Adaptation of Pb-Bi Cooled, Metal Fuel Subcritical Reactor for Use with a Tokamak Fusion Neutron Source


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Study Objectives

• Develop a nuclear design concept for a sub-critical transmutation reactor driven by a D-T tokamak fusion neutron source.

• Adapt nuclear technology being developed for ATW to identify a transmutation blanket.

• Analyze the performance of a tokamak transmutation facility.
Adaptation of ATW Nuclear Technology to a Fusion Driven Reactor

- Tritium Production
  - Addition of lithium for tritium self-sufficiency

- Tokamak Geometry
Tokamak Design

- Ohmic Heating Coils
- Toroidal Field Coils
- Reflector, Shield & Vacuum Vessel
- Plasma Chamber
- First Wall
- 1 Meter
- Reactor Region
Midplane Radial Build

\[ \Delta_{\text{OH}} | \Delta_{\text{TF}} | \Delta_{\text{in}} \]

\[ R_{\text{fc}} | R_{\text{mag}} \]

\[ \Delta_{\text{reac}} | \Delta_{\text{ou}} | \Delta_{\text{TF}} \]

\[ R_{\text{fc}} = \text{flux core radius} = 1.20 \text{ m} \]
\[ \Delta_{\text{OH}} = \text{OH solenoid } \Delta = 0.25 \]
\[ \Delta_{\text{TF}} = \text{TF coil } \Delta = 0.35 \]
\[ \Delta_{\text{in}} = \text{inner refl/shld} = 0.40 \]
\[ a = \text{minor radius} = 0.90 \]
\[ \Delta_{\text{reac}} = \text{reactor} = 0.40 \]
\[ \Delta_{\text{ou}} = \text{outer refl/shld} = 0.30 \]
\[ \Delta_{\text{gap}} = \text{outer gap} = \text{tbd} \]
\[ R_{\text{o}} = \text{major radius} = 3.10 \]
\[ R_{\text{mag}} = \text{magnet radius} = 1.80 \]

Note: refl/shld includes first wall, reflector, shield, and vacuum vessel
Tokamak Subcritical Reactor

- Reactor
- Plasma
- First Wall
- 1 Meter
Hexagonal Fuel Assembly

- **Fuel Cell**
  - Pin Diameter – 0.635 cm
  - Cladding Thickness – 0.056 cm
  - Pitch-to-Diameter – 1.727

- **Fuel Assembly**
  - 210 Fuel Pins, 7 Structural Pins

- **Volume Fractions**
  - Fuel – 0.14, Structure – 0.103, Coolant – 0.695

- **Materials**
  - Dispersion Fuel – TRU-10Zr/Zr
  - Structure/Clad – HT-9
System Design Constraints

- Plasma Physics Constraints
  - Tokamak Geometry
- Thermal Constraints
  - Power Density
- Radiation Damage Constraints
  - Shield Thickness
  - Fuel residence time
- Engineering Constraints
  - Lithium Concentration
  - Magnet Sizing
- Self Imposed
  - Total Power
  - Maximum Neutron Multiplication (k)
Magnet Radiation Damage Limits

Reflector / Shield Thickness Driver

- Designed as Lifetime Component
  - 40 Full Power Years
- Used Radiation Damage Limits
  - Ceramic Insulators
  - Fast fluence limit = 4E+22 n/cm²
- Optimize Shield to Dose Limits
  - Organic Insulators
  - Dose limit = 1E11 Rads
Tritium Balance

\[
\frac{dT(t)}{dt} = (1 - \alpha) * \mathcal{P}(t) - \mathcal{I}(t) - \lambda_T T(t)
\]

\(T(t)\) = Tritium inventory
\(\alpha\) = fractional loss of tritium
\(\mathcal{P}(t)\) = Tritium production rate
\(\mathcal{I}(t)\) = Fusion rate
\(\lambda_T\) = Tritium decay constant

Limit

\(T_{EOC} \geq T_{BOC} e^{\lambda_T t_{down}}\)

\(T_{BOC}\) = Startup tritium inventory at the beginning of cycle
\(T_{EOC}\) = Tritium inventory at the end of cycle
\(t_{down}\) = Down time between cycles
Time Behavior of Tritium Inventory

- **Tritium Inventory**
- **Time**
- **Startup Inventory**
- **End of Cycle Inventory**
- **Maximum Cycle Inventory**
Lithium Concentrations

- Tritium Production Cross Sections

<table>
<thead>
<tr>
<th></th>
<th>14 MeV</th>
<th>Fission Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li6</td>
<td>28.0 mb</td>
<td>330.7 mb</td>
</tr>
<tr>
<td>Li7</td>
<td>302.9 mb</td>
<td>20.0 mb</td>
</tr>
<tr>
<td>Nat Li</td>
<td>282.3 mb</td>
<td>43.3 mb</td>
</tr>
</tbody>
</table>

- Lithium Lead (Li$_{17}$Pb$_{83}$)
  - Enrichment ~20% Li-6

- Lithium in Lead Bismuth Eutectic (Pb$_{45}$Bi$_{55}$)
  - (Li$_x$Pb$_y$Bi$_z$)
  - Range of enrichments depending on $x$
  - Assuming 5% by volume Li – enrichment to ~40 a/o Li-6
### Other Design Limits

