Opening Plenary

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Nuclear Power:
Projected Growth and Futurities

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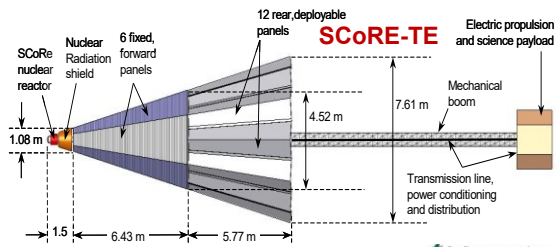
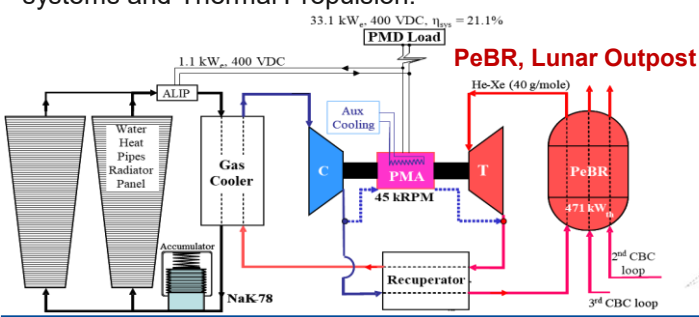
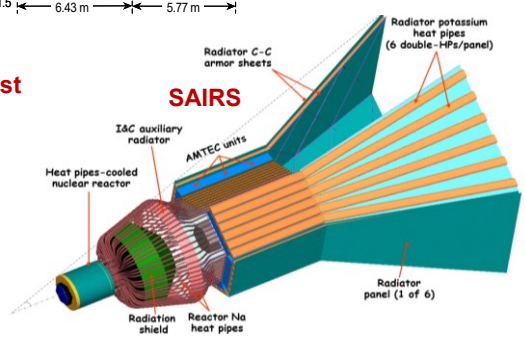
UNM-ISNPS: Space Nuclear Power

- **Since 1984**, through and beyond the Cold War.
- **Hosted** International Breaking Events 1989-95
- **Organized** International Annual Conf., **1984-2008**.
- **Edited** 50 Book Volumes and a Textbook.
- **Published** > 800 Articles and Technical Reports.
- **Advised and sponsored** 30 MS and 35 PhD.
- **Focus** is on nuclear radioisotope, reactor power systems and Thermal Propulsion.







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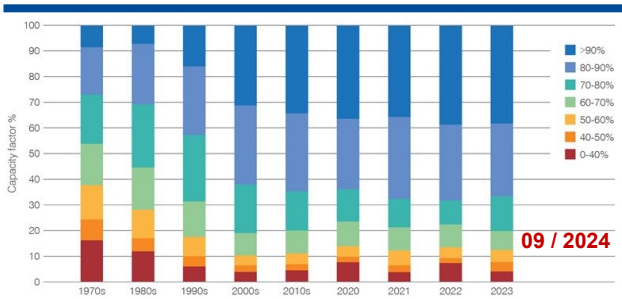
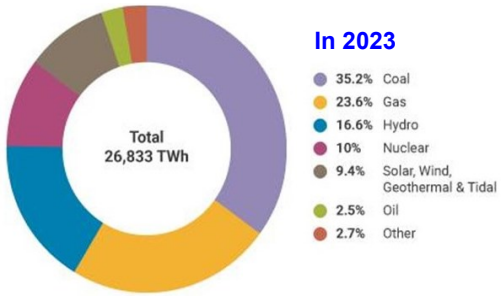
Present Nuclear Power Generation Worldwide



Long-term trends in capacity factors (source: World Nuclear Association, IAEA PRIS)
(Courtesy: World Nuclear Association)



- As of May 2024, **there are ~ 440 operating** nuclear plants in 32 countries, with **~ 390 GW_e** combined capacity**.**
- In 2023, these plants provided **26,833 TWh, ~ 10%** of the World's electricity.
- Worldwide plants 'capacity factor increased **from ~ 64% in 1980s to > 85% at present.**
- **~ 64 reactors in 15 countries are** under construction.
- *Nuclear generating capacity in U.S. by **94** reactors stands at **> 95 GWe** at a capacity factor > 92%, ~ 20% of total electricity.*

Projected Growth

At COP28 in Dubai (Nov. 23) and COP29 (Oct. 24), 31 Countries and > 120 companies signed a joint statement to TRIPLE global nuclear capacity by 2050, for the drive to cut greenhouse gas emissions.

