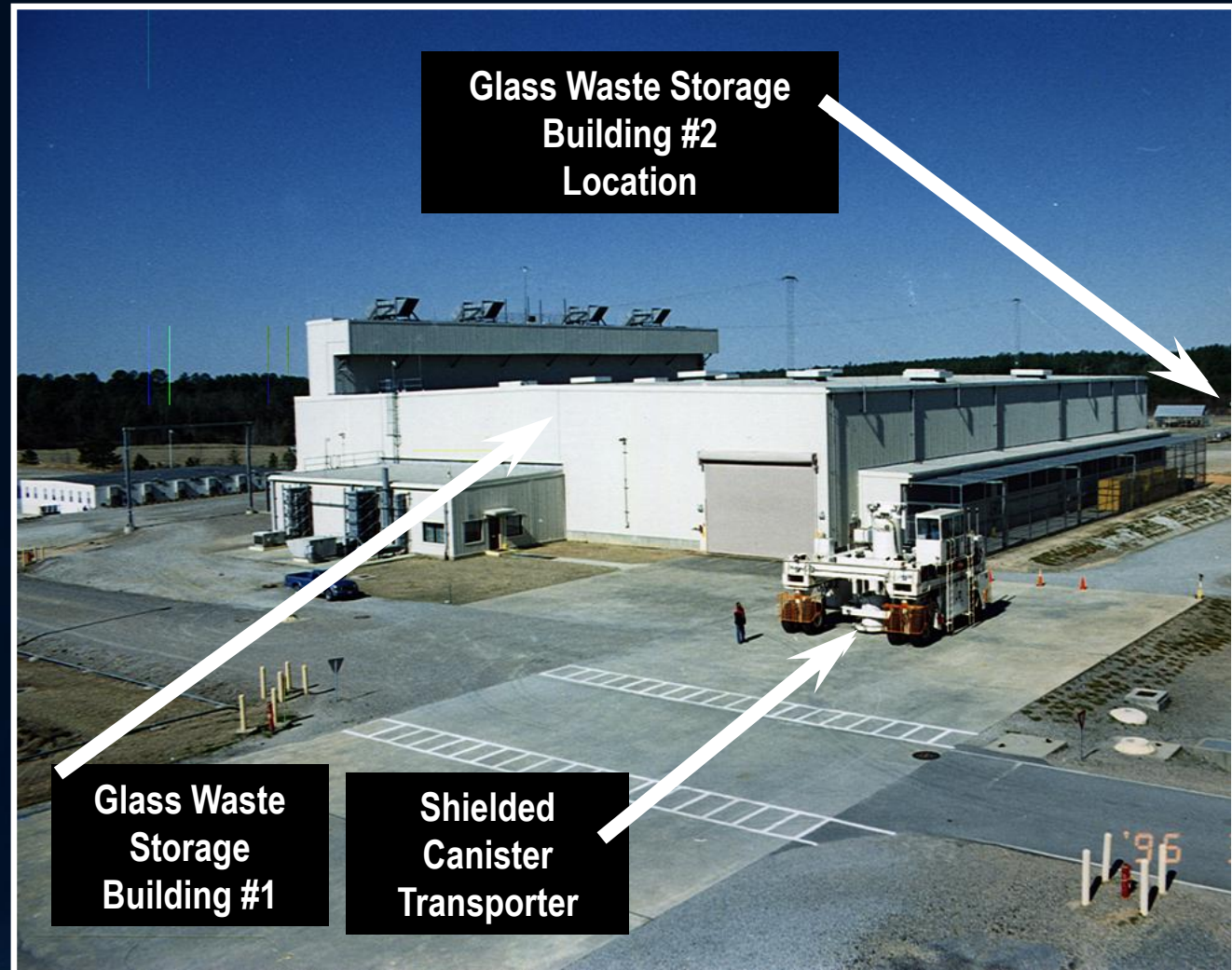
US HLW requiring disposal



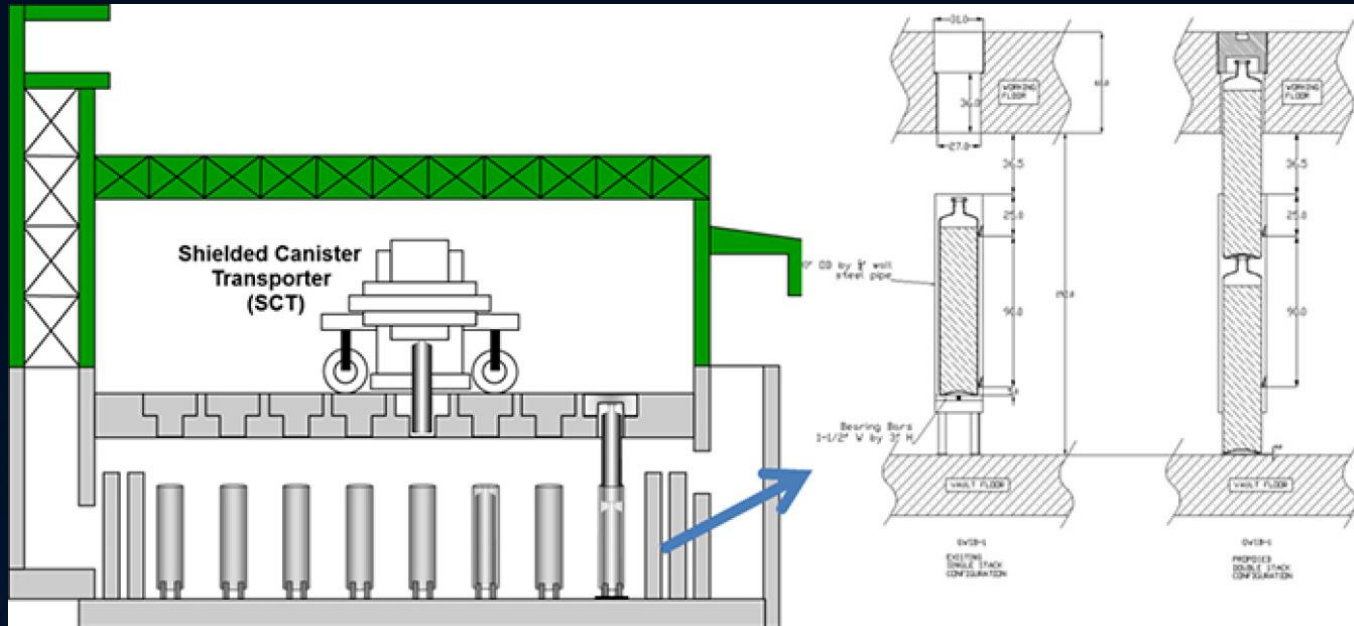
Vitrified HLW storage at SRS



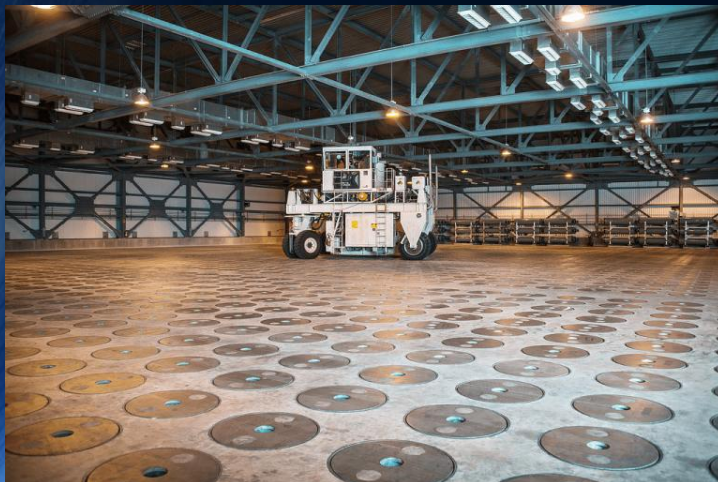
Design and Function:
Underground
reinforced concrete
storage vaults that are
seismically qualified for
safe interim storage of
immobilized glass-
waste filled canisters.



Vitrified HLW storage at SRS



Double stacking of canisters to maximize space utilization



Inside the Glass Waste Storage Building

Double stacking saved \$200M!

Functions of a Storage System for Spent Nuclear Fuel

- Thermal Performance
 - Manage heat load from stored spent fuel
- Radiological Protection
 - Protect workers from radiological hazards
- Confinement
 - Protection of environment from radioactive releases
- Sub-Criticality
 - Maintain criticality safety
- Retrievability
 - Allow for fuel transfer for final disposition or treatment
 - Allow for rearrangement of fuel storage configuration as needed

The fuel cladding is a critical confinement barrier and structural material for fuel integrity for the storage period and also for safe fuel retrieval and handling pending final disposition

Used Fuel and HLW storage

- Pool storage for at least 5 years
- Interim storage vs. final disposition
- Interim consolidated storage
 - Receive fuel in casks from reactor sites and store on above ground pad
 - High level security and routine monitoring
 - Private efforts in TX and NM stalled
 - Federal government considering as part of Nuclear Lifecycle Innovation Campuses (ID, LA, OK, TN, UT, WV)
- Deep geologic repository
 - Isolating radioactive waste in a stable underground geological formation to prevent harmful radioactivity from reaching the surface environment.

