Analysis of Neutron Reflection in Correlation Measurements

Jarrod D. Edwards, John K. Mattingly, and Sara A. Pozzi

Oak Ridge National Laboratory
P.O. Box 2008 MS-6010, Oak Ridge, TN 37831-6010

ABSTRACT

Nuclear Materials Identification System (NMIS) procedures that rely on the fast correlation measurement of neutrons and gamma rays from fission are in use at the Y-12 National Security Complex and elsewhere. In active measurements, an external source of neutrons is used to induce fission in the sample to be analyzed. Typically, a Cf-252 source inside an ionization chamber is used. Previous studies and measurements showed that the environment, primarily the proximity of the floor or a wall to the instruments, affects the measured signatures.

In this paper, we present an analysis of neutron reflection based on a large number of simulations performed with the MCNP-PoliMi code. The simulations were performed for the time-of-flight configuration. The Monte Carlo program and its post-processor allow us to partition the total signature into the 'direct' and 'scattered' components. The 'direct' component consists of uncollided neutrons and gamma rays traveling from the source to the detector. The 'scattered' component is composed of particles that were reflected from the floor. The aim of this paper is to identify and quantify the latter component.

The analysis of the data consisted of a search for an empirical fitting curve for the 'scattered' component of the signature. The fitting curve depends on a number of parameters that are mainly related to the geometry of the setup. The results show that the fitting procedure was able to model floor reflection with good approximation for the range of cases considered. Equations have been developed that approximate the neutron floor reflection and can be used in applications to calculate the floor reflection component so that it may be removed from the measured signatures.

INTRODUCTION

The Nuclear Materials Identification System (NMIS) is useful for many applications involving fissile materials, including identifying and quantifying such materials for nuclear materials control and accountability [1]. NMIS procedures that rely on the fast correlation measurement of neutrons and gamma rays from fission are in use at the Y-12 National Security Complex and elsewhere.

NMIS has two interrogation modes: active and passive. For active measurements, a Cf-252 source provides an external source of neutrons, which excite the target material. Two or more detectors, located near the material, acquire gamma and neutron radiation. In passive measurements, the Cf-252 source is omitted and spontaneous fission within the sample itself acts as the neutron source. Each NMIS measurement produces a time domain signature obtained from cross correlation between the detectors and the Cf-252 ion chamber, if present.

Radiation reaches the detector either by direct transmission from the source, source particles scattered from the environment, or from induced fission within the target material. Measurements have shown that the presence of particle reflection from the surrounding floor and walls complicates measured signatures. The goal of this paper is to identify and quantify the neutron reflection component of the measurement signatures from the floor. Analysis of photon reflection will be extended in a future study. Figure 1 shows a typical NMIS signature wherein the area following the dashed line is the discernible contribution due to reflection. The rest of the contribution is combined with the direct neutron contribution immediately to the left of the dashed line.

