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Towards Analysis of the Bowing Effect on Burnt Nuclear Fuel Compositions Using SERPENT

Assembly bow (PWR) and Channel bow (BWR) are widely observed

- Handling Difficulties
  - Incomplete control rod insertion
  - Axial offset anomaly

- Fuel / Reactor Simulations
  - Variation on moderation
    - Neutron spectrum
    - Isotopic concentrations
    - Fuel burn-up

- Computational Biases
  - Not take into account bowing effect
  - Biases between Post Irradiation Examination (PIE) simulations and measurements
Objectives

- Develop a methodology to investigate bowing effects
  - Use SERPENT Monte Carlo Continuous-Energy Depletion Code
  - Subdivide depletion zones for details
  - Compare the difference of isotopic concentrations

- Assess the capability of 3D modelling and SERPENT depletion calculation
  - 3D advanced and complicated modelling
  - Computational resource and time demanding
    - Neutron histories / Model size / Depletion zones
  - Study neutron source convergence

- Approach a preliminary simulation of bowing effects
  - On moderation
  - On isotopic concentrations
  - Against burn-up

- Quantify Numerical Bias for possible safety analyses
  - Optimize computational simulation models
Bow Mechanism

- Axial Compressive forces + Irradiation growth & Creep
  - Axial Load
  - Guide tube & Fuel pin

- S – shape and C – shape Assembly bow

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Fig. 1 – Load sharing and fuel rod growth - Ref. [1]

Fig. 2 – S-shape and C-shape assembly bow examples - Ref. [2]

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Methodology and Modelling

- Modelling 3D Fuel bow
  - Simplified into 3x3 pin lattice
  - Subdivide into 4320 depletion zones \([20 \times 3 \times 8 \times 9]\)
  - Max displacement is 1.5 mm \([5^{th}, 16^{th} \text{ layers}]\)
  - Two simulations (Nominal & Deformed)
    - \(\text{Rel. Diff} = \frac{C_D(i) - C_N(i)}{C_N(i)}, \ i = U^{235}, Pu^{239} \ldots\)

- Operational conditions

<table>
<thead>
<tr>
<th>Enrichment</th>
<th>Temperature</th>
<th>Power</th>
<th>Neutrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 w/o</td>
<td>900 K (Fuel)</td>
<td>0.025 KW/g</td>
<td>10,000 (per cycle)</td>
</tr>
<tr>
<td></td>
<td>600 K (Water)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Act. Cycles</th>
<th>Inact. Cycles</th>
<th>Burn-up step</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>25</td>
<td>0.5 MWd/kgU</td>
</tr>
</tbody>
</table>
Relative Diff. of Azimuthal U\textsuperscript{235} Concentration

Azimuthal U\textsuperscript{235} Concentration Relative Difference

U\textsuperscript{235} – 16\textsuperscript{th} layer

- **Left side:**
  - Enhance moderation
  - Less U\textsuperscript{235} remains

- **Right Side:**
  - Reduce moderation
  - More U\textsuperscript{235} remains

- **Total Effect:**
  - Cancel out?
Relative Diff. of Axial U\textsubscript{235} Concentration

\(U^{235}\) Relative Difference vs Burn-up

\(U^{235}\) – Full Life (0 – 40 MWd/kgU)
- Positive: 4\textsuperscript{th}, 5\textsuperscript{th}, 15\textsuperscript{th}, 16\textsuperscript{th}
- Indication: More U235 remains in bow
Convergence and Asymmetry problems

- **Asymmetry**
  - Symmetric conditions leading to asymmetry results
  - Asymmetry oscillates with burn-up
  - Asymmetry variation amplitude larger than relative differences

- **Reasons**
  - **Neutron source not converged in the full-size scale model**
  - Axial power perturbation accumulates -> depends on burn-up increment
  - Power uncertainty is larger towards two ends (**1.5%**) than the center (**0.3%**) 