USA

- The Biden administration is **unveiling a plan to triple US nuclear power capacity by 2050** to **~ 300 GW_e** by deploying an additional 200 gigawatts through plant restarts, upgrades and the construction of new reactors.
  - **Involves adding hundreds reactors of all shapes and sizes, *60 to 95 GWe of the total generating capacity could by SMRs and MMRs*.**
- **Job growth in U.S. nuclear energy sector is projected to triple by 2050.**
- **DOE announced $100M for a nuclear safety training and workforce development program.**
- **DOE's Office of Clean Energy Demonstrations issued a solicitation to award $900 million for domestic deployment of Gen III+- SMR technologies.**

Projected Growth (cont.)

IAEA:

- **In a high-case scenario outlook** projects nuclear electrical generating capacity in the world to increase to **950 GW_e** by **2050**, 2.5 times current capacity.
- **In a low-case scenario outlook** projects nuclear electrical generating capacity in the world to increase to **514 GWe**, ~ 40% more than today.
- **SMRs & MMRs** could *account for about **25%** of added capacity **in the high-case scenario*** and ***6% in the low-case scenario***, for both electricity and thermal power.

Organization for Economic Cooperation and Development (OECD):

(38 member countries work to address economic, social and environmental challenges of globalization.)

- **Notes an opportunity** and **possible role for SMRs and MMRs** to provide electricity and thermal power at off-grid mines relying on diesel or heavy fuel oil for their energy demands. ***They could be competitive*** *due to* ***high cost*** *of diesel for remote mines.*
- **SMRs and MMRs** for off-grid mining in remote areas will secure supply chain of **critical minerals,** such as niobium, lithium, cobalt and copper.

Projected Growth (cont.)

Europe:

- **Develop more nuclear power - including up to 90 GWe SMR capacity** – **reduces** CO_2 emissions, **lowers energy cost**, **lessens dependence** on energy imports, and **brings greater security** of supply, (Brussels-based Nucleareurope).
- **Add 150 GW_e installed nuclear capacity by 2050** will **save ~ 430 million tons of CO_2**, **save $338 bn** in total energy system costs, **reduce gas consumption** by **~ 180 billion cubic meters,** and **reduce** dependence on natural gas imports by up to 33%.
  - **European Commission** alliance for development of **SMRs**, selected "**ALFRED project**" proposed by Italy's Ansaldo Nucleare, together with Romanian and Belgian partners, and **Newcleo**, **to develop an advanced fourth-generation modular and smaller size lead-cooled fast reactor (LFR).**
  - **ALFRED Project will** explore working with other groups selected by the EU **to pool resources and know-how**, for a fast-track development and deployment of LFR technology.
- **UK government committed $393 million to develop a High Assay Low Enriched Uranium industry**, $257 million allocated to constructing fuels facility at **Urenco's** Capenhurst site.
- **UK government shortlist of SMR** competition includes: **(1) Westinghouse, (2) GE-Hitachi Nuclear Energy (GEH), (3) Holtec Britain, and (4) Rolls-Royce SMR.** They will potentially negotiate **multi-billion-pound nuclear technology development contracts** under the fast-track initiative to deliver **operational SMRs by mid-2030s**. (Sept 25, 2024).

Projected Growth: Data Centers – A Major Driver!

Nuclear reactor plants provide steady "baseload" power, making an attractive source of electric power for Data Centers, which operate continuously, 24/7.

