Benchmark Evaluation of Reactivity Measurements for Beryllium-Reflected Space Reactor Mockup

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Outline

- Historical Background
- What is the IRPhEP
- Small, Compact, Critical Assembly
  - Beryllium-Reflected Measurements
- Latest Evaluated Benchmark Measurements
  - Fuel Effect Reactivity Measurements
  - Neutron Absorbing and Moderating Material Reactivity Measurements
- Path Forward
- Conclusions
Small, Compact Critical Assembly (SCCA)

- Published Experiments
  - Tight-Pack-Array, Graphite Reflected
  - 1.506-cm-Array, Graphite Reflected
  - 1.506-cm-Array and 7-Tube Clusters, Beryllium Reflected
  - ORNL-TM-450, -561, and -655

- Possible 4th Series (logbook data)
  - Graphite and Beryllium Reflected
  - Potassium Replacement Measurements
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-UO₂
  - Fast Burst Reactors
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
ORCEF Vertical Assembly Machine
Graphite Reflected Assemblies
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 of the experimental series are published in DRAFT form

http://irpheap.inl.gov
http://www.oecd-nea.org/science/wprs/irphe/
Benchmark Evaluation Process

**INTERNATIONAL BENCHMARK PROGRAMS**

- **Benchmark Experiment Data**
  - Externally Available Technical Journals & Reports
  - Internal Reports, Letters & Memos
  - Logbooks
  - Drawings
  - Experimenter’s Annotated Copy of Published Reports
  - Experimenter’s (Retired or Working on Other Projects)

- **Short-Term Preservation**
  - Facilities Awaiting D&D

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

- **Peer Review (National and International Experts)**
  - Comprehensive Source of Externally Peer Reviewed Integral Benchmark Data

- **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
SCCA Fuel Elements

- **Type 347 SS Tubes**
  - With End Caps
  - 1.27 cm outer diameter
  - 30.48 cm in length

- **HEU-O₂ Pellets**
  - 93.2% \(^{235}\text{U}\)
  - 9.71 g/cm\(^3\)
  - 26 per Tube
  - 295.8 g per Tube

- **252-253 Tubes per Core**
SCCA-SPACE-EXP-003 – Beryllium Reflected

- 2 Critical Configurations
  - 1.506 cm \( \Delta \) Pitch
  - 7-Tube Clusters

- Measurements
  - Radial Fuel Worths
  - Material Worths
  - Fission Rate Distributions
  - Cadmium Ratio Distributions
  - Worth of K Coolant
SCCA-SPACE-EXP-003
Fuel Effect Reactivity Measurement

- Replace fuel tube with empty fuel tube
- Accident condition (-8.2 $\phi$)
SSCA-SPACE-EXP-003
Material Reactivity

