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***Abstract*–A series of experiments and numerical simulations using thermal-neutron time-correlated measurements has been performed to determine the neutron multiplication, M, of assemblies of highly-enriched uranium available at Idaho National Laboratory. The experiments used up to 14.4 kg of highly-enriched uranium, including bare assemblies and assemblies reflected with high-density polyethylene, carbon steel, and tungsten. A small ^{252}Cf source was used to initiate fission chains within the assembly. Both the experiments and the simulations used 6-channel and 8-channel detector systems, each consisting of ^{3}He proportional counters moderated with polyethylene; data was recorded in list mode for analysis. 'True' multiplication values for each assembly were empirically derived using basic neutron production and loss values determined through simulation. A total of one-hundred sixteen separate measurements were performed using fifty-seven unique measurement scenarios, the multiplication varied from 1.75 to 10.90. This paper presents the results of these comparisons and discusses differences among the various cases.**

I. Introduction

TIME-correlated thermal-neutron counting is a well-known technique for characterizing special nuclear material (SNM).[1] Both coincidence and multiplicity counting are used, for example, in nuclear material accountancy for determining SNM masses. The most common approach in this area is to use a shift-register electronic system and count the frequency of detection events within a moving time window.[2] Another technique frequently used for this type of analysis is the Feynman variance approach, where multiple time windows are used to analyze the data.[3-5] Today numerical modeling tools are capable of simulating these measurements; validation with experiments is required to verify their correctness.

To support measurement research in this area Idaho National Laboratory's (INL's) Nuclear and Radiological Activity Center is now facilitating experiments using the MARVEL assembly, a set of three highly-enriched uranium (HEU) disks with a combined weight of 20.2 kg.[6] In 2012 and 2013 neutron-counting experiments were performed at INL in an experimental campaign led by the Johns Hopkins University Applied Physics Laboratory using the middle and bottom components of MARVEL. This paper presents an overview of those experiments along with a brief description of simulations performed to support interpretation of the analytical data.

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II. Experiment

Work for this project took place in the test cell at INL's Zero-Power Physics Reactor (ZPPR) at the Materials and Fuels Complex (MFC), approximately 35 miles west of Idaho Falls, Idaho.[7] The ZPPR Cell is a 15.2-m (50-ft) diameter circular room with reinforced concrete walls and floors and an earthen overpack ceiling. The neutron background rate in the Cell, measured using a moderated ^{3}He-based neutron detector, is approximately 1/20th the level observed in Idaho Falls. The gamma-ray background rate in the Cell primarily originates from natural decay-series elements present in the concrete floor and walls and is typical for a shielded facility. The Cell's remote location from ZPPR's fissile material storage area ensures there is no gamma-ray background from SNM.

A. Materials

The MARVEL test assembly is the core of the former Argonne Fast Source Reactor. It consists of three distinct components, top, middle, and bottom, in the shape of cylindrical disks designed to be stacked one on top of another. For this research, only the middle and bottom components were used; hence, the discussion will focus on these two sections. However, additional details on all of the sections, as well as information on the Argonne Fast Source Reactor, can be found in Reference 6.

The middle section of the core has an HEU mass of 5.49 kg with an enrichment of 93.44% ^{235}U, 6.5% ^{238}U, and 0.06% ^{234}U. The middle section is 3.38 cm tall, 11.47 cm in diameter, and has a through-hole along its diameter with a diameter of 1.27 cm. The bottom section of the core has an HEU mass of 8.86 kg with an enrichment of 93.57% ^{235}U, 6.4% ^{238}U and 0.03% ^{234}U. The bottom section is 5.11 cm tall and 11.47 cm in diameter. Photographs and schematic drawings of these two parts of the MARVEL assembly are shown in Fig. 1 and Fig. 2.