- **Google's large data centers** would use **>1.0 GW_e**. ***SMRs and microreactors*** *can potentially provide most needed power.*
- **Google's** work with **Kairos Power** to buy **500 MW_e** from multiple **SMRs** to meet electricity demand for AI. First expected on online by 2030, followed by more deployments through 2035.
- **Amazon** collaborates with **X-energy** to **deploy 5 GW_e** of new nuclear projects by 2039,"*will be the largest deployment target of SMRs to date*," starting with **four 320-MWe Xe-100 plants** with Energy Northwest in central Washington.
- **Amazon Web Services (AWS) acquired a data center campus** adjacent to **Susquehanna nuclear power plant** in Salem Township, Pennsylvania.
- **Oracle invests > $10 billion** to build **hundreds of data centers**, at least one "in every country."
- **Microsoft and Constellation Energy** plan to reoperate TMI NPP unit-1 in Harrisburg, Pennsylvania **by 2028 to power AI needs**. The plant is expected to supply **~835 MW_e** to offset Microsoft's data center electricity consumption. Microsoft is expected to pay ≥ $100 per MWh.
- **OKLO** to provide **750 MW_e** to **two Data Centers**, bringing its deal pipeline to **2.1 GW_e**.

SMRs and MMRs

SMRs and MMRs are for >15-300 MWe and <15 MW_e equivalent, respectively.

- **MMRs likely be** fully fabricated, assembled, and sealed in the factory and transported to the operation site by truck, rail or a barge.
- **Some SMRs** could completely be built in factory or installed module by module at selected site.
- **SMRs and MMRs** offer many passive operation & safety features and long lives with HALEU fuels.
- **Small sizes are** suitable for distributed or integrated grids **< 4 GW_e** in capacity.
- **Candidates for remote operation and control** and **providing electricity and process heat** for district heating and a host of industrial and mining applications in arid and remote location.
- **Could readily slot** into brownfield sites of decommissioned coal-fired plants.
- **Mitigate financial risk.**
- **Shorten construction and deployment time,** potentially competing with other energy sources.
- **Small emergency planning zones,** radius **≤ 300 m for SMRs** and much less for **MMRs**.
- **Thermal & neutron energy spectrum**, **cooled** by **water, sodium, molten lead, HT gas or molten salt.**

✓ **DOE awarded four contracts to de-convert HALEU for SMRs, MMRs and Advanced Reactors:** (1) **Centrus**, *U.S. division of France's state-owned nuclear fuel company Orano, (2)* **GE Vernova**, *(3)* **BWXT**, *French Framatome, and (4)* ***Westinghouse*** (Oct. 2024).

SMRs and MMRs Projects

TerraPower Natrium Project

- Natrium, a sodium fast 345-MW reactor coupled with a gigawatt-scale molten salt energy storage system, is for **high-penetration of renewable grids** where variable power output is a concern.
- **DOE Advanced Reactor Demonstration Program** (ARDP) **authorized a 50/50 cost share** and up to **$2 billion** for the Natrium project.
- **Cost of the first-of-a-kind** Natrium demonstration plant, *to be built in Kemmerer, Wyoming,* include reactor design and licensing, codes and methods development, fuel development and qualification, and design, construction and operation of two supporting facilities: (a) the Natrium Fuel Fabrication Facility and (b) Sodium Test and Fill Facility. *The Na facility will test & demonstrate performance of first-of-a-kind equipment prior to operations in reactor plant*.

Project Pele

- **Demonstrate a high-temperature gas-cooled (HTGR) mobile MMR** for DOD future needs.
  - **Groundbreaking** at Idaho National Laboratory (INL) for a **full-scale of a transportable MR prototype** in **2026**.
  - When operational, it will be the "***first-ever Generation-IV" in U.S.***" (DOD-09 / 2024).
- **Reactor Plant will produce 1.0 to 5 MW_e** for INL's Critical Infrastructure Test Range Complex (CITRC) electrical test grid **for about three years**.
- **Reactor will be manufactured by** Lynchburg, Virginia, **BWXT.**

SMRs and MMRs Projects (Cont.)

