Update on Benchmark of Component Critical Configuration of KRUSTY

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KRUSTY Purpose

• Prototype and proof of concept for Kilopower Project
• HEU system reflected by BeO and steel
• Two Options:
  o Power source
  o Deep space probe
• Testing began Nov. 2017
  o Component critical configuration
    • BeO Worth
    • B₄C Worth
    • Benchmark configurations
• 28-hour test March 2018
Component Critical Configuration

- HEU fuel
  - 93.07% Enriched
  - 7.65 wt% molybdenum
  - Annulus with 8 slots
Component Critical Configuration

- **HEU fuel**
  - 93.07% Enriched
  - 7.65 wt% molybdenum
  - Annulus with 8 slots

Axial and Radial Views of Fuel
Component Critical Configuration

- **HEU fuel**
  - 93.07% Enriched
  - 7.65 wt% molybdenum
  - Annulus with 8 slots
- **BeO Reflectors**
  - Top, Bottom, and Ring
Component Critical Configuration

- **HEU fuel**
  - 93.07% Enriched
  - 7.65 wt% molybdenum
  - Annulus with 8 slots
- **BeO Reflectors**
  - Top, Bottom, and Rings

Radial and Axial Views of Top BeO Axial Reflector
Component Critical Configuration

- **HEU fuel**
  - 93.07% Enriched
  - 7.65 wt% molybdenum
  - Annulus with 8 slots
- **BeO Reflectors**
  - Top, Bottom, and Rings

Radial and Axial Views of Bottom BeO Axial Reflector
Component Critical Configuration

- **HEU fuel**
  - 93.07% Enriched
  - 7.65 wt% molybdenum
  - Annulus with 8 slots
- **BeO Reflectors**
  - Top, Bottom, and Rings

Radial and Axial Views of Inner BeO Reflector Rings (Cases 1 & 3)
Component Critical Configuration

- **HEU fuel**
  - 93.07% Enriched
  - 7.65 wt% molybdenum
  - Annulus with 8 slots

- **BeO Reflectors**
  - Top, Bottom, and Rings

Radial, Axial, and Individual Views of Outer BeO Reflector Rings (Cases 1 & 3)
Component Critical Configuration

- **25 cm HEU fuel**
  - 93.07% Enriched
  - 7.65 wt% molybdenum
  - Annulus with 8 slots
- **BeO Reflectors**
  - Top, Bottom, and Ring
- **Shielding**
  - Outer shields and multi-layered top and bottom
- **Critical Configuration (#3)**
  - 28.575 cm
  - Excess reactivity: 2.3¢
  - $k_{eff}$: 1.00016
## Benchmark Configurations

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Source Present</th>
<th>BeO Height (cm)</th>
<th>Top Plug Material</th>
<th>Bottom Plug Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yes</td>
<td>28.5750</td>
<td>BeO</td>
<td>BeO</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>28.8925</td>
<td>BeO</td>
<td>BeO</td>
</tr>
<tr>
<td>3</td>
<td>No</td>
<td>28.5750</td>
<td>BeO</td>
<td>BeO</td>
</tr>
<tr>
<td>4</td>
<td>No</td>
<td>28.8925</td>
<td>Al</td>
<td>BeO</td>
</tr>
<tr>
<td>5</td>
<td>No</td>
<td>29.2100</td>
<td>Al</td>
<td>Al</td>
</tr>
</tbody>
</table>
Benchmark Cases with AmBe Source

Case 1

Case 2

Extra Layer of BeO
Benchmark Cases 3 - 5

Case 3

Case 4

Case 5
Benchmark Cases 3 - 5

Height of Reflector Rings:
- Top Plug: BeO
  Bottom Plug: BeO
  28.5750 cm

Height of Reflector Rings:
- Top Plug: Al
  Bottom Plug: BeO
  28.8925 cm

Height of Reflector Rings:
- Top Plug: Al
  Bottom Plug: Al
  29.2100 cm
Sensitivity and Uncertainty Analysis

- Evaluated:
  - Measurement
  - Mass
  - Dimension
  - Composition
  - Position
  - Temperature

- One Billion Active Histories
  - Uncertainty of 2 pcm
  - Negligible: $\Delta k_{\text{eff}} < 2$ pcm

\[ \delta k_{\text{eff}} = \frac{u_i}{\delta x_i} (\Delta k_{\text{eff}}) \]

