Feasibility and Deployment Strategy of Water Cooled Thorium Breeder Reactors

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Contents

• Background and Motivations
• Core design of water cooled thorium breeder
• Deployment strategy
• Synergetic system with U-Pu reactors
• Proliferation resistance of Th cycle
• Generation cost
• Concluding remarks
Thorium Resource Map

World wide 
~1500 thousand tons
Energy Potential of Thorium

• It is often said that “thorium is more abundant in nature than uranium”.
• It is true but the current “identified quantity” is comparable with that of uranium.
• Assuming thorium use in breeder type reactors, energy of $\sim 10^6$ GWy could be potentially added.

  equivalent to 1,000 LWRs operation for several 1,000 years

• To achieve this, enough fissile material needed to ignite “wet” (fertile) thorium.
Objective / Motivations

- Develop water-cooled, oxide-fueled thorium breeder reactor
  - Why water/oxide ?
    - well-established plant/fuel technology
  - Why breeder ?
    - make full use of resource for world sustainability
  - Why thorium ?
    - Diversify fission energy resource
    - Smaller MA production
    - Breeding potential with negative void effect
    - No severe energetics during CDA
Breeder type thorium reactors

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<thead>
<tr>
<th></th>
<th>Past studies</th>
<th>Our study</th>
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<tbody>
<tr>
<td>Broader type</td>
<td></td>
<td>PHBR (PWR with tight pitch fuel &amp; D₂O) (TCU)</td>
</tr>
<tr>
<td></td>
<td>Breeding Ratio</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>Total Burnup</td>
<td>~15 GWd/t</td>
</tr>
<tr>
<td></td>
<td>Core Design</td>
<td>Heterogeneous Movable fuel</td>
</tr>
<tr>
<td></td>
<td>Pin gap</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Void Coeff.</td>
<td>Negative</td>
</tr>
<tr>
<td></td>
<td>Shutdown Margin</td>
<td>Enough</td>
</tr>
<tr>
<td>Moderator</td>
<td>Light water</td>
<td>Heavy water</td>
</tr>
<tr>
<td></td>
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Design window of 
\( \text{H}_2\text{O} \) cooled thorium breeder

Limit line for negative VRC

Geometrical gap limit (>1mm) for triangular

Limit line for breeding

Moderator to Fuel Volume Ratio (MFR) [-]
Design window of \( \text{D}_2\text{O} \) cooled thorium breeder
## Reactor / fuel type comparison

<table>
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<tr>
<th>Reactor type</th>
<th>Coolant</th>
<th>Fuel type</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLBR</td>
<td>H₂O</td>
<td>U-Pu oxide Th-Pu oxide Th-U233 oxide</td>
</tr>
<tr>
<td>(BWR with tight pitch)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PHBR</td>
<td>D₂O</td>
<td></td>
</tr>
<tr>
<td>(PWR with tight pitch)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

BLBR : Boiling Light water Breeder Reactor  
PHBR : Pressurized Heavy water Breeder Reactor
Fissile Inventory Ratio with Burnup for “PHBR”

Achievable Burnup [GWd/t] vs. MFR and Fissile Inventory Ratio with Burnup for “PHBR”

- U-Pu_11.5w%
- U-Pu_12.5w%
- U-Pu_13.5w%
- Th-Pu_15w%
- Th-Pu_15.6w%
- Th-Pu_17w%

MFR = 1.0

Higher enriched U-Pu

Higher enriched Th-Pu
Fissile Inventory Ratio with Burnup for “PHBR”

![Graph showing the relationship between Achievable burnup [GWd/t] and Fissile Inventory Ratio (FIR) for different fuel compositions.](image)

