INL/RPT-23-72111-Revision-0

Advanced Nuclear Energy Technology and Applications A Brief Primer

April 2023

Changing the World's Energy Future

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Idaho National Laboratory

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Prepared for Alaska Legislature Lunch and Learn

Idaho National Laboratory

Why Should We Care? The Bottom Line-

- New sizing and designs open new uses
  - Electricity – microgrids
  - Waste heat for district heating or heating microgrids (e.g. building complexes within constrained areas)
  - Process heat for industry

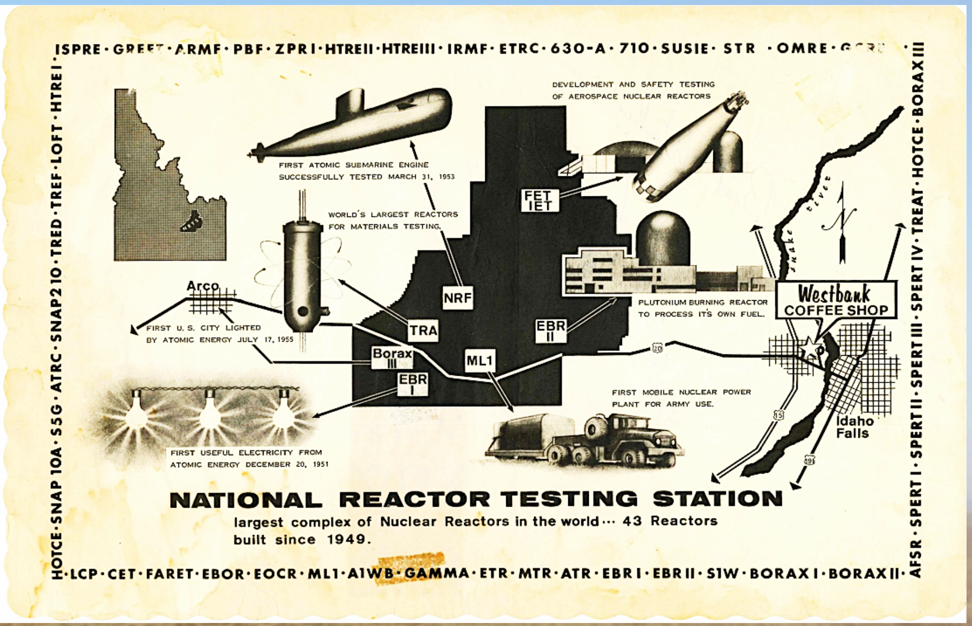
- Recent analyses show under what circumstances microreactors might be cost competitive in AK markets

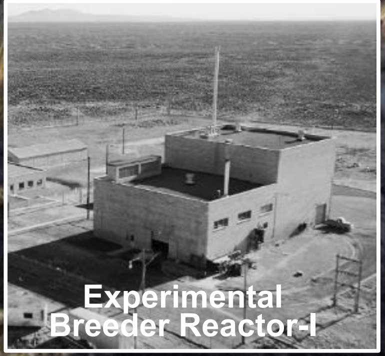
- The flexibility opens the potential to drive industrial processes, thus might be a key to unlock high value, low footprint industry (economic development)

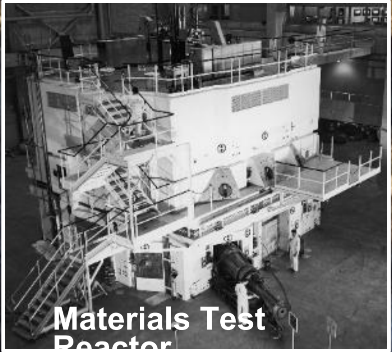
The Nation's Nuclear Energy Laboratory

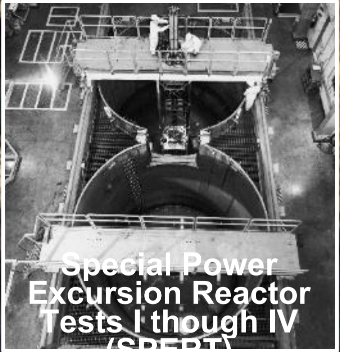
Over Seventy Years of Leading Into New Frontiers:

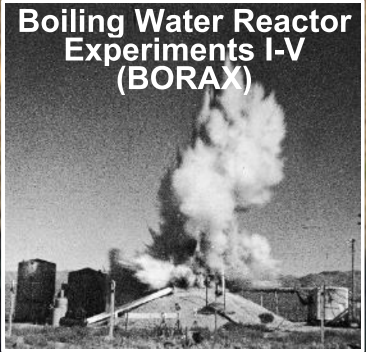
- First nuclear power plant
- First U.S. city to be powered by nuclear energy
- First submarine reactor tested; training of nearly 40,000 reactor operators until mid-90s
- First mobile nuclear power plant for the army
- Demonstration of self-sustaining fuel cycle
- Basis for LWR reactor safety
- Aircraft and aerospace reactor testing
- Materials testing reactors

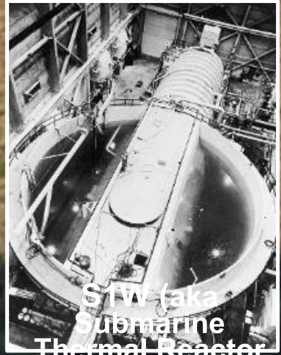


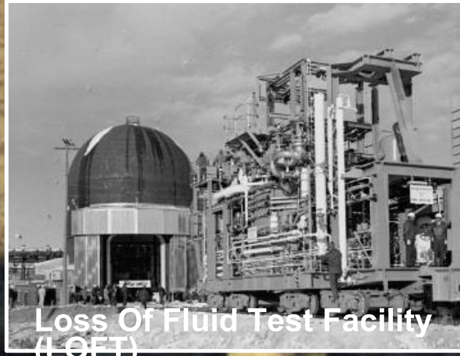

Experimental Breeder Reactor-I


Materials Test Reactor


Special Power Excursion Reactor Tests I though IV (SPERT)


Boiling Water Reactor Experiments I-V (BORAX)

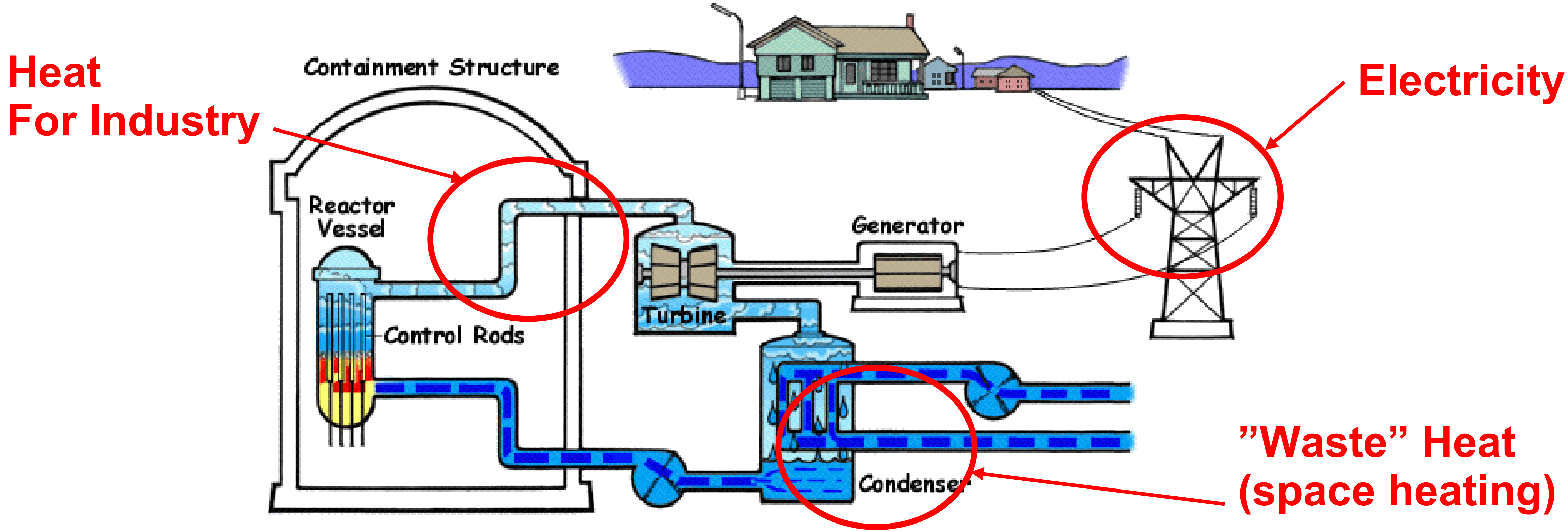

STW (aka Submarine Thermal Reactor (STR)


