Preliminary RAM-RODD results for the MUSiC subcritical configurations

Robert A. Weldon Jr,* Theresa E. Cutler,* Joetta M. Goda,* Jesson D. Hutchinson,* William L. Myers,* George E. McKenzie IV,* Alexander T. McSpaden,* Lauren A. Misurek*, and Rene G. Sanchez*

**Advanced Nuclear Technology (NEN-2), Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM, 87545, raw@lanl.gov*

INTRODUCTION

The Measurement of Uranium Subcritical and Critical (MUSiC) was performed at the DOE's National Criticality Experiments Research Center (NCERC) located in the Nevada National Security Site (NNSS). The measurement utilized the Rocky Flats shells [1] to perform benchmark measurements of similar highly enriched uranium (HEU) systems that span a wide range of reactivities. The Rocky Flats (RF) shells are 93.16% U-235 enriched metal hemishells that can be stacked concentrically. Ten configurations were measured with effective multiplication factors spanning between deeply subcritical (~ 0.64) through delayed critical. Details of the measured configurations are listed in Table 1.

This unique set of measurements with its large span of reactivies is being used to determine the range over which neutron noise techniques such as Feynman variance-to-mean [2], Rossi-alpha [3], and pulsed neutron source [4] techniques can be accurately employed for a bare HEU system. The results of the measurements will be published as a benchmark in The International Criticality Safety Benchmark Evaluation Project (ICSBEP) Handbook [5]. The results will support the growing amount of subcritical benchmark data, such as the SCRaP measurements [6], that is available to the community.

The measurements were performed using several different detector systems for the purposes of cross-validation and obtaining detector independent results. Four detector systems were deployed, three by the NCERC team and one from the University of Michigan. The detector systems included a Neutron Multiplicity Array Detector (NoMAD) system (similar to the MC-15 [7]), four small volume 0.635 cm (∅) × 7.59 cm ^{3}He detectors (ideal for measuring prompt neutron decay constants due to their fast recovery speed), the Rossi Alpha Measurements – Rapid Organic (n, γ) Discrimination Detector (RAM-RODD) [8], and the Organic Scintillator Array (OSCAR) [9]. RAM-RODD is an array of eight 5.08 cm (∅) × 5.08 cm EJ-309 organic scintillator detectors. OSCAR is a University of Michigan system and is an array of twelve 5.08 cm (∅) × 5.08 cm stilbene detectors. Details of measurements performed with OSCAR will be discussed in a separate talk [10].

The focus of this work is preliminary results obtained by RAM-RODD for the 8 subcritical configurations. Additional details on the measurements and on the setup and deployment of RAM-RODD will be discussed. Preliminary neutron noise analysis results including Rossi-alpha and Feynman-alpha will also be presented.

MUSIC EXPERIMENT SETUP

A picture of the experiment setup is shown in Figure 1. The measurements were performed on the Planet vertical lift machine [11] which was used for remote assembly of the upper and lower portion of the RF hemisphere shells. Note that additional details on the experiment setup and design can be found in [12] and [13].

The three NCERC detector systems are shown in Figure 1. The RAM-RODD detectors were grouped in pairs and positioned on the corners of the interface plate at a distance of ~ 47 cm from the center of the assembly. OSCAR (not pictured) was positioned at ~ 1.4 m from the center of the assembly. Fissions in the RF shell configurations were induced using a ^{252}Cf source placed at the center of the assembly. Each subcritical configuration was measured for a minimum of 1 hour.

TABLE I. Rocky Flats shells configurations with estimates of the multiplication.

Configuration	Shells	Mass (kg)	Multiplication	k_{eff}
1	3-24	13.0428	2.8	0.64
2	3-30	21.6432	3.9	0.74
3	3-34	29.0415	5.3	0.81
4	3-38	37.9617	8.3	0.88
5	3-40	42.9722	11.4	0.91
6	3-42	48.4099	18.4	0.95
7	3-44	54.2785	46.6	0.98
8	3-46 (60 mil spacer)	60.6183	-	~ 1
9	3, 5-46 (24 mil spacer)	60.4438	-	~ 1
10	9-46	59.2075	> 150	0.99