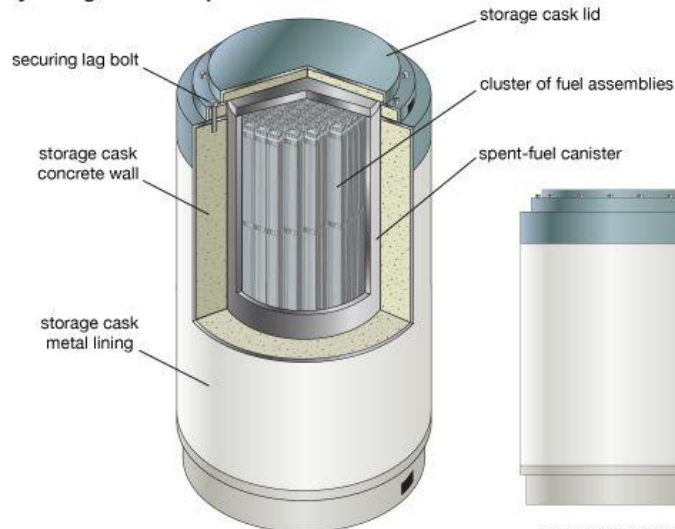


Used Fuel storage

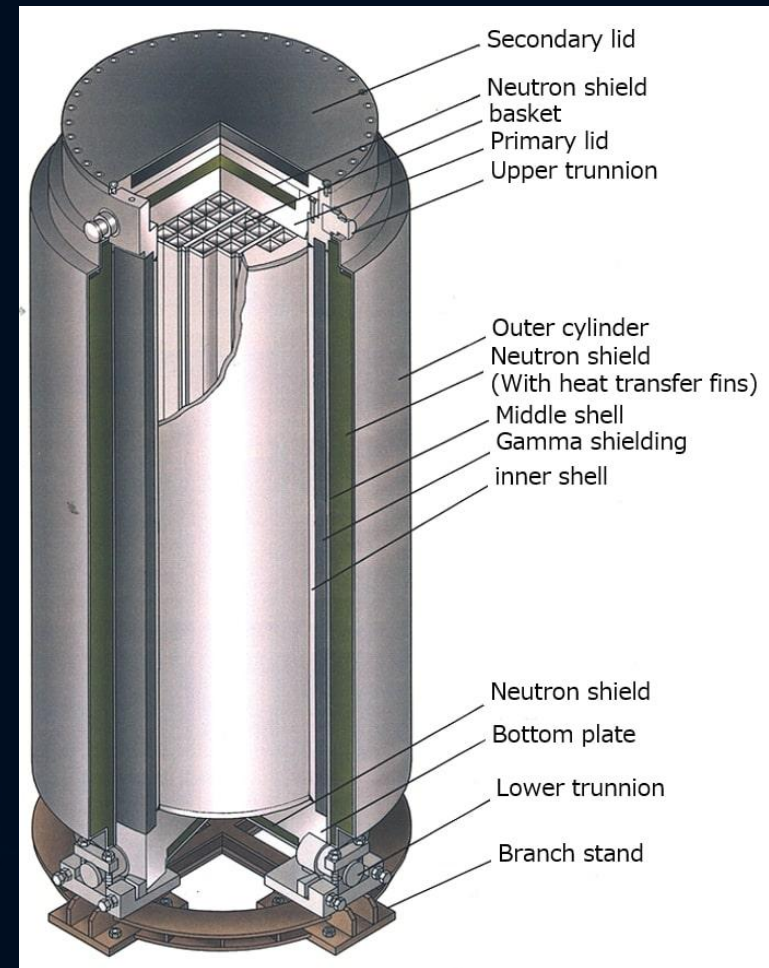


Plant Vogtle #3 Spent Fuel Pool

Dry storage cask for spent nuclear fuel



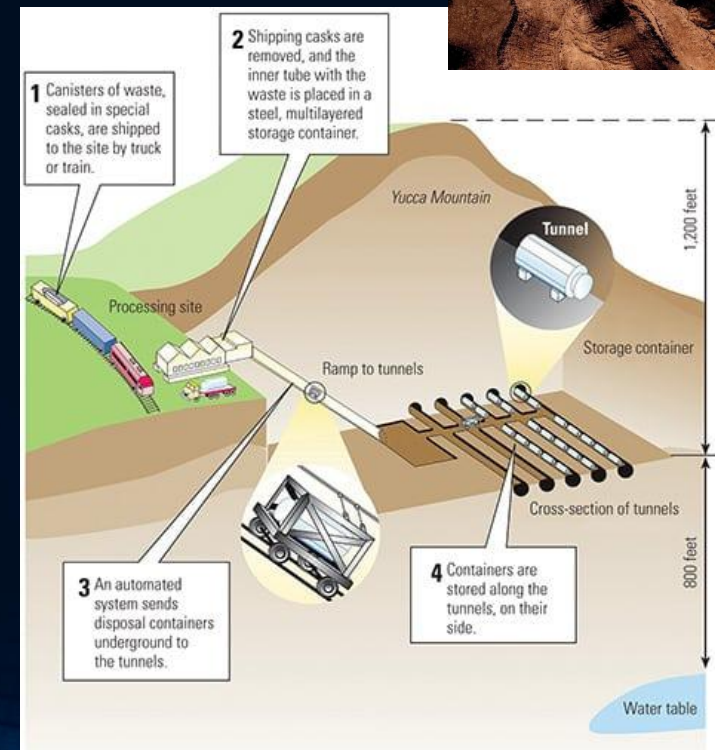
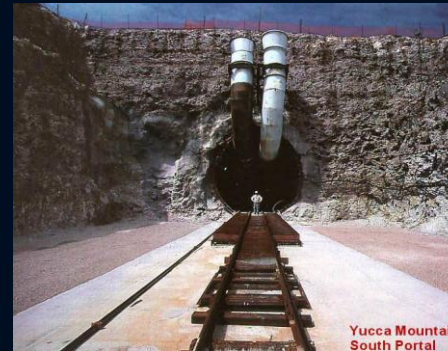
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Examples of Dry casks