OKLO:

- **Sodium-cooled fast reactor plant**, dupped "**Aurora**," of a**15 and 50 MW_e** configurations.
- Reactor design is based on **Experimental Breeder Reactor-II**, operated at Argonne-West,**1964-1994**.
- Plans to **build a demonstration-scale fuel fabrication facility** and **to commission** a commercial-scale Aurora reactor **at INL in 2027.**
- Signed an agreement **with Centrus to purchase HALEU**, from its Ohio enrichment facility.
- As of August 2024, has non-binding letters of intent (LOIs) **for ~ 1,350 MW_e of microreactors capacity, including 20-year term LOIs for 50 MW_e** to **Diamondback Energy's Permian Basin oil and gas operations and 100 MW_e** for **Wyoming Hyperscale's Data Center** operations, and "pre-agreement" for **500 MW_e** to **Equinix,** a **Data Center** operator.

X-Energy:

- Its **Xe-100 SMR** design is based on High-Temperature Gas-cooled Reactor (HTGR) technology.
- **Produces 80 MW_e**, or **200 MW_{th}**, and in a '**four-pack**' configuration for a total output of **320 MW_e**.
- **TRISO-X, LLC**, a wholly owned subsidiary of X-energy, manufactures proprietary TRISO fuel particles design to ensure supply and quality control.

SMRs and MMRs Projects (Cont.)

Westinghouse Electric Company:

- **Completed** front-end engineering and experiment design (FEEED) for a **prototype,** one-fifth scale version of eVinci. The **5-MW_e sodium heat pipes cooled reactor design**, is one of three that could be tested at the National Reactor Innovation Center's **DOME test bed at INL** "**as early as 2026,"** DOE said.
- **Developing AP300 SMR,** *based on AP1000 technology*, touted cost-effective and quicker to deploy.
- **Singed an MOU with Seaspan ULC to help expand nuclear projects** in Canada and around the world.

BWX and BWXT:

- **BWX Technologies, Inc. received second phase award** of a contract with the **Wyoming Energy Authority to assess** the viability of **deploying lead-cooled microreactor units in the state**.
- **BWXT Canada Ltd** and **GE Vernova's** plan to **manufacture, commercialize and advance global deployment of BWX-300 small modular reactor (SMR),** a Vernova-GE Hitachi design.
- **Wyoming industrial machinery company** partnering with **BWX** Technologies to deploy a **50 MW_e BWXT Advanced *Nuclear* microreactors** over the coming years to **provide process heat and electricity to industrial users.**

Aalo Atomics:

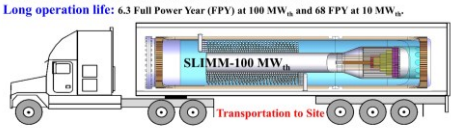
- **Signed MOU** with **Idaho Falls Power**, for a fleet of **Seven Aalo-1 Reactors**.
- Aalo's first reactor, **a sodium-cooled, LEU+ UZrH-fueled, and factory-fabricated**, will generate **30 MW_{th} or 10 MW_e.**

SMRs and MMRs: UNM's SLIMM

SLIMM – SALIENT DESIGN FEATURE

Modularity: With same reactor core design, nominal thermal power increases from 10 - 100 MW_{th} by simply increasing the height of the in-vessel chimney (2-8 m tall) and height and design of the Na-Na, helically coiled tube heat exchanger (HEX) at top of downcomer.

Long operation life: 6.3 Full Power Year (FPY) at 100 MW_{th} and 68 FPY at 10 MW_{th}.



Low-risk and attractive investment

- Low unit cost, short construction and deployment time (12-24 month).
- Additional units up to 30, could be added incrementally at a single site with increase demand.
- High efficiency (35-40%) for electricity generation using superheated steam Rankine cycle.
- Off-the-shelf materials and below atmospheric pressure operation.
- Small siting footprint and evacuation zone.
- No reactor accidents by design.

