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Development of a New Multiplying Assembly for Research, Validation, Evaluation, and Learning

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Abstract – **A new multiplying test assembly is under development at Idaho National Laboratory to support research, validation, evaluation, and learning. The item is comprised of three stacked, highly-enriched uranium (HEU) cylinders, each 11.4 cm in diameter and having a combined height of up to 11.7 cm. The combined mass of all three cylinders is 20.3 kg of HEU. Calculations for the bare configuration of the assembly indicate a multiplication level of >3.5 (k_{eff} = 0.72). Reflected configurations of the assembly, using either polyethylene or tungsten, are possible and have the capability of raising the assembly's multiplication level to greater than 10. This paper will describe the MCNP calculations performed to assess the assembly's multiplication level under different conditions and describe the resources available at INL to support the use of these materials. We will also describe some preliminary calculations and test activities using the assembly to study neutron multiplicity.**

I. Introduction

Neutron multiplication in assemblies of special nuclear material (SNM) is at the core of the discipline of nuclear engineering. It is important to be able to accurately predict the inherent ability of fissionable material assemblies to sustain nuclear chain reactions, and to predict how this characteristic of fissionable material assemblies will change due to different changes in physical parameters. Over the last half-century computer modeling and simulations have grown to become the primary research tool nuclear engineers use to understand these effect. Computer simulations are routinely used to explore how neutrons interact in many different types of multiplying assemblies, exploring problems ranging from reactors, to nuclear waste storage and disposition, to nonproliferation and nuclear security. However, hands-on experimental investigations and experimentation with SNM remains an invaluable component to work in this field.[1] Unfortunately, for several reasons, access to fissionable material for performing neutron multiplication experiments has diminished over the last two decades.

For several years researchers at Idaho National Laboratory (INL) have been working to develop and improve safe and secure access to SNM for research, validation, evaluation, and learning activities. The locus for these activities is INL's Materials and Fuels Complex (MFC) and the former Zero-Power Physics Reactor (ZPPR) facility. The ZPPR area includes several work areas including, most notably, the former reactor cell. The cell is a large high-bay area with a low-scatter floor and a high-capacity overhead crane. The facility possesses a diverse range of SNM for use in experiments including an inventory with multiple-grade plutonium items and multiple-enrichment uranium items, in both metallic and oxide forms.[2]

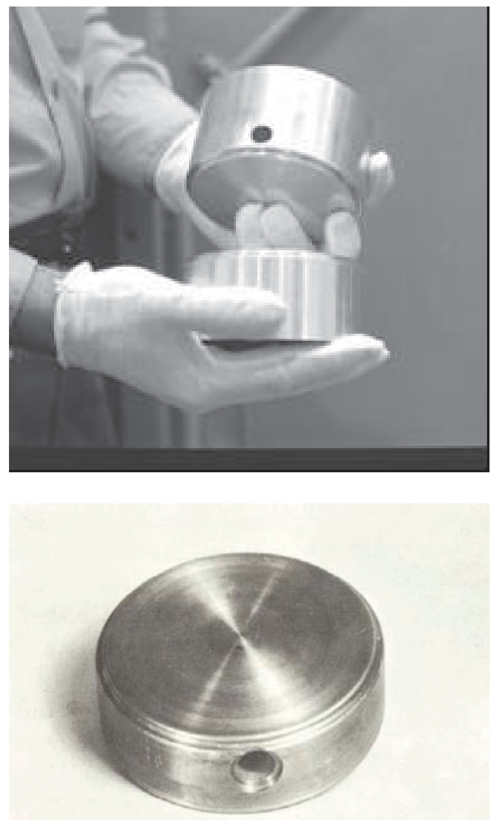

Fig. 1 An archival photograph of the three parts of the AFSR core (top) and a close-up photograph of the middle-section of the core (bottom).

Most recently, we have started to use a unique item in the ZPPR inventory – the Argonne Fast Source Reactor (AFSR) core. The AFSR core was previously used as the core of a low-power physics reactor at Argonne National Laboratory – West. 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. The disks are each 11.4 cm in diameter. The top section is 3.3-cm thick and weighs 5.9 kg; its enrichment is 93.5%. The middle section is 3.3-cm thick and weighs 5.5 kg; its enrichment is 93.4%. It has a 1.2-cm diameter hole entering from the outer edge going through the middle of the disk and exiting the other side. This hole can hold a radioisotope neutron source or other small item. The

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bottom section is 5.1-cm thick and weighs 8.9 kg; its enrichment is 93.5%. A photograph of all three parts of the AFSR core, and a close-up photograph of the middle section of the core, is shown in Fig. 1.

