BeRP Ball Reflected By Nickel Benchmark Evaluation

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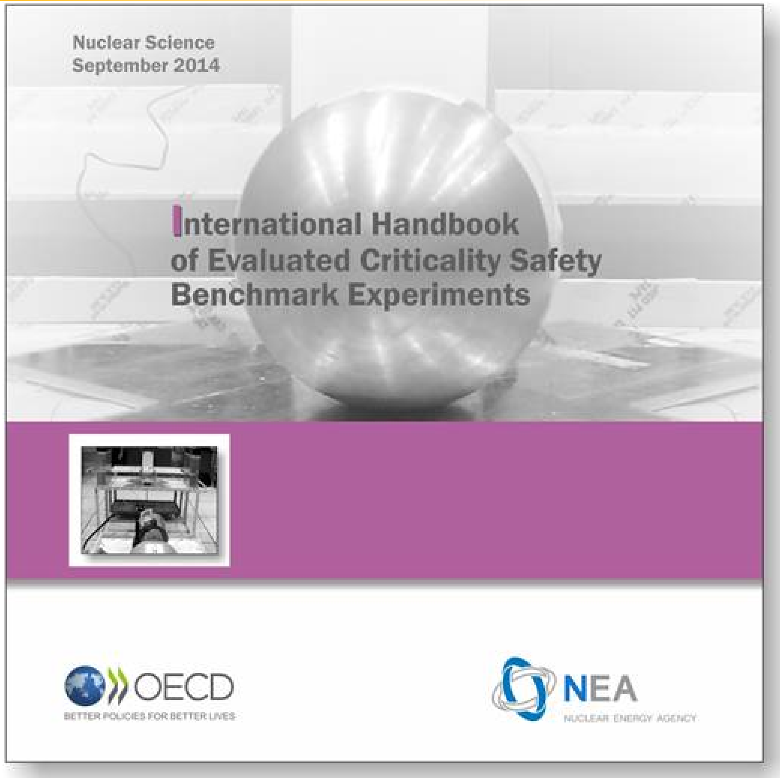
Presented at the NCSP Technical Seminar

LA-UR-15-21909

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**

- FUND: Fundamental physics measurements
- NCERC: Facility name
- PU: Source type: Pu fission
- HE3: Target material: He-3 detectors
- MULT: Experiment type: neutron multiplication measurements

Timeline

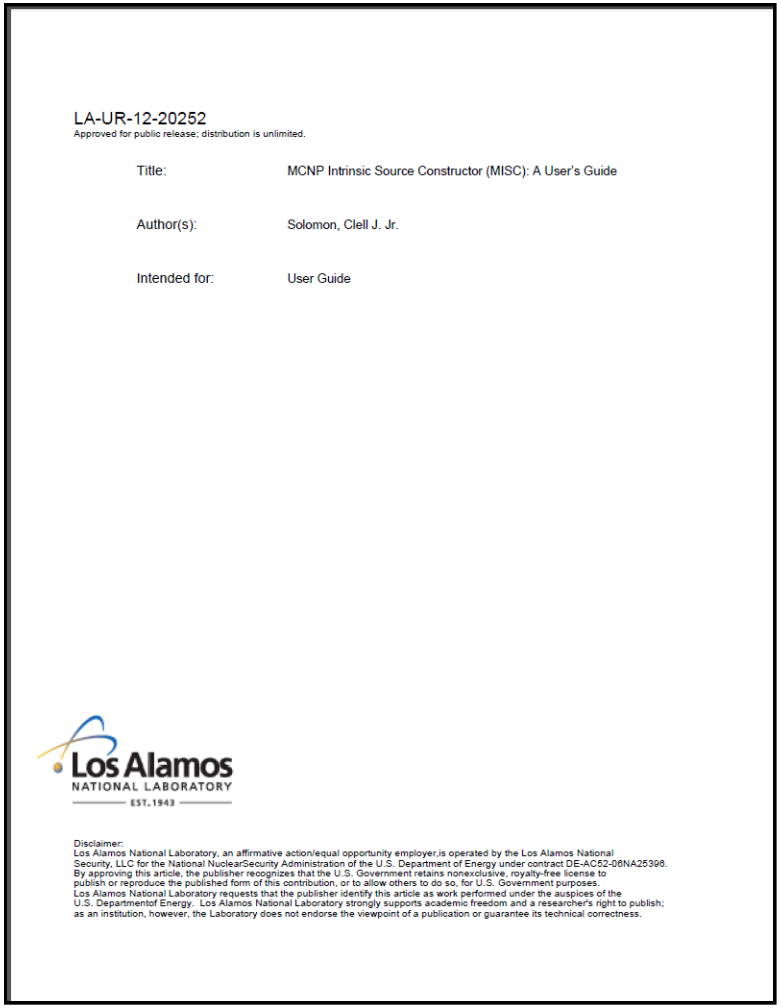
- **July 2007: Subcritical operations started at DAF including first BeRP ball measurements.**
- **September 2008: BeRP reflected by Ni measurements performed.**
- **2009-2010: Evaluation of BeRP/Ni measurements submitted to ICSBEP. The evaluation was rejected because the experimental uncertainties and 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 In addition, the simulation capabilities were outdated and not useful for users.**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 C_EdT 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.
  - October 2014: Evaluation included in the 2014 edition (CED-4b approved/complete).

More than your average benchmark

- **Simulation tools were needed to accurately reproduce the subcritical measurements:**
  - 1. MISC: new tool to accurately model source term (decay for material composition and proper neutron emission).


LA-UR-12-20252
Approved for public release; distribution is unlimited.

