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Promise and Challenges of Molten Salt Reactors

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November 29th, 2023

Avignon, France

SAMOSAFER Final Meeting

Molten Salt Reactor PROGRAM

Affordable, Safe, Carbon-Free Power

Why are molten salt reactors important?

- **Safety**
  - Low-pressure
  - No accidents that cannot be contained
  - Strong natural circulation heat rejection
  - Negative rapid reactivity feedback
  - Ability to defuel for shutdown
- **Cost**
  - Low-pressure → no high-strength components
  - Compact, nearby, dispatchable
  - Simpler safety
    - Lower-cost licensing
    - Fewer nuclear safety components
  - No fuel fabrication
- **High Exergy**
  - High thermodynamic efficiency
  - Better support for thermal processes
    - Thermochemical hydrogen production → liquid fuels
- **Additional Products**
  - Isotopes for medicine and industry
- **No Actinide Waste**
  - Indefinite fuel lifetime
  - No air pollution

- Metrics of human health and happiness improve steeply with access to adequate, affordable energy
    - Except – air quality
- Releasing massive quantities of combustion products into our air and water is damaging our planet

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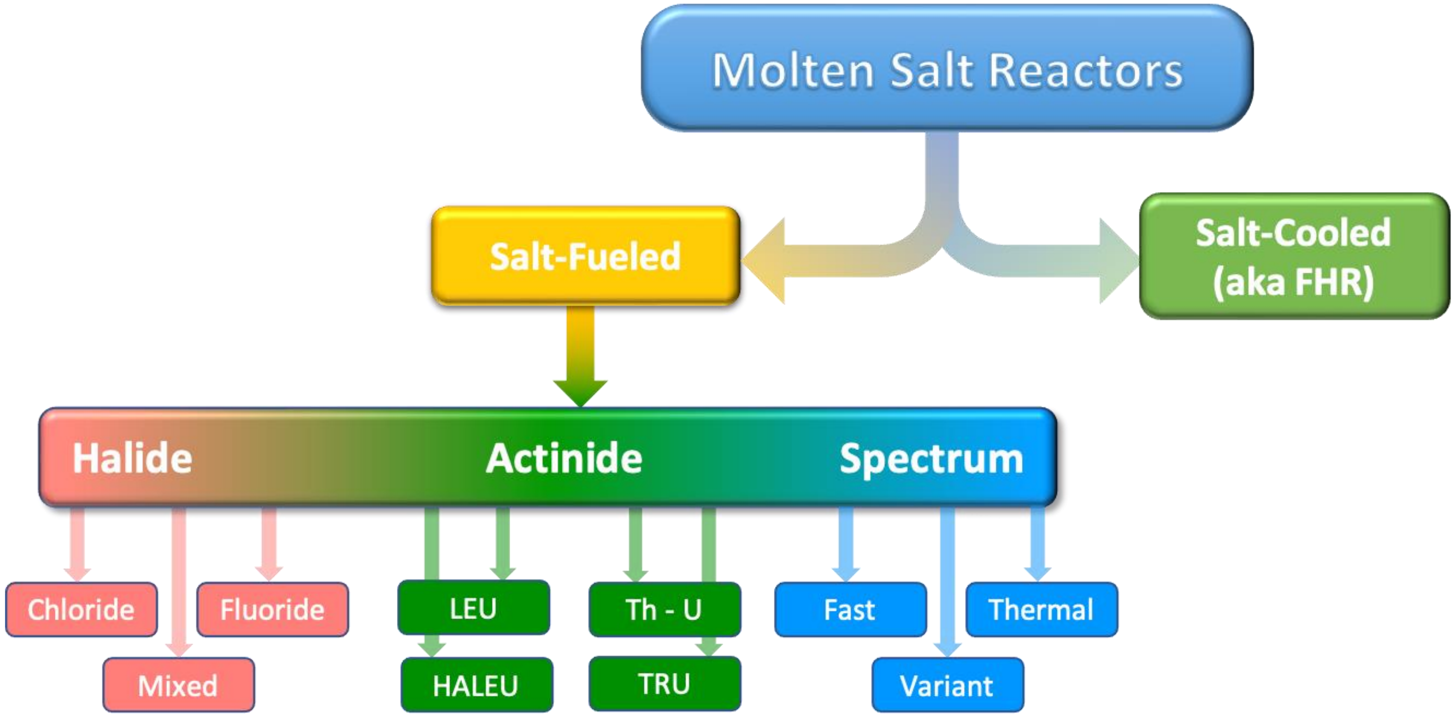
See for example - *Human well-being and per capita energy use*
https://doi.org/10.1002/ecs2.3978