Loss Of Fluid Test Facility (LOFT)

Nuclear Energy Fundamentals- The Fuel Cycle and Terms You Might Hear

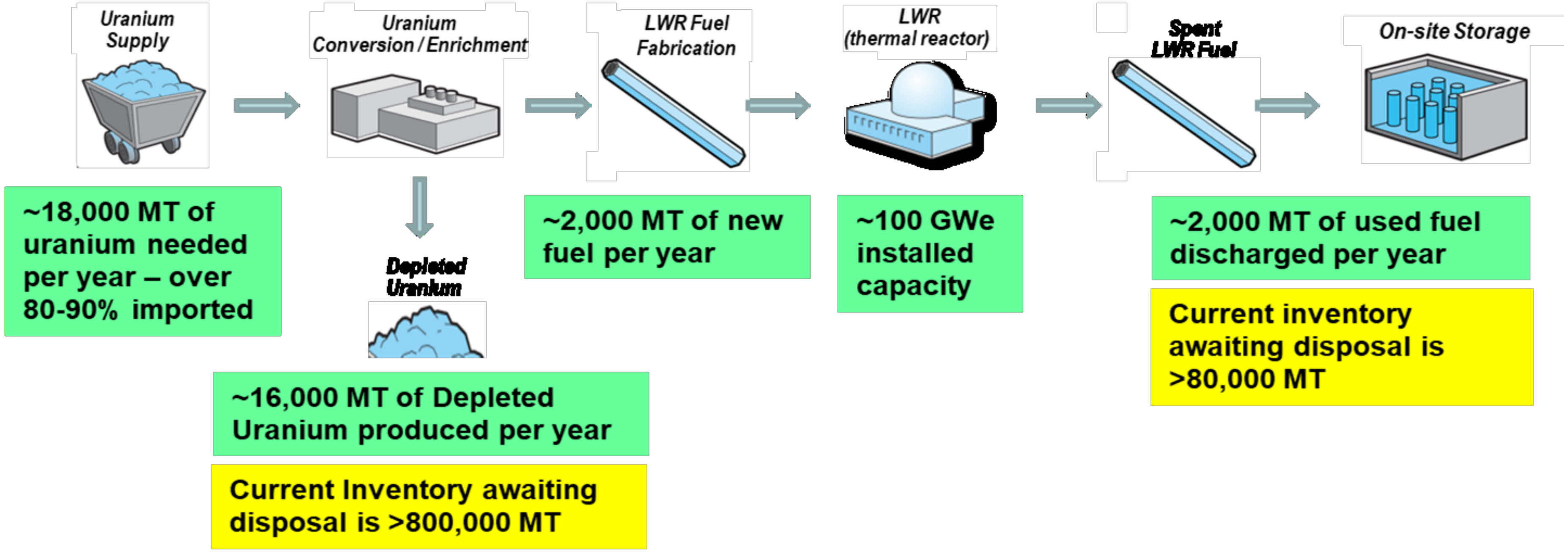
Nuclear Energy Basics

- The Objective - Boil Water (or heat a gas ……)
- Electricity --- AND PROCESS HEAT



A Boiling Water Reactor (BWR), A Type of Light Water Reactor (LWR)

Current U.S. (Open) Nuclear Fuel Cycle

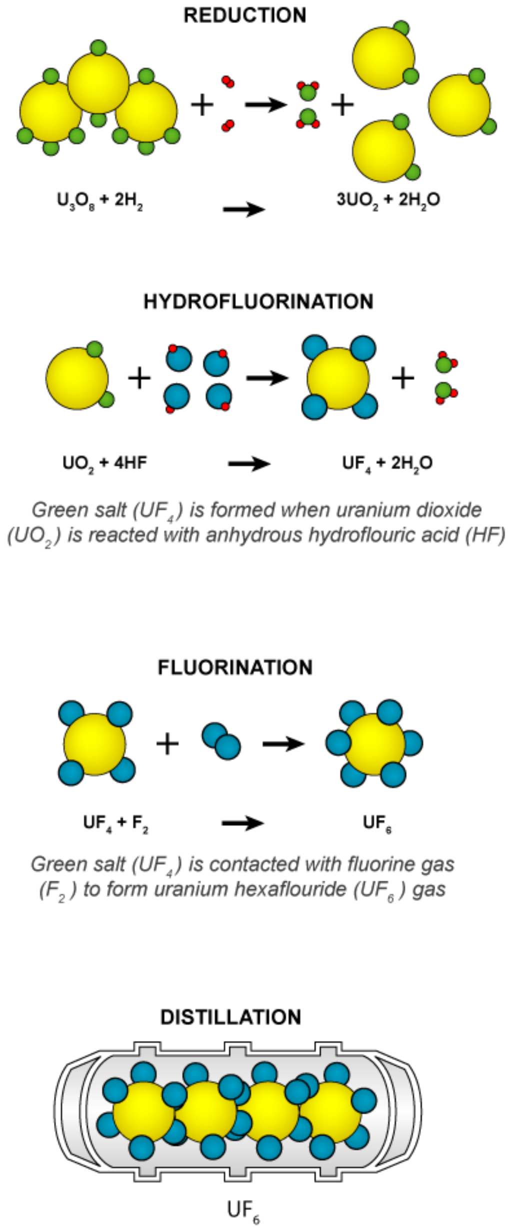


Mining and Milling

- A reliable source of enriched uranium is needed for reactor demonstrations and deployment
- Uranium is mined in three ways:
  - In situ leaching
  - Open pit mining
  - Underground mining
- Wyoming is the US's largest uranium producer, but most of our uranium is imported.
- Advanced reactors utilize low enriched uranium
  - Most use 19.75% U-235 enriched uranium (High-Assay Low Enrichment Uranium)
  - This is in comparison to LWRs which currently use < 5 %
- Supply chains for uranium and enrichment will be needed to support future reactor deployment.

Conversion

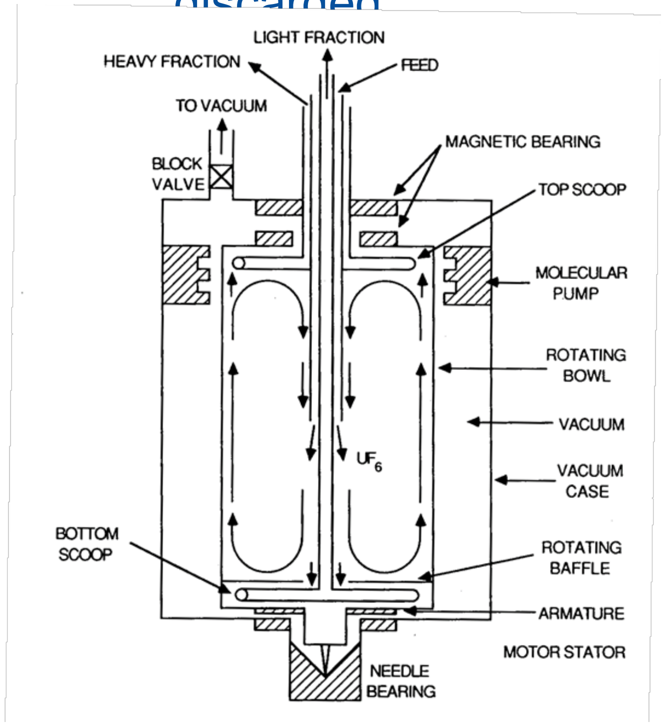
- Natural uranium (U) contains two isotopes
  - 0.7% is "fissile" ^{235}U which is easily split in a reactor
  - 99.3% is "fertile" ^{238}U which is not
- Fresh nuclear fuel in current reactors is ~4.5% fissile content, requiring enrichment:
  1. Convert the Uranium to a gas
  2. Spin the gas at high speeds in centrifuges
  3. The lighter ^{235}U partially separates from the heavier ^{238}U
- Natural uranium is in an oxide form (U_3O_8)
  - At the conversion plant U_3O_8 is converted to uranium hexafluoride (UF_6), which is a solid at room temperature but a gas at slightly higher temperatures
  - UF_6 is stored and shipped in large cylinders



