Progress Update on the MUSIC Critical Benchmark

Alexander McSpaden*, George McKenzie*, Rene Sanchez*

*Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM, 87544, mcspaden@lanl.gov

INTRODUCTION

The Measurement of Uranium Subcritical and Critical (MUSiC) experiment was carried out from December 2020 through April 2021 at the National Criticality Experiments Research Center (NCERC). This measurement campaign featured bare configurations of the Rocky Flats highly-enriched uranium (HEU) shells, with each configuration having different numbers of these shells. The goal of the experiment was to test multiple neutron multiplicity detectors and measurement methods for a large range of neutron multiplication values. The large range of multiplications allows researchers to see when the combination of detectors and methods break down as the configurations reach the delayed supercritical window [1, 2].

The critical configurations were the extreme end of the multiplication range in MUSIC configurations. A critical benchmark in the International Criticality Safety Benchmark Evaluation Project (ICSBEP) Handbook is planned to help further validate nuclear data. Even though there are many benchmarks focusing on the fast spectrum for highly-enriched uranium, an additional benchmark that is well documented and up to the modern standard of the handbook would be a welcome addition. Given that there are no other materials such as moderators or significant reflectors, and its similarity to Lady Govida[3, 4, 5], it is possible that this could be very useful for validation of ^{235}U nuclear data in the future.

CONFIGURATIONS

The Rocky Flats shells are a set of nesting HEU hemishells that can be used in any number of different ways depending on the experiment [6, 7]. These shells have already been used in ICSBEP benchmarks, including at Los Alamos [8, 9]. Table I lists the reported composition of the Rocky Flats shells. Figure 1 also shows a picture of a subset of these shells. These shells were placed into two separate stacks on the Planet vertical lift machine where final assembly was done remotely [10]. Figure 2 depicts a subcritical configuration of this experiment on Planet.

TABLE I. Rocky Flats Shells Reported Composition

Uranium Isotope	Mass Fraction (%)
234	1.02
235	93.16
236	0.47
238	5.35

Fig. 1. A Subset of the Rocky Flats Shells.

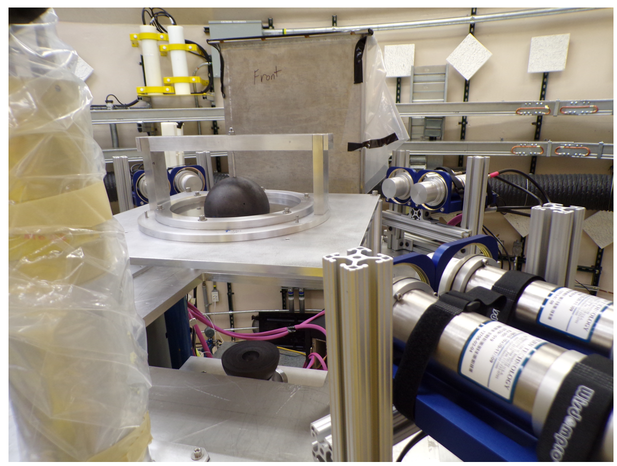

Fig. 2. A Subcritical Configuration Fully Separated on Planet.

Two critical configurations of Rocky Flats shells were measured as part of this campaign, along with eight subcritical configurations. The difference between the critical configurations was both in the number of shells present (and therefore uranium mass) and also the thickness of a spacer ring that served to separate the top and bottom stack of shells. The single shell absent from configuration 9 was one of the innermost, and therefore one of the most important in terms of reactivity. The space inside the innermost Rocky Flat shell is filled with aluminum, and the very center included a source holder for the ^{252}Cf.

TABLE II. MUSiC Critical Configurations

Configuration	Uranium Mass (kg)	Spacer Thickness (cm)
8	61.896	0.06096
9	61.721	0.1524

BENCHMARK MODELING

A detailed model was made in MCNP 6.2[11][1] that depicts all of the important features of the assembly. This includes such things as some of the structural features of the Planet vertical lift machine, the keyways inside the milling table, and the thread relief in the source holder. Figure 3 shows a view of this model for Configuration 8. Other details of the assembly were not included, but their effects on k_{eff} were analyzed. This was done either through experimental or computational means.

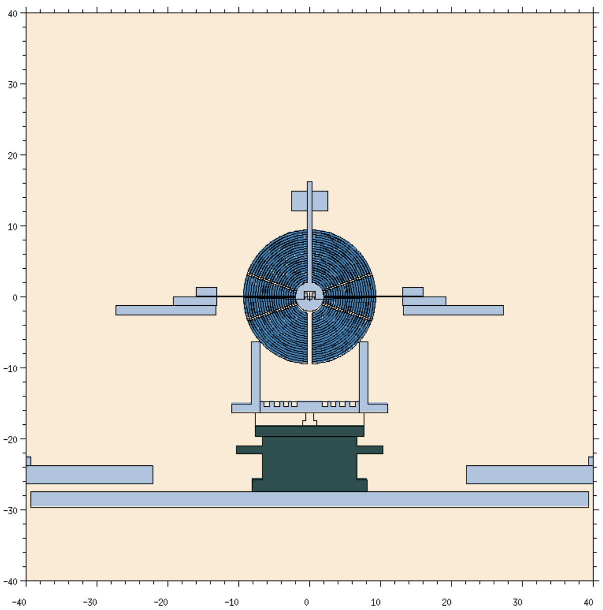

Fig. 3. A View of the Detailed MUSIC Model.