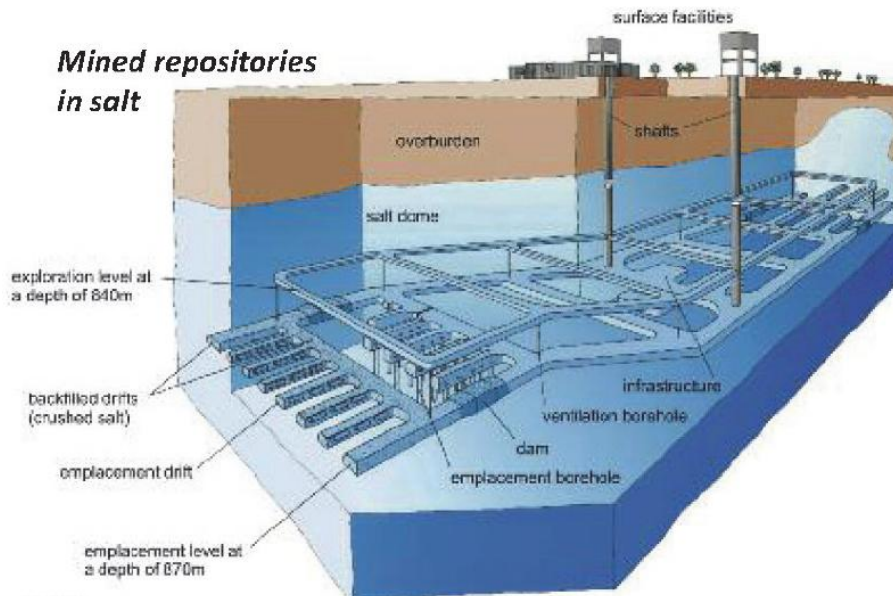
Yucca Mountain Project

- Nuclear waste policy act (1982) mandated US government to find HLW underground disposal site
- Amendment (1987) named Yucca Mountain as site
- Formed by volcanic eruption – “tuff” geology
- Construction began in late 80s and \$15B spent to date
- Obama administration canceled project in 2011 (“unworkable solution”)
- Attempts to restart YMP in 2018 but little progress
- Future uncertain but current Trump administration has not ruled out restarting
- Estimate to completion = \$97B