- **U-Pu_11.5w%**
- **U-Pu_12.5w%**
- **U-Pu_13.5w%**
- **Th-Pu_15w%**
- **Th-Pu_15.6w%**
- **Th-Pu_17w%**
- **Th-U233_6.6w%**
- **Th-U233_7.2w%**
- **Th-U233_7.7w%**
Detailed enrichment survey (PHBR, Th$_{233}$U fuel)
<table>
<thead>
<tr>
<th>Reactor type</th>
<th>Coolant</th>
<th>Fuel type</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLBR (BWR with tight pitch)</td>
<td>H$_2$O</td>
<td>U-Pu oxide Th-Pu oxide Th-U233 oxide</td>
</tr>
<tr>
<td>PHBR (PWR with tight pitch)</td>
<td>D$_2$O</td>
<td></td>
</tr>
</tbody>
</table>

BLBR: Boiling Light water Breeder Reactor  
PHBR: Pressurized Heavy water Breeder Reactor
Fissile Inventory Ratio & Burnup for “BLBR”

Achievable burnup [GWd/t] vs. Fissile Inventory Ratio (FIR) for different fuels and burn-up rates:

- U-Pu (10.4w%, 11.5w%)
- Th-Pu (13.7w%, 15w%, 15.6w%)
- Th-U233 (5.5w%, 6.7w%, 7.7w%)

Key points:
- MFR = 1.0
- Achievable burnup ranges from 50,000 to 3,00,000 GWd/t
- Different markers indicate varying fuel compositions and burn-up rates.
Doppler coefficients

Reference BWR

BLBR

PHBR

Reference BWR: Kashiwazaki-Kariwa Unit2, TEPCO
Void coefficients

Reference BWR: Kashiwazaki-Kariwa Unit2, TEPCO
Core specifications of PHBR

<table>
<thead>
<tr>
<th>Core design parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal power [MWt]</td>
<td>3500</td>
</tr>
<tr>
<td>Cycle length [days]</td>
<td>1300</td>
</tr>
<tr>
<td>Batch number</td>
<td>3</td>
</tr>
<tr>
<td>Fuel type</td>
<td>$^{232}$Th-$^{233}$U mixed oxide</td>
</tr>
<tr>
<td>$^{233}$U enrichment [wt%]</td>
<td>8</td>
</tr>
<tr>
<td>Core height [mm]</td>
<td>3700</td>
</tr>
<tr>
<td>Core Diameter [mm]</td>
<td>4050</td>
</tr>
<tr>
<td>Coolant</td>
<td>D$_2$O</td>
</tr>
</tbody>
</table>

- The core is designed for power of 3.5GWt with cycle length of 1,300 days by 3 batch refueling.
- It is simple homogenous core without any blankets.
- The enrichment of U-233 is about 7-8 wt%.
Fuel specifications of PHBR

<table>
<thead>
<tr>
<th>Fuel assembly</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembly Type</td>
<td>Hexagonal</td>
</tr>
<tr>
<td>Number of fuel assemblies</td>
<td>282</td>
</tr>
<tr>
<td>Fuel Assembly Pitch [mm]</td>
<td>230</td>
</tr>
<tr>
<td>Number of fuel pins in an assembly</td>
<td>169</td>
</tr>
<tr>
<td>Pellet diameter of fuel pin [mm]</td>
<td>13.1</td>
</tr>
<tr>
<td>Outer diameter of fuel pin[mm]</td>
<td>14.5</td>
</tr>
<tr>
<td>Fuel pin gap [mm]</td>
<td>3.1</td>
</tr>
<tr>
<td>Fuel Pin Pitch [mm]</td>
<td>17.6</td>
</tr>
<tr>
<td>Cladding material</td>
<td>Zircaloy-4</td>
</tr>
</tbody>
</table>

- Hexagonal pin arrangement enables smaller MFR with large enough pin gap of >3 mm that facilitates heat removal.
Control rods

- 19 Control rods are arranged over the core.
- Those CR design is based on Monju.
- The total rod worth at fully inserted position evaluated as -6.5 %dk/k that is enough at cold zero power.
Cladding material integrity

- Evaluated fast neutron fluence: $2.87 \times 10^{22} \text{ n/cm}^2$
  - because of long cycle length ($1,300 \times 3$ days) with hard spectrum
  - Limitation for Zircaloy-4: $1.5 \times 10^{22} \text{ n/cm}^2$

Other cladding material that can withstand higher fluence with small $\sigma_a$ has to be employed.
Impacts of SiC clad. on $k_{eff}$ and CR
By changing cladding material to SiC, neutronic performances were improved.

