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Author(s): Madison T. Sellers, Emily C. Corcoran, David G. Kelley
Royal Military College of Canada

Tim Goorley
Los Alamos National Laboratory

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A Preliminary Comparison of MCNP6 Delayed Neutron Emission from ^{235}U and Experimental Measurements

M.T. Sellers[1], J.T. Goorley[2], E.C. Corcoran[1*], D.G. Kelly[1]

[1]*Royal Military College of Canada, P.O. Box 17000 Stn Forces, Kingston, ON, K7K 7B4, *emily.corcoran@rmc.ca*
[2]*Monte Carlo Codes, MS: A143, Los Alamos National Laboratory, Los Alamos, NM, 87545, jgoorley@lanl.gov*

INTRODUCTION

A delayed neutron counting (DNC) system has been commissioned at the Royal Military College of Canada (RMCC). This system was modeled in MCNP6 Beta 2[1] and the delayed neutrons measured from the fission of ^{235}U were compared to MCNP6 predictions.

DESCRIPTION OF ACTUAL WORK

A Description of the Experiment

The DNC system at RMCC uses the SLOWPOKE-2 reactor as a source of neutrons. Samples containing ^{235}U were prepared as acidified aqueous solutions from certified reference standards (natural U standard CRM 4321C, NIST, Gaithersburg, MD, and depleted U standard CRM U005A 0.5064 ± 0.0003 atom% ^{235}U, New Brunswick Laboratory, Argonne, IL). Each solution was contained in heat sealed small polyethylene (PE) vials (LA Packaging, Yorba Linda, CA) with a nominal solution of 1 mL. To minimize the potential of solution leakage into the pneumatic tubing of the system, secondary containment was achieved using heat sealed 7 mL polyethylene vials (LA Packaging). By irradiating the inner and outer polyethylene vials without any fissile sample, the vials have been found to contain no impurities that contribute to the overall neutron count rate recorded by the DNC system [2]. Samples containing the fissile content were sent to an irradiation site inside the SLOWPOKE-2 beryllium reflector where they were exposed to a predominately thermal neutron spectrum for durations up to 60 s. After the samples were irradiated they were automatically sent, via pneumatic transfer system, to the neutron counting arrangement. This consisted of six 304 Stainless Steel (S.S.); Reuter Stokes ^{3}He detectors (RSP4-1613-202, GE Energy, Twinsburg, OH) embedded in a paraffin moderator. Samples were located at the center of the hexagonal detector array. A delay time of 3 s was employed to account for sample travel time from the irradiation site and the commencement of the delayed neutron count. Delayed neutrons were recorded as a function of time, in 0.5 s intervals.

The MCNP6 Model

The geometry of the DNC apparatus was modeled using the physical dimensions measured during DNC system commissioning. Fig. 1 shows a 2-D view of MCNP6 input geometry and materials. Experiments and modeling accommodated two smaller vials inside a larger polyethylene vial. In practice, solutions containing fissile content and air were located in the upper and lower vials, respectively, for both experimental runs and the MCNP6 model. The polyethylene capsules were modeled with dimensions provided by the manufacturer and the distances of the sample from the detectors were measured and then duplicated in the MCNP6 input deck. Each ^{3}He detector was modeled with two cells defining each fill gas area; one of which contains the active zone of the detectors as detailed by the provided technical specifications and the other a thin inactive portion surrounding the active cell where charge depositions were not recorded by the detector. Neutrons, tritons, and protons were all explicitly tracked in these calculations.

The temporal behavior of the experiment was modeled in the MCNP6 input deck by a time-dependent *sdef* card. The *sdef* card reproduced the SLOWPOKE-2 neutron flux by specifying both the energies of source neutrons and the duration for which the sample was irradiated. Several variations of neutron flux inputs were examined: one which contained just thermal neutrons, the other which accounted for the epithermal and fast flux measurements made in the specific irradiation site, and the final a 69-group energy spectrum. The thermal neutron spectrum was used, as an examination of the output of the three flux input decks showed no significant differences in the magnitude and behavior of the delayed neutrons produced.

Pulse Height (F8) tallies summed both the number of pulses and energy deposition from proton and triton tracks in the active zones of the six detectors, which started 1 s after the end of the irradiation time. The 1 s time bins of the F8 tallies recorded count rates for up to 180 s after irradiation and were further subdivided by the energy of the pulse. Although using the detector geometry for the irradiation is not physically accurate (because the U samples were actually in the reactor during their irradiation), it is expected that the energy distribution of the neutrons irradiating the sample is not significantly altered. The flux inside the model`s polyethylene vial was weighted to match experimental measurements of the thermal flux in that specific irradiation site, by using the *wgt* entry on the *sdef* card. Thus, the energy deposition in the ^{3}He tubes and the temporal nature of the delayed neutron emission after the irradiation of the fissile samples could be ascertained.

