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# Reevaluating the Thermal-Spectrum Molten Salt Breeder Reactor Fuel Cycle in a Modern Context

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Changing the World's Energy Future

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# Reevaluating the Thermal-Spectrum Molten-Salt Breeder Reactor Fuel Cycle in a Modern Context

International Workshop on the Chemistry of Fuel Cycles for Molten Salt Reactor Technologies
October 2–6, 2023
IAEA Headquarters, Vienna, Austria (and Virtual)

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# Thermal-Spectrum Molten-Salt Breeder Reactors (TS-MSBRs) Can Have Highly Advantageous Characteristics

- Potential for excellent safety, actinide resource utilization, proliferation resistance, waste generation, and exergy characteristics
- Realizing advantageous characteristics derives from a combination of proper design/engineering and inherent properties
  - Grossly unacceptable properties are possible with poor design choices
- TS-MSBR designs and technologies remain immature
  - United States has not had a focused TS-MSBR program in nearly 50 years
  - TS-MSBRs have progressed due to:
    - Technology development in related areas (fusion, materials, instrumentation)
    - General, worldwide molten-salt reactor (MSR) development activities
    - Molten-salt property measurement and evaluation
    - Safety evaluation methods and performance-based, technology neutral licensing

# MSR Fuel Cycle and Reactor are Intimately Connected and Need Coordinated Development

- TS-MSBRs and fuel cycles are more deeply intertwined than other reactors
  - Sizing, timing, and efficiency of fuel salt processing feeds back into reactor operation and fuel cycle design
  - Front, in-cycle, and back-end processing likely to take place on site
- Feedstock mixtures may be blended on site based upon reactor needs (e.g., shift redox, provide fertile feedstock, provide makeup)
- Actinide co-separation and fission product removal need to be coupled with the reactor to achieve breeding gain
- Fission product wastes need to be packaged into stable forms

# Thermal Spectrum Breeding Requires Intensive Fuel Salt Processing

- Neutron yield from $^{233}U$ is insufficiently high to achieve breeding without fuel salt chemical processing
- Two key steps to enable thermal spectrum breeding using the Th-U fuel cycle
  1. Remove parasitic neutron absorbers (e.g., fission gases and lanthanides) from core
  2. Remove $^{233}Pa$ from a high neutron flux for sufficient time to decay to $^{233}U$
- Historic MSBR design included the required processes to achieve breeding
  - Included several process steps with relatively direct access to unacceptably attractive fissile materials

# Key Requirement is Not Creating Accessible, Unacceptably Attractive Fissile Materials

- Key concepts are multi-batching, de-naturing, and co-separation
- Keep non-fissile fraction > 80%
- Minimize $^{239}$Pu production
  - Employ core heterogeneity to minimize resonance absorption in $^{238}$U
  - Minimize overall uranium concentration – sufficient to maintain criticality
    - Initial uranium concentration higher due to lower neutron yield from $^{235}$U
- Maximize $^{239}$Pu consumption
  - Align thermal flux peak with 0.3 eV fission peak
- Maximize $^{238}$Pu production
  - Co-separate $^{237}$U and to allow decay to $^{237}$Np

