CALIBRATION OF SCINTILLATION DETECTORS USING A DT GENERATOR

Jarrod D. Edwards, Sara A. Pozzi, and John T. Mihalczo

Oak Ridge National Laboratory
Oak Ridge, TN 37831-6010 PO Box 2008 Ms6010

ABSTRACT

The Nuclear Materials Identification System (NMIS) is in use domestically for the performance of non-destructive assays of fissile material. These procedures involve the fast correlation measurement of neutrons and gamma rays from fission using organic scintillation detectors. In active measurements, an external source of neutrons is used to induce fission in the sample to be analyzed. For measurement analysis and repeatability, it is important that the detectors operate at a known neutron energy threshold and detector efficiency.

Typically, active NMIS measurements make use of a Cf-252 external neutron source. Recent efforts have studied the use of DT generators as an alternative to Cf-252 sources. DT generators use alpha detectors to time tag monoenergetic 14 MeV neutrons in a directed cone. However, since it is desirable that the detector performance be characterized over a continuous spectrum of neutron energies, the time-of-flight determination of the detector efficiency as a function of energy requires that the 14 MeV neutrons be slightly moderated to reduce the neutron energy to the region of interest.

This paper describes how scintillation detector parameters may be determined using a DT generator in conjunction with a moderator. Time-of-flight measurements are simulated using MCNP-PoliMi, a modification of the Monte Carlo transport code MCNP that simulates the detector response. Moderator configurations of varying thickness and geometry are placed adjacent to the DT generator so that the 14 MeV neutrons produced by the DT reaction are slowed down to produce a varying energy spectrum. The position of the detector with respect to the source/moderator is also varied. The simulated detector efficiencies as a function of energy associated with each source-polyethylene configuration are then compared with that produced by a Cf-252 source. These results are used to determine the near optimum DT generator-moderator configuration for detection efficiency measurements.

Using these simulations, moderating the neutrons emitted by a DT generator with polyethylene produces a softer neutron energy distribution that can be used to adequately determine the detector characteristics over the desired energy range.

Key Words: DT generator, plastic scintillator, MCNP

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INTRODUCTION

Correlation measurements are widely used to investigate attributes of unknown nuclear materials. These attributes may include mass, enrichment, or geometry. For example, the Nuclear Materials Identification System developed by the Y-12 National Security Complex and the Oak Ridge National Laboratory is in use to perform non-destructive assays of fissile materials.[1] Two methods of performing correlation measurements are available for studying materials: active and passive. For active measurements, an external neutron source is used to excite the target material. Detectors placed around the target material are used to measure radiation from the target, and the signals from these detectors are correlated in various combinations. Additionally, by placing the neutron source in an ionization chamber, or near another detector, source-detector correlations can be obtained. These correlations are then analyzed to select features of the measurements that are related to the target attributes of interest. Passive measurements are similar, but do not require the use of an external neutron source due to spontaneous fission inherent in the material.

Cf-252 sources are commonly used as the external neutron source in active correlation measurements; however, DT generators are currently being studied for use as an alternative neutron source. DT generators produce monoenergetic 14 MeV neutrons through the fusion reaction between deuterium and tritium. An alpha detector incorporated into the DT generator time tags source neutrons emitted in a user-defined cone for correlation. Figure 1 shows a photograph of an API 120 DT neutron generator used with the permission of Thermo Electron Corporation.

Figure 1: Photograph of an API 120 DT neutron generator used with permission of Thermo Electron Corporation.

For measurement analysis and repeatability, it is important to characterize certain properties of the detectors. The two parameters that are typically used in detector calibration are the neutron energy threshold (T) and the maximum efficiency (E). These parameters must be obtained using

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calibration measurements. The goal of this paper is to determine the optimal geometry, material, and setup of a time of flight measurement involving a DT generator and an organic scintillator to determine the detector efficiency and neutron energy threshold.

It is desirable for the efficiency of each detector to be characterized over a continuous spectrum of neutron energies; thus, the 14 MeV source neutrons from a DT generator must be moderated slightly for the measurements. This must be done without significant distortion of the time of flight. Figure 2 illustrates a typical detector efficiency curve determined using a time of flight measurement with a Cf-252 source.