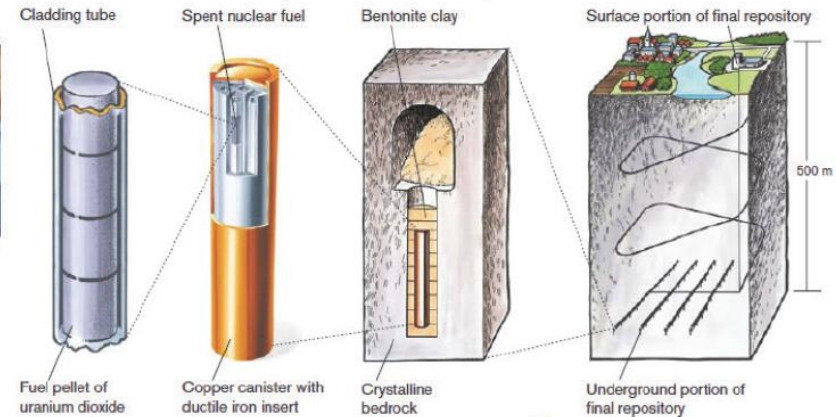


Other Deep Geologic Repository Types

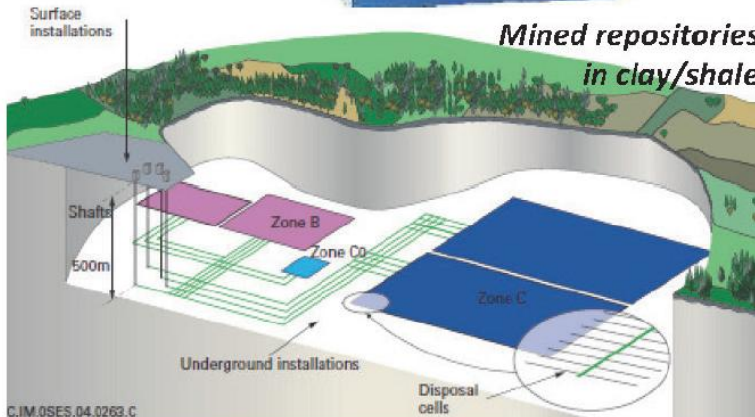
Mined repositories in salt



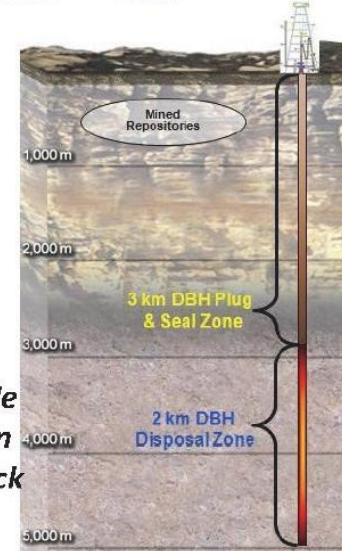
Mined repositories in crystalline rock



Mined repositories in clay/shale



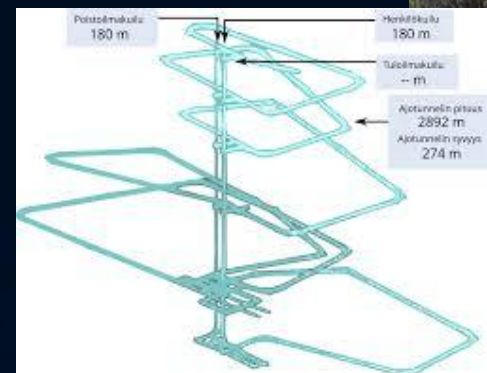
Deep borehole repositories in crystalline rock



All geology types considered workable with various pros and cons

Finland

- Onkalo diposal facility (near Olkiluoto NPP in Eurajoki municipality
 - Granite geology
- Construction began in 2004
- Construction completed in 2024
- Emplacement testing ongoing
- Operational in 2026!
 - 12 fuel assemblies in boron steel canister enclosing in copper capsule
 - Capsules overpacked in separate holes and backfilled with bentonite clay
- Completion by 2100 at total cost of ~\$6B



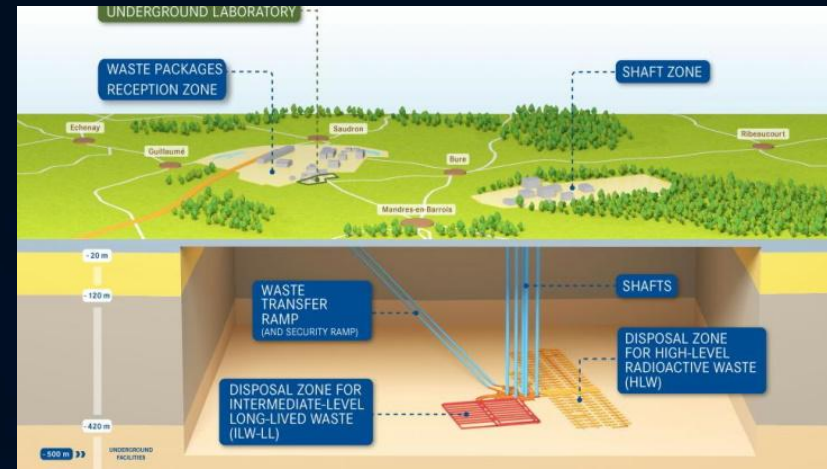
Sweden

- KBS-3 disposal facility (near Östhammar)
 - Granite geology
- Construction began in 2025
- Construction to be completed in ~10 years
- Construction cost of \$1.08B
- Project completion by 2100
 - Fuel assemblies in carbon steel canister enclosing in copper capsule
 - Capsules overpacked in separate holes and backfilled with bentonite clay
 - 500 m below surface
- Construction cost of \$1.08B



France

- Ciego (centre industriel de stockage géologique) disposal facility (near Bure)
- Clay geology
- License application applied for in 2023
- Government has 5 years to rule on application
- Facility will dispose of vitrified high level and intermediate level waste (France reprocesses used fuel and vitrifies fission products!!)



Canada and United Kingdom

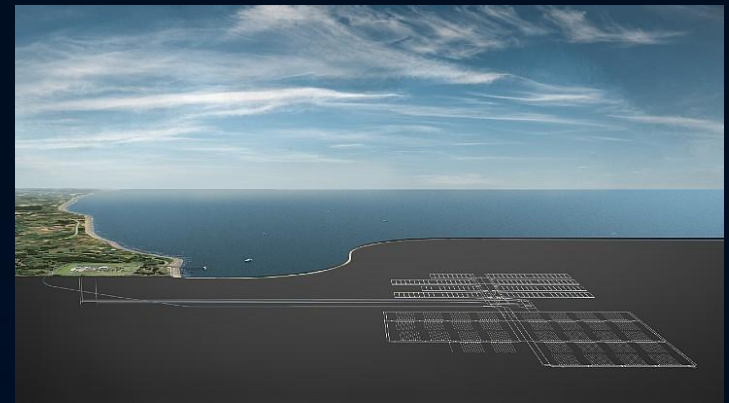
- Canada

- Site in Northwestern Ontario chosen in late 2024 - Wabigoon Lake Ojibway Nation (WLON) and the Township of Ignace volunteered
- Granite geology
- Projected to be operational in 2040s



