Evaluation of Transmutation Performances of TRU and LLFPs with a Super Fast Reactor

Haoliang Lu
Nuclear Professional School, the University of Tokyo
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The present study is the result of “Research and Development of the Super Fast Reactor” entrusted to The University of Tokyo by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT).
Overview

Geological disposal: to protect human health and the environment and to limit the burdens on future generations

- Igneous event
- Seismic event
- Cracks in waste package outer barrier
- General corrosion
Overview

Radionuclides contributing to total mean dose at 10000 years

\[ \text{Mean Annual Dose [mrem]} \]

\[ \text{Times [years]} \]

\[ \text{Joonhong Ahn, Human Environmental Design Studio, 2008.} \]

2009-3-12
Overview

Radionuclides contributing to total mean dose at 1 million years

\[\text{Overview}\]

Radionuclides contributing to total mean dose at 1 million yearsa

\[\text{Mean Annual Dose [mrem]}\]

\[\text{Times [years]}\]

\[\text{a: Joonhong Ahn, Human Environmental Design Studio, 2008.}\]
Overview

Recycling:

<table>
<thead>
<tr>
<th></th>
<th>MOX</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{239}\text{Pu}$, $^{240}\text{Pu}$, $^{241}\text{Pu}$, $^{242}\text{Pu}$</td>
<td></td>
</tr>
<tr>
<td>Minor Actinides (MA), such as $^{237}\text{Np}$, $^{241}\text{Am}$, $^{243}\text{Am}$, $^{244}\text{Cm}$, $^{245}\text{Cm}$</td>
<td>transmutation</td>
</tr>
<tr>
<td>Long Lived Fission Products (LLFPs), such as $^{99}\text{Tc}$, $^{129}\text{I}$, $^{135}\text{Cs}$, $^{90}\text{Sr}$, $^{79}\text{Se}$</td>
<td>transmutation</td>
</tr>
</tbody>
</table>
Overview

Super Fast Reactor (Super FR)

- Coolant is supercritical water: a relatively hard neutron spectrum in the seed assembly for MA transmutation
- Introduction of ZrH layer: a soft neutron spectrum for fuel in the blanket assembly for LLFPs transmutation
Overview

Evaluation of back end risk in Super FR

$^{135}\text{Cs}$: Toxicity is in direct proportion to the inventory

$^{237}\text{Np}$: Toxicity can be decreased only when the inventory is less than its solubility

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2009-3-12
Outline

Part 1: Transmutation of TRU

1. Selection of TRU
2. Analytic method and codes
3. Analysis of the transmutation capability
4. Effect of MA loading on the core performance

Part 2: Transmutation of LLFPs

1. Isotope selection
2. Computational model and method utilized
3. Transmutation of $^{99}$Tc and $^{129}$I
4. Transmutation of $^{135}$Cs

Conclusion
Part 1

Transmutation of TRU
Transmutation of TRU

Selection of TRU (1)

→ high yield

Composition of spent nuclear fuel (standard PWR 33GW/t, 10-year cooling)\(^a\)

1 tonne of SNF contains:
- 955.4 kg U
- 8.5 kg Pu
- Minor actinides (MAs)
  - 0.5 kg \(^{237}\text{Np}\)
  - 0.6 kg Am
  - 0.02 kg Cm
- Long-lived fission products (LLFPs)
  - 0.2 kg \(^{129}\text{I}\)
  - 0.8 kg \(^{99}\text{Tc}\)
  - 0.7 kg \(^{93}\text{Zr}\)
  - 0.3 kg \(^{135}\text{Cs}\)
- Short-lived fission products (SLFPs)
  - 1 kg \(^{137}\text{Cs}\)
  - 0.7 kg \(^{90}\text{Sr}\)
- Stable isotopes
  - 10.1 kg lanthanides
  - 21.8 kg other stable

\(^a\): NEA, Physics and Safety of Transmutation Systems, 2006.
Transmutation of TRU

Selection of TRU (2)