- SS347, W, Nb, CH₂, C, B₄C Rods
- SS, Al, and Cd Lids
### SCCA-SPACE-EXP-003

**Material Reactivity**

<table>
<thead>
<tr>
<th>Material</th>
<th>Form</th>
<th>Number</th>
<th>Location</th>
<th>Total Weight (g)</th>
<th>Total Reactivity (cents)</th>
<th>Reactivity Coefficient (cents/kg)</th>
<th>Logbook Reference Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 347 Stainless Steel</td>
<td>0.317 cm dia rods 30.5 cm long</td>
<td>90</td>
<td>All positions filled</td>
<td>1704</td>
<td>14.8</td>
<td>8.7</td>
<td>94</td>
</tr>
<tr>
<td>W</td>
<td>0.317 cm dia rods 30.5 cm long</td>
<td>46</td>
<td>Every other position</td>
<td>871</td>
<td>7.92</td>
<td>9.1</td>
<td>84, 86</td>
</tr>
<tr>
<td>W</td>
<td>0.317 cm dia rods 30.5 cm long</td>
<td>46</td>
<td>Every other position</td>
<td>2110</td>
<td>-4.27</td>
<td>-2.0</td>
<td>86, 87</td>
</tr>
<tr>
<td>Nb(b)</td>
<td>3/32 inch dia rods 30.48 cm long(c)</td>
<td>90(d)</td>
<td>All positions</td>
<td>1050</td>
<td>4.9</td>
<td>4.7</td>
<td>86, 107</td>
</tr>
<tr>
<td>CH2</td>
<td>0.317 cm dia rods 30.5 cm long</td>
<td>8</td>
<td>Odd number holes between 43-57</td>
<td>18.42(e)</td>
<td>24.43</td>
<td>1320</td>
<td>86, 88</td>
</tr>
<tr>
<td>C</td>
<td>0.120 inch dia rods 30.5 cm long(g)</td>
<td>23</td>
<td>Every 4th position</td>
<td>82</td>
<td>7.5</td>
<td>91</td>
<td>86, 94</td>
</tr>
<tr>
<td>B$_4$C</td>
<td>Filled with B$_4$C(g)</td>
<td>1</td>
<td>Center fuel tube position</td>
<td>30.5</td>
<td>-6.65</td>
<td>-220</td>
<td>91, 92</td>
</tr>
<tr>
<td>Stainless Steel(b)</td>
<td>Disc 0.317 cm thick for top of core tank</td>
<td>1</td>
<td>Top of core</td>
<td>1290</td>
<td>7.97(g)</td>
<td>6.2(g)</td>
<td>85, 86</td>
</tr>
<tr>
<td>Al(b)</td>
<td>Lid for top of core tank, 0.317 cm thick</td>
<td>1</td>
<td>Top of core</td>
<td>464</td>
<td>16.62(k)</td>
<td>36</td>
<td>85, 86</td>
</tr>
<tr>
<td>Al(b)</td>
<td>Lid for top of core tank, 0.159 cm thick</td>
<td>1</td>
<td>Top of core</td>
<td>226</td>
<td>8.14(l)</td>
<td>36(m)</td>
<td>85, 86</td>
</tr>
<tr>
<td>Cd(b)</td>
<td>Lid for top of core, 0.066 cm thick(a)</td>
<td>1</td>
<td>Top of core</td>
<td>286.5(e)</td>
<td>-45.7</td>
<td>-160(e)</td>
<td>91, 92</td>
</tr>
</tbody>
</table>
Benchmark Model Development

- Evaluated Uncertainties and Simplification Biases
  - MCNP5-1.60
  - ENDF/B-VII.0
- Both Detailed and Simple Benchmark Models Developed
  - Different End-Use
    - Nuclear Data
    - Computational Methods
Uncertainty Analyses

- Very precise measurements
  - Dimensions
  - Masses
  - Isotopics
  - Impurities

- Evaluated using perturbation analysis of parameters

Fuel Effect Worth:
- Fuel and fuel tube uncertainties evaluated as part of critical configuration
- All negligible for critical configurations except
  - Fuel tube composition – was systematic over all 253 fuel tubes and would be neg. for the worth of one fuel rod.
  - Mass of fuel per tube – had an effect of ±1.37 ℓ.

$10\% \sqrt{2}$ measurement uncertainty
Uncertainty Analyses

Neutron Moderating and Absorbing Material Worth:

- Evaluated for each material worth measurement:
  - Dimensions
  - Position
  - Composition

<table>
<thead>
<tr>
<th>Material</th>
<th>Components</th>
<th>Impurity or Mass (±)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS347 Rods</td>
<td></td>
<td>±0.1 e, ±2.49/√3 e</td>
</tr>
<tr>
<td>W Rods</td>
<td></td>
<td>±0.83/√3 e</td>
</tr>
<tr>
<td>Nb Rods</td>
<td></td>
<td>±0.23 e hydrogen to carbon ratio</td>
</tr>
<tr>
<td>CH₂ Rods</td>
<td></td>
<td>±0.19 e mass</td>
</tr>
<tr>
<td>Graphite Rods</td>
<td></td>
<td>±0.42/√3 e</td>
</tr>
<tr>
<td>B₄C Rod</td>
<td></td>
<td>±0.80 e impurity</td>
</tr>
<tr>
<td>SS Lid</td>
<td></td>
<td>±0.14e aluminum mass</td>
</tr>
<tr>
<td>Al Lids</td>
<td></td>
<td>±2.00/√3 e aluminum type</td>
</tr>
<tr>
<td>Cd Lid</td>
<td></td>
<td>±0.32 e impurity</td>
</tr>
</tbody>
</table>
# Uncertainty Evaluation