- United Kingdom

- Narrowed to 3 sites - Communities interested in hosting
- Mid Copeland (Cumbria)
- South Copeland (Cumbria)
- East Lincolnshire (NE England)



Mixed Oxide Fuel (MOX)

- **Mixed Oxide (MOX) fuel** is a nuclear fuel composed of more than one oxide of fissile material.
- Typically blends **PuO_2** with **Natural, Reprocessed, or Depleted UO_2**
- MOX provides a pathway to **close the nuclear fuel cycle** by recycling plutonium recovered from used nuclear fuel or dismantled military weapons.
- MOX fuel accounts for roughly **5%** of the new nuclear fuel used globally today.
- **By-Product Generation:** Plutonium is naturally created inside conventional nuclear power plants as a by-product of uranium irradiation.
- **Hidden Energy Source:** Over **one-third** of the energy produced in a standard nuclear reactor core comes from this generated plutonium fissioning in-situ.
- **The MOX Advantage:** Instead of storing separated plutonium as high-level waste, MOX isolates and blends it to displace the need for freshly mined and enriched uranium.

MOX Fuel Manufacturing

- **Powder Preparation:** PuO_2 and UO_2 powders are thoroughly mixed and pulverized. High homogeneity is required to prevent isotopic phase separation.
- **Pellet Pressing:** The blended powder is compressed mechanically into solid, cylindrical pellets.
- **Sintering:** Pellets are baked in a high-temperature furnace (sintered) into highly stable, durable ceramic fuel pellets.
- **Grinding & Inspection:** Pellets are ground to precise physical dimensions and inspected for structural density and micro-cracks.
- **Insertion into fuel assemblies just like UO_2 fuel**



Reactor Use

- **LWR Equivalency:** For Light Water Reactors (LWRs), the plutonium content is adjusted to about **5% to 7%**. This mimics the exact fissile behavior of standard Low-Enriched Uranium (LEU) fuel.
- **Drop-In Compatibility:** In most cases, a fraction of a commercial reactor core (often **one-third**) can accept MOX fuel bundles without requiring physical engineering alterations to the plant.

Country / Program	Material Source & Utilization	Status / Implementation
<u>France</u>	Recovers plutonium from domestic commercial spent fuel; fuels approx. 10% of its reactor fleet.	Active Industrial Scale (24 reactors)
Japan	Fuel is fabricated in France. Hope to expand to 12 reactors by 2030	Deployed in 4 reactors
Russia	Developing REMIX fuel (co-extracted U+Pu mix) and advanced dual-component fast reactor systems.	Transitioning to Commercial
India	Uses localized MOX production at Tarapur for commercial BWRs and upcoming Prototype Fast Breeder Reactors (PFBR).	Operational
<u>United States</u>	Focused historically on the Surplus Plutonium Disposition Program to destroy weapons-grade material.	Canceled – never started
United Kingdom	MOX fuel production stopped in 2011 and reprocessing stopped in 2022	Stopped – Excessive costs/policy shifts

Advantages/Disadvantages

- **Major Advantages** 👍

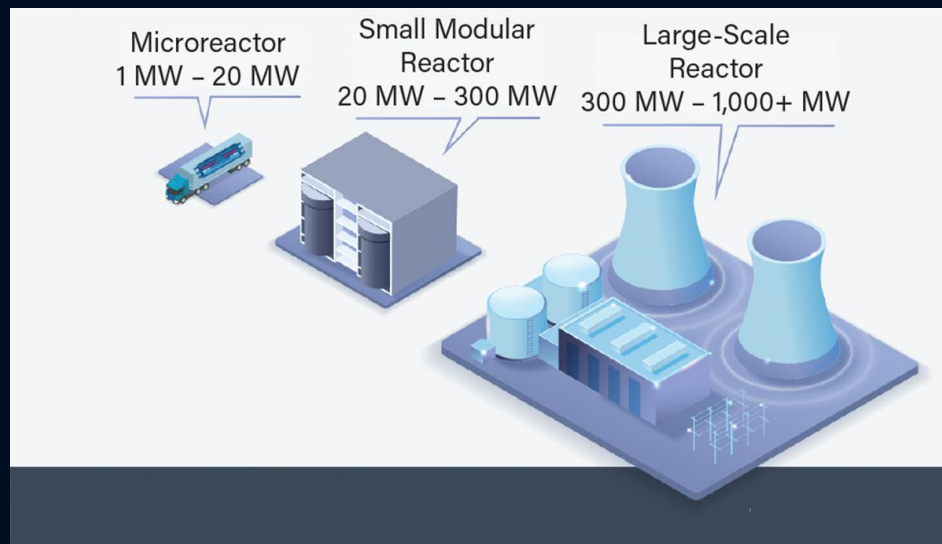
- **Resource Preservation:** Extends the lifespan of global uranium supplies by replacing fresh ore with recycled material.
- **Non-Proliferation:** Permanently transforms weapons-grade plutonium into electrical energy, burning it so it cannot be reused for military applications.
- **Waste Volume Reduction:** Lowers the volume of raw elemental plutonium going directly into long-term geological repositories.

