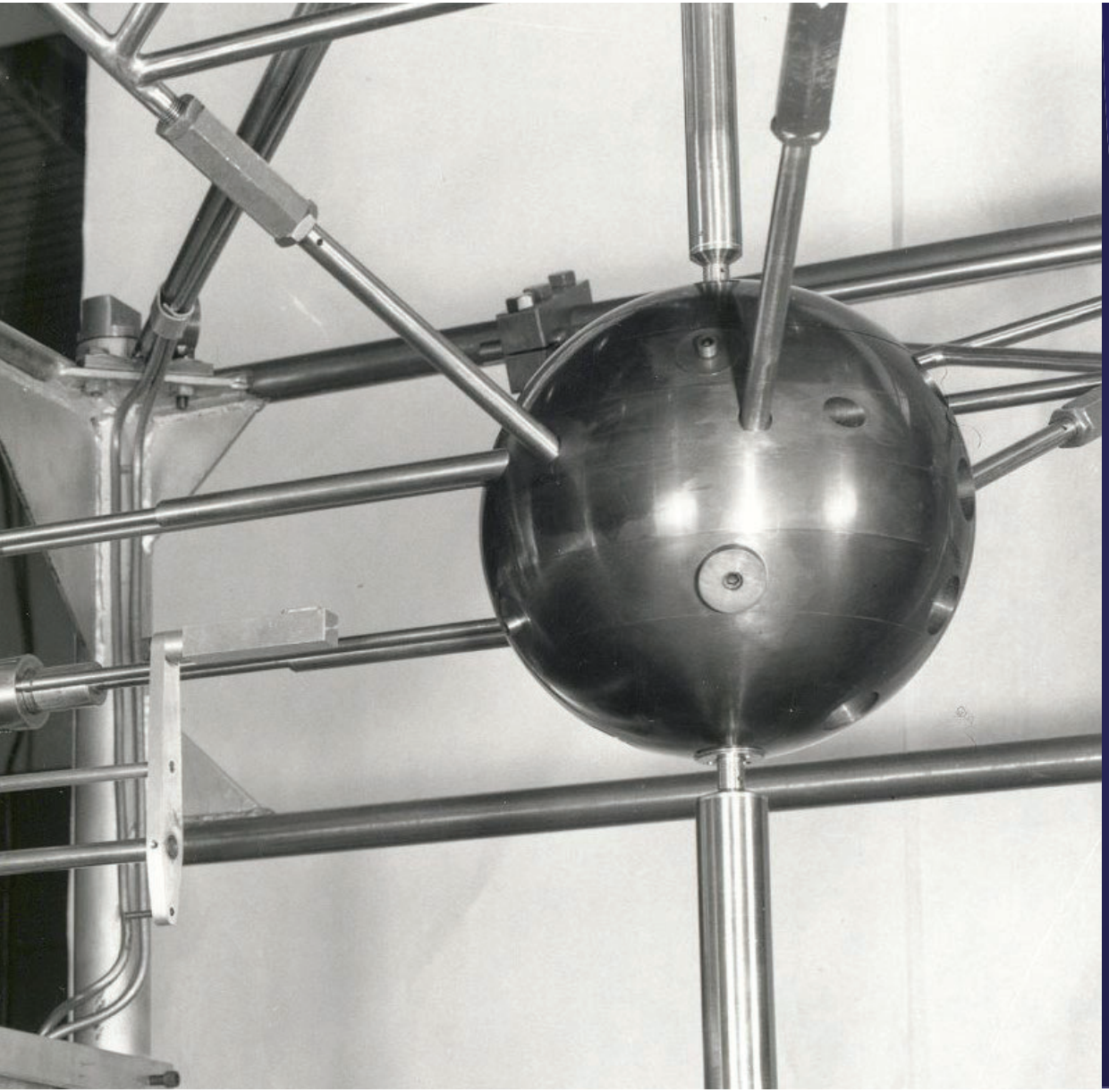

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Comparison of Predicted and Measured Subcritical Benchmark Uncertainties as a Function of Counting Time

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ANS Winter 2018

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Overview

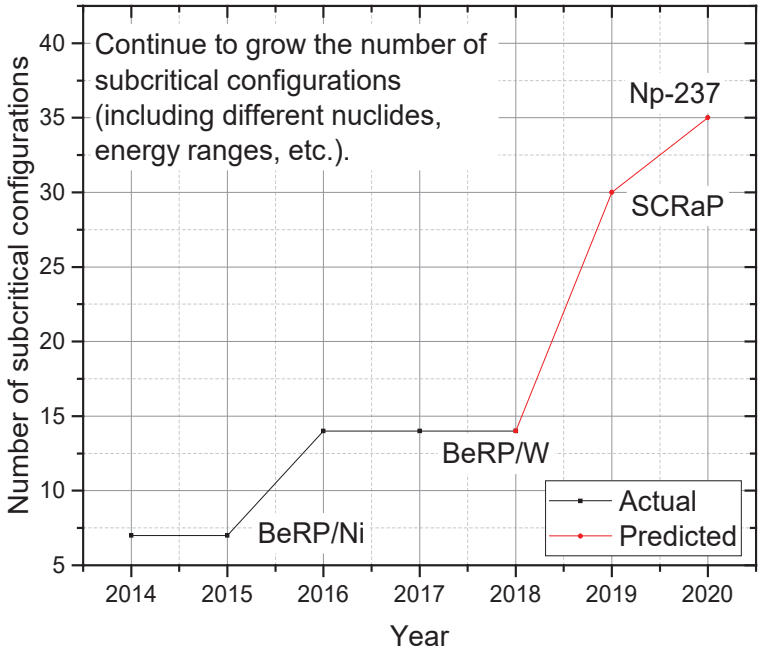
- Introduction
- Background
- Experiment design
- Method
- Results
- Conclusions

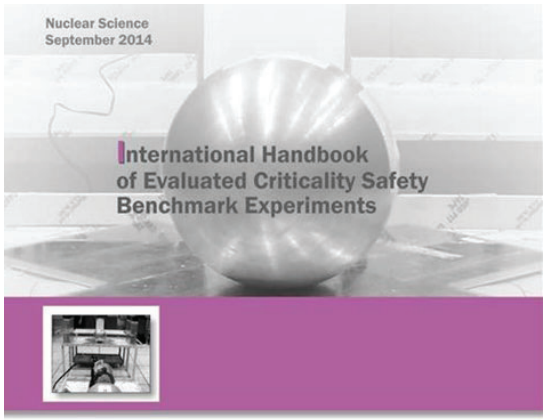
Introduction

- For subcritical benchmarks, the statistical uncertainties are generally a significant part of the overall experimental uncertainties.
- Previously, a method was introduced to estimate statistical uncertainties of benchmark parameters as a function of counting time using simulated data.
- This work compares these predicted uncertainties versus the uncertainties which were measured during the execution of a subcritical benchmark.

Background

- **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.**

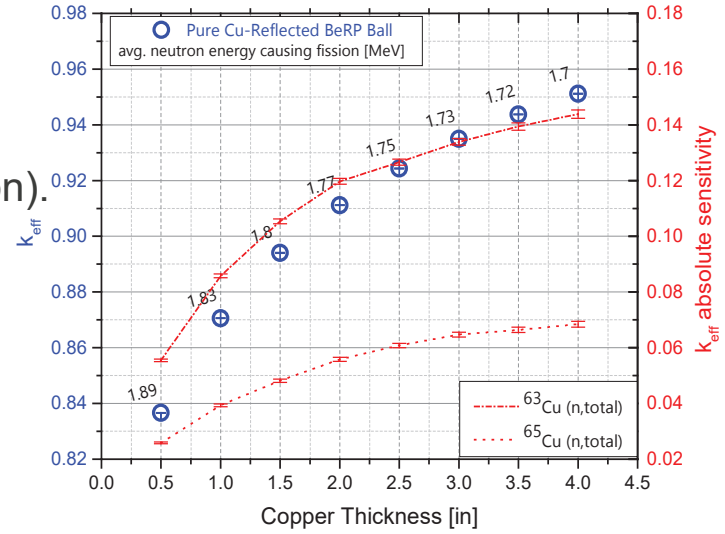




Background

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

- **Goals**
  - 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.
  - Subcritical experiments:
    - Improve subcritical simulation capabilities.
    - Improve analysis of measured data (uncertainty quantification).
    - Characterization of detector systems.



Experiment Design

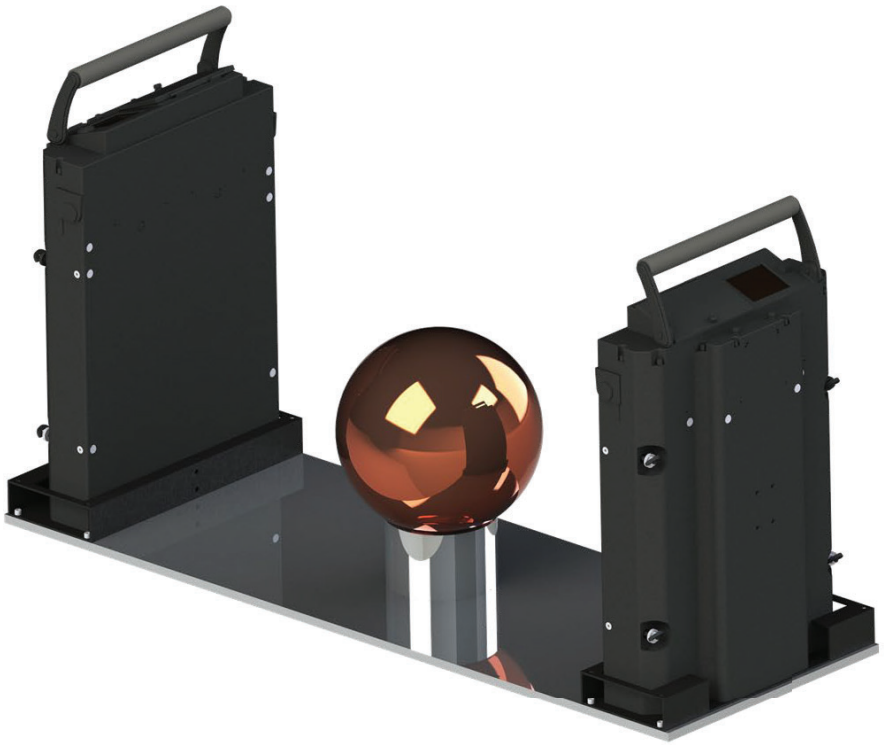
- **NoMAD (Neutron Multiplicity ^{3}He Array Detector) was used to measure three benchmark parameters:**
  - Detector singles count rate (R_1) i.e. the count rate in the detector system
  - Doubles count rate (R_2) i.e. the rate in the detector system in which two neutrons from the same fission chain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