Title:	MCNP Intrinsic Source Constructor (MISC): A User's Guide
Author(s):	Solomon, Clell J. Jr.
Intended for:	User Guide

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More than your average benchmark

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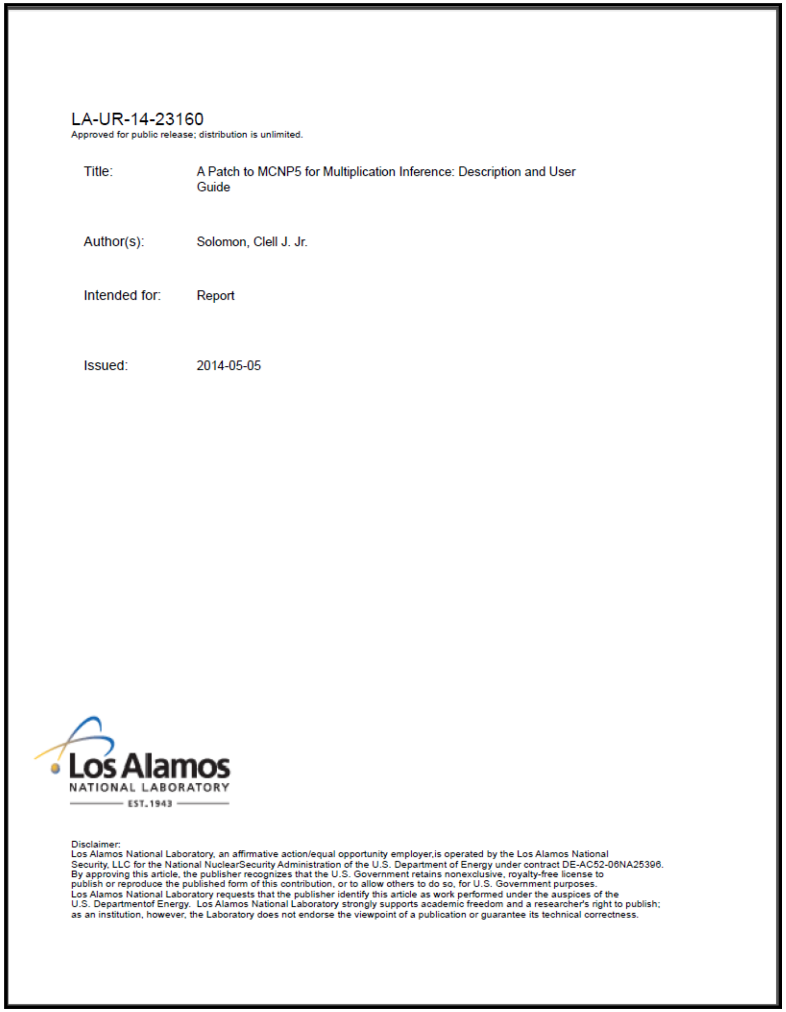
  - 1. MISC: new tool to accurately model source term (decay for material composition and proper neutron emission).
  - 2. MCNP5 implementation (list-mode patch).


LA-UR-14-23160
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Title:	A Patch to MCNP5 for Multiplication Inference: Description and User Guide
Author(s):	Solomon, Clell J. Jr.
Intended for:	Report
Issued:	2014-05-05

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More than your average benchmark

- **Simulation tools were needed to accurately reproduce the subcritical measurements:**
  - 1. MISC: new tool to accurately model source term (decay for material composition and proper neutron emission).
  - 2. MCNP5 implementation (list-mode patch).
  - 3. Ability to convert MCNP5 simulations to measured data format.

LA-UR-09-05257 September 21, 2009

User's Manual for the *convert.pl* PERL Script
Brian Temple

Abstract
This document is a user's manual for the PERL script *convert.pl* used to post-process multiplication simulation data generated from MCNP. The manual covers how to operate the code and describes how the code operates.

I. Introduction
The simulation and calculation process for producing synthetic multiplication data from MCNP for emergency exercises has been improved and streamlined by making changes to the existing post-processing codes. PERL scripts (cb2e*.pl/gpetodat.pl) are used to convert the ASCII format output from the MCNP multiplication patch into a binary format (op9.DAT) that is compatible with the NEUTRON REPLAY neutron diagnostics software (called REPLAY for short). This software is used by N-2 to read and analyze data from the NPOD detector measurements. The analysis includes calculating the moments and multiplication. FORTRAN codes (CHKIT and BRITER) are also used to calculate the moments and the multiplication directly from the MCNP multiplication patch ASCII output. The binary conversion and the moment/multiplication calculations in the two sets of codes are combined into the *convert.pl* PERL script. The new script is designed to make post-processing of the simulation data easier.

The user's manual is comprised of six sections covering the operation, installation, and details of the code. It is recommended the user read section II to understand the overall process for producing synthetic multiplication data with MCNP and problems with the current process. The user should read section III to understand how to input information, locate output, and operate the code. Section IV contains the definitions of the inputs/outputs and a detailed description on how data is processed in the code. All variables used in the code are described and related to the equations used in the Feymann variance-to-mean method of calculating multiplication. Section IV is for users who need to know additional details behind the operation of the code. Section V is a quick reference for operating the code and is an abbreviated version of the code operation in Section III. Section VI contains the instructions for downloading and installing *convert.pl* and its user's manual from SourceForge. **The users can get away with only reading Section V if they want the minimal amount of information to operate the code.**

II. Overview of Synthetic Multiplication Data Production
Producing synthetic multiplication data involves modeling the NPOD detector measurement of an object and post-processing the output. The synthetic multiplication data is produced by a special version of MCNP that simulates neutron counts in the detector and records the count time and count tube in a "non-standard" ASCII format output file (named *gpeou* by default). It is the frequency of counts in the tubes that is used with the Feymann variance-to-mean method to calculate moments and the multiplication. The simulation data in the *gpeou* file does not account for the deadtime in the tubes and electronics that occurs in real detectors. Therefore this deadtime must be incorporated into the synthetic data by removing sequential counts in each individual tube that occur

