Rethinking Fuel Cycles: Implications of Changing Gen-IV Technologies

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ARPA-E

Reducing the Impact of Used Nuclear Fuel from Advanced Reactors

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Outline (and Conclusions)

- The number of credible fuel cycle options have increased. We do not know if fissile resource economic limits will be important in the next several decades

- Economics may result in large-scale deployment of salt-cooled reactors because of their ability to deliver higher-temperature heat to the customer.

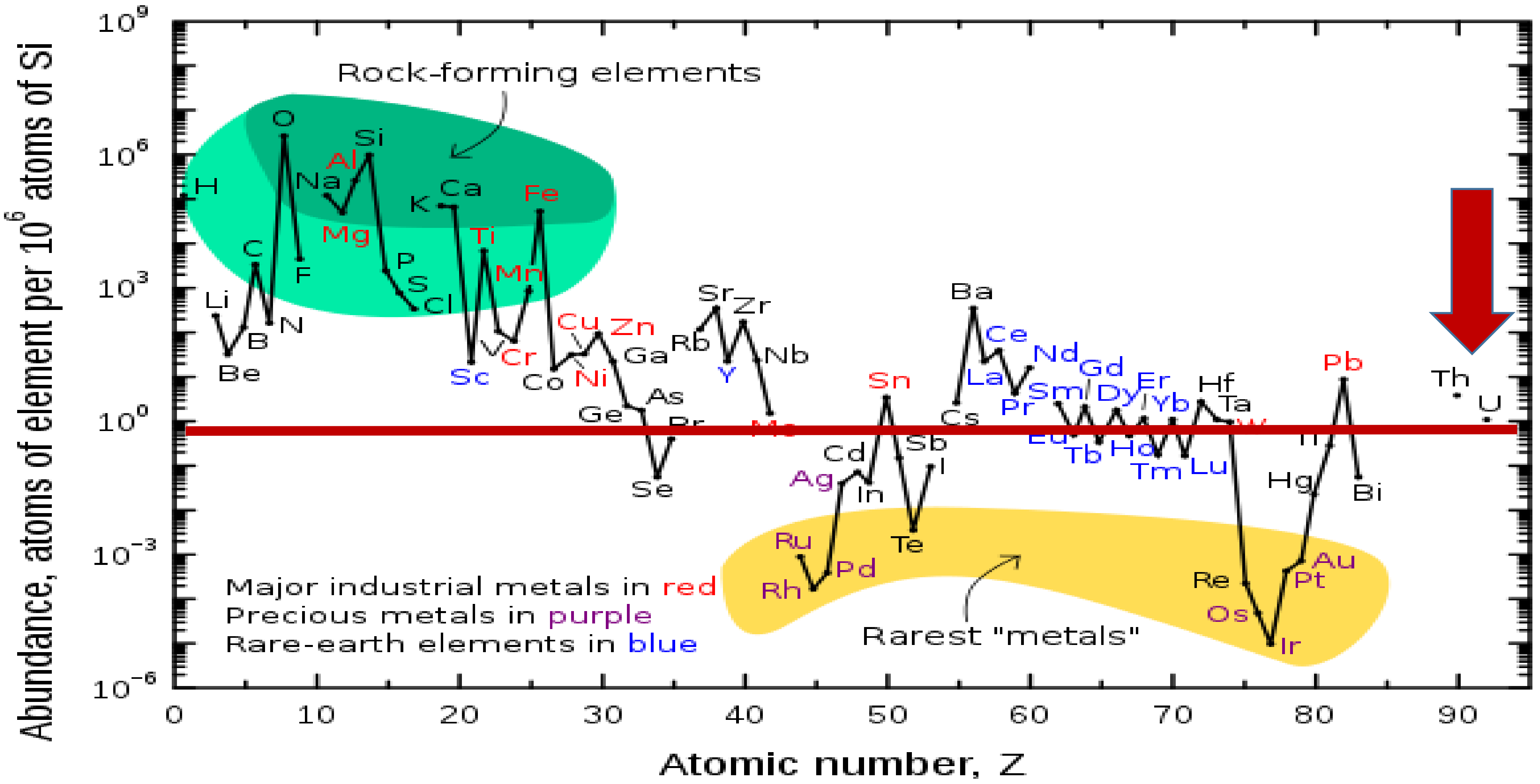
- There are massive economic and political incentives to rethink the back-end of the fuel cycle with co-location of reprocessing, waste treatment and disposal. May be able to reduce costs by 50%

