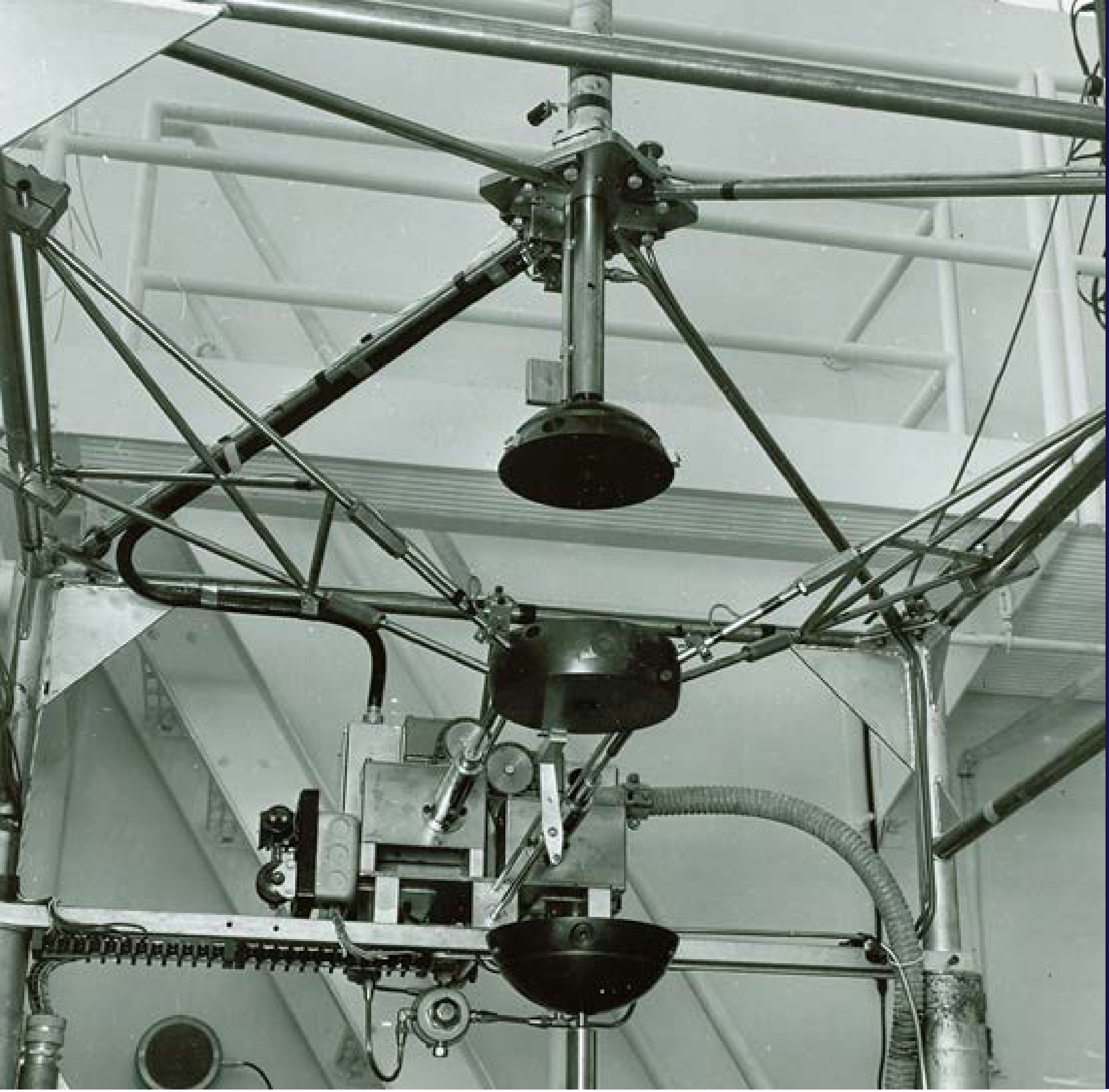

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Subcritical Copper-Reflected α-phase Plutonium (SCRαP) Sphere Benchmark

J. Hutchinson, R. Bahran, T. Cutler, W. Monange*, J. Arthur, M. Nelson, E. Dumonteil*

Los Alamos National Laboratory

Institut de Radioprotection et de Sûreté Nucléaire (IRSN)

NCSP TPR 2018

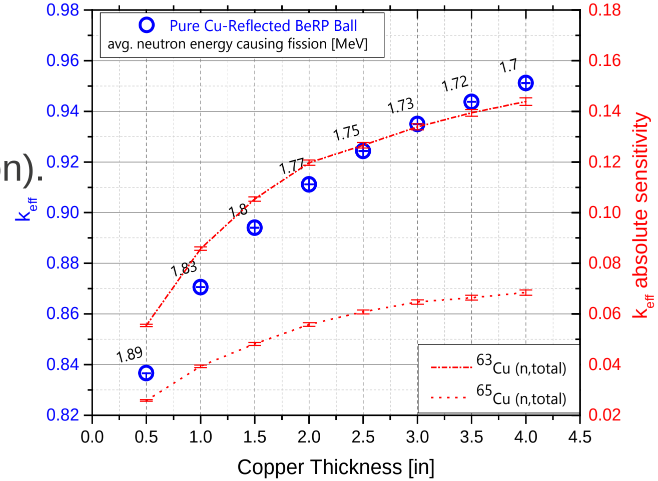
Overview

- Introduction
- Experiment Overview
- Preliminary Results
- Benchmark Status
- Future work (and other related work)

Design/Conduct/Analyze Subcritical Validation Experiments

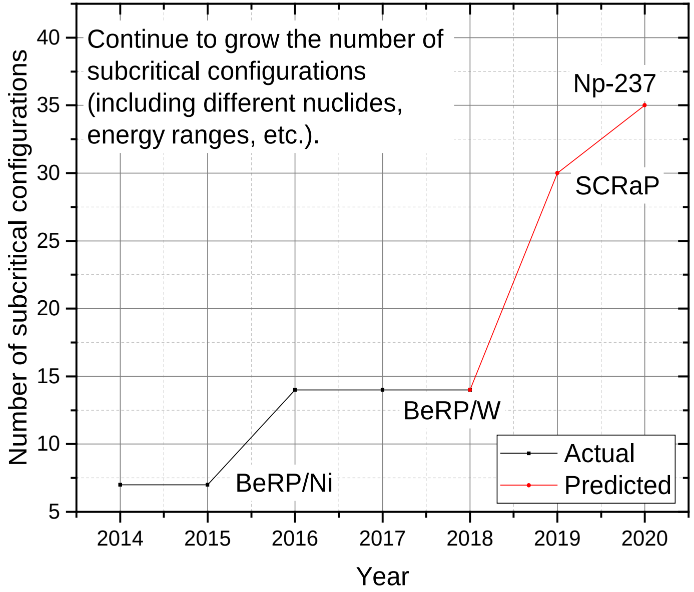
Designed to include a wide variety of:
- Energy Ranges (Thermal, Intermediate, Fast)
- Multiplication Ranges (Low, Medium, High)
- Materials (Fissile, Moderator, Reflector)
- Neutron Reactions

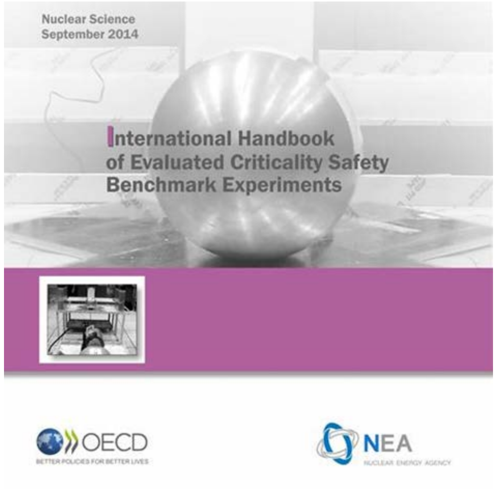
- **Goals**
  - o Critical and subcritical experiments:
    - Provide benchmarks that assist in nuclear data improvement.
      - Fill integral experiment deficiencies.
      - Design new experiments using “recent” S/U tools that are more sensitive than previous experiments.
  - o Subcritical experiments:
    - Improve subcritical simulation capabilities.
    - Improve analysis of measured data (uncertainty quantification).
    - Characterization of detector systems.