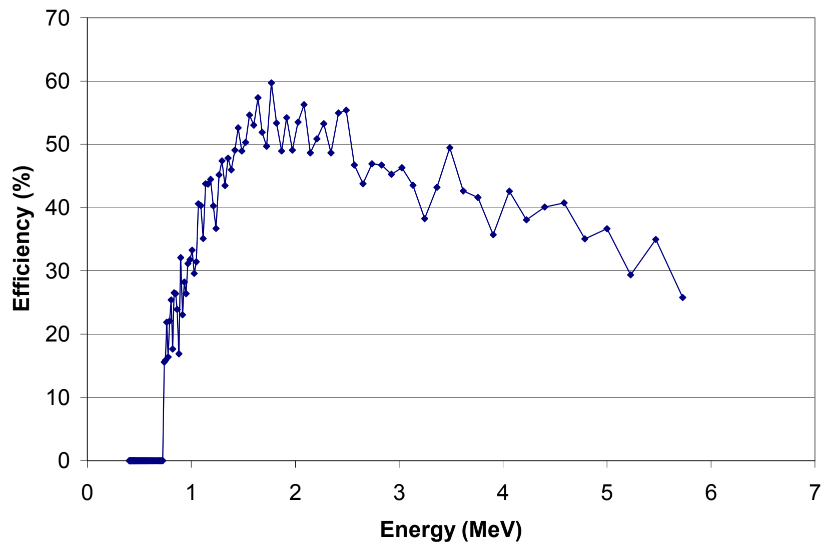

Figure 2: Typical detector efficiency as a function of energy

Two possible materials for moderating the source neutrons are polyethylene and graphite. By placing a block of one of these materials adjacent to the DT generator, the source neutrons will be slowed to produce a continuous energy spectrum that can be used for detector characterization.

SIMULATIONS

Monte Carlo methods were utilized to simulate time of flight measurements used to determine the neutron detection efficiency. Each model consists of three components: a plastic scintillator, a monoenergetic neutron source, and a block of moderating material. Two setups of the experimental equipment were modeled. In each setup the block was placed adjacent to the source, and source neutrons were directed in a cone toward the moderator to simulate the ability to time tag neutrons traveling in a directed cone using the DT generator. In the "parallel" setup, the detector was placed 100 cm from the source in line with the source and moderator, such that the source and detector were on opposite sides of the moderator. In the "perpendicular" arrangement, the detector was positioned such that the front face of the detector was centered with the left face of the moderator 100 cm from the source. Figures 3 and 4 illustrate the setups of the models.

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The scintillator was modeled using material information acquired from Saint-Gobain for the BC-420 model plastic scintillation detector.[2] The active detector dimensions are 9.5 x 9.5 x 10.16 cm. The average depth of detection is 3.3 cm.[3] In order to increase the probability of reaching the detector cell, the 9.5 cm detector dimensions were doubled in some cases to simulate a four-detector set. However, this should not alter the efficiency of the detector, which is much more dependent on detector thickness and scattering probabilities as opposed to impingent surface area. The moderating material is a small rectangular block with dimensions 5.08 cm x 5.08 cm x t cm, where t is varied from 1 – 10 cm.

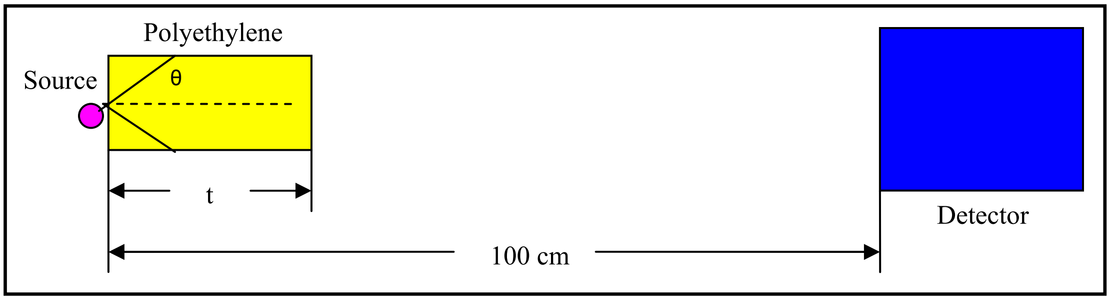

Figure 3: Sketch of the "parallel" experimental setup. The cone of the DT neutron emission is also shown.