Fissile and Fertile Fuel Resources

The number of credible fuel cycle options have increased. We do not know if fissile resource economic limits will be important in the next several decades

MIT Future of the Nuclear Fuel Cycle;
http://energy.mit.edu/research/future-nuclear-fuel-cycle/

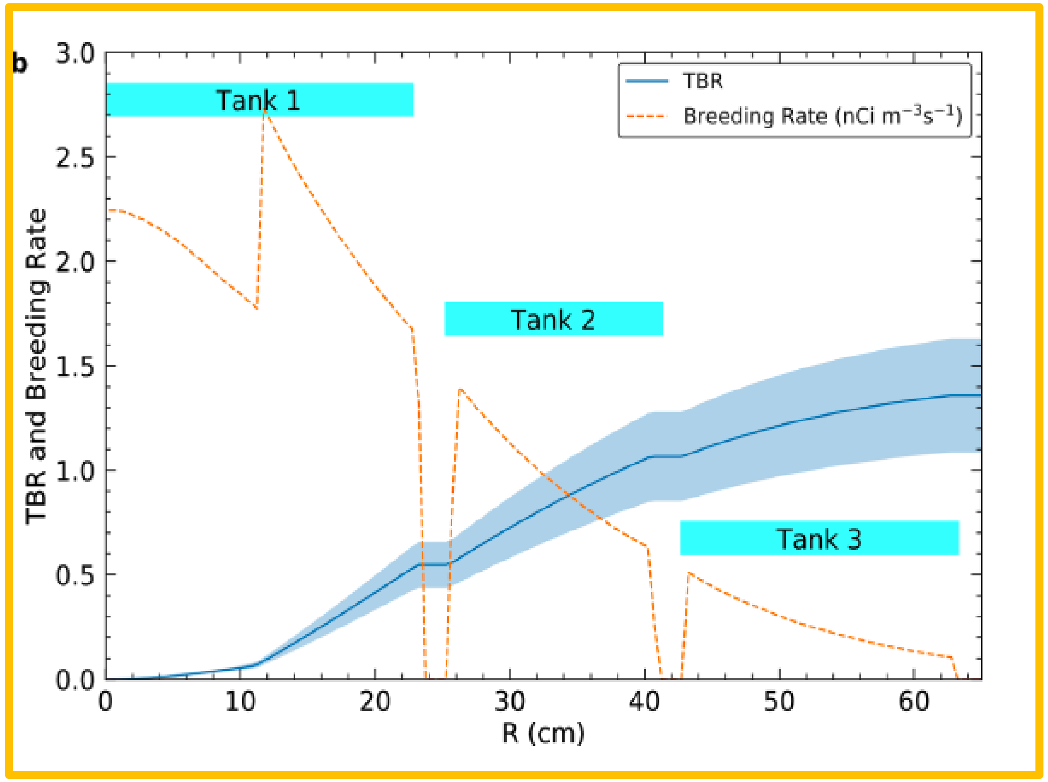
Uranium Not Particularly Rare: Running Out of Cheap Uranium is Not a Near-Term Problem



https://en.wikipedia.org/wiki/Abundance_of_elements_in_Earth's_crust

There is Real Competition for Long-term Sources of Fissile Fuel

- Traditional breeder reactor fuel cycles with reprocessing to produce plutonium and uranium-233
- Seawater uranium—costs are coming down via better chemistry
- Once-through breeder reactor fuel cycles (Terrapower: Traveling Wave Reactor and Molten Chloride Fast Reactor) where refuel with depleted uranium
- Fusion machines with high neutron breeding ratios (excess neutrons)



C. Forsberg, MIT Fission and Fusion Salt Activities: From Theory to Integral Experiments, ORNL Molten Salt Workshop, October 2020

