Subcritical Benchmark of the BeRP Ball Reflected by Tungsten

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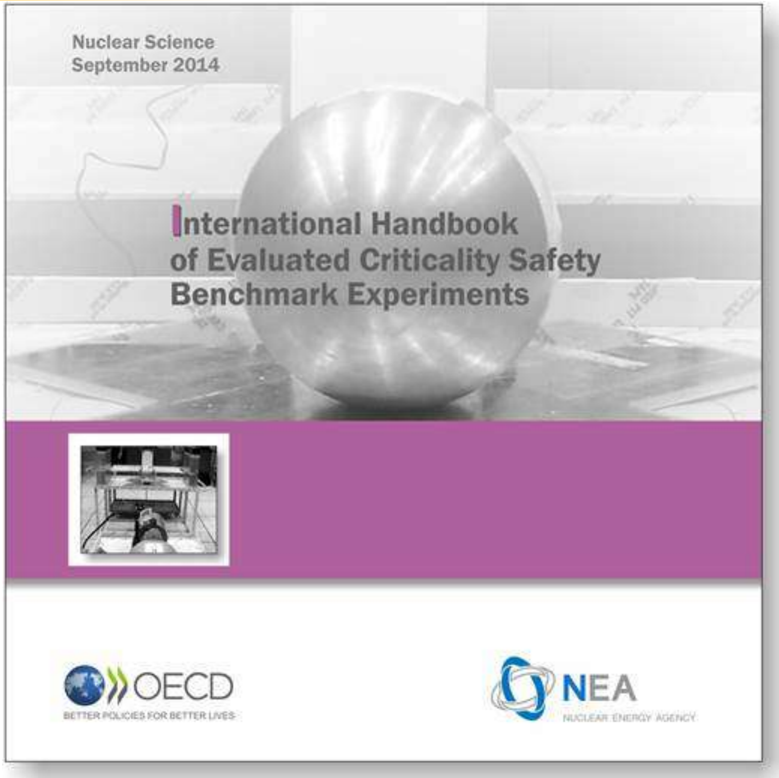
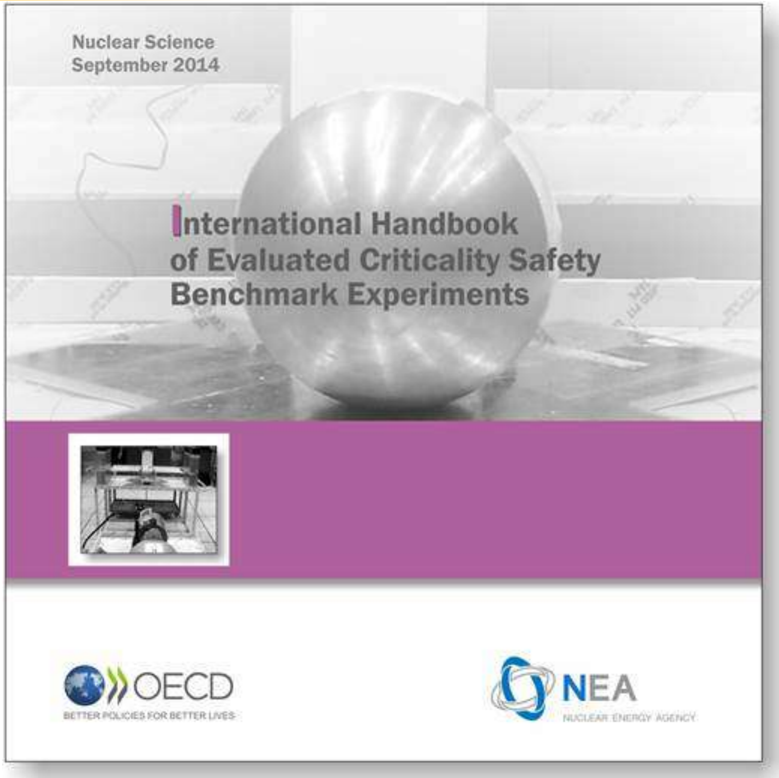
General Overview

- **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 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

- **The BeRP ball reflected by tungsten benchmark evaluation is very similar to the nickel evaluation.**
  - Same detectors
  - Same Pu sphere
  - Same experimental setup
  - Same data analysis methods
- **Included in the 2016 edition of the ICSBEP handbook.**
- **Benchmark measurements were performed in September 2012 at the National Criticality Experiments Research Center (NCERC).**
- **This work presents measurement and simulation results.**



Main difference between this talk and the NCSP TPR talk: all results here are final.

ANS transactions has preliminary results.

General Overview

- **Subcritical multiplying systems provide valuable information.**
  - Validation of nuclear data and codes.
  - Uncertainty quantification for various applications.
  - Allows for multiple configurations at various reactivity states for a single experiment.

- **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.

BeRP Ball

- **α-phase plutonium sphere (93.73 wt.% Pu-239)**
- **4483.884 g, 7.5876 cm diameter**
- **Calculated density 19.604 g/cm^3**
- **Encapsulated in SS 304 cladding**
- **Machined in 1980**
- **Previous benchmarks:**
  - Be reflected critical experiment (PU-MET-FAST-038)
  - HEU “reflected” “Rocky Flats Shells” (MIX-MET-FAST-013)
  - CSDNA subcritical noise measurements with polyethylene reflection (SUB-PU-MET-FAST-001)
  - Ni reflected subcritical experiment (FUND-NCERC-PU-HE3-MULT-001)

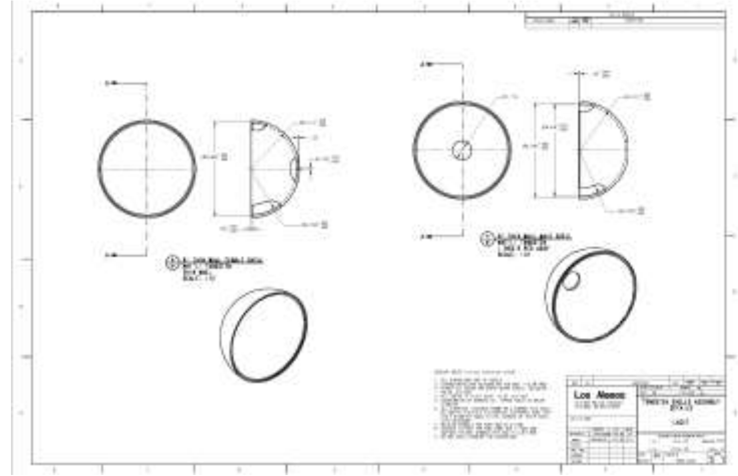
Tungsten shells

- Reactivity range: k_{eff} = 0.78 to k_{eff} = 0.94
- 8 configurations: 0 (bare), 0.5, 1.0, 1.5, 2.0, 2.5, 2.75, 3.0 inch-thick W
- 7 layers, each layer is composed of two hemishells
- Class 4 tungsten: nominally 97 wt.% W (balance mostly Ni and Fe)

Tungsten shells

- Average density of 18.567 g/cm³

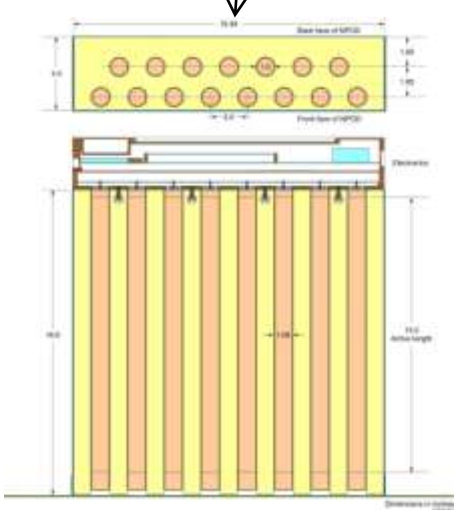
Outermost Nickel Shell Thickness (in.)	ID (in.)	OD (in.)	Measured Mass (g)		Calculated Volume (cm³)	Calculated Density (g/cm³)
	Male + Female Shell	Male + Female Shell	Male Shell	Female Shell	Male + Female Shell	Male + Female Shell
0.5	1.5375	2.0145	2608.3	2614.6	285.42	18.299
1.0	2.0205	2.5145	4786.1	4675.2	510.18	18.545
1.5	2.5205	3.0145	7276.4	6989.8	768.83	18.556
2.0	3.0205	3.5145	10258.5	9879.2	1078.66	18.669
2.5	3.5205	4.0145	13553.7	13253.6	1440.05	18.616
2.75	4.0205	4.2555	7811.1	7886.6	836.53	18.765
3.0	4.2615	4.5145	9382.9	9364.0	1012.55	18.515
Average						18.567