- high radioactivity and long half-life

Main properties of transurianium isotopes

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}$Pu</td>
<td>$9.79 \times 10^9$</td>
<td>87.4</td>
<td>$^{237}$Np</td>
<td>$2.31 \times 10^{10}$</td>
<td>$2.14 \times 10^6$</td>
</tr>
<tr>
<td>$^{239}$Pu</td>
<td>$8.79 \times 10^{10}$</td>
<td>$2.44 \times 10^4$</td>
<td>$^{241}$Am</td>
<td>$5.75 \times 10^{12}$</td>
<td>433</td>
</tr>
<tr>
<td>$^{240}$Pu</td>
<td>$3.59 \times 10^{11}$</td>
<td>6580</td>
<td>$^{242m}$Am</td>
<td>$5.04 \times 10^9$</td>
<td>141</td>
</tr>
<tr>
<td>$^{241}$Pu</td>
<td>$1.13 \times 10^{10}$</td>
<td>14.98</td>
<td>$^{243}$Am</td>
<td>$7.18 \times 10^{11}$</td>
<td>7370</td>
</tr>
<tr>
<td>$^{242}$Pu</td>
<td>$3.82 \times 10^{8}$</td>
<td>$3.869 \times 10^5$</td>
<td>$^{244}$Cm</td>
<td>$1.13 \times 10^{10}$</td>
<td>18.11</td>
</tr>
</tbody>
</table>

$^{239}$Pu, $^{240}$Pu, $^{241}$Pu, $^{242}$Pu, $^{237}$Np, $^{241}$Am, $^{242m}$Am and $^{243}$Am were selected.
Transmutation of TRU

Analytic method and codes (1)

**SWAT (JENDL-3.2):**
- an integrated system developed for analyses of the post irradiation examination, the transmutation of radioactive waste and the burn-up credit problem;
- a combination of the SRAC code for the cell calculation and the ORIGEN code for the burn-up calculation.

**SRAC (JENDL-3.3, 2003/4/24):**
- a code system applicable to neutronics analysis of a variety of reactor types.

**ORIGEN:**
- widely used for the evaluation of the fuel characteristics;
- a burn-up code with a very simple algorithm of the one-group energy theory;
- can treat a very large number of nuclides around 1000.
Transmutation of TRU

Analytic method and codes (2)

- **SWAT:**
  Form the relationship table between nuclide density and burnup

- **SRAC:**
  Obtain the node-wide burnup distribution at EOEC

- **Transmuted amount:**
  Interpolate the node-wise burnup by this relationship table

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A coupling scheme of transmutation calculation

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*a:* LZ, Cao. 16th Pacific Basin Nuclear Conference (16PBNC), 2008, P16P1293.
Transmutation of TRU

Analysis of the transmutation capability (1)

Case 1: Pu incineration capability of a reference core design

To evaluate the consumption amount of Pu and accumulation amount of MA without MA loading

Case 2: Homogeneous loading of MA in the seed assembly

To evaluate the performance with the maximum fraction of MA loading

Case 3: 5% of MA loaded in the seed assemblies and pure MA loaded in the blanket assembly

To improve the transmutation performance
## Transmutation of TRU

### Analysis of the transmutation capability (2)

#### Comparison of the transmutation performance\(^a\)

<table>
<thead>
<tr>
<th></th>
<th>Case 1 (0%MA)</th>
<th>Case 2 (4%MA)</th>
<th>Case 3 (5%MA+BLMA)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\Delta m) (Kg)</td>
<td>SF*</td>
<td>(\Delta m) (Kg)</td>
</tr>
<tr>
<td>(^{239}\text{Pu})</td>
<td>-208.77</td>
<td></td>
<td>-202.75</td>
</tr>
<tr>
<td>(^{240}\text{Pu})</td>
<td>-22.77</td>
<td></td>
<td>-22.79</td>
</tr>
<tr>
<td>(^{241}\text{Pu})</td>
<td>-8.73</td>
<td></td>
<td>-9.20</td>
</tr>
<tr>
<td>(^{242}\text{Pu})</td>
<td>-0.15</td>
<td></td>
<td>-0.97</td>
</tr>
<tr>
<td>Pu (Total)</td>
<td>-239.92</td>
<td>2.2</td>
<td>-233.77</td>
</tr>
<tr>
<td>(^{237}\text{Np})</td>
<td>0.51</td>
<td></td>
<td>-16.12</td>
</tr>
<tr>
<td>(^{241}\text{Am})</td>
<td>9.55</td>
<td></td>
<td>-1.63</td>
</tr>
<tr>
<td>(^{242m}\text{Am})</td>
<td>0.12</td>
<td></td>
<td>1.24</td>
</tr>
<tr>
<td>(^{243}\text{Am})</td>
<td>4.88</td>
<td></td>
<td>-0.54</td>
</tr>
<tr>
<td>MA (Total)</td>
<td>15.06</td>
<td></td>
<td>-17.05</td>
</tr>
<tr>
<td>TRU(MA+Pu)</td>
<td>-224.86</td>
<td>1.8</td>
<td>-250.82</td>
</tr>
</tbody>
</table>