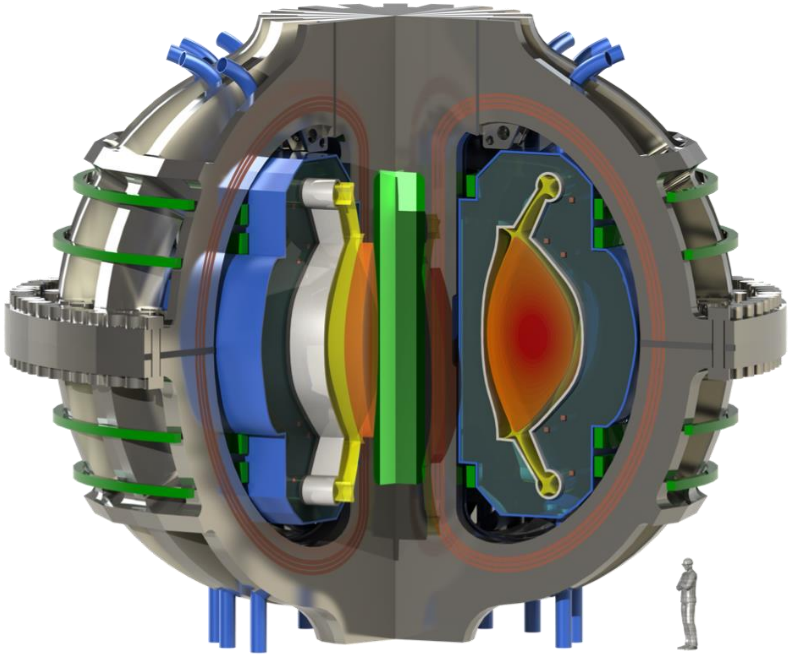
There is a Growing Diversity of Fuel Types and Cycles

Fuel	Fuel cycle	Notes
LWR/Traditional solid-fuel fast reactors	Closed or Open	Only option with large-scale laboratory and commercial experience
HTGR, FHR and SiC Matrix Fast Gas Reactors	Open or Closed Fuel Cycles	Fuel form improves safety (Graphite or SiC matrix) but refractory fuel difficult to process with large secondary waste generation and high burnup
Molten salt fueled reactors	Open or Closed	1. Multiple waste forms with some processing (Xe, Kr, etc.) at the reactor site, hot secondary wastes containing noble metal fission products and chloride/fluoride salts. 2. Option of on-site processing to reduce accident source term
Once-through breeder reactor	Open (Terrapower)	Extreme high burnup

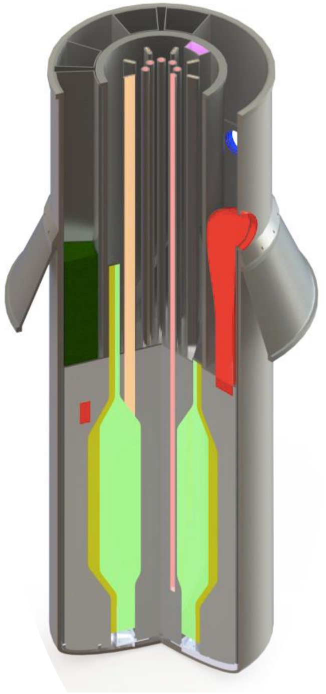
Salt Fission and Fusion Reactor Systems

Economics may result in large-scale deployment salt-cooled reactors because of their ability to deliver higher-temperature heat to the customer

All Salt Reactor Concepts Have Much in Common



Commonwealth Fusion ARC



Kairos Power FHR Solid Fuel

MSR (Fuel in Fluoride Salt)

Molten Fluoride Salt Fast Reactor

Moltex (Chloride Salt in pins, Clean Fluoride Salt Coolant)