http://www.theupa.org/uranium_technology/conversion/

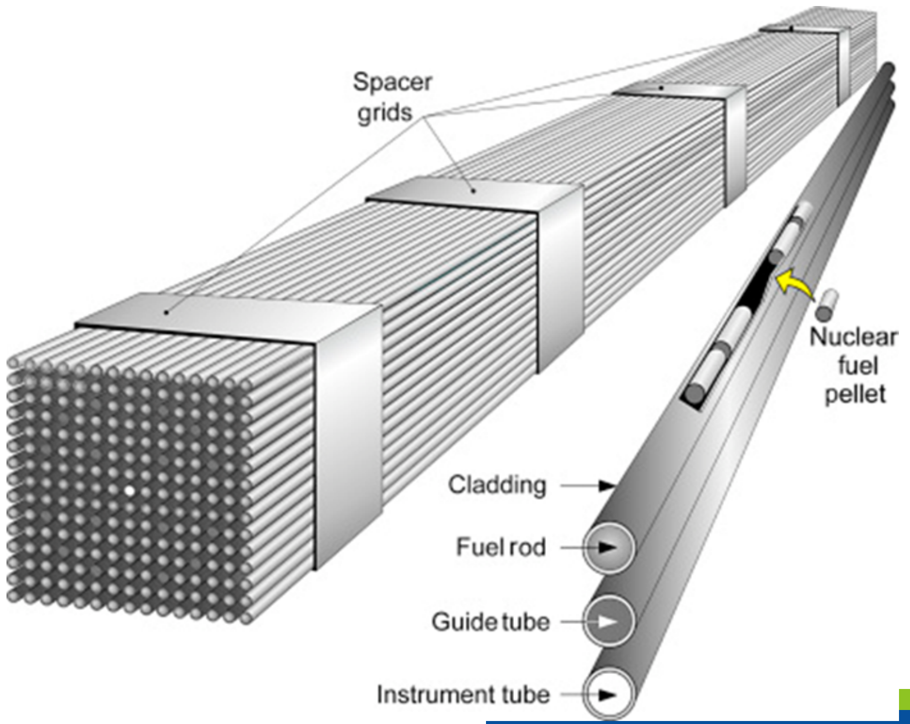
Enrichment

- Enrichment involves passing UF_6 through high-speed centrifuges
  - In each centrifuge the ratio of $_{235}U$ to $_{238}U$ is changed slightly into a "heavy fraction" scooped from the outside and a "light fraction" scooped from the inside
  - Hundreds of centrifuges are linked in "cascades" to produce enriched U while also generating larger amounts of depleted U that is discarded



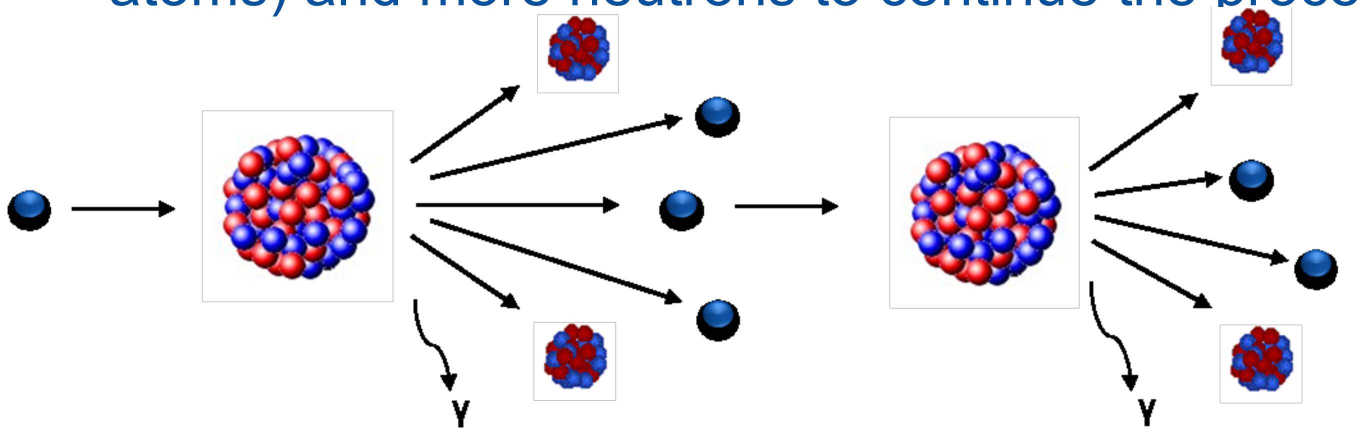
Fuel Fabrication

- Fuel fabrication is a multi-step process
  - UF_6 is received and converted to an oxide powder (UO_2)
  - The powder is pressed into pellets
  - The pellets are heated (sintered) to create a ceramic
  - The ceramic pellets are stacked inside cladding to make fuel rods, which are welded shut
  - The fuel rods are loaded into assemblies which are typically 16 to 17 inches square and ~16 feel long
  - The very slightly radioactive assemblies are inspected, then shipped to reactors
  - 150 to 250 assemblies are loaded into a core, depending on the reactor size.



Irradiation

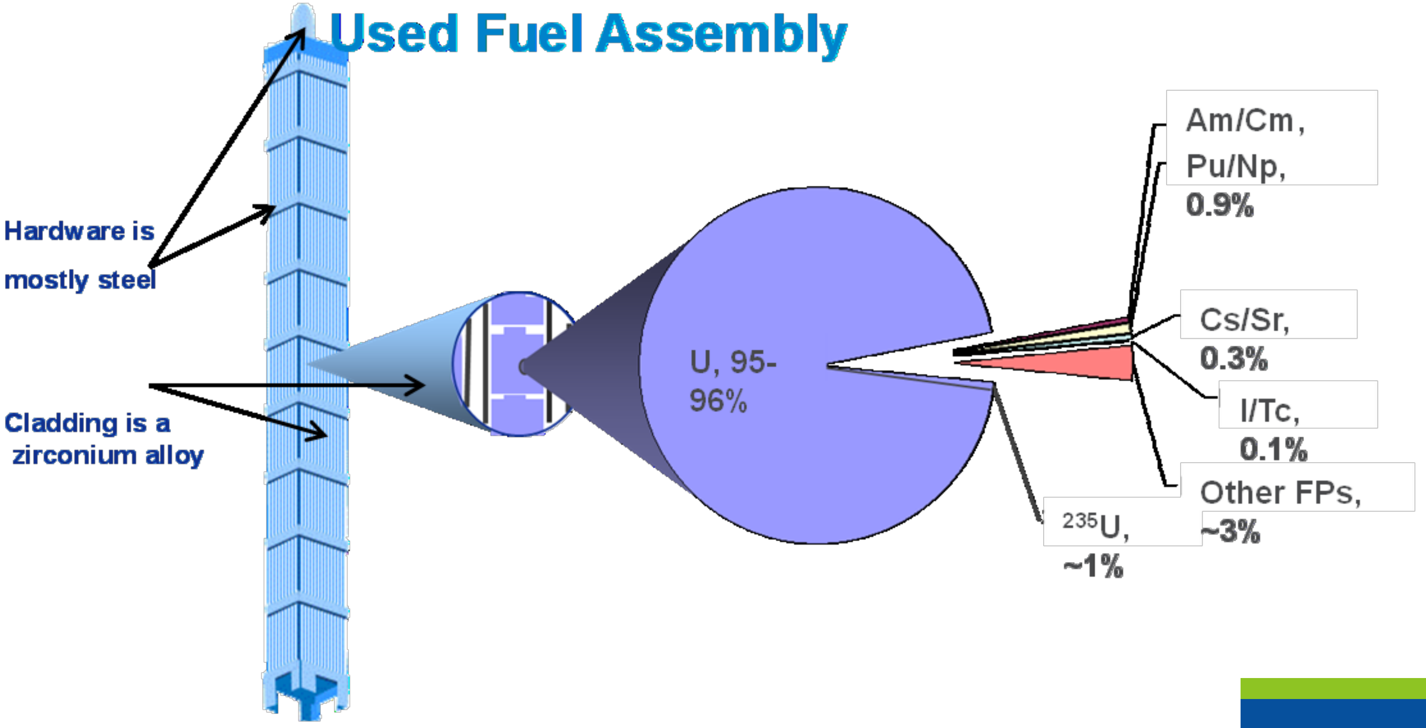
- In the reactor, nuclear fuel is irradiated for ~4.5 years
  - During this time, ^{235}U is fissioned (split) by neutrons to produce electricity
  - Fissioning results in heat, fission products (smaller atoms) and more neutrons to continue the process