Molten Salt Reactors are Nuclear Reactors in Which a Molten Salt Performs a Significant Function in Core



- Liquid- and solid-fueled variants
- Chloride-, fluoride-, and mixed halide-based fuel salts
- Salt and liquid-metal coolants
- Thermal, fast, time-variant, and spatially variant neutron spectra
- Wide range of power scales
- Intensive, minimal, or inherent fuel processing
- Multiple different primary system configurations
- Nearly all fuel cycles

Molten-Salt Breeder Reactors are MSRs that produce more fissile material than they consume

Breeding Enables MSRs to Scale to Meet Global Energy Needs for the Foreseeable Future

- Scale of world's energy requirements over the coming decades is well beyond capabilities of available fissile resources
  - Nuclear power currently only provides 4% of world primary energy and just over 10% of electricity
    - High-quality, high-temperature heat provided by MSRs facilitates meeting primary energy demands including transportation and process heat
  - World energy demand continues to increase
- World has substantial, near-term uranium supplies
  - Breeding becomes necessary to scale fission deployment sufficiently to be a substantial contributor to primary energy long-term
- Uranium enrichment is a proliferation vulnerable portion of existing fuel cycle that uses significant IAEA safeguards resources
  - Breeding significantly reduces reliance on uranium enrichment

Why Don’t Molten Salt Breeder Reactors (MSBRs) Already Exist?

- U.S. grid has been amply supplied by other technologies
  - Load growth slowed markedly by 1980
- MSBRs remain immature and require resources for development
  - MSBRs historically judged to be too risky, insufficiently important, and too proliferation vulnerable for government investment
  - Insufficient incentive to reconsider program closure
- MSBRs incorrectly perceived to generally and necessarily have substantial proliferation risks
  - Historically proposed fuel cycle included several steps with direct access to unacceptably attractive materials
    - Changing fuel cycle avoids generating separated fissile or fissile precursor materials
  - Consideration of proliferation risks only became prominent as historic MSBR program required expanded resources

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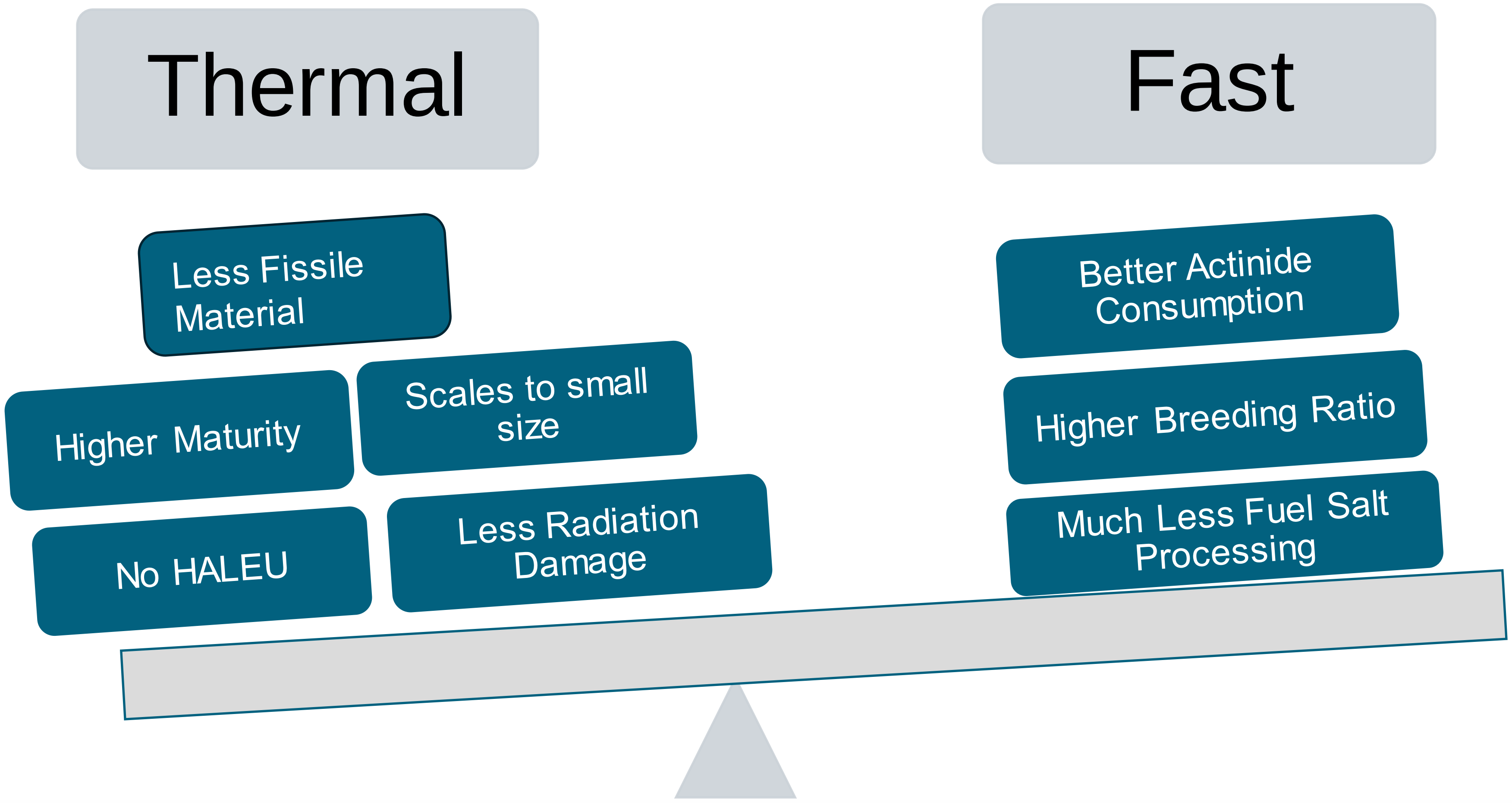
Liquid-fueled MSBRs offer the potential for affordable, safe, inexhaustible, energy with several nonproliferation advantages resulting in minimal potential for nuclear material diversion, and without significant actinide waste generation.