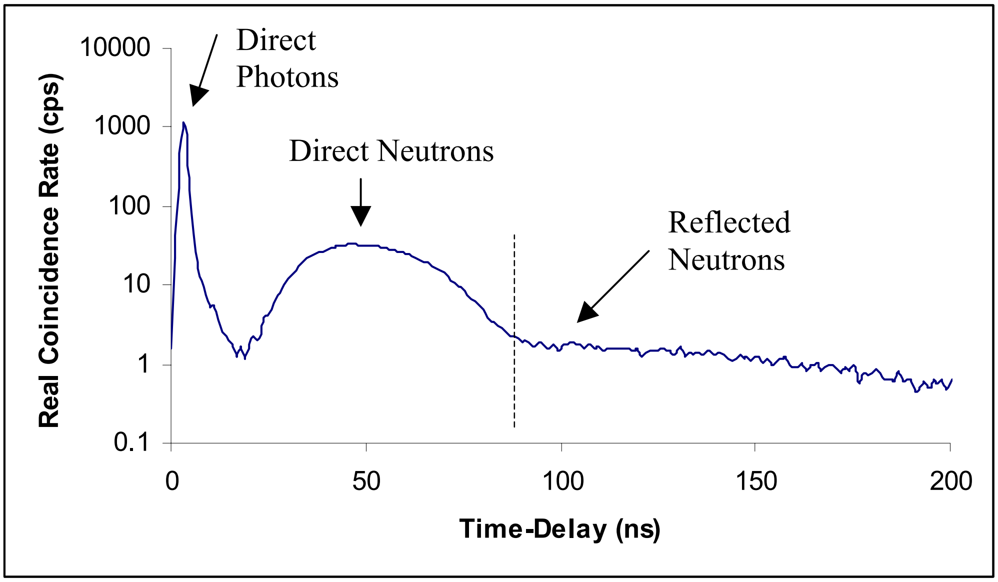


Figure 1: Example NMIS signature.

Because physical experiments are both time consuming and not readily quantifiable, simulations of experiments were performed using Monte Carlo methods. The experimental setups modeled were time of flight experiments using a Cf-252 source and one plastic scintillation detector wherein the distance between the source and detector and the height of the source-detector pair from the floor were varied. The simulations were processed and analyzed using Matlab™. This analysis was used to develop look-up tables and equations which approximate the contribution of neutron floor reflection to an NMIS signature. In this paper, a comparison of the model formed by the equations with the results of the simulations is presented. Finally, the model is compared with laboratory results.

SIMULATIONS

Experiments modeled were time of flight experiments using a Cf-252 source and one plastic scintillation detector. The source was positioned in line with the center of the detector face perpendicular to the floor. The distance, d, between the source and the detector was varied between 10 and 100 cm in 10 cm increments, and the height, h, of the source/detector pair was varied between 5 and 45 cm in 10 cm increments. The height of the detector was measured from the center of the vertical detector face. This established a matrix of 50 physical arrangements for simulation. Figure 2 illustrates the setup of the experiments.

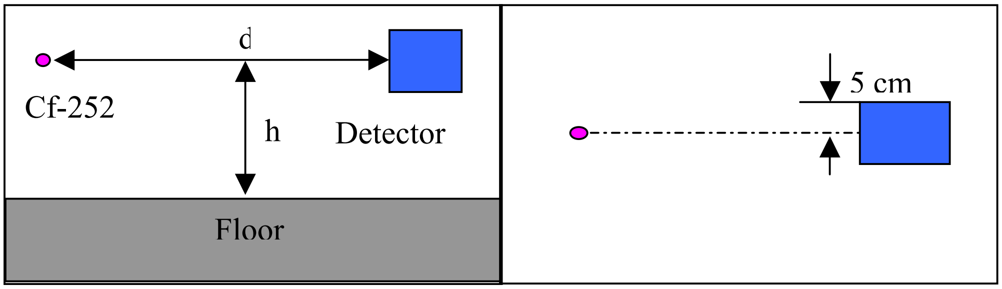


Figure 2: Sketch of geometry used in the simulations

The experiments were simulated using MCNP-PoliMi [2,3]. This code is a modification of the Monte Carlo particle transport code MCNP that enhances the realism of MCNP. In particular, MCNP–PoliMi samples neutron collisions types before performing secondary gamma generation. This is not the case in standard MCNP, where neutron collision and secondary gamma generation are uncorrelated. MCNP-PoliMi also has other features, such as the inclusion of fission sources as source particles, allowing the user to specify a number of fission events to be modeled as opposed to a specified number of neutrons or photons. Furthermore, 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. Cross sections used by MCNP are from ENDF-V and ENDF-VI.

The scintillator was modeled using material information acquired from Saint-Gobain for the BC-420 model plastic scintillation detector [4]. The active detector dimensions are 10x10x10 cm.

For typical NMIS measurements, the item being investigated, or the target, is located between the source and the detector. Thus, it is conceivable that neutrons reflected from the floor could collide with the target and scatter to the detector consequently increasing the contribution of the floor to the measurement signature. However, this contribution is assumed to be negligible because the compounding probabilities of a neutron scattering from the floor to the target, then from the target to the detector is sufficiently small to be ignored. Also, the target will likely contain neutron absorbers which will further decrease the likelihood that a neutron scattering from the floor to the target would reach the detector. Consequently, by eliminating the item of investigation from the simulations, the complexity of the simulations is decreased, and the applicability of the study is increased to include all target materials without a significant increase in error.