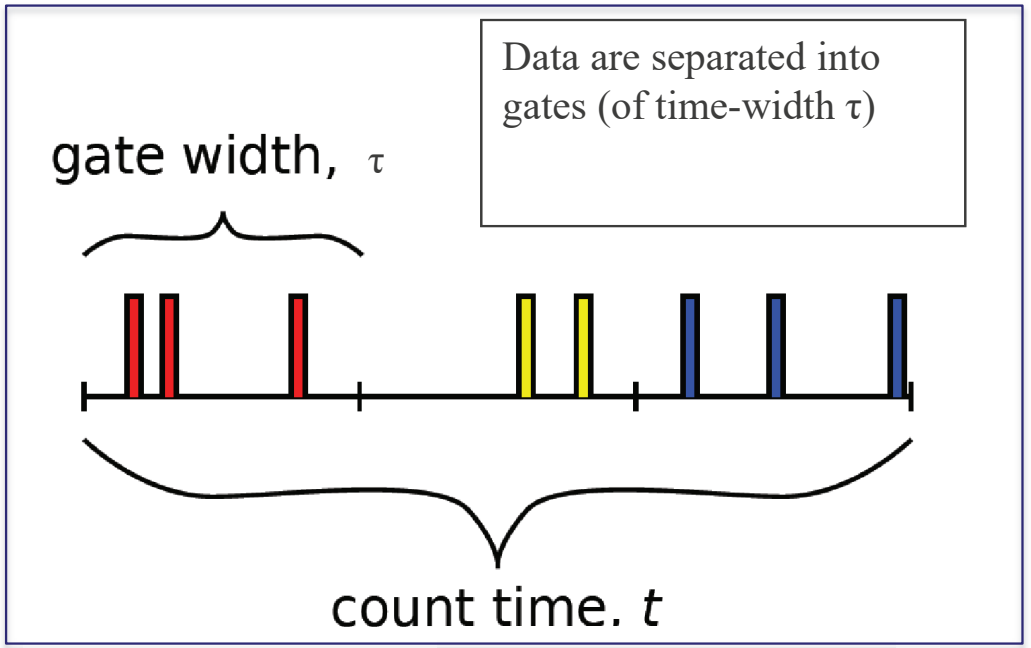
Records list-mode data (a time list of every recorded neutron event to a resolution of 128 nsec).

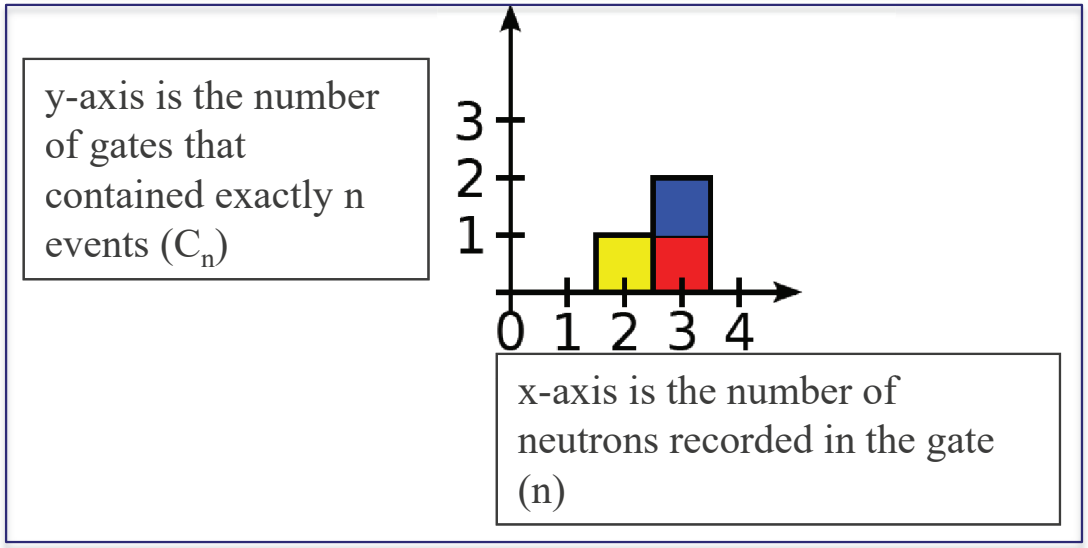
Photograph and MCNP® model of the NoMAD detector system.

15 He-3 tubes inside polyethylene.

Method

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

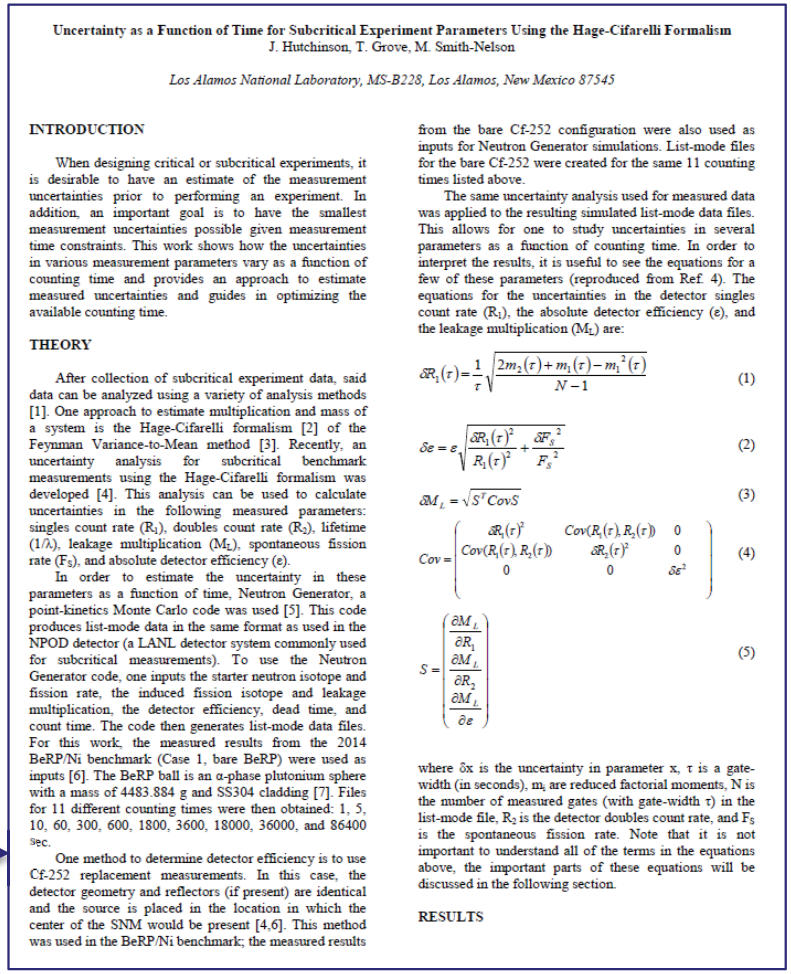




Method

- **It is important to have the smallest measurement uncertainties possible given time constraints.**
  - For all three benchmark parameters: singles count rate (R_1), doubles count rate (R_2), and leakage multiplication (M_L).
- **A method was developed to estimate the measured uncertainty as a function of counting time.**
- **This method was used to guide the counting times which were used.**
- **This work compares these estimates to the actual uncertainties that were measured.**

ANS Winter 2016



Uncertainty as a Function of Time for Subcritical Experiment Parameters Using the Hage-Cifarelli Formalism

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INTRODUCTION

When designing critical or subcritical experiments, it is desirable to have an estimate of the measurement uncertainties prior to performing an experiment. In addition, an important goal is to have the smallest measurement uncertainties possible given measurement time constraints. This work shows how the uncertainties in various measurement parameters vary as a function of counting time and provides an approach to estimate measured uncertainties and guides in optimizing the available counting time.

THEORY

After collection of subcritical experiment data, said data can be analyzed using a variety of analysis methods [1]. One approach to estimate multiplication and mass of a system is the Hage-Cifarelli formalism [2] of the Feynman Variance-to-Mean method [3]. Recently, an uncertainty analysis for subcritical benchmark measurements using the Hage-Cifarelli formalism was developed [4]. This analysis can be used to calculate uncertainties in the following measured parameters: singles count rate (R_1), doubles count rate (R_2), lifetime ($1/\lambda$), leakage multiplication (M_L), spontaneous fission rate (F_S), and absolute detector efficiency (ε).

In order to estimate the uncertainty in these parameters as a function of time, Neutron Generator, a point-kinetics Monte Carlo code was used [5]. This code produces list-mode data in the same format as used in the NPOD detector (a LANL detector system commonly used for subcritical measurements). To use the Neutron Generator code, one inputs the starter neutron isotope and fission rate, the induced fission isotope and leakage multiplication, the detector efficiency, dead time, and count time. The code then generates list-mode data files. For this work, the measured results from the 2014 BeRP/Ni benchmark (Case 1, bare BeRP) were used as inputs [6]. The BeRP ball is an α-phase plutonium sphere with a mass of 4483.884 g and SS304 cladding [7]. Files for 11 different counting times were then obtained: 1, 5, 10, 60, 300, 600, 1800, 3600, 18000, 36000, and 86400 sec.

One method to determine detector efficiency is to use Cf-252 replacement measurements. In this case, the detector geometry and reflectors (if present) are identical and the source is placed in the location in which the center of the SNM would be present [4,6]. This method was used in the BeRP/Ni benchmark; the measured results from the bare Cf-252 configuration were also used as inputs for Neutron Generator simulations. List-mode files for the bare Cf-252 were created for the same 11 counting times listed above.

The same uncertainty analysis used for measured data was applied to the resulting simulated list-mode data files. This allows for one to study uncertainties in several parameters as a function of counting time. In order to interpret the results, it is useful to see the equations for a few of these parameters (reproduced from Ref. 4). The equations for the uncertainties in the detector singles count rate (R_1), the absolute detector efficiency (ε), and the leakage multiplication (M_L) are:

$$\delta R_1(\tau) = \frac{1}{\tau}\sqrt{\frac{2m_2(\tau)+m_1(\tau)-m_1^2(\tau)}{N-1}} \quad (1)$$

$$\delta\varepsilon = \varepsilon\sqrt{\frac{\delta R_1(\tau)^2}{R_1(\tau)^2}+\frac{\delta F_S^2}{F_S^2}} \quad (2)$$

$$\delta M_L = \sqrt{S^T Cov S} \quad (3)$$

$$Cov = \begin{pmatrix} \delta R_1(\tau)^2 & Cov(R_1(\tau),R_2(\tau)) & 0 \\ Cov(R_1(\tau),R_2(\tau)) & \delta R_2(\tau)^2 & 0 \\ 0 & 0 & \delta\varepsilon^2 \end{pmatrix} \quad (4)$$

$$S = \begin{pmatrix} \frac{\partial M_L}{\partial R_1} \\ \frac{\partial M_L}{\partial R_2} \\ \frac{\partial M_L}{\partial \varepsilon} \end{pmatrix} \quad (5)$$

where δx is the uncertainty in parameter x, τ is a gate-width (in seconds), m_i are reduced factorial moments, N is the number of measured gates (with gate-width τ) in the list-mode file, R_2 is the detector doubles count rate, and F_S is the spontaneous fission rate. Note that it is not important to understand all of the terms in the equations above, the important parts of these equations will be discussed in the following section.