Molten Chloride Fast Reactor

Gen III Chloride Salt Concentrated Solar Power

Clean Flibe Salt: Massive Technology Overlap

Large Salt Technology Overlap

Market Basis for All Salt Systems is Higher Temperature Delivered Heat

Air Brayton Power Cycles, Heat Storage, Hydrogen, Industrial heat

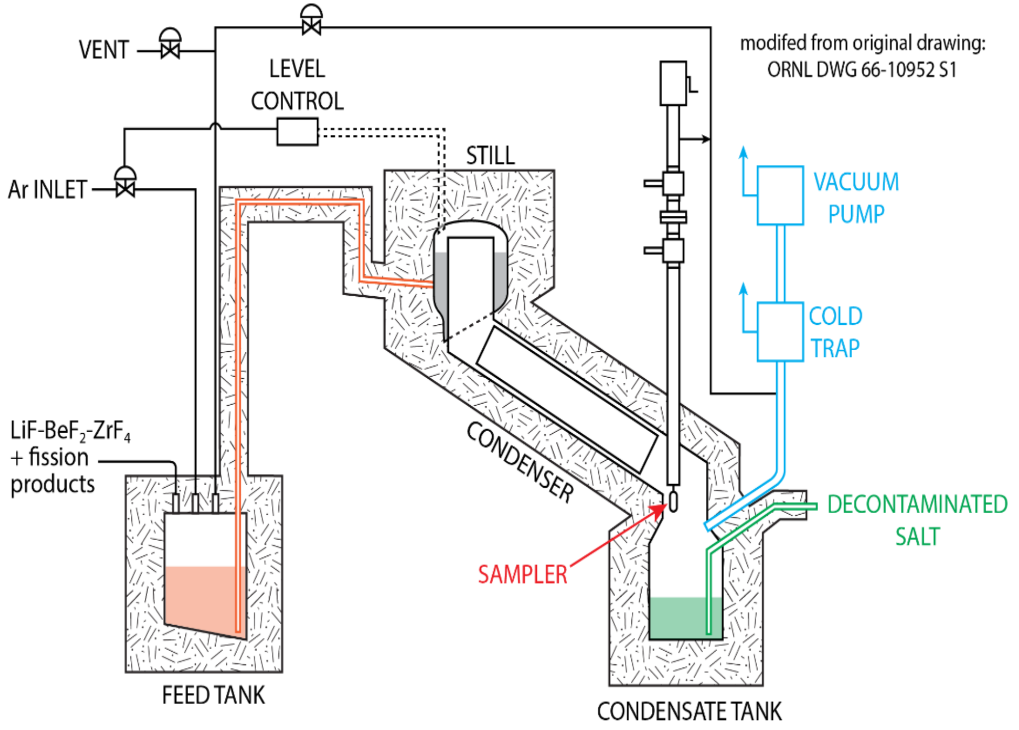
Coolant	Average Core Inlet Temperature (°C)	Average Core Exit Temperature (°C)	Ave. Temperature of Delivered Heat (°C)
Water	270	290	280
Sodium	450	550	500
Helium	350	750	550
Salt	**600**	**700**	**650**
Adv. Salt	**700**	**800**	**750**

Charles W. Forsberg (2020) Market Basis for Salt-Cooled Reactors: Dispatchable Heat, Hydrogen, and Electricity with Assured Peak Power Capacity, Nuclear Technology, 206:11, 1659-1685, DOI: 10.1080/00295450.2020.1743628 To link to this article: https://doi.org/10.1080/00295450.2020.1743628

Major Challenge: Salt Purification

Can Additive Manufacturing Redefine Salt Processing Options?

- Distillation is the traditional process for purification of liquids and reducing volumes of waste streams
- ORNL in the 1970s investigated vacuum distillation but low throughput
- High-temperature distillation (1400°C) would be a game changer but how to manufacture distillation column?
- Additive manufacture may enable Moly / Tungsten distillation column—but many questions



Vacuum distillation apparatus used by McNeese et al.

Brian J. Riley, Joanna McFarlane, Guillermo D. DelCul, John D. Vienna, Cristian I. Contescu and Charles W. Forsberg. “Molten salt reactor waste and effluent management strategies: A Review”, *Nuclear Engineering and Design*, **345**, 94-109 https://doi.org/10.1016/j.nucengdes.2019.02.002

Distillation Could Help All Salt Reactors

Coolant	Energy Source	Clean Salt Coolant	Fuel in Salt
Fusion	Fusion plasma	X (Fluoride)	
FHR	Solid fuel	X (Fluoride)	
Moltex	Liquid fuel salt in pins	X (Fluoride)	X (Chloride)
MSR	**Liquid fuel**		**X (Fluoride)**
MSR	**Liquid fuel**		**X (Chloride)**

But Tough High-Temperature and Corrosion Challenge to Build High-Performance Distillation Columns