Proliferation-Resistant MSBRs Possible with Different Spectra

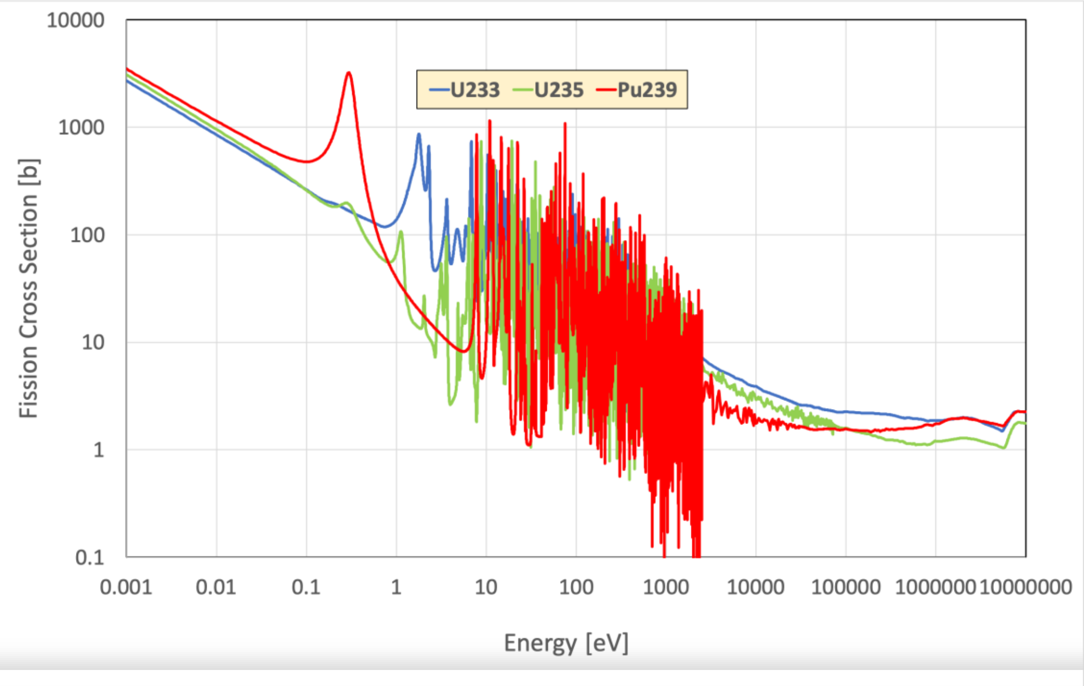


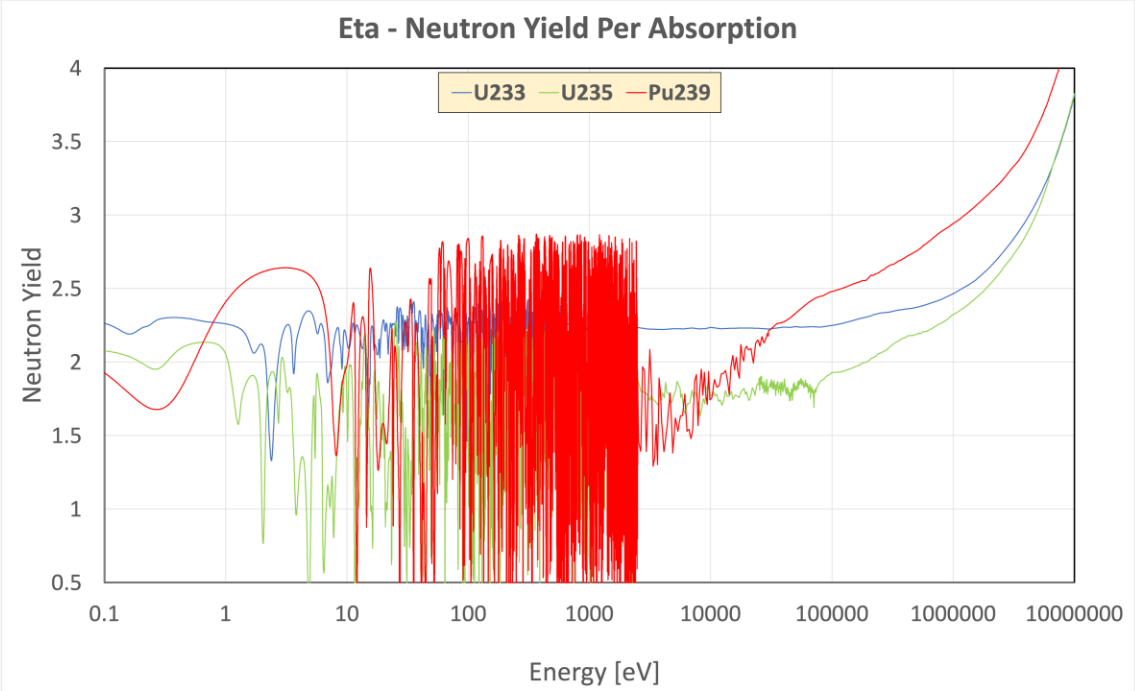
Mixed and flux-trapped spectra also possible

HALEU - high-assay, low-enrichment uranium

Fast and Thermal MSBRs Employ Different Paths to Achieve Common Objectives

- ^{239}Pu has highest neutron yield in fast neutron spectrum
  - Thorium frequently has higher solubility in fuel salts