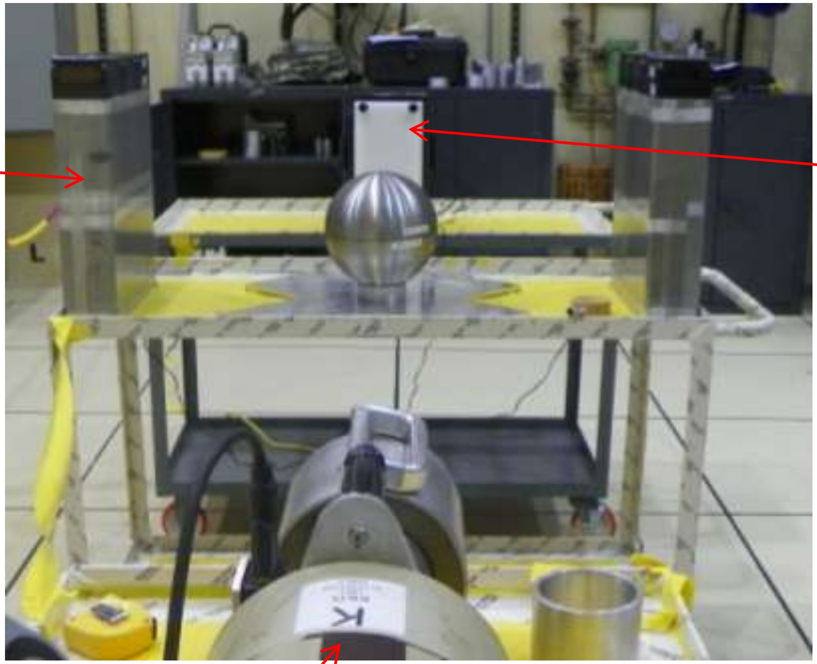


Detector setup

NPOD detectors: 15 He-3 tubes inside polyethylene and wrapped in Cd.

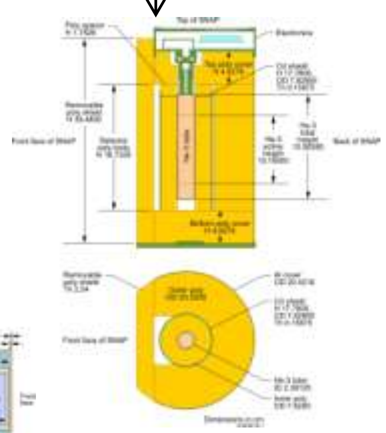
50.0 cm from center of BeRP to Cd face of NPOD.





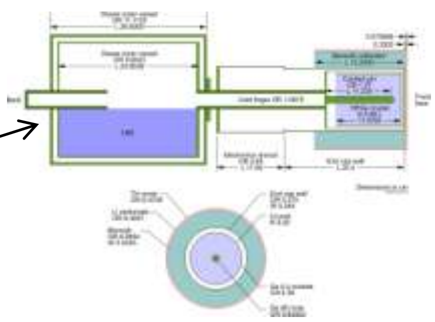
SNAP detector: Single He-3 tube inside polyethylene and Cd. Has a removable 1 inch-thick poly shield.

100.0 cm from center of BeRP to center of He-3 tube.



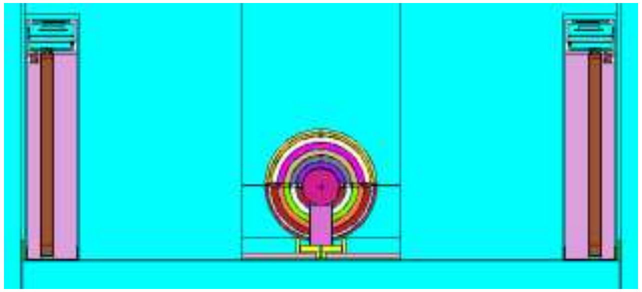
HPGe detector: LN2 cooled HPGe detector with bismuth collimator.

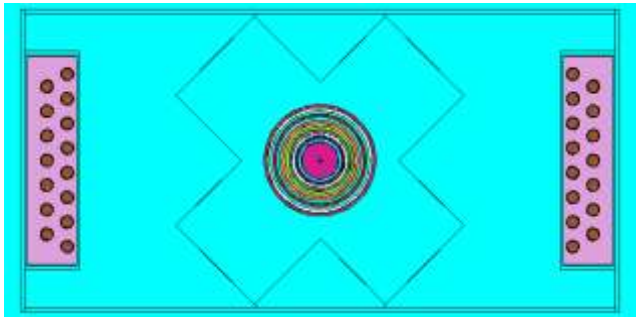
150.0 cm from center of BeRP to face of detector.

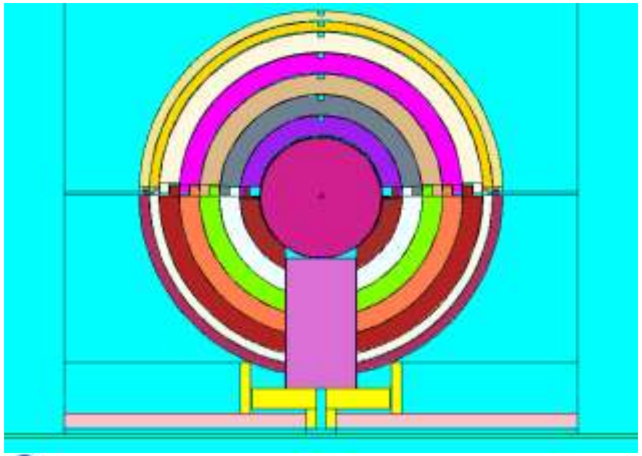


Model

- Detailed model includes Pu sphere, cladding, Al stands, Al base plate, carbon steel cart, detector systems, and concrete.
- Simplified model also included (no concrete, simplified geometry and materials).
- Biases described for both models.

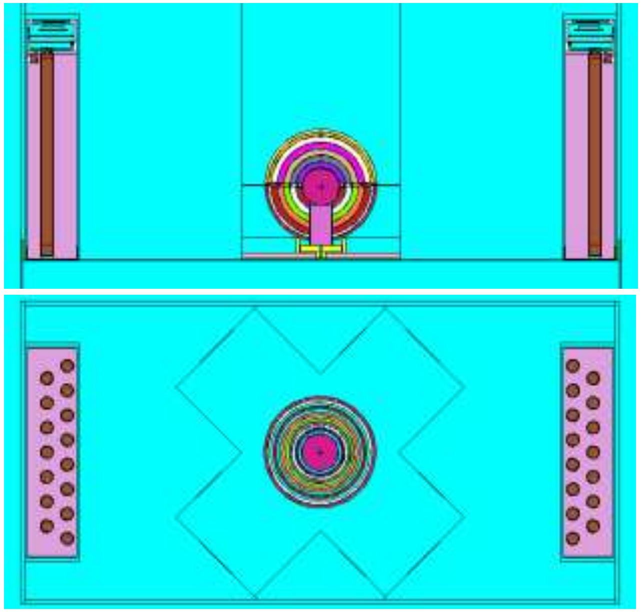






Model

- MCNP®6 with ENDF/B-VII.1 cross-sections was used for the benchmark models (used for sensitivity/uncertainty analysis to determine experimental uncertainties).
- Additional simulations performed using:
  - MCNP®6 with JEFF 3.1
  - MORET with ENDF/B-VII.1
  - MCNP®5 with ENDF/B-VII.1 (using the list-mode patch).



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

Documented in a LANL report and ICNC 2015 paper.

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). Uncertainties are purely statistical. 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.