RESULTS

Experiment Overview

- **SCRαP Experiment Design.**
  - 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 Configurations

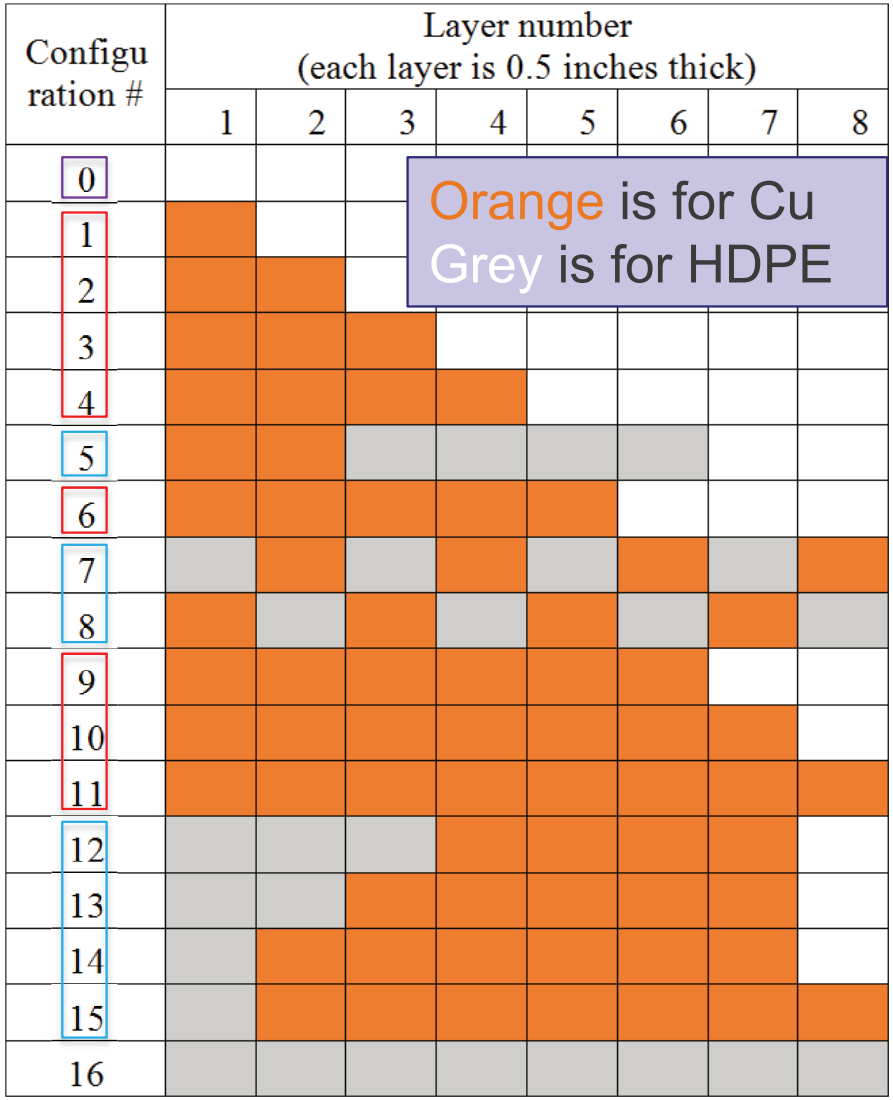
- **17 total configurations:**
  - 1 Bare
  - 8 Cu-only configurations
  - 7 Cu+HDPE configurations
  - 1 HPDE-only configuration
- **In order to determine the detector efficiency, Cf-252 source replacement measurements were performed.**
  - The source strength of the ^{252}Cf source at the time of the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

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

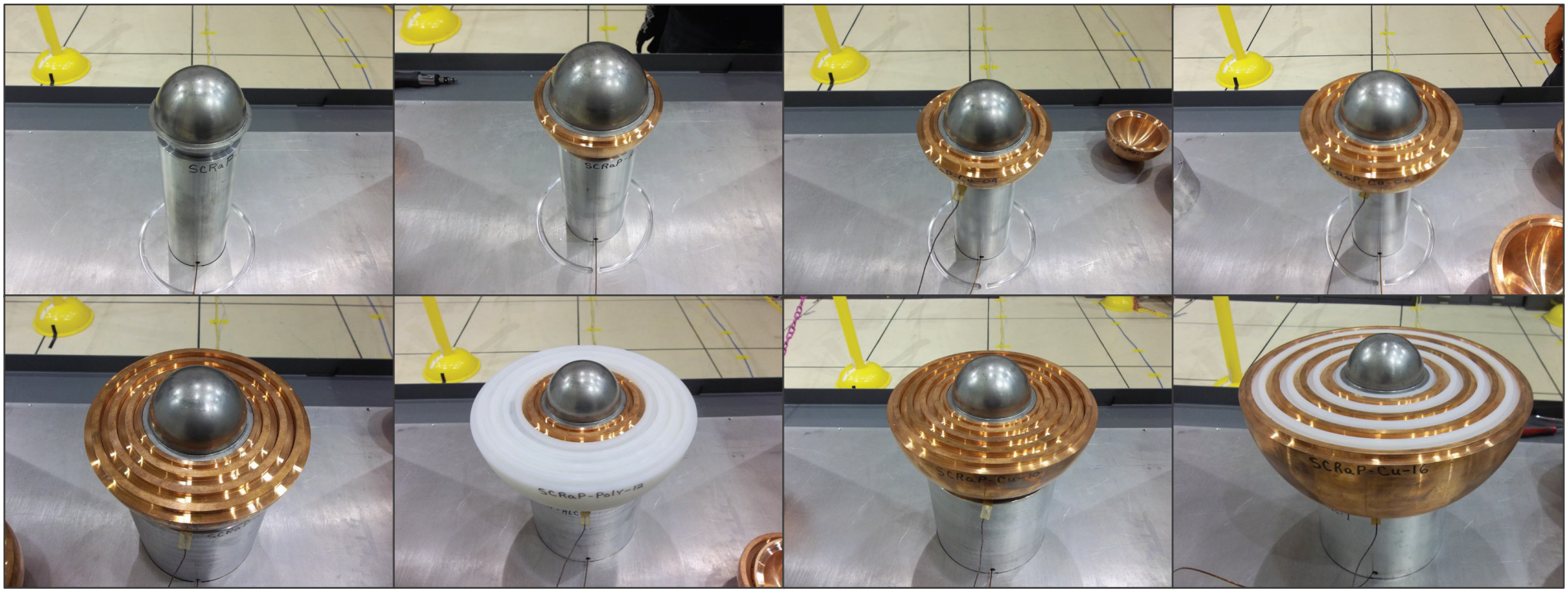
Orange is for Cu
Grey is for HDPE

Experiment Configurations

- **In the upcoming results, the configurations are combined into three groups:**
  - Bare: C00
  - Cu only configurations (no HDPE): C01, 02, 03, 04, 06, 09, 10, 11
  - Configurations with Cu and HDPE: C05, 07, 08, 12, 13, 14, 15
  - The results for the all HDPE configuration (C16) are not shown. This configuration was added during the measurement campaign.

