Benchmark Experiment for Fast Neutron Spectrum Potassium Worth Validation in Space Power Reactor Design

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  - J. Blair Briggs – INL
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Outline

- Historical Background
- What is the IRPhEP
- ORCEF Potassium Worth Measurement
- Evaluation and Results
- Path Forward
- Conclusions
HISTORICAL BACKGROUND
Oak Ridge Critical Experiments Facility

- Support criticality safety at Y-12
  - Storage, casting, and handling
  - Verification of calculation methods and cross section data

- Support various reactor designs
  - MPRE
  - SNAP
  - Fast Burst Reactors
ORCEF Vertical Assembly Machine
Medium Power Reactor Experiment (MPRE)

- **Space Reactor Design**
  - 1 MW(t), 140 kW(e)
  - Stainless Steel
  - Potassium Cooled
  - Rankine Cycle

- **Experiment Results**
  - Validation of Reactor Calculations
  - Validation of Reactor Physics Methods
  - Demonstrated Good Power Distribution, Nuclear Stability, and Control Characteristics
Previously Evaluated SCCA Experiments

- Experiments
  - Tight-Pack-Array, Graphite Reflected
  - 1.506-cm-Array, Graphite Reflected
  - 1.506-cm-Array and 7-Tube Clusters, Beryllium Reflected

- Additional Data
  - 93.2 % $^{235}$UO$_2$
  - Type 347 SS Clad
  - Various Reactor Physics Measurements
Oralloy Experiments and Benchmarks

- Bare Cylinders
  - HEU-MET-FAST-051
- Beryllium Reflected
  - HEU-MET-FAST-059
  - HEU-MET-FAST-069
- Thin Graphite Reflected
  - HEU-MET-FAST-071
- Poly Reflected
  - HEU-MET-FAST-076
- GROTESQUE
  - HEU-MET-FAST-081
- ORSPHERE
  - HEU-MET-FAST-100
- Potassium Worth
  - HEU-MET-FAST-045
- Complex Annuli
  - HEU-MET-FAST-083
- Bare Annuli
  - HEU-MET-FAST-074
- Interacting Cylinders
- Thick Graphite Reflected
Oralloy Measurement Uncertainties

- Very precise measurement capabilities at Y-12
  - Dimensions
    - ±0.0001 in.
  - Mass
    - ±0.01 g
  - Isotopics
    - ±1% $^{234}$U
    - < ±0.02 wt.% $^{235}$U & $^{236}$U
  - Impurities
    - ~500 ppm average content

- John T. Mihalczo
  - Experimenter still available for collaboration

- Further information available
  - ORNL/TM-2012/32
THE IRPHEP
Purpose of the International Reactor Physics Experiment Evaluation Project (IRPhEP)

- Collect and evaluate data in support of numerous nuclear energy and technology experiments
- Represent significant investments of time, infrastructure, expertise, and cost that might not have received adequate documentation
- Reactivity measurements, reaction rates, buckling, burnup, etc., that are of significant worth for current and future research and development efforts

If it is worth measuring, then it is worth evaluating.
IRPhEP Handbook

March 2014 Edition

- 20 Contributing Countries
- Data from 136 Experimental Series performed at 48 Reactor Facilities
- Data from 3 out of the 136 series are published in DRAFT form

http://irphep.inl.gov
http://www.oecd-nea.org/science/wprs/irphe/
**INTERNATIONAL BENCHMARK PROGRAMS**

### Benchmark Evaluation Process
- **Benchmark Experiment Data**
  - Externally Available Technical Journals & Reports
  - Internal Reports Letters & Memos
  - Logbooks
  - Drawings
  - Exponenter's Annotated Copy of Published Reports
  - Exponenters (Retired or Working on Other Projects)
  - Facilities Awaiting D&D

- **Evaluation Process**
  - Identify
  - Verify
  - Evaluate
  - Compile
  - Calculate
  - Document

- **Short-Term Preservation**

- **Peer Review** (National and International Experts)