- After the fissile material is depleted and fuel is “spent” and replaced during refueling
  - The highly radioactive used fuel is initially stored in water to “cool”, then may be transferred to dry storage

Used fuel characteristics

- Used fuel is composed mostly of ^{238}U, along with:
  - ~4% fission products
  - ~1% residual ^{235}U
  - ~1% heavier “transuranic” isotopes from neutron capture of ^{238}U (breeding)



Used Fuel Disposition Options

- After cooling, used fuel is currently stored waiting for final disposition
  - While used fuel becomes less radioactive with time, it remains a health hazard for thousands of years
- The disposition options are:
  - Direct disposal in a geologic repository designed to contain residual hazards for 100,000 years or more (current U.S. approach)
  - Recycling (practiced in some countries in Europe and Asia)
- Recycling separates the fuel:
  - Uranium and plutonium are recovered for reuse
  - Fission products and hardware are disposed in a geologic repository
  - Other transuranics may be recovered for reuse or included in the waste

Recycling Options

- With current reactors, only limited recycle is possible:
  - Recover the U for re-enrichment
  - Recover the Pu, which is mostly fissile
  - Results in ~30% more electricity from the original mined uranium and a small reduction in waste
  - Currently not cost effective

- With advanced reactors, continuous recycle may be cost effective:
  - Recover U, Pu, other transuranics (optional)
  - Irradiate in a fast spectrum reactor which supports enough breeding to produce fissile material as fast as it is consumed
  - Requires technology development

Nuclear Energy and Nuclear Reactors

Applications Today and Tomorrow

Global Supply Chain

- Materials (e.g. Uranium)
- Equipment / manufacturing
- *Services*
- Global Suppliers
- Estimated $8 T Global Market Through 2050

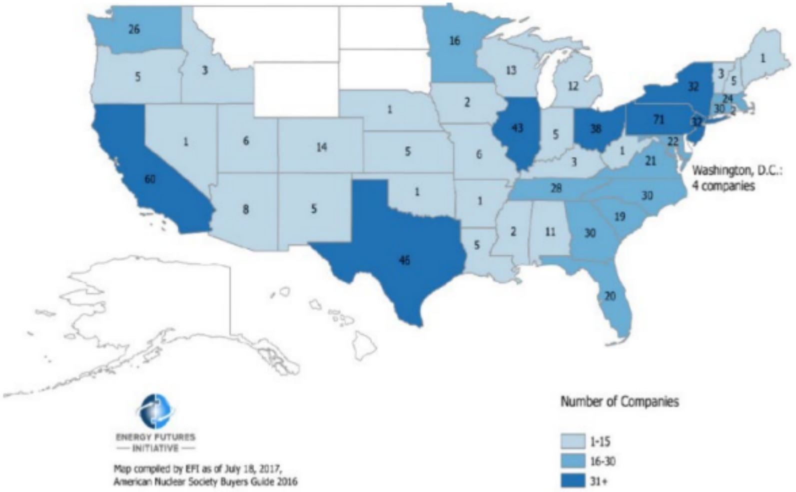
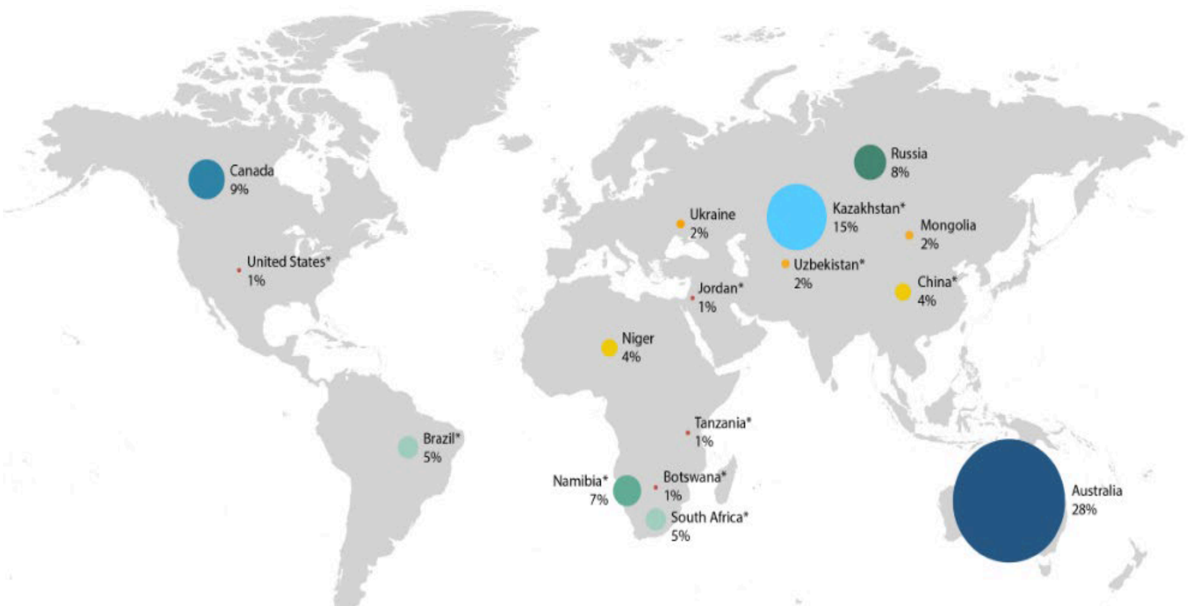
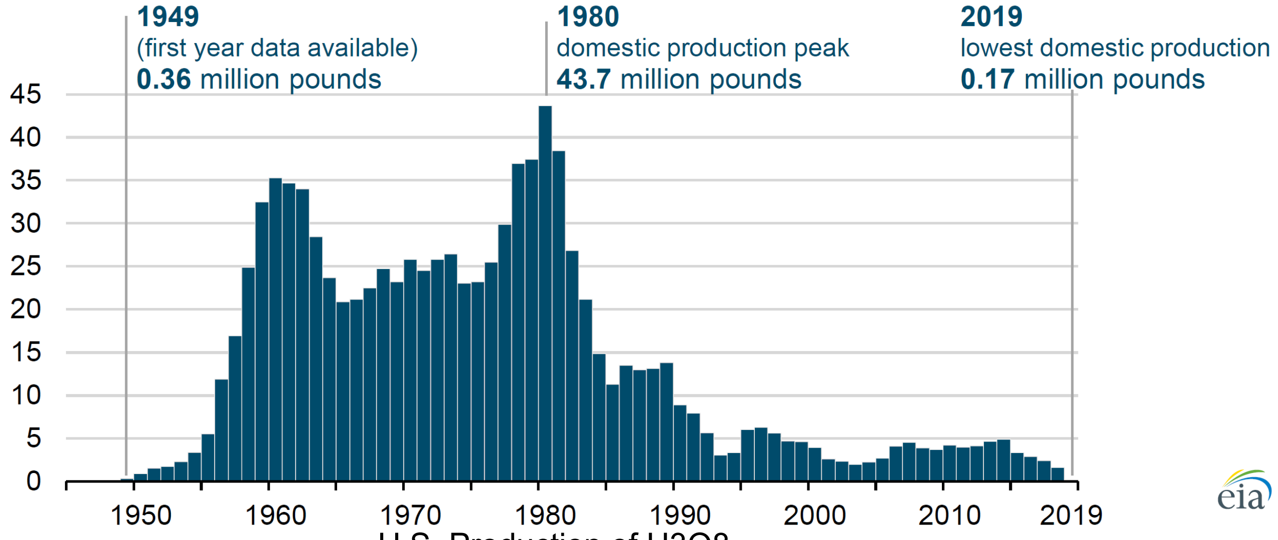