- Only ^{233}U has sufficiently high neutron yield at high temperatures to breed with thermal spectra





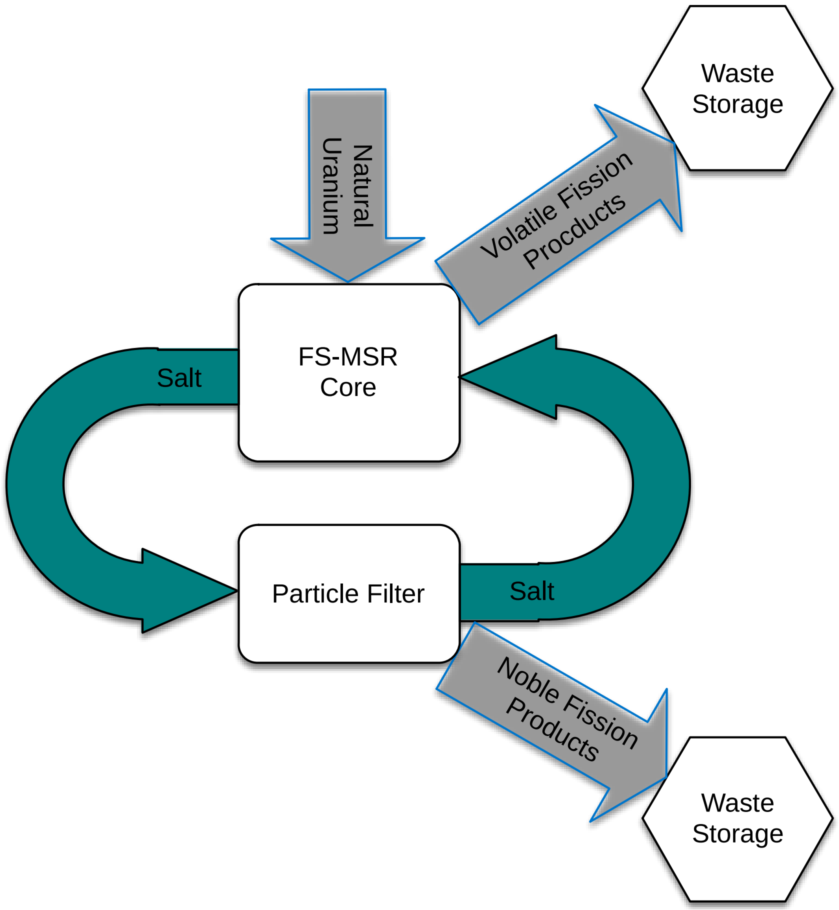
- Fission cross sections are much lower in fast region requiring more (8-10-fold) fissile material to maintain criticality
- Minimizing low atomic mass materials in core is key to hardening neutron spectrum
  - Low atomic mass materials employed to lower fuel salt melting point

