INL/RPT-23-72113-Revision-0

Advanced Nuclear Energy Technology, Applications & Alaska   A Brief Primer

April 2023

Changing the World's Energy Future

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Idaho National Laboratory

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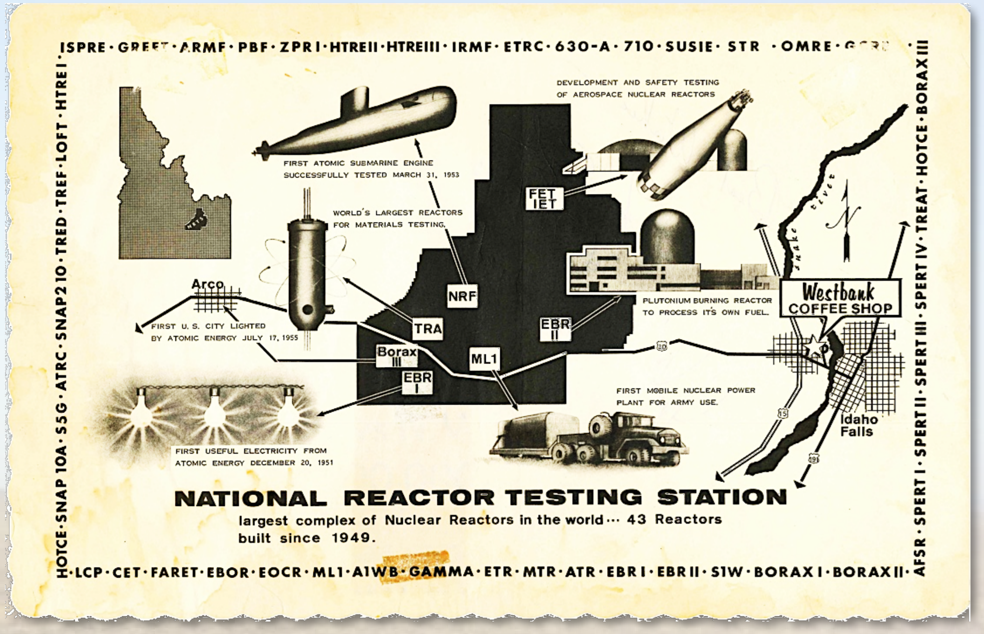
Advanced Nuclear Energy Technology, Applications & Alaska – A Brief Primer

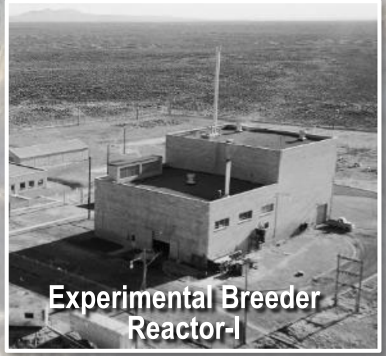
Prepared for Alaska House of Representatives

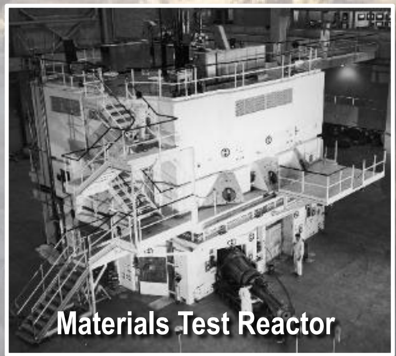
The Nation’s, and Wyoming’s, Nuclear Energy Laboratory

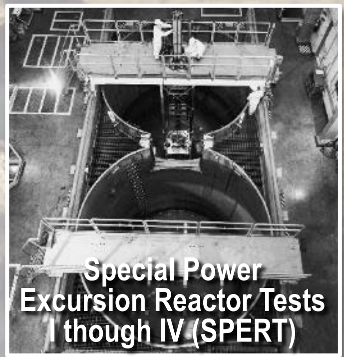
Over Seventy Years of Leading Into New Frontiers:

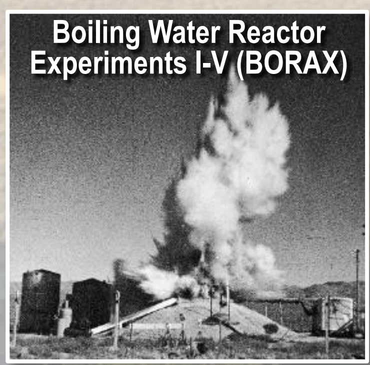
- First nuclear power plant
- First U.S. city to be powered by nuclear energy
- First submarine reactor tested; training of nearly 40,000 reactor operators until mid-90s
- First mobile nuclear power plant for the army
- Demonstration of self-sustaining fuel cycle
- Basis for LWR reactor safety
- Aircraft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