# Minimize the Potential to Misuse Uranium or the Facility

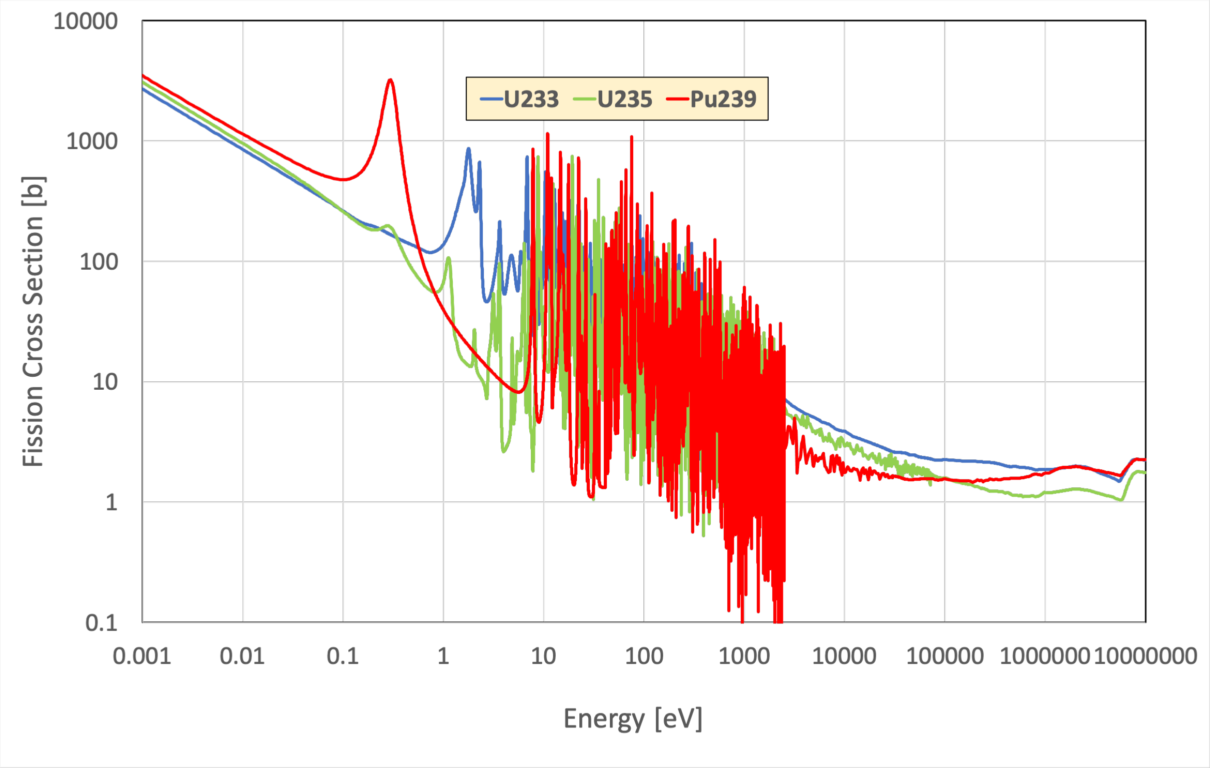
- Maintain adequately diluted isotopic composition
  - Non-fissile uranium (including $^{233}Pa$ precursor) fraction > 80% always
  - Do not include the specialized SSCs necessary to separate uranium or its $^{233}Pa$ precursor from other, non-fissile actinides
- Maximize self-guarding
  - Keep all trivalent actinides together
  - Build in non-fissile minor actinides

Historically proposed MSBR fuel cycle separated U and Pa individually from fuel salt on site with little or no-thought to the potential for misuse.

"…we will redirect funding of U.S. nuclear research and development programs to accelerate our research into alternative nuclear fuel cycles which do not involve direct access to materials usable in nuclear weapons." – President Carter April 7, 1977