Figure 1. Number of Nuclear Supply Chain Companies by State[9]

From “Nuclear Energy – Supply Chain Deep Dive Assessment, U.S. DOE 2022



Distribution of Uranium Recoverable at <$130/kg



U.S. Production of U3O8

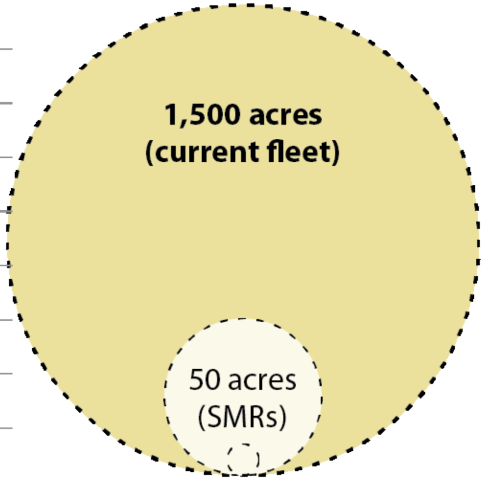
What's New

Why Do We (or Should We) Care

Terms That You Will Hear – And What They Mean

Existing (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**

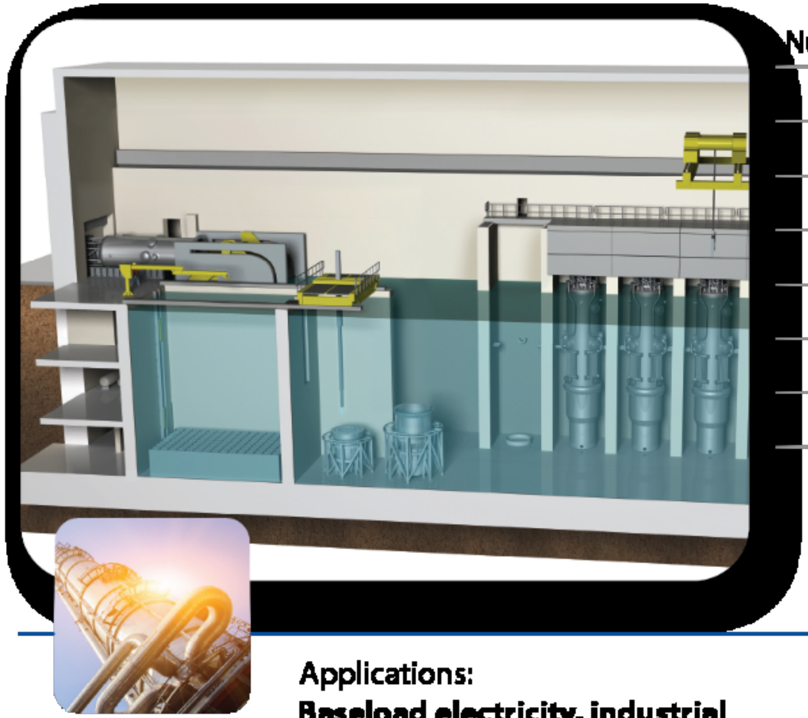


Applications:
Baseload electricity; 24/7
Coming soon: Hydrogen production

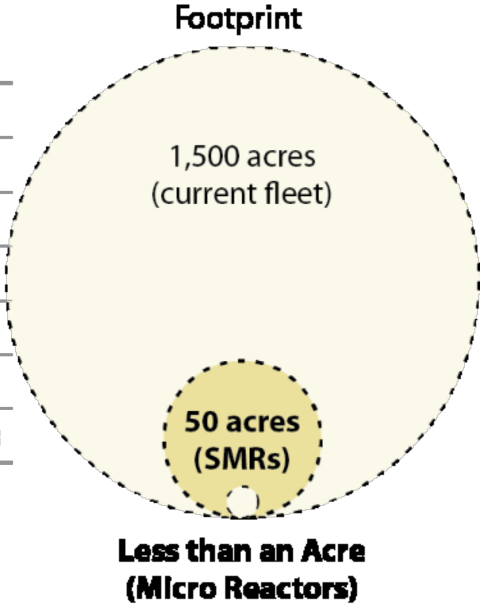
Did you know? In November 2018, the Union of Concerned Scientist recommended that federal and state governments adopt policies to preserve the low-carbon electricity the current fleet of nuclear reactors provides.

Slide courtesy of Kortny Rolston-Duce

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**



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

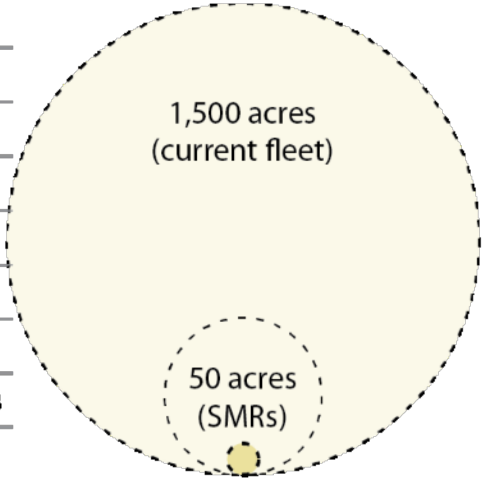
**NuScale SMR has completed NRC design approval with plan to start operation on INL site in 2029*

Slide courtesy of Kortny Rolston-Duce

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**

Footprint



Less than an Acre (Micro Reactors)

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

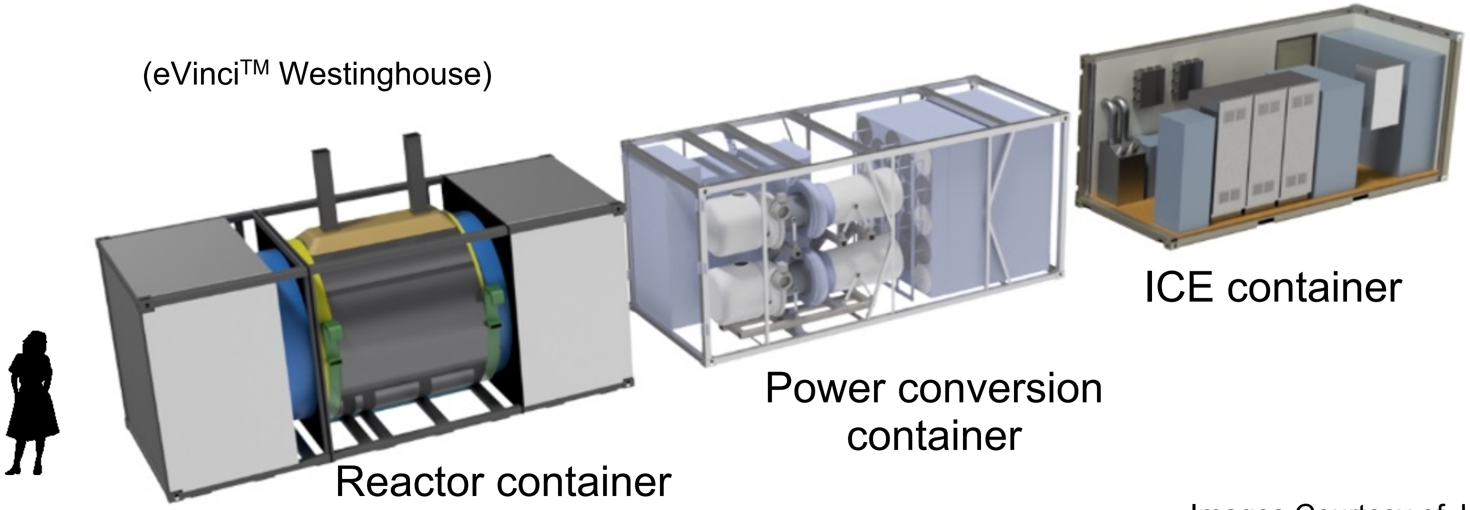
Sen. Lisa Murkowski, R-Alaska, April 4, 2019 Op-Ed in the Anchorage Daily News.

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."