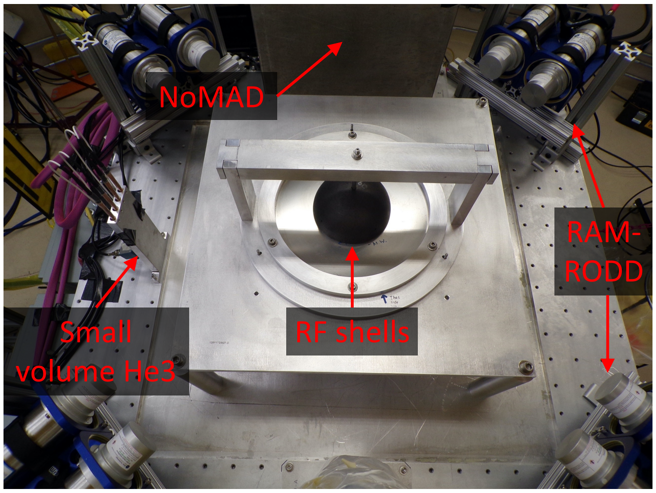

Fig. 1. MUSiC experiment setup.

THE ROSSI ALPHA MEASUREMENTS – RAPID ORGANIC (N, γ) DISCRIMINATION DETECTOR (RAM-RODD

RAM-RODD is an array of organic scintillation detectors that has been optimized for use in neutron noise measurements. Organic scintillators offer significantly better time resolution compared to commonly used ^{3}He based detector systems, such as the MC-15 or small volume ^{3}He tubes also used in MUSiC, due to the method of neutron detection. ^{3}He based systems generally rely on moderating fast neutrons to lower energies for increased detection efficiency of the ^{3}He(n,p)^{3}H reaction and have time resolutions on the order of hundreds of ns to µs. In contrast, organic scintillators directly detect fast neutrons via elastic scatter with time resolutions on the order of hundreds of ps to ns. The excellent time resolution makes organic scintillators well suited for measurements that employ time-correlated neutron noise analysis techniques.

The organic scintillator used for the system is 5.08 cm (∅) × 5.08 cm EJ-309 scintillator. EJ-309 is a liquid scintillator with pulse shape discrimination capability or the ability to distinguish between gamma and neutron interactions based on differences in the waveforms. The system is powered by an 8 channel CAEN R1470ETD desktop power supply module, and waveforms are digitized using a CAEN DT5730 (500 MHz, 14 bit) digitizer. The system's time resolution was measured utilizing the digitizer's onboard constant fraction discrimination and is 0.9 ns [8]. This excellent time resolution makes the system ideal for Rossi-α and Feynman-α analysis.

ROSSI-α AND FEYNMAN-α METHODS

The Rossi-α and Feynman-α methods are techniques that can be utilized to infer the effective multiplication factor (k_{eff}) from the prompt neutron decay constant (α). Inference is necessary because k_{eff} cannot be measured directly. Both methods are based on analyzing the statistical fluctuations of chain-reacting systems, and each is appropriate over different regimes of k_{eff}. Rossi-α is the appropriate analysis technique for subcritical k_{eff} values close to delayed critical and critical systems. Feynman-α is appropriate in the subcritical regime and is not appropriate for systems near or above delayed critical. The methods are comparable over a specific range of reactivites, and the determination of this range is currently being determined for MUSiC.

The Rossi-α method

The implementation of the Rossi-α method is simple. A neutron sensitive detector is used to record the time of neutron interactions as list-mode data. The difference in time between all interactions within a specified time window is calculated. The distribution of counts within the time difference window versus the time difference reveals the correlation between fission chain neutrons and time. The prompt neutron decay constant is then determined using this distribution. The method is described in detail in [4] and is briefly summarized below.

The prompt neutron decay constant is defined as

$$\alpha = \frac{1 - k_p}{l} \tag{1}$$

where k_p is the prompt multiplication factor and l is the prompt neutron lifetime. Here, l is defined as the average time a prompt neutron exists in the system before a terminating event. Note that Equation 1 is the positive definition of α, specific to subcritical assemblies ($\alpha = (k_p - 1)/l$ would be used for critical assemblies). The prompt neutron population (N) following the injection of neutrons into a multiplying assembly decays with a dependence on α as

$$N = N_0 e^{-\alpha t} \tag{2}$$

where t is time and N_0 is the population at $t = 0$. Reactivity (ρ) can also be defined in terms of α as

$$\rho = \frac{k_{eff} - 1}{k_{eff}} = \beta_{eff} - \alpha\Lambda \tag{3}$$

where β_{eff} is the effective delayed neutron fraction and Λ is the prompt neutron generation time (related to the prompt neutron life time, l, by $\Lambda = l/k_{eff}$).