Experimental Breeder Reactor-I


Materials Test Reactor


Special Power Excursion Reactor Tests I though IV (SPERT)

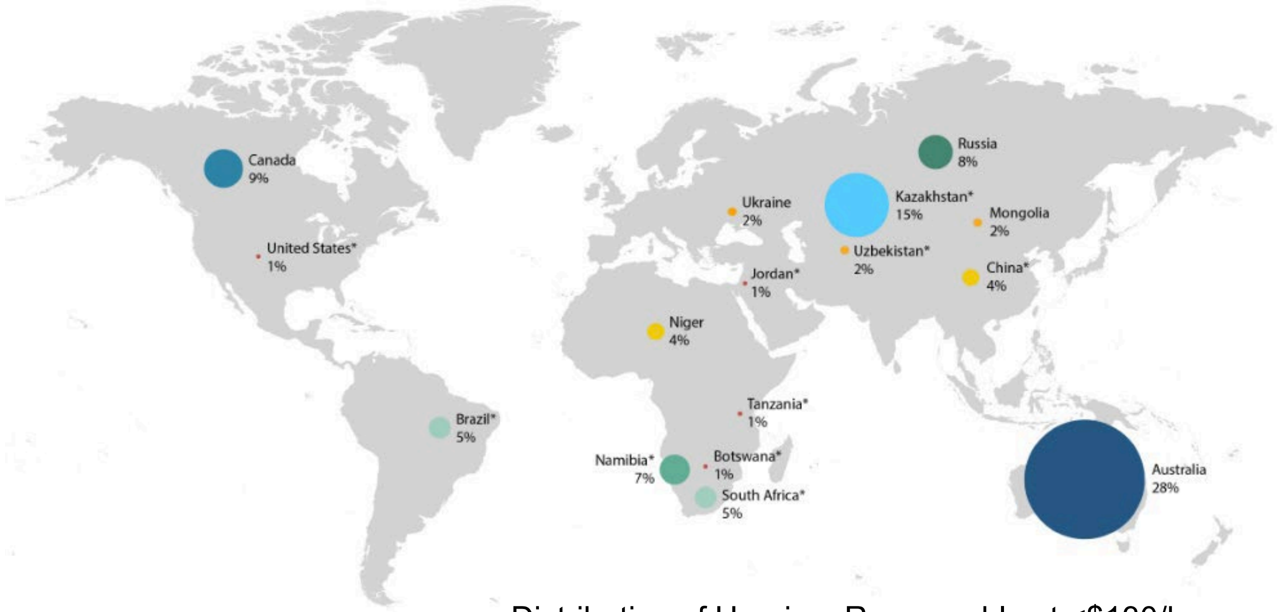

Boiling Water Reactor Experiments I-V (BORAX)


S1W (aka Submarine Thermal Reactor (STR)


Loss Of Fluid Test Facility (LOFT)

Global Supply Chain

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



Distribution of Uranium Recoverable at <$130/kg

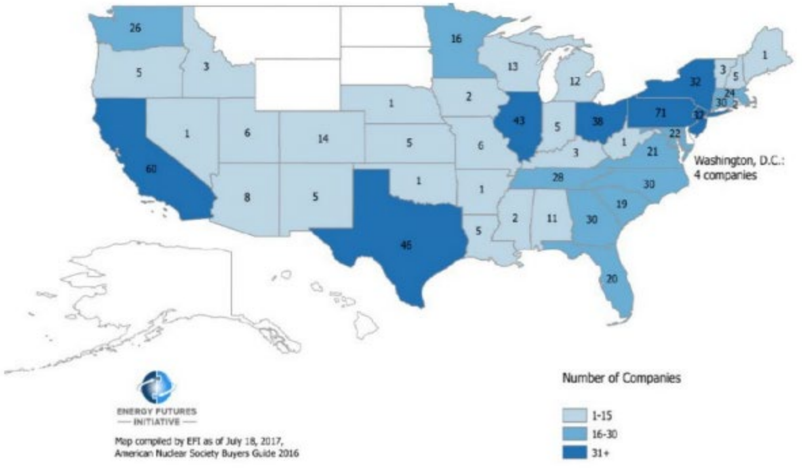
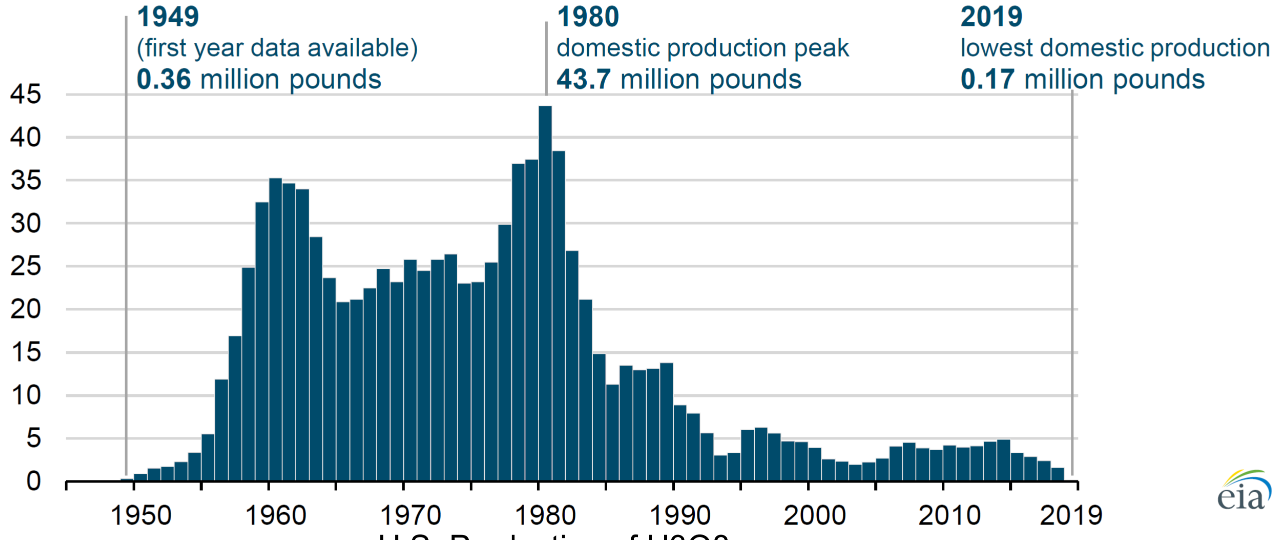