After developing new work control documentation and performing safety reviews to support using the AFSR core, it is now once-again available at INL for hands on research. There are many potential uses for this assembly. One primary use is as an educational aid for teaching people about nuclear criticality and safe practices. Another important use is support research related to developing instrumentation aimed at analyzing neutron multiplication. Coupled with this purpose is using the AFSR core for validating analytical and numerical models used in reactor physics kinetics. Lastly, an important use of the AFSR core is for test and evaluating instrumentation designed to analyze neutron multination signatures from fissionable materials. Coupling the AFSR core with the support infrastructure to allow changing the neutron multiplication (via changing geometry, changing reflectors, changing moderators, etc) produces a versatile Multiplying Assembly for Research, Validation, Evaluation, and Learning – MARVEL. This paper presents a background discussion of the value and importance of performing hands-on experiments with multiplying assemblies, presents simulation studies carried out to assess the neutron multiplication levels possible with different MARVEL configurations, and presents a simple example of an experimental use of two-thirds of the MARVEL to generate a $1/M$ plot.

A. Research, Validation, and Evaluation

In collaboration with partners at other institutions INL has been involved in research studying experimental methods related to measuring and interpreting neutron multiplicity and neutron multiplication for several years.[3-8] The development of the MARVEL test capability is based in part on interest in expanding the Laboratory's capabilities for performing work in this area. While prior work at INL has used large masses of SNM (e.g., ~10 kg of HEU, ~4 kg of Pu), rarely has prior work involved fissionable assemblies having multiplication levels in excess of 2. (One notable exception to this is prior work using a special set of inspection objects containing various combinations of uranium and plutonium.[9])

Most experimental research campaigns dealing with neutron multiplicity and neutron multiplication measurements are partnered with simulation activities. Typically only a handful of experiments may be performed during a particular testing cycle. However, ample access to high performance computing resources can augment parameter-bounding experiments to perform parametric analysis of variables not accessible through experiments, and to exhaustively carry-out sensitivity analyses for varying different parameters singly and in combination.[10] In a complimentary fashion, for computationally focused research efforts key measurements performed during experimental efforts are critically important for validating the accuracy and legitimacy of using simulation codes and associated post-processing algorithms for analysis and interpretation.[11]

An important subset of activities that takes place at INL's ZPPR facility is testing to evaluate the performance and use of commercial instrumentation designed to detect and characterize radioactive materials. Development of the MARVEL test capability will augment work performed at INL in this area by providing an accessible, variable, and repeatable multiplying assembly to use for testing different neutron multiplicity and neutron multiplication measuring instruments and systems.

B. Learning: Criticality Safety Training

Understanding the complicated and interdependent phenomena that impact how neutrons interact in nuclear material provides the foundation for designing and operating nuclear reactors. At a more personal level, this understanding is also vitally important for individuals charged with working with SNM, those who design instrumentation and systems to handle and process fissionable material, and those who ensure that these activities are performed safely.[12,13]

At INL a key resource for fissile material handlers (FMHs) and criticality safety officers (CSOs) is the study guide "Criticality Safety Basics for INL FMHs and CSOs."[13] This documents provides FMH and CSO candidates a comprehensive overview of the principles and underlying concepts of criticality safety and stresses the importance of criticality safety when handling fissionable materials outside nuclear reactors. As a part of this training, INL uses the mnemonic expression MERMAIDS to assist those working with fissionable materials in remembering the eight key criticality control factors:

- Mass
- Enrichment
- Reflection
- Moderation
- Absorption (neutron capture)
- Interaction
- Density and concentration
- Shape (geometry)

While classroom instruction, mentored training, and reading about these phenomena can provide a strong basis for working safely with fissionable materials, hands-on experiences can provide deeper and more-lasting understandings in some cases. Emphasizing this, the U.S. Department of Energy (DOE) has made a *requirement* that criticality safety engineers (CSEs) have a hands on experimental training experience with criticality "... to facilitate familiarity with the factors contributing to criticality, the physical behavior of systems at and near criticality, and a theoretical understanding of neutron multiplication processes in critical and subcritical systems."[14] The new multiplying assembly at INL will be used to support hands-on training exercises with existing and future INL FMH and CSO candidates, and to augment the training and continuing education of INL criticality safety engineers (CSEs).