For the various detector systems placed around the assembly, their effect on the system reactivity was determined experimentally by measuring the excess reactivity of the system both with and without them present. This gave an inferred Δ_k of -0.00036, and these detectors and associated fixtures were removed from the system for the detailed model. Other features were both included and excluded in the model to calculate a Δ_k. Such simplifications were done in an accumulating fashion, so that the model gradually shifted from the most detailed to the most simplified. This includes removing the Flattop critical assembly, which sits near where MUSIC was performed[12]. The effect of some of these simplifications are given in Table III for configuration 8.

SENSITIVITY AND UNCERTAINTY ANALYSIS

For the computation of k_{eff} uncertainties (u_k) due to mass and composition, the adjoint sensitivity method was employed

[1]MCNP® and Monte Carlo N-Particle® are registered trademarks owned by Triad National Security, LLC, manager and operator of Los Alamos National Laboratory. Any third party use of such registered marks should be properly attributed to Triad National Security, LLC, including the use of the designation as appropriate. For the purposes of visual clarity, the registered trademark symbol is assumed for all references to MCNP within the remainder of this paper.

TABLE III. A Sample of Δ_k Values due to Various Simplifications.

Parameter Removed	Configuration 8 Δ_k
Rocky Flats Impurities	-0.00001
Flattop Assembly	+0.00002
Screws, Pins, and Counterbores	-0.00002
Planet Structural Components	-0.00035
Concrete and Crane	-0.00063

as developed by Favorite et. al.[13]. This allows for the calculation of the relative sensitivity profiles of k_{eff} due to cross sections of various nuclides in a material. Expanding this to total cross section for a material provides a method to give the relative sensitivity coefficients of k_{eff} to the mass and composition of the components of a problem. Combining these coefficients with the uncertainty in the mass or composition of said component results in the u_k due to the uncertainties in mass or composition,

$$u_k = k_{eff,0}(\frac{u_\rho}{\rho})S_{k,\rho}, \tag{1}$$

where $k_{eff,0}$ is the k_{eff} of the unperturbed case, ρ is some parameter (such as density), and u_ρ is the percent uncertainty in that parameter. Using such a method allows for the computation of these values in one simulation, instead of multiple simulations for each component and each possible perturbation of these parameters.

Computing the u_k values due to positioning of components required more brute force methods. Each component was moved in the geometry according to the uncertainty in its position in the assembly. These perturbed simulations give a calculated value of Δ_k which can then be used as the u_k, or if the movement used was a bounding value, divided by $\sqrt{3}$ to give the proper u_k value.

PRELIMINARY RESULTS

The preliminary results for C-E for the two critical configurations are shown in Table IV. These results are based on computations of the detailed model with MCNP 6.2 and ENDF/B-VIII.0 cross sections[14], with each calculation using 3,500 generations of 5×10^5 neutrons each. This produces a statistical uncertainty of 1 pcm, or 0.00001 in k_{eff}. To produce the benchmark value of k_{eff} used for the experimental, the inferred k_{eff} values from the experiment are shifted by the total simplification effect from the simplifications made to the detailed model. These simplifications had a total effect of reducing k_{eff} by 0.00134. Experimental k_{eff} values are based on converting fitted reactor periods to reactivity using the reactor kinetics parameters associated with the Godiva critical experiment[15].

Given in Table V are the preliminary uncertainty values in k_{eff}, u_k, due to uncertainties in mass, composition, and positioning of objects in the assembly. Thankfully the mass

TABLE IV. MUSiC Critical Preliminary k_{eff} Results and C-E Values

Configuration	Benchmark	Calculated	C-E (pcm)
8	1.00068	0.99996	72
9	1.00080	0.99967	113

uncertainties are quite small, with many of the individual component u_k values being less than 1 pcm due to careful weighing of most of the parts both before and after the experiment. This is not a total inventory, as there will be additional positioning uncertainties, along with those due to temperature and dimensions that are not yet analyzed. These analyses are in progress, and will be presented to the ICSBEP Technical Review Group (TRG) at the next iteration of TRG meetings. Further benchmark evaluations of the subcritical configurations will be performed in the coming years.

TABLE V. Uncertainties in k_{eff} Due to Various Parameters.

Parameter	Configuration 8 u_k	Configuration 9 u_k
Masses	0.00006	0.00007
Positions	0.00002	0.00002
Compositions	0.00045	0.00046

CONCLUSIONS

Preliminary results show that the u_k uncertainties associated with MUSIC are quite low so far, which shows promise for this experiment to be used as a benchmark for nuclear data and measurement methods.

Work is still being done to infer a measured value for β_{eff} of this experiment. Given the multiple detector systems present, a comparison between measured values between detector systems will provide a useful bounding on potential values of this parameter, along with showing which system may be better suited to measured β_{eff} in such a fast system. Additionally, future work will also include comparisons of cross-section sensitivities between the MUSIC configurations and other fast HEU benchmark assemblies.