- **Key Challenges** 👎

- **Radiological Hazards:** Plutonium emits alpha particles and is highly toxic if inhaled, demanding costly, remote-controlled glovebox environments during fabrication.
- **Proliferation Risk Concerns:** The chemical separation (reprocessing) of spent fuel to retrieve plutonium raises political and security concerns regarding material diversion.
- **Economics:** Reprocessing spent nuclear fuel and manufacturing complex MOX elements is currently more expensive than open-cycle LEU manufacturing.

Small Modular Reactors and Microreactors

- **The Shift:** Traditional gigawatt-scale nuclear builds (like Plant Vogtle) faced massive cost overruns and delays.
- **The Solution:** Factory-fabricated, modular components shipped by truck or rail for rapid on-site assembly.
- The United States is home to a rapidly growing ecosystem of companies designing **Small Modular Reactors (SMRs)** (typically 30–300 MWe) and **Microreactors** (under 20 MWe) to provide flexible, carbon-free energy for industrial sites, data centers, and remote grids.



Small Modular Reactors – Established Vendors

- **Westinghouse Electric Company**

- *Flagship Design: AP300™ SMR (300 MWe)*
- *Profile: Scaled directly from the proven, globally deployed AP1000® pressurized water reactor, offering lower licensing and supply-chain risk.*



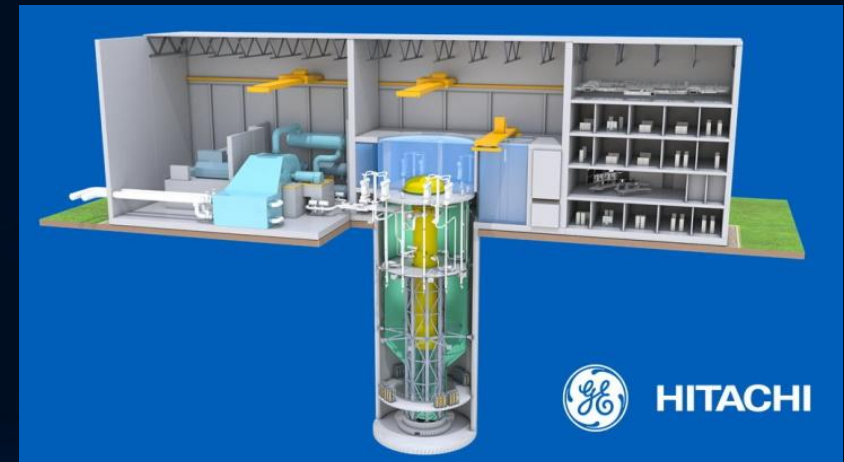
Westinghouse AP300

- **Holtec International**

- *Flagship Design: SMR-300 (~320 MWe per unit)*
- *Profile: Plans integration at brownfield sites like the Palisades nuclear plant in Michigan, optimizing twin-reactor shared infrastructure.*

- **GE Vernova / GE Hitachi**

- *Flagship Design: BWRX-300 (300 MWe)*
- *Profile: Water-cooled, natural circulation boiling water SMR leveraging passive safety systems and advanced construction methods.*



Small Modular Reactors – Venture Backed

- **TerraPower**

- *Flagship Design:* **Natrium®** (345 MWe sodium fast reactor with molten salt storage)
- *Profile:* Co-founded by Bill Gates; integrates thermal energy storage to decouple nuclear heat from electricity generation for grid flexibility.

- **X-energy**

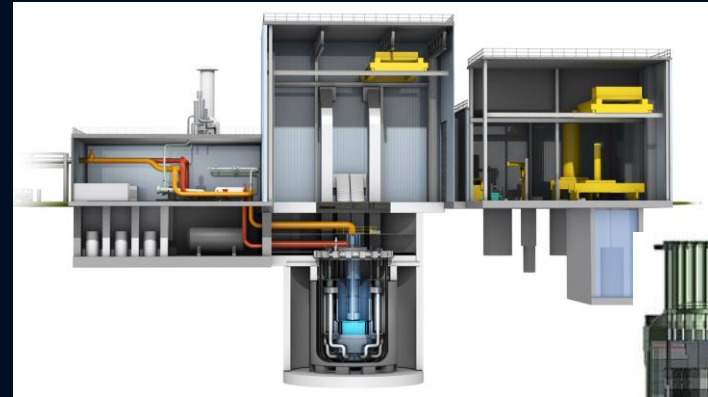
- *Flagship Design:* **Xe-100** (80 MWe high-temperature gas-cooled reactor)
- *Profile:* Backed by major industrial partners and Amazon; utilizes TRISO particle fuel that cannot melt down.