C. Neutron Multiplicity

Neutron multiplicity, $\nu_{n,\ prompt}$, refers to the number of neutrons emitted when an atom undergoes fission.[15] These neutrons are emitted 'promptly,' during the scission of the atom, and should not be confused by 'delayed' neutrons subsequently produced in the decay of β-unstable fission product atoms. The fission event may be spontaneous, owing to the natural decay of the radioactive atom, or it may be induced through a nuclear reaction, such as absorption of a neutron. The specific number of neutrons that will be emitted during a particular fission event is not predictable *a priori* but the distribution of the numbers of neutrons produced under identical circumstances, when repeated many times, is predictable and can be defined by a probability distribution for such events. These probability distributions are specific for each isotope, and specific depending upon the initiating conditions of the fission event (e.g., spontaneous fission versus neutron induced fission). For induced fission these distributions are further defined by the type and energy of the particle inducting the fission. Additional variables in the neutron multiplicity exit in terms of the energy and angular distributions of the prompt fission neutrons. A mean neutron multiplicity value, $\bar{\nu}_{prompt}$, may be defined for each probability distribution.

Neutron multiplicity is an important concept in the nuclear reactor physics and in nuclear safeguards. The MARVEL either system can provide a unique test-case for studying neutron multiplicity allowing, for example, studies comparing the neutron multiplicity from ^{238}U spontaneous fission and 235U neutron-induced fission (with a source driver) under different reflector/moderator conditions.

D. Neutron Multiplication, k_{eff}, and 1/M

Neutron multiplication, *M*, refers to the inherent characteristics of an assembly of fissionable material to extend the lifetime of a population of neutrons introduced into the assembly due to fission. Two terms may be defined, total multiplication and leakage multiplication.[16-19] The total multiplication, M_T, is the total number of neutrons <u>produced</u> in a fissionable assembly due to the introduction of one neutron into the assembly. The leakage (or net) multiplication, M_L, is the total number of neutrons that <u>escape</u> from a fissionable assembly due to the introduction of one neutron into the assembly. The leakage multiplication accounts for neutron production and capture in the assembly, and includes the source neutrons. It is not possible to measure the total number of neutrons produced in a fissionable assembly due to fission. Therefore, for experiments with multiplying assemblies, M_L is the multiplication term of primary interest since it is the neutrons escaping the assembly which are measured.

The leakage multiplication may be defined as

$$M_L = 1 + Q_f\left(\bar{\nu}_{prompt} - 1 - \alpha\right), \qquad (1)$$

where Q_f is the number of fissions (on average) produced by introduction of one neutron into the system, $\bar{\nu}_{prompt}$ is the neutron multiplicity for the system, and α is the ratio of the neutron capture cross section to the fission cross section in the assembly, for the mean neutron energy in the system.[19]

Leakage multiplication is often related to the effective multiplication factor, k_{eff}, of a fissionable assembly. The effective multiplication factor is the ratio, as shown in (2), of the neutrons produced by fission in one generation to the number of neutrons lost through absorption and leakage in the preceding generation.[20]

$$k_{eff} = \frac{\text{neutron production from fission in one generation}}{\text{neutron absorption in the preceding generation} + \text{neutron leakage in the preceding generation}} \qquad (2)$$

For a system with k_{eff} close to unity (near critical), the relationship between M_L and k_{eff} is

$$M_L = \frac{1}{1 - k_{eff}}. \qquad (3)$$

For a system not close to critical, however, the measured neutron leakage from a fissionable assembly is related to k_{eff} by the somewhat more complicated relation of (4).

$$M_L = 1 + \frac{k_{eff}\left(\bar{\nu}_{prompt} - 1 - \alpha\right)}{\bar{\nu}_{prompt}\left(1 - k_{eff}\right)}. \qquad (4)$$