Data from ENDF/B-VIII.0

Fast-Spectrum MSRs May Achieve Net Breeding without Actinide Separation

Fast Spectrum

- Parasitic neutron absorption is dominated by thermal neutrons
- Fast-spectrum MSRs have few thermal neutrons
  - Thorium can be used without protactinium separation
  - Thorium has high solubility in halide salts
- Neutron yield per fission increases substantially with incident neutron energy
  - Hardening neutron spectrum key design objective
- Avoiding fuel-salt processing substantially simplifies design and operations



ORNL/TM-2011/105

Fast-Spectrum MSRs Can Efficiently Consume Actinides from Spent Oxide Fuel

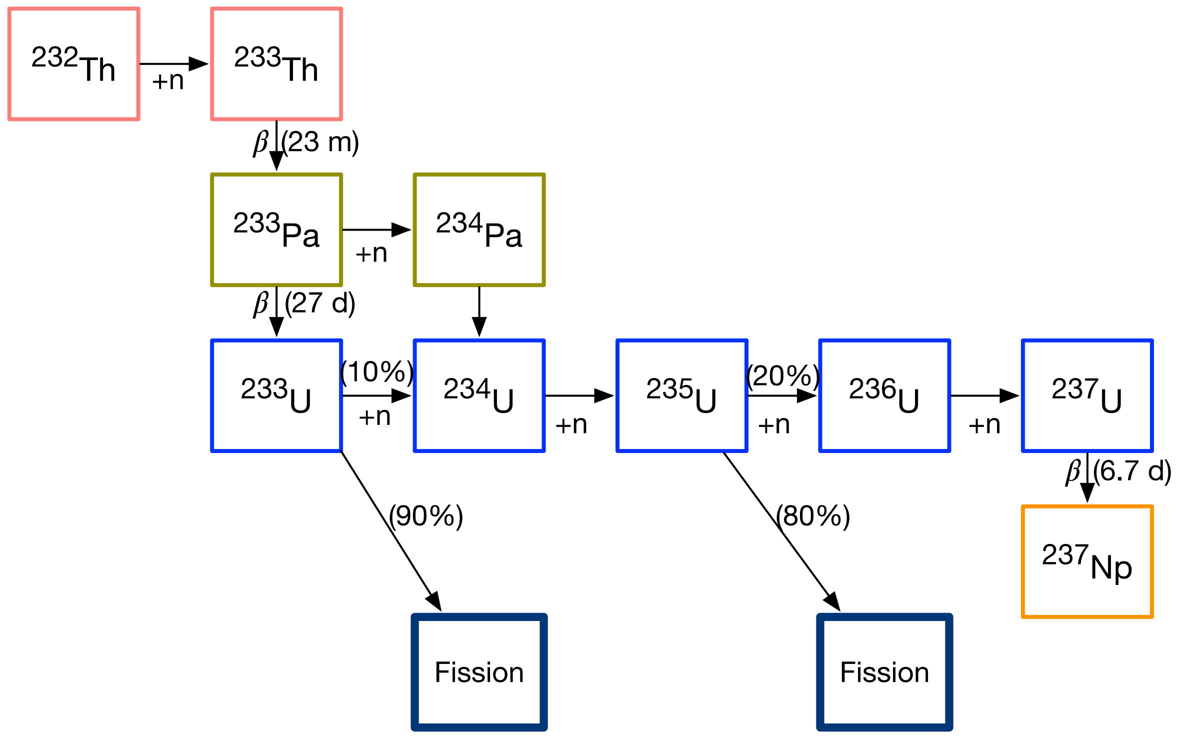
Fast Spectrum

- Consumes high-level waste from current generation of nuclear plants
- Actinide and fission product oxides are converted to chlorides in a molten salt bath
  - Electrorefining separates the actinides into fuel salt
  - High separation from fission fission products is not required
- Number of refining stages is based primarily on waste requirements
  - Reduce the waste stream classification by stripping actinides

