BeRP Ball Reflected By Nickel Benchmark Evaluation

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General Overview

- The BeRP ball reflected by nickel benchmark evaluation was published in the 2014 edition of the ICSBEP handbook.

- **This benchmark was the first:**
  - Published benchmark evaluation of measurements performed at NCERC (or anywhere inside DAF).
  - Benchmark evaluation using new MCNP capabilities for subcritical systems (the MCNP list-mode patch and MCNP6 list-mode capabilities).
  - Benchmark using the Feynman Variance-to-Mean method.
  - LANL-led subcritical experiment in the ICSBEP handbook.

- **This benchmark was the culmination of the last 5 years of subcritical experiment research funded by the NCSP.**
General Overview

- **Sub-critical multiplying systems provide valuable information.**
  - Validation of nuclear data and codes.
  - Uncertainty quantification for various applications.
  - Design of future measurements.

- **Monte Carlo simulations of an experimental subcritical benchmark:**
  - Help validate improvements in computational tools.
  - Provide better predictability and understanding in the sensitivities and uncertainties associated with subcritical systems.

- **These subcritical measurements are classified as fundamental physics measurements (Volume IX) in the ICSBEP handbook with the designator:**
  FUND-NCERC-PU-HE3-MULT-001

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**Fundamental physics measurements**

**Facility name**

**Source type:** Pu fission

**Target material:** He-3 detectors

**Experiment type:** neutron multiplication measurements
Timeline

- July 2007: Subcritical operations started at DAF including first BeRP ball measurements.
- September 2008: BeRP reflected by Ni measurements performed.
- 2009-2010: Evaluation of BeRP/Ni measurements submitted to ICSBEP. The evaluation was rejected because the experimental uncertainties and biases were not well understood and documented. In addition, the simulation capabilities were outdated and not useful for users.
- 2010-2012: NCSP-funded three year project to improve subcritical measurements. Focus on simulations and uncertainty analysis.
  - July 2011: Workshop held to discuss the future of subcritical measurements in Los Alamos. Attendees included personnel from LANL, OECD, CEA, INL, NCSU, ISU, and ANL.
Timeline

The BeRP/Ni experiment went through the CEdT process:

- Initial draft of CED-1 document sent to the team in late 2011.
- 7/18/12: CED-1 approval.
- 9/10/12: CED-2 approval.
- 9/14/12: CED-3a approval.
- Week of 9/17/12: Experiment execution.
- January 2013: CED-3b document sent to CED team (draft of Section 1 of the ICSBEP evaluation).
- 8/01/13: CED-3b approval.
- 3/17/14: Draft evaluation sent to external reviewers (effectively ending CED-4a).
- 4/14/14: Submitted draft evaluation to the ICSBEP working group.
- 5/16/14: ICSBEP working group provided action items for the evaluation.
- 7/18/14: Submitted draft addressing all action items to the ICSBEP subcommittee.
- 9/01/14: Submitted final version to ICSBEP.
More than your average benchmark

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  - 1. MISC: new tool to accurately model source term (decay for material composition and proper neutron emission).
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- 2. MCNP5 implementation (list-mode patch).
- 3. Ability to convert MCNP5 simulations to measured data format.
- 4. Ability to convert MCNP6 simulations to measured data format.
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This was also presented at the 2014 ANS winter meeting.
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This will be presented at the 2015 ICNC meeting.
More than your average benchmark

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  2. Measured data must be binned. A study was performed on various binning methods for benchmark applications.
  3. Uncertainty analysis had to be developed and validated.
  4. The external reviewer at LLNL performed independent data analysis using a different method.

LLNL and LANL results agreed very well. A detailed comparison is presented in the evaluation.
More than your average benchmark

- ALL of the documents mentioned above are included with the evaluation. This includes the source code for the MCNP5 list-mode patch.

- In addition, all references, appendices, and footnote documents are included.

- ALL measured data is included in the evaluation:
  - Raw list-mode neutron data.
  - Processed list-mode neutron data (using multiple binning methods).
  - Raw gamma spectra.

- These data make this by far the largest file size of any benchmark.
  - Total uncompressed file size for measured data is >1 GB.
  - For this reason, the OECD has two links for downloading the full 2014 edition (https://www.oecd-nea.org/science/wpnecs/icsbep/handbook.html):
    - 2. Volume IX: 0.99 GB zip file (the BeRP/Ni benchmark makes up 97% of this).
BeRP Ball

- $\alpha$-phase plutonium sphere (93.7 wt.% of Pu 239)
- 4.5 kg, 3.0” diameter
- Encapsulated in a SS 304 cladding
- Machined in 1980

Previous experiments:
- Be reflected critical experiment (PU-MET-FAST-038)
- HEU reflected "Rocky Flats Shells" critical experiment (MIX-MET-FAST-013)
- CSDNA subcritical noise measurements with polyethylene reflection (SUB-PU-MET-FAST-001) and nickel reflection
Nickel shells

- Reactivity range: $k_{\text{eff}} = 0.79$ to $k_{\text{eff}} = 0.92$.
- 7 configurations: Bare BeRP to 3.0 inch-thick Ni reflection.