# Thermal Spectrum Reactors Do Not Require HALEU

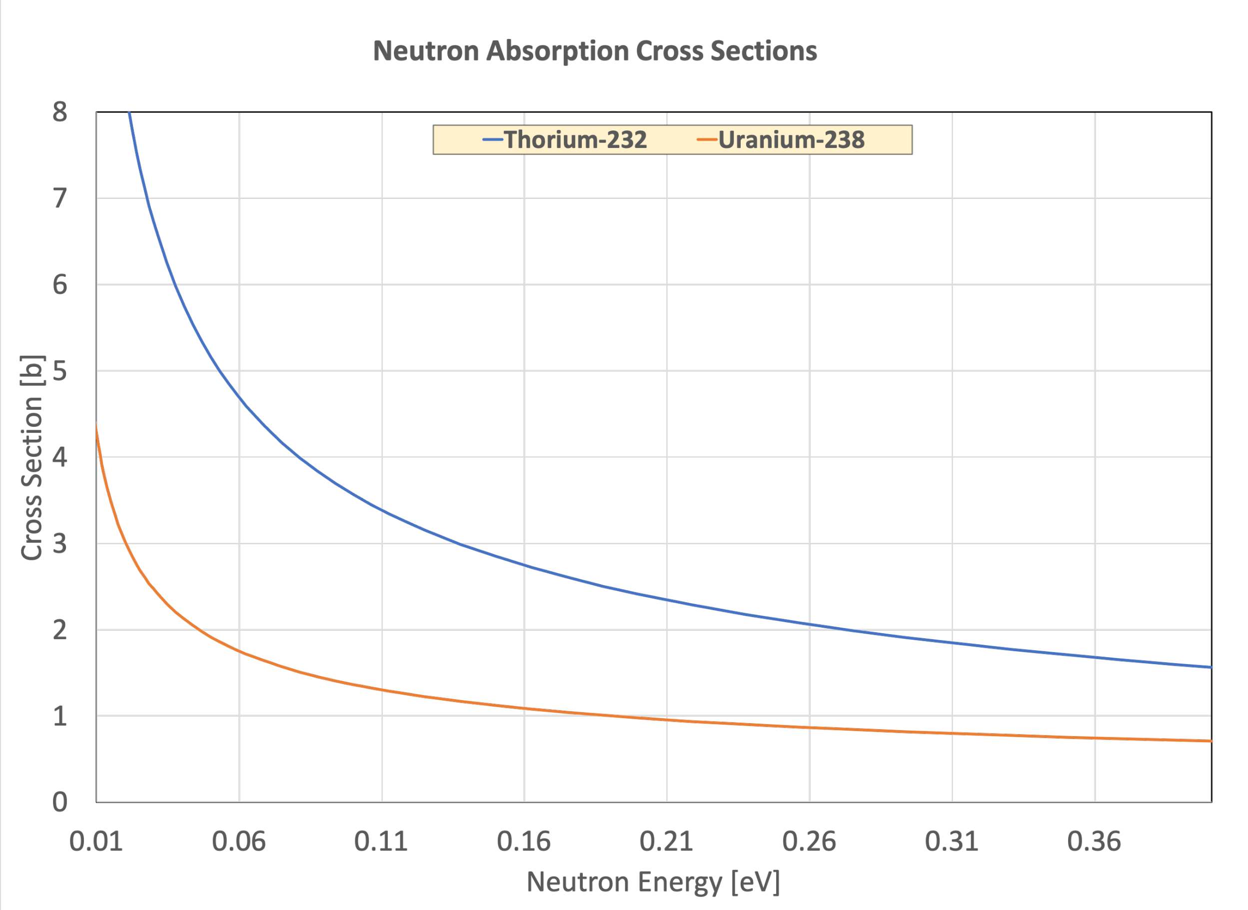
- High-assay, low-enrichment uranium (HALEU) is currently (and for an indefinite future period) in extremely limited supply
  - Program cost estimates to develop HALEU supply capabilities are $4–5 billion (Third Way 2023)
- Thermal-spectrum reactors require much lower fissile content
  - Thermal fission cross sections are much higher
  - Thermal-spectrum reactors can be made critical with less than 5 w% $^{235}U$
- Thorium is necessary for breeding gain
  - Near 300 meV $\eta$ ~2.3 for $^{233}U$; ~2.0 for $^{235}U$; ~1.7 for $^{239}Pu$
  - Breeding requires more $^{233}U$ fissions than $^{239}Pu$ fissions




