Recycling Issues Facing Target and RTL Materials of Inertial Fusion Designs

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Objectives

• Advise IFE designers on best option to manage HI hohlraum wall radwaste and Z-pinch RTL radwaste:
  – One-shot use, then dispose in repository, or
  – Recycle during plant life (45-50 y)

• Highlight pros and cons of once-through and recycling scenarios.

• Develop irradiation history and timeline for recycling approach.

• Examine conservative recycling approach without slag or transmutation product removal.

• Monitor waste level and dose to equipment during recycling.

• Determine economic impact of recycling approach.
Representative IFE-HI Power Plant

LLNL Close-Coupled Target Design

HYLIFE-II
(Thick Liquid Wall Concept)

- DT Capsule
- Foams
- Hohlraum Wall (60% of target mass)
- Flibe Jets
**Z-Pinch Power Plant**

**Recyclable Transmission Lines (RTL)**
- Top diameter = 1 m
- Bottom diameter = 0.1 m
- Length = 5 m
- Carbon Steel thickness = 0.0635 cm
- 50 kg* / RTL

* Needed for high electric efficiency.
## Key Parameters

<table>
<thead>
<tr>
<th></th>
<th>ARIES-IFE-HI</th>
<th>Z-Pinch</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target Yield</strong></td>
<td>460 MJ</td>
<td>3000 MJ</td>
</tr>
<tr>
<td><strong>Rep Rate</strong></td>
<td>4 Hz</td>
<td>0.1 Hz</td>
</tr>
<tr>
<td><strong># of Units per Plant</strong></td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td><strong># of Shots per FPY</strong></td>
<td>126 million</td>
<td>38 million</td>
</tr>
<tr>
<td><strong>Au/Gd Hohlraum Wall or RTL Thickness</strong></td>
<td>15 µm</td>
<td>0.635 mm</td>
</tr>
<tr>
<td><strong>Mass of Hohlraum Wall or RTL</strong></td>
<td><strong>0.1 g / target</strong></td>
<td><strong>50 kg / RTL</strong></td>
</tr>
<tr>
<td><strong>Volume of Hohlraum Wall or RTL</strong></td>
<td><strong>0.008 cm³ / target</strong></td>
<td><strong>6000 cm³ / RTL</strong></td>
</tr>
<tr>
<td><strong>Availability</strong></td>
<td>85%</td>
<td>85%</td>
</tr>
<tr>
<td><strong>Plant Lifetime</strong></td>
<td>40 FPY (47 y)</td>
<td>40 FPY (47 y)</td>
</tr>
</tbody>
</table>
Pros and Cons of Recycling Scenario

• **Pros:**
  – Low inventory of radwaste.
  – Negligible material cost.

• **Cons:**
  – May generate high-level waste that violates ARIES top-level requirements.
  – Require radioactive storage facility in target fab.
  – Need purification system to deliver highly pure materials.
  – No hands-on and no personnel access to target fab.
  – Slow, remotely controlled process.
  – Costly process.

**Do not recycle unless process offers advantages**
Hohlraum Wall Materials Represent < 1% of IFE-HI Waste Stream

Recycling is not a “must” requirement for IFE-HI designs
Hohlraum Wall Recycling?!

• It is acceptable among ARIES team members that hohlraum wall materials should not be recycled.

• However, we developed a recycling approach to understand the problem and highlight the cost penalty and design complexity added to HI designs.