Benchmark quantities

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Selected quantities

- Directly deduced from the Feynman histogram:
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  - R_2: doubles asymptotic counting rate
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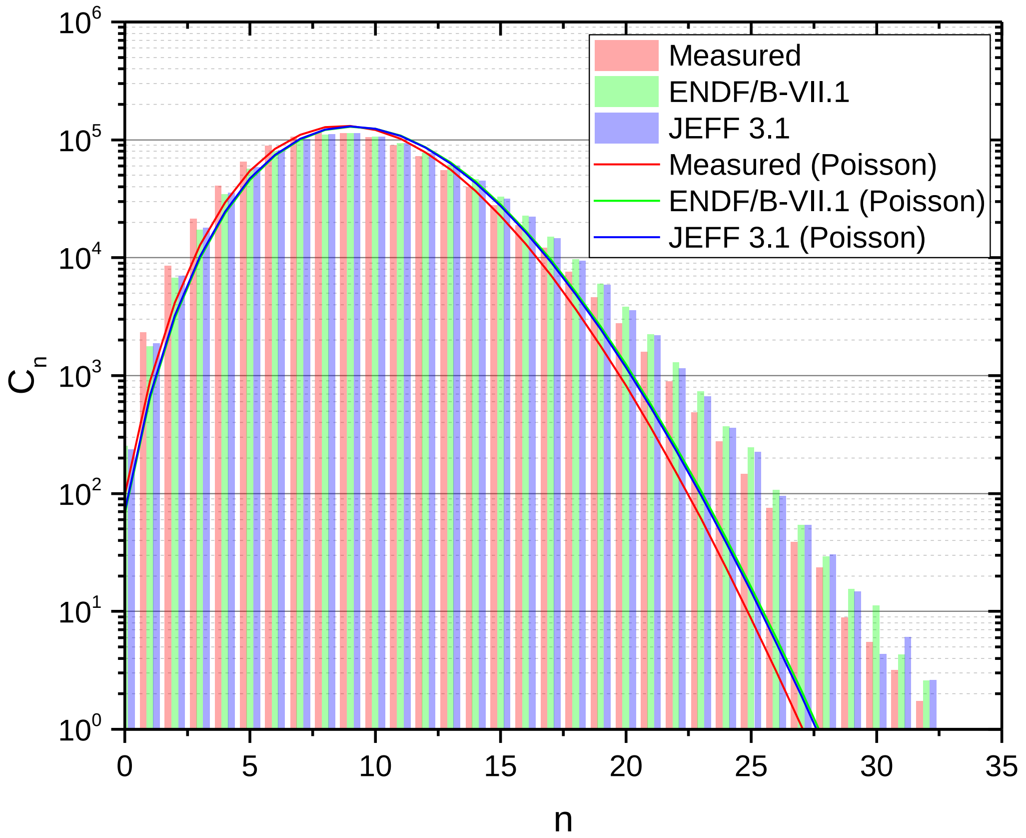
Note that k_{eff} is not a benchmarked quantity in this evaluation. Measured k_{eff} values are, however, given for each of the configurations.

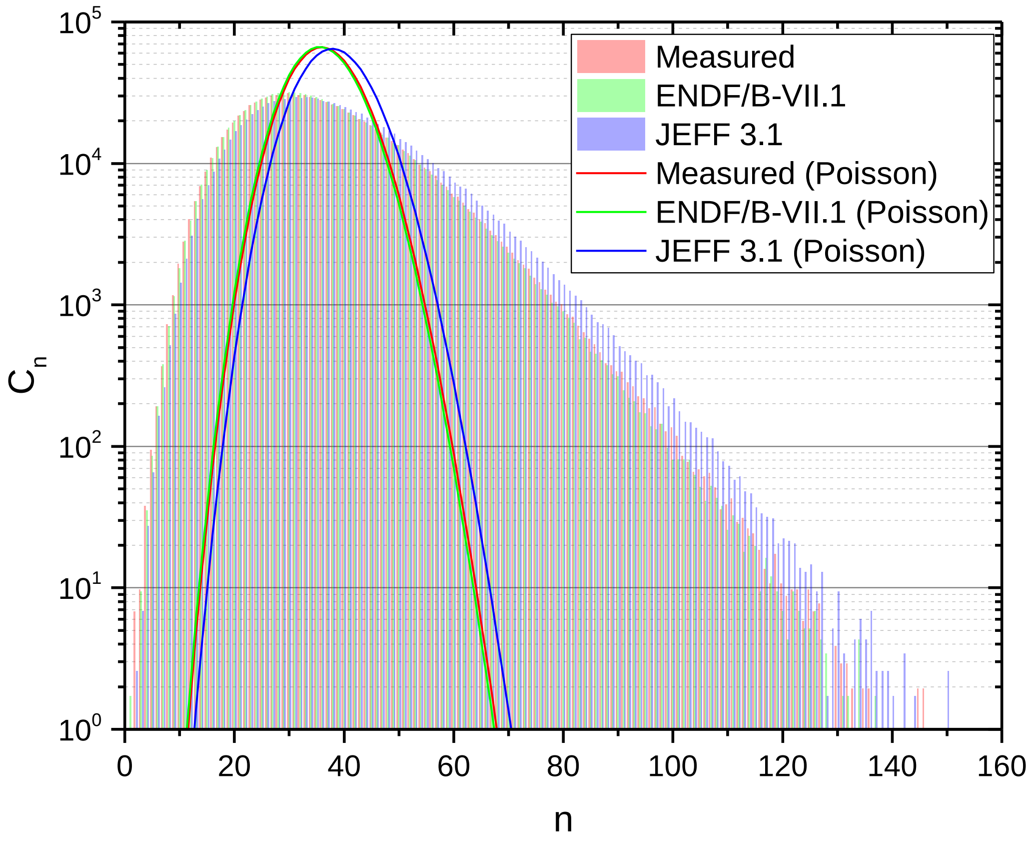
BeRP results: histograms



Bare configuration

Gate-width: 1024 micro-sec

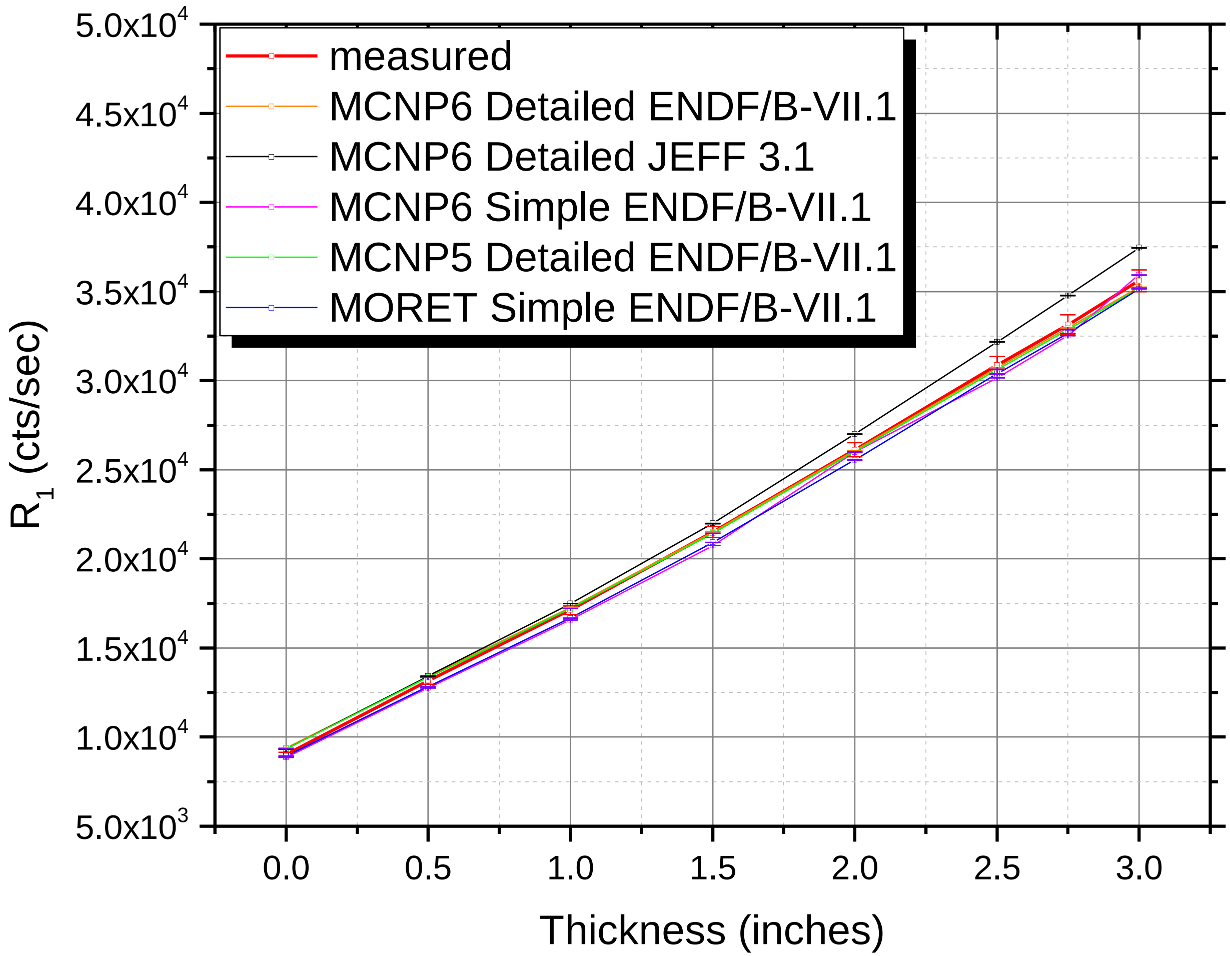
BeRP results: histograms



3.0 inch-thick W configuration

Gate-width: 1024 micro-sec

BeRP results: R_1 (singles counting rate)