- **Solutions**
  - Short length fuel model
  - More neutron histories -> limited by computational power
  - Alter S-shape to C-shape (change point symmetry to plane symmetry)
Solution I: Short Fuel Model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>32cm (0.1 x real)</td>
</tr>
<tr>
<td>Max disp.</td>
<td>0.15mm</td>
</tr>
<tr>
<td>Neutron</td>
<td>10,000 (1x)</td>
</tr>
<tr>
<td>Active cycle</td>
<td>300 (1.2x)</td>
</tr>
<tr>
<td>Inact. cycle</td>
<td>300 (12x)</td>
</tr>
<tr>
<td>$^{235}\text{U}$ Rel. Diff.</td>
<td>&lt; 0.25%</td>
</tr>
<tr>
<td>$^{239}\text{Pu}$ Rel. Diff.</td>
<td>&gt; -1%</td>
</tr>
<tr>
<td>Burn-up length</td>
<td>40 MWd/kgU 82 steps</td>
</tr>
<tr>
<td>Depletion zones</td>
<td>180 (1/24x)</td>
</tr>
<tr>
<td>Calculation Time</td>
<td>9 hours (1/5x) 96 cores (8x)</td>
</tr>
</tbody>
</table>
Solution II: C-shape and Symmetric Model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>320cm (real)</td>
</tr>
<tr>
<td>Max disp.</td>
<td>0.15mm</td>
</tr>
<tr>
<td>Neutron</td>
<td>100,000 (10x)</td>
</tr>
<tr>
<td>Active cycle</td>
<td>1000 (4x)</td>
</tr>
<tr>
<td>Inact. cycle</td>
<td>1000 (40x)</td>
</tr>
<tr>
<td>$U^{235}$ Rel. Diff.</td>
<td>&lt; 0.14%</td>
</tr>
<tr>
<td>$Pu^{239}$ Rel. Diff.</td>
<td>&gt; -0.27%</td>
</tr>
<tr>
<td>Burn-up length</td>
<td>30 MWd/kgU</td>
</tr>
<tr>
<td>62 steps</td>
<td></td>
</tr>
<tr>
<td>Depletion zones</td>
<td>60 (1/72x)</td>
</tr>
<tr>
<td>Calculation Time</td>
<td>50 hours (1x)</td>
</tr>
<tr>
<td></td>
<td>384 cores (32x)</td>
</tr>
</tbody>
</table>

$U^{235}$ Relative Difference vs Burn-up

$Pu^{239}$ Relative Difference vs Burn-up
Uncertainty of Results

- **Statistical Uncertainties**
  - Each calculated tally is provided with a statistical uncertainty
  - Statistical uncertainty of each transport step is not propagated to burn-up step
  - Thus, no statistical uncertainty of isotopic inventories
  - Possible Solution: Perform independent simulations with different random seeds

- **Systematic Error**
  - Fluxes and reaction rates are considered stationary in each step
  - Uniform isotopic concentration in each depletion zone
  - Non-linear Bateman Equation
    - $N_R = g(\phi_R) \neq E(g(\bar{\phi}))$
    - $N_R$ : Real isotopic concentration
    - $g(\phi_R)$ : Bateman Eq. solving with real flux
    - $E(g(\bar{\phi}))$ : Expectation of Bateman Eq. solving with Estimated flux
Conclusion

- A methodology to investigate bowing effects has been achieved

- A few preliminary simulations has been performed to illustrate
  - quantifying numerical bias
  - bowing effects on isotopic concentrations

- Convergence problems have been thoroughly investigated and solved
  - A few methods are suggested to converge
  - More Neutron, Smaller Size, Less depletion zones, C-shape, Symmetry

- Statistical uncertainty of the results are not available but analyses are present

- Future work ...
Future Work

- Progressive C-shape deformation with burn-up + more neutron histories
- Subdivisions on the C-shape model to investigate azimuthal isotopic concentrations
- Assembly bow

1/4 symmetry
Wir schaffen Wissen – heute für morgen

Thanks for your attention!

Questions?