ANALYSIS

There were two goals of the analysis of the MCNP-PoliMi data files. The first was to develop a time dependent shape function, which characterizes the shape of the floor reflection component of an active NMIS signature at a given time. This function is independent of the distance between the source and the detector, the height of the source-detector pair from the floor, and the neutron energy threshold of the detector. The second goal was to develop equations that could be used to adjust the shape function to fit the reflected component of a specific case signature. The characteristics that these equations approximate are the amplitude, mode, and full width at tenth maximum (FWTM) of the floor reflection component of the signature for a particular distance, height, and detector threshold.

Analysis of the data output from MCNP-PoliMi was performed using a postprocessor program developed in Matlab™. These data output files are a collision history for each particle that enters the detector cell. The postprocessor used the collision histories to separate the contributions to the detector response by neutrons that traveled directly to the detector from those that scattered from the floor. In addition, to model the detector response more accurately, the postprocessor converted energy depositions into light outputs, and ignored neutrons generating a light output lower than a user-specified threshold. The final output from the postprocessor included a time dependent histogram of the fraction of neutrons that arrived in the detector cell after having collided with the floor.

Each of the 50 simulations was postprocessed using 10 different neutron energy thresholds, 0.6 MeV to 1.5 MeV in 0.1 MeV increments. The resulting 500 cases were averaged using a 7 point floating average, and the amplitude (A), mode (m), and full-width at tenth maximum (w) was determined for each case. The histograms were then normalized using the following relationships:

(1) $\tilde{t} = \dfrac{t - m}{w}$

(2) $\tilde{y} = \dfrac{y}{A}$,

where t is the time bin, y is the fraction of neutrons from a given source fission arriving at the detector within time bin t, and $\tilde{t}$ and $\tilde{y}$ are the normalized t and y values, respectively. The result of this transformation was to give each an amplitude, mode, and full-width at tenth maximum of 1, 0, and 1, respectively. Figure 3 illustrates this normalization.

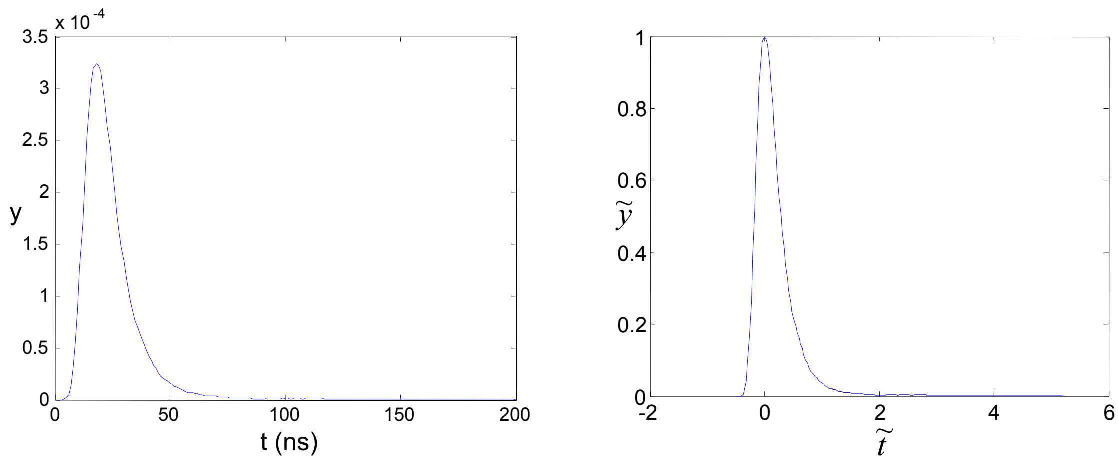


Figure 3: Normalization of the curves for the case d=10cm, h=5 cm, T=0.6 MeV

Next, the 500 resulting curves were combined to form one average, normalized histogram, which was used to determine the coefficients a, b, and c in the shape function, given by:

(3) $\tilde{y} = \exp\left(\frac{-(4\tilde{t})^2}{a\tilde{t}^2 + 2b\tilde{t} + c}\right)$

Using the shape function and the 500 normalized curves, the optimum amplitude, mode, and full-width at tenth max of the shape function was determined for each combination of distance, height, and threshold. Both the shape curve coefficients and case specific characteristics were determined using unconstrained nonlinear optimization. The amplitude, mode, and FWTM of the actual (non-normalized) curves were determined using the following relationships:

(4) $A = A_0 A'$

(5) $m = w'm' + m_0$

(6) $w = w_0 w'$

where A_0, m_0, and w_0 are the original amplitude, mode, and FWTM, respectively, and A', m', and w' are the optimized amplitude, mode, and FWTM of the shape function. These optimizations were performed recursively until the minimum cumulative error between the model and the simulated data was found.

In calculating the amplitude of the reflection curve, the dependence on distance (d) and height (h) may be reduced to the dependence on a single variable, reflection distance, which is the length of the path that a reflected neutron traveled. The reflection distance is calculated as follows:

(7) $R = 2\sqrt{\left(\frac{d}{2}\right)^2 + h^2}$

After making this substitution, the trend of the amplitude as a function of reflection distance is exponential. This is improved using a quadratic term in the exponential expression. In order to account for dependence on threshold, each coefficient in the quadratic term is substituted for a linear term dependent on threshold (T). Thus, the final equation for the amplitude of the reflection curve is:

(8) $A = \exp\left[(a_{00}T + a_{01})R^2 + (a_{10}T + a_{11})R + (a_{20}T + a_{21})\right]$

The trends for the mode and FWTM of the reflection curve are best fit using equations having a system of nested linear terms. Accordingly, the equation for the mode is linearly dependent on distance. The coefficients of this equation are each linearly dependent on height, and each of the coefficients in those expressions are linearly dependent on threshold. Therefore, the equations for mode and FWTM, respectively, are as follows:

(9) $m = \left[(b_{000}T + b_{001})h + (b_{010}T + b_{011})\right]d + (b_{100}T + b_{101})h + b_{110}T + b_{111}$

(10) $w = \left[(c_{000}T + c_{001})h + (c_{010}T + c_{011})\right]d + (c_{100}T + c_{101})h + c_{110}T + c_{111}$

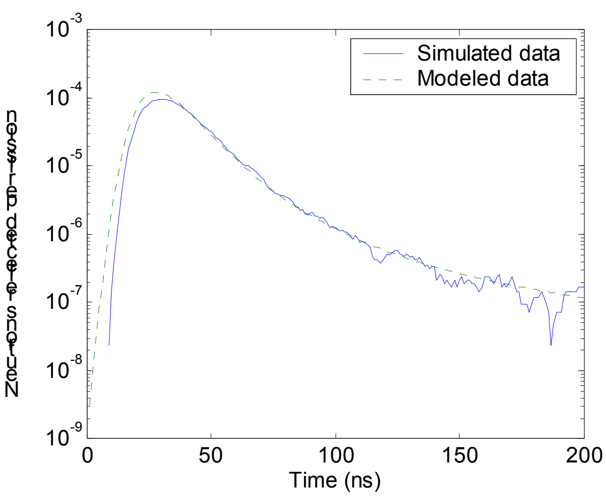
The optimized values of the coefficients in the shape function are: a = 1.6679, b = 0.9997, and c = 1.0859. Optimized values for the other equations are given in table 1.