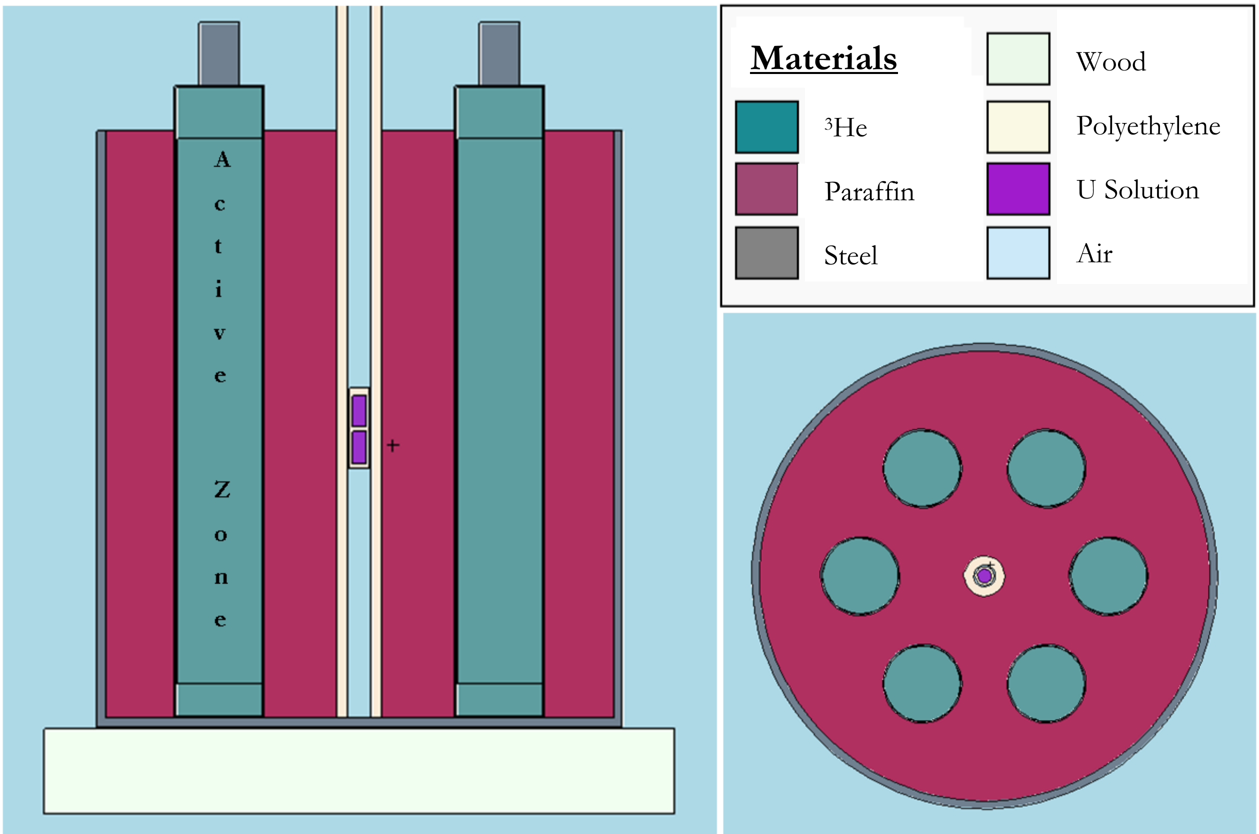

Fig. 1. MCNP6 Representation of Geometry and Materials

RESULTS

Neutron Detection Efficiency Comparisons

The efficiency of the DNC system was determined by a separate calculation, which tallied proton and triton creation and energy deposition inside the active portion of the detectors. A source was defined inside the detector system geometry that released neutrons with the activities and energies expected of delayed neutrons produced from the fission of ^{235}U. The number of proton/triton pairs that deposited energy above 0.191 MeV in the active portions of the detectors during the simulation was compared to the total number of neutrons produced by the U sample, and the efficiency of the system was determined to be 37 %. This value is slightly higher than the experimentally determined efficiency of 34 ± 5%, [2] but within experimental uncertainty (which is quoted with ±2σ) of the latter. Major source of uncertainty in the experimentally measured efficiency arise from the precision of the irradiation flux spectrum, energy discrimination levels and solution concentration.

