INL/MIS-23-72445-Revision-0

Microreactors Electrify the Future of Mining

May 2023

David E Shropshire

Changing the World's Energy Future

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

DISCLAIMER

This information was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness, of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. References herein to any specific commercial product, process, or service by trade name, trade mark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

INL/MIS-23-72445-Revision-0

Microreactors Electrify the Future of Mining

David E Shropshire

May 2023

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

May 12, 2023

David Shropshire
Nuclear Energy Economist
(David.Shropshire@inl.gov)

Microreactors Electrify the Future of Mining

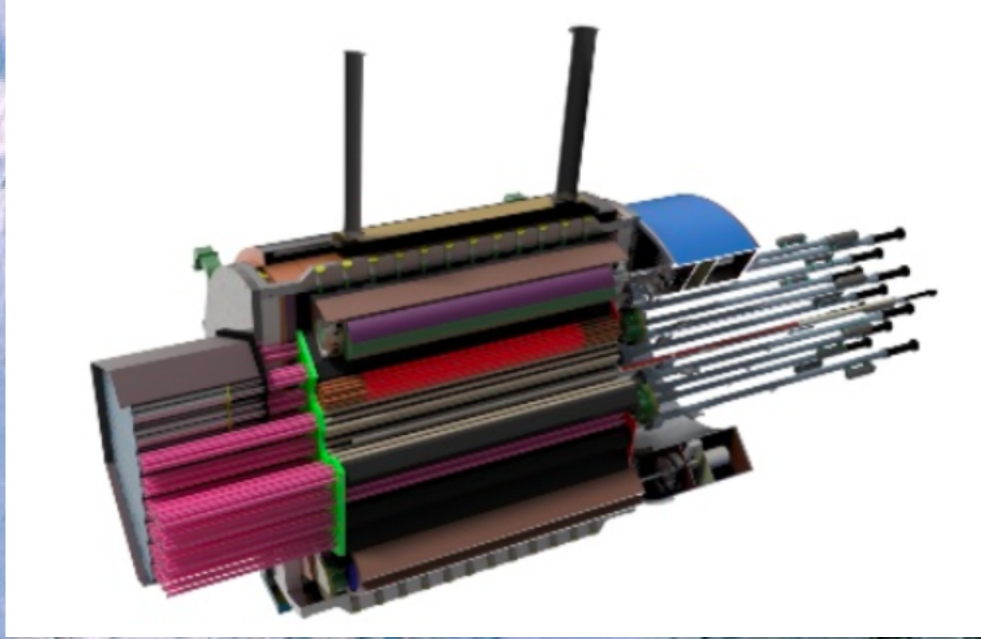
Joint Coeur d'Alene and Columbia Basin meeting of the Society for Mining, Metallurgy & Exploration

Battelle Energy Alliance manages INL for the
U.S. Department of Energy's Office of Nuclear Energy

Idaho National Laboratory

Outline

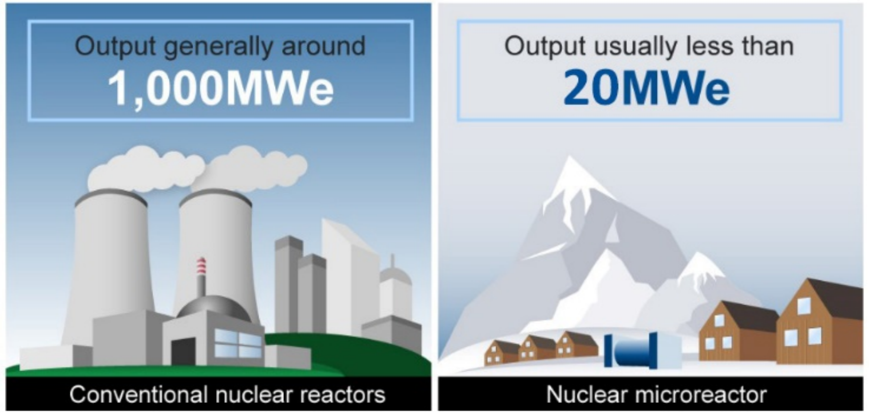
- Microreactor technology
- Potential markets
- Remote mining case study
- Extending product value chains
- Integrated mining operations
- ESG considerations