1

More than your average benchmark

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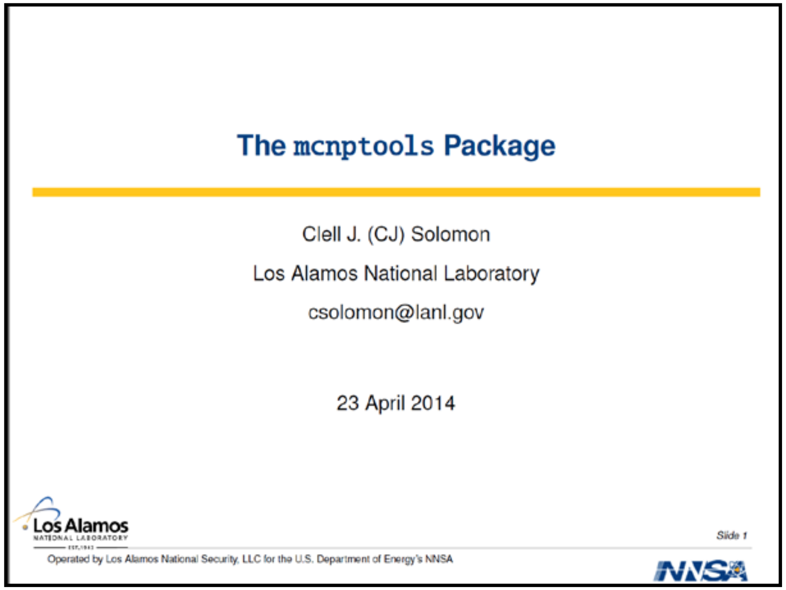
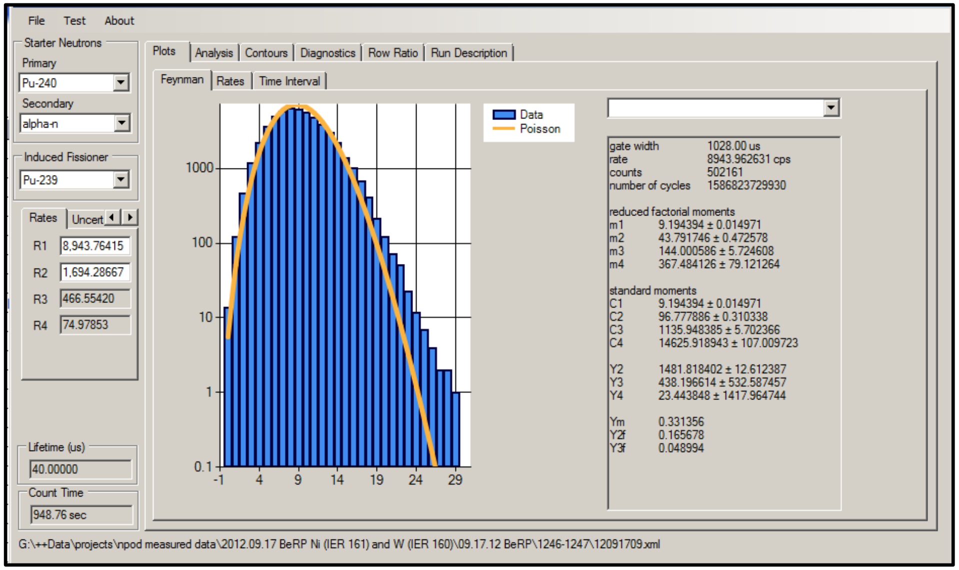
  - 1. MISC: new tool to accurately model source term (decay for material composition and proper neutron emission).
  - 2. MCNP5 implementation (list-mode patch).
  - 3. Ability to convert MCNP5 simulations to measured data format.
  - 4. Ability to convert MCNP6 simulations to measured data format.



More than your average benchmark

- **Measurement analysis work was also required:**
  - 1. Momentum: software written to read neutron data (funded by other programs).



More than your average benchmark

- **Measurement analysis work was also required:**
  - 1. Momentum: software written to read neutron data (funded by other programs).
  - 2. Measured data must be binned. A study was performed on various binning methods for benchmark applications.

This was also presented at the 2014 ANS winter meeting.

Deciphering the Binning Method Uncertainty in Neutron Multiplicity Measurements

Theresa Cutler, Mark Smith-Nelson, Jesson Hutchinson

1. Introduction

Neutron multiplicity measurements are important in determining mass, multiplication, and other parameters of fissionable material. In order to determine these parameters, various rates need to be determined and the analytical uncertainty estimation associated with these rates is complex. A simpler method to estimate the uncertainty is to determine the standard deviation from multiple measurements of the same configuration; in lieu of real measurements monte carlo simulations can be performed.

The uncertainty is dependent upon many factors including total count time, count rate, and how the data is sampled. Multiple sampling methods have been proposed over the years for various reasons ranging from hardware, computational and statistical limitations. With all these sampling methods, the data is binned into histograms. Multiple rates and the neutron lifetime are estimated by fitting derived parameters of these histograms.

This paper presents the results of monte carlo simulations of two separate objects; the first simulation is of plutonium which has a significant neutron output and the other is of highly enriched uranium, which has an almost negligible neutron output. The data from these simulations is then sampled with four different methods, the results are compared to each other as well to an analytical expression for the uncertainty, which was presented in a previous paper.

2. Introduction to theory

The Hage-Cifarelli formalism of the Feynman Variance-to-Mean method is often used to analyze data. This method requires binning the collected data into histograms, and calculating reduced factorial moments. These histograms are commonly referred to as Feynman histograms after Richard Feynman, the originator of this method [Feynman 1946].