The difference between the time of interaction of all neutron events within a given time window for a multiplying assembly is described by the probability density function

$$p(t)dt = Ae^{-\alpha t}dt + Bdt \tag{4}$$

where $Ae^{-\alpha t}$ describes the decay of the prompt neutron population and B describes the uniform accidental coincidence probability. Equation 4 is fit to the time difference distribution measured for an assembly near critical to estimate α.

The equations above are based on the point kinetics model for a reactor. This model assumes that the neutron spatial flux is time independent. While this assumption is generally true for assemblies at or near delayed critical, it is not true for subcritical systems and is an improper assumption for deeply subcritical systems. Because of the time dependence of the neutron spatial flux for subcritical systems there is a point below critical at which the Rossi-α method no longer provides an accurate estimate of the prompt neutron decay constant [14]. Work is currently underway to determine this value for MUSiC.

The Feynman-α method

The Feynman-α method, also referred to as the Feynman variance-to-mean method, can be used to infer k_{eff} of a subcritical system by utilizing the excess variance of the system when compared to random Poisson fluctuations. The excess variance (Y) is determined by taking the ratio of the variance of the counts within a given time window and the mean

$$Y = \frac{\overline{c^2} - \overline{c}^2}{\overline{c}} - 1 \tag{5}$$

where c is the number of counts in a given window. Note that Equation 5 is 0 for random Poisson fluctuations. Y is related to α by

$$Y = A\left(1 - \frac{1 - e^{\alpha t}}{\alpha t}\right) \tag{6}$$

where t is the selected time window and A is a constant. Y is calculated for various time windows to form a distribution from which α can be estimated via fitting Equation 6 to the distribution.

PRELIMINARY RESULTS

Feynman-α analysis and Rossi-α analysis have been performed on the data measured with RAM-RODD for the 8 subcritical configurations. Preliminary results of the Feynman-α and Rossi-α analysis for configuration 5 are shown in Figures 2 and 3. The preliminary α results estimated using both methods show good agreement, with a 7% difference between the preliminary α estimates obtained using Feynman-α and Rossi-α for configuration 5. The RAM-RODD results will also be compared with the results of measurements performed with the NoMAD detectors which will be discussed in detail in a related talk [15].

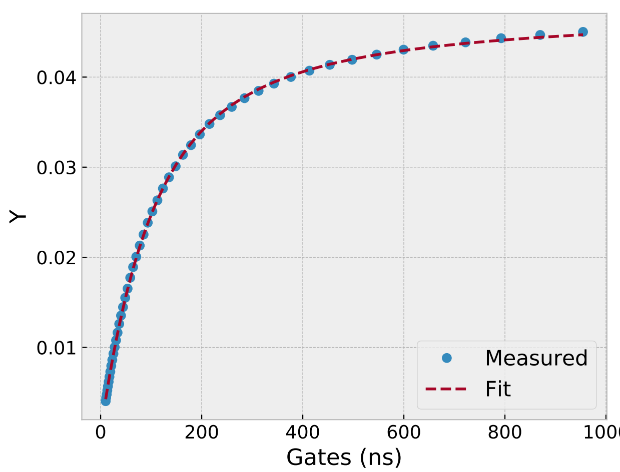

Fig. 2. Feynman-α analysis for configuration 5 measured data.

CONCLUSIONS

Neutron noise analysis methods including Rossi-α and Feynman-α were utilized to analyze 8 subcritical configurations of the HEU Rocky Flats shells measured with an optimized organic scintillator array called RAM-RODD. The analysis and results for all 8 configurations will be shown, discussed, and compared to the results measured by a NoMAD detector. These results are a subset of the full MUSiC experiment campaign results and support the goals of (1) determining the range of k_{eff} over which certain neutron noise techniques are appropriate for a bare HEU system and (2) using multiple detector systems to cross-validate results.