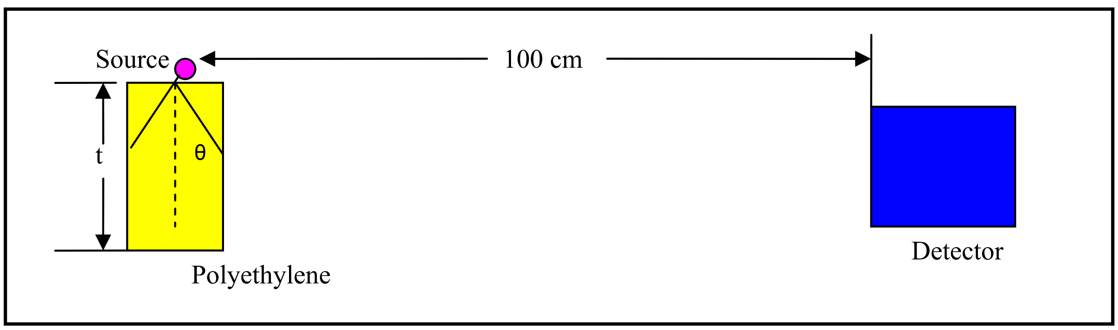

Figure 4: Sketch of the "perpendicular" experimental setup. The cone of the DT neutron emission is also shown.

The experiments were simulated using MCNP-PoliMi.[4] This code is a modification of the Monte Carlo particle transport code MCNP. MCNP-PoliMi allows the user to track all interactions between modeled particles and target nuclei within a specified cell by creating a data file that records information about each particle interaction within the cell. This data file may be postprocessed to determine neutron detection of the plastic scintillator. Cross sections used by MCNP are from ENDF-VI.

ANALYSIS

The intrinsic efficiency of the detector is defined as the ratio of the number of particles detected to the number of particles impinging on the detector. Thus, in order to calculate the efficiency of the simulated models, both of these quantities were determined independently from output generated by MCNP-PoliMi simulations.

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The number of particles detected was computed from a data file containing all interactions that occurred inside the detector cell. A postprocessing code computed the correlation between the source emission and detector response from the data file and generated a histogram of the number of particle detections correlated with source particle emission. Then, using time of flight calculations, the relationship between detected particles and particle energy was established, resulting in a histogram of detected particles binned according to energy intervals. This is valid only if the time it takes for the DT source neutron to scatter in the moderating material is small compared to the time of flight to the detector. A Monte Carlo simulation showed that this is indeed the case.

The number of particles impingent on the detector was determined using a standard MCNP energy tally. The tally tracked the number of particles that crossed the front face of the detector, and binned the results according to 140 keV energy intervals, thus establishing the spectrum of the impingent particles on the detector face. By taking this spectrum and normalizing it according to the 140 keV bin width, the neutron energy distribution was determined. Using this distribution, the number of particles impingent on the detector was obtained by interpolating the spectrum at the boundaries of the detected particle energy bins and multiplying these interpolated values by the width of the detected particle energy bins. Figure 5 illustrates the interpolation of spectrum values. This process resulted in a histogram of impingent particles which has the same bin size as that of the detected particle histogram. Finally, the ratio of these histograms could then be computed to find the efficiency with respect to energy. Figure 6 compares the calculated impingent particle time signature with that of the particles detected by the scintillator.