- $u_i$ – standard uncertainty
- $\delta x_i$ – value of the perturbation
- $\Delta k_{\text{eff}}$ – change in $k_{\text{eff}}$ across the perturbation
Preliminary Results for Case 3
## Selected Mass Uncertainties for Case 3

<table>
<thead>
<tr>
<th>Component</th>
<th>Uncertainty (pcm)</th>
<th>Error (pcm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>4.6</td>
<td>± 0.4</td>
</tr>
<tr>
<td>BeO Inner Rings</td>
<td>2.4</td>
<td>± 0.2</td>
</tr>
<tr>
<td>BeO Outer Rings</td>
<td>0.5</td>
<td>± 0.2</td>
</tr>
</tbody>
</table>
## Selected Geometry Uncertainties for Case 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Uncertainty (pcm)</th>
<th>Error (pcm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Height</td>
<td>3.3</td>
<td>± 0.1</td>
</tr>
<tr>
<td>Fuel Outer Diameter</td>
<td>2.7</td>
<td>± 0.4</td>
</tr>
<tr>
<td>BeO Inner Ring Height</td>
<td>25.0</td>
<td>± 0.2</td>
</tr>
<tr>
<td>BeO Inner Ring Inner Diameter</td>
<td>-2.4</td>
<td>± 0.2</td>
</tr>
<tr>
<td>BeO Inner Ring Outer Diameter</td>
<td>-6.5</td>
<td>± 0.2</td>
</tr>
<tr>
<td>BeO Outer Ring Height</td>
<td>-6.0</td>
<td>± 0.2</td>
</tr>
<tr>
<td>BeO Outer Ring Inner Diameter</td>
<td>-3.7</td>
<td>± 0.2</td>
</tr>
<tr>
<td>BeO Outer Ring Outer Diameter</td>
<td>-2.2</td>
<td>± 0.2</td>
</tr>
</tbody>
</table>
# Selected Material Composition Uncertainties for Case 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Uncertainty (pcm)</th>
<th>Error (pcm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{235}$Content in Fuel</td>
<td>4.2</td>
<td>± 1.7</td>
</tr>
<tr>
<td>Carbon Content in Fuel</td>
<td>4.3</td>
<td>± 1.4</td>
</tr>
<tr>
<td>Impurities in Outer Shields</td>
<td>-10.0</td>
<td>± 1.0</td>
</tr>
</tbody>
</table>
## Position and Temperature Uncertainties for Case 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Uncertainty (pcm)</th>
<th>Error (pcm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alignment of Central Core</td>
<td>4.6</td>
<td>± 1.2</td>
</tr>
<tr>
<td>Alignment of Platen</td>
<td>45.6</td>
<td>± 1.2</td>
</tr>
<tr>
<td>Gaps in BeO Reflector Rings</td>
<td>-90.6</td>
<td>± 1.2</td>
</tr>
<tr>
<td>Temperature</td>
<td>0.18</td>
<td>± 0.01</td>
</tr>
</tbody>
</table>
## Summary of Largest Uncertainties for Case 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$k_{\text{eff}}$ Combined Standard Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaps in BeO Reflector Rings</td>
<td>0.00091</td>
</tr>
<tr>
<td>Platen Alignment</td>
<td>0.00046</td>
</tr>
<tr>
<td>BeO Inner Ring Height</td>
<td>0.00025</td>
</tr>
<tr>
<td>Outer SS Shield Impurities</td>
<td>0.00010</td>
</tr>
<tr>
<td>BeO Inner Ring Outer Diameter</td>
<td>0.00006</td>
</tr>
<tr>
<td>Total</td>
<td>0.00107</td>
</tr>
</tbody>
</table>
## Summary of $k_{\text{eff}}$ for Case 3

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Simplification Bias</th>
<th>Experiment Uncertainty</th>
<th>Benchmark</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.00016 \pm 0.00007$</td>
<td>$-0.00005 \pm 0.00002$</td>
<td>$\pm 0.00107$</td>
<td>$1.00011 \pm 0.00107$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample Calculation</th>
<th>C – E (pcm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.00020 \pm 0.00002$</td>
<td>9</td>
</tr>
</tbody>
</table>
Future Work

- Incorporate action items from external reviewers and ICSBEP working group
- Refine/finalize the detailed and simplified models
- Further investigate the BeO gap uncertainty
Acknowledgements

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