Table 1: Coefficients for amplitude, mode, and FWTM model equations

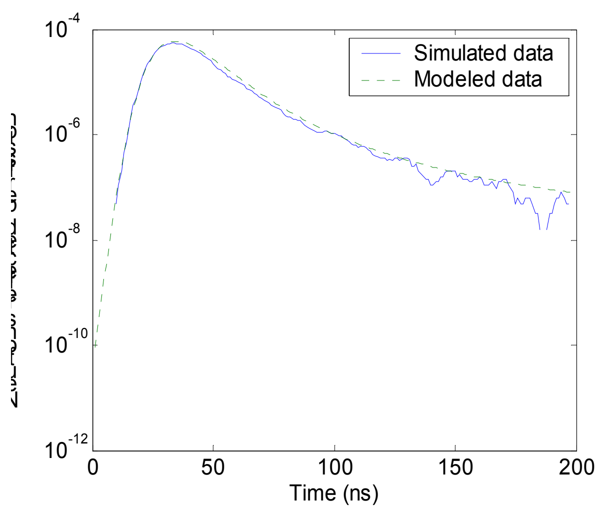
Amplitude		Mode		FWTM	
a_{00}	-2.7348E-05	b_{000}	7.87E-05	c_{000}	0.00323
a_{01}	1.9533E-04	b_{001}	-0.00364	c_{001}	-0.00422
a_{10}	5.0059E-03	b_{010}	-0.08395	c_{010}	-0.23623
a_{11}	-0.06450	b_{011}	0.49534	c_{011}	0.57201
a_{20}	-1.16266	b_{100}	-0.19358	c_{100}	-0.59150
a_{21}	-6.54230	b_{101}	1.23573	c_{101}	1.82940
		b_{110}	-2.07568	c_{110}	-2.20298
		b_{111}	8.56378	c_{111}	22.77148

RESULTS

A model of the contribution of neutron reflection by the floor to NMIS signatures has been developed. This model consists of a time-dependent function that characterizes the shape of the curve and three other functions which adjust the amplitude, mode, and full width at tenth max of that curve according to the distance between the source and the detector, the height of the source detector pair, and the energy threshold at which the detector is set. The model developed using the fitting procedure provided a good approximation to simulated results. Figures 4 and 5 illustrate this approach for a few cases throughout the ranges covered.

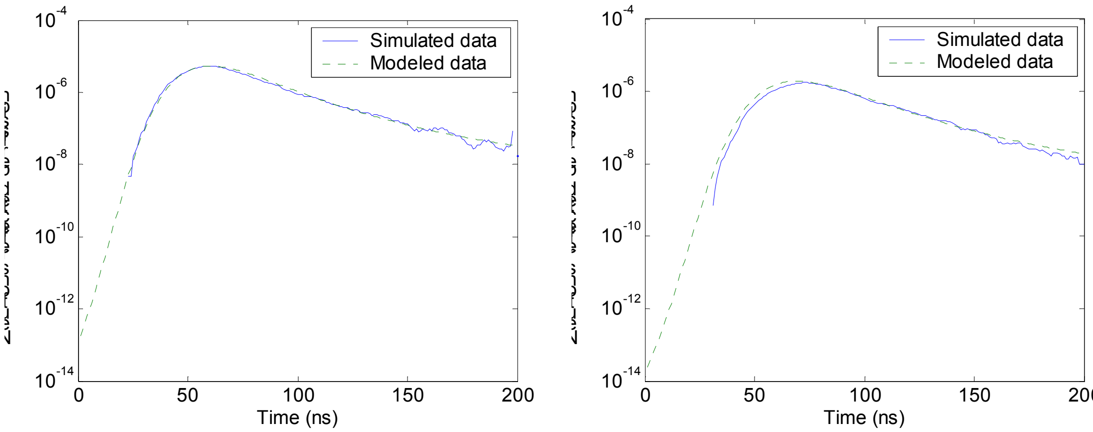


(a)



(b)

Figure 4: Comparison of data with model for: (a) d=10 cm, h=15 cm, and T=0.6 MeV, and (b) d=30 cm, h=15 cm, and T=0.8 MeV



(c) **(d)**

Figure 4 continued: Comparison of data with model for: (c) d=70 cm, h=35 cm, and T=1.2 MeV, and (d) d=100 cm, h=45 cm, and T=1.5 MeV

Figure 5 illustrates how the model compares with an NMIS measurement. Because in the experiment we are unable to partition the signature into its 'direct' and 'scattered' components, the fitting uses the reflection models developed here in conjunction with direct models previously developed to fit both components simultaneously. At early times the shape function, Equation 3, results in small corrections that are not physical. Alternatives to Equation 3 are under investigation to eliminate those early time contributions.