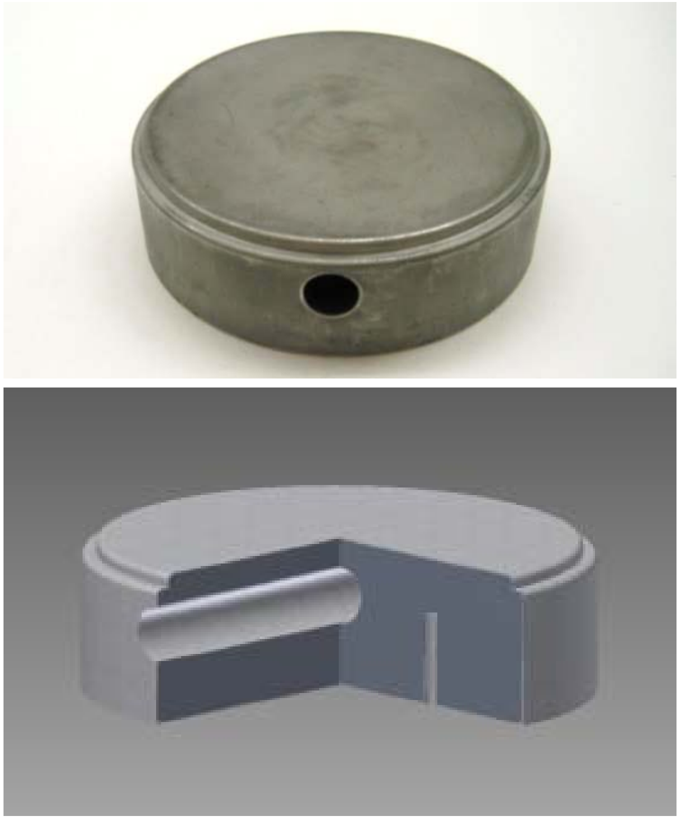

Fig. 1 Photograph of the middle component of the MARVEL core (top) and schematic rendering of the same section (bottom).

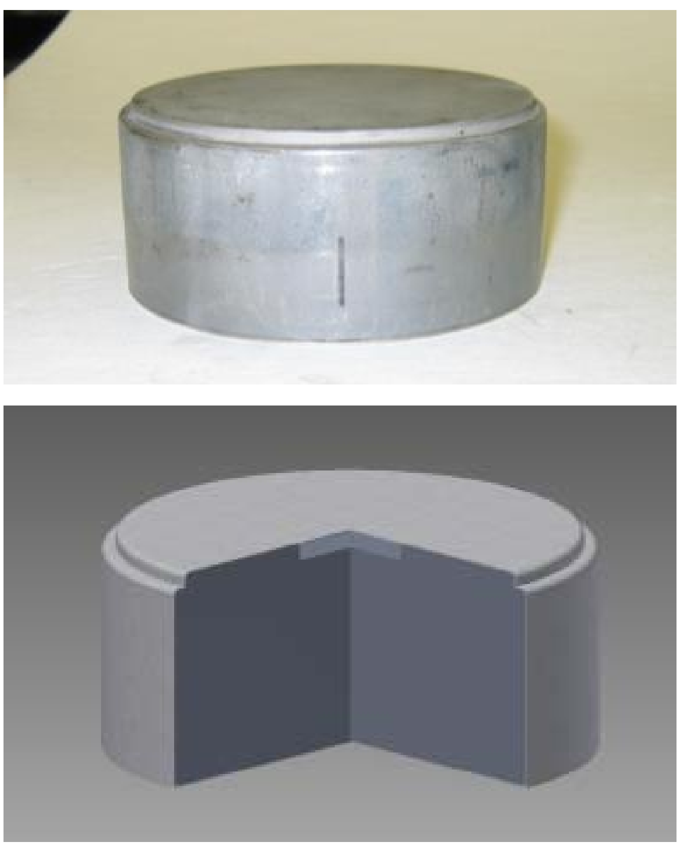

Fig. 2 Photograph of the bottom component of the MARVEL core (top) and schematic rendering of the same section (bottom).

The experiments for this project primarily used a sealed ^{252}Cf source to induce fission in the core components. The source was a model M10 capsule from Frontier technology Corp. (Xenia, Ohio). The activity of this source was known to be more than 15% from the "declared" value. Therefore, an iterative set of analyses comparing simulations with experiments using the source was performed to estimate its intensity; the source strength as of November 2012 was estimated to be 2670 fissions s^{-1}. For the subsequent measurement campaigns, the source was corrected for natural decay of ^{252}Cf when performing analyses.