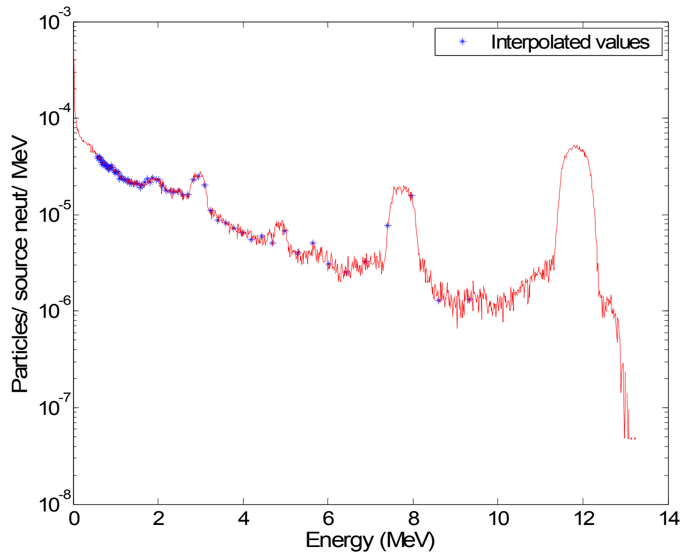

Figure 5: Illustration of the interpolation at detected energy boundaries using the impingent particle distribution for the case involving a 6 cm polyethylene moderator in a perpendicular measurement configuration.

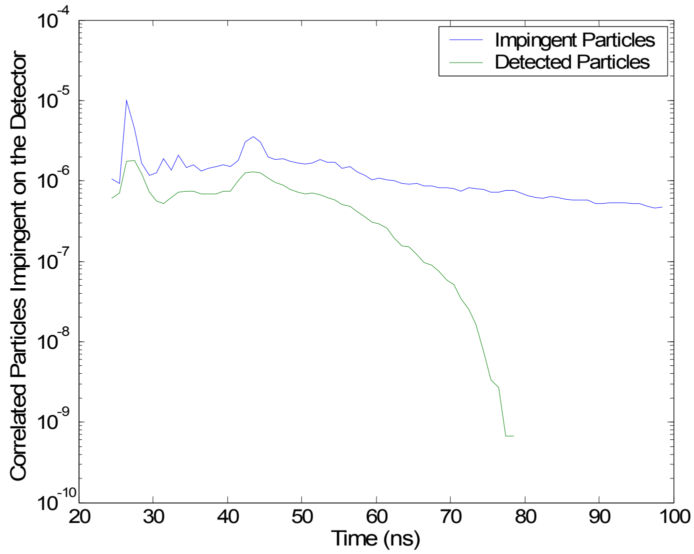

Figure 6: Comparison of particles impingent on the detector with particles detected for the case involving a 6 cm polyethylene moderator in a perpendicular configuration.

RESULTS

Three aspects of the experimental arrangement were varied in the simulations: the thickness of the moderator block, the material of the block, and the position of the detector. By studying the effect of changing each of these components in the measurement, sufficient information was gathered to determine a good configuration for obtaining the efficiency of the detector using a DT generator.

First, the thickness of the moderator block was varied from 1 – 10 cm in one cm increments. These simulations were performed using a polyethylene moderator block in a "parallel" configuration with the source and detector. The results of these simulations show that the spectra do not appear to change significantly for a polyethylene moderator thicker than 6 cm.

Furthermore, the neutron energy spectrum was tallied at a side of the moderator block in addition to the side facing the detector. From these tallies, the spectrum appears isotropic with respect to the front and sides of the polyethylene moderator at energies below 10 MeV. However, at all thicknesses in the parallel configuration, the contribution by uncollided 14 MeV neutrons is very large when compared to the contribution by lower energy neutrons. Thus, the "perpendicular" detector configuration shown in figure 4 was selected to remove this contribution from the neutron energy spectra. Figure 7 illustrates the 14 MeV peak in the neutron spectrum tallied at the detector face in parallel configuration with a 6 cm polyethylene moderator. For the perpendicular configuration, a moderator thickness of 10 cm was selected in order to maximize the number of collisions of neutrons in the moderator, thus increasing the probability of a source neutron being directed toward the detector and decreasing the required measurement time without significantly changing the resulting energy spectrum.