Slide courtesy of Kortny Rolston-Duce

Microreactors in a "nuclear battery" framework

Moving from construction to manufacturing



Images Courtesy of Jacopo Buongiorno & Rob Freda, MIT

- Plug-and-play system producing 1-50 MW of heat
- Carbon emissions free
- Dry cooling (no water needed)
- Standardized, factory fabricated
- Transportable in ISO containers
- Semi-autonomous operation
- Offsite refuelling every 5-10 years
- No onsite storage of radioactive material
- Very small footprint
- US suppliers are in the lead (Westinghouse, BWXT, X-energy)

The March Toward "Embedded", Localized Energy As A Competitive Advantage

Alaska Applications – Railbelt and Remote?

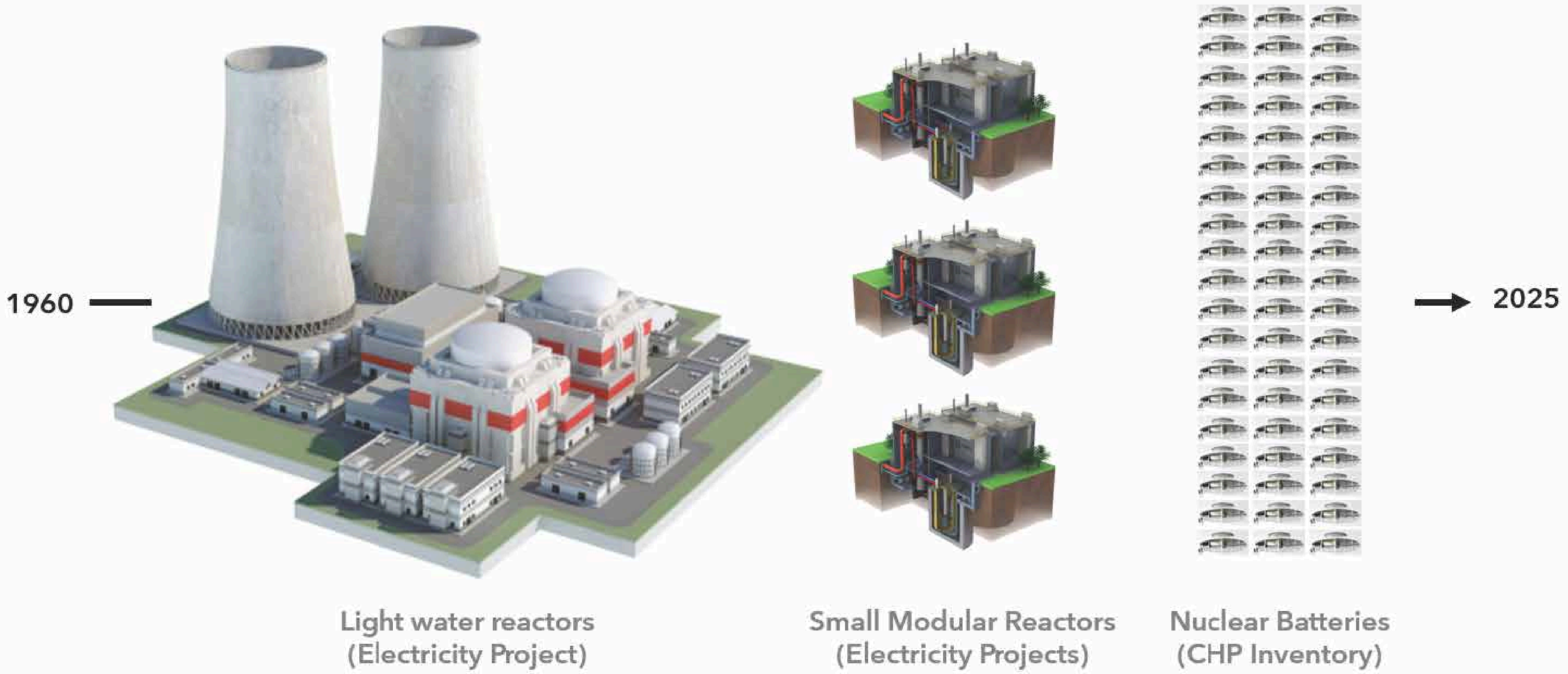


Image Courtesy of ANPEG

* All nuclear batteries are microreactors, but not all microreactors are nuclear batteries

Microreactor Concepts and Developers (2023)

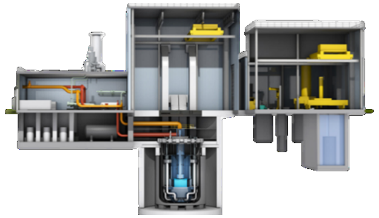
Developer	Name	Type	Power Output (MWe)	Fuel	Coolant
Alpha Tech Research Corp.	**ARC Nuclear Generator**	**MSR**	**12 MWe**	**LEU**	**Fluoride Salt**
BWXT	**BANR**	**HTGR**	**17 MWe**	**TRISO**	**Helium**
General Atomics	**GA Micro**	**HTGR**	**1-10 MWe**	—	**gas**
HolosGen	**HolosQuad**	**HTGR**	**13 MWe**	**TRISO**	**Helium/CO2**
Micro Nuclear, LLC	**Micro Scale Nuclear Battery**	**MSR/heat pipe**	**10 MWe**	**UF4**	**FLiBe**
Nano Nuclear	**ZEUS**	**FR/HTGR**	**1 MWe**	**UO2**	**Helium**
NuGen, LLC	**NuGen Engine**	**HTGR**	**2-4 MWe**	**TRISO**	**Helium**
NuScale Power	**NuScale Microreactor**	**LM/heat pipe**	**< 10 MWe**	**Metallic**	**Liquid Metal**
Oklo	**Aurora**	**SFR/heat pipe**	**1.5 MWe**	**Metallic**	**Sodium**
Radiant Nuclear	**Kaleidos Battery**	**HTGR**	**1.2 MWe**	**TRISO**	**Helium**
Ultra Safe Nuclear	**MicroModular Reactor**	**HTGR**	**5 MWe**	**TRISO**	**Helium**
Westinghouse	**eVinci**	**Heat pipe**	**5 MWe**	**TRISO**	**Sodium**
X-energy	**Xe-Mobile**	**HTGR**	**7.4 MWe**	**TRISO**	**Helium**

Evaluation of AK Applications - Key Takeaways

- Several studies over the years assessing commercial nuclear power costs (e.g. Galena, ACEP, NEI, MIT/EMA)
  - Levelized Cost of Electricity (LCOE)
  - System Costs

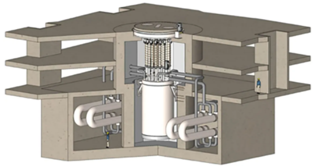
- MacDonald and Parsons (2021) and Parsons (2023) - MIT:
  - EMA = MIT, UA, UM, UW, BSU and INL collaboration
  - Minimize system cost v. LCOE
  - Considers microreactors *as part of a portfolio* of electrical and heat generators
  - Capital and operating costs
  - Consider prototypic generic applications:
    - Railbelt
    - Remote Community (Nome)
- Key takeaways
  - If waste heat can be used for heating, microreactors very competitive (remote and railbelt)
  - Nome application – cost comparative to wind-storage-diesel

Accelerating advanced reactor demonstration and deployment

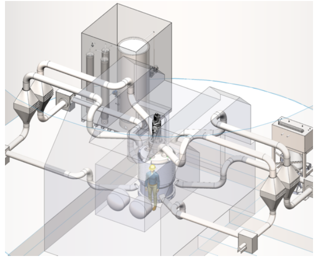


2030

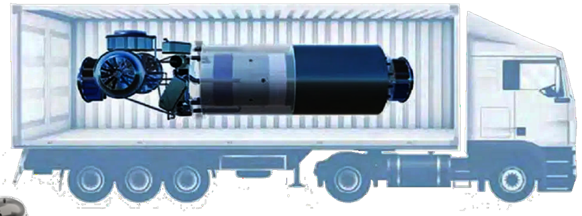
Natrium Reactor
TerraPower & General Electric
2029