• Among wide range of candidate hohlraum wall materials, we selected three materials for this study:
  – Gold/Gadolinium (50/50 wt%)
  – Tungsten
  – Lead
IFE-HI Target Recycling Process
(Hohlraum Wall Materials Spend ≥ 2 days Outside Chamber)

**Chamber**
- Target Injection (3 - 10 s)
- Hohlraum Debris, Liquid Vapor, Buffer Gas, and Others

**Target Final Assembly Facility**
- Hohlraum Wall Fabrication Facility
- Other Hohlraum Materials
- DT Filled Capsules

**Cooling Period**
- t_2 (? ; < 2 y)
- t_3 (1 d)
- t_4 (1 d)

**Heat recovery, T extraction, and Filtration process**
- t_1 (~1 min)

**Liquid Breeder + Others**

**Buffer Gas, D, T, and Transmutation Products**
### Design Criteria and Codes

<table>
<thead>
<tr>
<th><strong>Waste disposal rating (WDR)</strong></th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>(for <strong>Class C</strong> low-level waste)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Clearance Index</strong></th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>(for waste containing traces of radionuclides)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Recycling dose</strong></th>
<th>3000 Sv/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>(for <strong>advanced</strong> remote handling equipment)</td>
<td></td>
</tr>
</tbody>
</table>

- **Codes and data:**
  - DANTSYS Neutral-particle transport code:
  - ALARA **Pulsed** activation code:
    - Exact modeling of all pulses (~10,000)
  - FENDL-2 Nuclear Data:
    - 175 neutron and 42 gamma group structure
One-Shot Use Scenario Generates Very Low Level Waste White recycling Generates High-Level Waste

<table>
<thead>
<tr>
<th></th>
<th>One-Shot Use Scenario</th>
<th>Recycling Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WDR</td>
<td>CI</td>
</tr>
<tr>
<td>Gold/Gadolinium</td>
<td>$2 \times 10^{-8}$</td>
<td>42</td>
</tr>
<tr>
<td>Tungsten</td>
<td>$2 \times 10^{-6}$</td>
<td>14.9</td>
</tr>
<tr>
<td>Lead</td>
<td>$2 \times 10^{-5}$</td>
<td>5.6</td>
</tr>
</tbody>
</table>

* No cooling period. No transmutation product removal.
Cooling Period Controls WDR and Dose

Au/Gd generates high-level waste that violates ARIES requirements

All materials meet advanced RH limit with < 10 d cooling periods
# Recommended Cooling Periods that Satisfy Design Limits

<table>
<thead>
<tr>
<th></th>
<th>Cooling Period for WDR &lt; 1</th>
<th>Cooling Period for Dose &lt; 3000 Sv/h</th>
<th>Recommended Cooling Period</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Au/Gd</strong></td>
<td>&gt; 2 y*</td>
<td>9.5 d</td>
<td>—*</td>
</tr>
<tr>
<td></td>
<td>(158\text{\textsuperscript{Tb}})</td>
<td>(196\text{\textsuperscript{Au}})</td>
<td></td>
</tr>
<tr>
<td><strong>Tungsten</strong></td>
<td>0</td>
<td>6.2 d</td>
<td>6.2 d</td>
</tr>
<tr>
<td></td>
<td>(186\text{\textsuperscript{mRe}, 178\textsuperscript{nHf}})</td>
<td>(184\text{\textsuperscript{Re}})</td>
<td></td>
</tr>
<tr>
<td><strong>Lead</strong></td>
<td>13 d</td>
<td>&lt; 1 d</td>
<td>13 d</td>
</tr>
<tr>
<td></td>
<td>(208\text{\textsuperscript{Bi}, 202\textsuperscript{Pb}})</td>
<td>(203\text{\textsuperscript{Pb}, 202\textsuperscript{Tl}})</td>
<td></td>
</tr>
</tbody>
</table>

* Insignificant inventory reduction for cooling period exceeding 2 y.
### Recycling Doubles HI Cost of Electricity

<table>
<thead>
<tr>
<th></th>
<th>One-Shot Use Scenario</th>
<th>Recycling Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost per Target</td>
<td>$0.4</td>
<td>$3.15</td>
</tr>
<tr>
<td>Change to COE</td>
<td>~10 mills/kWh</td>
<td>~70 mills/kWh</td>
</tr>
<tr>
<td>COE</td>
<td>~70 mills/kWh</td>
<td>~130 mills/kWh</td>
</tr>
</tbody>
</table>

Doubling COE to recycle materials that present no waste burden to IFE-HI designs is unacceptable.
IFE-HI Conclusions

• HI Hohlraum walls represent small waste stream (< 1% of total nuclear island waste)
  ⇒ recycling is not a “must” requirement for IFE-HI concept.

