ANALYSIS OF SCINTILLATOR PULSE-HEIGHT FOR NUCLEAR MATERIALS IDENTIFICATION

James A. Mullens, Jarrod D. Edwards*, and Sara A. Pozzi
Oak Ridge National Laboratory
P.O. Box 2008, MS-6010, Oak Ridge, TN 37831-6010

ABSTRACT

We describe the application of a Monte Carlo code for the simulation of active correlation measurements performed on uranium spheres of varying mass and enrichment. The measurements are performed on uranium metal using a DT neutron generator as the interrogation source, and a scintillation detector. The simulation is able to keep track of the neutron time of arrival, the pulse height, and the incident neutron energy. We show how this information can be used to determine the uranium mass and enrichment with increased sensitivity compared to previously studied methods.

INTRODUCTION

Passive and active measurements performed with organic scintillators have been shown to have a wide range of applications in nuclear nonproliferation, international safeguards, nuclear material control and accountability, national security, and counter-terrorism programs. One current measurement technology, the Nuclear Materials Identification System [1], employs organic scintillators to detect neutrons and gamma rays emitted by fissile material configurations. In the current setup, the pulses from the detectors generate signatures that have been shown to be related to the properties of the fissile material under investigation.

In this paper, we investigate the possibility of using the detector pulse heights to obtain information on the fissile assembly. The pulse heights from the scintillator are related to the energy deposited by the incident particles, and thus convey information about the incident energy spectrum. The energy spectrum is related to the characteristics of the fissile assembly: for example, it is possible to distinguish fissile metal from oxide. Figure 1 illustrates the difference in the shape of the neutron energy spectra escaping uranium metal spheres of varying mass and enrichment.

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* On research assignment at Oak Ridge National Laboratory

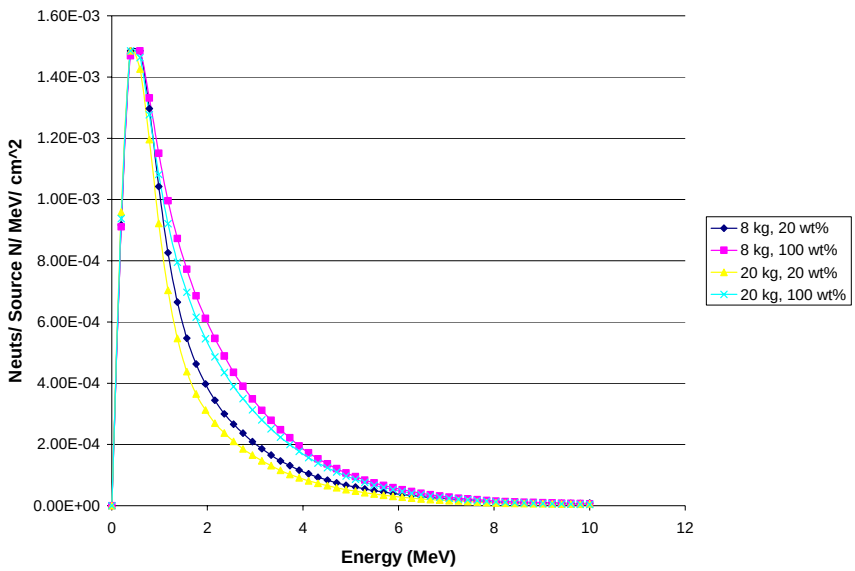


Figure 1. Comparison of the neutron leakage spectra from uranium spheres of varying masses and enrichments.

We present a number of Monte Carlo simulations of a typical measurement setup, consisting of an interrogation source, a uranium metal sphere of varying mass and enrichment, and a plastic scintillator. A specifically developed simulation code is used to determine the pulse heights generated in the detectors and store them as a function of time following the originating DT neutron event. The resulting signatures are analyzed and prominent features are identified. The proposed method based on the pulse-height analysis is an enhancement to current measurement methodologies that will lead to the acquisition of signatures that are more sensitive to the properties of the fissile assembly.