Fuel Salt Needs to Be Intensively Processed to Enable Thermal-Spectrum Breeding

Thermal Spectrum

- Protactinium-233 has a high thermal neutron capture neutron cross section (~20 b @ 90 meV)
  - Fission product absorption is primarily at thermal energies
- Minimize the thermal neutron fluence on the ^{233}Pa to enable decay to ^{233}U
  - Frequent co-separation
  - Low-power density
- Maintain sufficient ^{238}U within fuel salt to avoid generating attractive nuclear material
  - Uranium is always denatured



Th-U neutron interactions with typical thermal spectrum branching ratios

Proliferation Resistance Results From Combining Multiple Fuel-Cycle Management Concepts in an Innovative Manner

Thermal Spectrum

1. Co-separation
   - Keeps all trivalent actinides together (i.e., Pu and/or ^{233}U are never isolated)
2. Denaturing
   - Low-enrichment uranium (e.g., in LWR fuel) is denatured
   - Fuel salt includes ^{233}U, ^{235}U, and ^{238}U
     - Composition always meets IAEA requirement for highest conversion time
3. Multi-batching
   - All fissile materials (and precursors) aged together ex-core
   - Uranium-233 generated within low-enrichment uranium environment
     - No ^{233}Pa separation
   - After initial startup, only inexpensive fertile feedstocks (e.g., natural uranium and thorium) needed

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Aluminum is Thermodynamically Favorable to Separate Actinides from Fluoride Salts

Thermal Spectrum

- Historic MSBR program employed bismuth-based reductive extraction to separate actinides from lanthanides
  - Substantial engineering effort expended to develop compatible materials and non-dispersing contactors (to prevent carryover)
- Aluminum is a more thermodynamically favorable solvent for co-separating all trivalent actinides from fluoride fuel salt (MUCH more compatible)
  - No electricity required
- Demonstrated by French fuel chemistry program in 2006 (Conocar et al. 2006, DOI: 10.13182/NSE06-A2611)
  - Attractive performance (rapid, efficient, high selectivity) in laboratory
    - No capability of separating fissile actinides from non-fissile, trivalent actinides
  - Method remains immature with substantial unknowns

MSBRs Have the Potential For a Unique Combination of Advantageous Features

- No materials more attractive than LEU or self-guarding and mixed actinides in the fuel cycle
  - Breeding without reprocessing
  - Th and/or U_{nat} are the equilibrium (i.e., makeup) feedstock materials
- Highest exergy of any reactor class
  - Well suited to support thermochemical processes including hydrogen and liquid hydrocarbon biofuels
- No actinide waste stream
  - Fuel salt has no mechanical lifetime limit so can reused indefinitely
  - Actinides progressively build up to equilibrium concentrations
- Strong passive safety features
  - Low pressure (contain)
    - Smaller potential source term (fission product removal)
  - Excellent natural circulation heat transfer (cool)
  - Effective negative reactivity feedback (control)
- Lower costs
  - Low-pressure (less massive components and structures – increased factory fabrication)
  - Simpler safety

Thermal
Fast

Rapid Thermal-Spectrum MSBR Maturation Possible (with adequate resources)

Thermal Spectrum

- Substantial technology base from historic MSBR program
- No-long duration development activities identified
  - Multiple parallel technology advancements needed
    - Fuel salt processing
    - Regulatory process
    - Advanced materials development and testing
    - Utility-scale components
    - Integrated system modeling
  - No long-duration fuel or material qualification required
    - Safety functions performed by proven materials

Fast-Spectrum MSBRs Have Enormous Potential and Substantial Technical Challenges

Fast Spectrum

- Much less historical information available
- Higher power density implies
  - More radiation damage to nearby materials
  - More demanding hydraulic component performance
  - More demanding passive cooling during accidents
  - Adequate fissile material solubility limit
- Require substantial fissile material for initial startup
  - Ability to obtain fissile materials from wastes from current fleet
- Chloride salts result in more complex corrosion issues

Thank you

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