Figure 1. Number of Nuclear Supply Chain Companies by State[9]

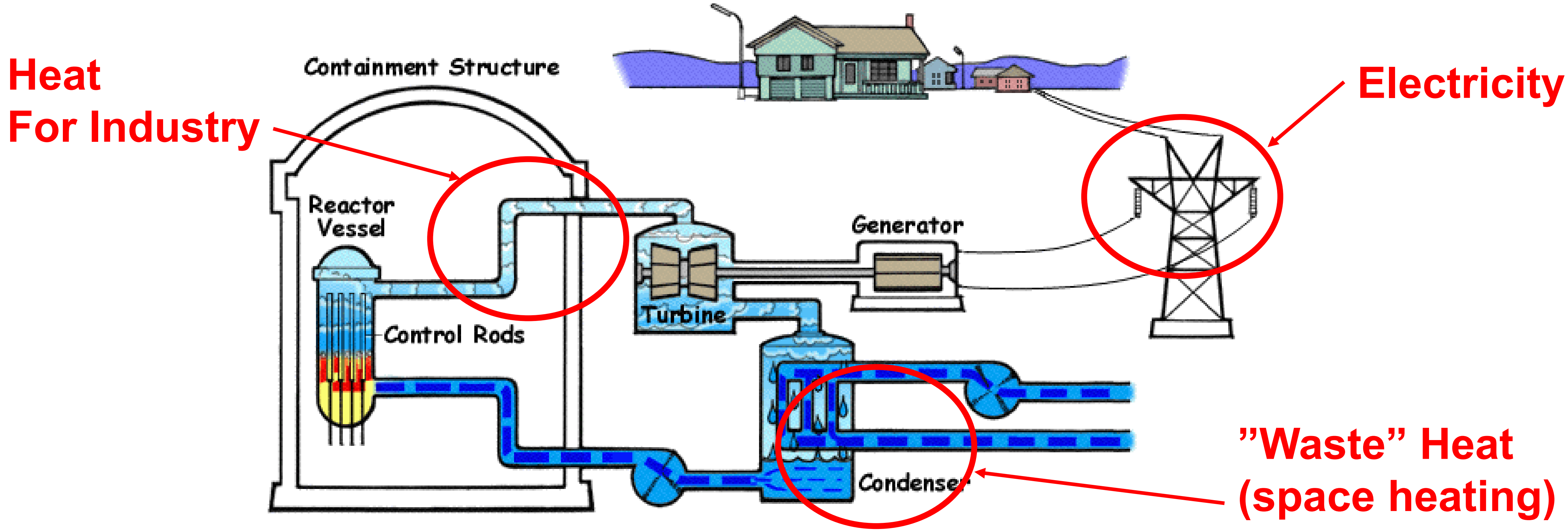
From "Nuclear Energy – Supply Chain Deep Dive Assessment, U.S. DOE 2022



U.S. Production of U3O8

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)