Recent Advances in Subcritical Experiments

- **Many organizations (LANL, LLNL, SNL, IAEA, IRSN, CEA, universities, and others) have pursued subcritical experiments and/or simulations in recent years.**
- **2014: BeRP-nickel published in ICSBEP handbook (the culmination of several years of subcritical experiment research).**
- **2016: BeRP-tungsten published in ICSBEP handbook.**



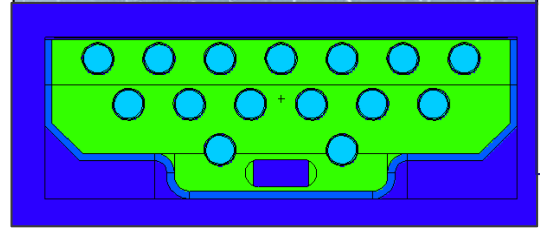


Experiment Overview

- **SCRαP Experiment Design described in CED-2 document.**
  - BeRP (Beryllium-Reflected Plutonium).
    - 4.5-kg WG α-phase stainless-steel clad plutonium sphere.
    - Originally used in Be-reflected critical experiment (no Be was present for this experiment).
  - High-purity nested copper shells
    - C101 Cu alloy (99.99 wt.% Cu).

Experiment Design

- **NoMAD (Neutron Multiplicity ^{3}He Array Detector) was used to measure three benchmark parameters:**
  - o Detector singles count rate (R_1) i.e. the count rate in the detector system
  - o Doubles count rate (R_2) i.e. the rate in the detector system in which two neutrons from the same fission chain are detected
  - o Leakage multiplication (M_L) i.e. the number of neutrons escaping a system per starter neutron.



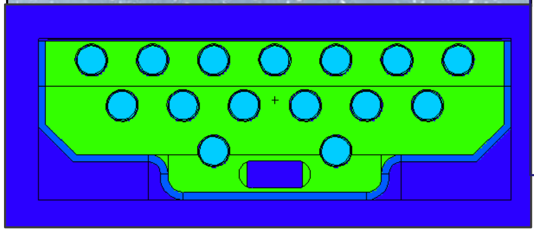
Records list-mode data (a time list of every recorded neutron event to a resolution of 128 nsec).

Photograph and MCNP® model of the NoMAD detector system.

15 He-3 tubes inside polyethylene.

Experiment Design

For the SCRαP experiment, two NoMAD systems were present and collected data in the same time list.



Records list-mode data (a time list of every recorded neutron event to a resolution of 128 nsec).

Photograph and MCNP® model of the NoMAD detector system.

15 He-3 tubes inside polyethylene.

Experiment Configurations

- **17 total configurations:**
  - 1 Bare
  - 8 Cu-only configurations
  - 7 Cu+HDPE configurations
  - 1 HPDE-only configuration
- **In order to determine the detector efficiency, Cf-252 source replacement measurements were performed.**
  - The source strength of the ^{252}Cf source at the time of the measurements was 7.59e5 fissions/sec +/- 1.0%.

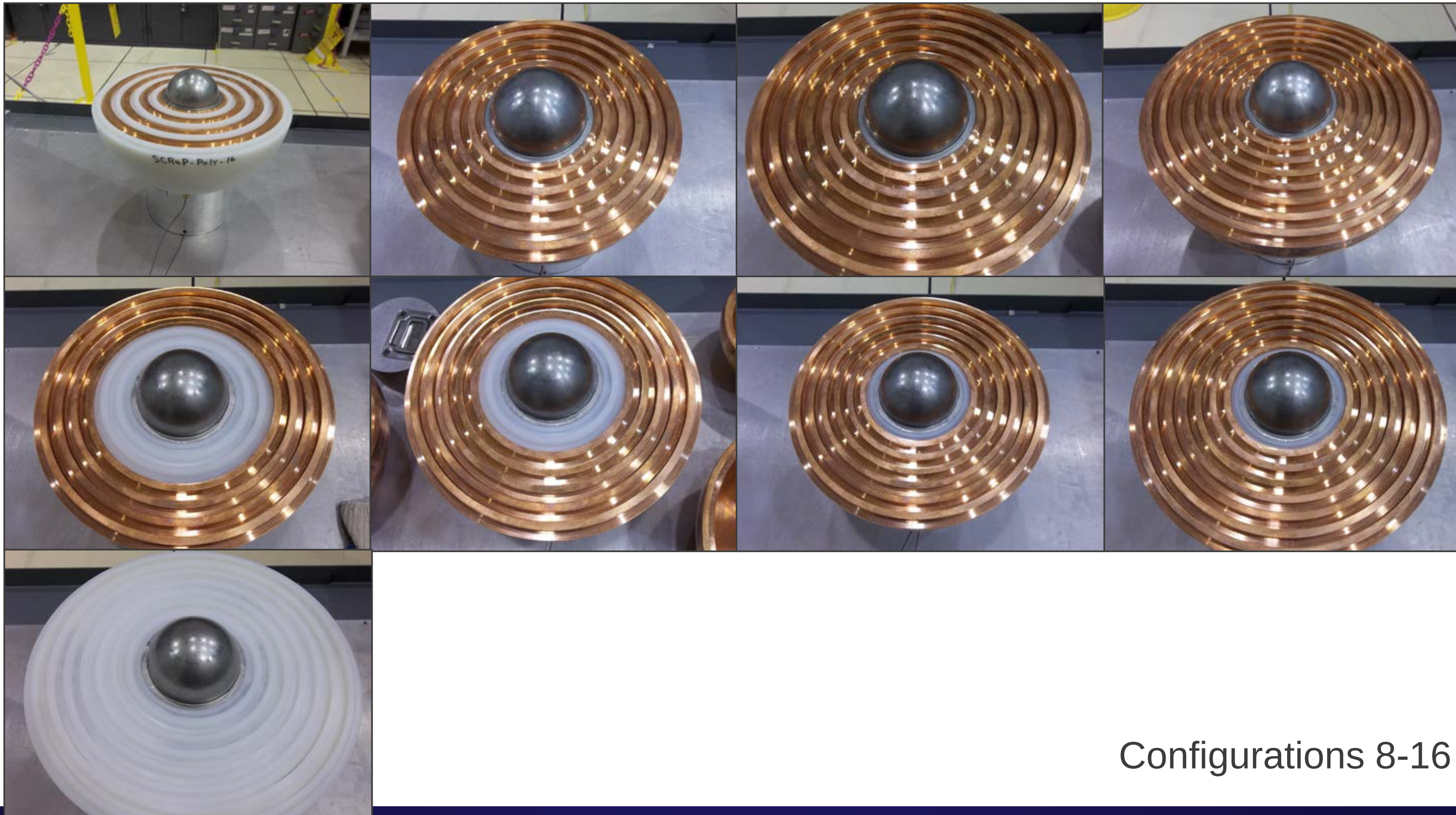
Orange is for Cu
Grey is for HDPE

Configuration #	Layer number (each layer is 0.5 inches thick)							
	1	2	3	4	5	6	7	8
0								
1	Orange							
2	Orange	Orange						
3	Orange	Orange	Orange					
4	Orange	Orange	Orange	Orange				
5	Orange	Orange	Grey	Grey	Grey	Grey		
6	Orange	Orange	Orange	Orange	Orange			
7	Grey	Orange	Grey	Orange	Grey	Orange	Grey	Orange
8	Orange	Grey	Orange	Grey	Orange	Grey	Orange	Grey
9	Orange	Orange	Orange	Orange	Orange	Orange		
10	Orange	Orange	Orange	Orange	Orange	Orange	Orange	
11	Orange	Orange	Orange	Orange	Orange	Orange	Orange	Orange
12	Grey	Grey	Grey	Orange	Orange	Orange	Orange	
13	Grey	Grey	Orange	Orange	Orange	Orange	Orange	
14	Grey	Orange	Orange	Orange	Orange	Orange	Orange	
15	Grey	Orange	Orange	Orange	Orange	Orange	Orange	Orange
16	Grey	Grey	Grey	Grey	Grey	Grey	Grey	Grey