<table>
<thead>
<tr>
<th></th>
<th>Zircaloy-4</th>
<th>SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burnup reactivity loss</td>
<td>%dk/kk’</td>
<td>-1.81</td>
</tr>
<tr>
<td>Control rod worth</td>
<td>%dk/kk’</td>
<td>13.58</td>
</tr>
<tr>
<td>Av. discharged burnup</td>
<td>GWd/ton</td>
<td>74.47</td>
</tr>
<tr>
<td>Fissile Inventory Ratio</td>
<td>–</td>
<td>1.039</td>
</tr>
</tbody>
</table>
Void reactivity coefficient

Zone wised local void coefficients at EOEC
Zircaloy case (%dk/kk’/%void)

<table>
<thead>
<tr>
<th>Zone</th>
<th>Inner core Zone (1st layer)</th>
<th>Middle core Zone (5th layer)</th>
<th>Outer core Zone (10th layer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper zone (360~370cm)</td>
<td>-2.58E-08</td>
<td>-1.23E-07</td>
<td>-8.32E-08</td>
</tr>
<tr>
<td>Middle zone (180~190cm)</td>
<td>+4.95E-08</td>
<td>-4.32E-07</td>
<td>-1.20E-06</td>
</tr>
<tr>
<td>Lower zone (0~10cm)</td>
<td>-2.58E-08</td>
<td>-1.21E-07</td>
<td>-8.52E-08</td>
</tr>
</tbody>
</table>

SiC case (%dk/kk’/%void)

<table>
<thead>
<tr>
<th>Zone</th>
<th>Inner core Zone (1st layer)</th>
<th>Middle core Zone (5th layer)</th>
<th>Outer core Zone (10th layer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper zone (360~370cm)</td>
<td>-3.74E-08</td>
<td>-1.48E-07</td>
<td>-7.48E-08</td>
</tr>
<tr>
<td>Middle zone (180~190cm)</td>
<td>-1.24E-07</td>
<td>-1.11E-06</td>
<td>-1.15E-06</td>
</tr>
<tr>
<td>Lower zone (0~10cm)</td>
<td>-3.54E-08</td>
<td>-1.48E-07</td>
<td>-7.87E-08</td>
</tr>
</tbody>
</table>

Coefficients are negative all over the core.
Neutron fluence and spectrum

<table>
<thead>
<tr>
<th>Zircaloy-4</th>
<th>Fast fluence</th>
<th>Limitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiC</td>
<td>$2.87 \times 10^{22}$</td>
<td>$&lt; 1.5 \times 10^{22}$</td>
</tr>
<tr>
<td></td>
<td>$2.88 \times 10^{22}$</td>
<td>$&lt; 8.0 \times 10^{22}$</td>
</tr>
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Deployment scenario

- **Current phase**
  - Natural uranium
  - UOX Fuel Fabrication → LWR → Reprocessing → Disposal
- **Transition phase**
  - Thorium
    - (Th,Pu)O\(_2\) Fuel Fabrication → (Th,Pu)O\(_2\) Fueled PHBR
    - Reprocessing → Disposal
- **Breeder phase**
  - Thorium
    - (Th,U-233)O\(_2\) Fuel Fabrication → (Th,U-233)O\(_2\) Fueled PHBR
    - Reprocessing → Disposal
Replacement of U-LWR by Th-HPWR

60GWe U-LWRs can be replaced within a century.
Reprocessing capacity and SF amount

Pu supply from LWR exhausted within a century.