- **Future Use**
  - Advanced Modeling and Simulation
  - Analytical Methods Development, Validation, and Verification
  - Reactor Design and Licensing
  - Training
  - Criticality and Reactor Safety Analysis
  - Fuel Cycle and Related Activities
  - Range of Applicability and Experiment Design
  - Nuclear Data Refinement

**Comprehensive Source of Externally Peer Reviewed Integral Benchmark Data**
Potassium

K

19

39.098
Potassium Worth Experiment

- Oralloy Annuli
  - 7” ID (~18 cm)
  - 13” OD (~33 cm)
  - 5.6” H (~14 cm)

- SS 304 Cans
  - Empty or
  - 2.4 kg K
  - +10.32 ¢
Detailed Benchmark Model Development
Including Gaps from Imperfections

- Individual Part Heights
- Stack Height
- Unevenness of Parts
- Small Neutron Streaming Paths
- Similar Effect Radially
## TABLE 1. Total Experimental Uncertainty in the Potassium Worth Measurement Experiments.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Configuration 1 (Empty Cans)</th>
<th>Configuration 2 (Potassium-Filled)</th>
<th>Potassium Worth Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (K)</td>
<td>0.00004</td>
<td>0.00004</td>
<td>--</td>
</tr>
<tr>
<td>Experiment reproducibility (φ)</td>
<td>0.00013</td>
<td>0.00013</td>
<td>0.00004</td>
</tr>
<tr>
<td>Measured reactivity worth (φ)</td>
<td>0.00032</td>
<td>0.00032</td>
<td>--</td>
</tr>
<tr>
<td>$\beta_{\text{eff}}$</td>
<td>0.00005</td>
<td>negligible</td>
<td>--</td>
</tr>
<tr>
<td>Uranium diameter (cm)</td>
<td>negligible</td>
<td>negligible</td>
<td>--</td>
</tr>
<tr>
<td>Uranium height (cm)</td>
<td>negligible</td>
<td>negligible</td>
<td>--</td>
</tr>
<tr>
<td>Uranium stack height (cm)</td>
<td>0.00006</td>
<td>0.00006</td>
<td>--</td>
</tr>
<tr>
<td>Steel can diameter (cm)</td>
<td>negligible</td>
<td>negligible</td>
<td>0.00001</td>
</tr>
<tr>
<td>Steel can radial thickness (cm)</td>
<td>0.00003</td>
<td>negligible</td>
<td>0.00003</td>
</tr>
<tr>
<td>Steel can height (cm)</td>
<td>negligible</td>
<td>negligible</td>
<td>0.00002</td>
</tr>
<tr>
<td>Steel can end thickness (cm)</td>
<td>negligible</td>
<td>negligible</td>
<td>0.00003</td>
</tr>
<tr>
<td>Steel can lateral placement (cm)</td>
<td>negligible</td>
<td>negligible</td>
<td>--</td>
</tr>
<tr>
<td>Lateral assembly alignment (cm)</td>
<td>negligible</td>
<td>negligible</td>
<td>--</td>
</tr>
<tr>
<td>Vertical assembly alignment (cm)</td>
<td>negligible</td>
<td>negligible</td>
<td>--</td>
</tr>
<tr>
<td>Gaps between parts (cm)</td>
<td>negligible</td>
<td>negligible</td>
<td>--</td>
</tr>
<tr>
<td>Assembly separation (cm)</td>
<td>negligible</td>
<td>negligible</td>
<td>--</td>
</tr>
<tr>
<td>Uranium mass (g)</td>
<td>negligible</td>
<td>negligible</td>
<td>--</td>
</tr>
<tr>
<td>$^{234}$U content (wt.%)</td>
<td>negligible</td>
<td>negligible</td>
<td>--</td>
</tr>
<tr>
<td>$^{235}$U content (wt.%)</td>
<td>0.00010</td>
<td>0.00010</td>
<td>--</td>
</tr>
<tr>
<td>$^{236}$U content (wt.%)</td>
<td>negligible</td>
<td>negligible</td>
<td>--</td>
</tr>
<tr>
<td>Uranium impurities (ppm)</td>
<td>negligible</td>
<td>negligible</td>
<td>--</td>
</tr>
<tr>
<td>Stainless steel mass (g)</td>
<td>negligible</td>
<td>negligible</td>
<td>0.00002</td>
</tr>
<tr>
<td>Stainless steel Cr content (wt.%)</td>
<td>negligible</td>
<td>negligible</td>
<td>--</td>
</tr>
<tr>
<td>Stainless steel Ni content (wt.%)</td>
<td>negligible</td>
<td>negligible</td>
<td>--</td>
</tr>
<tr>
<td>Stainless steel Mn content (wt.%)</td>
<td>negligible</td>
<td>negligible</td>
<td>--</td>
</tr>
<tr>
<td>Stainless steel (C, Si, P, S, &amp; N) content (wt.%)</td>
<td>negligible</td>
<td>negligible</td>
<td>--</td>
</tr>
<tr>
<td>Stainless steel impurities (ppm)</td>
<td>negligible</td>
<td>negligible</td>
<td>--</td>
</tr>
<tr>
<td>Potassium mass (g)</td>
<td>NA</td>
<td>negligible</td>
<td>&lt;0.00001</td>
</tr>
<tr>
<td>Potassium impurities (ppm)</td>
<td>NA</td>
<td>negligible</td>
<td>&lt;0.00001</td>
</tr>
<tr>
<td>Potassium bubbles or voiding</td>
<td>NA</td>
<td>negligible</td>
<td>&lt;0.00001</td>
</tr>
<tr>
<td><strong>Total Experimental Uncertainty</strong></td>
<td><strong>0.00037</strong></td>
<td><strong>0.00037</strong></td>
<td><strong>0.00006</strong></td>
</tr>
</tbody>
</table>
Simple Benchmark Model Development

