Radiological Issues for Thin Liquid Wall Options

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UW
Objectives

• Develop activation approach for liquid wall supply methods:
  – Tangential injection
  – Porous wall injection

• Identify activation issues for candidate liquid wall (LW) materials:
  - Liquid Metals
    - LiPb
    - Pb
    - Sn
  - Molten Salts
    - Flibe

• Consider two extreme activation cases:
  – No mixing of LW material with breeder (worst case)
  – Mixing of LW material with breeder inside and outside chamber (proposed for ARIES-IFE-HIB)

• Develop design solutions for activation problems

* No major activation problems expected for Li
# (LiF)$_2$, BeF$_2$. Flinabe (NaF, LiF, BeF$_2$) exhibits similar behavior
Activation Assessment

• Includes:
  – **Activity** for safety analysis
  – **Decay heat** for LOCA/LOFA analysis
  – **Waste management:**
    • **Means for waste minimization:**
      – Use same liquid breeder for LW
      – Clean-up LW and reuse in other devices
      – Clear from radiologically controlled area if Clearance Index < 1 (unlikely)
    • **Waste disposal in repositories:**
      – Generate only low level waste (LLW) to meet ARIES requirements
      – Any high level waste (HLW)?
# LW and Breeder Options

## Blanket:

<table>
<thead>
<tr>
<th>Liquid breeders:</th>
<th>Candidate LW Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Preferred</td>
</tr>
<tr>
<td>LiPb*</td>
<td>LiPb*</td>
</tr>
<tr>
<td>Flibe</td>
<td>Flibe</td>
</tr>
<tr>
<td>Flinabe</td>
<td>Flinabe</td>
</tr>
<tr>
<td>Li#</td>
<td>Li#</td>
</tr>
<tr>
<td>LiSn</td>
<td>LiSn</td>
</tr>
</tbody>
</table>

**Recommendation:** Use same breeder for LW to minimize waste

## Solid breeders:

- Li$_2$O**, Li$_2$ZrO$_3$, Li$_4$SiO$_4$, Pb**
- Sn, Ga
- Li$_2$TiO$_3$, LiAlO$_2$**

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* HIBALL (UW-1981), HIBALL-II (UW-1984), LIBRA (UW-1990), LIBRA-SP (UW-1995)
* OSIRIUS (LLNL-1992)
* LIBRA-LiTE (UW-1991)
** Prometheus (MDC-1992)
Ex-chamber residence time $\approx 50$ s, per Waganer

In-chamber residence time for LW is unknown $\Rightarrow$ parameterize it
Tangential Injection Option

- No outside mixing of LW with breeder
- Heat recovery, T extraction, and cleanup processes
- LW Vapor/Drops, Hohlraum Debris, Buffer Gas

LW
Solid Wall
Blanket

LW Material
Hohlraum Debris, T, Buffer Gas, and Transmutation Products
Porous Wall Injection - Option I
(Liquid Breeder Blanket - Proposed for ARIES-IFE)

Use same breeder for LW to minimize waste

Route breeder exiting supply channel through blanket to increase $\Delta T$ and enhance thermal conversion efficiency

Heat recovery, T extraction, and Clean up processes

Hohlraum Debris, T, Buffer Gas, and Transmutation Products

LW Vapor/Drops, Hohlraum Debris, Buffer Gas
Porous Wall Injection - Option II
(Solid Breeder Blanket - Prometheus type)

No mixing with solid breeder outside chamber (Prometheus type)
Representative Radial Build for LiPb Breeder Using ARIES-AT Design Rules

- SiC/SiC composite structure and LiPb LW/coolant/breeder
- Design parameters (per Raffray):
  - SiC $T_{\text{max}}$ 1000 °C
  - Surface heat flux $\leq$ 1 MW/m²
  - Chamber radius $\geq$ 6 m
  - LiPb $\Delta T$ 200-300 °C
  - LiPb velocity 4-6 m/s
  - LiPb $T_{\text{max}}$ 1100 °C
  - LW Thickness 1 mm
Activation Parameters and Assumptions

- Perkins’ neutron spectrum for HIB target (av. $E_n=11.75$ MeV)
- Parameters:
  - Target yield: $458.7$ MJ
  - Rep rate: $4$ Hz (0.25 s between pulses)
  - Chamber radius: $6$ m
  - Neutron wall loading: $2.8$ MW/m²
  - Plant lifetime: $40$ FPY
  - Availability: $85\%$
- In-chamber residence time for LW depends on evaporation and condensation processes. LW may survive thousands of pulses before being processed and re-injected into chamber

  ⇒ Parameterize in-chamber residence time between 0.25 s (1 pulse) and several tens of minutes (~10,000 pulses)

- Impurities included in all materials
- LW materials only. No target debris
- Same radial build used for all LW candidates
- No mixing during operation. Mixing with breeder @ EOL*
- Waste disposal rating (WDR) evaluated at 100 y after operation using Fetter’s limits for LiPb, Pb, and Sn and NRC-10CFR61 limits for Flibe and Flinabe
- Exact model of all pulses using ALARA pulsed activation code