Non-proliferation or end-of-life handling

- Factory fabricated, assembled and sealed.
- Transported to site on an 18-wheeler truck, by rail, or on a barge.
- At site, SLIMM is installed below ground and mounted on seismic insolation bearing to guard against missile attack and earthquake.
- No onsite storage of either fresh or used fuel.
- Only 65 days to a few months of on-site storage needed after end-of-life shutdown, before safely returned to factory and replaced with new unit.

Walk-away safe and inherently load-following

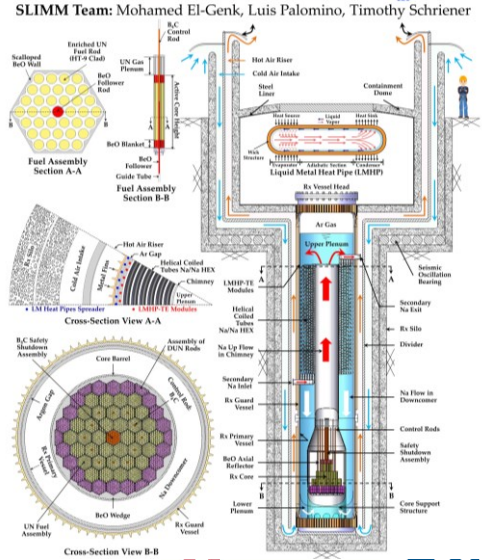
- Passive operation: Cooled by natural circulation of in-vessel liquid sodium during nominal operation and after shutdown, aided with 2-8 m tall chimney and a compact Na-Na HEX.
- Passive and redundant means of decay heat removal: (i) In-vessel Na-Na HEX; (ii) Liquid metal heat pipes (LMHPs) embedded in the primary vessel wall and; (iii) Natural circulation of air.
- No Pressure vessel: Operates below atmospheric pressure (low vapor pressure of in-vessel Na).
- Large mass of in-vessel liquid Na (> 40 MT) provides large safety margin of several hundred degrees below boiling during nominal operation and after shutdown.
- Large negative temperature reactivity feedback: Could shutdown the reactor without active control and ensure inherent load-following of the plant unit.
- Auxiliary electrical power generation: LMHPs coupled to thermoelectric (TE) energy conversion modules, generate auxiliary power, independent of on-site and off-site sources.
- Redundant reactor control and emergency shutdown.

Niche market:

- Distributed and integrated electrical grids with renewable energy sources.
- Electricity generation and process heat production for industrial uses and district heating.
- Isolated and small communities, island nations, advance bases, Data Centers and mining activities.

Scalable LIquid Metal cooled small Modular Reactor (SLIMM), 10 – 100 MW_{th}

SLIMM Team: Mohamed El-Genk, Luis Palomino, Timothy Schriener

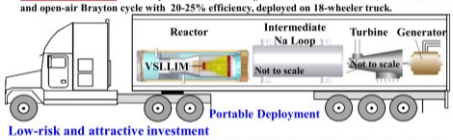


SMRs and MMRs: UNM's VSLIMM

VSLLIM – SALIENT DESIGN FEATURE

Modularity, portability and long life

- **Modularity:** with same core design and 1-2 m tall chimney, nominal reactor power increases from 1.0 to 10 MW_{th}, simply by scaling up the in-vessel Na-Na HEX in downcomer.
- **Portable deployment:** Entire power unit, including the reactor, Na/air HEX, radiation shielding, and open-air Brayton cycle with 20-25% efficiency, deployed on 18-wheeler truck.



Low-risk and attractive investment

- Low unit cost, short construction and deployment time (~12-18 month), and quality assurance.
- Reactor unit could also be installed at a permanent site, below ground and mounted on seismic isolation bearings, to protect against missile attack and earthquake, and coupled to Rankine cycle for electricity generation at thermal efficiency of up to 35%.
- Provide both electricity and high-temperature process heat for industrial uses and district heating.
- Use off-the-shelf materials, operates below atmospheric pressure, and offers many redundant and passive safety and operation features.

Non-proliferation and end-of-life handling

- No onsite storage of either fresh or used fuel.
- Reactor units are factory fabricated, assembled and sealed.
- Within 6-12 months after end-of-life shutdown, used reactor units would be safely returned to factory or a processing facility, and replaced with new one.