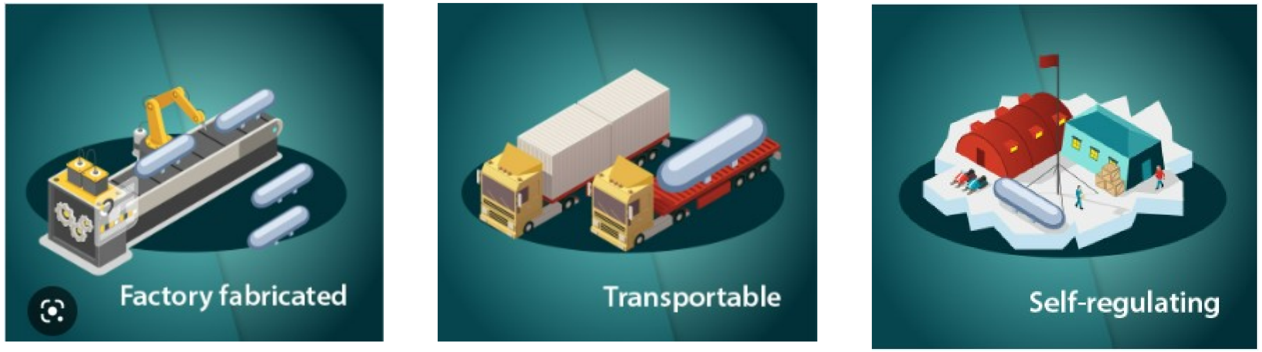
Westinghouse eVinci heat pipe microreactor

This work is funded by the U.S Department of Energy Microreactor Program and supported by research conducted by the INL led Emerging Energy Markets Analysis Initiative (https://ema.inl.gov).

What are Microreactors?



Source: GAO. | GAO-20-380SP

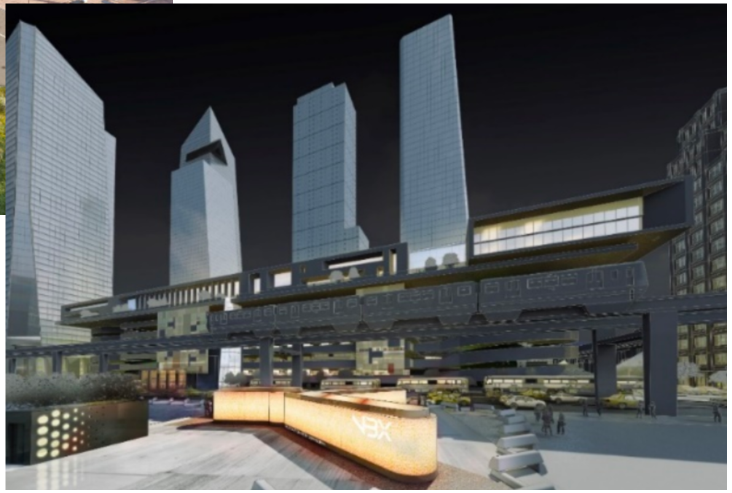


- Much smaller and simpler than traditional nuclear power reactors.
- Technologies evolving from advances in materials, space reactor technologies, advanced nuclear fuels, and modeling & simulation.

- Minimum site preparation
- Flexible operation
- Enhanced safety
- Refueling (every 2-10 years)
- Operational lifetime: 5 – 20 years.

Uses and Characteristics

Nuclear Battery Examples



Possible Markets

- Remote Mining Operations
- Military Installations
- Federal Facilities, critical loads
- University Campuses, critical loads
- Small Rural Community (Alaska)
- Rural Hub Community
- Islands (Puerto Rico)
- Regional Utility (e.g., Alaska Railbelt)
- Megacities (embedded with industry)
- Marine Propulsion
- Disaster Relief

Characteristics:

- Uninterrupted source of zero-emission electricity.
- Provides a direct heat source.
- Needs a relatively small amount of land for the energy produced.
- Air cooled or minimal water usage.
- Small site boundary.
- Semi-autonomous operation.