* Conservative assumption
WDR - Tangential Injection
(No Outside Mixing with Breeder)

- WDR increases with LW residence time and saturates at ~ 40 min
- LW materials generate tons of HLW unless residence time and/or exposure time are controlled
- Sn and Flibe have lower WDR compared to Pb and LiPb
- **To reuse materials in other devices or dispose as LLW waste:**
  - Limit LW service life ⇒ higher inventory. Use fresh LiPb and Pb after 2-3 y and fresh Sn and Flibe after 14-16 y if in-chamber residence time ≥ 40 min (Bi impurity control below 43 wppm helps prolong LiPb/Pb service lifetime),
  - Or, control in-chamber residence time to ≤ 2-3 s for Pb/LiPb and 20-25 s for Sn/Flibe
  - Or, filter out cup(s) of transmutation products and dispose as HLW
On-line removal of transmutation products relaxes limits on residence/exposure times, thus reduces EOL inventory, but generates cup(s) of HLW.

<table>
<thead>
<tr>
<th></th>
<th><strong>Option I</strong></th>
<th></th>
<th><strong>Option II</strong></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Max Residence Time</td>
<td>Exposure Time</td>
<td>Residence Time</td>
<td>Max Exposure Time</td>
</tr>
<tr>
<td><strong>WDR</strong>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LiPb</td>
<td>69</td>
<td>3 s</td>
<td>47 y</td>
<td>≥ 40 min</td>
</tr>
<tr>
<td>Pb</td>
<td>81</td>
<td>2.5 s</td>
<td>47 y</td>
<td>≥ 40 min</td>
</tr>
<tr>
<td>Sn</td>
<td>6</td>
<td>20 s</td>
<td>47 y</td>
<td>≥ 40 min</td>
</tr>
<tr>
<td>Flibe</td>
<td>9</td>
<td>25 s</td>
<td>47 y</td>
<td>≥ 40 min</td>
</tr>
</tbody>
</table>

* ≥ 40 min in-chamber residence time and 47 y of operation
WDR - Porous Wall Injection (Outside Mixing with same Breeder)

- **Example:** Liquid breeder used in all components. Proposed for ARIES-IFE
- Blanket controls volumetric average WDR
- WDR is not sensitive to in-chamber residence time of LW
- Results for 47 y of operation:

<table>
<thead>
<tr>
<th></th>
<th>WDR*</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiPb</td>
<td>10</td>
</tr>
<tr>
<td>Flibe</td>
<td>0.8</td>
</tr>
</tbody>
</table>

- No waste disposal problem identified for Flibe even without clean-up system
- To reuse LiPb in other devices or dispose as LLW, filter out cup(s) of transmutation products and dispose as **HLW**
- Do not limit exposure time for sizable breeders (> 1000 tons)

* No transmutation removal.
WDR - Porous Wall Injection
(No Outside Mixing with Breeder - Prometheus-type)

- Example: Solid breeder blanket with Pb (or Sn) seeping from supply channel through porous wall
- 1 mm thick LW controls volumetric average WDR
  ⇒ Need more accurate evaluation for in-chamber residence time
- Results for ≥ 40 min residence time and 47 y of operation:

<table>
<thead>
<tr>
<th></th>
<th>WDR*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb</td>
<td>14</td>
</tr>
<tr>
<td>Sn</td>
<td>0.94</td>
</tr>
</tbody>
</table>

- No waste disposal problem identified for Sn even without clean-up system
- Without LW contribution, WDR of Pb in supply channel is ~2 ⇒ HLW
- To reuse Pb in other devices or dispose as LLW, filter out cup(s) of Bi and dispose as HLW

* No transmutation removal
# 86% from LW and 14% from supply channel
## Main Contributors to WDR

<table>
<thead>
<tr>
<th>Source</th>
<th>Nuclides</th>
</tr>
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<tbody>
<tr>
<td>LiPb, Pb</td>
<td>$^{208}\text{Bi}$</td>
</tr>
<tr>
<td>Sn</td>
<td>$^{108\text{m}}\text{Ag}$, $^{121\text{m}}\text{Sn}$, $^{126}\text{Sn}$</td>
</tr>
<tr>
<td>Flibe</td>
<td>$^{14}\text{C}$</td>
</tr>
</tbody>
</table>
Conclusions

• Employ same breeder for LW to minimize waste volume
• Tangential injection case without clean-up system:
  – All LW materials generates HLW if in-chamber residence time exceeds 2-25 s, depending on materials
• Porous wall injection case without clean-up system:
  – No waste disposal problems identified for Sn and Flibe
  – LiPb and Pb generate HLW if employed for 47 y
• On-line clean-up system removes cup(s) of transmutation products (HLW) and allows tons of LW materials to be reused in other devices or disposed as LLW
• Some results are sensitive to in-chamber residence time that is unknown and needs to be determined