Beam Window Design for ADS system in JAEA

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Introduction

- JAEA has investigated 800MWt LBE cooled Accelerator-Driven System (ADS) to transmute minor actinides (MA).
- Many inherent issues
  - Design of beam window
  - Accelerator reliability
  - LBE technology
  - Reactor physics with MA fuel
  - . . .
- Beam window will be used in the following severe condition
  - heat generation by proton beam
  - external pressure by LBE
  - creep deformation at high temperature
  - corrosion in LBE
  - irradiation damage
Previous study*

- Ellipse model
  - 235mm radius and 2mm thickness at the top

- It’s feasible, but more feasible concept (hemisphere, thicker) is required to mitigate the design condition

*: T. Sugawara, et al., JNST, 47 (10), 2010
To realize the small burnup reactivity, **subcriticality adjustment rod (SAR) is introduced to the ADS**

- Burnup analysis
- Particle transport analysis
- Thermal hydraulics analysis
- Structural analysis

→ **More feasible beam window concept**
Calculation condition

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal power</td>
<td>800 MWt</td>
</tr>
<tr>
<td>Coolant</td>
<td>LBE</td>
</tr>
<tr>
<td>Inlet temperature</td>
<td>300°C</td>
</tr>
<tr>
<td>Coolant velocity</td>
<td>2.0 m/sec</td>
</tr>
<tr>
<td>Upper limitation of keff</td>
<td>0.97</td>
</tr>
<tr>
<td>Operation period</td>
<td>600 EFPDs</td>
</tr>
<tr>
<td>Number of fuel assemblies</td>
<td>84</td>
</tr>
<tr>
<td>Pitch</td>
<td>233.9 mm</td>
</tr>
<tr>
<td>Width</td>
<td>232.9 mm</td>
</tr>
<tr>
<td>Number of fuel pins per assembly</td>
<td>391</td>
</tr>
<tr>
<td>Composition</td>
<td>(MA+Pu)N+ZrN</td>
</tr>
<tr>
<td>Pin outer diameter</td>
<td>7.65 mm</td>
</tr>
<tr>
<td>Thickness of cladding tube</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Pin pitch</td>
<td>11.48 mm</td>
</tr>
<tr>
<td>Active height</td>
<td>1000 mm</td>
</tr>
</tbody>
</table>
Calculation flow

- Burnup analysis
  - Proton beam current
  - Particle transport analysis
  - Heat generation distribution
  - Thermal hydraulics analysis
  - Temperature distribution
  - Structural analysis
    - Stress, strain, buckling pressure

Calculation code:
- ADS3D
- PHITS
- STAR-CCM+
- ANSYS
Burnup analysis

• ADS3D code* was employed
  • Neutron transport in 3D geometry (deterministic method) and burn-up calculation were performed

• Calculation condition
  • 3 SARs (B₄C type) were placed in fuel region
  • To prevent the SAR drawing, tungsten block was added to the SAR.
  • All SARs were drawn 20cm by each 100days during the operation

*: T. Sugawara, et al., JNST, 53, 12, 2016
Results

• The k-eff value would be maintained 0.97 during the cycle because it is possible to move SARs by mm/sec unit.
• This concept could maintain the proton beam current about 10mA (20mA in the previous study)
Particle transport analysis

- PHITS code was employed.
- Gaussian profile was assumed.

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<tr>
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<th>This study</th>
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<tbody>
<tr>
<td>Proton beam energy [GeV]</td>
<td>1.5</td>
<td>←</td>
</tr>
<tr>
<td>Proton beam current [mA]</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Beam duct radius [mm]</td>
<td>235</td>
<td>←</td>
</tr>
<tr>
<td>Shape of beam window</td>
<td>Ellipse</td>
<td><strong>Hemispherical</strong></td>
</tr>
<tr>
<td>Thickness of beam window at top [mm]</td>
<td>2.0</td>
<td>←</td>
</tr>
<tr>
<td>Thickness of beam duct [mm]</td>
<td>10.0</td>
<td>←</td>
</tr>
<tr>
<td>1σ of Gaussian profile for proton beam [mm]</td>
<td>111.6</td>
<td>←</td>
</tr>
</tbody>
</table>

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Results

- The maximum heat density was about 40 W/cc/mA in the spallation target.
- The heat density at the top of the beam window was 27 W/cc/mA.

Fig. Heat generation distribution in target region

Fig. Heat generation distribution in beam window
Thermal hydraulics analysis

• STAR-CCM+ code was employed

LBE velocity at the inlet: 2.0 m/sec
LBE temperature at the inlet: 300 °C
Turbulence model: k-ԑ model
Material of beam window: T91 steel

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Results

- The maximum temperature in the beam window was 409°C (516°C in previous study)
- The maximum difference of the temperature in the beam window was 27°C (55°C in previous study)
Structural analysis

• ANSYS code was employed

• Parametric survey was performed by changing the thickness (1-4 mm) of beam window.

• Approximate value derived from the following equation was used.

\[ T(t) = T_0 + Q(r) \left( \frac{t_0^2}{2} \right) \left( 1 - \left( \frac{t}{t_0} \right)^2 \right) / \lambda \]

T: Temperature at thickness t, To: Temperature at outer surface
Q(r): Heat generation density at r, t₀: Thickness
λ: Thermal conductivity
Results

- Maximum temperature was less than 500°C even if t=4 mm
- Von Mises stresses of all cases satisfied the criteria 3Sm
- The buckling pressure with 4 mm thickness was 3.6 times larger than the value with 2 mm thickness

→ Non-linear buckling analysis is required as the future work
### Summary

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</tr>
<tr>
<td>Proton beam current [mA]</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Number of SAR</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Beam duct radius [mm]</td>
<td>235</td>
<td>⇐</td>
</tr>
<tr>
<td>Shape of beam window</td>
<td>Ellipse</td>
<td>Hemispherical</td>
</tr>
<tr>
<td>Thickness of beam window at top [mm]</td>
<td>2.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Buckling pressure</td>
<td>4.1 [MPa]*</td>
<td>More than 3.6 times larger**</td>
</tr>
</tbody>
</table>

*: by non-liner buckling analysis
**: by liner buckling analysis
Concluding remarks

• To realize the small burnup reactivity, subcriticality adjustment rod (SAR) is introduced to the ADS.
• Maximum proton beam current was reduced from 20 to 10 mA by the use of 3 SARs.
• Through the coupling analyses, more feasible beam window concept (hemispherical shape, 4 mm thickness) was presented.

Acknowledgement
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