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)
### There is a Growing Diversity of Fuel Types and Cycles

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Fuel cycle</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>LWR/Traditional solid-fuel fast reactors</td>
<td>Closed or Open</td>
<td>Only option with large-scale laboratory and commercial experience</td>
</tr>
<tr>
<td>HTGR, FHR and SiC Matrix Fast Gas Reactors</td>
<td>Open or Closed Fuel Cycles</td>
<td>Fuel form improves safety (Graphite or SiC matrix) but refractory fuel difficult to process with large secondary waste generation and high burnup</td>
</tr>
</tbody>
</table>
| 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
- Molten Chloride Fast Reactor
- Gen III Chloride Salt Concentrated Solar Power
- Moltex (Chloride Salt in pins, Clean Fluoride Salt Coolant)

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

<table>
<thead>
<tr>
<th>Coolant</th>
<th>Average Core Inlet Temperature (°C)</th>
<th>Average Core Exit Temperature (°C)</th>
<th>Ave. Temperature of Delivered Heat (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>270</td>
<td>290</td>
<td>280</td>
</tr>
<tr>
<td>Sodium</td>
<td>450</td>
<td>550</td>
<td>500</td>
</tr>
<tr>
<td>Helium</td>
<td>350</td>
<td>750</td>
<td>550</td>
</tr>
<tr>
<td>Salt</td>
<td>600</td>
<td>700</td>
<td>650</td>
</tr>
<tr>
<td>Adv. Salt</td>
<td>700</td>
<td>800</td>
<td>750</td>
</tr>
</tbody>
</table>

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.

Distillation Could Help All Salt Reactors

<table>
<thead>
<tr>
<th>Coolant</th>
<th>Energy Source</th>
<th>Clean Salt Coolant</th>
<th>Fuel in Salt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fusion</td>
<td>Fusion plasma</td>
<td>X (Fluoride)</td>
<td></td>
</tr>
<tr>
<td>FHR</td>
<td>Solid fuel</td>
<td>X (Fluoride)</td>
<td></td>
</tr>
<tr>
<td>Moltex</td>
<td>Liquid fuel salt in pins</td>
<td>X (Fluoride)</td>
<td>X (Chloride)</td>
</tr>
<tr>
<td>MSR</td>
<td>Liquid fuel</td>
<td></td>
<td>X (Fluoride)</td>
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<tr>
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<td>X (Chloride)</td>
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</tbody>
</table>

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

Mining & Milling → Uranium Enrichment and Fuel Production → Light Water Thermal Reactor → Interim SNF Storage → Waste Disposal

LWR-Fast Reactor (FR) Fuel Cycle

Mining & Milling → Uranium Enrichment & Fuel Production → Light Water Thermal Reactor → Interim SNF Storage → Spent Fuel Reprocessing → Waste Disposal

Reflects Order Defense Facilities Were Built

Fast Reactor → Fuel Fabrication

Natural Uranium, Depleted Uranium, or Thorium
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)

- 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.
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