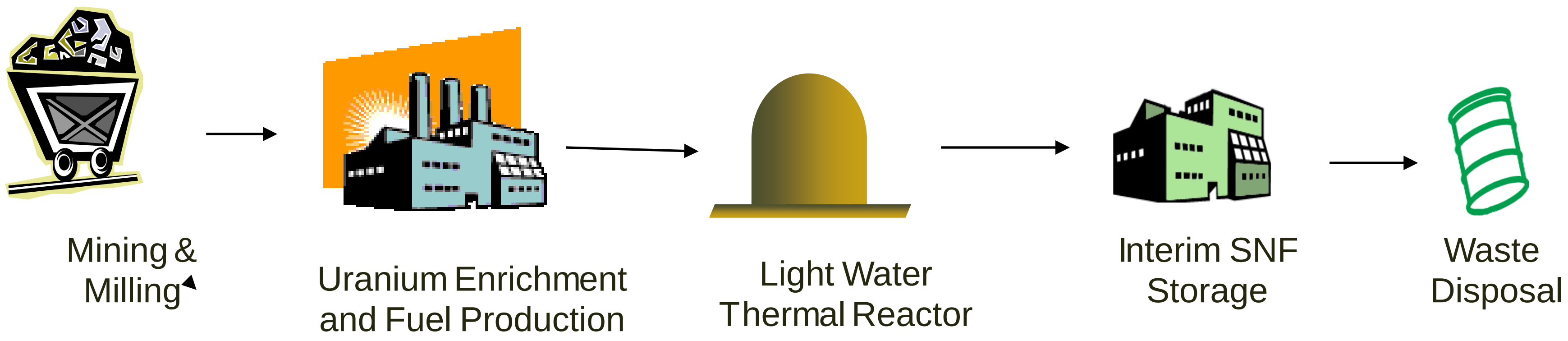
Fuel Reprocessing and Repositories

Need to Rethink the "Cold War" Fuel Cycle

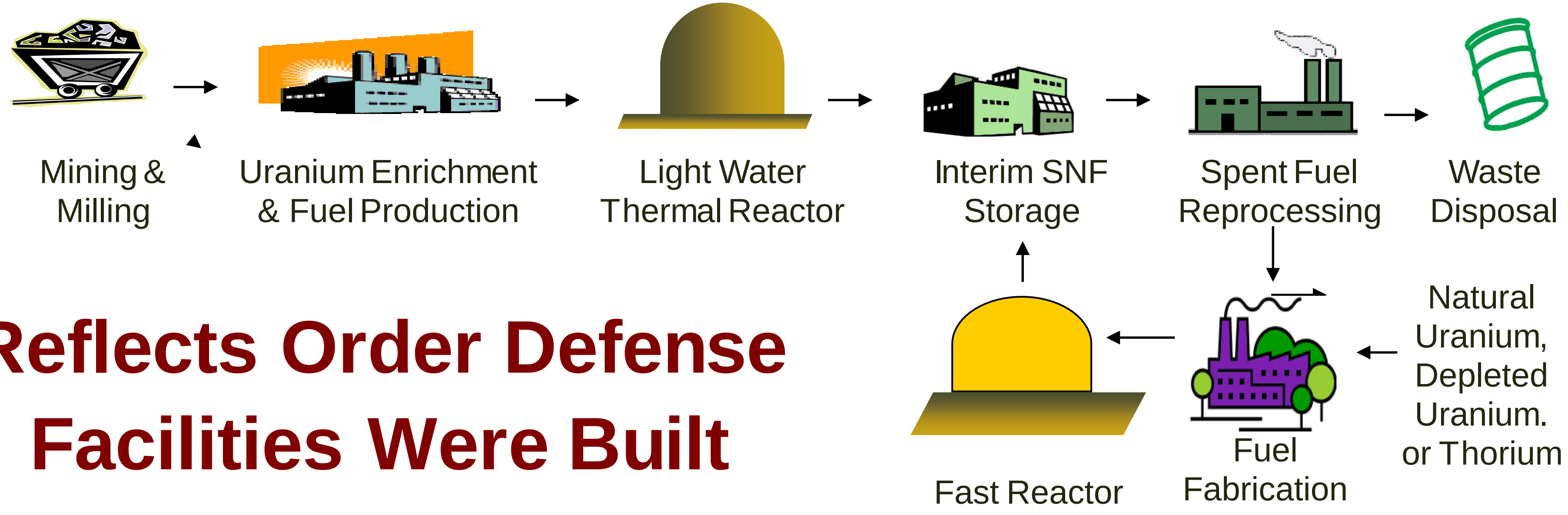
There are massive economic and political incentives to rethink the fuel cycle with co-location of reprocessing, waste treatment and disposal. May reduce costs by 50% with Increased Safety and Reduced Environmental Impacts