When performing subcritical neutron multiplication experiments it is often common to work in an iterative approach. One begins with some starting condition for the experiment; for example, a bare assembly of fissionable material (when using HEU a separate neutron source is often used, to increase the neutron signal strength). A measure of the leakage neutron signal, N_0, is recorded with an appropriate detector. Then, modifications are made to the system that increase k_{eff} for the system (e.g., adding fuel to the system, or adding moderating materials to partially surround the system), increasing the leakage multiplication of the system and increasing the measured neutron signal to a new level, N_1 ($N_1 > N_0$). This process is continued, allowing collection of increasingly larger neutron counts, N_i. Presuming that the system cannot be made critical, then eventually, as $i \rightarrow \infty$, N reaches some equilibrium value, N_∞. Starting with N_0, for each change in the experiment, the ratio $M = N_i / N_0$ is recorded. A plot of 1/*M* versus the changes being made to the system (e.g., fuel mass addition, moderator mass addition, etc.) is then made for each step change of the variable. Initially, *M* is often observed to increase significantly as changes are made to the system. If the system is capable of going critical then $M \rightarrow \infty$; however, if the system cannot go critical then *M* (and 1/*M*) will trend to an equilibrium level where further adjustments to the system no longer increase the system's multiplication level. At this point the k_{eff} value for the system is also constant.

E. Neutron Fission Parameters

The MARVEL core components are comprised of ^{235}U and ^{238}U, with a ^{235}U enrichment of approximately 93.5%. Important neutron-induced fission parameters for uranium are provided in Table 1. For the MARVEL material enrichment the total spontaneous neutron yield is approximately 1 s^{-1} kg^{-1}. The neutron yields for each component (neglecting multiplication for the moment) are 5.9, 5.5, and 8.9 s^{-1} for the top, middle, and bottom sections, respectively. This level is quite low; to augment this an external neutron source is used for experiments. Both an americium-lithium (α,n) neutron source and a ^{252}Cf-spontaneous fission source are available. The preferred configuration is to insert the ^{252}Cf source inside the hole in the middle section of the MARVEL assembly; this serves as the driving source for the assembly, providing the base-line neutron intensity for determining multiplication as a) additional components of the core are moved within proximity of the middle section and/or b) reflectors and/or moderators are brought within proximity of the assembly. It is also possible to drive the assembly using an external, pulsed neutron source using either a deuterium-deuterium (DD, 2.5-MeV) or deuterium-tritium (DT, 14.1-MeV) electronic neutron generator (ENG).

TABLE 1 ^{235}U AND ^{238}U NEUTRON FISSION PARAMETERS [21,22,23]

Parameter		^{235}U	^{238}U
Y_{SF}	Spontaneous-fission (SF) neutron yield, n s^{-1} kg^{-1}	0.299	13.6
σ	Fission cross section, barns	2.08 (14.1 MeV) 1.29 (2 MeV) 2734 (thermal)	1.15 (14.1 MeV) 0.53 (2 MeV)
$\bar{\nu}_{prompt}$	Average prompt neutron yield (multiplicity), n $fission^{-1}$	4.6 (~14 MeV) 2.57 (fission spec.) 2.41 (thermal) 1.86 (SF)	4.5 (~ 14 MeV) 2.79 (fission spec.) 2.01 (SF)
$\bar{E}_{prompt}$	Average prompt neutron energy, MeV	2.03 (14 MeV) 1.935 (thermal)	1.99 (14 MeV)
$\bar{\nu}_{delayed}$	Average delayed neutron yield, n $fission^{-1}$	0.0165 (1.45 MeV) 0.0158 (thermal)	0.0412 (3.01 MeV)
$\bar{E}_{delayed}$	Average delayed neutron energy, MeV	0.43	0.49

Values followed by parenthesis indicate quantities associated with fission induced by neutrons with an energy or energy-spectrum given in the parenthesis.

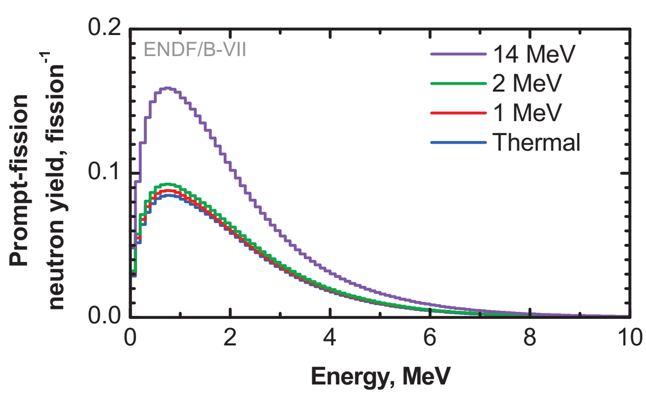

Fig. 2 Neutron spectrum from ^{235}U due to induced fission from source neutrons ranging from thermal energies to 14 MeV. (Data from the ENDF/B-VII database.)