Major fission cross sections—data from ENDF/B-VII.0

# Maximizing Thorium to Uranium Concentration Ratio Maximizes Breeding Ratio

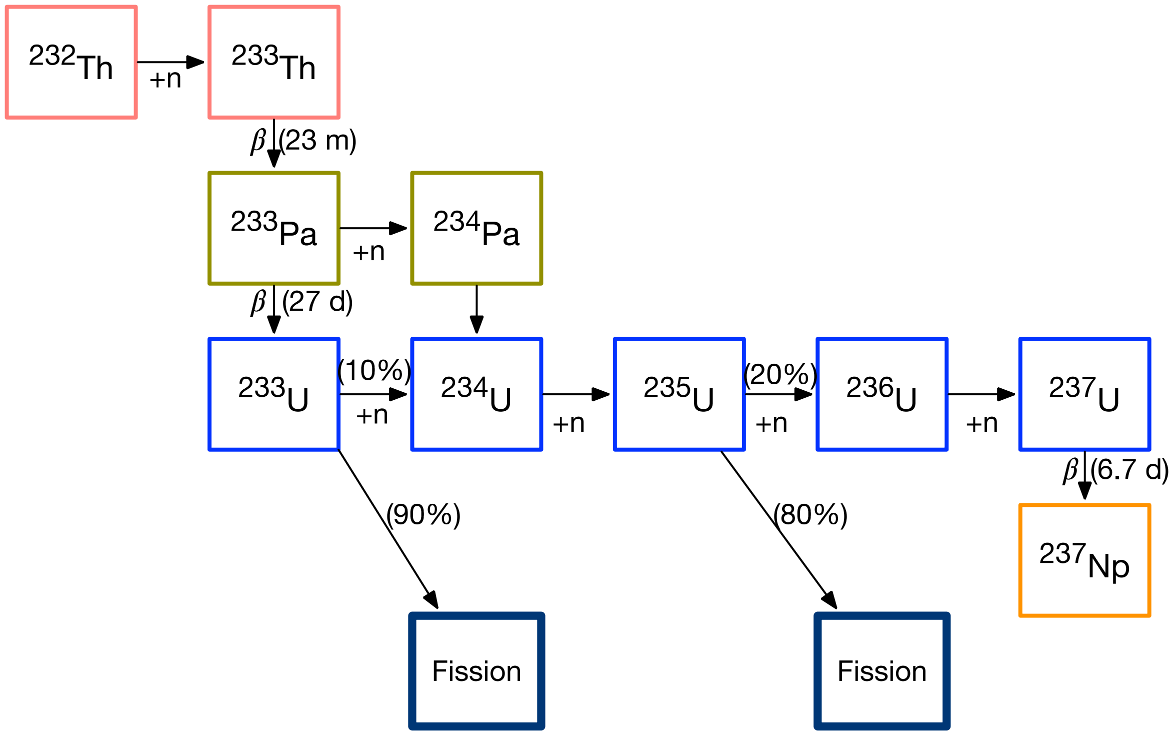
- Fuel salt uranium will be a mixture of $^{233}U$, $^{235}U$, and $^{238}U$
  - Non-fissile $^{238}U$ fraction > 80%
  - Equilibrium feedstock will be mixture of Th and $U_{nat}$
- Historic MSBR fuel salt was intended to be $^{7}LiF$-$BeF_2$-$ThF_4$-$^{233}UF_4$ with 71-16-12-~0.4 mole %)
- Modern design
  - Maximizes $ThF_4$ content (~15 mole %)
    - Lower concentration at startup
  - Provides sufficient uranium to maintain criticality (~1 mole % at equilibrium)
    - Higher concentration for startup




Thorium has twice the $^{238}U$ capture cross section at 300 meV—data from ENDF/B-V.III

# Multi-Batching Provides $^{233}$Pa Time To Decay In a Low-Flux Environment

- Liquid fuel salt batches frequently exchanged (e.g., weekly)
  - Requires multiple fuel salt batches
- $^{233}$Pa has a high neutron capture cross section
  - ~10 b at 300 meV
- Remaining outside of core for 3+ half-lives minimizes parasitic neutron capture
  - $^{233}$Pa half-life ~ 27 days
  - Provides time for fuel salt processing
- Increases $^{238}$Pu fraction due to enhanced $^{237}$Np production from $^{237}$U decay ex-core
  - $^{237}$U neutron capture cross section ~80 b at 300 meV




Th-U neutron interactions with typical thermal-spectrum branching ratios

# Aluminum is Thermodynamically Favorable to Separate Actinides from Fluoride Salts

- 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

# TS-MSBRs Could Be an Important Element of Achieving Energy and Climate Goals

- Realizing their potential requires sustained investment
  - Government program is needed to trigger private sector investment
- Technology remains immature but within striking distance
  - High-temperature technologies have advanced markedly over the decades since the United States had a TS-MSBR program
- Excellent passive safety characteristics
- No actinide waste stream
- Highest exergy of any reactor class
- Not dependent on HALEU
- Appealing proliferation resistance potential
  - Avoids need for future uranium enrichment
  - All uranium > 80% $^{238}U$
  - Only small quantities of $^{239}Pu$; diluted with progressively larger quantities of non-fissile actinides

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