Advanced BWR Criticality Safety with Quantified Uncertainty Using Various SCALE Modules

Dean Price, Majdi I. Radaideh, Tomasz Kozlowski

Department of Nuclear, Plasma, and Radiological Engineering,
University Of Illinois at Urbana-Champaign,
Talbot Laboratory, 104 South Wright Street, Urbana, Illinois, 61801, USA
Contents

• Background
• Advanced BWR Depletion Cases (T-Depl and T5-Depl)
• Criticality Calculations (CSAS5/KENO-V.a)
• Sensitivity and Uncertainty Analyses (TSUNAMI-3D)
• BWR Isotopic Uncertainty Quantification (Sampler)
• Summary
Objectives

• Review our activities on BWR criticality safety based on NEUP funded project on “Cask Misload Evaluation Techniques”.

• Build a set of computational models in SCALE to capture BWR design complexities for a single lattice
  • Control rod insertion.
  • Gadolinium presence.
  • Heterogenous radial and axial enrichment.
  • Part-length rods.
  • Axial burnup and void fraction profiles.
  • Partial control rod insertion.
  • Control rod movement.

• Investigate the effect of such complexities on the burnup credit and cask $k_{\text{eff}}$ uncertainty.

• Incorporate BWR spent fuel assay data to quantify the isotopic uncertainty in cask $k_{\text{eff}}$.

Previous Cask Misloading Efforts

BWR Misloading (Radaideh et al.)

PWR Misloading (Wagner)


Contents

• Background

• **Advanced BWR Depletion Cases (T-Depl and T5-Depl)**

• Criticality Calculations (KENO-V.a)

• Sensitivity and Uncertainty Analyses (TSUNAMI-3D)

• BWR Isotopic Uncertainty Quantification (Sampler)

• Summary
Methodology

- Depletion on verified models is done with TRITON.
- Benchmarking the lattice models with other codes.
- The calculated spent fuel isotopics are placed into a cask modelled in KENO-V.a.
- Sampler is used to calculate the uncertainty in lattice $k_{\infty}$
BWR Data and Resources (Fensin)

- Model is based on GE 10x10 design
  - 74 UO₂ rods
  - 18 UO₂ + Gd₂O₃ rods
  - 2 Large Water rods
- Axial enrichment heterogeneity
  - 7 axial layers with heterogenous enrichment and part length rods.
- Natural uranium is used at lattice lower and upper axial layers.

BWR Data and Resources (Marshall, ORNL)

Control Blade History

Axial coolant density distribution

Model Benchmarking

• Relevant isotopic concentration is benchmarked using different codes

• Different 2D and 3D cases are considered.

• Good agreement is observed
2D Results ($k_\infty$ vs Burnup)

C5: 3D model with core-averaged axial coolant density.

C6: C5 model with non-uniform axial coolant density.

C7: C6 model with partial control rod insertion (i.e. 33%)

C8: C7 model with variable axial enrichment and part-length rods (See Fig. 1)

C9: C8 model with control rod movement during depletion

BWR 3D Cases (T5-DEPL)
3D Results ($k_\infty$ vs Burnup)

3D Results: Isotopic Inventory

- **The 2D case C1** is considered the reference case to which other cases are compared.

- **Initial U-235 and U-238 amounts differ for C8 and C9** compared to other cases due to the vanished locations and axial heterogeneity.

- **3D cases deplete Gd-155 slowly** due to the axial burnup profile at the boundaries.

- **Control rod movement (C9) enhances Pu-239 breeding** due to the spectrum hardening.

- **The 2D case reaches the reactivity peak faster** due to the uniform depletion.
Contents

• Background
• Advanced BWR Depletion Cases (T-Depl and T5-Depl)

• Criticality Calculations (KENO-V.a)
• Sensitivity and Uncertainty Analyses (TSUNAMI-3D)
• BWR Isotopic Uncertainty Quantification (Sampler)
• Summary
Note: the cask was assumed flooded by full density water to simulate accident scenarios

GBC-68 Cask Model (KENO-V.a)

Misloaded Assembly

Burned Assembly

Burned gadolinium rod

Burned UO$_2$ rod

Water in poison panel gap

SS-304 structure

Zircaloy-2 tube

Water layer

Boral plate (B$_4$C)

Coolant region (Air or full density water)

Cask Criticality

• Results from fuel discharged at 40GWD/MTU
• Rodded cases yield more critical cask
• Heterogeneous enrichment has little effect on cask criticality
• Cask criticality results for C7-C9 are in progress

<table>
<thead>
<tr>
<th>Case Number</th>
<th>Description</th>
<th>$k_{\text{eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C0</td>
<td>Pure UO2</td>
<td>0.65864</td>
</tr>
<tr>
<td>C1</td>
<td>Homo</td>
<td>0.67702</td>
</tr>
<tr>
<td>C2</td>
<td>Homo, CR</td>
<td>0.72709</td>
</tr>
<tr>
<td>C3</td>
<td>Hetero</td>
<td>0.67792</td>
</tr>
<tr>
<td>C4</td>
<td>Hetero, CR</td>
<td>0.72966</td>
</tr>
<tr>
<td>C5</td>
<td>Constant void</td>
<td>0.71671</td>
</tr>
<tr>
<td>C6</td>
<td>Void distribution*</td>
<td>0.65610</td>
</tr>
</tbody>
</table>