Whether the assembly is driven via spontaneous fission, either of the two radioisotope neutron sources, DD- or DT-ENGs, or reflected and/or moderated neutrons originating from these sources, the neutron fission spectrum mean energy is expected to be similar, as shown in Fig. 2. The neutron multiplicity probability distributions for thermal-neutron induced fission in ^{235}U, for 2 MeV neutrons inducing fission in ^{235}U and ^{235}U, and for spontaneous fission in ^{238}U and ^{252}Cf are presented in Fig. 3.[24] Significant differences exist between the spontaneous fission of ^{238}U, neutron-induced fission in ^{235}U, and spontaneous fission of ^{252}Cf.

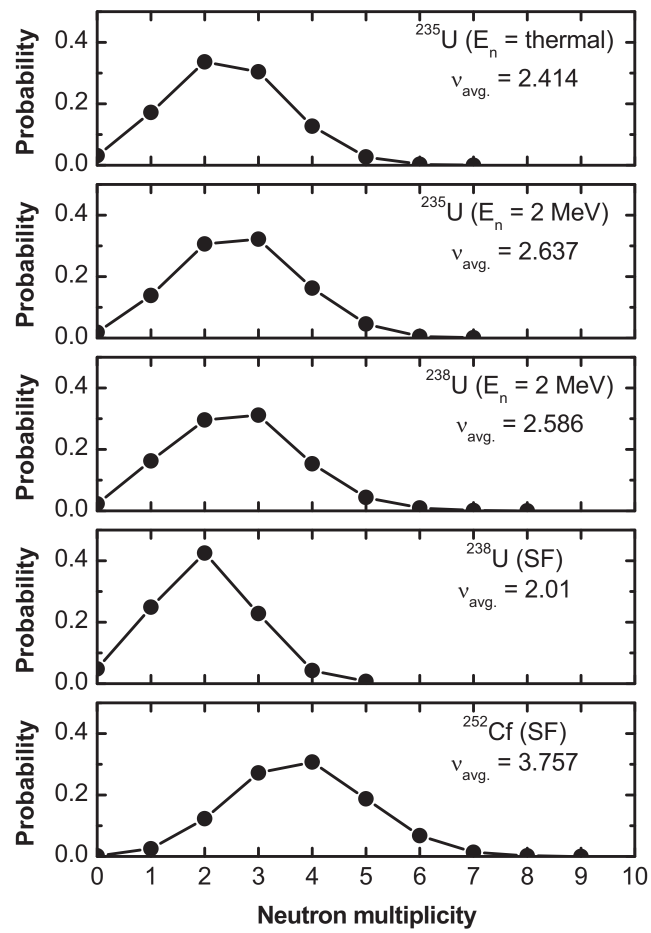

Fig. 3 Induced-fission (neutron energy, E_n, thermal or 2 MeV) and spontaneous-fission (SF) multiplicity distributions for ^{235}U, ^{238}U, and ^{252}Cf.[24]

II. MARVEL MODELING AND SIMULATION

The Monte Carlo n-Particle computer code (MCNP 5), with k-code, was used to assess the bare, unreflected effective multiplication factor, k_{eff}, for several possible configurations of the three MARVEL core components.[25] As-built dimensional measurements were used for the core components, in the model and correct isotopic composition values were used for each section. The top part of the core contains a small penetration, to allow insertion of small diagnostic instruments (e.g., a micro fission chamber or thermocouple). The middle and lower sections of the core contain a recessed channel designed to allow these components to be mounted into a positioning assembly. The hole passing along the diameter of the middle section is not centered axially but is closer to the side with the recessed channel. Eight geometric arrangements were analyzed, as depicted in Fig. 4. For each case, the calculated k_{eff} values, and the leakage multiplication values (determined using (3)), are presented in Table 2.