The Feynman histograms bin the data into counts per time-bin of length τ; these time bins are also known as gate-widths. Further, the reduced factorial moments are also calculated based on the chosen gate-width. The first, second, and third factorial moment equations are given below.

$$\overline{m_{1!}(\tau)} = \frac{\sum_n n C_n}{\sum_n C_n},$$

$$\overline{m_{2!}(\tau)} = \frac{\sum_n n(n-1) C_n}{2! \sum_n C_n}, \text{ and}$$

$$\overline{m_{3!}(\tau)} = \frac{\sum_n n(n-1)(n-2) C_n}{3! \sum_n C_n}.$$

In the factorial moment equations, n equals the number of detected neutrons within a time bin, and C_n equals the number of times n neutrons were detected within the time bin.

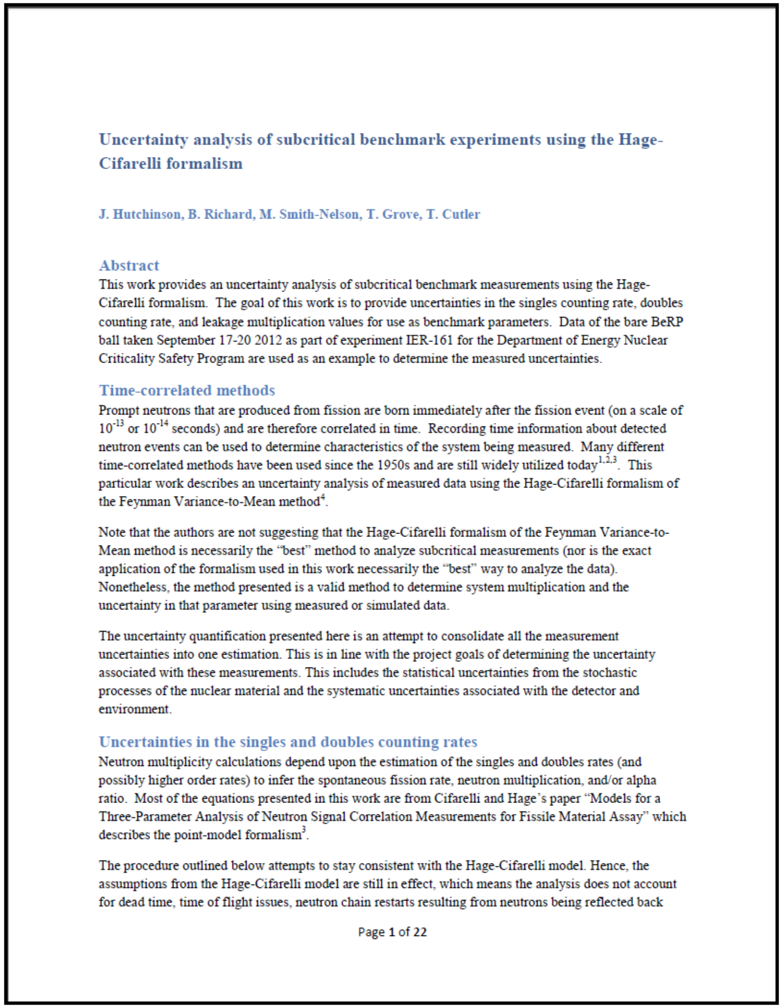
The singles, doubles, and triples rates computed from the Hage-Cifarelli method are functions of the reduced factorial moments of the individual Feynman histograms. The rates are labeled as R_1, R_2, and R_3, respectively. The background and derivation of these parameters are discussed in another paper [Cifarelli 1986]. The equations below show the simplified results.

1

More than your average benchmark

- **Measurement analysis work was also required:**
  - 1. Momentum: software written to read neutron data (funded by other programs).
  - 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.

This will be presented at the 2015 ICNC meeting.



Uncertainty analysis of subcritical benchmark experiments using the Hage-Cifarelli formalism

J. Hutchinson, B. Richard, M. Smith-Nelson, T. Grove, T. Cutler

Abstract

This work provides an uncertainty analysis of subcritical benchmark measurements using the Hage-Cifarelli formalism. The goal of this work is to provide uncertainties in the singles counting rate, doubles counting rate, and leakage multiplication values for use as benchmark parameters. Data of the bare BeRP ball taken September 17-20 2012 as part of experiment IER-161 for the Department of Energy Nuclear Criticality Safety Program are used as an example to determine the measured uncertainties.

Time-correlated methods

Prompt neutrons that are produced from fission are born immediately after the fission event (on a scale of 10^{-13} or 10^{-14} seconds) and are therefore correlated in time. Recording time information about detected neutron events can be used to determine characteristics of the system being measured. Many different time-correlated methods have been used since the 1950s and are still widely utilized today[1,2,3]. This particular work describes an uncertainty analysis of measured data using the Hage-Cifarelli formalism of the Feynman Variance-to-Mean method[4].

Note that the authors are not suggesting that the Hage-Cifarelli formalism of the Feynman Variance-to-Mean method is necessarily the "best" method to analyze subcritical measurements (nor is the exact application of the formalism used in this work necessarily the "best" way to analyze the data). Nonetheless, the method presented is a valid method to determine system multiplication and the uncertainty in that parameter using measured or simulated data.

The uncertainty quantification presented here is an attempt to consolidate all the measurement uncertainties into one estimation. This is in line with the project goals of determining the uncertainty associated with these measurements. This includes the statistical uncertainties from the stochastic processes of the nuclear material and the systematic uncertainties associated with the detector and environment.

Uncertainties in the singles and doubles counting rates

Neutron multiplicity calculations depend upon the estimation of the singles and doubles rates (and possibly higher order rates) to infer the spontaneous fission rate, neutron multiplication, and/or alpha ratio. Most of the equations presented in this work are from Cifarelli and Hage's paper "Models for a Three-Parameter Analysis of Neutron Signal Correlation Measurements for Fissile Material Assay" which describes the point-model formalism[3].