Hermes
Kairos
2026



MCRE
Southern Co. & TerraPower
2025



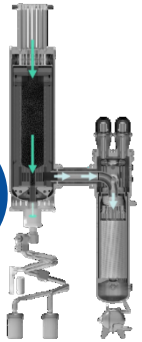
Project Pele Microreactor
DoD
2024

SMR
UAMPS & NuScale
2029-2030

Eielson AFB
2027

Xe-100
X-energy
2027

Aurora
Oklo Inc.
TBD



LOTUS Test Bed
NRIC
2024

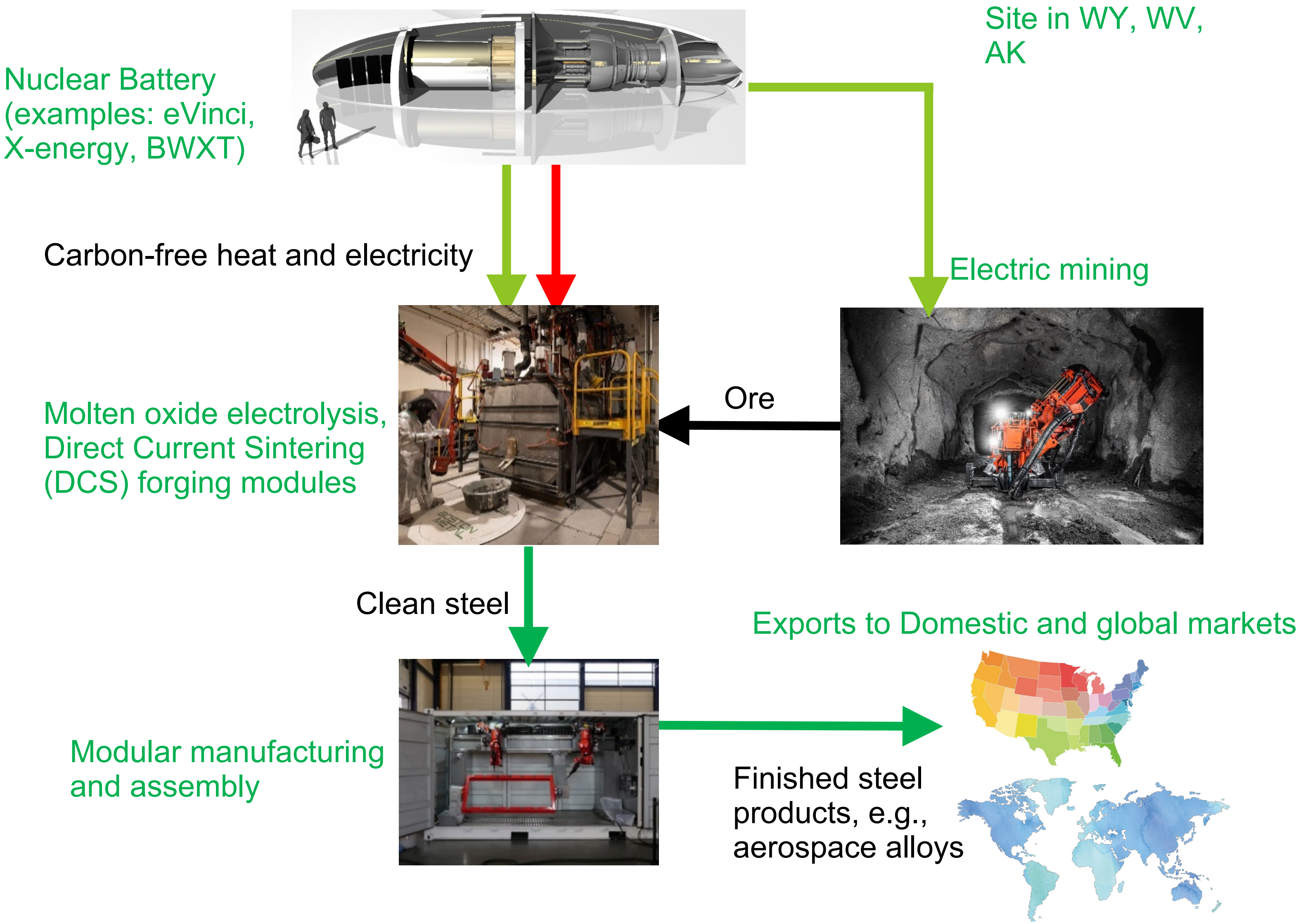
MARVEL
DOE
2024

DOME Test Bed
NRIC
2024

NRIC National Reactor Innovation Center

Other Slides of Possible Interest

NUCLEAR BATTERY + ADVANCED INDUSTRIAL PRODUCTION = MAJOR DISRUPTOR



Images Courtesy of Jacopo Buongiorno, MIT

A key enabler to move higher on the industrial value chain

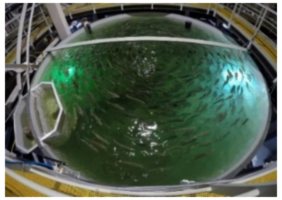
THIS APPROACH APPLIES ACROSS EVERY SECTOR OF THE ECONOMY

military bases

microgrids (remote communities, islands)

mining sites

indoor farming



indoor aquaculture

high-end metals, ceramics and glass

data centers

desalinatio
n

portable pharma

time

Slide Courtesy of Jacopo Buongiorno, MIT

Licensing – Past and Future

- Recent Experience
  - NuScale SMR – 42 months for design certification (completed !)
  - Oklo Aurora Microreactor – 10 CFR 52 - 36 month planned review period; recently NRC denies license application w/out prejudice (i.e. they are welcome to start again)

- NRC is Considering ”Risk-Informed, Technology Inclusive Regulatory Framework for Advanced Reactors” – i.e. a new “Part 53”
  - This is a long, in-depth rule making process

- NRC is Analyzing Microreactor Licensing Strategies *Using Existing Authorities*
  - Key elements of consideration
    - Standardized design, standard site conditions
    - Factory manufactured – license the manufacturing process
    - Operations standardized
    - No spent fuel storage at operations location
    - Generic EIS

Licensing Commercial Power Reactors

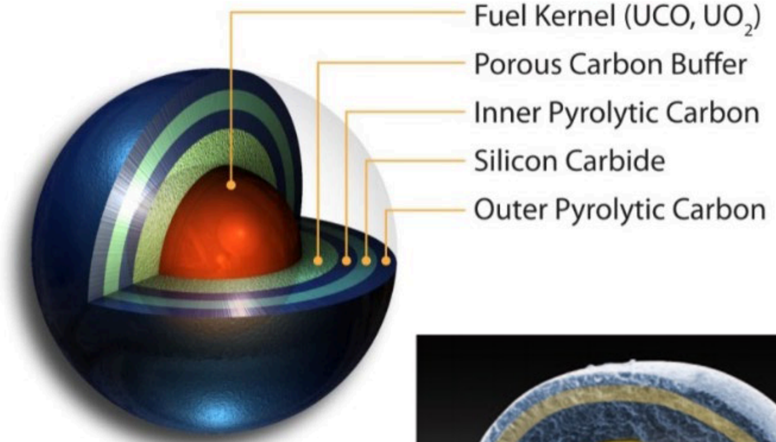
- All commercial power reactors operate under NRC licenses
  - Originally issued for 40 years
  - Subsequent licenses extended to 60 and 80
- NRC has sole licensing authority; but states have permitting authorities necessary for plant operation
- 3 basic licensing paths
  - 10 CFR 50 – Construction licenses followed by Operating License (EACH ~ 36 months)
  - 10 CFR 52 –Combined Construction and Operating License refencing a certified design (~30 months)
  - 10 CFR 52 - Combined Construction and Operating License NOT referencing a certified design (~36 months)
- Design certification is NOT licensing – don't mix the two up …….

Key Enablers

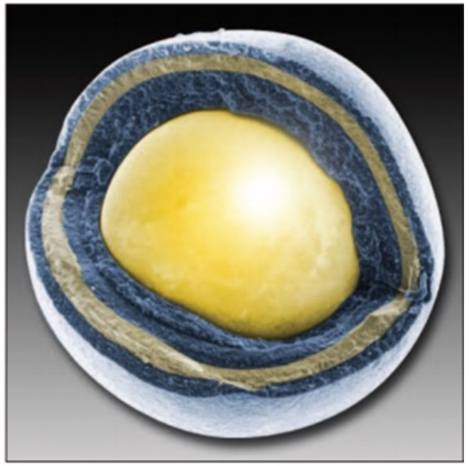
- New materials
  - High-assay, low-enriched (HALEU) nuclear fuel central to most all advanced reactors
  - Today's commercial fuels contain less than 5% uranium-235
  - HALEU slightly less than 20%
  - Longer core life, smaller size, advanced performance – more “gas in the tank”
  - TRISO fuel form
  - Metallic fuel form

- New digital techniques
  - Remote monitoring, security, performance
  - Entirely new business models for deployment ?

