Article 4: Fuel analysis

Victor Cabello, Piotr Dobrzynski, Zhakuoi Fang, Michal Jaros, Aurelien Mattei
Introduction

- PWR civil marine core 333 MWth for the long operation (20 years)
- Comparasion between two designs
  - Uniform 15% U-235 enriched UO₂
  - Checkerboard configuration with 18% enriched micro-heterogeneous ThO₂-UO₂ duplex fuel
- Political and technical issues
- Scope
  - Fissile loading
  - Neutronic analysis of burnable poisons, control rods and core loading patterns
Design methods

- A circular core optimizes the neutron leakage
- 112 assemblies with a 13x13 subassembly arrangement
  - WIMS-10 used for subassembly design analysis
  - PANTHER used for the whole core design
- Layout of the checkerboard composition and fuel design
Burnable poison design

- Use of soluble boron is not possible
- A thin ZrB$_2$ coating on the UO$_2$ pellet is the optimal design (IFBA)
  - 95% enriched B-10 is used
  - High thickness is used 150 $\mu$m instead of standard 590 nm due to previous calculations
  - 95% interception of incident neutrons
- Comparison between 5 numbers of IFBA rods in the assembly for both designs
  - 29 IFBA pins
  - 33 IFBA pins
  - 37 IFBA pins
  - 41 IFBA pins
  - 45 IFBA pins
Comparison between the number of pins

- Increase in the number of pins leads to higher poison longevity and initial reactivity suppression
Comparison between the number of pins

- Checkerboard fuel exhibits smaller swing for less than 37 IFBA pins due to the enhanced breeding of fissile material (U-233).

- Due to the high neutron absorption effectiveness, with the higher number of pins, the beneficial build-up of U-233 is delayed.

- Checkerboard design outperforms UO2 in terms of reactivity hold-down.
Analysis of IFBA thickness effect

- An additional optimization is made in order to obtain the minimum $k_\infty$ at the BOL while maintaining $k_\infty > 1$ during the whole cycle.

- 41 pins with 205 $\mu$m is chosen as best design for both cases.

- An additional effect occurs - pins coated in poison have higher fissile content during MOL and EOL, allowing the assembly to stay critical for more time.
Control rod design

- For lower fuel or moderator temperatures, the reactivity is increased.
- These low-power conditions have to be taken into account for a rapid shutdown.

Consequently, the required reactivity worth of the control bank is ~0.33.
Control rod material

- Hafnium, boron carbide and an Ag-In-Cd alloy are compared as CR materials.
- The 20-rod bank worth at full insertion is evaluated:

<table>
<thead>
<tr>
<th>Material</th>
<th>$\Delta \rho$(Checkerboard)</th>
<th>$\Delta \rho$(UO$_2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hafnium</td>
<td>0.208</td>
<td>0.203</td>
</tr>
<tr>
<td>$\text{B}_4\text{C}$</td>
<td>0.333</td>
<td>0.326</td>
</tr>
<tr>
<td>Ag-In-Cd</td>
<td>0.207</td>
<td>0.202</td>
</tr>
</tbody>
</table>

The worth of $\text{B}_4\text{C}$ rods is way greater, hence this material is chosen as an absorber in the CR.
Whole-Core Analysis

- To assess the effects of neutron leakage and spatial flux dependence
- 112 assemblies divided into three radial zones A, B and C
- Radial zoning pattern: BP-zoning (Burnable Poisons)

<table>
<thead>
<tr>
<th>Zone</th>
<th>LBL*</th>
<th>HBL**</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>33</td>
<td>41</td>
</tr>
<tr>
<td>B</td>
<td>17</td>
<td>33</td>
</tr>
<tr>
<td>C</td>
<td>9</td>
<td>25</td>
</tr>
</tbody>
</table>

*LBL – lower BP loading
**HBL – higher BP loading
One of the main objectives: to keep the radial form factor (RFF) below 1.55 throughout the core life.

The graph shows the Radial Form Factor (RFF) over time for different core configurations:
- U-LPL
- U-HPL
- CHK-LPL
- CHK-HPL
- Limit

The HBL scheme is below the required limit, indicating that the ratio of the maximum channel power to the average channel power across the reactor core is within acceptable limits.

U – core with all-UO₂ fuel
CHK – core with checkboard fuel
Whole-Core Analysis

- $k_{\text{eff}}$ over time for the radial-zoning core loading pattern:

- Lower BP loading $\Rightarrow$ 7% longer core life (23 vs. 21.5 years)
- Checkboards cores exhibit 2% longer core life compared to the UO$_2$ cores

Higher thermal “fertile capture-to-fissile absorption ratio” of CHK $\Rightarrow$ efficient breeding of U-233
Whole-Core Analysis

- Negative FTC
- Values in checkerboard more negative than that in UO2 (due to Th-232)
Whole-Core Analysis

- MTC more negative in checkerboard core until 20 years
- MTC decreases with burnup
Conclusions

- Less burnable absorber for checkerboard;
- Easier reactivity control for checkerboard;
- Greater worth of control rods for checkerboard;
- BP-zoning can meet the required core lifetime while maintaining reasonable values for the neutronic safety parameters for both cores;
- Longer core lifetime for checkerboard;
- Further analysis for checkerboard required in the future