The procedure outlined below attempts to stay consistent with the Hage-Cifarelli model. Hence, the assumptions from the Hage-Cifarelli model are still in effect, which means the analysis does not account for dead time, time of flight issues, neutron chain restarts resulting from neutrons being reflected back

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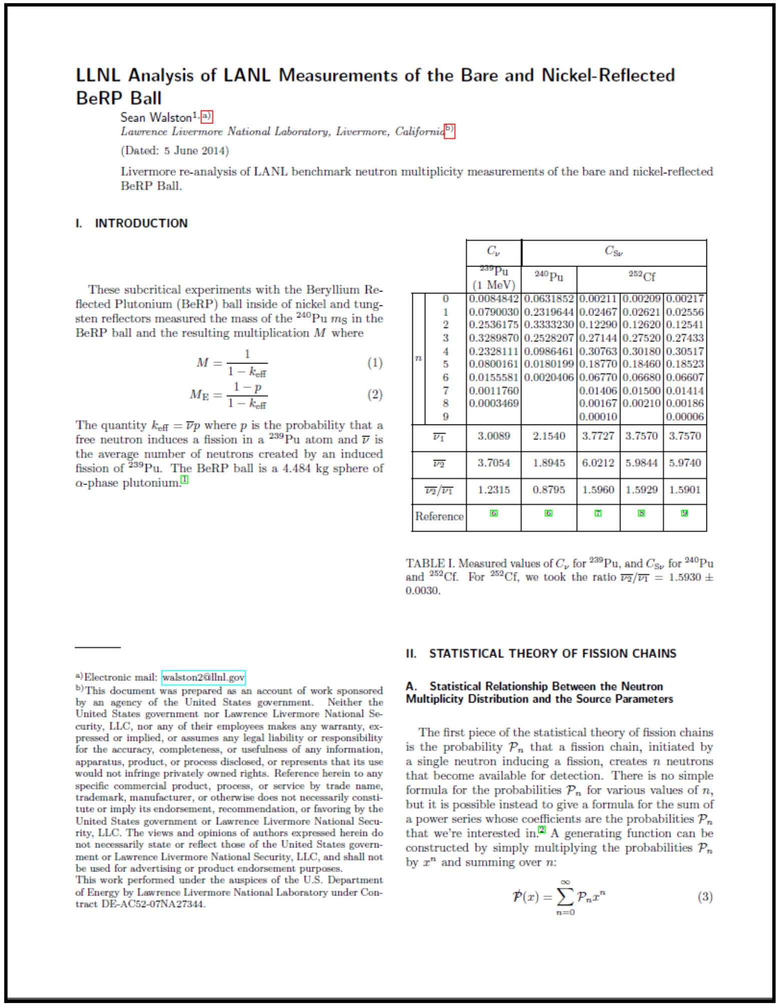
More than your average benchmark

- **Measurement analysis work was also required:**
  - 1. Momentum: software written to read neutron data (funded by other programs).
  - 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.



LLNL Analysis of LANL Measurements of the Bare and Nickel-Reflected BeRP Ball

Sean Walston[1,a)]
Lawrence Livermore National Laboratory, Livermore, California[b)]

(Dated: 5 June 2014)

Livermore re-analysis of LANL benchmark neutron multiplicity measurements of the bare and nickel-reflected BeRP Ball.

I. INTRODUCTION

These subcritical experiments with the Beryllium Reflected Plutonium (BeRP) ball inside of nickel and tungsten reflectors measured the mass of the ^{240}Pu m_S in the BeRP ball and the resulting multiplication M where

$$M = \frac{1}{1 - k_{\text{eff}}} \tag{1}$$

$$M_E = \frac{1 - p}{1 - k_{\text{eff}}} \tag{2}$$

The quantity $k_{\text{eff}} = \overline{\nu} p$ where p is the probability that a free neutron induces a fission in a ^{239}Pu atom and $\overline{\nu}$ is the average number of neutrons created by an induced fission of ^{239}Pu. The BeRP ball is a 4.484 kg sphere of α-phase plutonium.[1]

		C_ν	$C_{S\nu}$			
		^{239}Pu (1 MeV)	^{240}Pu	^{252}Cf		
n	0	0.0084842	0.0631852	0.00211	0.00209	0.00217
	1	0.0790030	0.2319644	0.02467	0.02621	0.02556
	2	0.2536175	0.3333230	0.12290	0.12620	0.12541
	3	0.3289870	0.2528207	0.27144	0.27520	0.27433
	4	0.2328111	0.0986461	0.30763	0.30180	0.30517
	5	0.0800161	0.0180199	0.18770	0.18460	0.18523
	6	0.0155581	0.0020406	0.06770	0.06680	0.06607
	7	0.0011760		0.01406	0.01500	0.01414
	8	0.0003469		0.00167	0.00210	0.00186
	9			0.00010		0.00006
$\overline{\nu_1}$		3.0089	2.1540	3.7727	3.7570	3.7570
$\overline{\nu_2}$		3.7054	1.8945	6.0212	5.9844	5.9740
$\overline{\nu_2}/\overline{\nu_1}$		1.2315	0.8795	1.5960	1.5929	1.5901
Reference		[6]	[6]	[7]	[8]	[9]

TABLE I. Measured values of C_ν for ^{239}Pu, and $C_{S\nu}$ for ^{240}Pu and ^{252}Cf. For ^{252}Cf, we took the ratio $\overline{\nu_2}/\overline{\nu_1} = 1.5930 \pm 0.0030$.

II. STATISTICAL THEORY OF FISSION CHAINS

A. Statistical Relationship Between the Neutron Multiplicity Distribution and the Source Parameters

The first piece of the statistical theory of fission chains is the probability $\mathcal{P}_n$ that a fission chain, initiated by a single neutron inducing a fission, creates n neutrons that become available for detection. There is no simple formula for the probabilities $\mathcal{P}_n$ for various values of n, but it is possible instead to give a formula for the sum of a power series whose coefficients are the probabilities $\mathcal{P}_n$ that we're interested in.[2] A generating function can be constructed by simply multiplying the probabilities $\mathcal{P}_n$ by x^n and summing over n:

$$\acute{\mathcal{P}}(x) = \sum_{n=0}^{\infty} \mathcal{P}_n x^n \tag{3}$$

a) Electronic mail: walston2@llnl.gov

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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/wpncs/icsbep/handbook.html) :
    - 1. Volumes I-VIII: 1.63 GB zip file.
    - 2. Volume IX: 0.99 GB zip file (the BeRP/Ni benchmark makes up 97% of this).