MONTE CARLO SIMULATIONS

The MCNP-PoliMi code [2] was used to simulate the time-correlation measurements performed on uranium metal spheres of varying mass and enrichment. Mass varied from 8 to 20 kg and enrichment varied from 0.2 to 100 wt%. Figure 2 shows a schematic drawing of the configuration for the simulations.

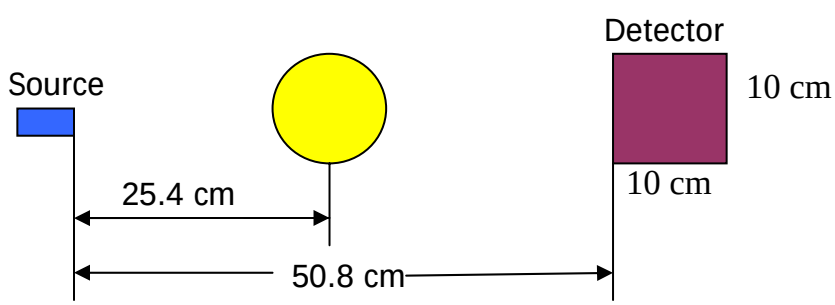


Figure 2. Schematic drawing of measurement setup in MCNP-PoliMi.

In this measurement setup, the 14.1 MeV neutrons from a DT neutron source are used to induce fission in the uranium metal sample. It is assumed that the time of emission of the DT neutron is known by use of an associated particle detector, which detects the alpha particle that is emitted together with the neutron by the DT reaction. This technique provides the trigger pulse for the correlation measurement as well as information on the direction of the outgoing neutron. Using the alpha particle detector, the time trigger can occur only with the DT neutrons that are emitted in a user-specified cone. In the simulations, this cone had an angle of 10.5 degrees and was directed towards the center of the uranium sphere. The detector modeled was a plastic scintillator having dimensions 10 cm x 10 cm x 5 cm.

Figure 3 shows a source-detector correlation for the 14 kg, 60 wt% enriched uranium sphere. The detections that occur in the scintillation detector have a well-defined time characteristic. The first particles to arrive at the detector following the emission of the source neutrons are the gamma rays from induced fission and inelastic scattering in the uranium sample. These gamma rays arrive on the detector approximately 8 ns following the DT neutron event. Then, the direct neutrons from the DT source are detected in the peak at 11 ns. The induced fission neutrons form the third, broad peak at times 15 to 70 ns. This peak also includes source neutrons scattered from the uranium sphere.

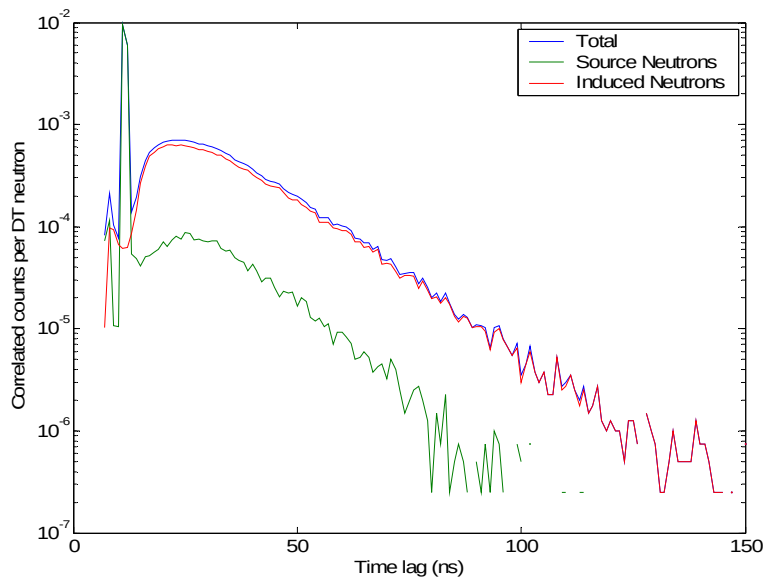
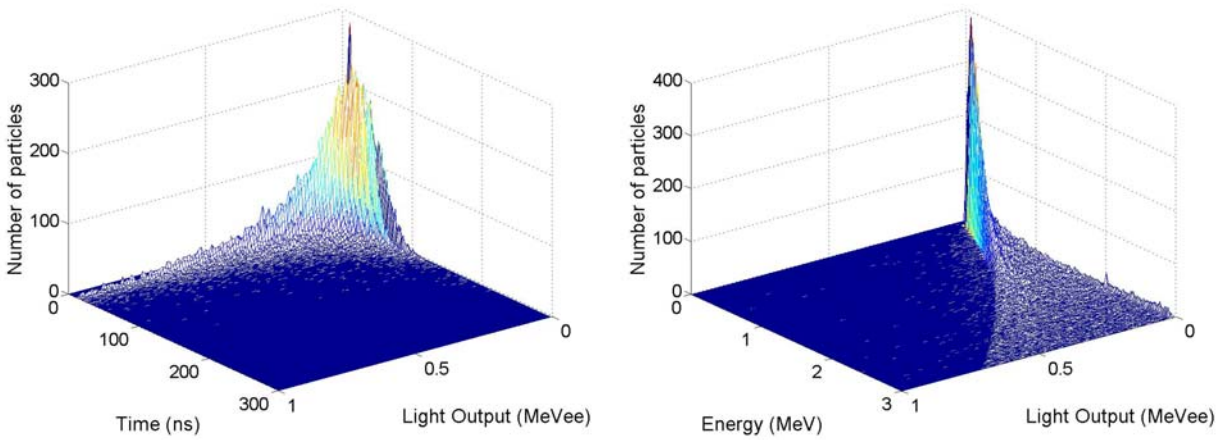