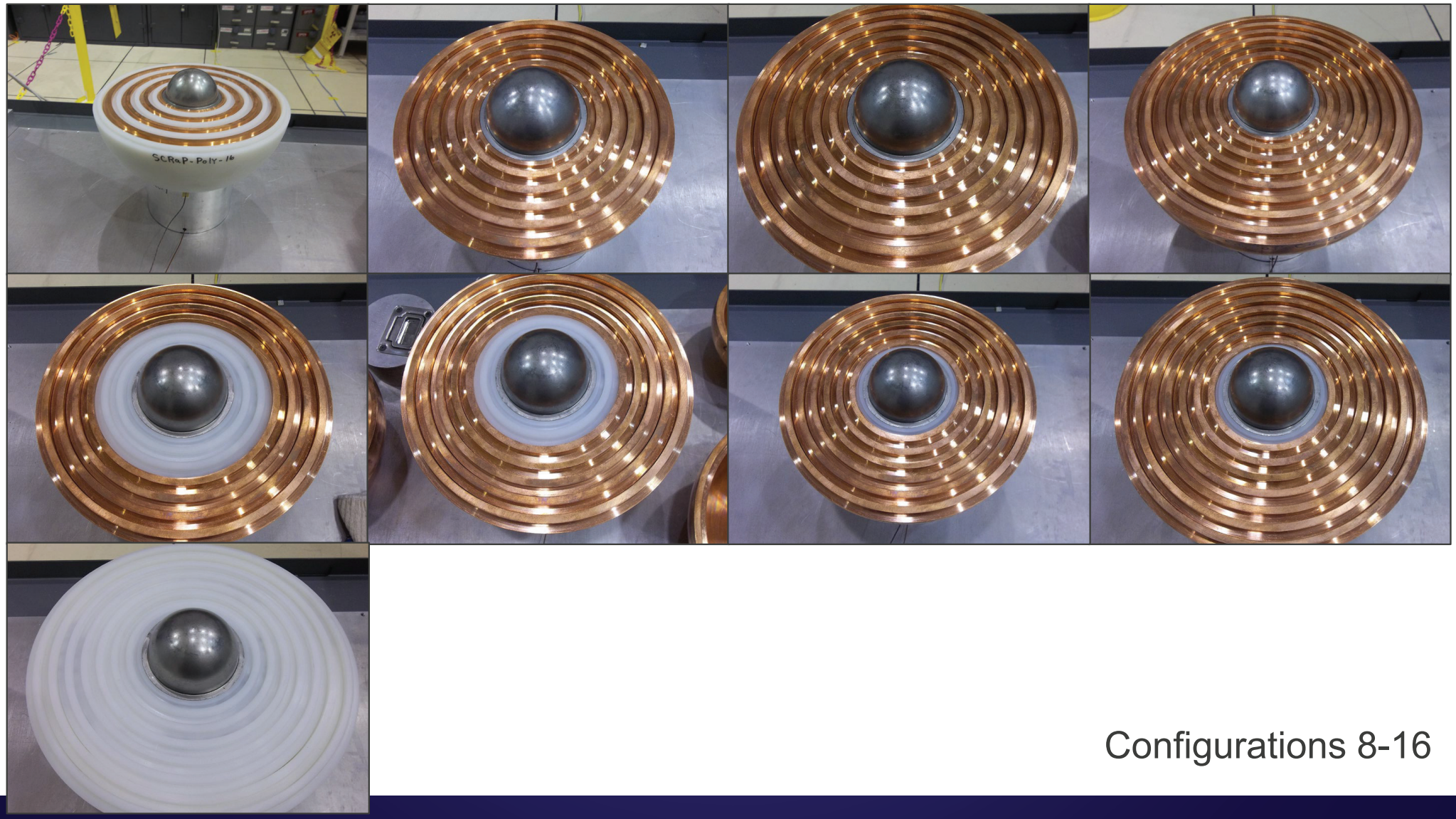


Experiment Configurations



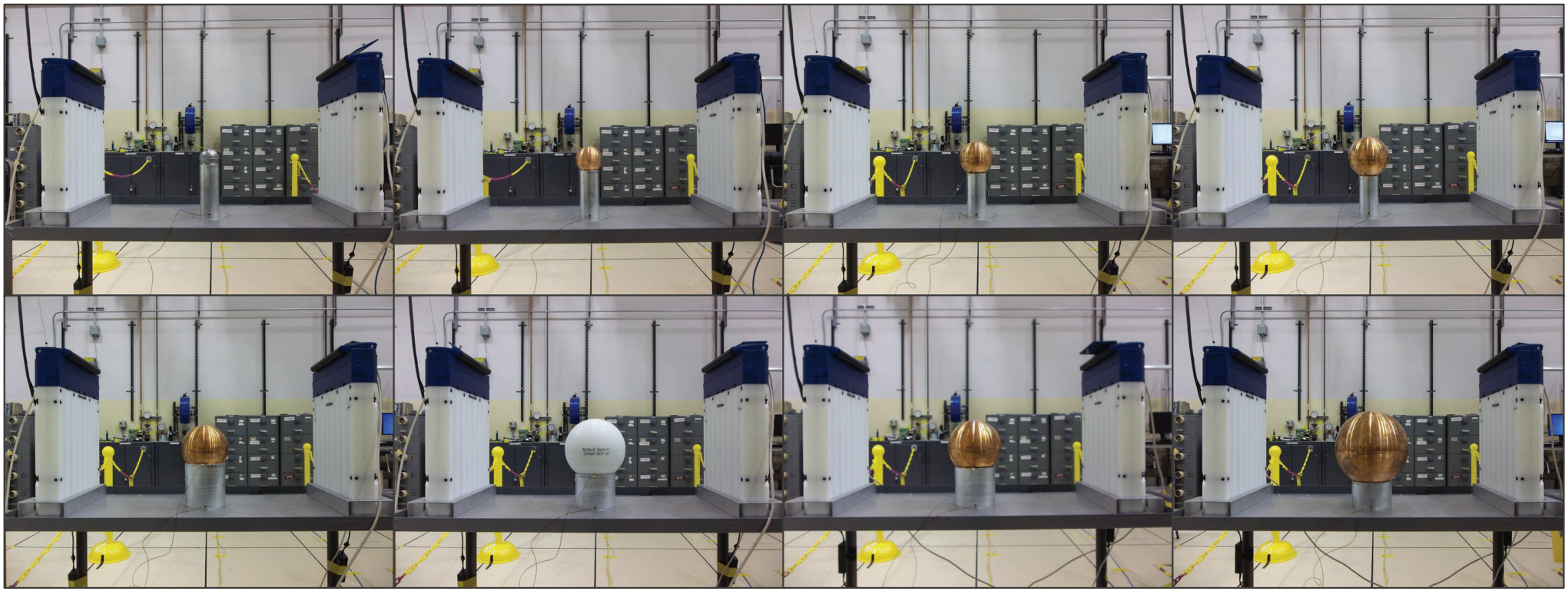
Configurations 0-7

Experiment Configurations



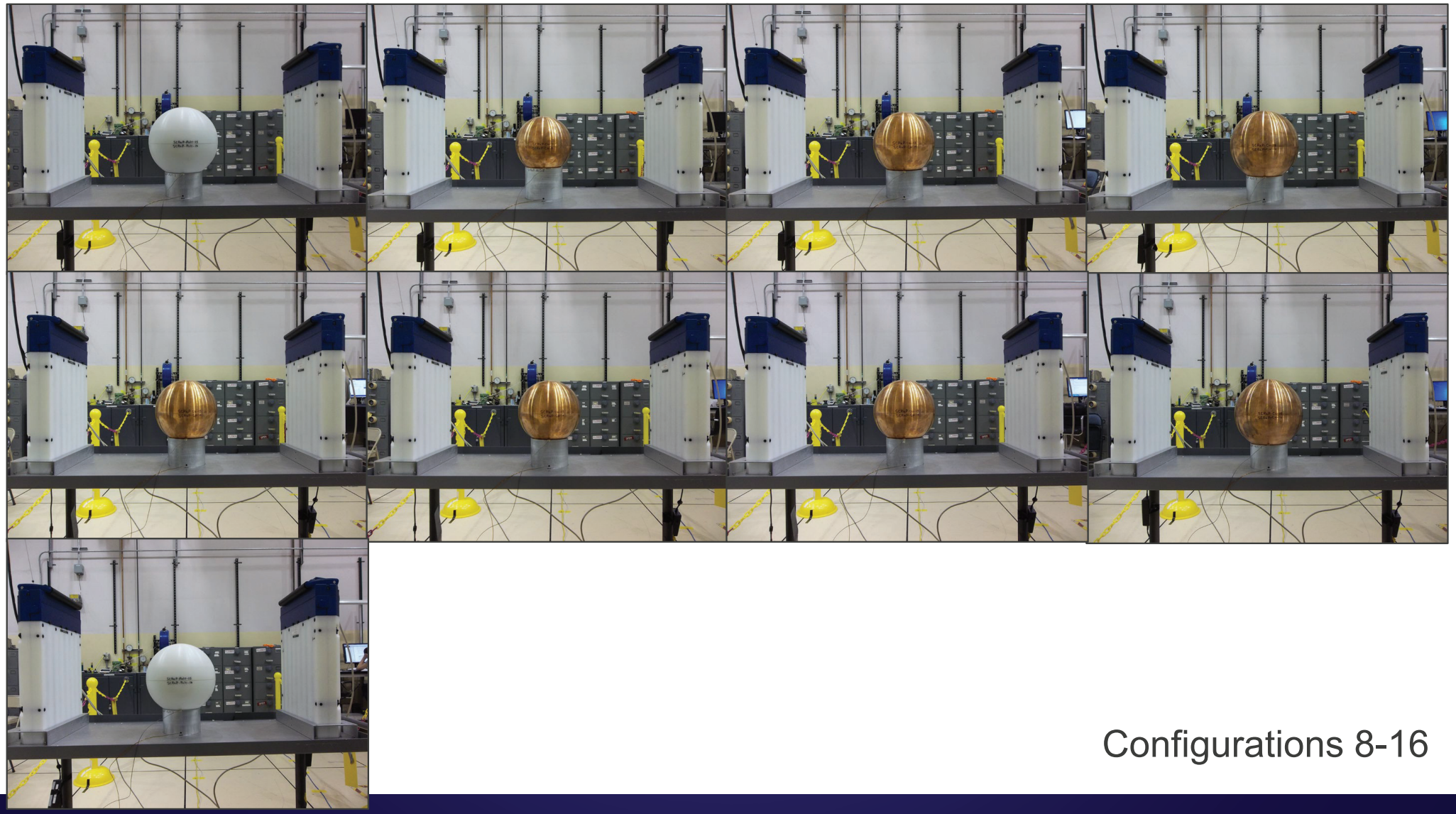
Configurations 8-16

Experiment Configurations



Configurations 0-7

Experiment Configurations



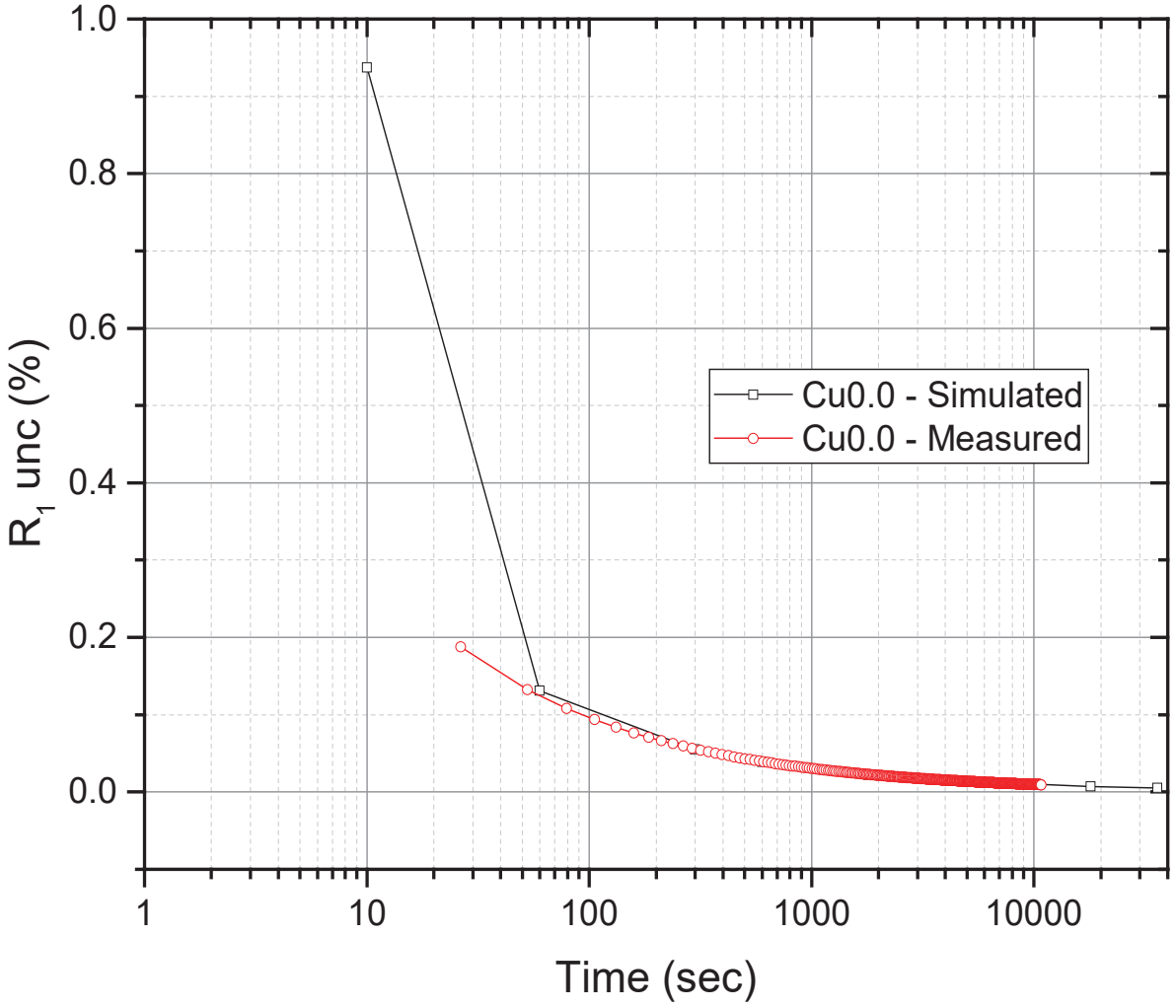
Configurations 8-16

Results

- **The measured list-mode data files (900-1800 sec each) were split info much smaller files.**
- **Smaller files were 5e5 events (6-27 sec measurement times).**
- **The results from these smaller files can be combined to get the measured uncertainties in R_1, R_2, and M_L as a function of counting time.**
- **A 0-D Monte Carlo code was used to generate the simulated data.**
  - Inputs include the BeRP ball spontaneous fission rate (taken from previous BeRP ball benchmarks), the leakage multiplication (determined from MCNP® criticality eigenvalue simulations), and the detector efficiency (based on historical measurements).
  - Simulations were performed during the design phase.