BeRP Ball

- α-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

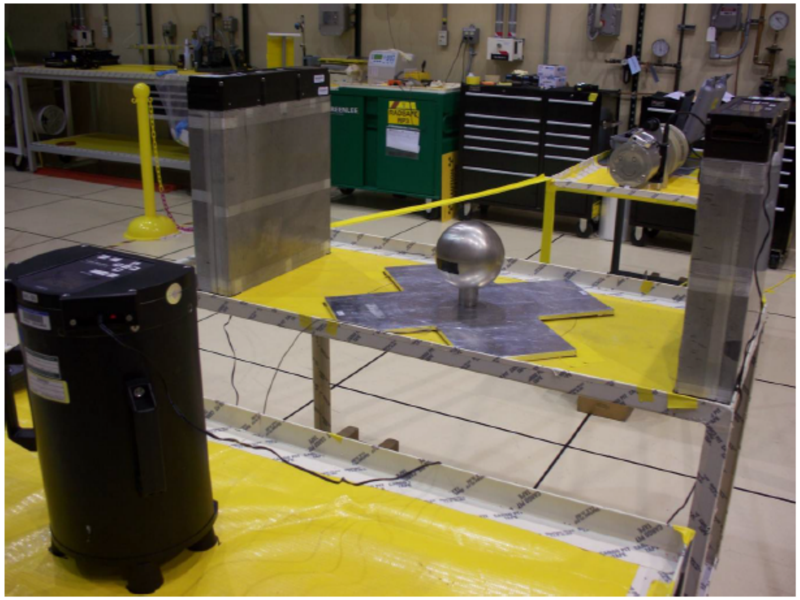
- Reactivity range: k_{eff} = 0.79 to k_{eff} = 0.92.
- 7 configurations: Bare BeRP to 3.0 inch-thick Ni reflection.

- 6 layers, each being 0.5” thick $\rightarrow$ 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 $\overline{\nu}$)
  - R_2: doubles asymptotic counting rate (related to $\overline{\nu(\nu-1)}$)
- 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.

Benchmark quantities

- Must be deduced from well-known and fieldproven techniques
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Selected quantities

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

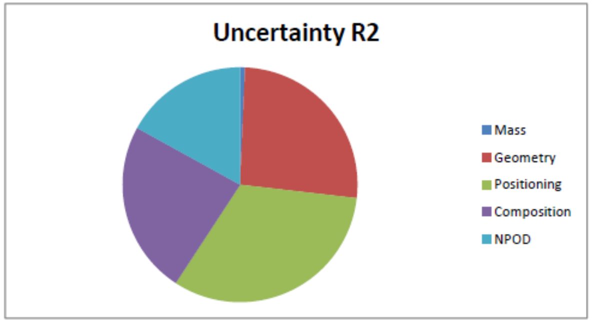
Note that k_{eff} is not a benchmarked quantity in this evaluation. Measured k_{eff} values are, however, given for each of the seven configurations in the evaluation.

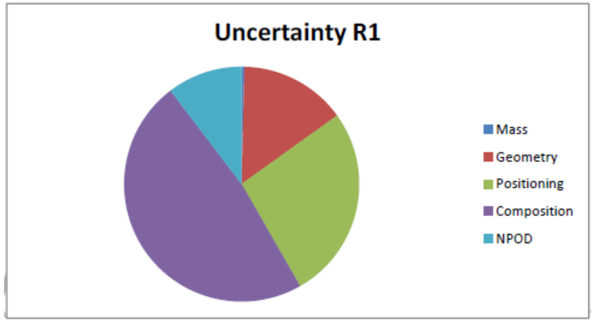
Sensitivity/Uncertainty Study – Experimental Data

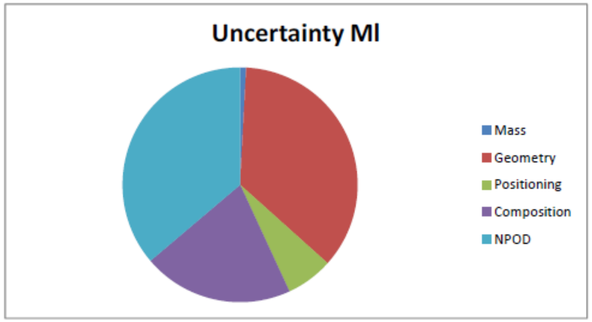
Illustration on the 3.0” thick reflected case