Separate Back-End Facilities Are An Historic Accident

Once-through Fuel Cycle

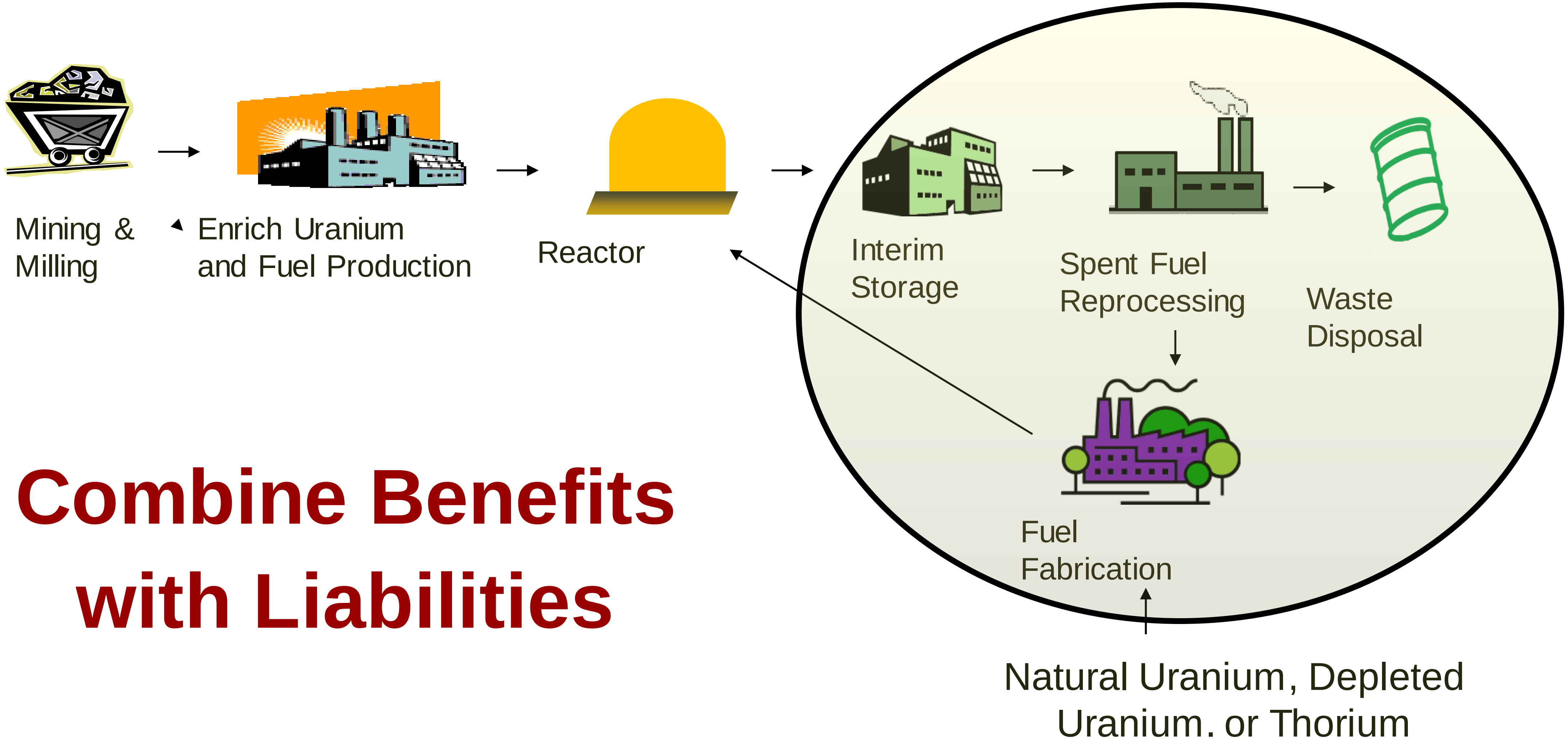


LWR-Fast Reactor (FR) Fuel Cycle



Reflects Order Defense Facilities Were Built

What If We Combined the Backend of the Fuel Cycle Into a Single Facility?