Experiment Configurations

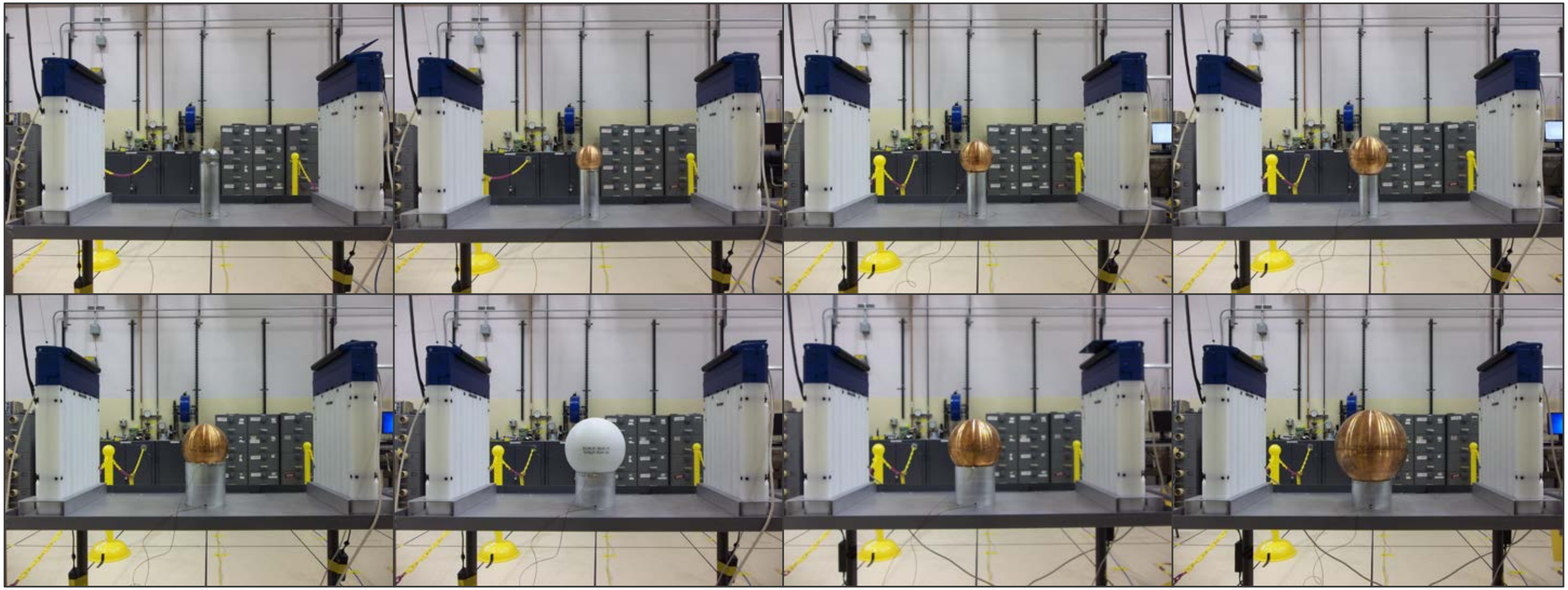
Configurations 0-7

Experiment Configurations



Configurations 8-16

Experiment Configurations

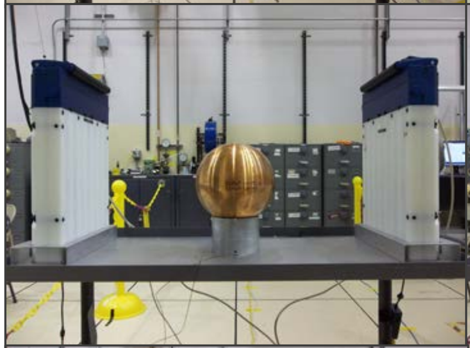
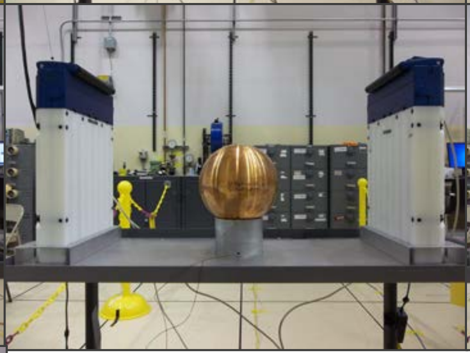
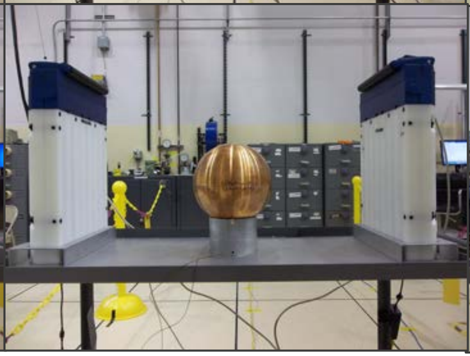
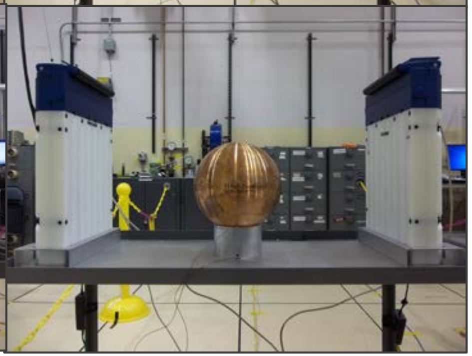


Configurations 0-7

Experiment Configurations



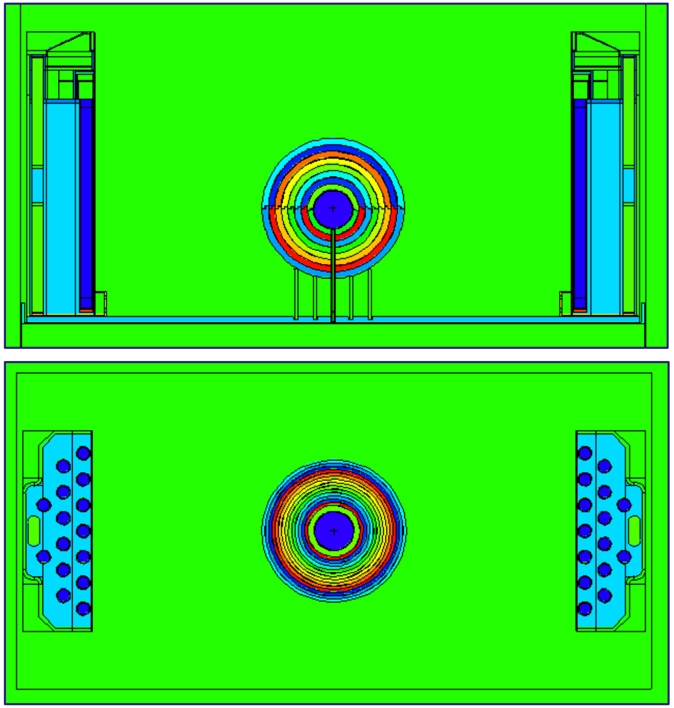



Configurations 8-16

Simulations

- Performed using MCNP6 (LANL) and MORET 5.D with neutron noise plugin (IRSN).
- A script was written to generate an lmx file (the same format as the NoMAD list-mode data) from the MCNP PTRAC (A. McSpaden).
- Section 4 will include results from both codes and will include ENDF/B-VII.1, VIII.0, and JEFF cross-sections.