SS 304 can (2)

R 8.732520
R 8.890000
R 16.510000

14.181666

6.350000
5.323840

Void (Case 1) or Potassium (Case 2)

0.513080

7.620000
6.593840

Void (Case 1) or Potassium (Case 2)

7.106920

HEU annulus

Dimensions in cm

"Simple is good."
-Jim Henson
### Biases and Measured Corrections

**TABLE 2.** Calculated Biases for the Potassium Worth Measurement Experiments.

<table>
<thead>
<tr>
<th>Bias/Correction</th>
<th>Configuration 1 (Empty Cans) $[\Delta k_{\text{eff}}]$</th>
<th>Configuration 2 (Potassium-Filled) $[\Delta k_{\text{eff}}]$</th>
<th>Potassium Worth Measurement $[\Delta k_{\text{eff}}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Room Return Effects</td>
<td>-0.00093</td>
<td>-0.00086</td>
<td>--</td>
</tr>
<tr>
<td>2. Removal of Stainless Steel Diaphragm</td>
<td>+0.00054</td>
<td>+0.00054</td>
<td>--</td>
</tr>
<tr>
<td>3. Removal of Support Structure</td>
<td>-0.00106</td>
<td>-0.00106</td>
<td>--</td>
</tr>
<tr>
<td>4. Temperature Effects</td>
<td>negligible</td>
<td>negligible</td>
<td>--</td>
</tr>
<tr>
<td>5. Removal of Steel Can Impurities</td>
<td>negligible</td>
<td>negligible</td>
<td>--</td>
</tr>
<tr>
<td>6. Removal of Potassium Impurities</td>
<td>NA</td>
<td>negligible</td>
<td>--</td>
</tr>
<tr>
<td><strong>Total Bias for Detailed Model (1-6)</strong></td>
<td><strong>-0.000145</strong></td>
<td><strong>-0.000138</strong></td>
<td><strong>+0.000007</strong></td>
</tr>
<tr>
<td>7. Removal of HEU Impurities</td>
<td>-0.00021</td>
<td>-0.00022</td>
<td>--</td>
</tr>
<tr>
<td>7+8. Removal of HEU Impurities and Homogenization of Annuli</td>
<td>-0.00027</td>
<td>-0.00023</td>
<td>--</td>
</tr>
<tr>
<td>9. Simplification of Can Geometries</td>
<td>+0.00013</td>
<td>+0.00006</td>
<td>--</td>
</tr>
<tr>
<td>7-9. Combined Simplification Calculation</td>
<td>-0.00012</td>
<td>-0.00015</td>
<td>--</td>
</tr>
<tr>
<td><strong>Total Bias for Simple Model (1-9)</strong></td>
<td><strong>-0.000157</strong></td>
<td><strong>-0.000153</strong></td>
<td><strong>+0.000004</strong></td>
</tr>
</tbody>
</table>
### TABLE 3. Experimental and Benchmark Eigenvalues for Critical Configurations.