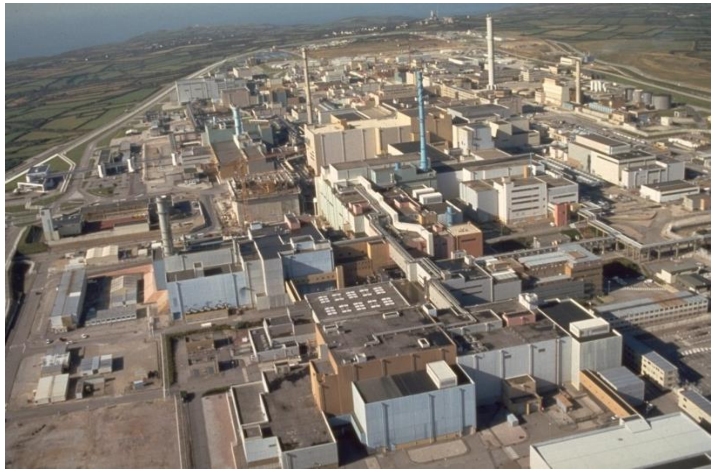
Combine Benefits with Liabilities

Co-Locating Reprocessing and Waste Disposal Facilities Has Major Impacts

Hanford (Washington State)

- On-site waste disposal
- 5000-7000 MTU/y (33 MTU/day maximum)
- Short-cool, low-burnup defense SNF

LaHague (France)



Courtesy of COGEMA

- Off-site waste disposal
- 2 x 800 MTU/y
- Aged commercial SNF
- Much larger facility with lower throughputs

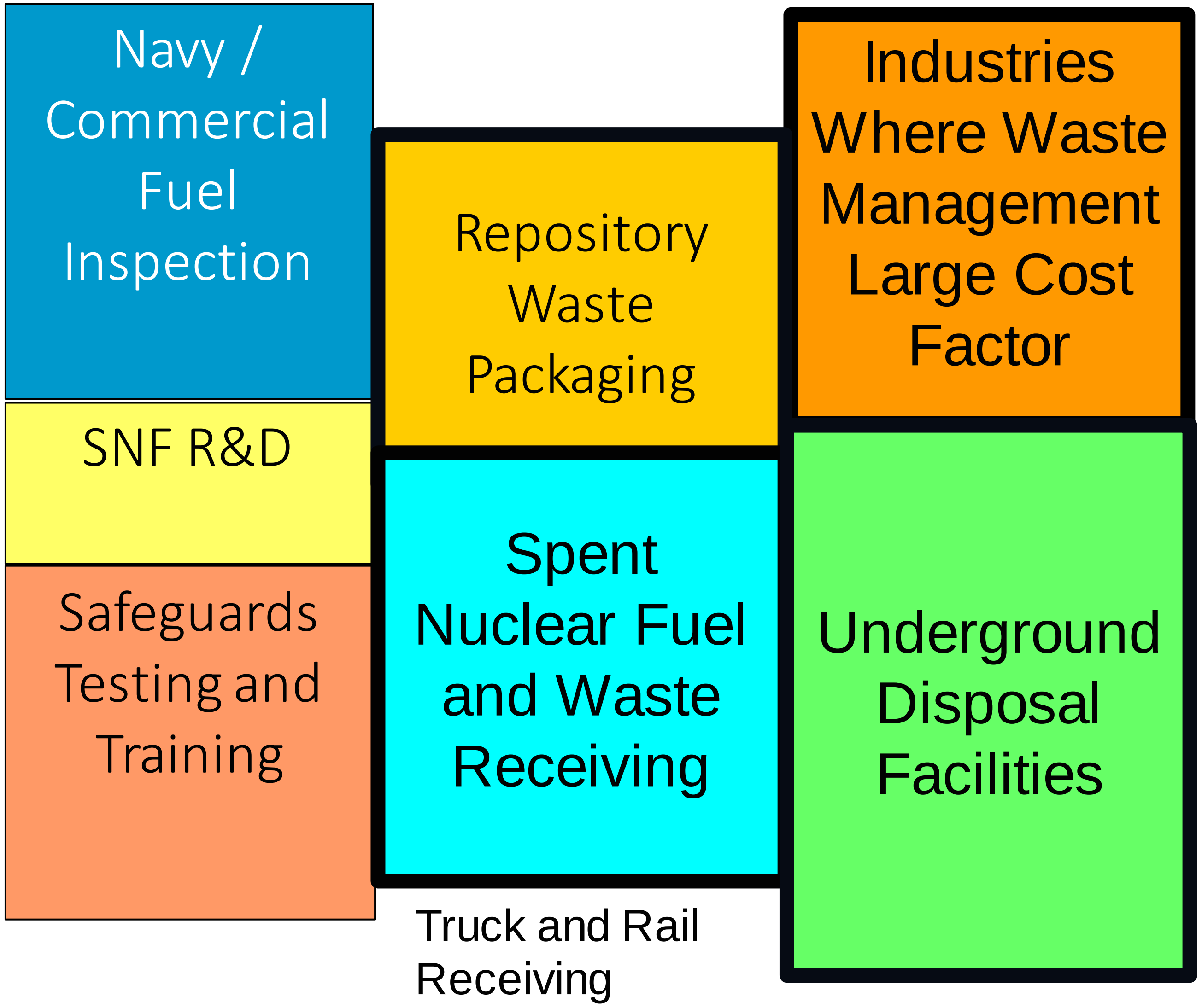
- Hanford waste disposal problems because of on-site surface disposal
- No problem if salt repository had been directly under the site.
- Massive economic and environmental advantages of co-location