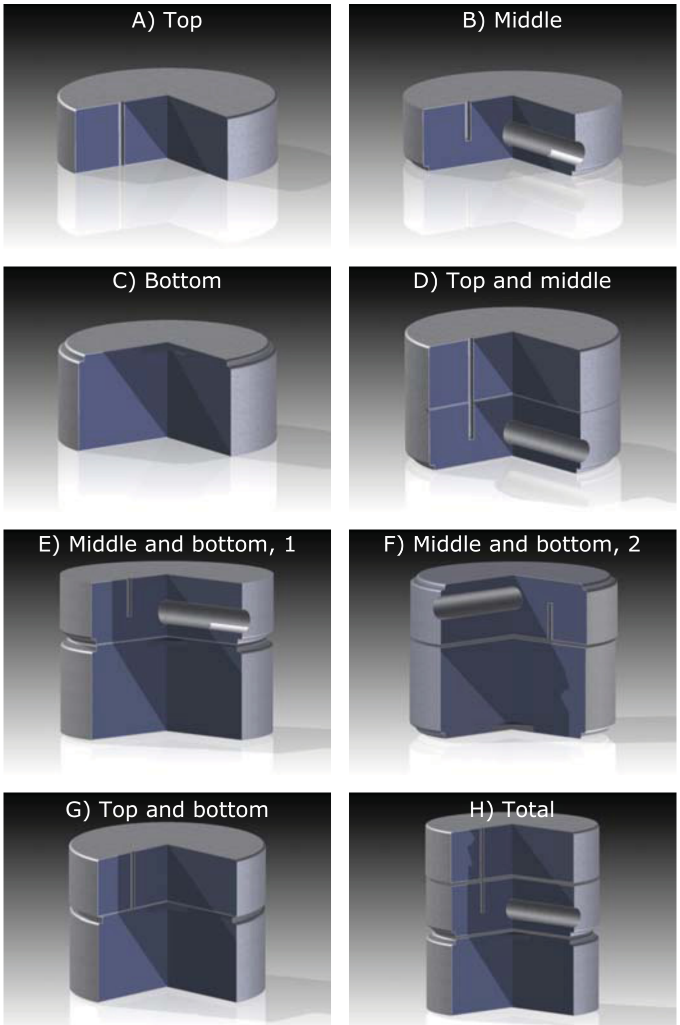

Fig. 4 Eight geometric arrangements of the MARVEL core components.

TABLE 2 SIMULATED k_{eff} VALUES FOR EIGHT MARVEL CORE COMPONENT CONFIGURATIONS

Configuration	k_{eff}	M_L
A) Top	0.4362 ± 0.0003	1.774
B) Middle	0.4097 ± 0.0003	1.694
C) Bottom	0.5398 ± 0.0004	2.173
D) Top and middle	0.5990 ± 0.0004	2.494
E) Middle and bottom,1	0.6509 ± 0.0004	2.865
F) Middle and bottom, 2	0.6579 ± 0.0004	2.923
G) Top and bottom	0.6700 ± 0.0004	3.030
H) Total	0.7248 ± 0.0005	3.634

M_L values determined using equation (3).

Additional simulations were performed to determine the effective multiplication factor for two-different configurations when surrounded by reflectors (which in some cases also moderate neutrons) of polyethylene, graphite, stainless steel, and tungsten. The plot of k_{eff} versus reflector thickness for the top MARVEL core competent is shown in Fig. 5; a similar plot for the top and bottom (layout G of Fig. 4), is shown in Fig. 6.

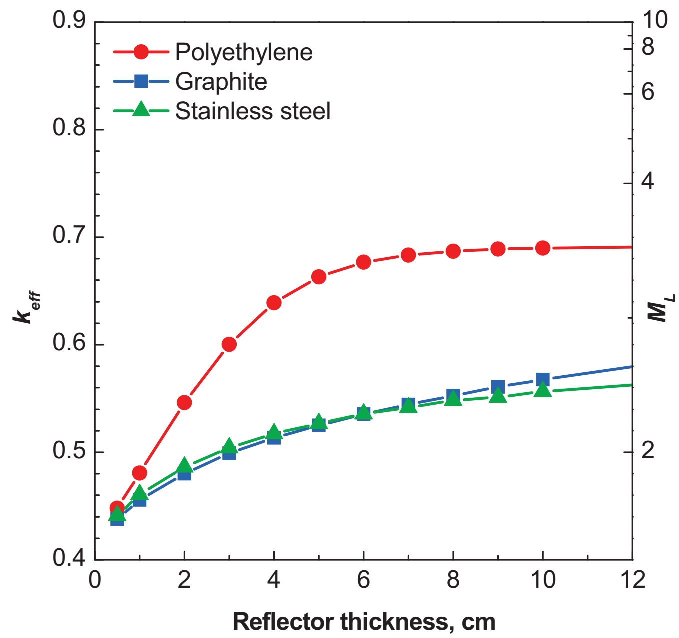

Fig. 5 The relationship between k_{eff}, M_L, and reflector thickness for the top MARVEL core component surrounded by polyethylene, graphite, or stainless steel.