Case Study on Remote Mining in Alaska (Example)

Source: Wikipedia

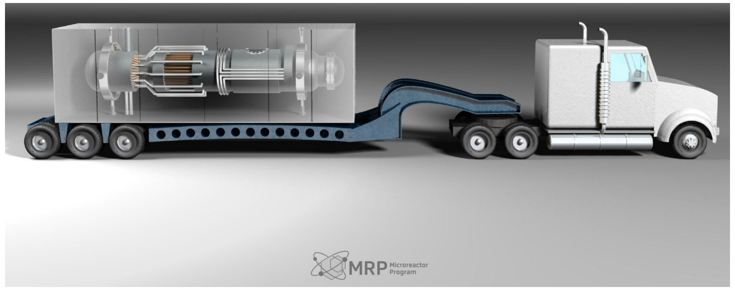
Red Dog Mine

- Large zinc and lead mine in a remote region of Alaska
- 80 miles north of Kotzebue
- Owned and operated by the Canadian mining company Teck Resources.

- Employees: 480 (seasonal)
- Power capacity
  - Mine: 40 MW
- Expected mine life: 2030
  - Potential for adjacent pits

- Site includes eight 5MW diesel generators (total capacity of 40MW).
- Red Dog operations require approximately 40,000 gallons of diesel fuel per day (annual 14.6M)
  - $35M estimated annual cost
  - 79% consumed for mine site generators
- Fuel barged in and shuttled from port to mine
- Worker housing provided on-site

Potential Application of Microreactors to Alaska Mining



- Move to on-site zero-emission electricity production.
- Replace diesel generators with 5-10 MWe microreactors, phased-in over time.
- Improve energy resilience and energy cost stability.
- Avoid environmental damage from oil spills and air pollution.

Source: Komatsu.com

- Power electric-drive mining trucks, battery drills, excavators, loaders, load-haul dumpers, autonomous water trucks, etc.
- District heating for worker housing.

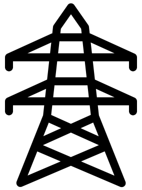
Extending Mining Value-Chains

- Hydrogen production for fuel cell (FC) vehicles
- Industrial heat and cooling for operations
- Secondary ore processing
- Incrementally provision microreactor modules as energy needs expand.

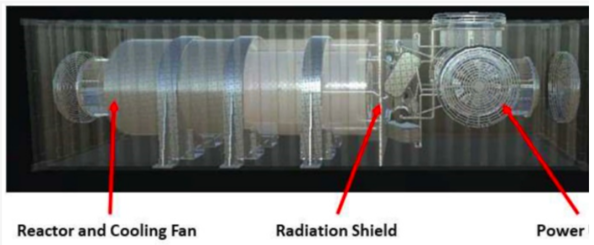
Microreactors as part of Integrated Mining Operations

- Full electrification of mines, with ore processing on-site.

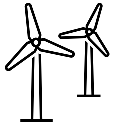
Energy Sources



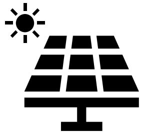
Local Electricity Grid
(as backup source, if available)



Microreactor
(Primary Source)



Wind Power (if available)



PV Solar Power (if available)

Energy Management

Microgrid Controls

Energy Storage
- Hydrogen

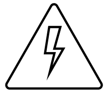
Power Generation
(thermal energy conversion)

Mobile Equipment Powering
- Fuel Cells and Batteries

Heating & Cooling Applications
- High grade and low grade

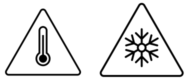
Mining Operations

Examples:

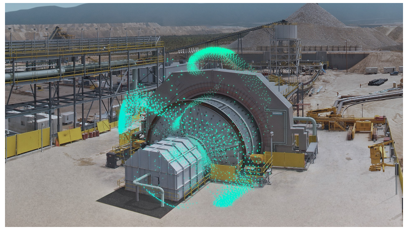


Mining Equipment
- Drilling
- Excavation

Mobile Equipment
- Loading and hauling trucks
- Scaling
- Cleaning



Ore Processing
- Calcination
- Heat exchangers



Possible production, economic, and flexibility benefits

- Production benefits:
  - Lower electric equipment costs
  - Less need for tunnel ventilation and cooling
  - Smaller tunnels and less rock waste
  - Improved environmental compliance
- Flexibility benefits
  - Mobile microreactors are not fixed assets, they could be redeployed to new mine locations in response to market conditions, declining ore quality, or mine closure
  - Business models: leased heat and power (EMA Frontiers Initiative)

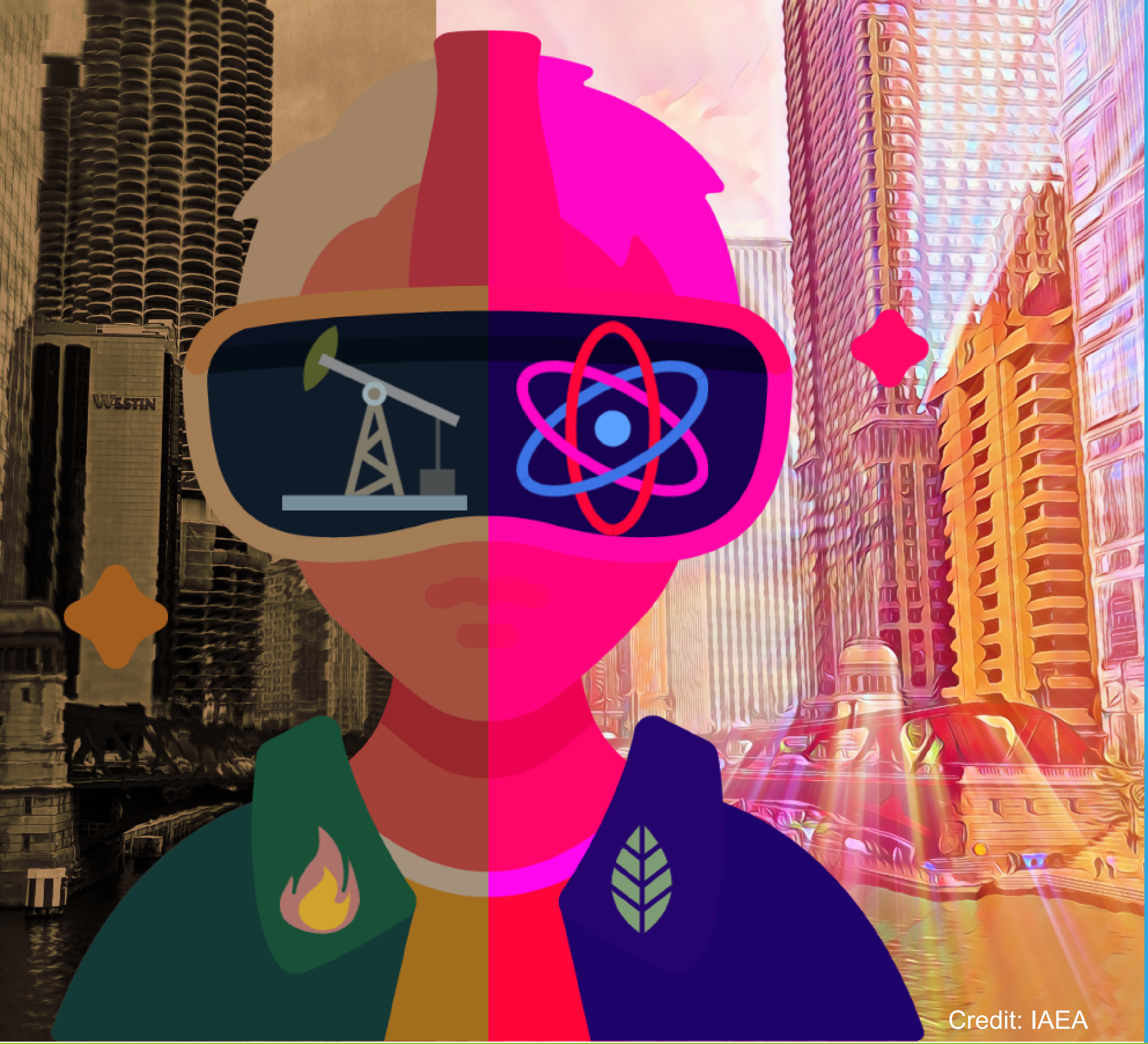
- Economic benefits:
  - Improved economics for mining and processing clean energy components:
    - Adding Combined Heat and Power (CHP) could increase capital cost ceiling by up to $5,000/kWe vs. natural gas, and $12,000/kWe vs. diesel (Alaska)
    - Favorable investment and production tax treatment under the Inflation Reduction Act, Infrastructure Investment and Jobs Act, and other laws
    - Cost credits for EV battery minerals (Al, Co, Li, rare earths, +others) and intermediary products (e.g., graphite anodes)