B. Reflectors

Four sets of reflectors were used for this project: two reflectors made of high-density polyethylene (HDPE), one reflector made of carbon steel, and one reflector made of tungsten. One HDPE reflector set consisted of disks of 22 cm diameter and thickness 5 cm, and rings of HDPE of varying thicknesses with an inner diameter of 12 cm and an outer diameter of 22 cm. For work with these reflectors the HEU was placed in the center of one of the solid disks, surrounded with rings, and then capped with the second solid disk. Different rings could be selected for each configuration of SNM to match the height of the assembly. The density of the HDPE was 0.9501 g cm^{-3}. The second HDPE reflector set consisted of two disks of diameter 42 cm and thickness 5 cm, and rings of HDPE of varying thickness with an inner diameter of 12 cm and an outer diameter of 42 cm. These were selected and used in the same way as with the 5-cm thick HDPE reflector set to match the thickness of the inner SNM assembly.

The carbon steel and tungsten reflectors were identical in shape. Each set consisted of eight cylindrical wedge sections with an inner radius of 6 cm, an outer radius of 11 cm, and a height of 22.3 cm. Each set also had two solid disks measuring 11.95 cm in diameter and 5-cm thick. For use, the HEU sections would be placed on one solid disk, the top disk would be placed on the HEU, and then the wedges would be placed around the circumference of the assembly. To keep the HEU centered within these reflectors, aluminum disks were placed below and above the core, as needed. These aluminum disks were also used as spacers between the core sections, in order to vary the multiplication levels. (These same spacers were also used with the HDPE reflectors, to separate the two HEU components.) The density of the carbon steel was 7.90 g cm^{-3}; the density of the tungsten was 18.13 g cm^{-3}.

Fig. 3 Photographs of a configuration where two MARVEL core parts are separated by 2 cm of aluminum, and reflected with 5 cm of polyethylene. The upper image shows the HEU resting on one 5-cm thick disk of polyethylene, the lower photograph shows the assembly after the remaining polyethylene was placed around the HEU. The M value for this configuration was 6.04.

C. Detectors

Measurements were carried out using two sets of polyethylene-moderated ^{3}He proportional counters, one set included a 6-channel detector system, the other an 8-channel detector system. Data from each system of detectors was collected in list mode and recorded for off-line analysis. In addition to varying the assembly configuration, the detectors were periodically moved to different positions around the assembly. Detailed measurements were taken to record the location and orientation of the detector systems with respect to the assembly. This was of critical importance for the subsequent creation and interpretation of the simulations, since the absolute detection efficiency of the detector arrays is a key parameter needed for interpreting the simulated data an comparing it with experiments.

D. Execution

The experiments involved different detector arrangements and different core configurations. A particular experiment is defined by its arrangement and its configuration. The different detector arrangements included making changes in detector orientation, detector spacing, and detector distance from the core. The core configurations included changing the HEU mass (i.e., using one or two components), the separation between the components, and the reflector. A listing of the core configurations studied in this effort is provided in Table 1. The ^{252}Cf source described above was placed in the central cavity of the middle section of the core to serve as a source of neutrons for fission in the different core arrangements. A pair of photographs showing one core configuration is provided in Fig. 2. Fifty-seven separate experiment scenarios were studied using the core configurations listed below.

TABLE 1 SUMMARY OF DIFFERENT CORE CONFIGURATIONS

Core Components	Aluminum Spacer, cm	Reflector	Reflector Thickness, cm	'True' M
M	0	None	--	1.75
M+B	0	None	--	3.19
M+B	1	None	--	2.71
M+B	2	None	--	2.45
M+B	3	None	--	2.28
M	0	HDPE	5	3.26
M+B	0	HDPE	5	8.90
M+B	0	HDPE	15	10.90
M+B	2	HDPE	5	6.04
M+B	2	HDPE	15	7.17
M	0	Carbon Steel	5	2.11
M+B	0	Carbon Steel	5	4.96
M+B	1	Carbon Steel	5	4.00
M+B	2	Carbon Steel	5	3.45
M	0	Tungsten	5	2.35
M+B	0	Tungsten	5	6.18
M+B	2	Tungsten	5	4.23

M = middle, B = Bottom

III. SIMULATIONS

High-fidelity radiation transport models were generated for each experiment scenario using the MCNPX-PolIMi code package.[8] The 'true' M value for each case was determined empirically using the neutron production and loss tallies from the simulations. These 'true' values have been included in Table 1 for reference. Additionally, data tallies were collected for the time-correlated neutron capture events in the modeled detector assemblies of each detector array. In post processing the data from these tallies were written to a separate file in list-mode format indicating the time of arrival and detector for each event recorded within the two detector arrays. This data format mirrored the way data was recorded from the experimental measurements, allowing the same analysis software tools to be applied to both the measured data and the simulated 'data'.