## Fuel Effect Reactivity Measurements and Uncertainties

<table>
<thead>
<tr>
<th>Distance from Core Center (Fuel Tube Position)</th>
<th>Experimental Worth with Experimental Uncertainty ($\phi$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 cm (1)</td>
<td>-32.0 ± 4.73</td>
</tr>
<tr>
<td>2.59 cm (2)</td>
<td>-32.0 ± 4.73</td>
</tr>
<tr>
<td>5.23 cm (3)</td>
<td>-30.8 ± 4.57</td>
</tr>
<tr>
<td>7.75 cm (4)</td>
<td>-27.2 ± 4.08</td>
</tr>
<tr>
<td>10.48 cm (5)</td>
<td>-25.5 ± 3.86</td>
</tr>
<tr>
<td>10.56 cm (6)</td>
<td>-25.6 ± 3.87</td>
</tr>
<tr>
<td>11.78 cm (7)</td>
<td>-22.6 ± 3.48</td>
</tr>
<tr>
<td>Accident Configuration Worth</td>
<td>-8.2 ± 1.79</td>
</tr>
</tbody>
</table>

## Material Reactivity Measurements and Uncertainties

<table>
<thead>
<tr>
<th>Absorbing or Moderating Material</th>
<th>Experimental Worth with Experimental Uncertainty ($\phi$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 Stainless Steel 347 Rods</td>
<td>14.8 ± 2.10</td>
</tr>
<tr>
<td>46 Stainless Steel 347 Rods</td>
<td>7.92 ± 1.82</td>
</tr>
<tr>
<td>46 Tungsten Rods</td>
<td>-4.27 ± 0.77</td>
</tr>
<tr>
<td>90 Niobium Rods</td>
<td>4.9 ± 0.69</td>
</tr>
<tr>
<td>8 Polyethylene Rods</td>
<td>24.43 ± 3.46</td>
</tr>
<tr>
<td>23 Graphite Rods</td>
<td>7.5 ± 1.10</td>
</tr>
<tr>
<td>$\text{B}_4\text{C}$ Filled Tube</td>
<td>-6.65 ± 0.94</td>
</tr>
<tr>
<td>Stainless Steel Lid</td>
<td>7.97 ± 1.38</td>
</tr>
<tr>
<td>0.3175 cm Thick Al Lid</td>
<td>16.62 ± 2.64</td>
</tr>
<tr>
<td>0.15875 cm Thick Al Lid</td>
<td>8.14 ± 1.66</td>
</tr>
<tr>
<td>Cadmium Lid</td>
<td>-45.7 ± 6.46</td>
</tr>
</tbody>
</table>
Simplification Bias

- Simplifications were made core configurations had a negligible effect on the worth measurements.

Bias Uncertainty of $\sim 1.6 - 1.7 \, \text{¢}$
Simplification Bias

- Simplifications were made core configurations had a negligible effect on the worth measurements.

Bias Uncertainty of ~1.6 – 1.7¢

90 Rods
- SS and Nb

46 Rods
- SS and W

8 CH₂- 43-57, odd #’s
Simplification Bias

- Simplifications were made core configurations had a negligible effect on the worth measurements.