*SF(supporting factor): relative to the yield amount of a PWR with the same power in the same duration

\(^a\): LZ, Cao. 16th Pacific Basin Nuclear Conference (16PBNC), 2008, P16P1293.
Effect of MA loading on the core performance

Comparison of the core characteristics\textsuperscript{a}

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant outlet temperature [°C]</td>
<td>502.5</td>
<td>509.6</td>
</tr>
<tr>
<td>Maximum cladding surface temperature [°C]</td>
<td>635.7</td>
<td>642.3</td>
</tr>
<tr>
<td>Flow rate [kg/s]</td>
<td>820.5</td>
<td>824.9</td>
</tr>
<tr>
<td>Coolant void reactivity [%dk/k]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BOEC</td>
<td>-0.839</td>
<td>-0.992</td>
</tr>
<tr>
<td>EOEC</td>
<td>-1.712</td>
<td>-0.289</td>
</tr>
</tbody>
</table>

\textsuperscript{a}: LZ, Cao. 16th Pacific Basin Nuclear Conference (16PBNC), 2008, P16P1293.
Part 2
Transmutation of LLFPs
Transmutation of LLFPs

Selection of LLFPs

Transmutation capability

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Capture cross section [barn]</th>
<th>Decay half-life [y]</th>
<th>Effective Transmutation half-life [y]</th>
<th>Yield in a PWR [kg/GWe-yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fast spectrum</td>
<td>Thermal spectrum</td>
<td>Fast spectrum</td>
<td>Thermal spectrum</td>
</tr>
<tr>
<td>79Se</td>
<td>0.002</td>
<td>0.33</td>
<td>6.5E+4</td>
<td>1.1E+4</td>
</tr>
<tr>
<td>90Sr</td>
<td>0.01</td>
<td>0.08</td>
<td>29</td>
<td>2.2E+4</td>
</tr>
<tr>
<td>93Zr</td>
<td>0.09</td>
<td>1.03</td>
<td>1.5E+5</td>
<td>244</td>
</tr>
<tr>
<td>94Nb</td>
<td>0.22</td>
<td>4.22</td>
<td>2.0E+4</td>
<td>100</td>
</tr>
<tr>
<td>99Tc</td>
<td>0.45</td>
<td>9.32</td>
<td>2.1E+5</td>
<td>49</td>
</tr>
<tr>
<td>107Pd</td>
<td>0.53</td>
<td>2.79</td>
<td>6.5E+6</td>
<td>42</td>
</tr>
<tr>
<td>126Sn</td>
<td>0.007</td>
<td>0.03</td>
<td>1.0E+5</td>
<td>3.1E+3</td>
</tr>
<tr>
<td>129I</td>
<td>0.35</td>
<td>3.12</td>
<td>1.6E+7</td>
<td>63</td>
</tr>
<tr>
<td>135Cs</td>
<td>0.07</td>
<td>2.48</td>
<td>2.3E+6</td>
<td>314</td>
</tr>
<tr>
<td>137Cs</td>
<td>0.01</td>
<td>0.03</td>
<td>30</td>
<td>2.2E+3</td>
</tr>
<tr>
<td>151Sm</td>
<td>2.09</td>
<td>660</td>
<td>89</td>
<td>11</td>
</tr>
</tbody>
</table>