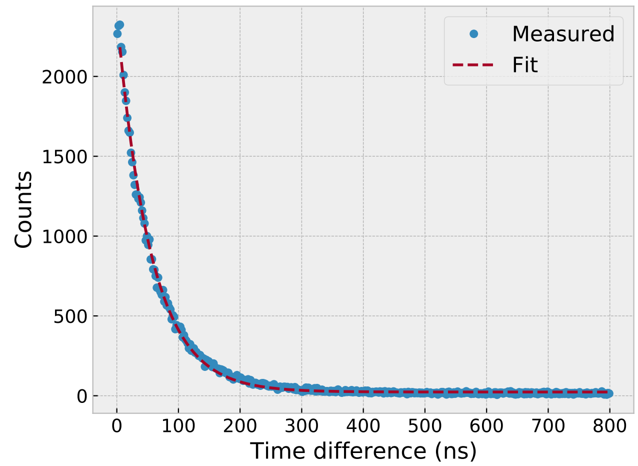

Fig. 3. Rossi-α analysis for configuration 5 measured data.

ACKNOWLEDGMENTS

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.

REFERENCES

1. R. ROTHE, "Extrapolated experimental critical parameters of unreflected and steel-reflected massive enriched uranium metal spherical and hemispherical assemblies," Tech. rep., Lockheed Idaho Technologies Co. (1997).
2. R. P. FEYNMAN, F. DE HOFFMANN, and R. SERBER, "Dispersion of the neutron emission in U-235 fission," *Journal of Nuclear Energy (1954)*, **3**, *1-2*, 64–IN10 (1956).
3. J. D. ORNDOFF, "Prompt neutron periods of metal critical assemblies," *Nuclear Science and Engineering*, **2**, *4*, 450–460 (1957).
4. G. R. KEEPIN, *Physics of nuclear kinetics*, Addison-Wesley Pub. Co. (1965).
5. OECD-NEA, *International Criticality Safety Benchmark Evaluation Project* (2019).
6. T. CUTLER, J. ARTHUR, and J. HUTCHINSON, "Copper and Polyethylene-Reflected Plutonium-Metal-Sphere Subcritical Measurements," *In: International Handbook of Evaluated Criticality Safety Benchmark Experiments*, **[DVD]/Nuclear Energy Agency – Paris : OECD Nuclear Energy Agency** (2019), (NEA;7328).
7. C. E. MOSS, E. B. SORENSEN, and M. A. SMITH-

NELSON, *MC-15 user manual*, Los Alamos National Laboratory, LA-UR-16-27099 (2016).

8. R. A. WELDON, T. E. CULTER, J. D. HUTCHINSON, G. E. MCKENZIE IV, L. MISUREK, and E. B. SORENSEN, "Rossi Alpha Measurements – Rapid Organic (n, γ) Discrimination Detector (RAM-RODD) system capabilities," Tech. rep., Los Alamos National Laboratory (LANL), Los Alamos, NM (United States), LA-UR-20-28902 (2020).
9. M. Y. HUA, C. A. BRAVO, A. T. MACDONALD, J. D. HUTCHINSON, G. E. MCKENZIE, B. C. KIEDROWSKI, S. D. CLARKE, and S. A. POZZI, "Rossi-alpha measurements of fast plutonium metal assemblies using organic scintillators," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, **959**, 163507 (2020).
10. F. DARBY and ET. AL., "Comparison of Neutron Multiplicity Counting Estimates with Trans-stilbene, EJ-309, and He-3 Detection Systems," *American Nuclear Society Winter Meeting 2021*, **submitted** (2021).
11. R. SANCHEZ and ET. AL., "A New Era of Nuclear Criticality Experiments, The First Ten Years of Planet Operations at NCERC," *Nuclear Science and Engineering*, **Submitted** (2021).
12. R. WELDON, T. CUTLER, J. HUTCHINSON, W. MYERS, G. MCKENZIE, A. MCSPADEN, and R. SANCHEZ, "Application of the rossi-alpha method to simulations of HEU and organic scintillators," *Transactions of the American Nuclear Society*, **11** (2020).
13. A. MCSPADEN, T. CUTLER, J. HUTCHINSON, W. MYERS, G. MCKENZIE, J. GODA, and R. SANCHEZ, "MUSIC: A CRITICAL AND SUBCRITICAL EXPERIMENT MEASURING HIGHLY ENRICHED URANIUM SHELLS," *International Conference on Nuclear Criticality 2019* (2019).
14. G. E. MCKENZIE IV, "Limits on Subcritical Reactivity Determination Using Rossi- and Related Methods," *University of Illinois PhD Dissertation*.
15. A. MCSPADEN and ET AL., "Validation of Jezebel Reactivity Coefficients and Sensitivity Studies," *American Nuclear Society Winter Meeting 2021*, **submitted** (2021).