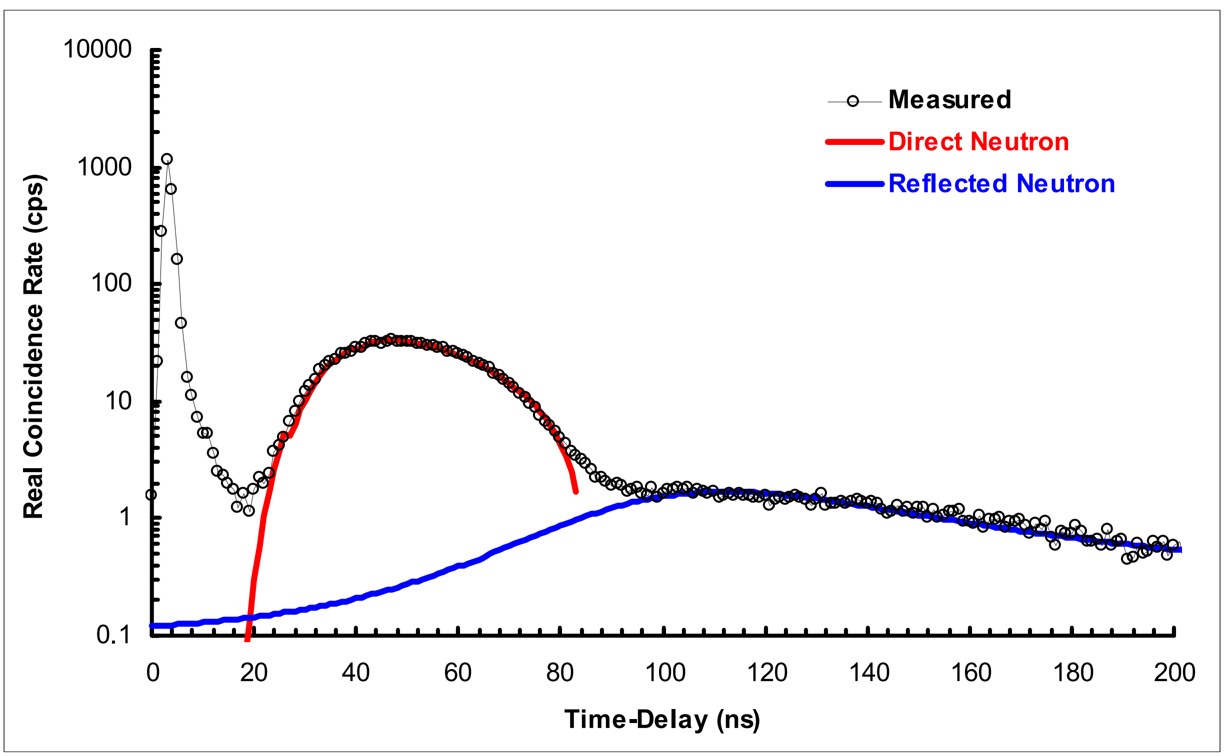


Figure 5: Comparison of model with NMIS laboratory measurement

CONCLUSION

The portion of an NMIS signature due to neutron reflection from the floor may be adequately quantified using Monte Carlo methods. Equations have been developed that approximate this contribution well. These equations, as well as the tables of amplitudes, modes, and FWTMs used to develop them, are currently being used in applications to calculate the floor reflection component so that it may be removed from measured signatures. In this application, a previously developed model which approximates the 'direct' neutron component is used to determine the efficiency and threshold of the detector. Then, using the Hooke-Jeeves algorithm, the 'direct' and 'reflected' components are optimized simultaneously.

The floor reflection model may be modified for the use of a liquid scintillator instead of a plastic scintillator. Also, additional simulations were performed which demonstrated that the results do not change significantly depending on the type of concrete used in the measurement. There are, however, some limitations to this study, which future work could improve upon. An adjustment needs to be made so that, for early times, reflected neutrons are not calculated which could not physically have occurred. The model is further limited by the fact that the external source must have the same neutron angular and energy distribution as Cf-252. Also, the model could be improved by accounting for the detector response to photon reflection and secondary photon generation.

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