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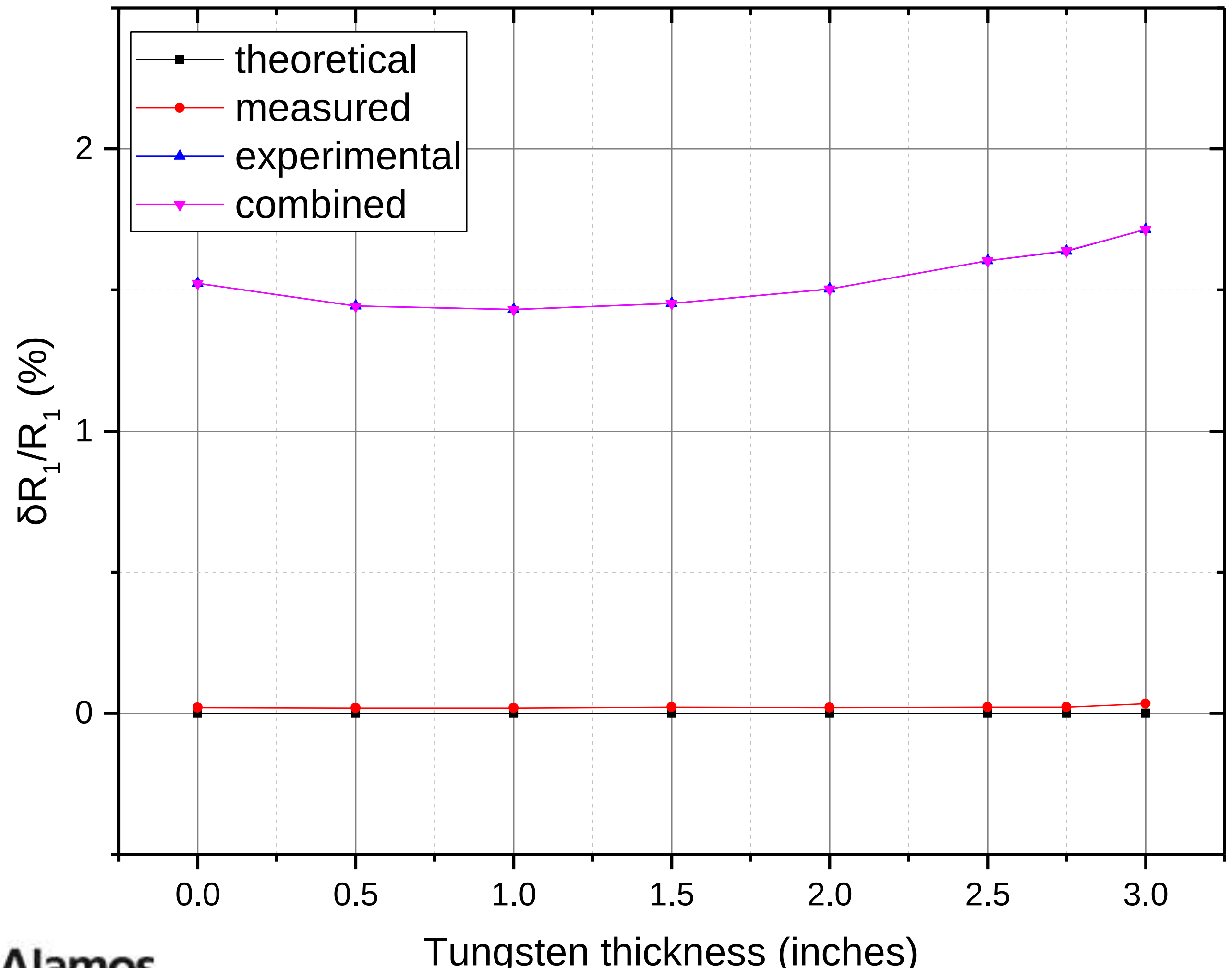
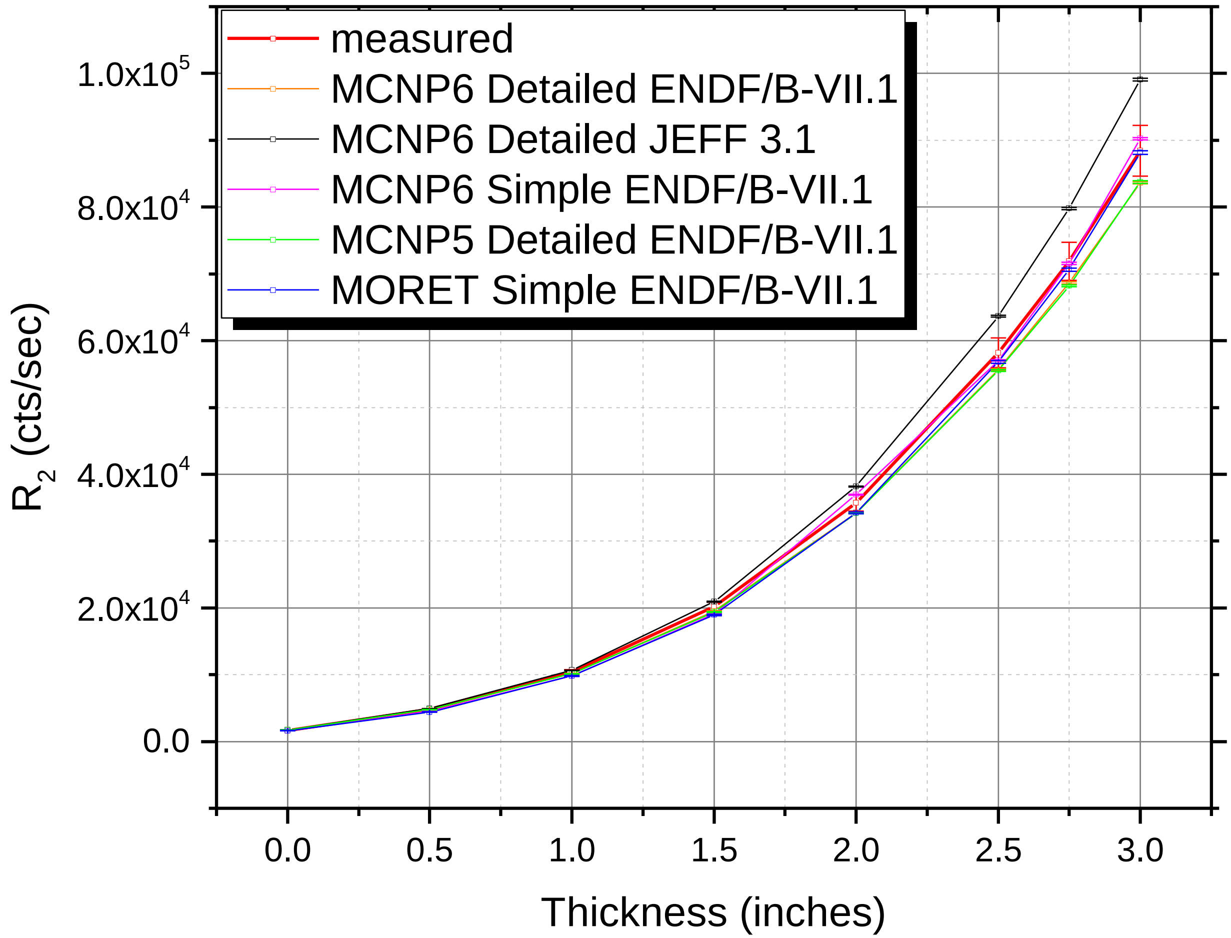