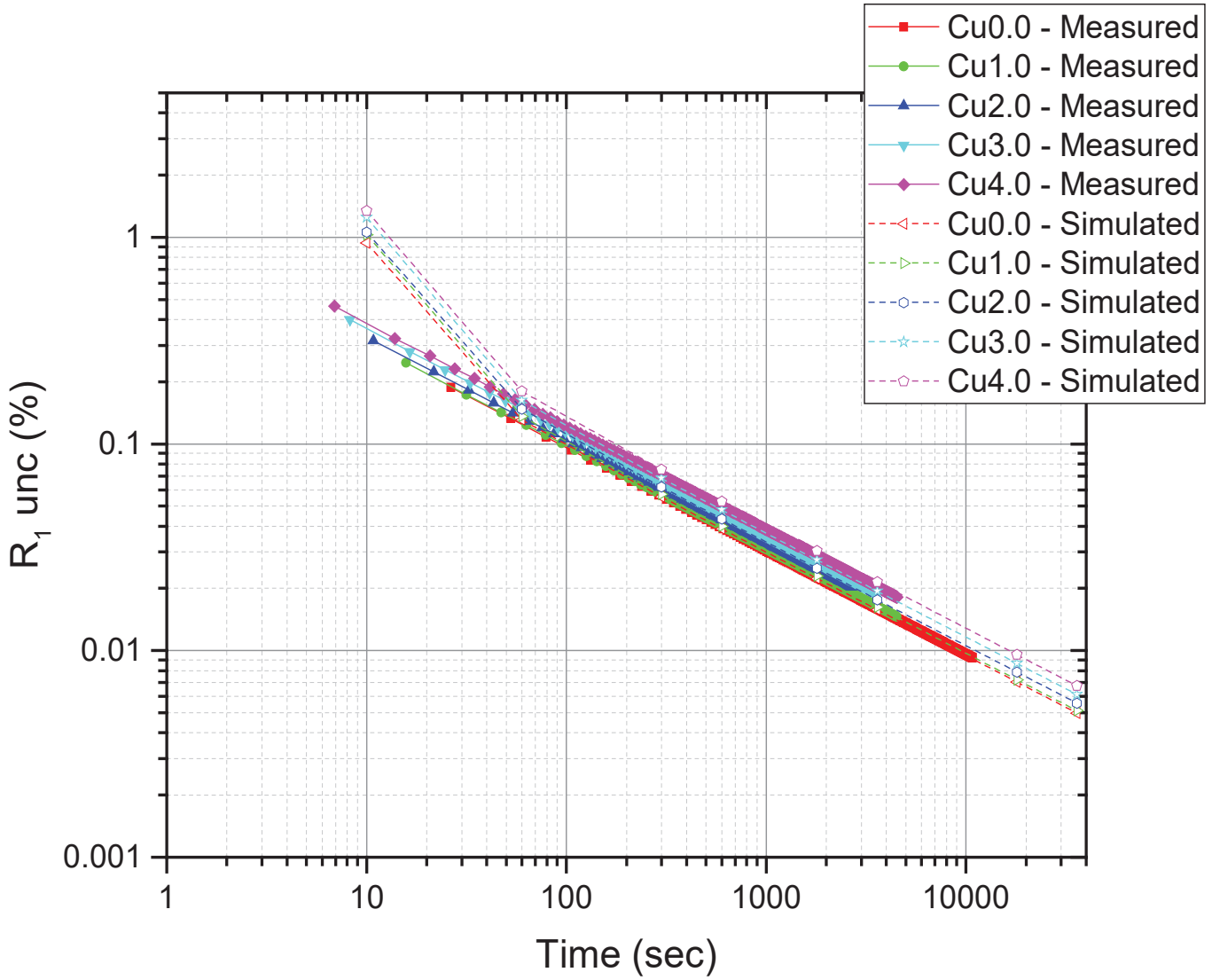
Results: R_1

- **Configuration 0 (bare BeRP)**
  - Measured and simulated results agree very well when the counting time is > 60 sec.
  - Disagreement < 60 sec is likely due to the fact that in the simulations, fission is not possible before t=0, so the count rate will be low until the system reaches a steady state.



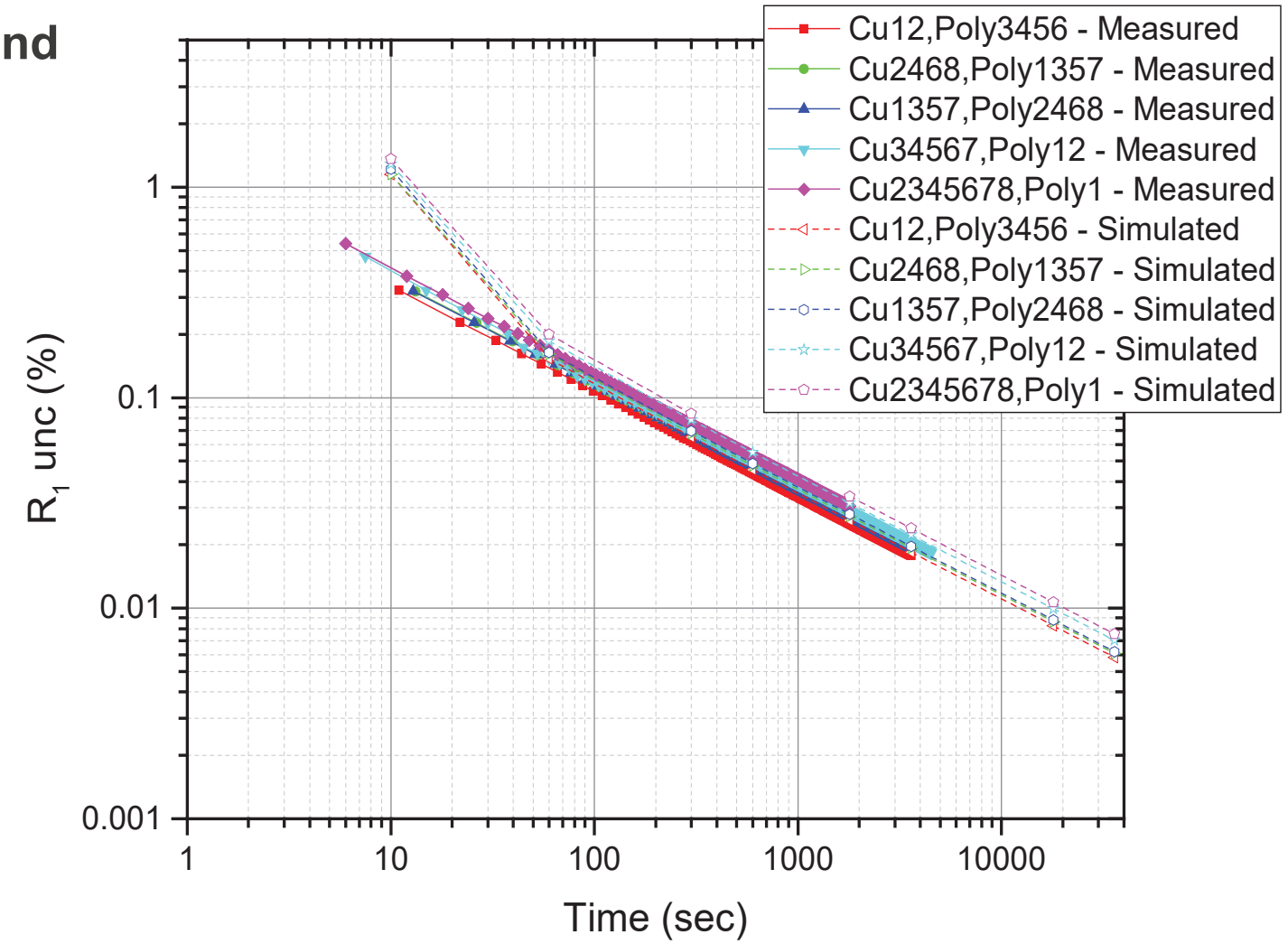
Results: R_1

- **Configuration with Cu reflection only (no HDPE)**
  - Good agreement when counting time > 60 sec.