Figure 3. Correlation signature determined by simulating active interrogation of a 14kg, 60% enriched U sphere.

The correlation shown in Figure 3 was obtained with the MCNP-PoliMi code and its post-processor. The MCNP-PoliMi data output is described in Reference 2. The data output contains information on the collisions occurring in the detector cell. This information must be post-processed to obtain the detector response. A specifically modified code was used to determine the quantities of interest in this study: energy of the incident particle, pulse amplitude, and time of detection. The latter two quantities, pulse amplitude and time of detection, are measurable in an experiment. The pulse amplitude is related to the energy of the incident particle by the detector response matrix [3].

In addition to the correlation signature, we analyzed the data for induced neutron events for all uranium metal samples. The results can be displayed in two matrices: one representing the number of induced neutron events recorded as a function of energy and pulse amplitude, and the other representing the number of induced neutron events recorded as a function of pulse amplitude and time of detection. An example of these two matrices is shown in Figure 4 for the 14 kg, 60 wt% enriched uranium sample. This figure illustrates that the number of induced neutron events has a peak near the origin and decreases with respect to both time and light output as well as to energy and light output.



(a) (b)

Figure 4. Induced neutron events in the detector as a function of:
(a) Time and pulse amplitude and (b) Energy and pulse amplitude

ANALYSIS

The goal of the analysis was to obtain the mass and enrichment of the uranium metal spheres on the basis of the features extracted from the measured time vs. light output matrix (Figure 4a) and the correlation signature (Figure 3). By analyzing selected features from the simulated measurements, a model may be developed to accomplish this goal.

The first feature selected was the volume of the peak in the measured time vs. light output matrix, V. This volume is determined by adding the matrix cells that are greater than a given threshold. Figure 5 illustrates the variation of this peak with respect to both mass and enrichment. The volume of this peak increases with enrichment for all masses. It increases with mass for enrichments greater than 20 wt.%. Both effects can be explained by considering the neutron multiplication in the sample: multiplication increases with mass and with enrichment.