IV. ANALYSIS

Many approaches exist for interpreting time-correlated list-mode data from nuclear fission events in nuclear assemblies. For this project a comprehensive approach, based on the Feynman-variance technique but modified for this project, was implemented. A periodic triggered-multiplet scheme was chosen as the basis for analyzing the time-correlated data; this approach allows the number of gates to be maximized while minimizing the uncertainty in the multiplet distributions.[9] With this scheme, successively longer time windows were applied to list-mode data, derived either from measurements or simulated measurements, and the number of neutrons residing in each window was tallied. The multiplet distribution was constructed from the number of times (0, 1, 2, etc.) neutrons occur in the window. Moments of the multiplet distribution were calculated and used to generate Y_{2F} and Y_{3F} plots for each case. M values were derived from asymptotic fits to the Y_{2F} plots for each case, using simulation-derived efficiency values. An example of the results from the analysis of experimental and simulated data for one of the detector arrays analyzing the middle and bottom sections of the core, bare and without an aluminum spacer (M = 3.19), is shown in Fig. 4. This example is representative of the level of agreement between simulation and experiment for most of the cases studied here. Less agreement was found, however, for the highly moderating 15-cm thick HDPE reflector. Less agreement also occurred when the absolute detector efficiency of a setup was low or when counting statistics were poor.

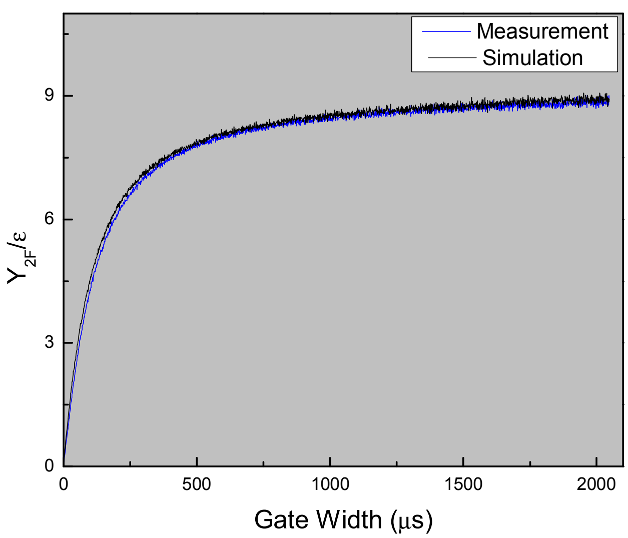

Fig. 4 A representative example of the analysis of experimental and simulated list-mode data sets.

V. DISCUSSION

Two sets of data, one from each detector array, were collected for each of the fifty-seven experiment scenarios, one of the measurement scenarios was analyzed twice. There were a total of 116 separate trials. The empirical 'true' value for M was bounded within 1σ for 104 of the simulated experiments, outside 1σ but within 2σ for 11 cases, and outside 2σ but within 3σ for 1 case. The empirical value for M was bounded within 1σ for 84 of the measured experiments, outside 1σ but within 2σ for 26 cases, and outside 2σ but within 3σ for 6 cases. The outlier cases were those where the absolute detector efficiencies were low and/or where total data collection times were insufficient to generate high-quality Y_{2F}/ε plots (where it was difficult to assess asymptotic limits for the plotted data). Plots showing the agreement between measurements and simulations and the empirically-derived M values are shown in Fig. 5 and Fig. 6 for the 6-channel and 8-channel detector arrays, respectively. (Some of the experiments involved using the detector arrays in far-from-optimal configurations, including cases with very low solid angles, very large stand-off distances, and very-short collection times. These data are included in the breakdown listed above for total performance but have been omitted from the plots below since they were only meant for exploratory purposes and not meant for use in assessing the capabilities of this technique.) For the non-exploratory configurations shown in the following figures agreement between the simulations and the empirical values (R^2 = 0.9970), and between the measured data and the empirical values (R^2 = 0.9945), were both generally good across the multiplication range reported here.