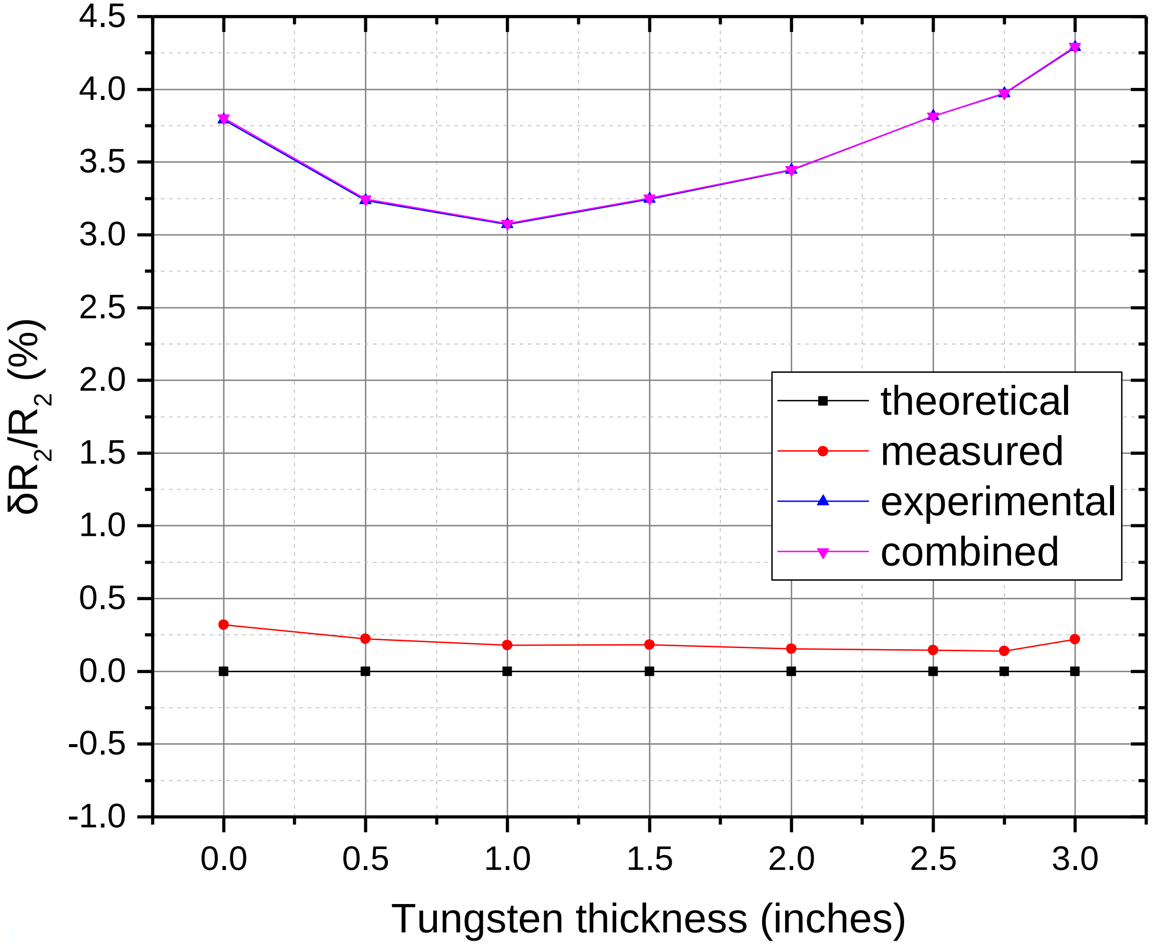
Experimental (systematic) uncertainties dominated the total combined uncertainty.

Uncertainties in 30 different experimental parameters contribute to the experimental uncertainties.

BeRP results: R_2 (singles counting rate)

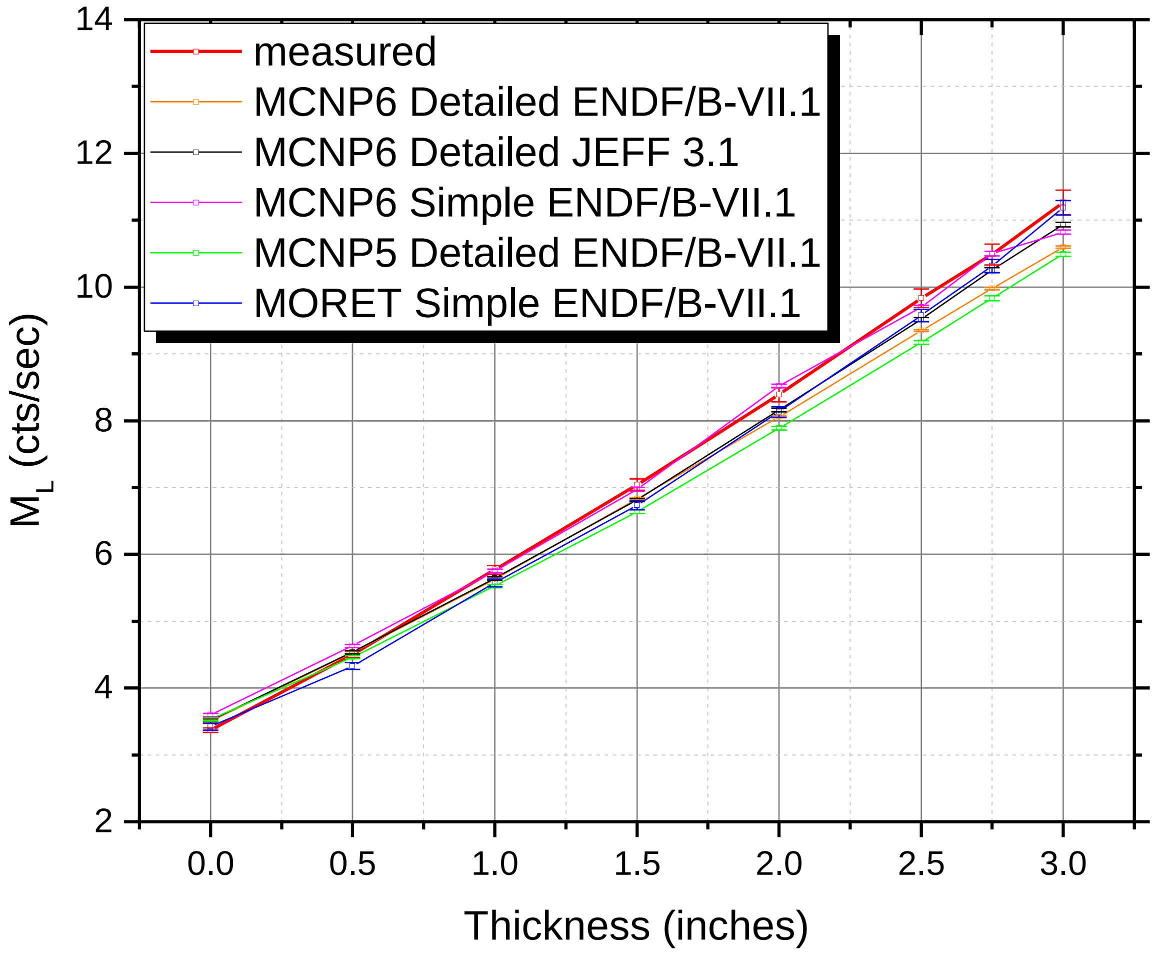


BeRP results: R_2 (singles counting rate)