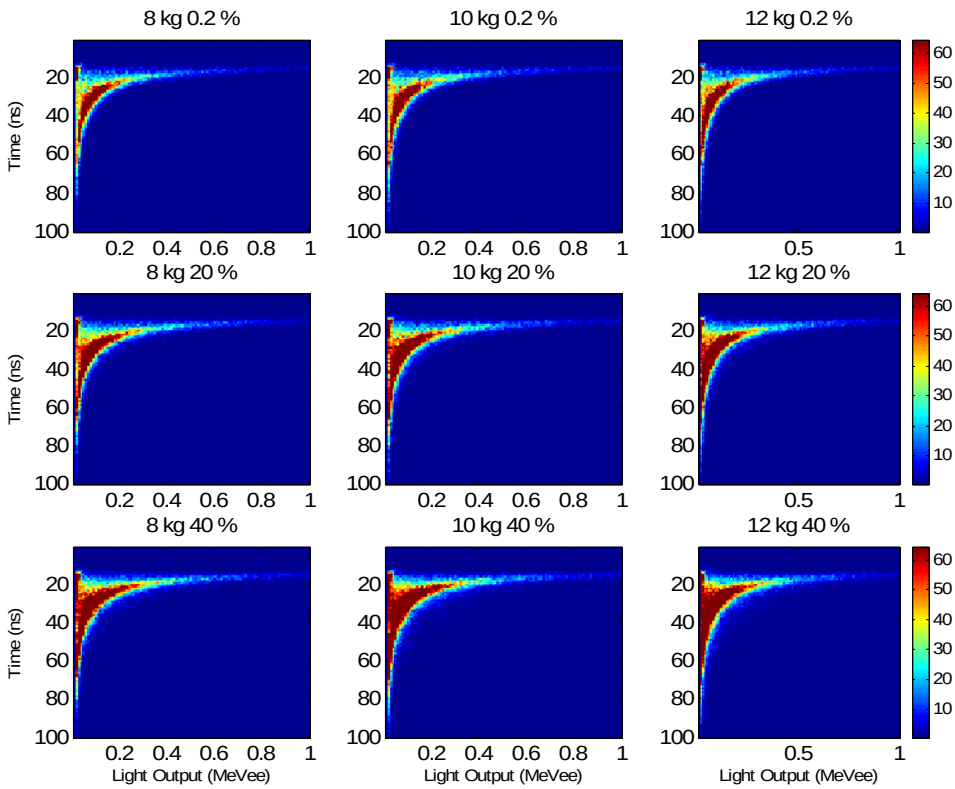


Figure 5. Neutron events as a function of time and light output for various combinations of mass and enrichment

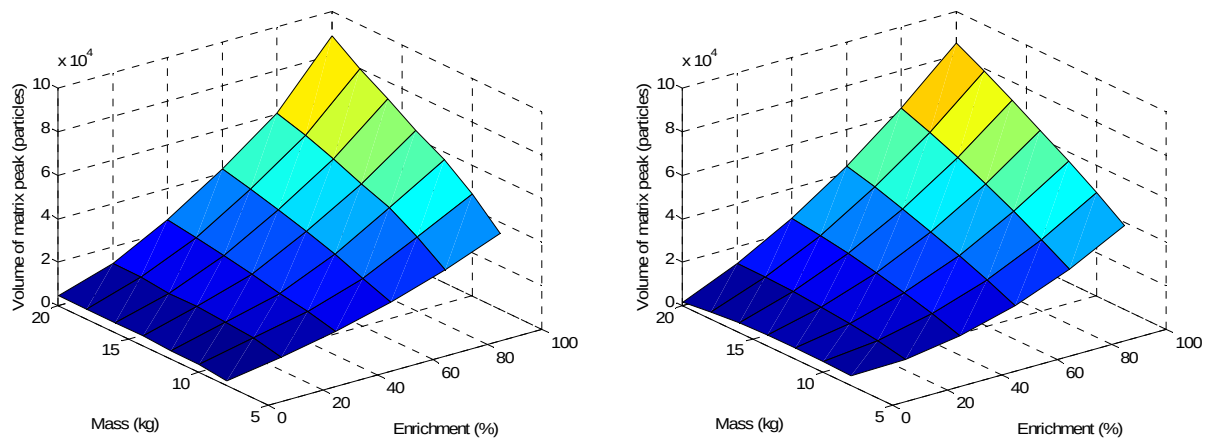
The volume of this peak is more sensitive to changes in enrichment than a previously studied method, which involved integrating the "induced" neutron peak. Table 1 shows this increased sensitivity by comparing the ratios of the feature at 100 wt.% enrichment to the feature at 0.2 wt.% enrichment for both the integral of the "induced" peak and the volume of the time/pulse height matrix peak.