- **Kairos Power**

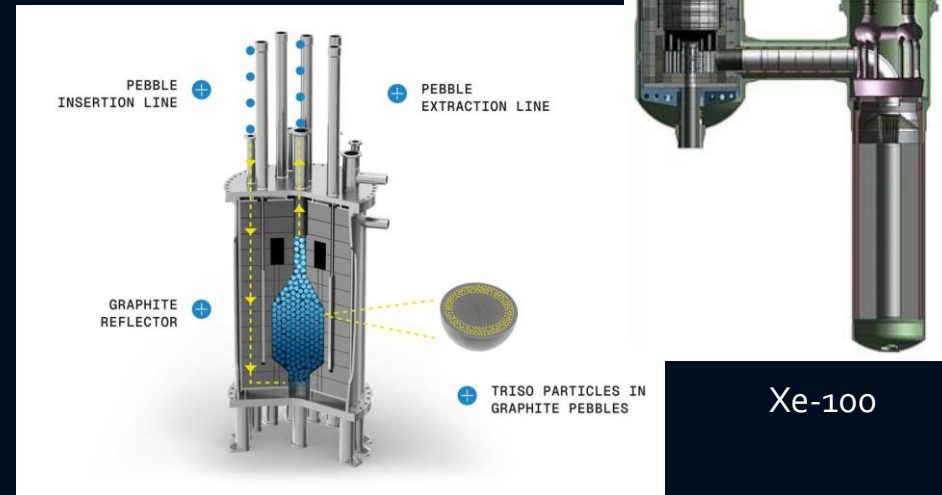
- *Flagship Design:* **KP-FHR** (Fluoride salt-cooled high-temperature reactor)
- *Profile:* Partnering with Google to deploy advanced reactors using low-pressure liquid salt coolant.

- **NuScale Power**

- *Flagship Design:* **NuScale Power Module (NPM)** (Pressurized water technology generating 77 MW). Passive cooling with “walkaway design.”
- *Profile:* First design to receive NRC approval. Projects with TVA and Romania. Problems with cost increases.



Natrium



Xe-100

KP-FHR

Emerging Microreactors

- **Oklo Inc.**

- *Flagship Design:* **Aurora** (compact fast microreactor)
- *Profile:* Operates on an "own-and-operate" model, designed to run on recycled nuclear fuel and refuel only once a decade. Criticality (8.26). Deployment at INL (2028)

- **NANO Nuclear Energy**

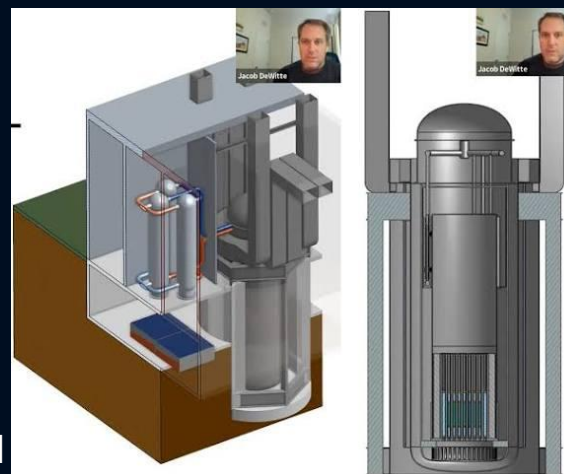
- *Flagship Designs:* **KRONOS MMR™**, **ZEUS™**, and **LOKI MMR™**
- *Profile:* Publicly listed microreactor developer focusing on portable, on-demand, solid-core and gas-cooled micro-architectures.

- **Radiant Industries**

- *Flagship Design:* **Kaleidos** (1 MWe portable high-temperature gas microreactor)
- *Profile:* Designed for transport via standard shipping containers to replace remote diesel generators. Full power at INL (8/26)

- **Antares Nuclear**

- *Flagship Design:* **R1 microreactor** (200-300 KWe system passively cooled by sodium heat pipes using TRISO fuel)
- *Profile:* Integrated shielding and transport cradle. Targeted for military applications. Selected for Army Janus Program at Fort Bragg. Office in Aiken. Criticality demonstrated (6/28)



Aurora



Kaleidos

Active U.S. Nuclear Plant Restart Projects

The United States is actively advancing three major commercial nuclear reactor restart projects—Palisades in Michigan, the Crane Clean Energy Center at Three Mile Island in Pennsylvania, and Duane Arnold in Iowa—driven by skyrocketing electricity demand from artificial intelligence data centers and billions in federal financing.

Reactor Name	Location	Capacity	Owner / Operator	Tech / PPA Partner	Federal Funding	Target Restart Date
Palisades Nuclear Plant	Covert Township, MI	800 MW	Holtec International	Midcontinent ISO (Grid)	\$1.52 Billion DOE Loan	Late 2026 / Early 2027 ????
Crane Clean Energy Center (Formerly Three Mile Island Unit 1)	Middletown, PA	835 MW	Constellation Energy	Microsoft (20-year PPA)	\$1.0 Billion DOE Loan	Late 2027
Duane Arnold Energy Center	Linn County, IA	615 MW	NextEra Energy	Google (25-year PPA)	\$1.9 Billion DOE Loan	Early 2029