Energy Deposition in ^{3}He Detectors

In ^{3}He detectors the incident neutron reacts with the helium isotope and produces a triton (^3_1H) and proton (^1_1p) through the following process [3]:

$$^3_2He + \, ^1_0n \rightarrow \, ^3_1H + \, ^1_1p \qquad \text{Q Value} = 0.764 \text{ MeV}$$

In an ideal ^{3}He detector all kinetic energy of the reaction products would be recorded by the detector, resulting in a singular peak at 0.764 MeV. However, many of the reaction products will come into contact with the wall of the detector and some of the kinetic energy produced in a neutron-^{3}He reaction will not be recorded by the apparatus. The net charge deposited after each triton-proton reaction will range from 0.191 MeV (the kinetic energy of the triton produced in the reaction) to the total reaction energy of 0.764 MeV.

Fig. 2 illustrates the experimentally measured energy deposition in all six detectors for small amounts of ^{235}U delayed neutron production. Also depicted at energies less than 0.191 MeV, is the γ-background contribution from the fission process and (n,γ) reactions of non-fissile samples present in the matrix. Although the γ-background was recorded for this particular trial, it is excluded from the recorded count rates in typical DNC system operation. Significant broadening of the peak at 0.764 MeV is, in part, a consequence of the modest energy resolution of the apparatus.

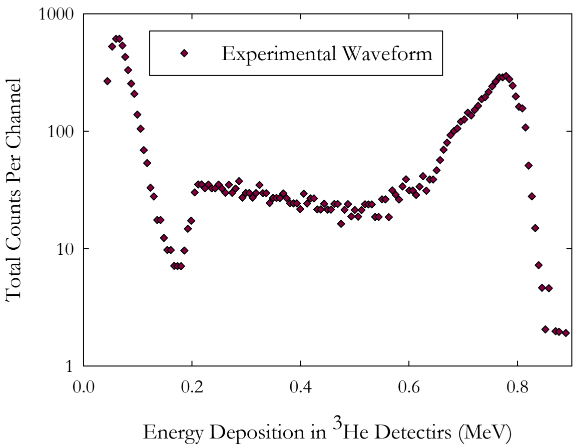

Fig. 2. Measured Experimental Waveform

A Gaussian Energy Broadening, *GEB* tally card was used in MCNP6 to represent the energy broadening resultant from the low energy resolution. Various full widths at half maxima (FWHMs) were defined and assumed to be energy independent. The result for a 50 keV, energy independent FWHM modeled in MCNP6 is shown below in Fig.3. As evident in Fig. 3, the 50 keV GEB model does not account for the entire experimental energy spectrum. There are several possible sources of the discrepancies observed, these include; (i) the experimental possibility of an energy dependent FWHM value, (ii) potential recombination effects which were not accounted for in the current MCNP model, and (iii) significant photon pulse pile up in the experimental system, which would result in higher than predicted background energies.

Comparison of ACE and CINDER Delayed Neutron Production

A comparison of two identical input decks with changes in the *dnb* option in the phys:n card identified differences in the ACE (ENDF/B-VII.0) and CINDER (lib00c, Oct 2, 2000) *dnb* option outputs (which had *dnb* values of -1001 and -101, respectively). Table I shows that, whilst the same number of prompt neutrons are produced for each input file, the number of delayed neutrons per source particle differs between the ACE and CINDER outputs. A comparison of the delayed neutron temporal behavior for CINDER and ACE models also had significant variations, as shown in Fig. 4.

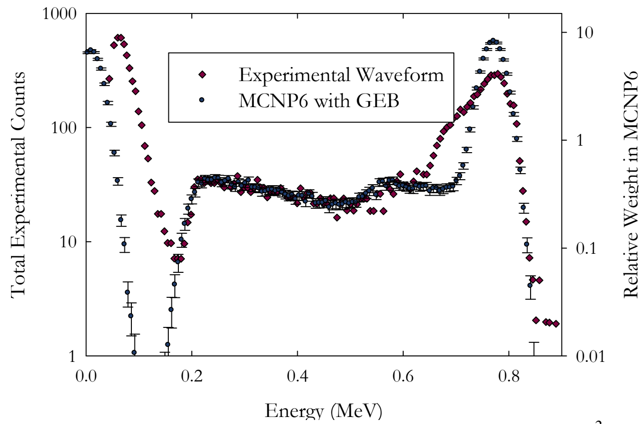

Fig. 3. MCNP6 & Measured Energy Deposition in ^{3}He Detectors

Initial Comparisons of Absolute Delayed Neutron Emission from the Irradiation of ^{235}U

Hundreds of data sets have been collected for the delayed neutron production resultant from the irradiation of ^{235}U under a variety of irradiation times, fissile content and neutron flux. Fig. 4 is a representative example of the comparison between experimental measurements for the irradiation of ^{235}U, and MCNP6 predictions using both CINDER and ACE *dnb* options. ACE model delayed neutron predictions were systematically less than observed count rates for count times up to 3 min. The temporal behavior of ACE and experimental results was consistent and the slight variations in magnitude can be attributed the previously mentioned uncertainties in DNC system efficiency. A comparison of CINDER MCNP6 output and experimentation shows a slight overestimation of delayed neutron production and a deviation in the die-away behavior at count times greater than 100 s. A direct comparison of ACE and CINDER indicates ACE was a more successful predictor of measured delayed neutron temporal behavior.