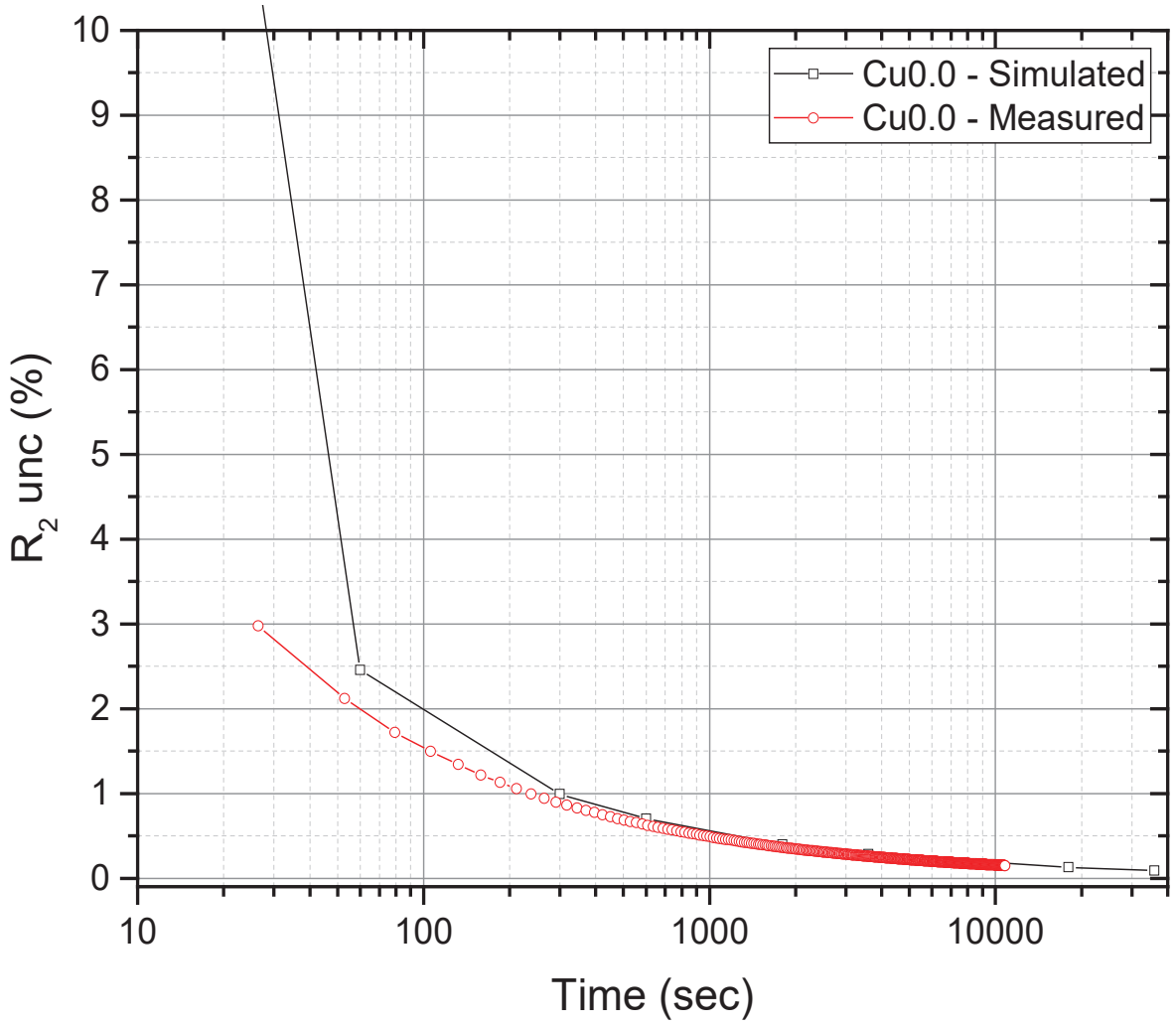
Results: R_1

- **Configuration with Cu and HDPE reflection**
  - Good agreement when counting time > 60 sec.



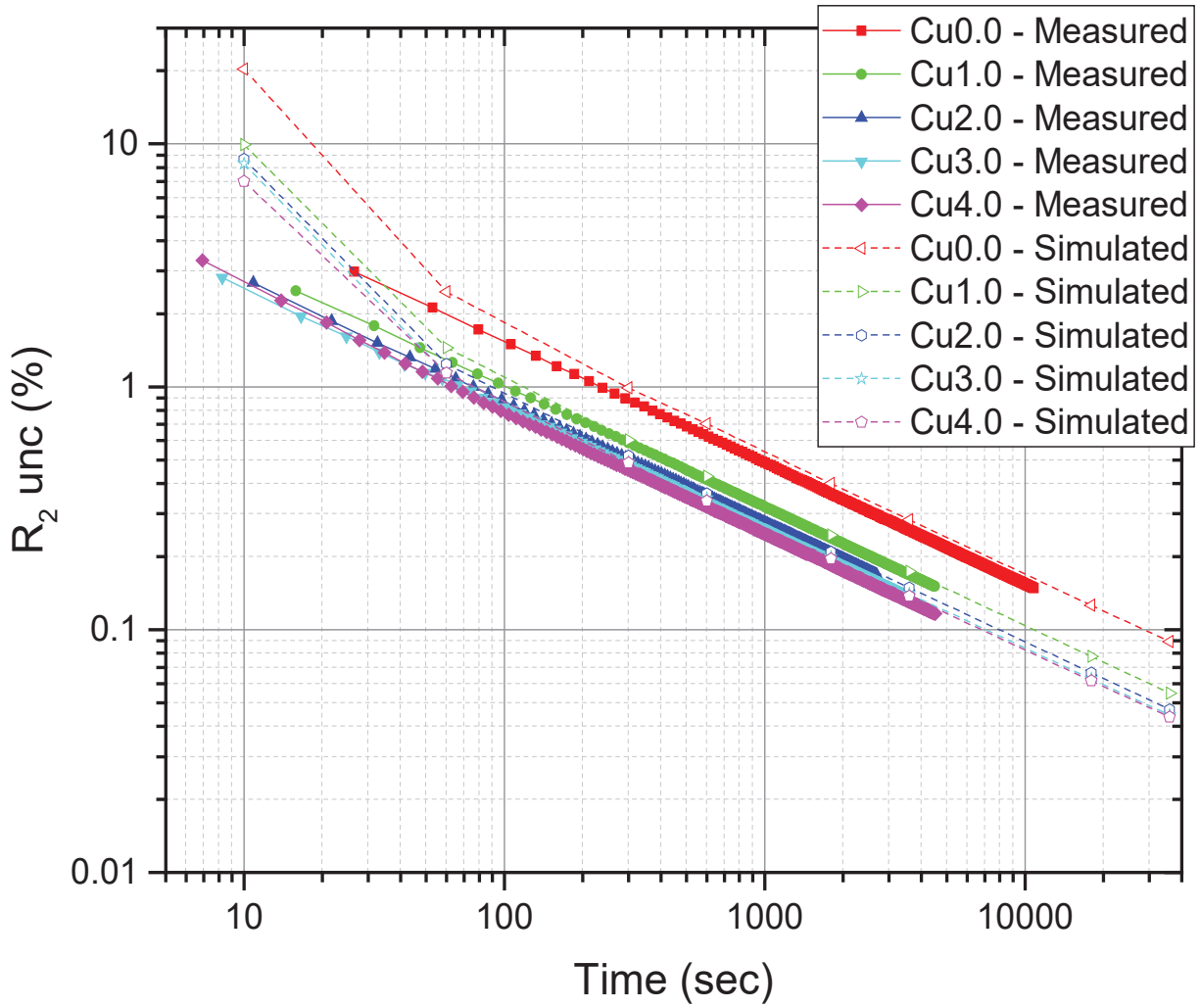
Results: R_2

- **Configuration 0 (bare BeRP)**
  - Similar to R_1 results.
  - Measured and simulated results agree very well when the counting time is > 120 sec.



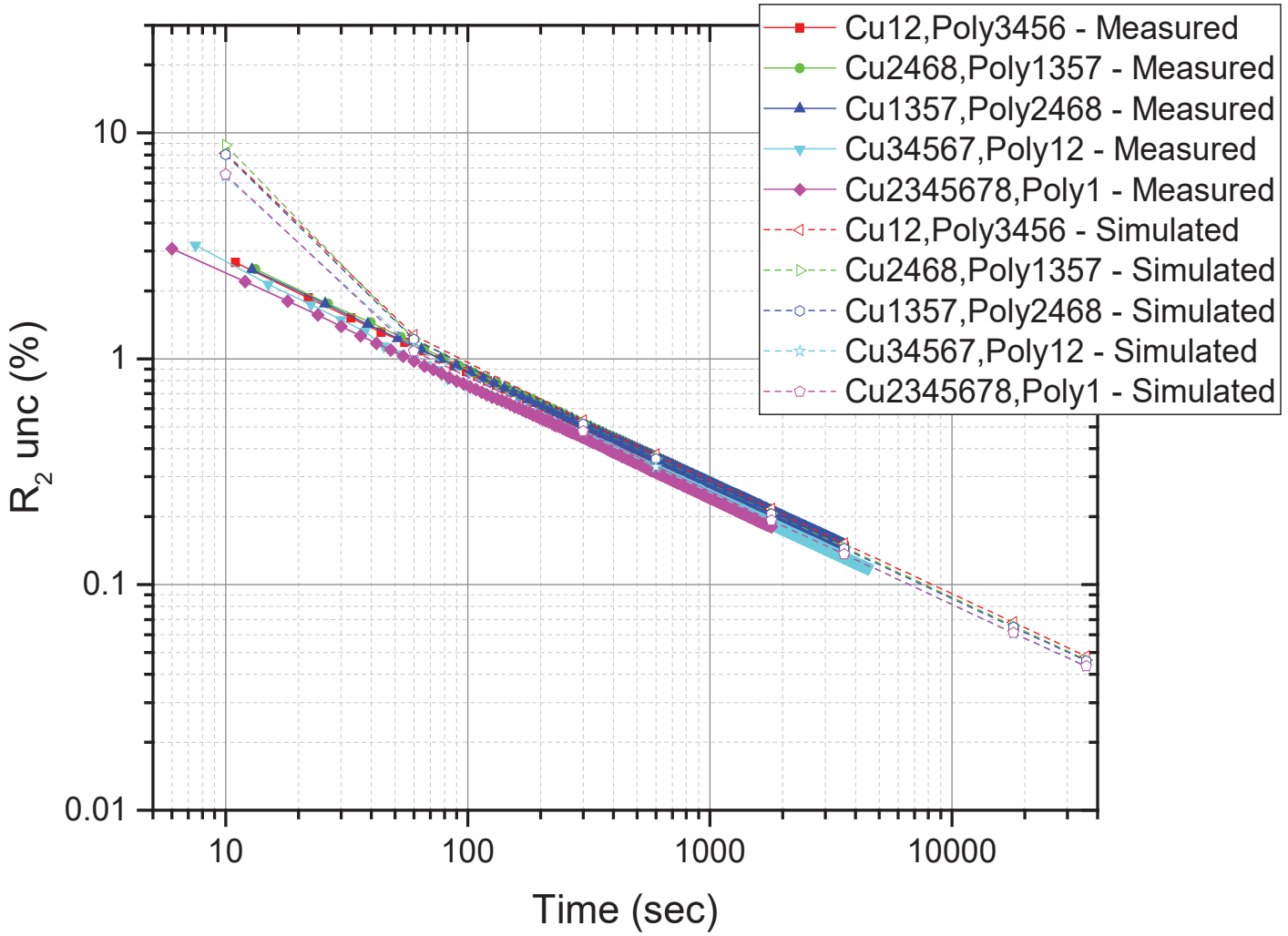
Results: R_2

- **Configuration with Cu reflection only (no HDPE)**
  - Good agreement when counting time > 120 sec.



Results: R_2

- **Configuration with Cu and HDPE reflection**
  - Good agreement when counting time > 120 sec.



Results

- **Note from all R_1 and R_2 graphs that if the counting times continued to increase, the uncertainties would continue to decrease (and would approach 0 as the counting time approaches infinity).**

$$\lim_{T\to\infty} \delta R_x = 0$$

Here T is the total counting time, and δR_x is the uncertainty in R_1 or R_2.