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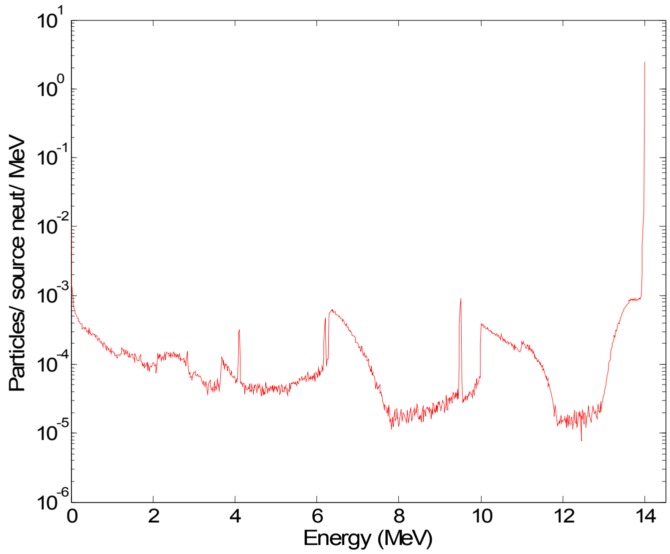
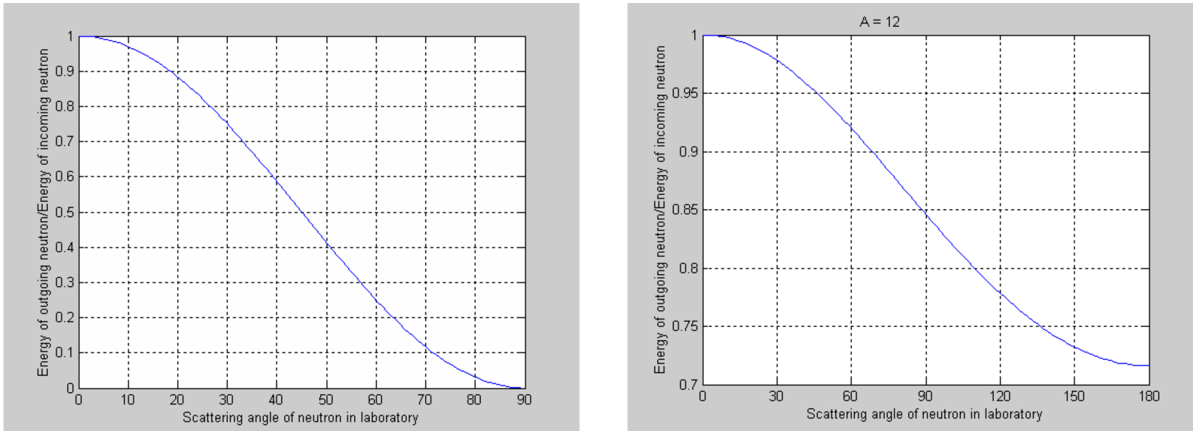


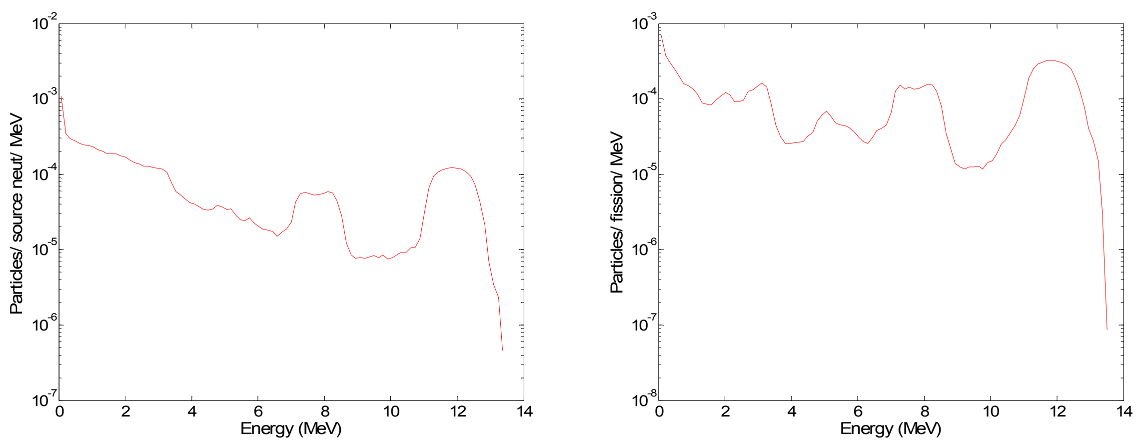
Figure 7: Neutron spectrum impingent on a detector using a 6 cm polyethylene moderator in a parallel configuration