Preliminary Results

Singles count rate (R_1)

Reduced factorial moment:

$$m_r(\tau) = \frac{\sum_{n=0}^{\infty} n(n-1)\cdots(n-r+1)\,p_n(\tau)}{r!}$$

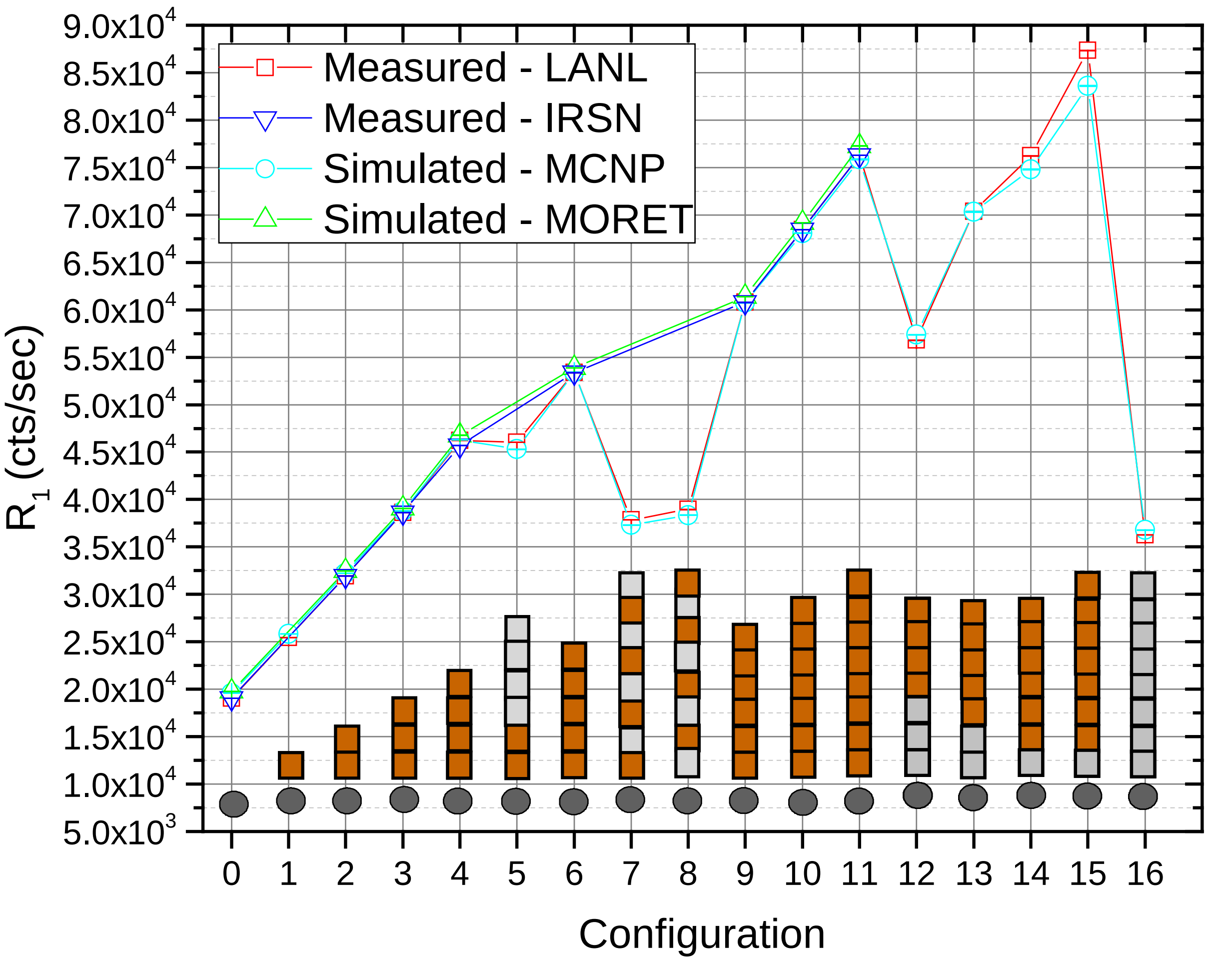
normalized fraction of gates that recorded n events:

$$p_n(\tau) = \frac{C_n(\tau)}{\sum_{n=0}^{\infty} C_n(\tau)}$$

Singles count rate:

$$R_1(\tau) = \frac{m_1(\tau)}{\tau}$$

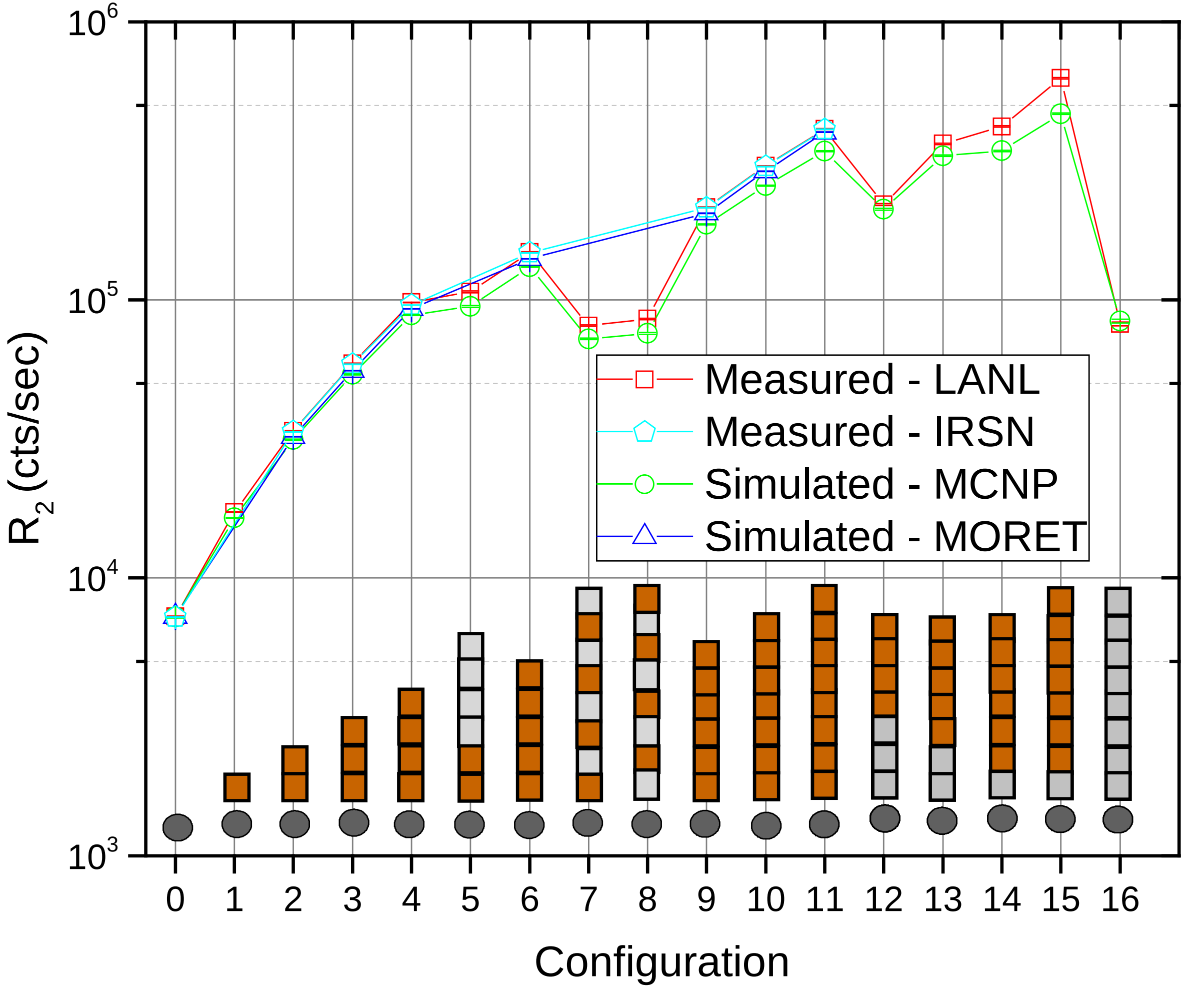
Gate-width (τ)



Doubles count rate (R_2)