Why Should We Care? The Bottom Line-

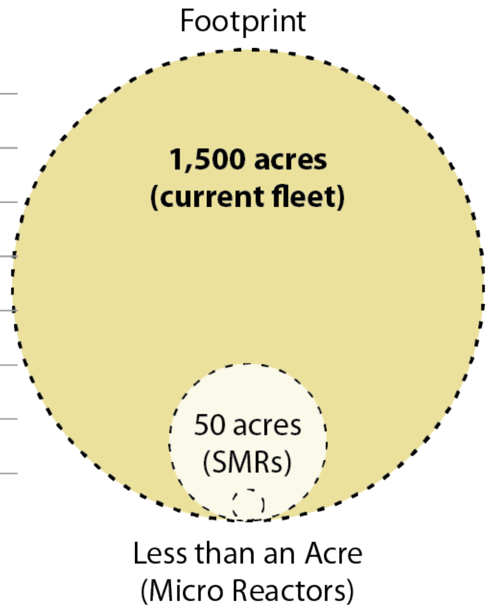
- New sizing and designs open new uses
  - Electricity – microgrids
  - Waste heat for district heating or heating microgrids (e.g. building complexes within constrained areas)
  - Process heat for industry

- 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)

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**



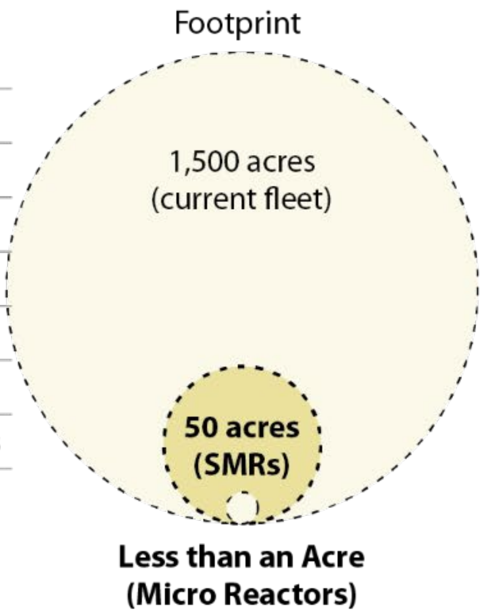
Applications:
Baseload electricity; 24/7
Coming soon: Hydrogen production

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

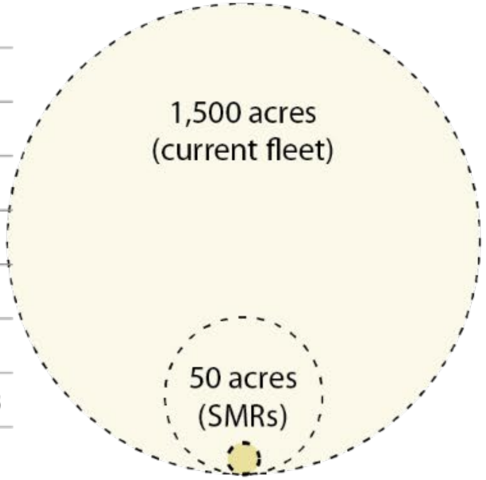
**NuScale SMR has completed NRC design approval with plan to start operation on INL site in 2029*

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

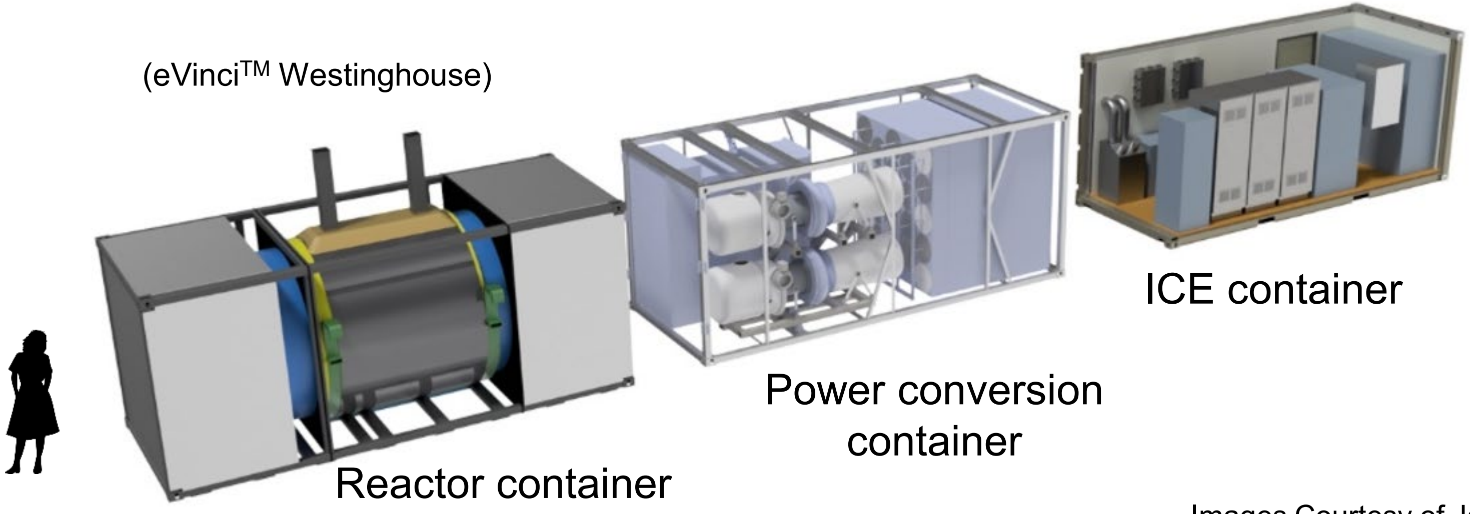
Sen. Lisa Murkowski, R-Alaska, April 4, 2019 Op-Ed in the Anchorage Daily News.