<table>
<thead>
<tr>
<th>Case</th>
<th>Steel Can Content</th>
<th>Experimental</th>
<th>Bias</th>
<th>Benchmark Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Detailed</td>
<td>Void</td>
<td>0.99957 ± 0.00037</td>
<td>-0.00145 ± 0.0004</td>
<td>0.9981 ± 0.0004</td>
</tr>
<tr>
<td>2 Detailed</td>
<td>Potassium</td>
<td>1.00025 ± 0.00037</td>
<td>-0.00138 ± 0.0005</td>
<td>0.9989 ± 0.0004</td>
</tr>
<tr>
<td>1 Simple</td>
<td>Void</td>
<td>0.99957 ± 0.00037</td>
<td>-0.00157 ± 0.0005</td>
<td>0.9980 ± 0.0004</td>
</tr>
<tr>
<td>2 Simple</td>
<td>Potassium</td>
<td>1.00025 ± 0.00037</td>
<td>-0.00153 ± 0.0006</td>
<td>0.9987 ± 0.0004</td>
</tr>
</tbody>
</table>

### TABLE 4. Experimental and Benchmark Potassium Worth.

<table>
<thead>
<tr>
<th>Case</th>
<th>Experimental</th>
<th>Bias</th>
<th>Benchmark Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detailed (Δk/k)</td>
<td>0.00068 ± 0.00006</td>
<td>0.00007 ± 0.00003</td>
<td>0.00075 ± 0.00007</td>
</tr>
<tr>
<td>Detailed (¢)</td>
<td>10.3 ± 1.1</td>
<td>1.1 ± 0.4</td>
<td>11.4 ± 1.2</td>
</tr>
<tr>
<td>Simple (Δk/k)</td>
<td>0.0068 ± 0.00006</td>
<td>0.00004 ± 0.00005</td>
<td>0.00072 ± 0.00008</td>
</tr>
<tr>
<td>Simple (¢)</td>
<td>10.3 ± 1.1</td>
<td>0.6 ± 0.7</td>
<td>11.0 ± 1.3</td>
</tr>
</tbody>
</table>
WHAT DO WE EXPECT
HEU Cylinder Experiments
Typically Calculate Low
## Eigenvalue Results – As Expected