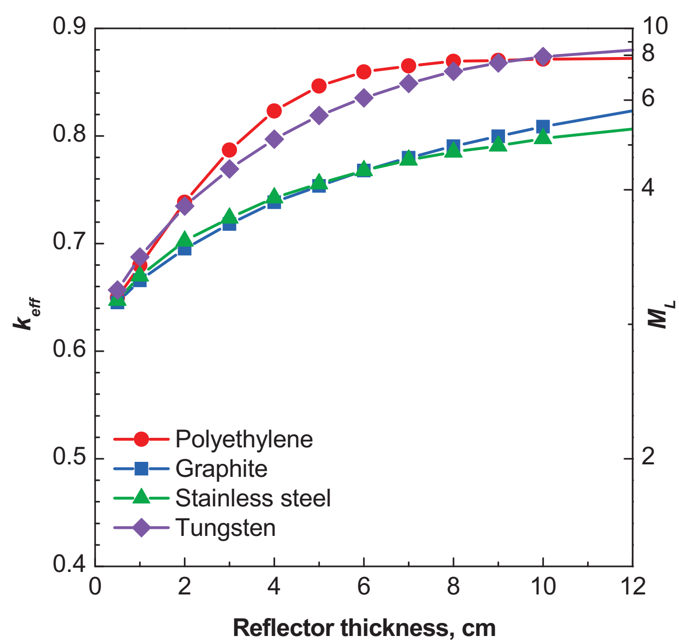

Fig. 6 The relationship between k_{eff}, M_L, and reflector thickness for the top and bottom MARVEL core components surrounded by polyethylene, graphite, stainless steel, or tungsten.

III. Demonstration Experiment

In September, 2012, the first set of hands-on subcritical experiments was performed using the MARVEL components. Custom-fitting reflector/moderator assemblies are typically used for these types of tests (see for example, reference 1.) Unfortunately, for this first set of tests with the MARVEL components, custom-fit reflectors/moderators were not yet available. Instead, standard 2-in. (5.1-cm) × 4-in. (10.2-cm) × 8-in. (20.3-cm) polyethylene bricks were used to surround the assembly, one brick at a time. The experiment used the top and bottom parts of the core, as shown in layout G of Fig. 4.

The experiment started by placing the stacked core components on a steel support plate under which was an array of cadmium-wrapped, polyethylene-moderated ^{3}He tubes. This served as the leakage neutron detector for the experiment. An AmLi (α,n) neutron source, packaged inside a steel crimp-lid can, was placed on top of the core components. Neither the core components, the AmLi source, nor the detectors were moved during the experiments. A recoding was made of the neutron counts in the detector array, all counts were taken for 50 s and had a statistical precision of <1%. After this, one by one, polyethylene bricks were placed around the assembly and neutron count readings were taken. The loading pattern is shown in Fig. 7 together with a photograph of the assembly taken after placement of the eighth brick. Fourteen bricks were emplaced singly, after this eight more bricks were placed over the top of the assembly and polyethylene bricks, covering the top with 4 inches (10.2 cm) of polyethylene.

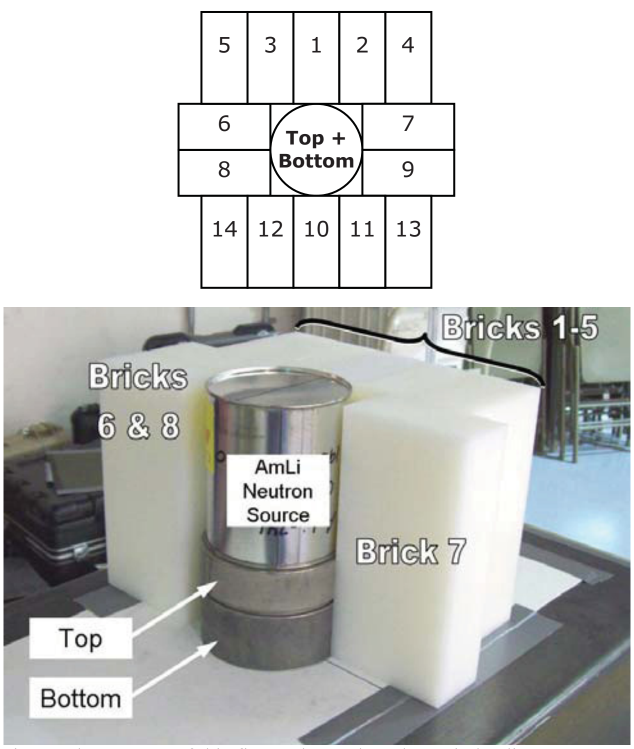

Fig. 7 The top part of this figure shows the schematic loading pattern used to place polyethylene bricks around the top and bottom MARVEL core components. The lower part of this figure is a photograph showing the assembly after brick number 8 was put in place. Also, the location of the AmLi neutron source is visible.