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

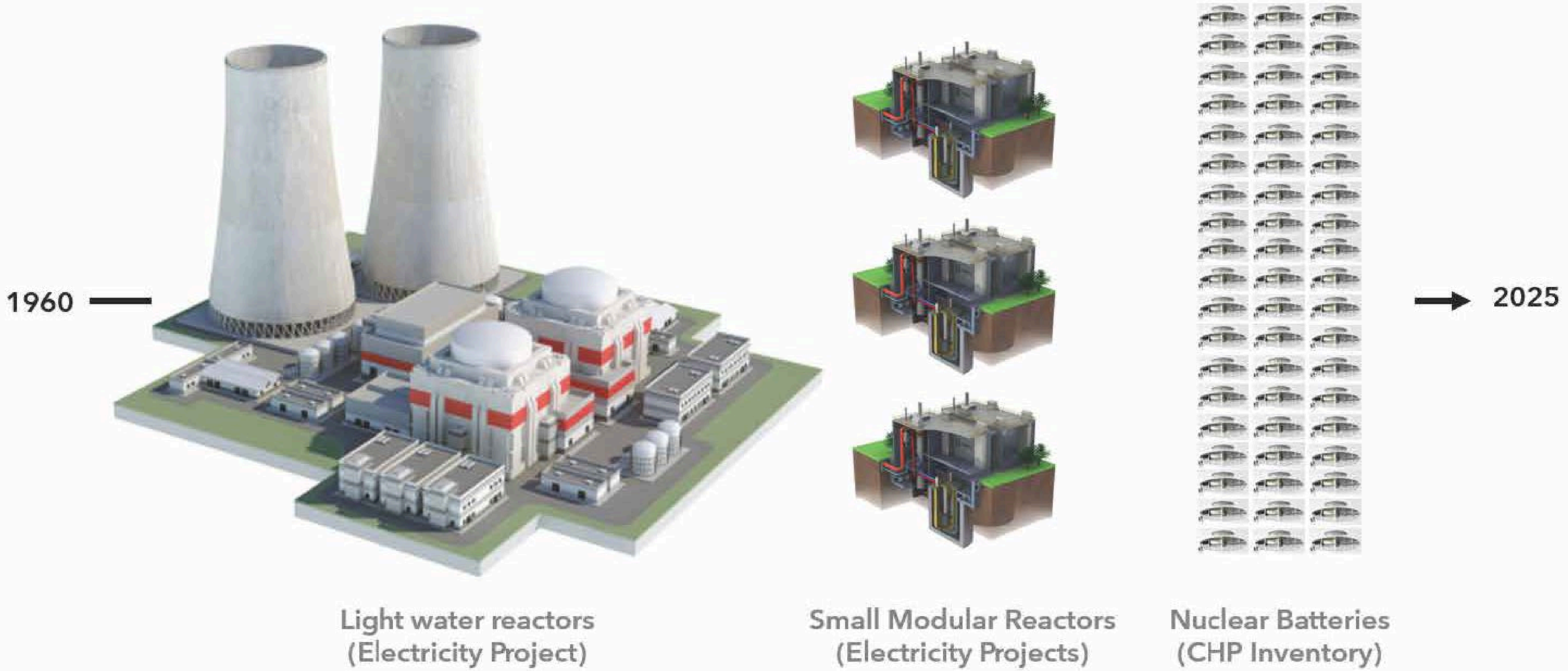
Moving from construction to manufacturing – Expanding AK Application



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



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

Image Courtesy of Rob Freda, MIT / ANPEG

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

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

Alaska Microreactor Applications – A step toward a systems view as a decision tool

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

- Guiding principles –
  - Costs of microreactors that have not been built are uncertain !
  - Price v. value – what do you want, and need? Community desires?