Walk-away safe

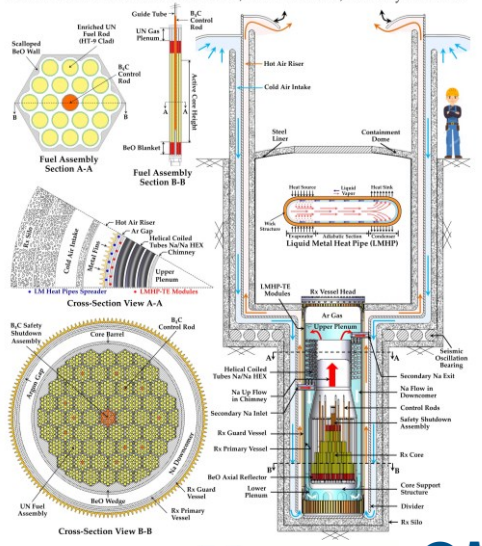
- **Passive Operation:** Reactor is cooled by natural circulation of in-vessel liquid sodium during nominal operation and after shutdown, aided by in-vessel chimney and Na-Na HEX.
- **Passive and redundant decay heat removal:**
  - ✓ In-vessel Na-Na HEX.
  - ✓ Liquid metal heat pipes (LMHPs) embedded in primary vessel wall and coupled to redundant, passive thermoelectric (TE) energy conversion elements for electricity generation and cooled by ambient air.
  - ✓ Natural circulation of ambient air along the outer surface of the reactor guard vessel.
- **No pressure vessel:** Owing to the low vapor pressure of in-vessel liquid sodium.
- **Large mass of in-vessel Liquid Na** maintains its temperature, hundreds of degrees below boiling point, during nominal reactor operation & after shutdown.
- **Large negative temperature reactivity feedback:** Capable of shutting down the reactor without active control, in addition to ensuring inherent load-following of the plant.
- **Auxiliary power generation:** Using LMHPs-TE modules, independent of on-site & off-site sources.

Niche market

- Distributed and integrated electrical grids, electricity generation, and/or production of process heat for industrial uses, seawater desalination, district/space heating.
- Arid regions, remote communities, and advanced bases with no or limited access to water, an electrical grid or fossil fuel year around, and Data Centers.

Very-small Scalable LIquid Metal cooled Modular Reactor (VSLIMM), 1.0 – 10 MW_{th}

VSLIMM Team: Mohamed El-Genk, Luis Palomino, Timothy Schriener



Futurities: Now Comes the Hard Part …

- **Develop** effective means for workforce development and **training** on **CRITICAL SKILLS** for industry's needs.
- **Overcome** licensing uncertainty, and **speed** process.
- **Build & deploy 150 Gen III+ and IV large and medium reactor plants** of **standardized designs** in U.S. **by 2050** and **many SMRs and MMRs,** as needed**,** for **Data Centers and various industries**.
- **Pursue economies of series production** (**design once and build many**) for low cost & short construction.
- **Emphasize responsible and effective management** to complete projects **on budget and on time**
- **Ensure** adequate national supply of LEU and HALEU fuels.
- **Strengthen** coalitions among communities.
- **Concentrate** on **proven licensed technology**, and **standardize processes and scheduling for the avoidance of timetable and cost overruns.**
- **Down select FOK SMRs and MMRs designs,** subject to an **actual cost curve & projected markets.**
- **Empower US nuclear industry to compete internationally for all reactor types and sizes.**
- **Empower Industry to capture a global market share through effective marketing strategies** to underdeveloped countries in Africa, Middle East, and Asia through **affordable financing** (**e.g.: loan guarantees, public-private financing, partnerships** with host countries)**..**
- **Establish,** in collaboration of IAEA, a bank for **nuclear fuel** and **promote safe NP** worldwide.
- **Develop and implement** secure strategies for **storage**, **future processing, and disposal** of SNF.

THE END

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