44 independent uncertainties on experimental data divided in 4 broad categories

	R_1	R_2	M_l
Combined uncertainties	2.19 %	3.49 %	0.76 %







Models

Detailed model

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

LANL HPC system

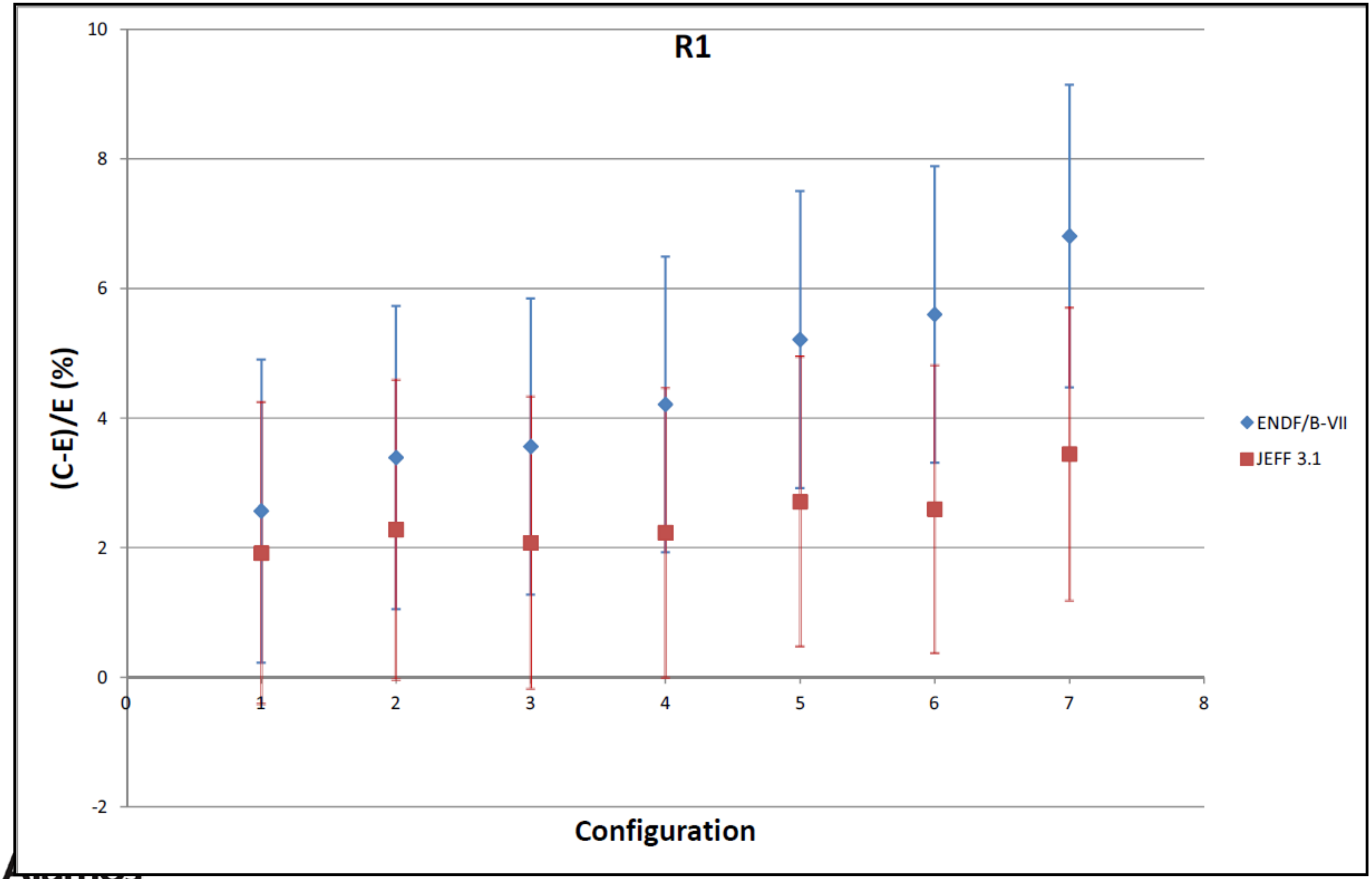
Simplified model

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

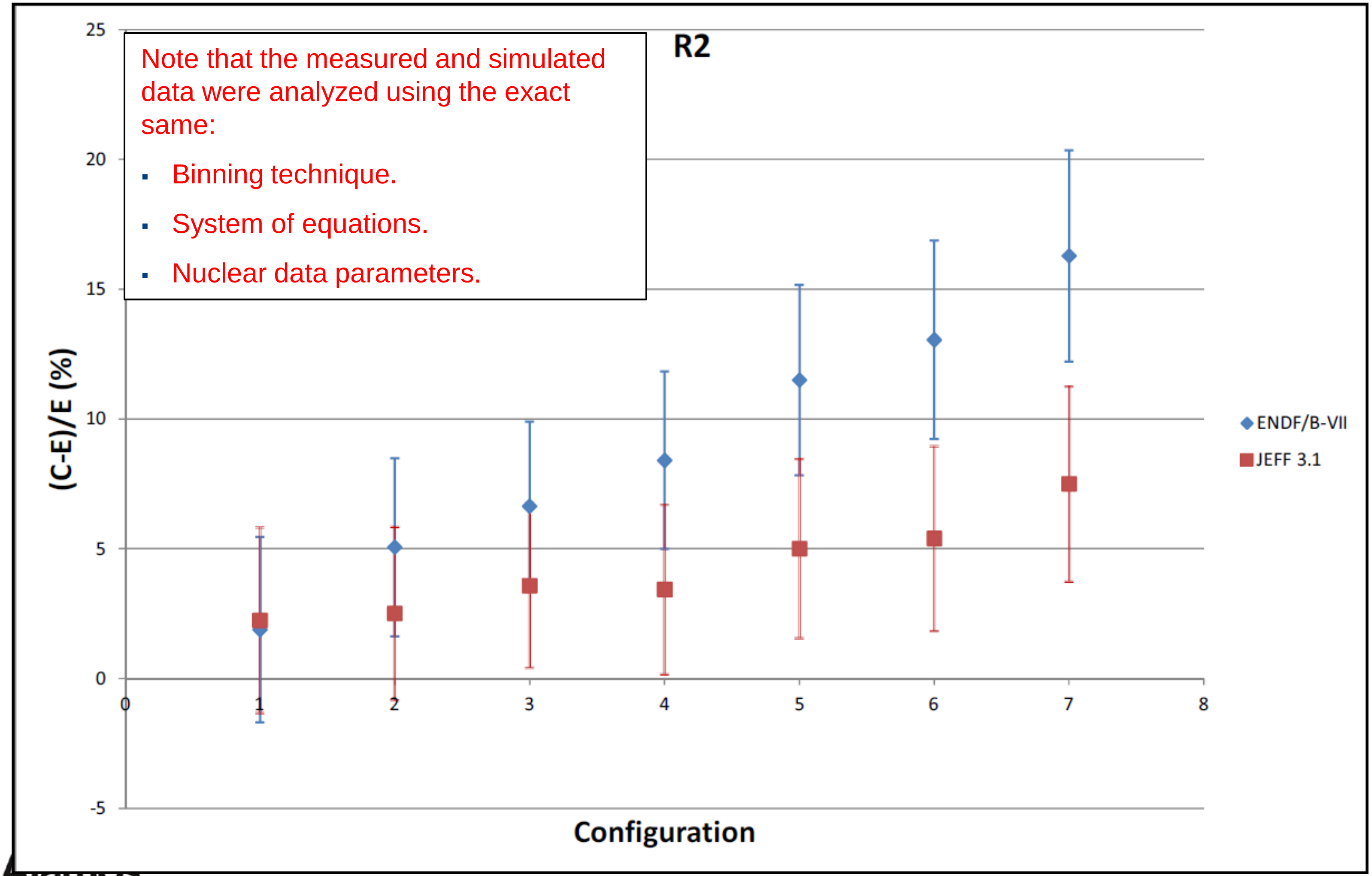
Global/individual simplification biases have been estimated and are included in the evaluation