- 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
    - ”Generic” Remote Community and Nome

The Capital Ceiling Analyses – MIT (2021)

- What is the maximum cost of an (uncertain) MR that would be competitive?
  - Minimizes the “guessing game” and hyperbole about capital costs
  - Helpful for resource planning
- Key parameters
  - Natural gas available?
  - Heating use?
  - Emissions credits?

Community	Natural gas available?	CHP accessible?	No emission reduction target	25% emission reduction target
Railbelt community	Yes	No	$4,700/kWe	Not tested
		Yes	$8,300 /kWe	>$30,000/kWe
Mine & Remote community	No	No	$12,500/kWe	Not tested
		Yes	$12,500/kWe	>$30,000/kWe

Key Takeaways

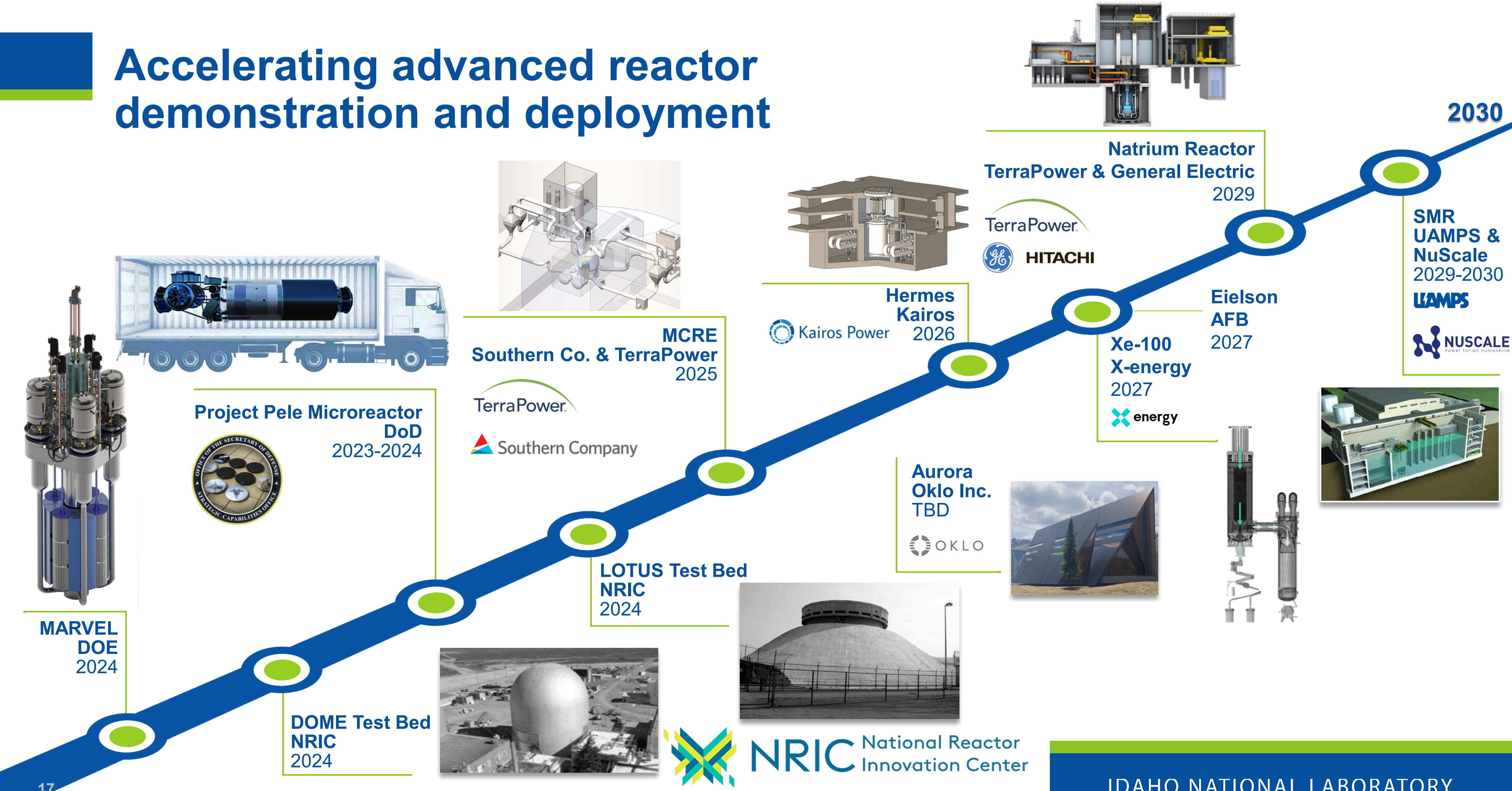
- If one can use microreactor waste heat for space heating – the technology can be quite competitive
  - Note: space heating applications are limited due to availability of district heating v. individual on-site heating units, distance of heating need to reactor
- Availability of natural gas is important (gas is low-cost generator – but doesn't provide allot of waste heat)
- If modest emission credits added, the technology is quite competitive
  - The analyses don't account for the range of emissions and other credits now available
- Railbelt
  - Location of heat load, and how CHP may be priced (regulatory structure – "terms of trade") will be key for cost competitiveness
  - Consideration for Railbelt Reliability Council and future planning?