The results from this experiment are shown in Fig. 8. The first five bricks have a small but noticeable effect, slowly increasing the multiplication level of the assembly. Addition of bricks six through eight have a much large impact, as they begin to close-in the core pieces. Further increases are observed as the last side of the assembly is enclosed. Covering the top of the assembly was found to increase the multiplication by approximately 29%. With the sides and top of the assembly surrounded with polyethylene, the observed multiplication factor for this experiment, derived using the measured multiplication value for 22 polyethylene bricks, was 0.67. As expected, this is less than the simulated value of 0.87 shown in Fig. 6 for the ideal case completely surrounding the entire assembly with 10 cm of polyethylene. The primary cause for this difference is that a non-trivial fraction of the source neutrons are measured in the detectors directly without interacting in the HEU, thus artificially raising the denominator in the equation for *M*. Performing the experiment using more polyethylene underneath the assembly, placing the neutron source inside the top-section experimental hole, and moving the neutron detectors closer to the assembly would all serve to increase the observed multiplication level and work to improve the fidelity between the idealized simulations and the experiments.

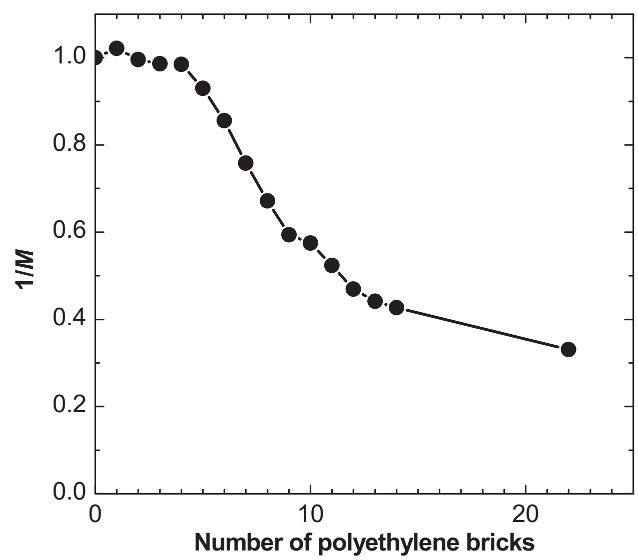

Fig. 8 1/M plot for stacking polyethylene bricks around the assembly of the top and bottom MARVEL components.

IV. Summary

Activities are underway at Idaho National Laboratory to return the AFSR core to operational use as a subcritical multiplying assembly to support research, validation, evaluation, and learning activities - MARVEL. In support of this goal a series of initial simulations has been performed to assess the bare, unreflected effective multiplication factor, k_{eff}, for eight different geometric arrangements of the core's three components: top; middle, and bottom. The bare k_{eff} values range from 0.4362 for the top section of the core to 0.7248 for all three parts of the core. An inaugural experimental campaign has been performed, using the top and bottom sections of the core with polyethylene shield bricks, to demonstrate the capability of using the MARVEL assembly for performing a traditional 1/M 'approach-to-critical' experiment. Future work underway at INL to improve the usefulness of the MARVEL components for performing research, validation, evaluation and learning exercises in support of multiplication-related studies includes: acquisition of a small ^{252}Cf spontaneous-fission neutron source suitable for insertion inside the middle section of the core; acquisition of a set of modular, cylindrical reflectors made of polyethylene and tungsten, to allow the execution of more detailed and more reproducible 1/M-type experiments; the acquisition of a smaller neutron detector capable of being placed directly underneath the core, and developing higher-fidelity models of the experimental apparatus, including the neutron source, the detector, and the reflectors.

V. Acknowledgements

We would like to acknowledge the dedicated work of the INL staff at the Materials and Fuels Complex ZPPR facility, and thank them for their assistance in working to return the AFSR core to service. We would also like to thank the other INL staff who have participated in this effort, in particular Todd Taylor of INL's Criticality Safety department.

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