- 6 layers, each being 0.5” thick → maximum thickness: 3.0”
- Each layer is composed of 2 combined shells
Measurement setup

Experimental configuration and instrumentation

- Two NPODs, aka multiplicity counters, 15 He3 tubes inside a polyethylene body which provide list-mode data

- Construction of the Feynman histograms to deduce the asymptotic counting rates $R_1$, $R_2$, ($R_3$ ...)
  - $R_1$: singles asymptotic counting rate (related to $\bar{\nu}$)
  - $R_2$: doubles asymptotic counting rate (related to $\nu(\nu - 1)$)

- 1 SNAP, aka gross neutron counter

- 1 HPGE, gamma detector
**Benchmark quantities**

- Must be deduced from well-known and fieldproven techniques
- Fundamental quantities having nevertheless a practical meaning
- Accessible and reliable uncertainty determination
- Must enable the discrimination without any ambiguity of each studied configuration

### Selected quantities

- **Directly deduced from the Feynman histogram:**
  - $R_1$: singles asymptotic counting rate
  - $R_2$: doubles asymptotic counting rate
- **$M$: neutron multiplication**

Beneficial because they are basic quantities (easy to measure). Unfortunately the values are dependent upon the detector system.

Leakage multiplication beneficial because the value is independent of the detector system used (note that the uncertainty is still dependent upon the detector system). A more advanced parameter that involves additional calculation and assumptions to obtain.
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Note that $k_{\text{eff}}$ is not a benchmarked quantity in this evaluation. Measured $k_{\text{eff}}$ values are, however, given for each of the seven configurations in the evaluation.
Sensitivity/Uncertainty Study – Experimental Data

Illustration on the 3.0” thick reflected case

44 independent uncertainties on experimental data divided in 4 broad categories

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<th>R₁</th>
<th>R₂</th>
<th>M₁</th>
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<td>3.49 %</td>
<td>0.76 %</td>
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Uncertainty R₁

Uncertainty R₂

Uncertainty M₁
Models

Detailed model
- As close as possible to engineering specifications
- Impurities are modeled
- Expensive simulations (3.0-in / 2 hours / 128 proc. / MCNP5-Moonlight)

Simplified model
- Simplified geometry
  - BERP ball
  - Detectors
- No impurities
- Concrete walls removed
- Large improvements in computational time (3.0-in / 15 min. / 128 proc. / MCNP5-Moonlight)

Global/individual simplification biases have been estimated and are included in the evaluation.

Room return and detector presence on the benchmark quantities was evaluated.
Comparison Experiment-Simulation on $R_1$
Comparison Experiment-Simulation on $R_2$

Note that the measured and simulated data were analyzed using the exact same:

- Binning technique.
- System of equations.
- Nuclear data parameters.
For all three benchmark quantities JEFF 3.1 resulted in values closer to the experimental results than ENDF/B-VII.
Conclusions

- Criteria is met to make this benchmark (Ni) acceptable, for the three benchmarked quantities

- Results can still be improved:
  - Methodological biases induced by calibration experiments
  - Composition of the polyethylene used in the NPODs

- Preliminary results for the W benchmark are encouraging: submission next year

- Good starting point to go beyond: inference model benchmark

- Study of the response given by the Gamma detector (gamma coincidences)
Future work

- In September 2012, measurements were also performed with the BeRP ball reflected by Tungsten.
  - Planned to submit to ICSBEP for May 2015 meeting but funding was suspended due to recent NCERC critical assembly shutdown. Work will resume later in 2015 and the evaluation will be submitted for the May 2016 meeting. LLNL and IRSN will both provide external reviews.

- Many IERs exist related to subcritical measurements. Two important ones for LANL include:
  - 1. IER-111: BeRP ball reflected by copper.
    - This would further the subcritical experiments capability. Training of staff on subcritical experiment execution will also be performed.
    - IRSN has expressed interest in these measurements (see IRSN-AM4-IE16-T&E1).
    - Will build upon recent measurements on Caliban, Godiva-IV, Planet (Lucite class foils experiment), and Flat-Top (with HEU core).
    - Will be the only measured list-mode data set on a thermal system in which reactivity states from control rod worth curves can be compared.
Acknowledgements

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  - The subgroup for this benchmark at the ICSBEP consisted of members from the US, France, UK, Slovenia, and Russia.
  - Members from LLNL, ORNL, and INL contributed both at ICSBEP and on the Critical Experiments Design Team (CEdT).
  - NEN-6 and NSTec helped with support at the DAF to accomplish these measurements.
  - Benoit Richard and Theresa Cutler should be recognized for the huge amount of effort they put into this work.
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  - We would like to thank Gregory Keefer and Sean Walston from LLNL and John Bess from INL. Their thorough reviews greatly improved the quality of the evaluation.
  - Last, we would like to thank Bill Myers, Dave Hayes, Avneet Sood, and Bob Margevicius for their continued support of this work.