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{Blanket}}$</td>
<td>3000 MWt (~1 GWe)</td>
</tr>
<tr>
<td>$k$</td>
<td>0.95</td>
</tr>
<tr>
<td>Power Density</td>
<td>175 kW/l</td>
</tr>
<tr>
<td>Cladding Lifetime</td>
<td>25% BU - go to DPA limit</td>
</tr>
<tr>
<td>First Wall Lifetime</td>
<td>DPA Limit</td>
</tr>
<tr>
<td>$P_{\text{fus}}$</td>
<td>~ 200 MW</td>
</tr>
</tbody>
</table>
Equilibrium Fuel Cycle

LWR SNF → UREX → Pyro → Transmute → Waste
REBUS Fuel Cycle Code

- ANL Fast Reactor Fuel Cycle Code
- Same Code used by ANL for ATW Calculations

- Equilibrium Cycle Calculations
  - Input Target Beginning of Cycle K-eff
  - Input Irradiation Cycle Parameters
  - Input External Cycle Parameters
  - Iterates on Fuel “Enrichment”
    Volume HM/(Volume Zr + Volume HM)

- Calculates Fuel Cycle Parameters
  - Enrichment, Isotopic Composition
  - Power Density, Burnup, Source Strength
  - Mass Flow, Feed, Recycle, Waste
Cycle Variation of Key Parameters

- Instantaneous Tritium Breeding Ratio
- Neutron Multiplication
- Tritium Production
- Fusion Rate

Time (Full Power Days)
## Preliminary Result

<table>
<thead>
<tr>
<th>Case Name</th>
<th>LBE-5-40</th>
<th>LiPb-20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant</td>
<td>Lead-Bismuth w/ Lithium</td>
<td>Lithium Lead</td>
</tr>
<tr>
<td>Li-6 Enrichment</td>
<td>40 a/o Li-6</td>
<td>20 a/o Li-6</td>
</tr>
<tr>
<td>Li Volume Fraction</td>
<td>5 v/o</td>
<td>n/a</td>
</tr>
<tr>
<td>Fuel Batches</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Cycle Length (FPD)</td>
<td>624</td>
<td>624</td>
</tr>
<tr>
<td>Enrichment</td>
<td>43%</td>
<td>45%</td>
</tr>
<tr>
<td>BOC k</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>EOC k</td>
<td>0.86</td>
<td>0.86</td>
</tr>
<tr>
<td>BOC Fusion Power</td>
<td>41 MW</td>
<td>41 MW</td>
</tr>
<tr>
<td>EOC Fusion Power</td>
<td>127 MW</td>
<td>125 MW</td>
</tr>
<tr>
<td>Discharge Burnup</td>
<td>21%</td>
<td>20%</td>
</tr>
<tr>
<td>Cladding Damage</td>
<td>112 dpa</td>
<td>107 dpa</td>
</tr>
<tr>
<td>FW Damage</td>
<td>22 dpa/cycle</td>
<td>21 dpa/cycle</td>
</tr>
<tr>
<td>Tritium EOC / BOC</td>
<td>16</td>
<td>30</td>
</tr>
<tr>
<td>Reactor Power Density</td>
<td>118 kW/l</td>
<td>118 kW/l</td>
</tr>
</tbody>
</table>
Preliminary Transmutation Results

- Cycle Length = 624 FPD
  = 1.7 FPY

- Fuel Residence Time = 3 cycles

- Transmutation Rate ~2 MTHM/cycle
  ~ 1.1 MT/FPY
# Fuel Composition

<table>
<thead>
<tr>
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<th></th>
<th>LiPb-20</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SNF Feed</td>
<td>Fresh Fuel</td>
<td>Discharged</td>
<td>Fresh Fuel</td>
</tr>
<tr>
<td>Loading (MTHM)</td>
<td>10.2</td>
<td>8.2</td>
<td>10.5</td>
<td>8.6</td>
</tr>
<tr>
<td>Inventory* (MTHM)</td>
<td>27.5</td>
<td>25.6</td>
<td>28.5</td>
<td>26.6</td>
</tr>
<tr>
<td>U</td>
<td>0.4%</td>
<td>4.4%</td>
<td>5.2%</td>
<td>4.5%</td>
</tr>
<tr>
<td>Np</td>
<td>4.2%</td>
<td>3.6%</td>
<td>3.4%</td>
<td>3.5%</td>
</tr>
<tr>
<td>Pu</td>
<td>83.2%</td>
<td>77.9%</td>
<td>76.6%</td>
<td>77.9%</td>
</tr>
<tr>
<td>Pu-239</td>
<td>52.8%</td>
<td>30.2%</td>
<td>24.4%</td>
<td>29.7%</td>
</tr>
<tr>
<td>Am</td>
<td>10.0%</td>
<td>13.2%</td>
<td>13.6%</td>
<td>13.2%</td>
</tr>
<tr>
<td>Cm</td>
<td>0.1%</td>
<td>0.9%</td>
<td>1.3%</td>
<td>0.9%</td>
</tr>
</tbody>
</table>

* Inventory is the beginning of cycle & end of cycle actinide mass
Preliminary Conclusions

• Nuclear design feasible
  – Two Pb cooled options
    • 5% Li enriched to 40% Li-6 in LBE
    • Li-17Pb-83 enriched to 20% Li-6
  – Metal Fuel
    • TRU-10Zr dispersed in Zr
    • 30 - 45 v/o TRU

• Transmutation fuel cycle
  – 3 batch, 1.5 - 2 FPY cycle
  – ~2 MTHM fissioned per cycle
Future Work

• Optimized Fusion Cycle
  – Batches, Cycle Lengths, Shielding, Lithium, Reactivity Compensation, ...

• Waste Management Performance
  – Repository Requirements, Toxicity, Proliferation, Decay Heat, ...

• Examine Criticality Safety Margin
  – High Leakage Configuration

• Benchmarking