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Transmutation of LLFPs

Selection of LLFPs

Isotopic separation requirement

- $^{99}$Tc: not require isotopic separation
- $^{129}$I: not strongly require isotopic separation
- $^{94}$Nb, $^{107}$Pd, $^{135}$Cs, $^{151}$Sm: require isotopic separation due to lower weight fraction

Isotope properties of some LLFPs

<table>
<thead>
<tr>
<th>Element</th>
<th>Isotopic composition (weight percent [%]; capture cross section [barn])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb</td>
<td>$^{93}$Nb(90.0; 0.41), $^{94}$Nb(10.0; 4.22)</td>
</tr>
<tr>
<td>Tc</td>
<td>$^{98}$Tc(0.0008, not available), $^{99}$Tc(99.9992; 9.32)</td>
</tr>
<tr>
<td>Pd</td>
<td>$^{104}$Pd(18.75; 0.66), $^{105}$Pd(32.84; 3.79), $^{106}$Pd(15.54; 0.28), $^{107}$Pd(19.47; 2.79), $^{108}$Pd(13.38; 7.08), $^{109}$Pd(0.02; 0.28)</td>
</tr>
<tr>
<td>I</td>
<td>$^{127}$I(22.98; 4.89), $^{129}$I(77.02; 3.12)</td>
</tr>
<tr>
<td>Cs</td>
<td>$^{133}$Cs(76.41; 10.6), $^{134}$Cs(0.292; 11.3), $^{135}$Cs(16.83; 2.48), $^{137}$Cs(6.47; 0.03)</td>
</tr>
<tr>
<td>Sm</td>
<td>$^{150}$Sm(63.90; 14.8), $^{151}$Sm(2.55; 660), $^{152}$Sm(26.27; 74.5), $^{154}$Sm(7.28; 1.51)</td>
</tr>
</tbody>
</table>

Transmutation of LLFPs

Selection of LLFPs

- Repository impact

- $^{99}$Tc and $^{129}$I are soluble in the groundwater and hardly sorbed by the rocks

- The groundwater transport of $^{135}$Cs can be retarded due to its sorption on rock

- According to the back end risk evaluation, the transmutation of $^{135}$Cs is very important and necessary

*: NAGASAKI Shinya. Backend risk evaluation, the 14th report of the construction of the plant concept, the 3rd meeting for the super critical pressure light water cooled reactor, 2008.
Transmutation of LLFPs

Computational model and method utilized

Obtain the burn-up for each assembly by the whole core calculation

Make a table between the density of isotopes and burn-up for each transmuted assembly by pin cell calculation

Obtain the transmuted amount
Transmutation of LLFPs

Transmutation of $^{99}\text{Tc}$ and $^{129}\text{I}$ (1)

Four criteria: (1) Minimizing space-volumes for loading  (2) Decrease capture of parasitic neutrons  (3) Melting point  (4) Compatibility with cladding

Material form for $^{99}\text{Tc}$: Metallic form (melt temperature is 2250°C, no gas production, no material compatibility problem between $^{99}\text{Tc}$ and cladding)

Material form for $^{129}\text{I}$: CuI (insoluble in water and stable in air, introduce a Cu liner to avoid strong corrosion between the cladding and fuel under irradiation conditions)

<table>
<thead>
<tr>
<th>Metal iodide</th>
<th>Melting temperature [$^\circ\text{C}$]</th>
<th>Density of metal iodide [g/cm$^3$]</th>
<th>Density of iodine [g/cm$^3$]</th>
<th>Initial loaded amount [kg]</th>
<th>Transmutation rate [%/yr]</th>
<th>Transmuted amount [kg/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaI</td>
<td>661</td>
<td>3.67</td>
<td>3.10</td>
<td>1287</td>
<td>1.176</td>
<td>15.1</td>
</tr>
<tr>
<td>CaI$_2$</td>
<td>783</td>
<td>4.01</td>
<td>3.46</td>
<td>1435</td>
<td>1.198</td>
<td>17.2</td>
</tr>
<tr>
<td>MgI$_2$</td>
<td>633</td>
<td>4.43</td>
<td>4.04</td>
<td>1673</td>
<td>1.215</td>
<td>20.3</td>
</tr>
<tr>
<td>CuI</td>
<td>595</td>
<td>5.62</td>
<td>3.75</td>
<td>1556</td>
<td>1.454</td>
<td>22.6</td>
</tr>
</tbody>
</table>
Transmutation of LLFPs