Deployable capacity of PHBR depends on
- Pu stockpile
- Installed U-LWR capacity
- Reprocessing capacity
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Synergetic system with U-Pu reactors

- Sustainable energy system with matured plant technology
- Diversified fission resources
- Efficient MA transmutation & easier fuel handling (less heat)
- Better energy balance than ADS
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## Indice for difficulties in diversion

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<tr>
<th></th>
<th>Critical Mass</th>
<th>Enrichment technology</th>
<th>Implosion technology</th>
<th>Heat production</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-235</td>
<td>48kg</td>
<td>Required</td>
<td>Not required</td>
<td>None</td>
</tr>
<tr>
<td>Pu (Weapon grade)</td>
<td>10kg</td>
<td>Not required</td>
<td>Required</td>
<td>Small</td>
</tr>
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## Cost impact

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<th>Cost reduction factors</th>
<th>Cost increase factors</th>
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<tr>
<td>No need for enrichment (vs. LWR)</td>
<td>Heavy water coolant (vs. LWR)</td>
</tr>
<tr>
<td>Proven PWR plant technology (vs. FBR)</td>
<td>Tritium production (vs. LWR)</td>
</tr>
<tr>
<td>Cheaper resource (vs. UO$_2$ fuel)</td>
<td>Challenging reprocessing technology (vs. UO$_2$ fuel)</td>
</tr>
<tr>
<td></td>
<td>High gamma fuel handling (vs. UO$_2$ fuel)</td>
</tr>
</tbody>
</table>
Cost evaluation of PHBR

\[
\text{Generation cost} = \frac{\text{Fuel cost} + \text{Capital cost} + \text{O&M cost [yen]}}{\text{Generated energy [kWh]}}
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Assumed Values</th>
<th>Unit</th>
</tr>
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<tr>
<td>Power output</td>
<td>3450 MWe</td>
<td></td>
</tr>
<tr>
<td>Burnup</td>
<td>61.2 GWd/t</td>
<td></td>
</tr>
<tr>
<td>Cycle length</td>
<td>1,000 days</td>
<td></td>
</tr>
<tr>
<td>Cycle interval</td>
<td>30 days</td>
<td></td>
</tr>
<tr>
<td>Batch number</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Capacity factor</td>
<td>97%</td>
<td></td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Parameters assumed</th>
<th>Low</th>
<th>Nominal</th>
<th>High</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction</td>
<td>130</td>
<td>279</td>
<td>428</td>
<td>( \times 10^3 ) yen/kWe</td>
</tr>
<tr>
<td>Th Fuel</td>
<td>0.01</td>
<td>7.3</td>
<td>15.9</td>
<td>( \times 10^6 ) yen/ton</td>
</tr>
<tr>
<td>Fabrication</td>
<td>210</td>
<td>262</td>
<td>314</td>
<td>( \times 10^6 ) yen/tonHM</td>
</tr>
<tr>
<td>Reprocessing</td>
<td>210</td>
<td>262</td>
<td>314</td>
<td>( \times 10^6 ) yen/tonHM</td>
</tr>
</tbody>
</table>
**Generation cost**

LWR (5.3 yen/kWe)
Evaluated by FEPC in 2004.
Plant: 1300MWe PWR

FBR (2.6 yen/kWe)
Evaluated by JAEA in 2010.
Plant: 1500MWe MOX-FBR
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Remarks (1/2)

• Thorium resource is abundant but available fissile mass determines how many thorium reactors can be deployed.

\[ \text{Th reserves} \neq \text{Energy derived from thorium.} \]

• Pressurized heavy water breeder reactor (PHBR) with Th-U233 fuel shows breeding capability with high burnup (>60GWd/t) and negative void effect.

\[ \text{Tritium and ThO}_2\text{ reprocessing are tough challenges.} \]
• All LWRs can be replaced by PHBR by using Pu recovered from the LWR’s SF within a century.

  PHBR works both in transition and sustainable phase.

• Careful examination should be made for proliferation resistance of Th-cycle.

  Strong gamma ≠ High proliferation resistance.

• Generation cost of thorium fueled PHBR could be competitive with LWR owing to high BU and CF.

  Further study required to reduce uncertainty.
What I want to share

• Th shows some preferable characteristics but is **not magic fuel**.
  – It is basically the same as Uranium.

• Th reactor produces similar nuclear wastes if the cycle is not closed.
  – Closed cycle just minimizes the waste.

• Scientists must be humble, objective; mustn’t exaggerate.