Environmental, Social and Governance (ESG) Considerations for using Microreactors

- Increasingly, policy signals indicate market movement toward decarbonization of energy systems.
- Mining companies are faced with economic trade-offs (e.g., job losses, lower revenues) associated with shifts to new energy technology.
- The market is likely moving toward finding ways to value the environmental impact of commodities.
- First movers are finding ways to position themselves to be competitive from many angles.
- Electrification of mining operations through use of microreactors could be a step towards meeting ESG goals.

Interior Alaska mining industry is clearly feeling both external and internal pressures to decarbonize operations. Both hard rock mines in the region have set clear ESG goals which explicitly target energy production and consumption. At a different level, pressure from the federal level to penalize carbon intensity or incentivize industrial decarbonization is becoming increasingly probable and will likely impact operational costs.

In Wyoming, "Customers are saying that what we're doing isn't good enough and want to know what we're going to do to reduce emissions further." If synthetic trona producers were to decarbonize so as to produce advantaged products, that could increase consumer choices.



Summary

- How do you envision the future of mining?
- Is there a place for microreactors in your company's plans?

Idaho National Laboratory

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.

Known Microreactor Concepts Under Development in the United States

Developer	Name	Type	Power Output (MWe/MWth)	Fuel	Coolant	moderator	refueling interval	PCU
Alpha Tech Research Corp	**ARC Nuclear Generator**	**MSR**	**12 Mwe/30 MWth**	**LEU**	**Flouride salt**		**intermittent**	
BWXT	BANR	HTGR	17 MWe/50 MWth	TRISO	Helium	graphite	5 years	Brayton Cycle
General Atomics	GA Micro	HTGR	1-10 MWe		gas			?
HolosGen	HolosQuad	HTGR	13 MWe	TRISO	Helium/CO2		10 years	Brayton Cycle
Micro Nuclear, LLC	Micro Scale Nuclear Battery	MSR/heat pipe	10 MWe	UF4	FLiBe	YH	10 years	
Nano Nuclear	Zeus	FR/HTGR	1.0 MWe/2.5 MWth	UO2	Helium			Brayton Cycle
NuGen, LLC	NuGen Engine	HTGR	2-4 MWe	TRISO	Helium			Integral direct cycle
NuScale Power	NuScale Microreactor	LMTM/heat pipe	<10 MWe	metallic	Liquid Metal	Liquid Metal	10 years	TPV
Oklo	Aurora	SFR/heat pipe	1.5 MWe	metallic	Sodium		10+ years	
Radiant Nuclear	Kaleidos Battery	HTGR	1.2 MWe	TRISO	Helium	graphite	4-6 years	
Ultra Safe Nuclear	MicroModular Reactor	HTGR	5 MWe/15 MWth	TRISO	Helium	graphite	20 years	Rankine
Westinghouse	eVINCI	heat pipe	5 MWe/15 MWth	TRISO	Sodium	graphite	8 years	Brayton Cycle
X-Energy	XENITH	HTGR	5 MWe/10 MWth	TRISO	Helium	graphite	3+ years	Open air Brayton Cycle