ACKNOWLEDGEMENTS

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

REFERENCES

1. A. MCSPADEN, T. CUTLER, J. HUTCHINSON, R. BAHRAN, W. MYERS, G. MCKENZIE, J. GODA, and R. SANCHEZ, “IER 488: Measurement of Uranium Subcritical and Critical (MUSiC) CEDT Phase-2 Final Design,” (2018).
2. 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).
3. R. PETERSON, “LADY GODIVA; AN UNREFLECTED URANIUM-235 CRITICAL ASSEMBLY,” *LA-01614* (1953).
4. R. PETERSON and G. NEWBY, “An Unreflected U-235 Critical Assembly,” *Nuclear Science and Engineering*, **1:2**, 112–125 (1956).
5. R. LABAUVE, “HEU-MET-FAST-001: Bare, Highly Enriched Uranium Sphere (Godiva),” *In: International Handbook of Evaluated Criticality Safety Benchmark Experiments*, **[DVD]/Nuclear Energy Agency. - Paris : OECD Nuclear Energy Agency** (2002), (NEA;7328).
6. R. ROTHE, “Extraploated Experimental Critical Parameters of Unreflected and Steel-Reflected Massive Enriched Uranium Metal Spherical and Hemispherical Assemblies,” *INEEL report INEEL/EXT-97-01401* (1997).
7. J. HUTCHINSON, J. BOUNDS, T. CUTLER, D. DINWIDDIE, J. GODA, T. GROVE, D. HAYES, G. MCKENZIE, A. MCSPADEN, J. MILLER, W. MYERS, E. A. O. FERRER, R. SANCHEZ, T. SMITH, K. STULTS, N. THOMPSON, and J. WALKER, “A New Era of Nuclear Criticality Experiments: The First 10 Years of Radiation Test Object Operations at NCERC,” *Nuclear Science and Engineering*, **195**, *sup1*, S80–S98 (2021).
8. D. LOAIZA, R. BREWER, and R. SANCHEZ, “Neptunium-237 Sphere Surrounded by Hemispherical Shells of Highly Enriched Uranium,” *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, **NEA/NSC/DOC/(95)03/I**, SPEC–MET–FAST–008 (2009).
9. R. SANCHEZ and D. LOAIZA, “Plutonium Sphere Surrounded by Highly Enriched Uranium,” *In: International Handbook of Evaluated Criticality Safety Benchmark Experiments*, **[DVD]/Nuclear Energy Agency. - Paris : OECD Nuclear Energy Agency** (2005), (NEA;7328).
10. R. SANCHEZ, T. CUTLER, J. GODA, T. GROVE, D. HAYES, J. HUTCHINSON, G. MCKENZIE, A. MCSPADEN, W. MYERS, R. RICO, J. WALKER, and R. WELDON, “A New Era of Nuclear Criticality Experiments: The First 10 Years of Planet Operations at NCERC,” *Nuclear Science and Engineering*, **195**, *sup1*, S1–S16 (2021).
11. C. WERNER, J. ARMSTRONG, F. BROWN, J. BULL, L. CASSWELL, L. COX, D. DIXON, R. FORSTER, J. GOORLEY, H. HUGHES, J. FAVORITE, R. MARTZ, S. MASHNIK, M. RISING, C. SOLOMON, A. SOOD, J. SWEEZY, A. ZUKAITIS, C. ANDERSON, J. ELSON, J. DURKEE, R. JOHNS, G. MCKINNEY, G. MCMATH, J. HENDRICKS, D. PELOWITZ, R. PRAEL, T. BOOTH, M. JAMES, M. FENSIN, T. WILCOX, and B. KIEDROWSKI, “MCNP Users Manual - Code Version 6.2,” *Los Alamos National Laboratory*, **LA-UR-17-29981** (2017).

12. D. HAYES, T. BREDEWEG, T. CUTLER, J. GODA, T. GROVE, J. HUTCHINSON, J. LAMPROE, G. MCKENZIE, A. MCSPADEN, W. MYERS, R. SANCHEZ, and J. WALKER, "A New Era of Nuclear Criticality Experiments: The First 10 Years of Flattop Operations at NCERC," *Nuclear Science and Engineering*, **195**, *sup1*, S37–S54 (2021).
13. J. FAVORITE, Z. PERKÓ, B. KIEDROWSKI, and C. PERFETTI, "Adjoint-Based Sensitivity and Uncertainty Analysis for Density and Composition: A User's Guide," *Nuclear Science and Engineering*, **185**, *3*, 384–405 (2017).
14. D. BROWN and ET. AL., "ENDF/B-VIII.0: The 8th Major Release of the Nuclear Reaction Data Library with CIELO-project Cross Sections, New Standards and Thermal Scattering Data," *Nuclear Data Sheets*, **148**, 1 – 142 (2018), special Issue on Nuclear Reaction Data.
15. G. KEEPIN, *Physics of Nuclear Kinetics*, Addison-Wesley series in nuclear science and engineering, Addison-Wesley Publishing Company (1965).