Doubles count rate:

$$R_2(\tau) = \frac{Y_2(\tau)}{\omega_2(\lambda,\tau)}$$



Leakage Multiplication (M_L)

$$M_L = \frac{-C_2 + C_4}{2C_1}$$

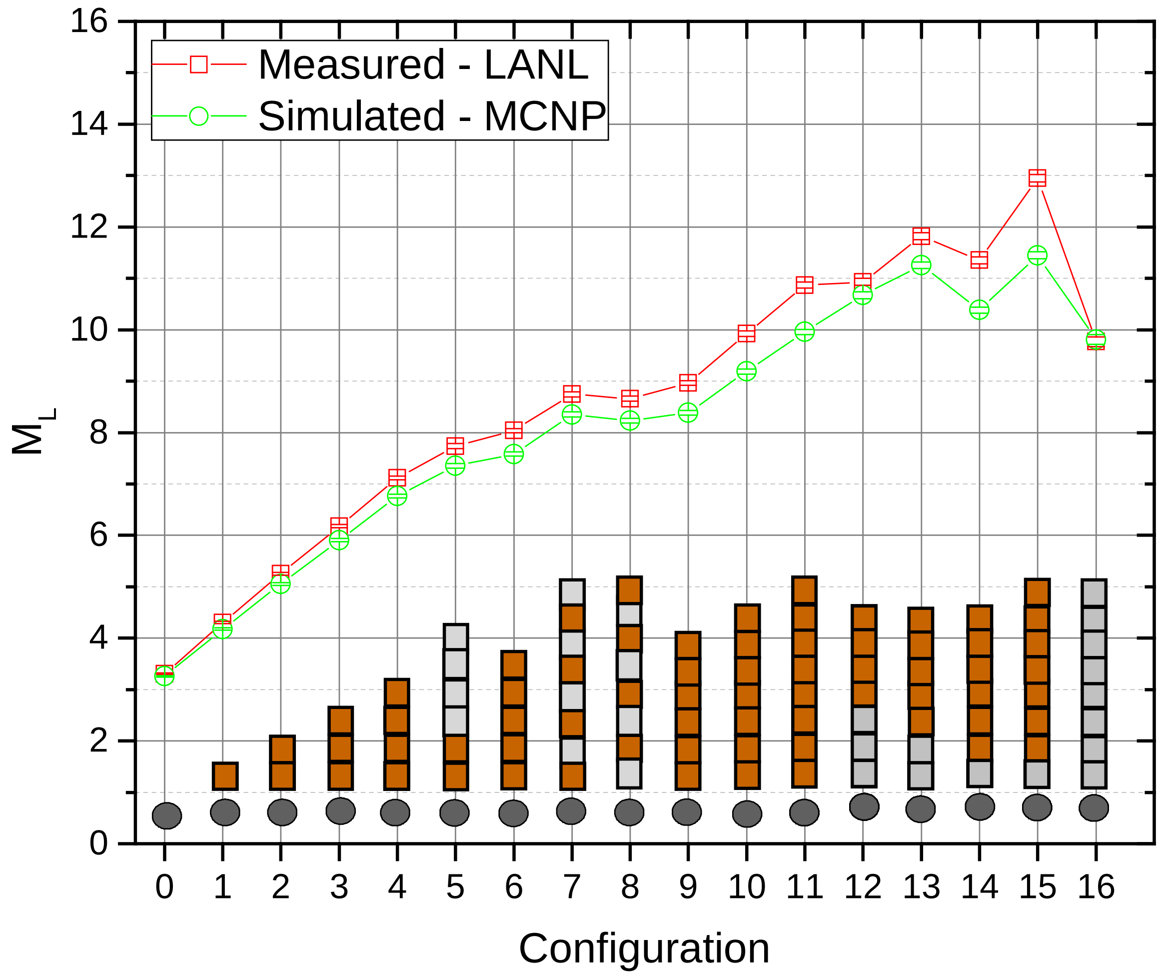
with

$$C_1 = \frac{\bar{\nu}_{S(1)}\bar{\nu}_{I(2)}}{\bar{\nu}_{I(1)} - 1}$$

$$C_2 = \bar{\nu}_{S(2)} - \frac{\bar{\nu}_{S(1)}\bar{\nu}_{I(2)}}{\bar{\nu}_{I(1)} - 1}$$

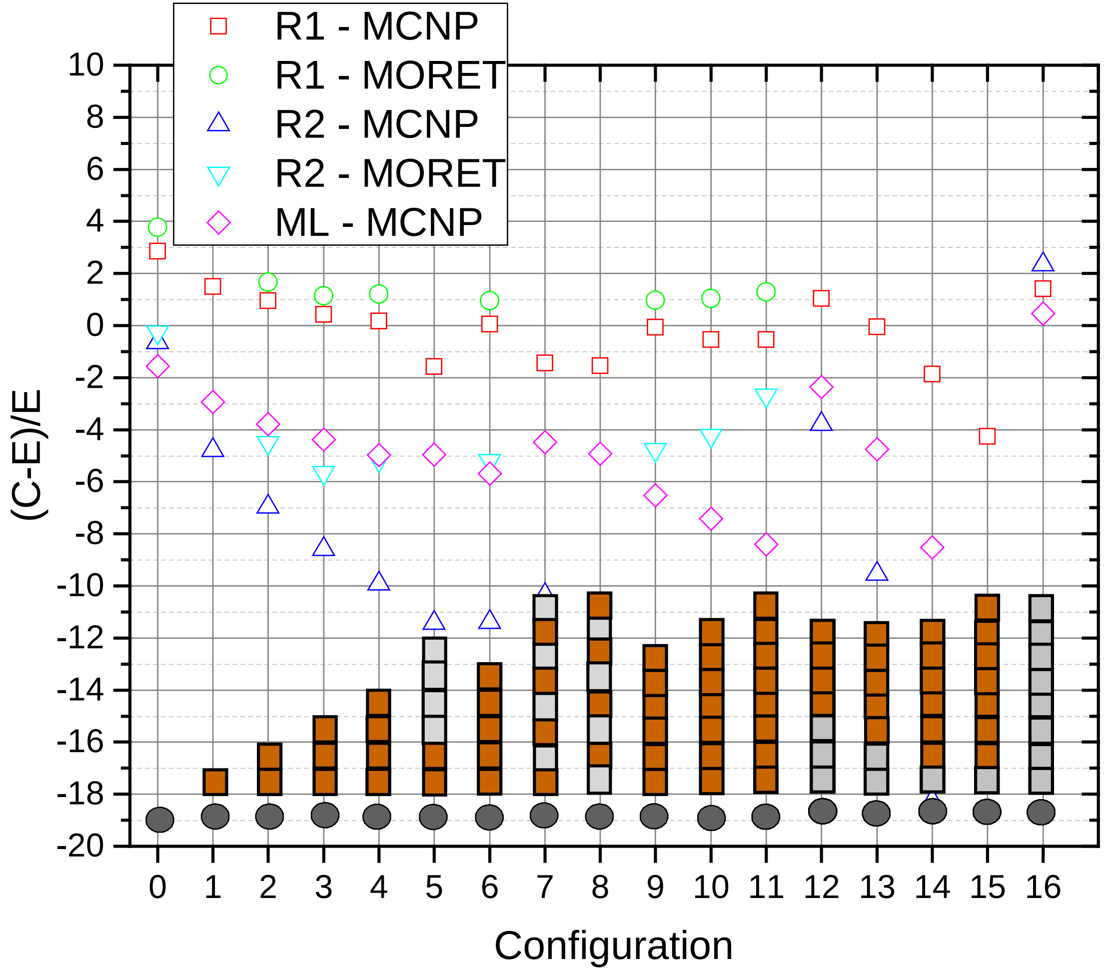
$$C_3 = -\frac{R_2(\tau)\bar{\nu}_{S(1)}}{R_1(\tau)\varepsilon}$$

$$C_4 = \sqrt{C_2^2 - 4C_1C_3}$$



Measurement and simulation comparison

- **MCNP simulations performed using MCNP 6.2.**
- **MORET simulations performed using MORET 5.D with neutron noise plugin.**
- **Both used ENDF/B-VII.1 cross-sections.**