Two moderator materials were studied: polyethylene and graphite. The primary mechanism for a DT neutron to be directed toward the detector in a perpendicular configuration with these materials is through a collision with a carbon nucleus. This results from the fact that a neutron loses all of its energy through a 90^o elastic scattering in the lab system from a hydrogen nucleus; whereas a neutron colliding with a carbon nucleus may even undergo backscattering and still retain some of its original energy. Figure 8 illustrates neutron energy loss as a function of the scattering angle in the laboratory system in an elastic scattering collision with a hydrogen and a carbon nucleus. Figure 9 shows the neutron spectra impingent upon a plastic scintillator placed in a perpendicular configuration with 10 cm blocks of polyethylene and graphite. Two prominent peaks can be observed in each of these spectra. The peak at higher energy can be explained by neutron elastic scattering on C. The energy of the outgoing neutron for a 90 degree scattering angle is 14.0*0.85=11.91 MeV. The peak occurring at neutron energy 7.5 MeV, approximately, can be explained by 1^{st} level inelastic scattering. The cross sections for these two reactions are 0.82 b for elastic scattering and 0.48 b for inelastic scattering (En=14 MeV). Figure 10 shows the calculated efficiency curves for these cases in addition to a reference curve calculated from a simulation of a standard time of flight measurement with Cf-252. This curve was used as a basis of comparison for the curves developed from simulations involving the DT neutrons. In each curve, the expected detector efficiency and threshold are indicated. Neutron energy threshold can be determined by linearly fitting the rising edge of the efficiency curve and determining the intercept of that curve with the energy axis.



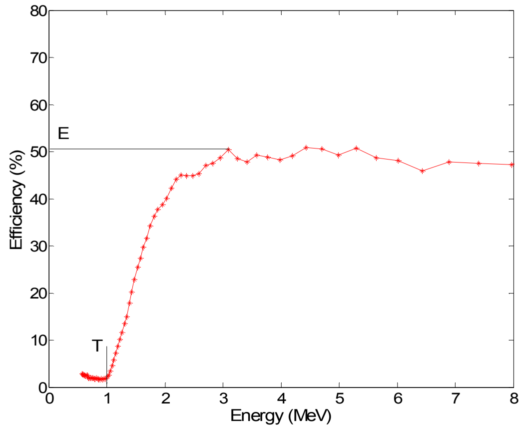
(a) (b)

Figure 8: Illustration of fractional neutron energy loss with respect to scattering angle as a result of a collision with a) a hydrogen atom and b) with a carbon atom.

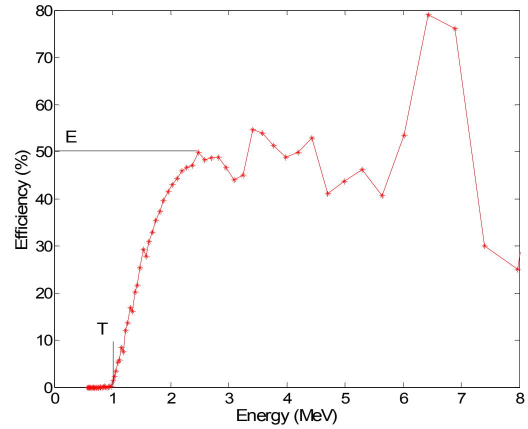


(a) (b)

Figure 9: Neutron spectra impingent on the detector for a perpendicular configuration using an a) 10 cm polyethylene moderator and b) a graphite moderator.