Nome Study (2023 – MIT, BSU, UA)

- Extended 2021 analyses to a specific location
  - Community perspectives (BSU) and economic analyses (MIT)
- Heating demand is ¾ of energy load, electricity is ¼
  - District heating is not established,
  - Study focus on electrical production
- Analyzed 4 options
  - Present (diesel + wind)
  - 2 architectures with different diesel, wind+storage
  - One with microreactor, diesel, and wind
- All showed ~ same system costs ($0.42-$0.45 per kWh)
- What if expansion of industrial facilities are analyzed?

Suggest: Detailed brief from study experts (MIT, BSU and UA) and extend economic and public perception to planning scenarios

Accelerating advanced reactor demonstration and deployment



Other Slides of Possible Interest

Microreactors, Transportable reactors –
Back to the Future !

- PM-1 – Sundance Wyoming – Transportable Reactor Power Radar

Wyoming – Leadership at the Frontier

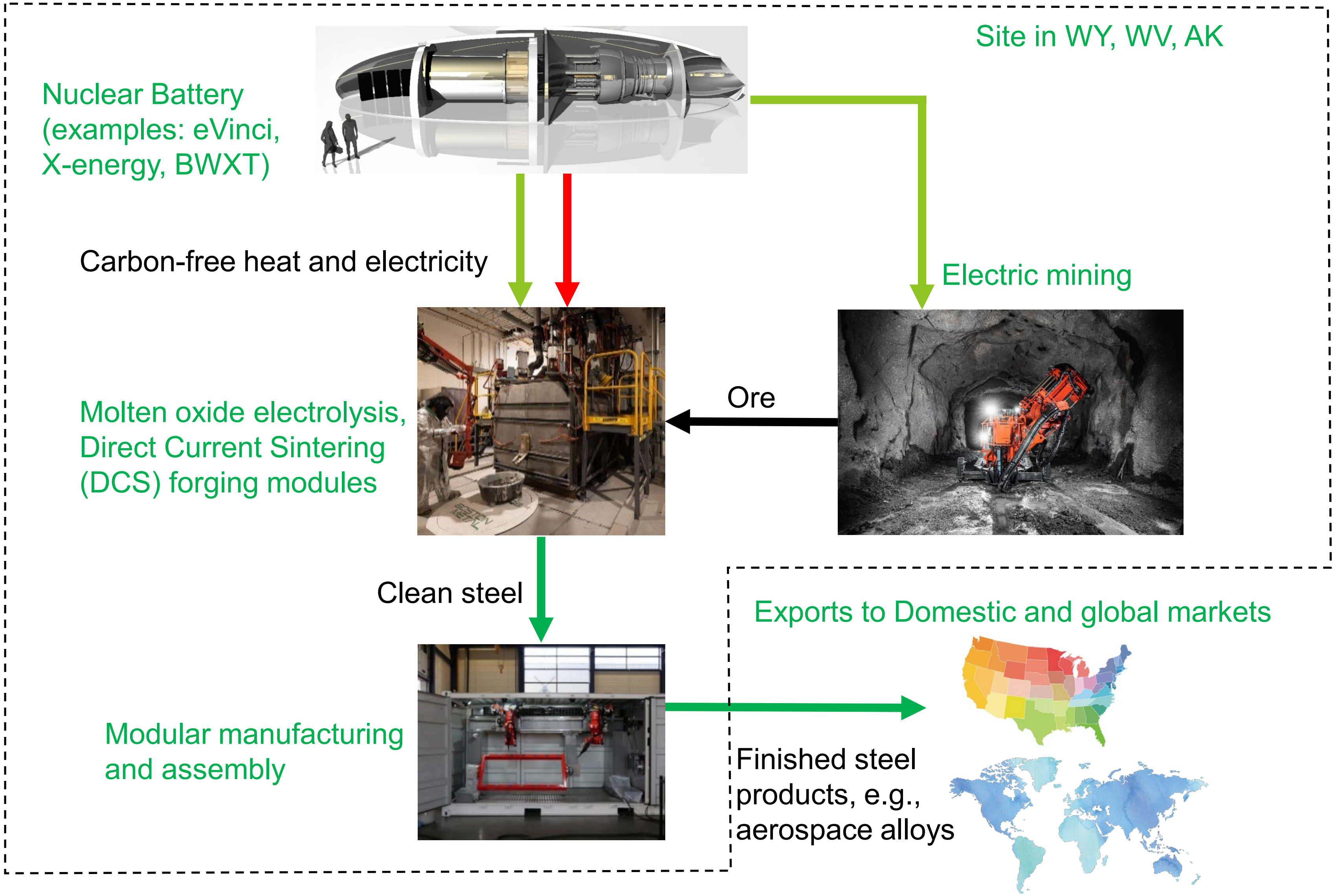
The "New Frontier" – Low Emissions Power AND Industrial Processes