- **This is not true for leakage multiplication (M_L).**
  - M_L depends on the uncertainties associated with R_1, R_2, and the detector efficiency (ε).
  - The method used to determine ε for this work involved ^{252}Cf replacement measurements.

$$\epsilon = \frac{R_1}{\bar{\nu}_{S1} F_S}$$

Count rate for ^{252}Cf measurements.

Fission rate from source certificate.

Average neutrons emitted per fission.

Results

- **Using this method for detector efficiency, the lowest possible uncertainty in detector efficiency is proportional to the uncertainty in the fission rate.**

$$\lim_{\delta R_1 \to 0} \delta\varepsilon / \varepsilon = \delta F_S / F_S$$

The % uncertainty in F_S for the specific source used was 1%.

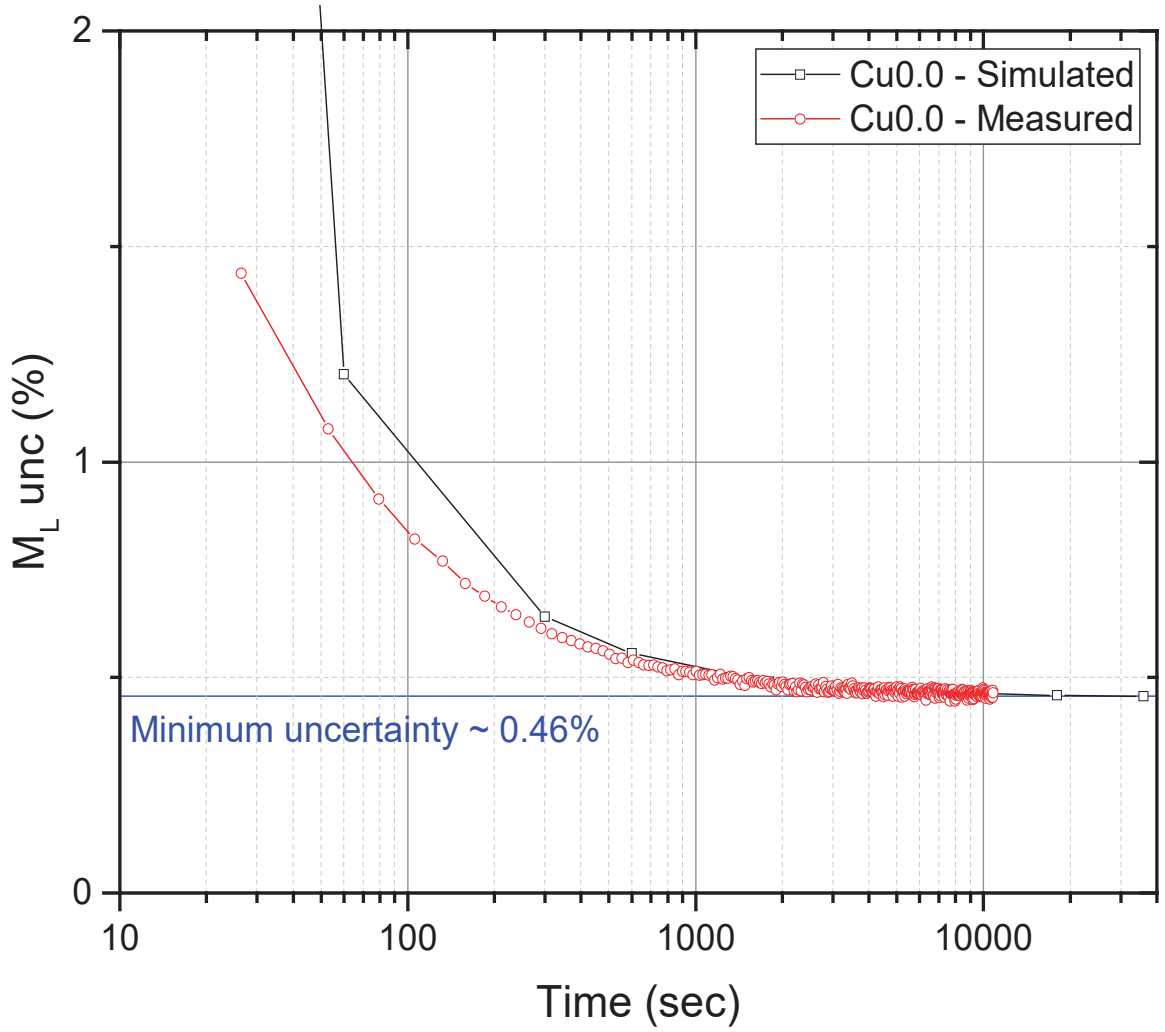
- **This results in:**

$$\lim_{\delta R_1 \to 0, \delta R_2 \to 0} \delta M_L / M_L = \left| \frac{\partial M_L}{\partial \varepsilon} \delta\varepsilon \right|$$

$\frac{\partial M_L}{\partial \varepsilon}$ is configuration dependent.

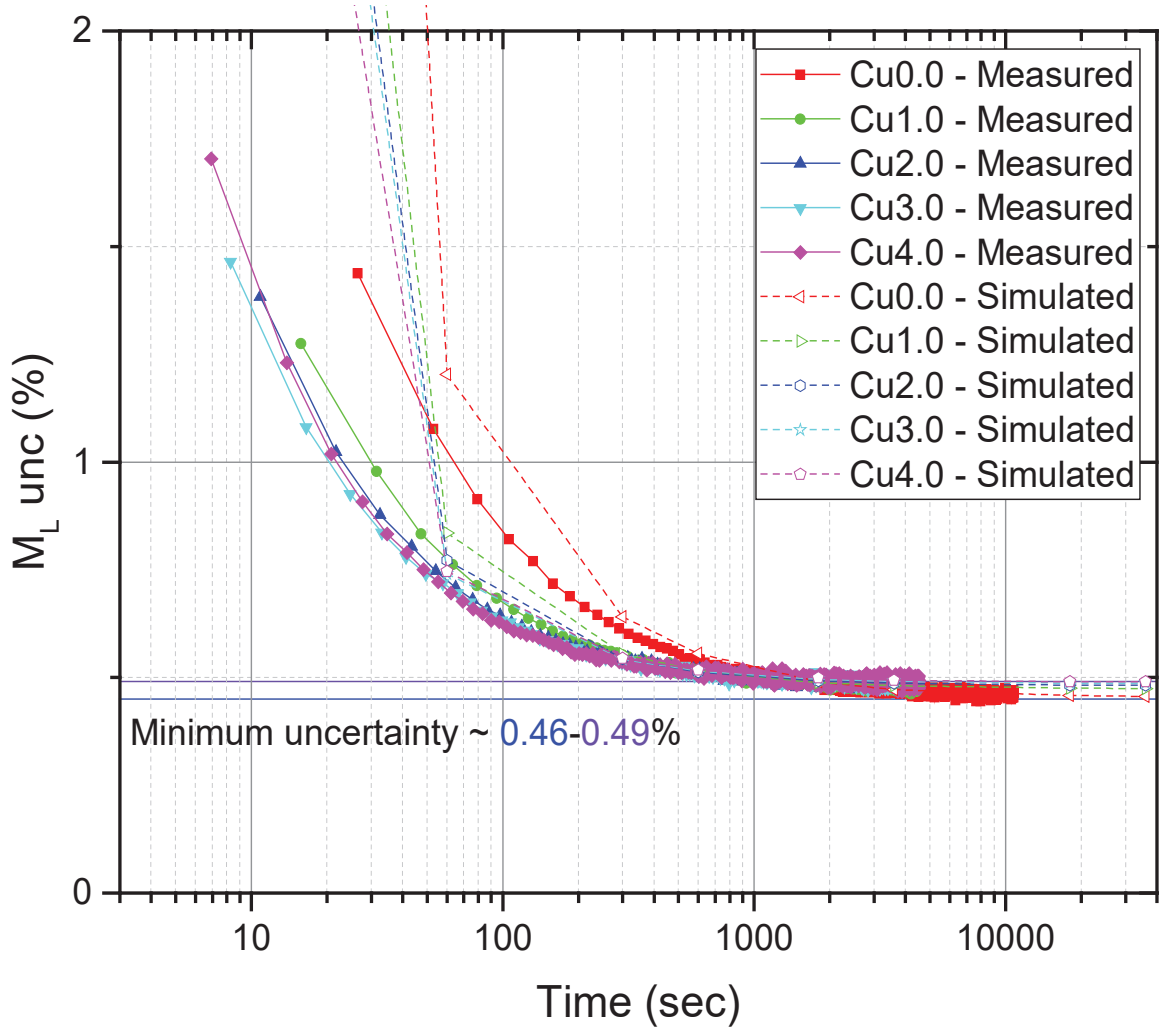
Results: M_L

- **Configuration 0 (bare BeRP)**
  - Similar to R_2 results.
  - Measured and simulated results agree very well when the counting time is > 120 sec.
  - The minimum uncertainty is ~0.46%.