EBR-II Metallic Fuel Casting



TRISO Fuel Particle

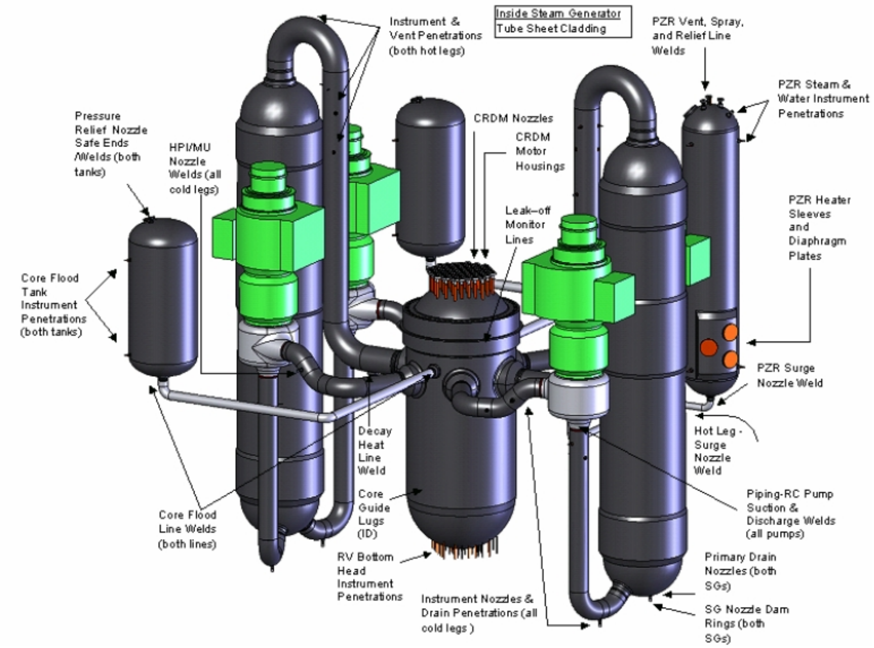


Why Size Matters, and Why This Evolution?

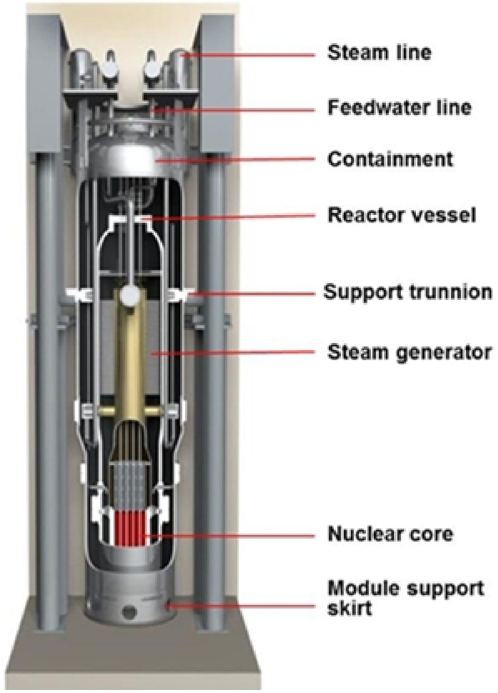
- Large size pursued principally for efficiencies of scale and to match rapidly growing electric markets
  - Larger the better
- Implications:
  - Significant for safety systems: System pressure, decay heat removal, reactor control mechanisms, emergency planning
  - NOT modular – generally each a unique massive construction project
  - Construction complexity (capital at risk, financing costs, etc)
  - Mis-match in market (load) and generation size as economies mature (growth rate) = underutilized capital
  - Limited to grid service application
- Size (power) increase as industry matured –
  - Learning
  - Chasing efficiencies of scale
  - Application space

Integrated Small Reactor – reactor and several components in one vessel

Simplified systems
Fewer Failure Modes



Typical PWR Reactor



IPWR Reactors

Slide courtesy of George Griffith, INL

Microreactor Cost Assessments a limited snapshot

Preliminary estimates for cost of producing electricity - *Not Including credits and not system cost*

Timeframe		Cost Targets at Cumulative Number of Builds				
1st Units	**Profile Markets**	**1-9**	**10**	**100**	**1,000**	**10,000**
2020-2030	FOAK units/ DoD Units	<$0.60/kWh				
2030-2035	Remote Operations		<$0.50/kWh	<$0.35/kWh	<$0.20/kWh	<$0.15/kWh
2035-2040	Distributed Energy			<$0.35/kWh	<$0.20/kWh	<$0.15/kWh
2040-2050	Resilient Cities				<$0.20/kWh	<$0.15/kWh

Credit: DOE Microreactor Program, Shropshire, Black, and Araujo; 2021, Global Market Analysis of Microreactors, INL/EXT-21-63214.

AK Remote Applications Present Average Cost: $0.54 / kWh (average)

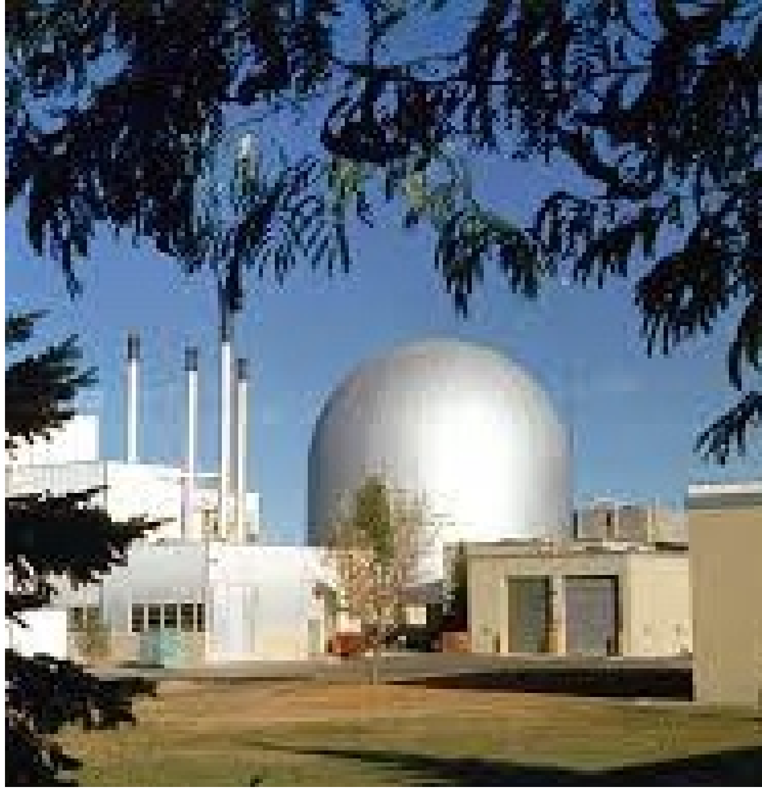
Note: Capital costs usually ~ 70% of COE for nuclear

Advanced Reactors and Passive Safety – The Important Role of Demonstrations

- Many decades of experience in demonstrating advanced technologies
  - Similar to approaches in other industries Develop, demonstrate, improve

- Experimental Breeder Reactor – 2
  - Sodium cooled fast reactor
  - Operated very successfully for 30 years
  - Demonstrated power production, plant operations, and "inherent safety" of this class of technology
    - Most aggressive accident scenarios tested: Loss of coolant flow and loss of heat sink

- Lean on this knowledge base



EBR-II, a sodium cooled fast reactor, demonstrated inherent safety in 1986 and operated successfully and effectively for 30 years

1) Demonstrated natural circulation
2) Loss of flow without shutdown
3) Loss of heat sink without shutdown
4) Demonstrated industrial operations
5) Demonstrated decommissioning