Bias Uncertainty of $\sim 1.6 - 1.7 \text{¢}$
## Benchmark and Sample Calculation Results

### Calculation Results for Fuel Effect Reactivity

<table>
<thead>
<tr>
<th>Distance from Core Center (Fuel Tube Position)</th>
<th>Detailed Benchmark Model Value (ε)</th>
<th>Calculated Reactivity (ε)</th>
<th>(C-E)/E^{(a)}</th>
<th>C/E Ratio^{(a)}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 cm (1)</td>
<td>-32.00 ± 5.014 (15.7%)</td>
<td>-31.67 ± 1.18</td>
<td>-1.0% ± 15.9%</td>
<td>0.99</td>
</tr>
<tr>
<td>2.59 cm (2)</td>
<td>-32.00 ± 5.014 (15.7%)</td>
<td>-30.14 ± 1.18</td>
<td>-5.8% ± 15.2%</td>
<td>0.94</td>
</tr>
<tr>
<td>5.23 cm (3)</td>
<td>-30.80 ± 4.861 (15.8%)</td>
<td>-28.47 ± 1.18</td>
<td>-7.6% ± 15.1%</td>
<td>0.92</td>
</tr>
<tr>
<td>7.75 cm (4)</td>
<td>-27.20 ± 4.411 (16.2%)</td>
<td>-27.21 ± 1.18</td>
<td>0.0% ± 16.8%</td>
<td>1.00</td>
</tr>
<tr>
<td>10.48 cm (5)</td>
<td>-25.50 ± 4.203 (16.5%)</td>
<td>-24.57 ± 1.18</td>
<td>-3.6% ± 16.5%</td>
<td>0.96</td>
</tr>
<tr>
<td>10.56 cm (6)</td>
<td>-25.60 ± 4.215 (16.5%)</td>
<td>-23.18 ± 1.18</td>
<td>-9.5% ± 15.6%</td>
<td>0.91</td>
</tr>
<tr>
<td>11.78 cm (7)</td>
<td>-22.60 ± 3.828 (16.9%)</td>
<td>-20.40 ± 1.08</td>
<td>-9.7% ± 16.0%</td>
<td>0.90</td>
</tr>
<tr>
<td>Accident Configuration Worth</td>
<td>-8.20 ± 2.448 (29.9%)</td>
<td>-8.04 ± 1.18</td>
<td>-1.9% ± 32.6%</td>
<td>0.98</td>
</tr>
</tbody>
</table>

^{(a)} “E” is the experimental benchmark value. “C” is the calculated value.
# Benchmark and Sample Calculation Results

## Calculation Results for Material Reactivity

<table>
<thead>
<tr>
<th>Absorbing or Moderating Material</th>
<th>Detailed Benchmark Model Value ($\phi$)</th>
<th>Calculated Reactivity ($\phi$)</th>
<th>$(C-E)/E$ (%)</th>
<th>C/E Ratio(a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 Stainless Steel 347 Rods</td>
<td>14.80 ± 2.675 (18%)</td>
<td>21.44 ± 1.18</td>
<td>44.9% ± 27.4%</td>
<td>1.45</td>
</tr>
<tr>
<td>46 Stainless Steel 347 Rods</td>
<td>7.92 ± 2.467 (31%)</td>
<td>8.45 ± 1.18</td>
<td>6.7% ± 36.4%</td>
<td>1.07</td>
</tr>
<tr>
<td>46 Tungsten Rods</td>
<td>-4.27 ± 1.776 (42%)</td>
<td>-1.11 ± 1.08</td>
<td>-74.0% ± 27.6%</td>
<td>0.26</td>
</tr>
<tr>
<td>90 Niobium Rods</td>
<td>4.90 ± 1.802 (37%)</td>
<td>8.45 ± 1.18</td>
<td>72.4% ± 67.8%</td>
<td>1.72</td>
</tr>
<tr>
<td>8 Polyethylene Rods</td>
<td>24.43 ± 3.841 (16%)</td>
<td>22.83 ± 1.18</td>
<td>-6.6% ± 15.5%</td>
<td>0.93</td>
</tr>
<tr>
<td>23 Graphite Rods</td>
<td>7.50 ± 1.997 (27%)</td>
<td>7.76 ± 1.18</td>
<td>3.4% ± 31.7%</td>
<td>1.03</td>
</tr>
<tr>
<td>B,C Filled Tube</td>
<td>-6.65 ± 1.919 (29%)</td>
<td>-8.22 ± 1.18</td>
<td>23.6% ± 39.8%</td>
<td>1.24</td>
</tr>
<tr>
<td>Stainless Steel Lid</td>
<td>7.97 ± 2.162 (27%)</td>
<td>9.83 ± 1.18</td>
<td>23.4% ± 36.6%</td>
<td>1.23</td>
</tr>
<tr>
<td>0.3175 cm Thick Al Lid</td>
<td>16.62 ± 3.121 (19%)</td>
<td>19.65 ± 1.18</td>
<td>18.2% ± 23.3%</td>
<td>1.18</td>
</tr>
<tr>
<td>0.315875 cm Thick Al Lid</td>
<td>8.14 ± 2.353 (29%)</td>
<td>8.86 ± 1.18</td>
<td>8.9% ± 34.6%</td>
<td>1.09</td>
</tr>
<tr>
<td>Cadmium Lid</td>
<td>-45.70 ± 6.659 (15%)</td>
<td>-31.94 ± 1.18</td>
<td>-30.1% ± 10.5%</td>
<td>0.70</td>
</tr>
</tbody>
</table>