- **Leadership: Wyoming Energy Authority – A Strategic Framework**
- **Generation**
  - Put zero emission electrons on the regional grid
- **Supply Chain**
  - Selectively capture slices of the $8T market
  - E.g. Wyoming Innovative Entrepreneurs
- **Value Chain**
  - Low emission industry (e.g. chemicals, steel, data, etc)– EXPORT LEADERDSHIP
  - The manufacturing of equipment to do that (reactor parts, professional services, etc)
  - The new business to sell and service all that

Wyoming Governor Mark Gordon, representatives, and WEA visited INL on May 4, 2022.

Major Disruptor

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

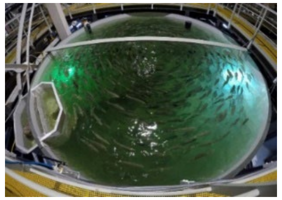
Including marine platforms


military bases


microgrids (remote communities, islands)


mining sites


indoor farming


indoor aquaculture


high-end metals, ceramics and glass


data centers


desalination


portable pharma

time

Slide Courtesy of Jacopo Buongiorno, MIT

The Nuclear Regulatory Commission Licenses Commercial Power Reactors

- All commercial power reactors operate under NRC licenses
  - Originally issued for 40 years
  - Subsequent licenses extended to 60 and 80

- Licensing Framework
  - 10 CFR 50 – Construction licenses followed by Operating License
  - 10 CFR 52 – Design approval/Combined Construction and Operating License

- Recent/current experience
  - NuScale SMR – 10 CFR 52 – 42 months for design approval
  - Oklo Aurora Microreactor – 10 CFR 52 - 36 month planned review period; recently NRC denies license application
  - Staff working on microreactor licensing strategies

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Leading into A New Frontier

- Global industries are shifting to value emissions content all products and services
  - a business *reality* with significant national security implications for the US and her allies
- This is a new global frontier of economic competition. The US must lead into this new frontier. And this leadership in many respects will come from states.
- Wyoming has always been a cornerstone in US economic competitiveness (energy, transportation, agriculture, minerals …)
- And today, Wyoming is again taking on a leadership role to position the state, and our nation, as leaders in low emissions, secure industry and manufacturing
- And its built in part on advanced nuclear energy, Wyoming role as a first-mover, and the innovative strategies, partnerships, and investments to realize the future now.
- This is the “regional to global” strategy for a clean energy transition its time is NOW

Leading Into the Frontier -Innovation In All that we do

- Innovative partnerships and policy must meet technology innovation to secure our national position in global markets
- Innovative partnerships will build capacity quickly. Innovative policy will pave the way for finance, regulatory structure, and community ownership of sustainable economic development.
- The Emerging Energy Markets (EMA) Initiative is an example of innovative partnerships
  - Multi-disciplinary, multi-state team to help build capacity and capability necessary to lead into the new frontier

MARVEL Can Enable a New Class of Nuclear Reactors

(Microreactor Applications Research, Validation & EvaLuation)

Project Goals:

- Rapid development of a small-scale microreactor that provides a platform to test unique operational aspects and applications of microreactors

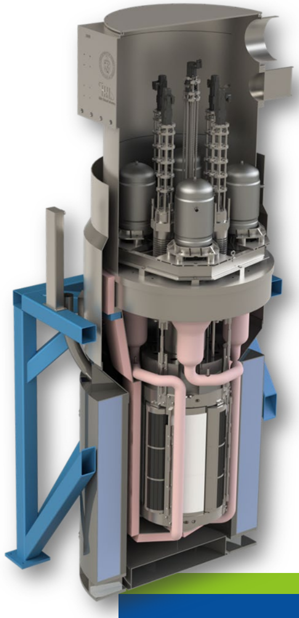
Primary Objectives:

- Operational microreactor in the most **accelerated timeline** possible
- Produce **combined heat and power (CHP)** to a functional **microgrid**
- **Share lessons learned** with commercial developers
- **Train** future operators

U.S. DOE Sponsor Program:

MRP Microreactor Program

Create momentum,
Champion rapid technology maturation to de-risk industry
Collaborate and engage microreactor end-user companies



- 100 kW-thermal
- 20 kW-electric
- ~10 feet tall
- < 12 tons
- 2 operators
- Self-regulating

Slide courtesy of Dr. John Jackson