Transmutation of $^{99}\text{Tc}$ and $^{129}\text{I}$ (2)

For $^{99}\text{Tc}$:

- be loaded homogeneously by commingling it with fuel
- Reduce the effect of self-shielding by mixing
- Enhance the thermal conductivity of fuel due to the high thermal conductivity of $^{99}\text{Tc}$

Geometry of blanket assembly
Transmutation of LLFPs

Transmutation of $^{99}\text{Tc}$ and $^{129}\text{I}$ (3)

For $^{129}\text{I}$:

- CuI is used and mixed with fuel to reduce the self-shielding
- Including both $^{127}\text{I}(23.7\%)$ and $^{129}\text{I}(76.3\%)$ to avoid the expense of isotopic separation
- Annular target material enclosing moderator is utilized in the target assembly
  - make the effective capture cross-section be slightly larger due to more reduced self-shielding effect
  - reduced the local peaking power substantially due to the filtering of thermal neutrons
- Using a copper-liner at the inside of cladding to prevent corrosion

Geometry of the target pin loaded with I
Transmutation of LLFPs

Transmutation of $^{99}$Tc and $^{129}$I (4)

Comparison of the results

<table>
<thead>
<tr>
<th>Reactor type</th>
<th>$^{99}$Tc</th>
<th></th>
<th>$^{129}$I</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast reactor</td>
<td>5.0</td>
<td>54.4</td>
<td>2.59</td>
<td>7.4</td>
</tr>
<tr>
<td>BWR</td>
<td>4.4</td>
<td>-</td>
<td>-</td>
<td>1.42</td>
</tr>
<tr>
<td>LWR</td>
<td>3.6</td>
<td>-</td>
<td>-</td>
<td>1.4</td>
</tr>
<tr>
<td>Super FR</td>
<td>5.36</td>
<td>247.8</td>
<td>11.8</td>
<td>2.79</td>
</tr>
</tbody>
</table>

*SF (supporting factor): relative to the yield amount of a PWR with the same power in the same duration

The transmuted amounts are also larger than the yields in Super FR, which are 18.05kg for $^{99}$Tc and 5.77kg for $^{129}$I.
## Transmutation of LLFPs

### Transmutation of $^{99}$Tc and $^{129}$I (5)

#### Comparison of the core characteristics

<table>
<thead>
<tr>
<th></th>
<th>Reference core</th>
<th>Core loading with Tc</th>
<th>Core loading with I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant outlet temperature [$^\circ$C]</td>
<td>502.5</td>
<td>510.8</td>
<td>509.6</td>
</tr>
<tr>
<td>Maximum cladding surface temperature [$^\circ$C]</td>
<td>635.7</td>
<td>637.9</td>
<td>637.9</td>
</tr>
<tr>
<td>Average discharged burnup [Mwd/kgHM]</td>
<td>72.98</td>
<td>72.92</td>
<td>72.99</td>
</tr>
<tr>
<td>Maximum local void reactivity [pcm]</td>
<td>BOEC -21.5</td>
<td>-37.8</td>
<td>-25.1</td>
</tr>
<tr>
<td></td>
<td>EOEC -19.1</td>
<td>-17.1</td>
<td>-8.8</td>
</tr>
</tbody>
</table>
Transmutation of LLFPs

Transmutation of $^{135}$Cs (1)

Isotopic composition of Cs isotopes in the spent fuel for different types of reactor