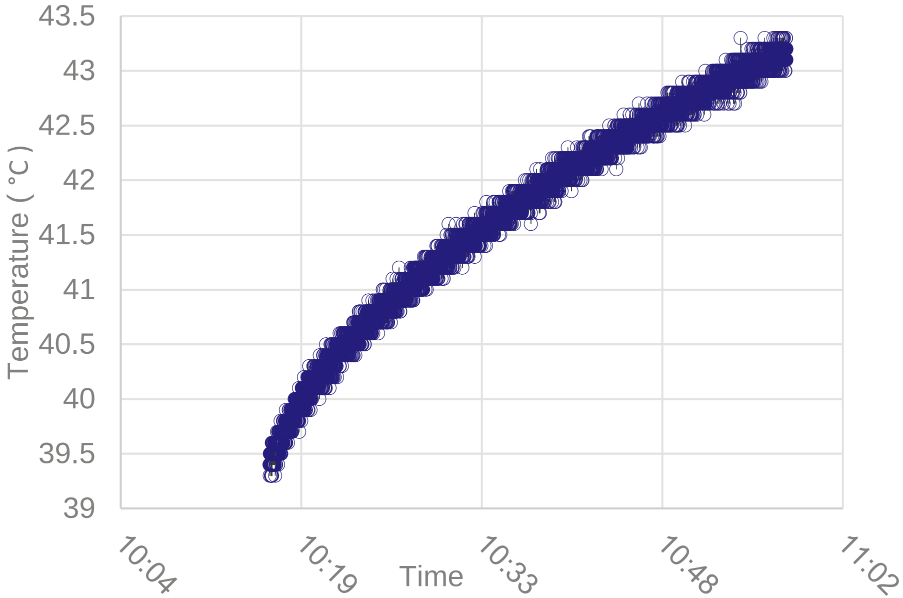
Measurement and simulation comparison

- **(C-E)/E comparison of 2017 model (old) and current model (new).**
- **Many of the configurations (especially those with significant HDPE) have gotten much closer to the measured results.**
- **Changes to the model include:**
  - Updated compositions (impurity analysis).
  - Inclusion of gaps.
  - Other geometry modifications.

Config	R_1		R_2		M_L	
	new	old	new	old	new	old
0	2.8%	-0.1%	-0.6%	-8.4%	-1.6%	-2.2%
1	1.5%	0.1%	-4.8%	-6.5%	-2.9%	-2.6%
2	0.9%	0.4%	-7.0%	-6.5%	-3.8%	-3.7%
3	0.4%	0.5%	-8.6%	-6.4%	-4.4%	-4.1%
4	0.2%	-0.6%	-9.9%	-8.7%	-5.0%	-4.8%
5	-1.6%	2.3%	-11.4%	-7.5%	-5.0%	-8.1%
6	0.0%	-0.2%	-11.4%	-8.6%	-5.7%	-5.8%
7	-1.4%	3.4%	-10.4%	5.2%	-4.5%	-0.5%
8	-1.5%	-0.9%	-11.3%	-10.3%	-4.9%	-6.2%
9	-0.1%	0.2%	-13.1%	-9.5%	-6.5%	-7.6%
10	-0.5%	0.5%	-15.1%	-9.8%	-7.4%	-8.8%
11	-0.5%	0.8%	-17.0%	-10.6%	-8.4%	-10.7%
12	1.0%	13.2%	-3.8%	35.7%	-2.4%	2.3%
13	0.0%	7.7%	-9.5%	15.2%	-4.8%	-4.2%
14	-1.9%	4.7%	-18.3%	2.4%	-8.5%	-7.6%
15	-4.3%	3.2%	-25.6%	-2.9%	-11.6%	-10.5%
16	1.4%	60.3%	2.4%	184.9%	0.5%	9.7%

Temperature Data

- **Temperature and Environmental Data Collected for all Configurations**
  - o Ambient temp, pressure, and humidity
  - o BeRP ball and Outer Reflector temp
  - o First subcritical measurement of the BeRP ball with temperature data collected during all measurements
    - Lesson-learned from BeRP/W and BeRP/Ni benchmarks to have detailed temperature data
  - o BeRP ball temp changes more with thin metal reflectors, and with cases where there is significant amounts of polyethylene (Cases 1, 2, and 5, 7, 8, and 16, respectively).
  - o Configurations with thick total reflector have smallest outer reflector temperature change



BeRP ball temperature during Configuration 2
(BeRP ball with 1” Cu reflector)

Benchmark Status

- SCRaP will go to ICSBEP in October.
- Section 1: draft complete (part of CED-4a, which was just submitted).
- Section 2: draft complete (part of CED-4a, which was just submitted).
- Section 3: draft is partially complete.
- Section 4 and Appendices: not complete yet.
- Models are not complete but at ~95% level.

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Volume IX

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COPPER- AND POLYETHYLENE- REFLECTED PLUTONIUM-METAL-SPHERE SUBCRITICAL MEASUREMENTS

Evaluators

Theresa Cutler
Jennifer Arthur
Los Alamos National Laboratory

Internal Reviewers
Jesson Hutchinson
Rian Bahran

Independent Reviewers

Sean Walston
Gregory Keefer
Lawrence Livermore National Laboratory

Wilfried Monange
IRSN

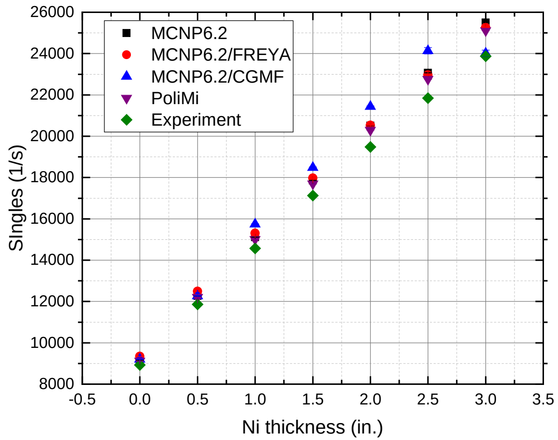
What's next?

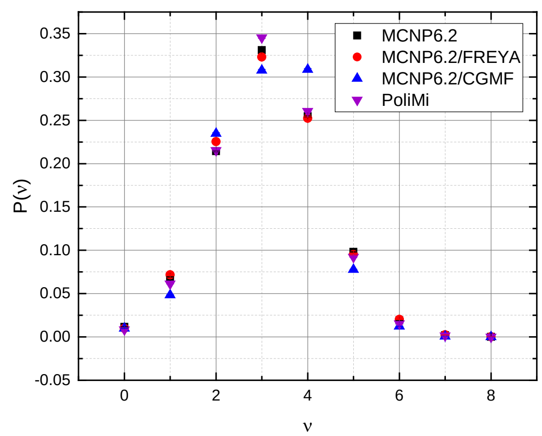
- Finish ICSBEP evaluation.
- ALL parameters will be compared to simulated list-mode data.
- Simulations will be compared for a variety of codes (MCNP, Polimi, etc.) with correlated fission event generators (FREYA, CGMF) and various nuclear data libraries (ENDF/B-VII.1, VIII, and JEFF-3.2).

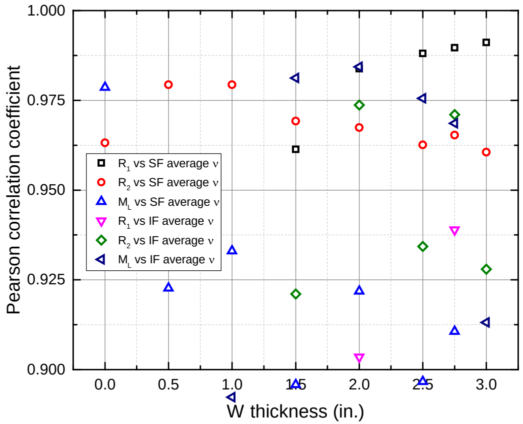
Correlated physics of fission radiation transport codes

- **Simulations of LANL International Criticality Safety Benchmark Evaluation Project (ICSBEP) reflected plutonium (BeRP) ball subcritical measurements have been conducted**
  - o Using various radiation transport codes that take into account the correlated physics of fission neutrons
  - o Correlations between discrepancies in observables of interest and discrepancies in the underlying nuclear data are being investigated

J. Arthur, R. Bahran, J. Hutchinson, M. Rising, S. Pozzi, *Comparison of the Performance of Various Correlated Fission Multiplicity Monte Carlo Codes*. Las Vegas, NV: ANS Winter Meeting and Nuclear Technology Expo, 2016, LA-UR-16-24512**.**