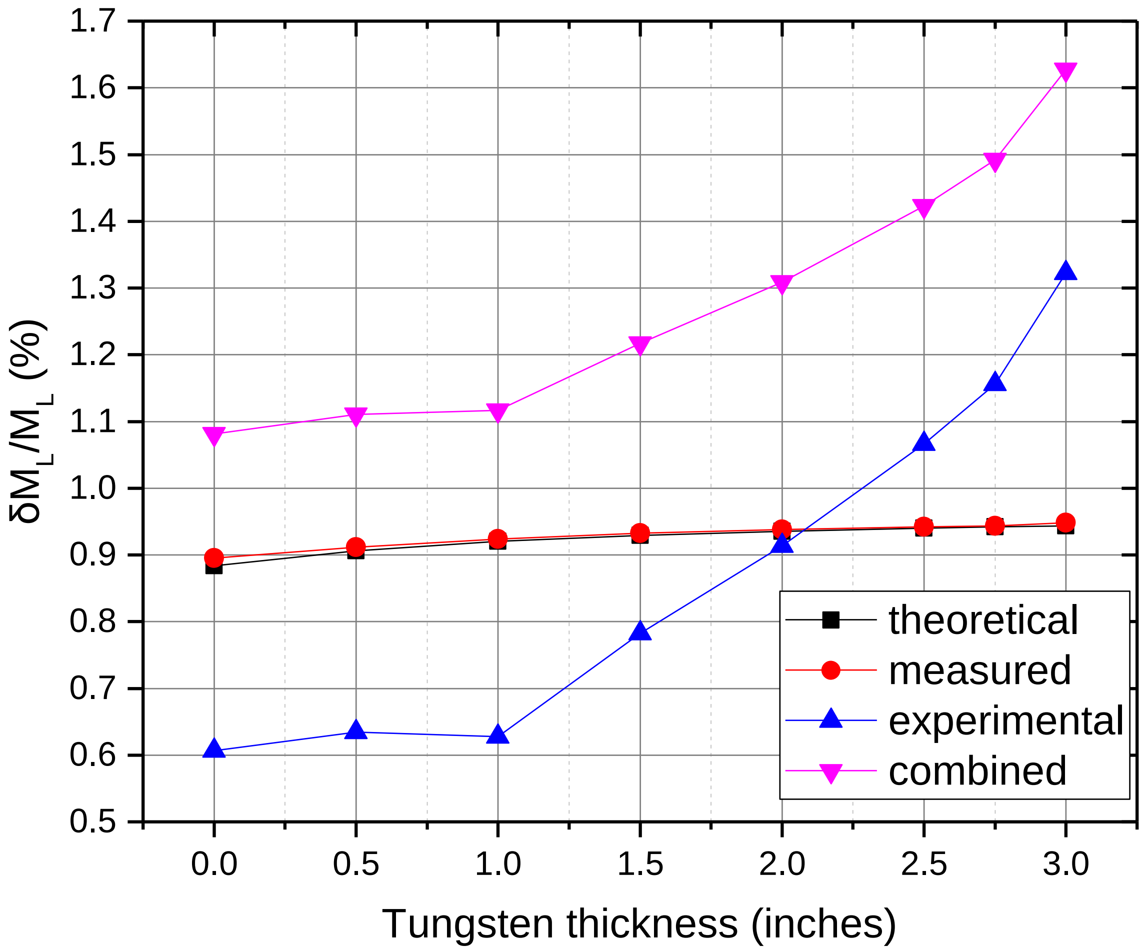


Experimental (systematic) uncertainties dominated the total combined uncertainty.

BeRP results: leakage multiplication



BeRP results: leakage multiplication



Experimental and measurement uncertainties both contribute significantly to the total combined uncertainty.

BeRP results: ranking of major experimental uncertainties

R_1

Parameter	Case							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
NPOD (distance from BERP ball lengthwise)	1	1	1	1	1	1	1	1
Polyethylene mass	2	2	2	2	2	4	4	4
Composition of concrete	3	3	3	4	5	5	5	-
Plutonium sphere radius (includes both tolerance and temperature variation)	-	-	4	3	3	2	2	2
Tungsten shells thickness by configuration	-	-	-	-	4	3	3	3
Plutonium assay	-	-	-	-	-	-	-	5

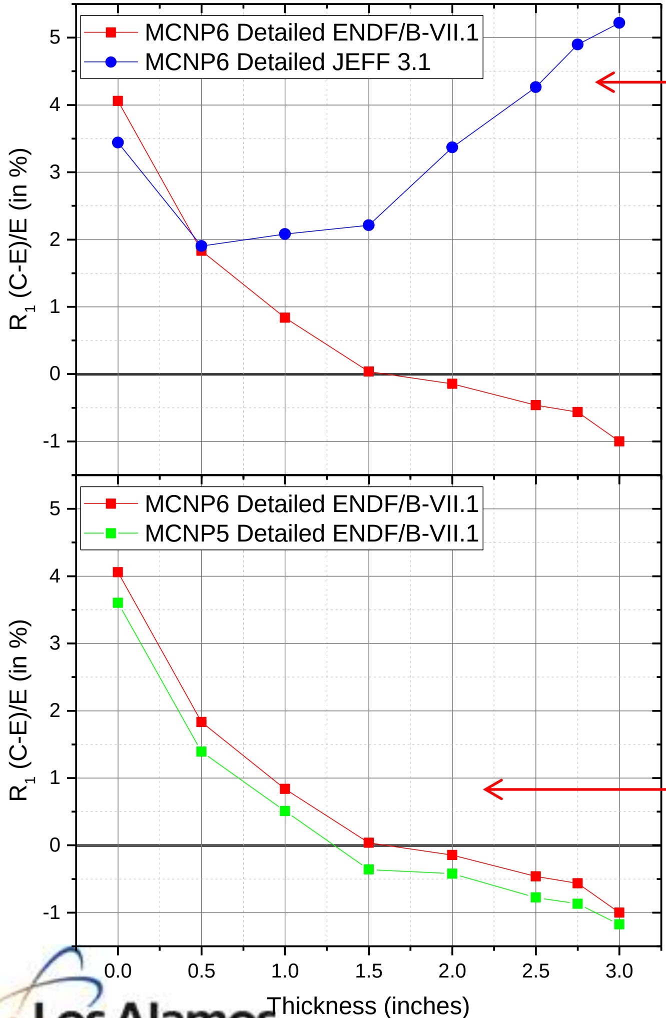
R_2

Parameter	Case							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Polyethylene mass	1	2	2	3	4	5	-	-
NPOD (distance from BERP ball lengthwise)	2	1	1	1	1	2	2	3
Plutonium sphere radius (includes both tolerance and temperature variation)	3	3	3	2	2	1	1	1
Composition of concrete	-	4	-	5	-	-	-	-
Tungsten shells thickness by configuration	-	-	4	4	3	3	3	2
Plutonium assay	-	-	-	-	5	4	4	4
Deadtime	-	-	-	-	-	6	5	5

M_L

Parameter	Case							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Plutonium sphere radius (includes both tolerance and temperature variation)	1	1	1	1	3	2	2	1
Deadtime	-	2	2	2	1	1	1	3
Tungsten shells thickness by configuration	-	-	3	3	2	3	3	2
Plutonium assay	-	-	4	-	4	-	-	-

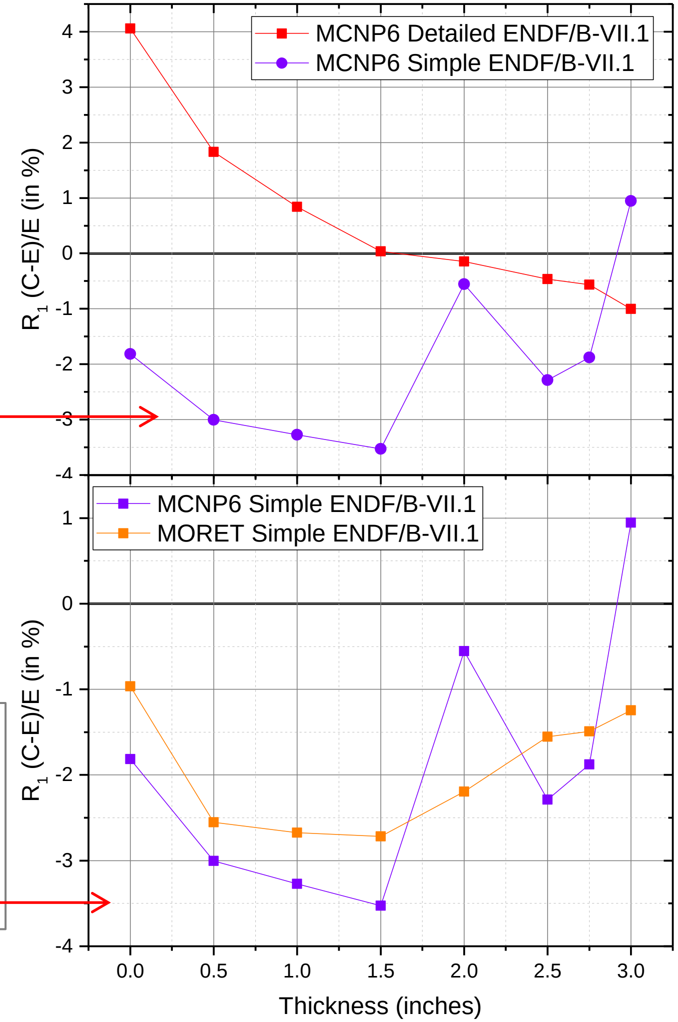
Simulation comparisons (R_1)