All statistical uncertainty is within 10 pcm

• Results from fuel discharged at 40GWD/MTU
• Rodded cases yield more critical cask
• Heterogeneous enrichment has little effect on cask criticality
• Cask criticality results for C7-C9 are in progress

*based on DH1, the void distribution based on the average throughout the core
Contents

• Background
• Advanced BWR Depletion Cases (T-Depl and T5-Depl)
• Cask Criticality Calculations (KENO-V.a)
• Sensitivity Analysis (TSUNAMI-3D)
• BWR Isotopic Uncertainty Quantification (Sampler)
• Summary
Nuclear Data Sensitivity (Cask $k_{\text{eff}}$) via TSUNAMI-3D


### Case C0

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Reaction1; Reaction 2</th>
<th>$\Delta k/k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-238</td>
<td>n, gamma; n, gamma</td>
<td>0.220</td>
</tr>
<tr>
<td>Pu-239</td>
<td>fission; fission</td>
<td>0.207</td>
</tr>
<tr>
<td>U-235</td>
<td>nubar; nubar</td>
<td>0.151</td>
</tr>
<tr>
<td>Pu-239</td>
<td>fission; n, gamma</td>
<td>0.131</td>
</tr>
<tr>
<td>Pu-239</td>
<td>n, gamma; n, gamma</td>
<td>0.095</td>
</tr>
</tbody>
</table>

### Case C1

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Reaction1; Reaction 2</th>
<th>$\Delta k/k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-238</td>
<td>n, gamma; n, gamma</td>
<td>0.209</td>
</tr>
<tr>
<td>Pu-239</td>
<td>fission; fission</td>
<td>0.193</td>
</tr>
<tr>
<td>U-235</td>
<td>nubar; nubar</td>
<td>0.159</td>
</tr>
<tr>
<td>Pu-239</td>
<td>fission; n, gamma</td>
<td>0.128</td>
</tr>
<tr>
<td>Pu-239</td>
<td>n, gamma; n, gamma</td>
<td>0.096</td>
</tr>
</tbody>
</table>

### Case C2

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Reaction1; Reaction 2</th>
<th>$\Delta k/k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pu-239</td>
<td>fission; fission</td>
<td>0.201</td>
</tr>
<tr>
<td>U-238</td>
<td>n, gamma; n, gamma</td>
<td>0.190</td>
</tr>
<tr>
<td>U-235</td>
<td>nubar; nubar</td>
<td>0.142</td>
</tr>
<tr>
<td>Pu-239</td>
<td>fission; n, gamma</td>
<td>0.142</td>
</tr>
<tr>
<td>Pu-239</td>
<td>n, gamma; n, gamma</td>
<td>0.114</td>
</tr>
</tbody>
</table>
Cask $k_{\text{eff}}$ Isotopic Sensitivities based on C0 depletion (EOL)

\[ S_i = \frac{\Delta k/k}{\Delta N_i/N_i} \]
Contents

• Background
• Advanced BWR Depletion Cases (T-Depl and T5-Depl)
• Cask Criticality Calculations (KENO-V.a)
• Sensitivity Analysis (TSUNAMI-3D)
• BWR Isotopic Uncertainty Quantification (Sampler)
• Summary
Computational vs Data-driven (Computational method)

Modeling Part (Pick any case C0-C9)

- BWR Data (Configuration, Enrichment, Core, etc.)
- Model Development
- Model Validation

Input Uncertainty (Geometry, Operating, fuel design)

Depletion UQ

- Nuclear Data Covariances ENDF/B-VII (Cross-Sections, Yield, etc.)

Sample 1
Sample 2
Sample 3
Sample M

N1
N2
N3
Nm

\[ \mu_n \pm \sigma_n \] for each isotope

Criticality Safety UQ

- \[ k_{\text{eff}} \pm \sigma_{\text{ISO}} \]
- \[ k_{\text{eff}}^1 \]
- \[ k_{\text{eff}}^2 \]
- \[ k_{\text{eff}}^3 \]
- \[ k_{\text{eff}}^M \]

Sample 1
Sample 2
Sample M

\[ \text{Sample } N_j \sim \text{Normal (}[\Sigma N_j, \Sigma N_j] \]
Computational vs Data-driven (Data method)