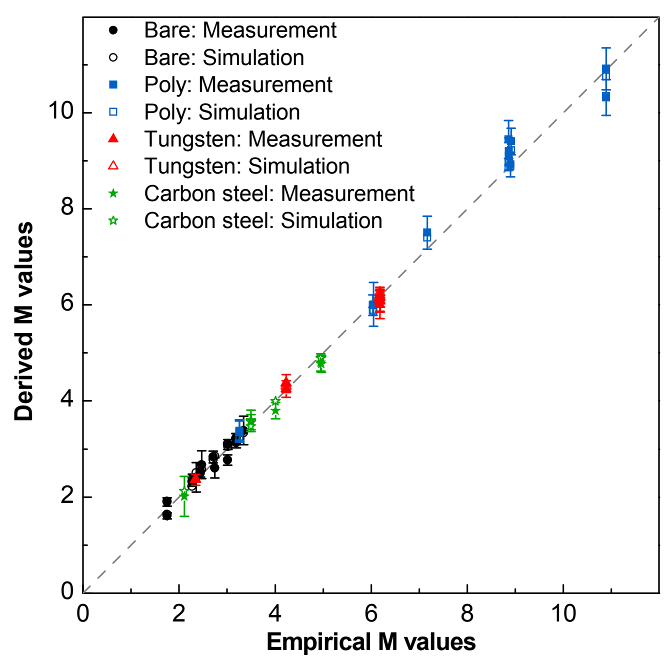

Fig. 5 Comparison of measurement-derived and simulation-derived M values versus empirically determined M values for 41 measurements performed using the 6-channel detection system.

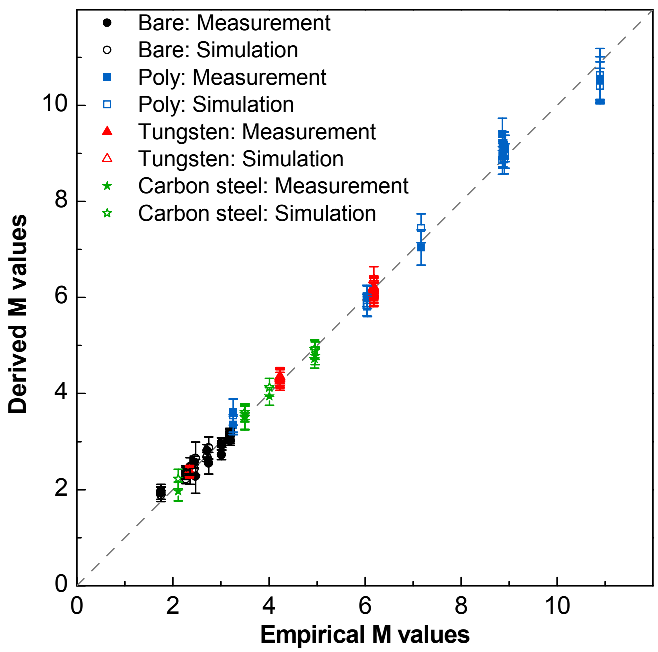

Fig. 6 Comparison of measurement-derived and simulation-derived M values versus empirically determined M values for 41 measurements performed using the 8-channel detection system.

Direct analysis using a standard point-kinetics framework was possible for the bare cases, and when the material was reflected with 5 cm of HDPE, carbon steel, and tungsten. When the material was reflected with 15-cm of HDPE a modification to the basic framework was required, recognizing that the best agreement was found by assuming single neutrons induced the majority of fission events in the assembly rather than correlated neutrons (i.e., spontaneous fission events from the ^{252}Cf source). Also, for these cases the average neutron energy inducing fission was reduced, recognizing that the best agreement was found using the neutron number distributions for 1-MeV neutron induced fission rather than fission-spectrum neutron induced fission.

Further research in this area would be beneficial towards improving the method. One area of interest would be to investigate the impact of high-neutron background and correlated-neutron background environments on the implementation of this technique. A second area of study would be to investigate information that can be extracted from the total shape of the Y_{2F} curve, beyond merely determining the asymptote value of the Y_{2F} parameter. A third area of great interest would be to assess how active neutron interrogation, using a pulsed electronic neutron generator, could be used to both facilitate and complement the analysis described here. Lastly, examination of the behavior of the Y_{3F} parameter for multiplying-assembly configurations, to address its high statistical uncertainty, would be useful to determine how to incorporate this information into the analysis process.

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