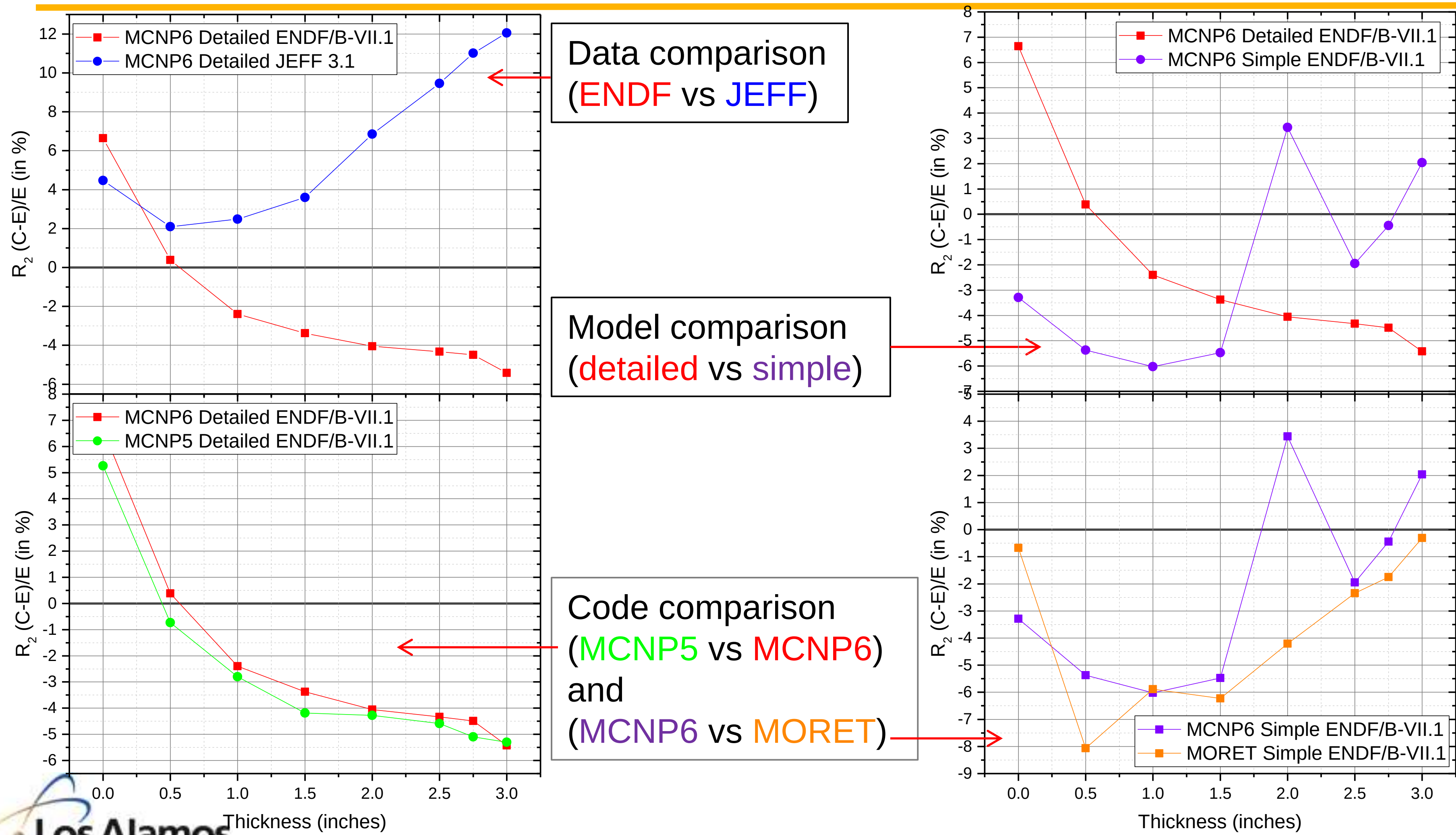
Data comparison (ENDF vs JEFF)

Model comparison (detailed vs simple)

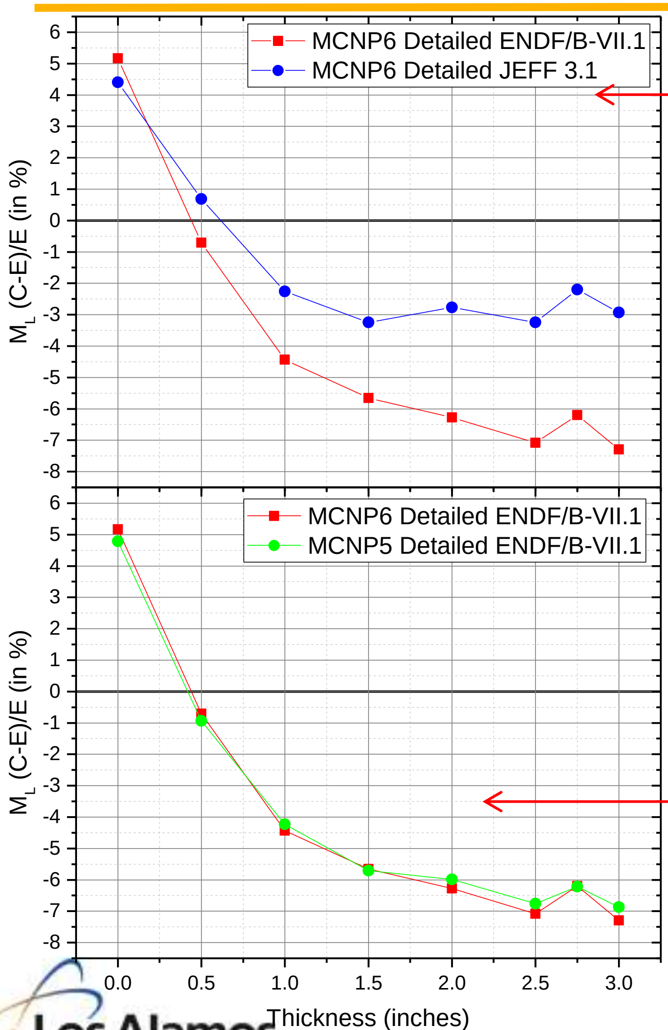
Code comparison (MCNP5 vs MCNP6) and (MCNP6 vs MORET)



Simulation comparisons (R_2)



Simulation comparisons (M_L)



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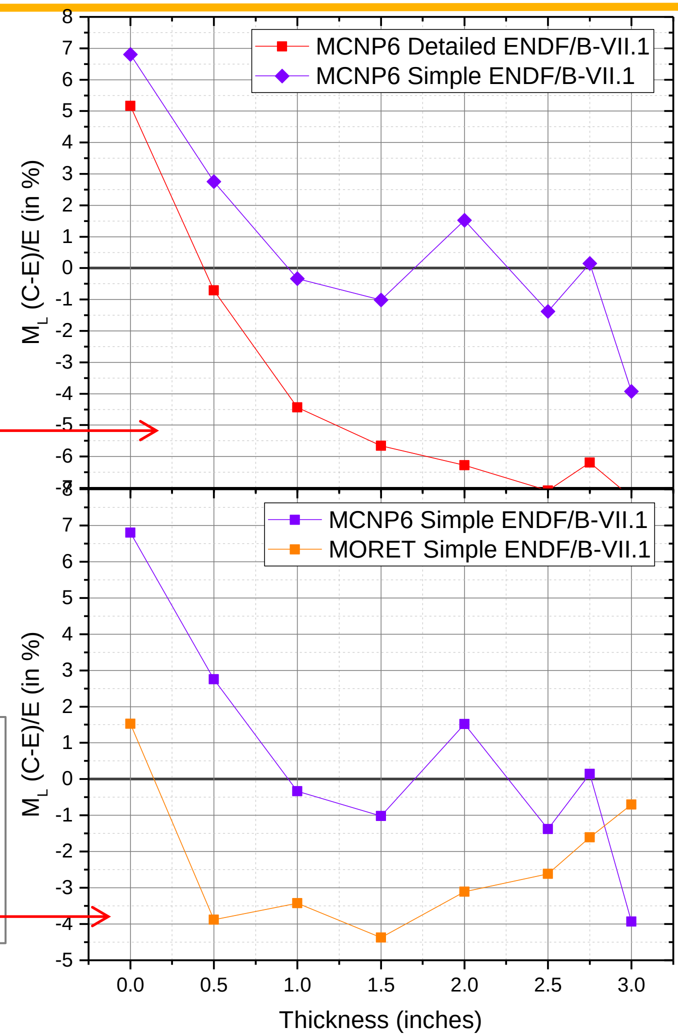