(a)



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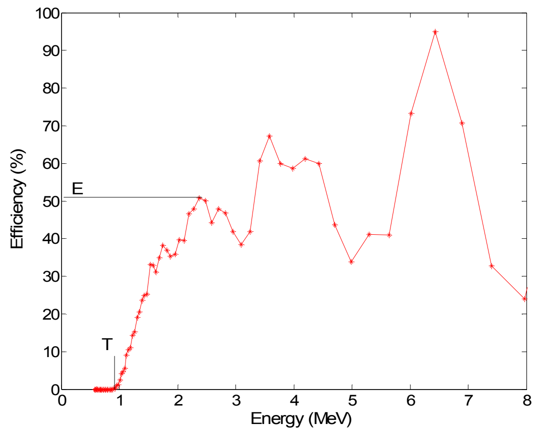

(c)

Figure 10: Illustration of detector efficiency calculated using a a) standard time of flight measurement with Cf -252, b) a perpendicular detector configuration 10 cm graphite moderator and c) a perpendicular configuration using a 10 cm polyethylene moderator.

Figure 10 ((a)-(c)) shows that it is possible to obtain the energy threshold T and efficiency E on the basis of the efficiencies obtained with both the graphite and the polyethylene moderator. However, the region between 6 and 7 MeV is anomalously large, possibly due to the aforementioned peaks in the neutron spectrum due to carbon. This hypothesis is confirmed by the fact that this peak is more pronounced in the curve associated with the graphite moderator, which has a much higher number density of C than the polyethylene. This phenomenon may also be explained by poor energy resolution at large energies due to the one nanosecond time binning of the postprocessor.

The detector count rate can be determined from the time correlation signature of the measurement with polyethylene. First, the histogram of correlated counts per source particle must be integrated over the entire time-lag range to calculate the total number of counts per source particle. To find the number of source particles directed in the cone, the maximum DT generator intensity, 10^8 neutrons/sec, is multiplied by the solid angle of the cone and divided by 4π. Then, knowing the total number of detections per source particle, and the total source particle intensity, the detector count rate is calculated to be approximately 1800 neutrons / sec. This corresponds to a total measurement time of approximately 40 seconds to achieve the statistical accuracy of the simulation.

CONCLUSION

The efficiency and neutron energy threshold of a plastic scintillator can be determined by using time of flight methods with a DT generator and a polyethylene moderator. The dimensions for the moderator are 5.08 x 5.08 x 10.0 cm. The measurement setup is to place the moderator directly in front of the aperture of the DT generator and the detector 100 cm from the aperture at a 90^o angle from the source/moderator. The time required for this measurement is approximately 40 seconds for a DT generator intensity of 10^8 neutrons/sec.

Additional recommended work includes the study of additional moderator materials, such as H_2O. It may also prove beneficial to study the placement of the detector at other angles from the DT source and moderator assembly or to reduce the time intervals established by the postprocessor to 0.1 ns time bins.

REFERENCES

1. J.T. Mihalczo, J.A. Mullens, J.K. Mattingly, and T.E. Valentine, "Physical Description of Nuclear Materials Identification System (NMIS) Signatures", Nuclear Instruments and Methods in Physics Research Section A 450, pp. 531 (2000).

2. Saint-Gobain Crystals and Detectors, Inc., "Scintillation Products", Newbury, OH, ©2001

3. S.A. Pozzi, J.A. Mullens, and J.T. Mihalczo, "Analysis of Neutron and Photon Detection Position for the Calibration of Plastic (BC-420) and Liquid (BC-501) Scintillators," Nuclear Instruments and Methods in Physics Research Section A, in press.

4. S.A. Pozzi, E. Padovani, and M. Marseguerra, "MCNP-PoliMi: A Monte Carlo Code for Correlation Measurements," Nuclear Instruments and Methods in Physics Research A, 513/3 pp. 550-558, 2003.