**TABLE 5. Comparison of Simple Benchmark and Calculated Eigenvalues.**

<table>
<thead>
<tr>
<th>Case</th>
<th>Code</th>
<th>Neutron Cross Section Library</th>
<th>Calculated</th>
<th>Benchmark Experiment</th>
<th>$\frac{C - E}{E}$ %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$k_{eff}$ ± 1σ</td>
<td>$k_{eff}$ ± 1σ</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>MCNP6</td>
<td>ENDF/B-VII.1</td>
<td>0.99542 ± 0.00002</td>
<td>0.9980 ± 0.0004</td>
<td>-0.26 ± 0.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ENDF/B-VII.0</td>
<td>0.99556 ± 0.00002</td>
<td></td>
<td>-0.24 ± 0.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JEFF-3.1</td>
<td>0.99227 ± 0.00002</td>
<td></td>
<td>-0.57 ± 0.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JENDL-3.3</td>
<td>0.99982 ± 0.00002</td>
<td></td>
<td>0.18 ± 0.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SERPENT2</td>
<td>ENDF/B-VII.0</td>
<td>0.99558 ± 0.00003</td>
<td>-0.24 ± 0.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>KEN0-VI</td>
<td>ENDF/B-VII.0</td>
<td>0.99528 ± 0.00003</td>
<td>-0.27 ± 0.04</td>
</tr>
<tr>
<td>2</td>
<td>MCNP6</td>
<td>ENDF/B-VII.1</td>
<td>0.99564 ± 0.00002</td>
<td>0.9987 ± 0.0004</td>
<td>-0.31 ± 0.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ENDF/B-VII.0</td>
<td>0.99577 ± 0.00002</td>
<td></td>
<td>-0.30 ± 0.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JEFF-3.1</td>
<td>0.99242 ± 0.00002</td>
<td></td>
<td>-0.63 ± 0.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JENDL-3.3</td>
<td>0.99996 ± 0.00002</td>
<td></td>
<td>0.12 ± 0.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SERPENT2</td>
<td>ENDF/B-VII.0</td>
<td>0.99581 ± 0.00003</td>
<td>-0.29 ± 0.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>KEN0-VI</td>
<td>ENDF/B-VII.0</td>
<td>0.99549 ± 0.00003</td>
<td>-0.32 ± 0.04</td>
</tr>
</tbody>
</table>
# Potassium Worth – Not Expected

**TABLE 6.** Comparison of Simple Benchmark and Calculated Potassium Worth.

<table>
<thead>
<tr>
<th>Code</th>
<th>Neutron Cross Section Library</th>
<th>Calculated $\rho(\psi)$ ± $1\sigma$</th>
<th>Benchmark Experiment $\rho(\psi)$ ± $1\sigma$</th>
<th>$\frac{C - E}{E}$ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCNP6</td>
<td>ENDF/B-VII.1</td>
<td>3.4 ± 0.4</td>
<td>11.0 ± 1.3</td>
<td>-69 ± 5</td>
</tr>
<tr>
<td></td>
<td>ENDF/B-VII.0</td>
<td>3.2 ± 0.4</td>
<td></td>
<td>-71 ± 5</td>
</tr>
<tr>
<td></td>
<td>JEFF-3.1</td>
<td>2.3 ± 0.4</td>
<td></td>
<td>-79 ± 4</td>
</tr>
<tr>
<td></td>
<td>JENDL-3.3</td>
<td>2.1 ± 0.4</td>
<td></td>
<td>-81 ± 4</td>
</tr>
<tr>
<td>SERPENT2</td>
<td>ENDF/B-VII.0</td>
<td>3.6 ± 0.6</td>
<td></td>
<td>-67 ± 7</td>
</tr>
<tr>
<td>KENO-VI</td>
<td>ENDF/B-VII.0</td>
<td>3.2 ± 0.6</td>
<td></td>
<td>-71 ± 6</td>
</tr>
</tbody>
</table>

- **Unknown Experimental Error?**
- **Error in Cross Section Data?**
THE PATH FORWARD
SCCA-SPACE-EXP-003
Potassium Calandria
Conclusions

- ORCEF Potassium Worth Experiment Evaluated as Benchmark
- Calculations of the Worth Appear Incorrect
- Need to Evaluate Additional Potassium (or NaK) Experiments for Further Validation
Cross Section Library Comparison

- CENDL-3.1
- ENDF/B-VII.0
- ENDF/B-VII.1
- JEFF-3.1
- JENDL-3.3
- JENDL-4.0
- TENDL-2012

(C-E)/E %

Libraries:
- CENDL-3.1
- ENDF/B-VII.0
- ENDF/B-VII.1
- JEFF-3.1
- JENDL-3.3
- JENDL-4.0
- TENDL-2012

Shapes:
- "Lady Godiva"
- COMET
- VNIITF Sphere
- VNIITF Cylinder
- VNIIEF Sphere
- ORCEF Slab
- ORCEF Cylinder
- GROTESQUE
- ORSPHERE
- ORSPHERE

Dimensions:
- 720.0x540.0