Simulation comparison summary

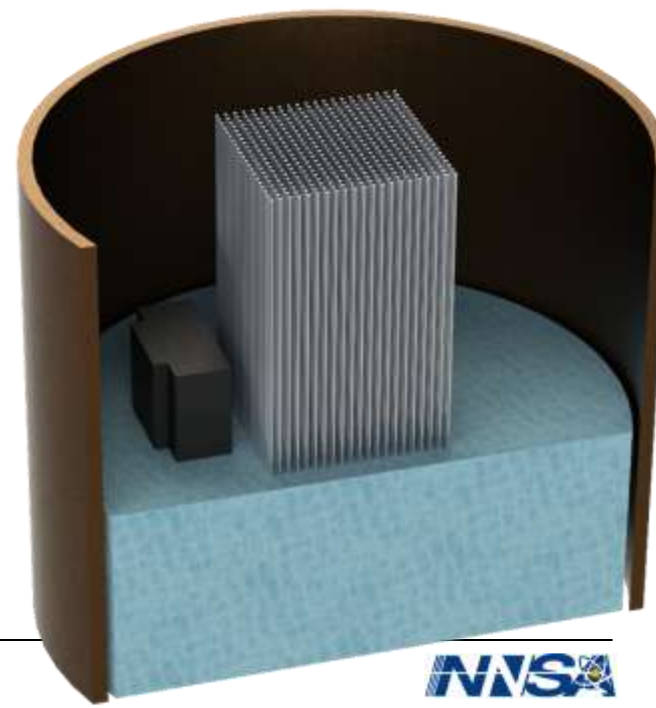
- **Nuclear data comparisons:**
  - For M_L, JEFF 3.1 is better than ENDF/B-VII.1 for highly-reflected systems (>1“ W).
  - Both have very similar trends for M_L.
  - For R_1 and R_2, very different trends.
  - ENDF better for highly-reflected systems for R_1 and R_2.
- **Code comparisons:**
  - MCNP5 and MCNP6 give nearly identical results.
  - MCNP6 and MORET have somewhat similar trends.

Conclusions and future work

- **Eight subcritical configurations were measured with a plutonium sphere reflected by tungsten.**
- **All configurations were analyzed.**
- **ALL measured data are included in the evaluation.**
  - Raw list-mode neutron data.
  - Processed list-mode neutron data (using multiple binning methods).
  - Raw gamma spectra.
- **The BeRP/W evaluation is included in the 2016 edition of ICSBEP.**
  - In VOLUME IX, identifier FUND-NCERC-PU-HE3-MULT-002.
- **Talk in tomorrow's "critical and subcritical experiments" session describes sensitivity/uncertainty analysis for design of subcritical experiments.**
  - This talk uses data from the BeRP/W evaluation.

Conclusions and future work

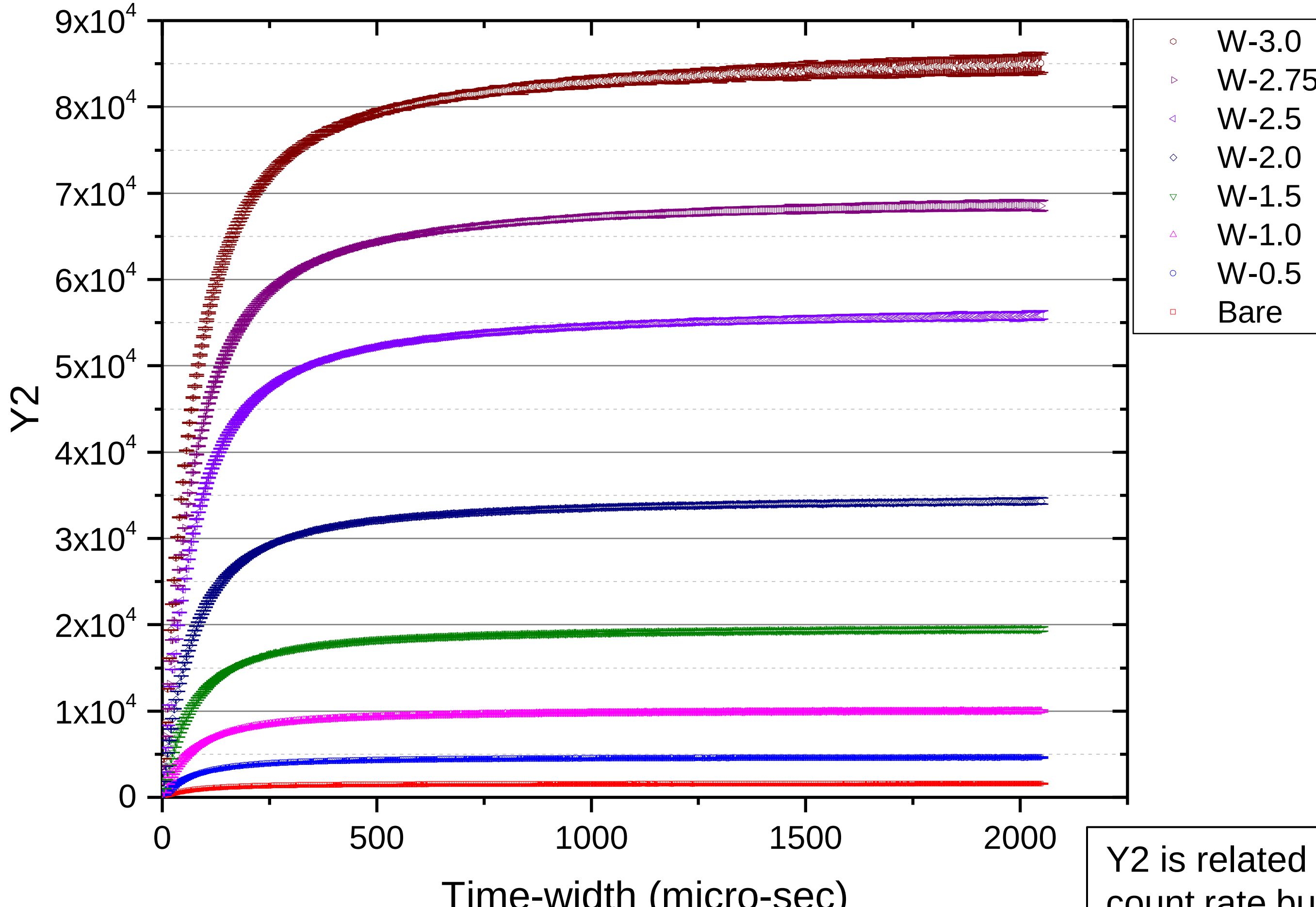
- **Many IERs exist related to subcritical measurements. Two important ones for LANL include:**
  - 1. IER-~~111~~422: Subcritical Copper-Reflected α-phase Plutonium (SCRαP) Integral Experiment.
    - Currently in CED-3b.
    - Joint experiment with US, IRSN, and AWE.
  - 2. IER-178: Measurements on the RPI Reactor Critical Facility (RCF).
    - Will build upon recent measurements on Caliban, Godiva-IV, Planet (Lucite class foils experiment), and Flat-Top (with HEU core).
    - See presentation tomorrow afternoon in the “critical and subcritical experiments” session!



Acknowledgements

- This work was supported by the DOE Nuclear Criticality Safety Program, funded and managed by the National Nuclear Security Administration for the Department of Energy.
- This benchmark was a very large effort and would not have been possible without help from the following:
  - Members from LLNL, ORNL, and INL contributed both at ICSBEP and on the Critical Experiments Design Team (C_EdT).
  - 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.
  - We would also like to thank Mark Smith-Nelson for participation in the measurement effort and C.J. Solomon for advancing the simulation capabilities required for this work.
  - We would like to thank Gregory Keefer and Sean Walston from LLNL, Gregory Caplin and Wilfried Monange from IRSN, 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.

Extra



Y2 is related to doubles count rate but does not include detector lifetime