Computational-driven Approach

Input parameters’ uncertainty for criticality safety applications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1-σ (%)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pellet radius</td>
<td>0.14%</td>
<td>[9, 10]</td>
</tr>
<tr>
<td>Clad Inner Diameter</td>
<td>0.43%</td>
<td>[9, 10]</td>
</tr>
<tr>
<td>Clad Outer Diameter</td>
<td>0.46%</td>
<td>[9, 10]</td>
</tr>
<tr>
<td>Material</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U-235 wt%</td>
<td>0.60%</td>
<td>[8]</td>
</tr>
<tr>
<td>Gd$_2$O$_3$ wt%</td>
<td>1.67%</td>
<td>[8]</td>
</tr>
<tr>
<td>UO$_2$ Density</td>
<td>0.13%</td>
<td>[9, 10]</td>
</tr>
<tr>
<td>Operating</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific Power</td>
<td>1.67%</td>
<td>[8, 11, 12]</td>
</tr>
<tr>
<td>Coolant Density</td>
<td>3.33%</td>
<td>[8, 11, 12]</td>
</tr>
<tr>
<td>Fuel Temperature</td>
<td>3.33%</td>
<td>[8, 11, 12]</td>
</tr>
<tr>
<td>Nuclear Data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutron Cross-sections</td>
<td>56group-COV</td>
<td>[3]</td>
</tr>
<tr>
<td>Fission Yield</td>
<td>56group-COV</td>
<td>[3]</td>
</tr>
<tr>
<td>Decay Data</td>
<td>56group-COV</td>
<td>[3]</td>
</tr>
</tbody>
</table>

Correlation matrix between actinides based on case C1


Data-driven Approach

Irregular value by SCALE-6 for Am-241

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Geometry</th>
<th>$\bar{R}_n$</th>
<th>$\sigma_{R_n}$</th>
<th>$N_s^n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-234</td>
<td>8x8, 7x7</td>
<td>1.077</td>
<td>0.079</td>
<td>20</td>
</tr>
<tr>
<td>U-235</td>
<td>8x8, 7x7, 6x6</td>
<td>0.992</td>
<td>0.055</td>
<td>32</td>
</tr>
<tr>
<td>U-236</td>
<td>8x8, 7x7, 6x6</td>
<td>0.979</td>
<td>0.020</td>
<td>32</td>
</tr>
<tr>
<td>U-237</td>
<td>8x8, 7x7, 6x6</td>
<td>0.999</td>
<td>0.005</td>
<td>32</td>
</tr>
<tr>
<td>Pu-238</td>
<td>8x8, 7x7, 6x6</td>
<td>0.968</td>
<td>0.101</td>
<td>32</td>
</tr>
<tr>
<td>Pu-239</td>
<td>8x8, 7x7, 6x6</td>
<td>1.006</td>
<td>0.052</td>
<td>32</td>
</tr>
<tr>
<td>Pu-240</td>
<td>8x8, 7x7, 6x6</td>
<td>0.997</td>
<td>0.037</td>
<td>32</td>
</tr>
<tr>
<td>Pu-241</td>
<td>8x8, 7x7, 6x6</td>
<td>0.949</td>
<td>0.102</td>
<td>32</td>
</tr>
<tr>
<td>Pu-242</td>
<td>8x8, 7x7, 6x6</td>
<td>1.008</td>
<td>0.062</td>
<td>32</td>
</tr>
<tr>
<td>Am-241</td>
<td>8x8, 7x7</td>
<td>1.087</td>
<td>0.121</td>
<td>20</td>
</tr>
</tbody>
</table>

$\bar{R}_n$: mean of the bias (C/E)

$\sigma_{R_n}$: standard deviation of the bias

$N_s^n$: number of experimental samples used

Final cask $k_{\text{eff}}$ Uncertainty due to isotopic Uncertainty

The calculations were done using KENO-V.a + Sampler for 500 samples

<table>
<thead>
<tr>
<th>Method</th>
<th>Nominal $k_{\text{eff}}$</th>
<th>$\bar{k}_{\text{eff}}$</th>
<th>1-$\sigma$ (%)</th>
<th>$\sigma_{k_{\text{eff}}}$ (pcm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computational (Uncorrelated)</td>
<td>0.79747</td>
<td>0.79762</td>
<td>0.39</td>
<td>314</td>
</tr>
<tr>
<td>Computational (Correlated)</td>
<td>0.79747</td>
<td>0.79812</td>
<td>0.50</td>
<td>403</td>
</tr>
<tr>
<td>Data-driven</td>
<td>0.79747</td>
<td>0.79601</td>
<td>1.20</td>
<td>953</td>
</tr>
</tbody>
</table>


Contents

• Background
• Advanced BWR Depletion Cases (T-Depl and T5-Depl)
• Cask Criticality Calculations (KENO-V.a)
• Sensitivity Analysis (TSUNAMI-3D)
• BWR Isotopic Uncertainty Quantification (Sampler)

• Summary
Summary

• Advanced BWR modelling is necessary to capture the complexities associated with the BWR design, which in turn yield an accurate criticality safety calculations.

• 2D modelling shows minimal effects of radial enrichment averaging.

• 3D models show different behaviour for U-235 and Gd-155 depletion, and Pu-239 breeding.

• In general, the uncertainty due to cross-section covariances decreases during the cycle.

• The data driven method for performing UQ on the cask yields a higher uncertainty (additional enchantment of the database will be done in future).

• Correlation between isotopes tends to increase the $k_{eff}$ uncertainty due to isotopic uncertainty.

• Our future work will focus on combining the computational and data-driven approaches into one hybrid approach through quantifying the code bias.

• Even when flooded, the BWR cask remains subcritical in all cases analysed.
Thank you!

• **Our publications for more info**


• **To come soon**