M. S. Gerber, A Brief History of the Purex and UO3 Facilities, WHC-MR-0437 (1993)

Collocation Enables Use of Processes With Larger Waste Volumes and Lower Costs

- Waste treatment/processing/transport dominate reprocessing cost
- Three criteria
  - Economics
  - Minimize volume to meet transport requirements
  - Waste form performance
- If no transport, two criteria with benefits
  - Low cost waste forms (cement HLW, Calcine declading wastes, etc.)
  - Better waste form performance (diluted radionuclides and chemical species)

Consolidated Back-end /Repository Facilities Reduce Costs and Repository Institutional Challenges



- Minimize Cost/Risk of Transportation
- Large savings in processing of all types
- Workforce
  - Repository ~2000
  - Integrated backend: 4000-6000
- Community / state incentives to host

Conclusions

- GenIV reactors open up multiple fuel cycles with no clear winners
- Market may drive salt-cooled-reactor deployment and incentives for better methods to purify salts—both clean coolant salts and fuel salts
- Massive economic and institutional incentives for combined backend facilities—But requires simultaneous rethinking of technology and institutions

Biography: Charles Forsberg

Dr. Charles Forsberg was the Executive Director of the Massachusetts Institute of Technology Nuclear Fuel Cycle Study. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory. He is a Fellow of the American Nuclear Society, a Fellow of the American Association for the Advancement of Science, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding chemical engineering contributions to nuclear energy, including his work in waste management, hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design. Dr. Forsberg earned his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. He has been awarded 11 patents and has published over 300 papers including multiple papers on design options for repositories and alternative geochemical methods to reduce radionuclide releases from repositories.

High-Temperature Salt Distillation

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Your Picture Here

Proposed Innovation/question

- All reactors with salt coolants need salt cleanup systems
- Distillation is the traditional liquids separation and purification option because of low cost, simplicity and minimum secondary wastes
- High-temperature distillation (1200°C) requires additive manufacture of refractory alloy column with high corrosion resistance
- Require fabrication, corrosion control strategy and understanding complex phase diagrams

Impact

- Discuss which impact areas are effected by your question and/or which areas can be addressed by your innovation
- **Economics:** Potential for radical cost reductions and process simplification
- **Safeguards & Security:** Impact here…
- **Regulatory Requirements:** Impact here…
- **Resource Utilization:** Impact here…
- **Siting Options & Requirements:** Impact here…
- **Existing Infrastructure:** Impact here…

Additional Impact Areas

- Development of high-temperature distillation opens up separations options for other chemical separations