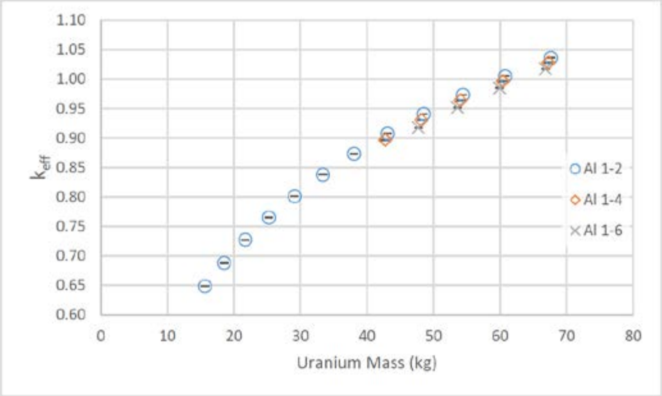






IER 488: A Subcritical/Critical HEU Experiment

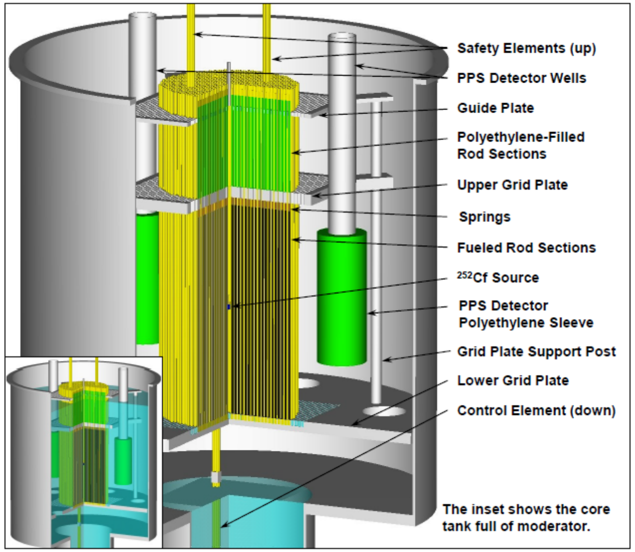
- Collaboration between LANL and IRSN
- Benchmark measurements at NCERC using HEU at a wide variety of multiplication/reactivity levels with the Rocky Flats shells
- Measurements would continue improvement and validation of subcritical measurement techniques, computational methods, and nuclear data for ^{235}U and ^{238}U.
- Multiple neutron sources, detectors, and analysis methods



- CED-1 Preliminary Design in approval process now
- CED-2 Final Design Q4

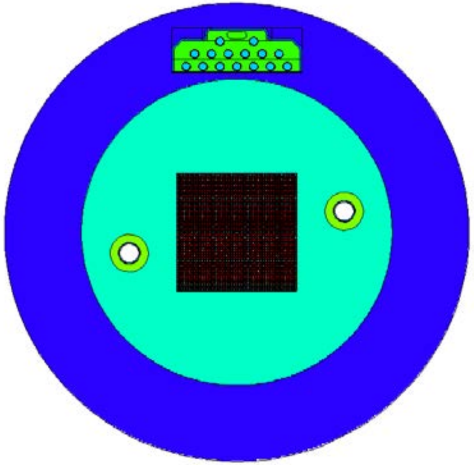
SNL 7uPCX reactor benchmark

- Proposing a series of advanced subcritical benchmark measurements at the zero-power SNL reactor using LANL neutron multiplicity detectors
  - Apply research reactor protocol from CaSPER to benchmark-quality measurement
- Diversity of achievable configurations is unique in contrast to previous subcritical benchmark measurements in ICSBEP handbook.



Preliminary simulation results:
R_1=6.0E3 s^{-1}
R_2=1.9E5 s^{-1}

Given a ~1e5 n/s Cf-252 source in the center.



Thank you for your attention.

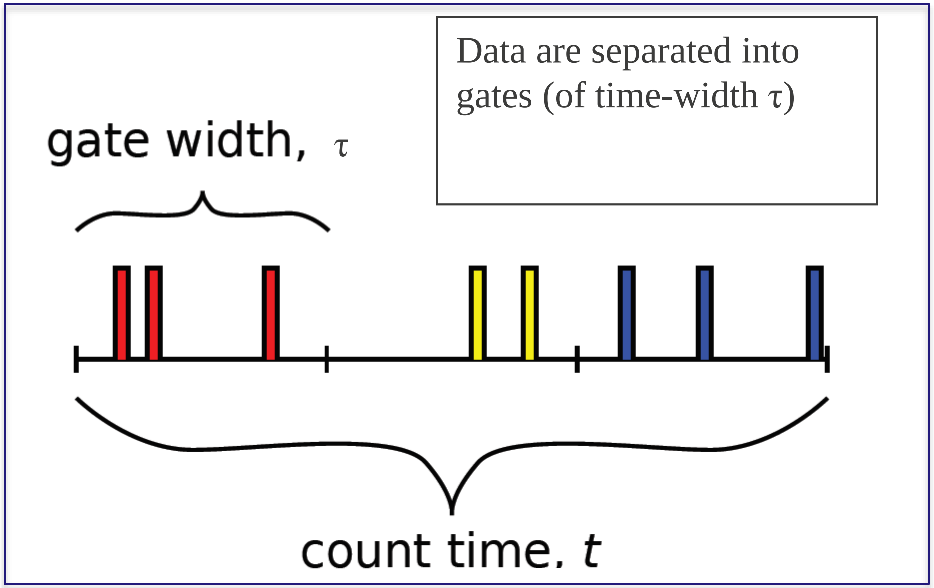
NCERC
NATIONAL CRITICALITY EXPERIMENTS RESEARCH CENTER

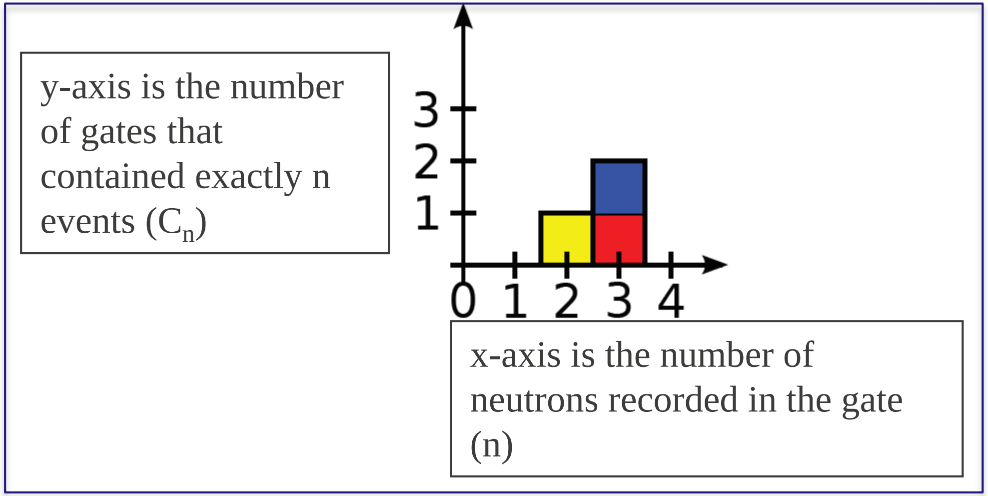
This work was supported by the DOE Nuclear Criticality Safety Program, funded and managed by the National Nuclear Security Administration for the Department of Energy.

