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Conceptual design of a thorium supplied thermal molten salt wasteburner

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$^1$DTU Nutech, $^2$Seaborg IVS, $^3$DTU Diplom, & $^4$Niels Bohr Institute
The Project

• Me: Troels Schönfeldt: PhDr - Advanced cold neutron moderators @ DTU Nutech and ESS Neutronics
• 168 hours/week. A PhD study is 37.5 hours/week (=> 77.7% spare-time)... So we started a company
• Seaborg IVS:
  – We now consist of 10 unpaid physicist, chemists and engineers
  – We focus on nuclear reactor technologies, with special focus on molten salt reactors and thorium
• Here you will be presented with our, still very preliminary, Seaborg WasteBurner, the SWaB
Kickoff

• In December 2014 we were invited to join the “Feasibility Study for the Development of a Pilot Scale Molten Salt Reactor in the UK”, by:

• The SWaB design - a single salt thermal molten salt wasteburner
• The SWaB is currently under evaluation by UK experts
• Also, it turns out that 130.5 hours/week of spare times is not really a lot
Our constraints

1: No weapons!
- No separation of Pu/Pa from U
- Highly “denatured” U and Pu
- Decreasing weapon “quality”

2: Inherently safe
- Rely on physics
- Any active system must be redundant

3: Wasteburner
- Negative net TRU production
- Evolve towards the closed thorium fuel cycle

4: Thermal spectrum operation
- Because it has tremendous advantages
- Inefficiency of TRU burning should be compensated for by enhanced neutron economy

5: Modular (Economical):
- decrease construction/decommission cost
- Shipyard style manufacturing - mass-production

Early drawing of the “bottle”.

DTU Nutech
Center for Nuclear Technologies
The “product”

Reactor class:
S. Delpech et al., Reactor physic and reprocessing scheme for innovative molten salt reactor system. Journal of fluorine chemistry, 2009
**Method**

- Reactor model
- MCNPX (& Cinder)
- Degasser
- Chemistry
- Refueler
- Time-evolve SNF
- Rebalance 78LiF-22AcF₄ and volume
- Initial fuel from LWR
- Material
- Neutronics
- Spectrum

Note: The diagram illustrates the flow of processes including reactor model, MCNPX (or Cinder), degasser, chemistry, refueler, time-evolve SNF, rebalance of 78LiF-22AcF₄ and volume, and initial fuel from LWR. The processes are connected with arrows indicating the flow of material and information.
Initial fuel and alternatives

**Flame reactor:**
SNF -> Fluoride salts and removes:
- 99.1% U (as UF$_6$)
- 0.1% other Ac
- 99% FP (extracted)

**Initial fuel (10 year storage):**
45% U (~1.3% enriched)
45% Pu (~68% fissile)
5% FP (only non-gasses)
5% minor Ac (mainly Am)

<table>
<thead>
<tr>
<th>Component</th>
<th>Processed Waste</th>
<th>4.5% $^{235}$U</th>
<th>19.99% $^{235}$U</th>
<th>93% $^{235}$U</th>
<th>100% $^{239}$Pu</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{232}$Th fraction</td>
<td>86.7%</td>
<td>6.9%</td>
<td>73.3%</td>
<td>93.9%</td>
<td>97.6%</td>
</tr>
</tbody>
</table>

Source: GAO analysis of DOE data.
Salt and moderator

Iterative optimization of geometry and spent fuel to Th ratio (Ac => xTh+yAc\textsubscript{SNF} optimized to $K_{\text{eff}} \approx 1.05$)

Using this tool, we were able to analyze several moderator and carrier salt candidates in a matter of days.
Control

1: Huge “instant” negative response, mainly from salt density change.
2: Small “slow” positive response from graphite heating. (Problematic)

Daily control using online chemistry. Hourly control using 4 graphite fine-tuning rods ($\Delta k_{\text{eff}}=0.88\times 254$ pcm)
Absorbing control rods for full shutdown only (= better neutron economy)
Pot outer dimension: 190x190x340 cm$^3$
Blanket thickness: 15-22 cm
Moderator: Graphite (r=75 cm, l=300 cm)
Operation temperature 700°C-900°C
Flow speed: 38.1 l/s
Salt volume: ~6 m$^3$ (~5 m$^3$ in core)
Salt composition: $^{78}\text{LiF}^{22}\text{AcF}_4$ (99.95% $^7\text{Li}$)
- 100Ac $^87\text{Th}+6\text{U}+6\text{Pu}+1\text{Ac}_m$ (starting)
- Melting point <568°C
- Salt evaporation starts: >1300°C
Running the cycle with our (thermal-epithermal) spectrum utilizes **83.1%** of the fuel and produce **16.9%** americium waste – but \( \text{eta}=0.88 \) (sustainable is \( \text{eta}>>1 \))
Running the cycle with our (thermal-epithermal) spectrum utilizes virtually all the fuel and produce **4.56 ppm** americium waste and **eta=1.06** – however...
Neutron loss

The changing leakage over time, is caused by significant inventory changes from “over-fueling” (and Th removal) to keep the core critical.

Our thorium cycle has \( \eta = 1.06 \)
But we lose 10-13% neutrons.

<table>
<thead>
<tr>
<th>Actinide component</th>
<th>Initial</th>
<th>30 years</th>
<th>60 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thorium</td>
<td>86.7%</td>
<td>59.6%</td>
<td>39.9%</td>
</tr>
<tr>
<td>Uranium</td>
<td>6.3%</td>
<td>21%</td>
<td>32%</td>
</tr>
<tr>
<td>Plutonium</td>
<td>6.3%</td>
<td>16%</td>
<td>23%</td>
</tr>
<tr>
<td>Minor Ac</td>
<td>0.6%</td>
<td>3.0%</td>
<td>4.8%</td>
</tr>
<tr>
<td>Fissile Pu/Pu</td>
<td>67.8%</td>
<td>53.1%</td>
<td>48.5%</td>
</tr>
</tbody>
</table>
60 years, at 50 MW$_{th}$:
**Net negative transuranic production of ~1 ton!**
We do not have an underlying closed thorium fuel cycle.
But with the production of $^{233}$U we are getting closer.
Next step: SWaB -> CUBE
Seaborg WasteBurner -> Compact Used fuel BurnEr

Fix reactivity feedback from graphite expansion
- graphite slabs instead of salt pipes

Increase fine-tuning rods reactivity span
- move rods to a more central position

Reduce Pu (and Ac\textsubscript{m}) inventory
- minimize salt volume (double blanket?)
- optimize moderator configuration
- remove Am online
- increase UF6 evaporation in fuel processing

Increase neutron economy
- reduce leakage (ultra compact)
- add outer reflector

Funding needed for two activities:
System engineering and multi physics
Chemistry system design and verification