<table>
<thead>
<tr>
<th></th>
<th>PWR</th>
<th>LMFBR</th>
<th>Super FR</th>
<th>Thermal capture cross section [barn]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight fraction [%]</td>
<td>Yield [kg/GW·yr]</td>
<td>Weight fraction [%]</td>
<td>Yield [kg/GW·yr]</td>
<td></td>
</tr>
<tr>
<td>$^{133}$Cs</td>
<td>76.41</td>
<td>34.19</td>
<td>32.3</td>
<td>-</td>
</tr>
<tr>
<td>$^{134}$Cs</td>
<td>0.292</td>
<td>0.13</td>
<td>0.6</td>
<td>-</td>
</tr>
<tr>
<td>$^{135}$Cs</td>
<td>16.83</td>
<td>7.53</td>
<td>37.4</td>
<td>-</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>6.47</td>
<td>2.89</td>
<td>29.7</td>
<td>-</td>
</tr>
</tbody>
</table>

Nuclear reaction chain for cesium isotopes

$^{133}$Cs (stable)$^\Rightarrow$$^{134}$Cs (2.0648y)$^\Rightarrow$$^{135}$Cs (2.3×10⁶y)$^\Rightarrow$$^{136}$Cs (13.16d)$^\Rightarrow$$^{137}$Cs (30.07y)$^\Rightarrow$$^{134}$Ba (stable)$^\Rightarrow$$^{136}$Ba (stable)$^\Rightarrow$$^{137}$Ba (stable)

Cs$_2$CrO$_4$ (2.97g/cm$^3$) $>$ CsCl (2.63g/cm$^3$)
Transmutation of $^{135}$Cs (2)

The neutron moderator by hydride is too strong. Weak moderator can be used to

- Make the capture cross-section of $^{135}$Cs meaningful magnitude compared to those of $^{133}$Cs and $^{134}$Cs
- Suppress the decreasing in neutron flux level

Transmutation of $^{135}$Cs (2)

Transmutation of $^{135}$Cs (3)

Delay the element-wise cesium

$^{137}$Cs $\rightarrow$ $^{137}$Cs + $^{137}$Ba

Half-life is 30y
After 90y delay

Weight fraction:
$^{137}$Cs: 29.6%
$^{135}$Cs: 40.2%

Weight fraction:
$^{137}$Cs: 5.00%
$^{135}$Cs: 54.2%

Transmuted amount: 4.34kg
Transmutation rate: 1.65%

Transmuted amount: 5.25kg
Transmutation rate: 1.49%

21% increment for transmuted amount
Transmutation of LLFPs

Transmutation of $^{135}$Cs (4)

Three rings’ target assemblies were loaded in the core to improve the transmuted amount of $^{135}$Cs. The transmuted amount is 18.2kg, transmutation rate is 0.53%.

\[
\text{Produced amount of } ^{135}\text{Cs (7.5kg) in LWR} = 2.4 \quad < \quad \text{Produced amount of } ^{135}\text{Cs (36.8kg) in SFR}
\]

The core with 3 rings’ target assemblies
# Transmutation of LLFPs

## Transmutation of $^{135}$Cs (5)

Comparison of the core characteristics

<table>
<thead>
<tr>
<th></th>
<th>Reference core</th>
<th>Transmutation core loaded with Cs (3 rings)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant outlet temperature [°C]</td>
<td>502.5</td>
<td>498.9</td>
</tr>
<tr>
<td>Maximum cladding surface temperature [°C]</td>
<td>635.7</td>
<td>637.0</td>
</tr>
<tr>
<td>Average discharged burnup [Mwd/kgHM]</td>
<td>72.98</td>
<td>72.70</td>
</tr>
<tr>
<td>Maximum local void reactivity [pcm] BOEC</td>
<td>-21.5</td>
<td>-11.8</td>
</tr>
<tr>
<td></td>
<td>BOEC</td>
<td>-19.1</td>
</tr>
<tr>
<td></td>
<td>EOEC</td>
<td>-2.0</td>
</tr>
</tbody>
</table>
Conclusion

- A supporting factor of 2.1 can be achieved for TRU;

- For the transmutation of $^{99}$Tc and $^{129}$I, the supporting factors of 11.8 and 6.2 can be achieved respectively;

- For the transmutation of $^{135}$Cs, a supporting factor larger than 2 can be achieved by loading three rings’ target assemblies in the core’s reflector region, but the transmuted amount is still less than the yield of Super FR;

- The yields of $^{237}$Np, $^{241}$Am, $^{243}$Am, $^{99}$Tc and $^{129}$I in Super FR can be incinerated completely.