Backup slides

Analysis method

- **Neutron noise analysis**
  - o Rossi-alpha
  - o Time interval analysis
  - o Feynman variance to mean
    - Hansen Dowdy
    - Hage-Cifarelli
  - o Others…
- **Analysis method used here will be documented in the SCRaP benchmark.**





Singles count rate (R_1)

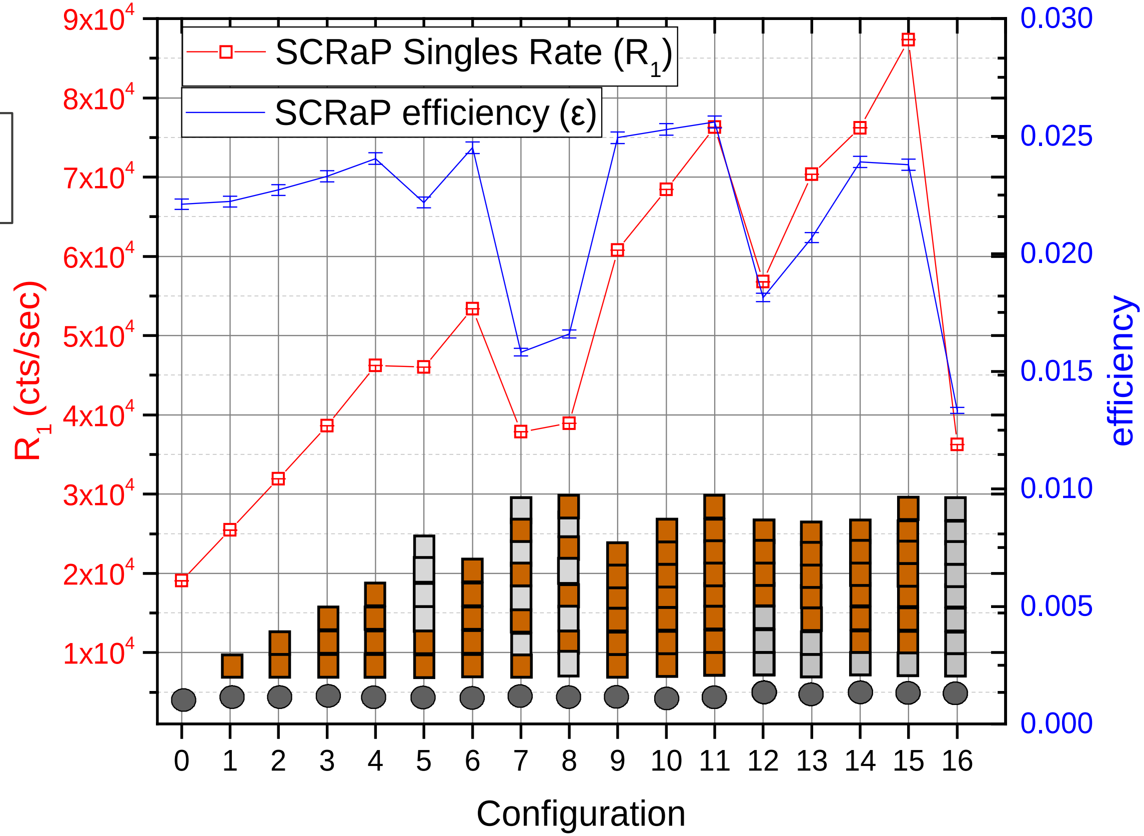
Detector efficiency (from Cf-252 measurements):

$$\varepsilon = \frac{R_1(\tau)}{F_S \bar{\nu}_{S(1)}}$$

This is the count rate from the Cf-252 measurements.

F_S is the reported spontaneous fission emission rate of the ^{252}Cf source.

$\bar{\nu}_{S(1)}$ is the average number of neutrons emitted per ^{252}Cf fission.

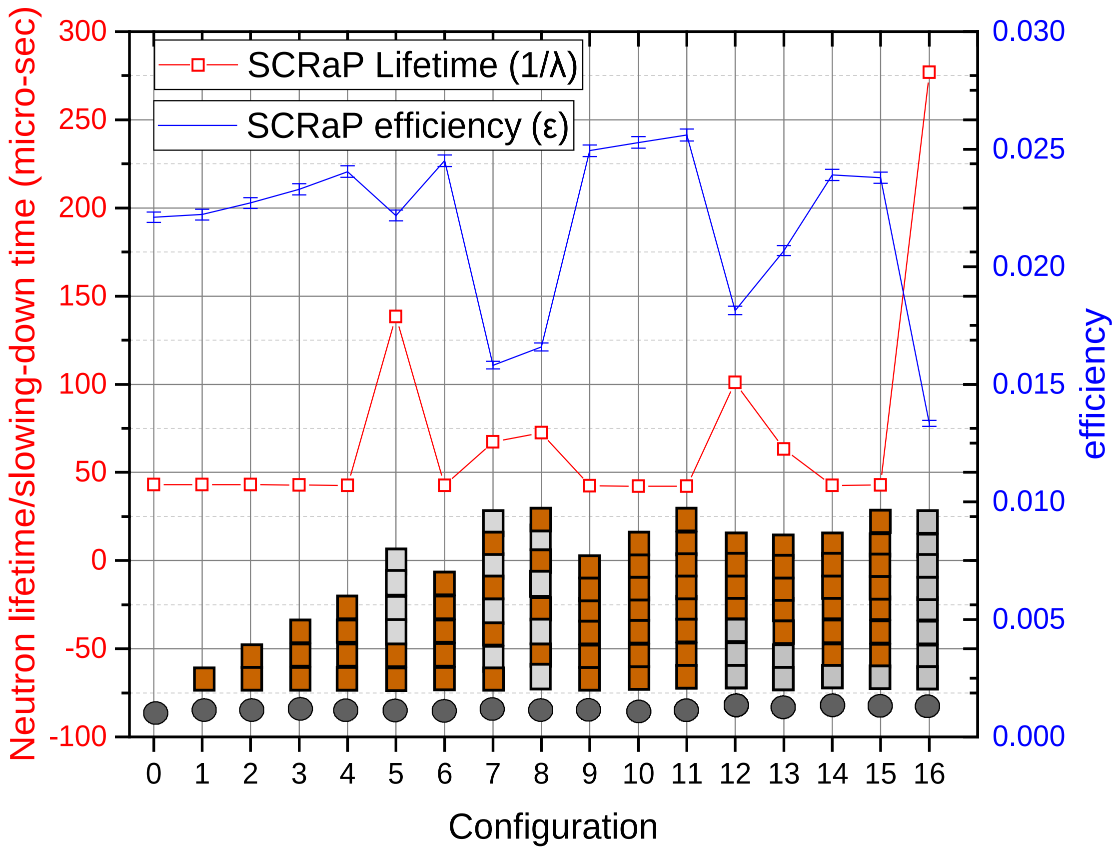


Plotted together to show that the reason that the count rate goes down significantly for the configurations with HDPE is due to the decrease in efficiency (which is caused by neutron absorption primarily in the hydrogen).

Neutron lifetime/slowing-down time

The focus of recent (and upcoming work).

Neutron lifetime/slowing-down time (1/λ or 1/α) can be found by fitting either Y_2 or Rossi-α data.



The NoMAD detector system has a slowing-down time of around 40 micro-seconds.
For the configurations with Cu only, the result is approximately 40 micro-seconds as expected, but it is significantly larger for the configurations that include HDPE hemishells.

Leakage multiplication (M_L)

$$M_L = \frac{-C_2 + C_4}{2C_1}$$

with

$$C_1 = \frac{\bar{\nu}_{S(1)}\bar{\nu}_{I(2)}}{\bar{\nu}_{I(1)} - 1}$$

$$C_2 = \bar{\nu}_{S(2)} - \frac{\bar{\nu}_{S(1)}\bar{\nu}_{I(2)}}{\bar{\nu}_{I(1)} - 1}$$

$$C_3 = -\frac{R_2(\tau)\bar{\nu}_{S(1)}}{R_1(\tau)\varepsilon}$$

$$C_4 = \sqrt{C_2^2 - 4C_1C_3}$$

$\bar{\nu}_{S(1)}$ 1st factorial moment of ^{240}Pu P_ν

$\bar{\nu}_{S(2)}$ 2nd factorial moment of ^{240}Pu P_ν

$\bar{\nu}_{I(1)}$ 1st factorial moment of ^{239}Pu P_ν

$\bar{\nu}_{I(2)}$ 2nd factorial moment of ^{239}Pu P_ν

Assumes that there are no emissions from (α,n) neutrons.

Leakage multiplication is related to the multiplication factor (k_{eff}).