(a) “E” is the experimental benchmark value. “C” is the calculated value.
Summary of What is Currently Evaluated

- **Three graphite-reflected criticals**
  - Varying reflector thicknesses
  - Varying fuel rod pitch
  - Radial cadmium ratio distributions
  - Graphite plug worth
  - Center fuel rod worth
  - Axial and radial fission-rate distributions

- **Two beryllium-reflected criticals**
  - Varying fuel rod configurations
  - Axial cadmium ratio distributions
  - Axial and radial fission-rate distributions
  - Fuel Effect Reactivity Measurements
  - Material Reactivity Measurements

Two new critical configurations will be added for the potassium worth measurements.
Worth of Potassium in Core

Currently only one benchmark to validate potassium
Conclusions

- **MPRE Critical Assemblies Evaluated**
  - Three graphite-reflected
  - Two beryllium-reflected

- **Reactivity Measurements Evaluated**
  - Higher uncertainty
  - Unique measurements

- **Reactor physics measurements**
  - Graphite measurements evaluated
  - Beryllium measurement evaluation in progress
Acknowledgments

- John T. Mihalczo (Experimenter) – ORNL
- Mike Murphy (Reviewer) – UKAEA (retired)
- Scientists, engineers, and administrative support from over 20 countries participating in the ICSBEP and IRPhEP
Extra Slides
Purpose of the International Criticality Safety Benchmark Evaluation Project (ICSBEP)

- Identify comprehensive sets of critical benchmark data
  - Verify the data to the extent possible
- Evaluate data and quantify overall uncertainties
- Compile the data into a standardized format
  - Single source of formally documented work
ICSBEP Handbook

September 2013 Edition

- 20 Contributing Countries
- Spans nearly 65,000 Pages
- Evaluation of 558 Experimental Series
- 4,798 Critical, Subcritical, or $K_\infty$ Configurations
- 24 Criticality-Alarm/ Shielding Benchmark Configurations – numerous dose points each
- 155 fission rate and transmission measurements and reaction rate ratios for 45 different materials

http://icsbep.inel.gov/
http://www.oecd-nea.org/science/wpnecs/icsbep/
SCCA-SPACE-EXP-001 – Graphite Reflected

- 2 Critical Configurations
  - Thick Radial, Thin Axial
  - Thin Radial, Thick Axial
- Tight-Packed Fuel
- Fission-Rate Distributions
- Cadmium-Ratio Distributions
SCCA-SPACE-EXP-002 – Graphite Reflected

- 1 Critical Configuration
  - Balanced Reflector
    - Flat Axial and Radial Power Profile (Goal)
- 1.506 cm Δ Pitch
- Repeated Reactor Physics Measurements