Table I. Example Delayed Neutron Emissions for ACE and CINDER Models

	ACE	CINDER
dnb option	-1001	-101
Total Prompt Neutrons	1.1e7	1.1e7
Total Delayed Neutrons	7.3e4	8.7e4

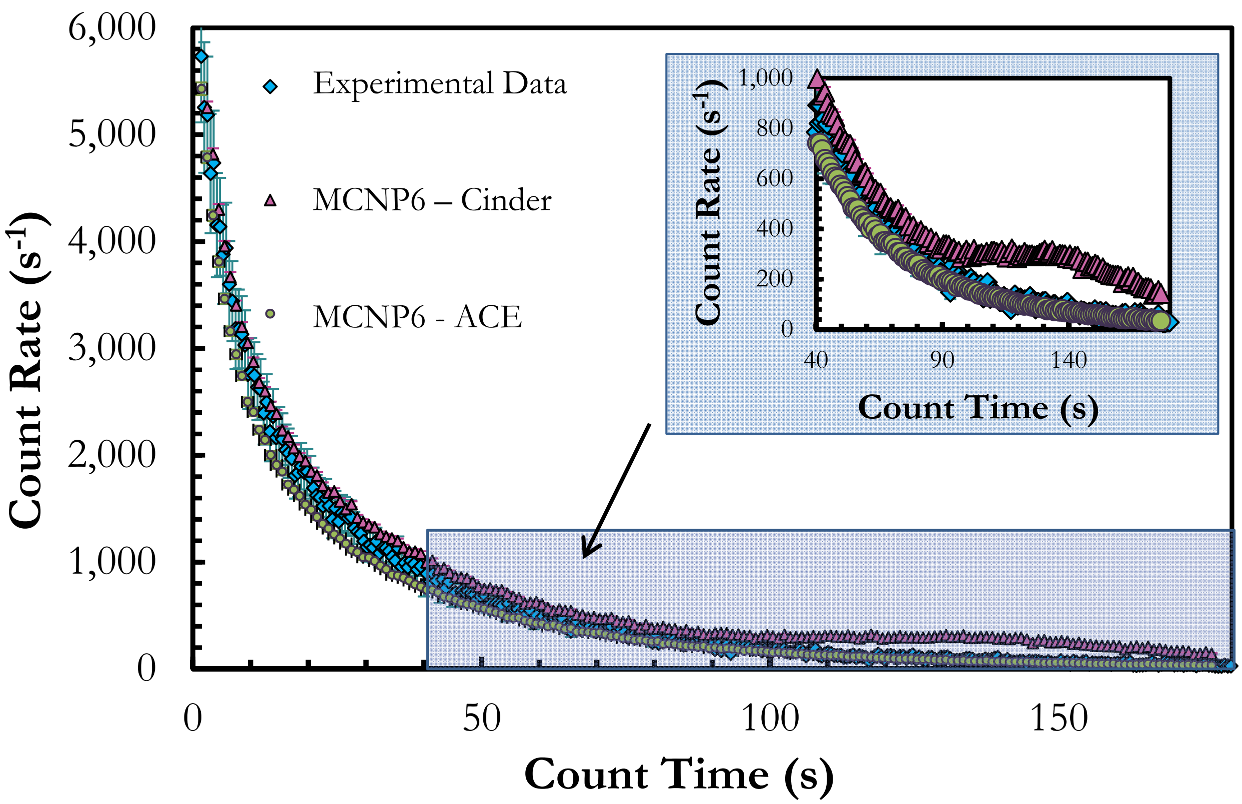

Fig. 4. Delayed Neutron Temporal Behavior: Experimental & MCNP6 Absolute Comparisons of Fission of ^{235}U

FUTURE WORK

Further experimentation and MCNP6 comparisons will include the analysis of ^{239}Pu, ^{233}U, and mixtures of the fissile isotopes ^{233}U, ^{235}U and ^{239}Pu. Proposed upgrades to DNC system hardware aim to both reduce uncertainties in delay time and shorten this delay time by decreasing the transfer time between the irradiation site and counter and by initiating counting more rapidly. These changes will also allow the examination of the delayed neutron die-away after shorter delays. MCNP6 model development will continue to explore available options pertaining specifically to the modeling of detector physics and delayed neutron production.

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