• Use low-cost materials once-through and dispose as Class A LLW instead of using expensive materials (such as Au and Gd).
  One-shot use scenario offers:
  – Attractive safety features  – Less complex design
  – Radiation-free target Fab  – Lowest COE

• Target factory designers prefer dealing with non-radioactive hohlraum wall materials and this assessment supports the feasibility of no-recycling approach for HI concepts.
Z-Pinch Power Plant

Carbon Steel
50 kg / RTL

Flibe Foam

Less intense neutron flux and softer spectrum at RTL result in much lower activity, WDR, CI, and dose.

Hohlraum Wall

RTL

Flibe Jets

Target

Activity (Ci/m³)

Time After Shutdown (s)

10^{-3} 10^{-1} 10^1 10^3 10^5 10^7 10^9 10^{11}

10^0 10^2 10^4 10^6 10^8 10^{10}

1 min 1 h 1 d 1 m 1 y 100 y
RTL Recycling is a “Must” Requirement to Minimize Waste Stream and Enhance Economics

Without RTL recycling
Total RTL mass = 80 M Tons
Fabricated Steel Unit Cost = $10/kg
Total RTL cost = ~$800B

With RTL recycling
1.5 day RTL inventory
Total RTL mass = 8,000 Tons
Total RTL cost ~ $80M
RTL Recycling Process

(RTL Materials Spend ~1.5 day Outside Chamber)

- **RTL Debris**
  - Cooling Period
  - **Cooling Period**
  - **RTL Fabrication and Inspection**
  - Foam and Reflector Fabrication
  - **One Day Storage**
  - **Final RTL and Target Assembly**
  - Cartridge Insertion

- **Heat recovery, T extraction, and separation processes**
  - D, T and Transmutation Products
  - **Target Debris** (W, Be, CH)
  - **Target Capsules**
  - **One Day Storage**
  - **Final RTL and Target Assembly**
  - **Cartridge Insertion**

Times:
- $t_1$ (~1 min)
- $t_2$ (?)
- $t_3$ (14 h)
- $t_4$ (1 d)
- $t_5$ (10 s)
## RTL Results

<table>
<thead>
<tr>
<th></th>
<th>Results</th>
<th>Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WDR</strong></td>
<td>$10^{-7}$ Class C</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>$10^{-3}$ Class A</td>
<td></td>
</tr>
<tr>
<td><strong>Clearance Index</strong></td>
<td>0.1 @ 100 y</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1 @ 50 y</td>
<td></td>
</tr>
<tr>
<td><strong>Recycling dose rate (Sv/hr)</strong></td>
<td>160</td>
<td>3000</td>
</tr>
</tbody>
</table>
Z-Pinch Conclusions

• RTL recycling is a “must” requirement for Z-pinch concept to minimize heavy metal throughput and enhance economics.

• Carbon Steel RTLs satisfy design requirements when recycled for entire plant life even without cooling period:
  – Class A low-level waste ⇒ Shallow land burial
  – Clearance index < 1 ⇒ Release to commercial market after 50 y
  – Dose < 160 Sv/hr ⇒ No hands-on recycling

• Online removal of transmutation products helps meet design requirements with wide margin, but complicates recycling process and generates high level waste.

• Recycling process must be accomplished remotely in 1.5 day.

• Advanced remote handling equipment should be developed to handle high dose rate (200 Sv/hr or more).

• COE should reflect cost of RTL remote recycling.
Overall Conclusions

- Recycling offers advantages to Z-pinch while adds complexity and cost to HI systems.

- **Recommendations:**
  - Use low-cost hohlraum wall materials for HI targets once-through, then dispose in repositories.
  - Recycle RTLs of Z-pinch.