Room return and detector presence on the benchmark quantities was evaluated.

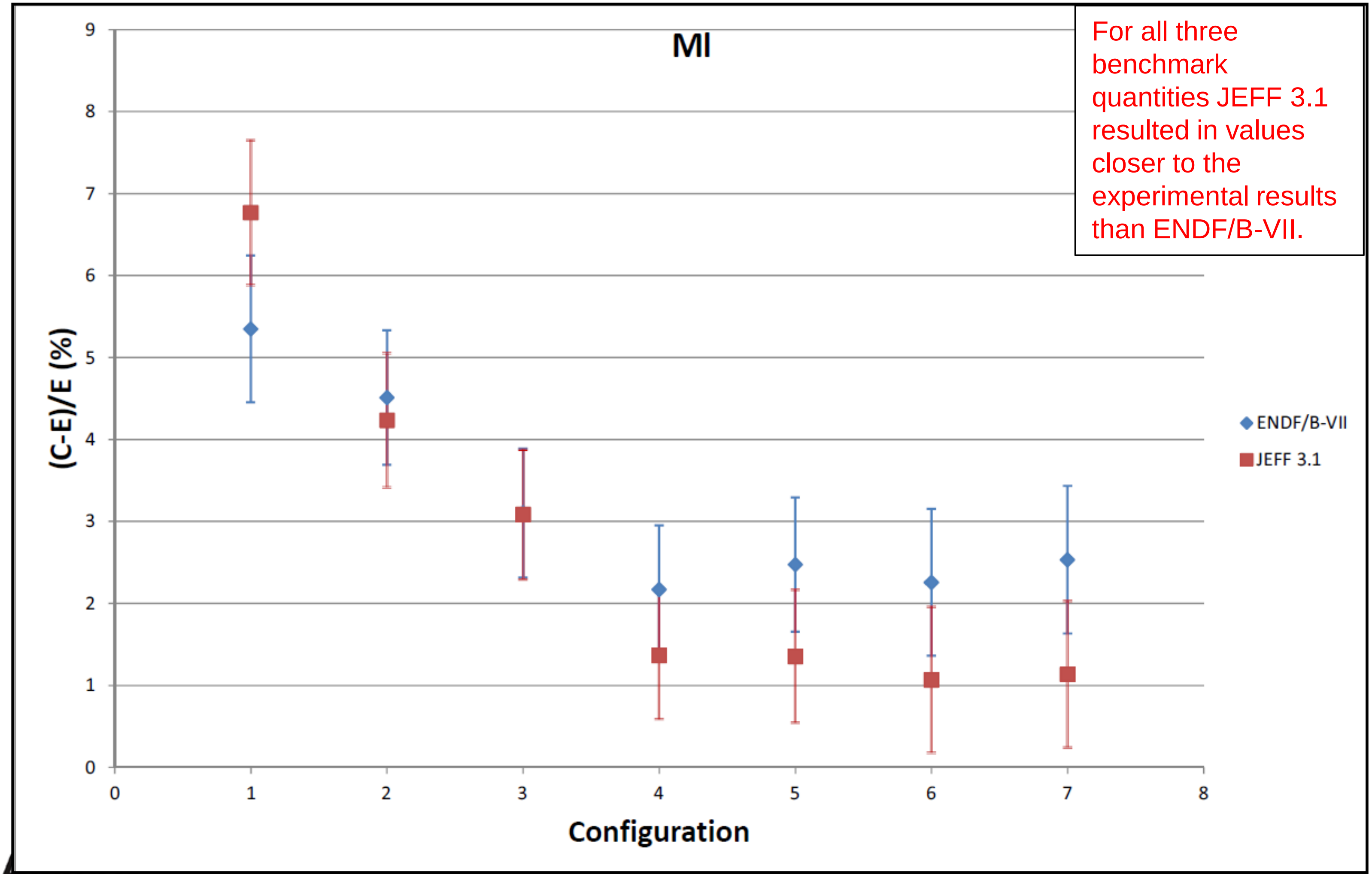
Comparison Experiment-Simulation on R_1



Comparison Experiment-Simulation on R_2



Comparison Experiment-Simulation on M_L



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 ← Investigated in the BeRP/W benchmark.
  - Composition of the polyethylene used in the NPODs ← New chemical analysis data will be included in the BeRP/W benchmark.
- Preliminary results for the W benchmark are encouraging: submission next year
- Good starting point to go beyond: inference model benchmark ← Applications past a benchmark evaluation.
- 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).
  - 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).
    - 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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