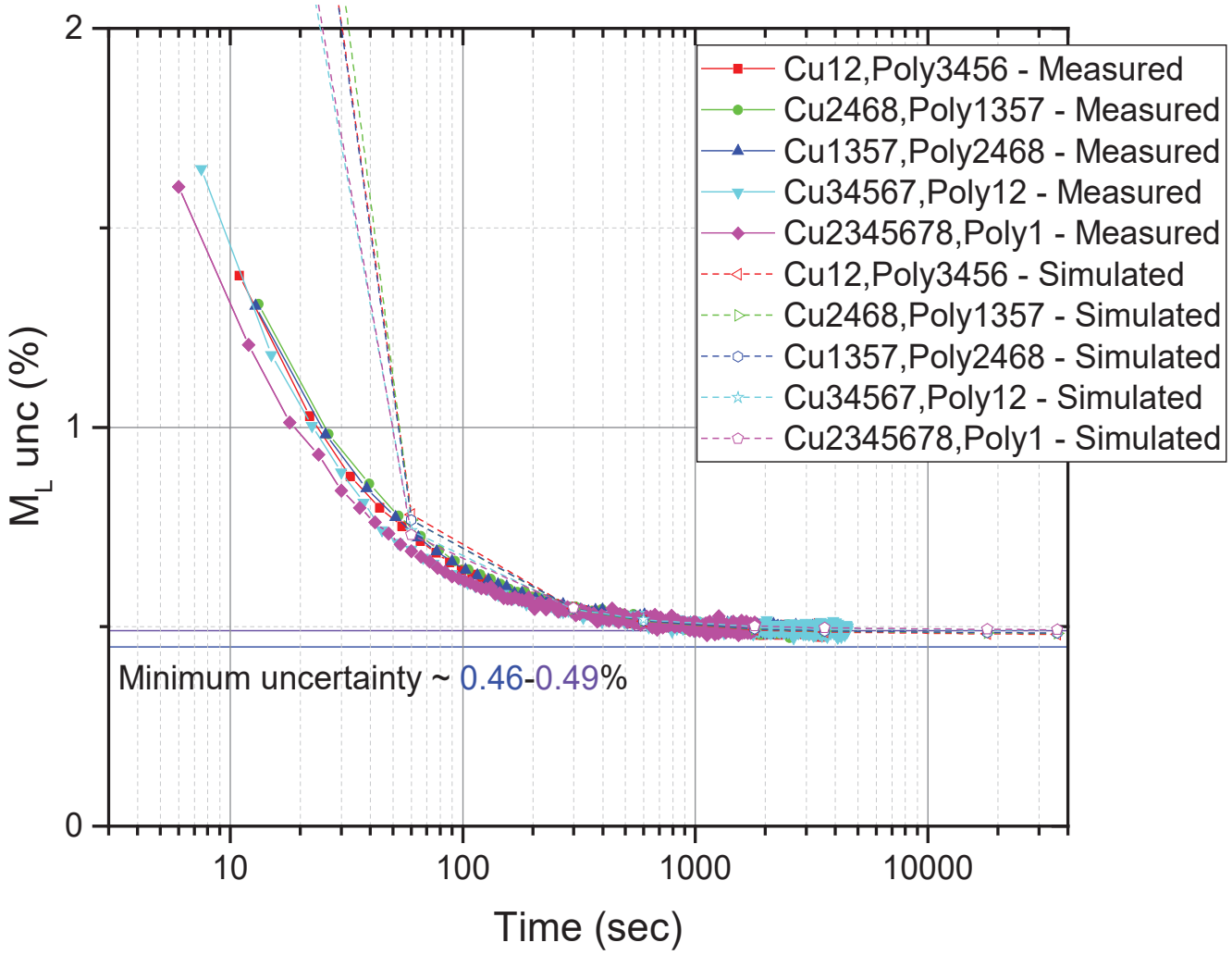
Results: M_L

- **Configuration with Cu reflection only (no HDPE)**
  - Measured and simulated results agree very well when the counting time is > 120 sec.
  - The minimum uncertainty is ~0.46-0.49%.



Results: M_L

- **Configuration with Cu and HDPE reflection**



Results

- **The design document stated that the goal was to have M_L uncertainties < 2% greater than the theoretical minimum.**
  - Times listed in green are those that are greater than the predicted time for 1% above theoretical uncertainty.
  - The time listed in red is less than that predicted for 2%.
  - The last column shows the actual percentage greater than the theoretical uncertainty in M_L that was achieved using the measured data. It can be seen that the goal of less than 2% was achieved for all configurations.

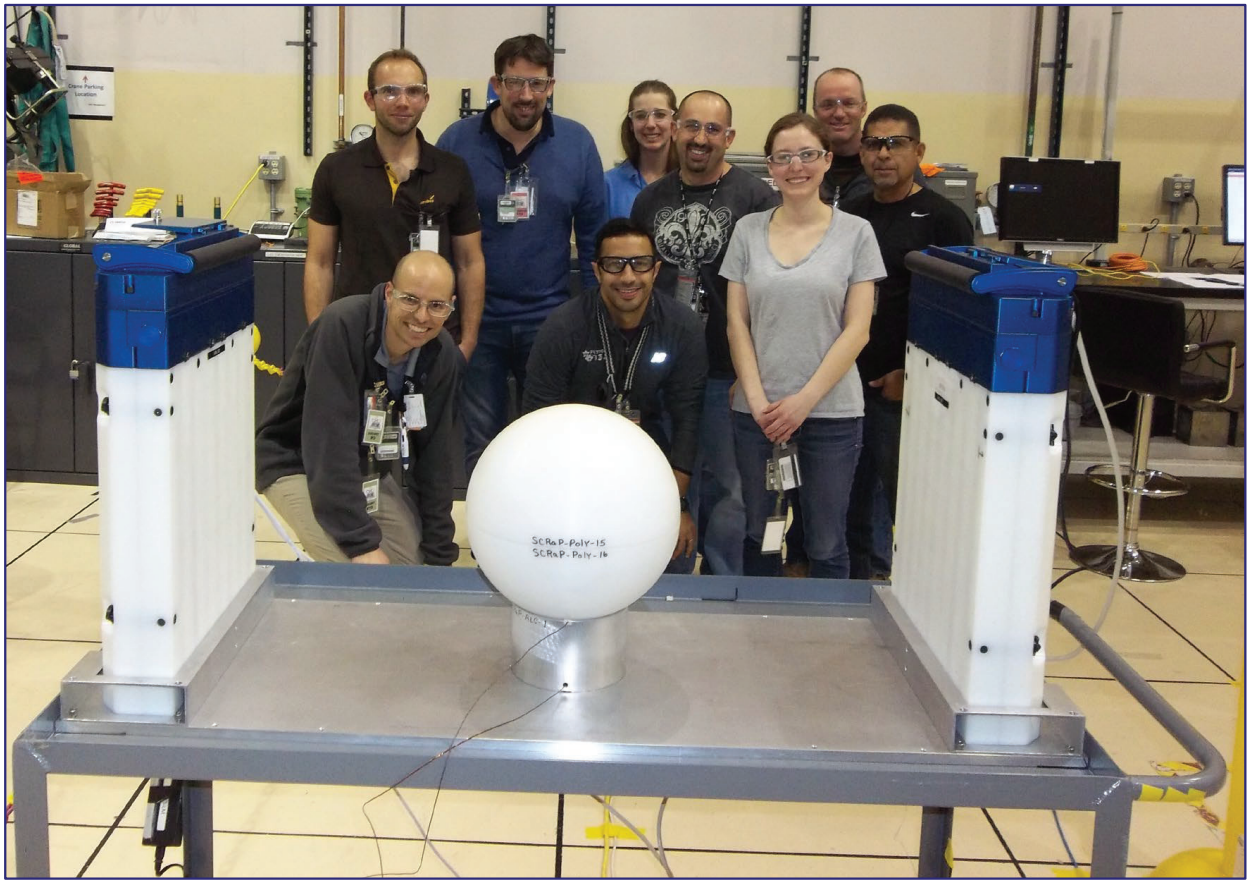
Configuration	Time to 2% (sec)	Time to 1% (sec)	Actual Time (sec)	M_L Unc % greater
Cu0.0	4740	9360	10800	1.1
Cu0.5	2550	5070	5400	1.3
Cu1.0	1890	3750	4500	1.1
Cu1.5	1560	3210	3600	1.2
Cu2.0	1440	3030	2700	1.4
Cu2.5	1410	3090	3600	1.0
Cu3.0	1440	3330	3600	0.9
Cu3.5	1500	3780	3600	0.9
Cu4.0	1620	4440	4500	0.7
Cu12,Poly3456	1500	3120	3600	1.1
Cu2468,Poly1357	1440	3090	2700	1.5
Cu1357,Poly2468	1440	3180	3600	1.1
Cu4567,Poly123	1620	4440	4500	0.8
Cu34567,Poly12	1920	6120	4500	0.7
Cu234567,Poly1	1920	6120	5400	0.6
Cu2345678,Poly1	2610	10020	1800	1.7
Total (seconds)	30600	75150	68400	
Total (hours)	8.5	20.9	19	

Values listed in green are those that were less than 1% (above the theoretical minimum).

Conclusions

- **A method was introduced in 2016 (ANS Annual Meeting) which was used to determine uncertainty in R_1, R_2, and M_L as a function of counting time.**
  - The 2016 work had simulated and measured data of the bare BeRP ball. Measured data was limited to 4 data points.
- **Simulations were performed and the method was applied during the design phase of the SCRαP experiment (CED-2 document and 2017 ANS Winter).**
- **This work compares the simulations used in the design phase against measured data.**
  - Unlike the 2016 work, new capabilities were used which allow one to determine the uncertainty at any discrete counting time.
- **It can be seen that as long as the counting time is > 120 seconds, the measured and simulated uncertainties agreed very well.**
- **This method should continue to be used when designing future subcritical benchmark experiments.**

Thank you for your attention.



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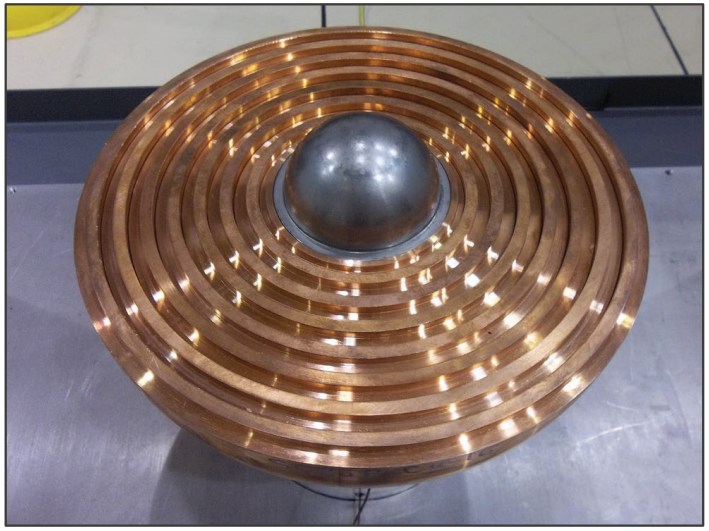

This work was supported by the DOE Nuclear Criticality Safety Program, funded and managed by the National Nuclear Security Administration for the Department of Energy.

Backup

$$\frac{\partial M_L}{\partial R_1} = \frac{a_3}{R_1 a_4}$$

$$\frac{\partial M_L}{\partial R_2} = -\frac{a_3}{R_2 a_4}$$

$$\frac{\partial M_L}{\partial \epsilon} = \frac{a_3}{\epsilon a_4}$$

This is why $\frac{\partial M_L}{\partial \varepsilon}$ is different for the different configurations.

$$0 = a_1 M_L^2 + a_2 M_L + a_3$$

$$a_1 = \frac{\nu_{\bar{S}1}\nu_{\bar{I}2}}{\nu_{\bar{I}1} - 1}$$

$$a_2 = \nu_{\bar{S}2} - \frac{\nu_{\bar{S}1}\nu_{\bar{I}2}}{\nu_{\bar{I}1} - 1}$$

$$a_3 = -\frac{R_2 \nu_{\bar{S}1}}{R_1 \epsilon}$$

$$M_L = \frac{-a_2 + \sqrt{a_2^2 - 4a_1 a_3}}{2a_1} = \frac{-a_2 + a_4}{2a_1}$$

$$a_4 = \sqrt{a_2^2 - 4a_1 a_3}$$