Table 1. Comparison of the sensitivity of the integral of the neutron peaks with that of the volume of the time/pulse height peak using the ratios of the respective values at 100 wt.% to the values at 0.2 wt.%.

Mass (kg)	Ratio of integral of "induced" peaks	Ratio of volumes of matrix peak
8	2.04	15.42
10	2.26	13.26
12	2.49	15.01
14	2.73	14.01
16	3.02	16.53
18	3.31	17.32
20	3.64	19.31

The volume of the peak of the time/pulse height matrix may be approximated by Equation (1), which was determined using multiple least square regression (MLSR) techniques and has a corresponding adjusted R^2 value of 0.996. Figure 6 illustrates the comparison between the simulated volume data and the results of Equation (1).

$$\widehat{V} = -2610 + 1294M - 53.86M^2 - 367.2E + 3.757E^2 + 41.55ME \qquad (1)$$

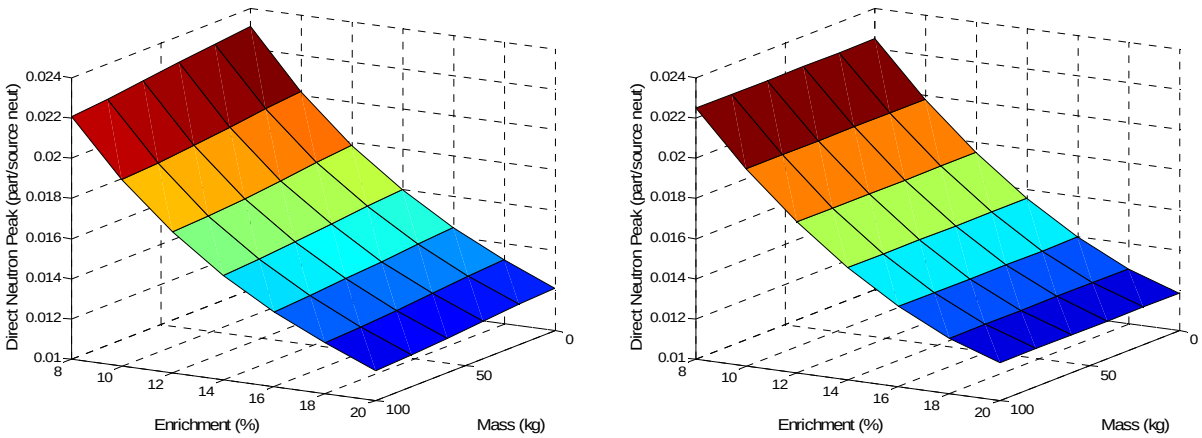


(a) (b)

Figure 6. Comparison of the (a) measured values of the volume of the matrix peak with (b) values of the volume calculated using Equation (1).

The second feature selected was the integral of the direct source neutron peak in the correlation signature, N. This is equal to the total number of uncollided neutrons detected. This feature tends to decrease quadratically with mass. This can be approximated by Equation (2), which was also determined using MLSR and results in an adjusted R^2 value of 0.9924. Figure 7 illustrates the comparison between the measured values of the direct neutron peak and the results of Equation (2).

$$\widehat{N} = 0.036668 - 0.0021298M + 0.0000445M^2 \qquad (2)$$



(a) (b)

Figure 7. Comparison of the (a) measured values of the direct neutron peak (b) values of the volume calculated using Equation (2).

Feature $\hat{N}$ is related to the total neutron cross section of the sample that is being analyzed. The total cross section of U-235 is greater than the total cross section of U-238 for 14.1 MeV neutrons. This explains the slight variation of this feature with enrichment. This feature decreases with increasing mass because the neutron attenuation increases with mass.

The mass and enrichment of a uranium sphere may be determined using Equations (1) and (2). First, Equation (2) is used to determine the mass of the sphere from the direct neutron peak in the correlation signature. Then, using this mass, the enrichment may be determined using the volume of the peak in the time/light output matrix and Equation (1). These equations were tested using 4 additional uranium spheres having the following masses and enrichments: 13 kg / 10 wt.%, 15 kg / 90 wt.%, 17 kg / 50 wt.%, and 9 kg / 50 wt.%. For these cases, the masses were determined within 2.3% difference, and the enrichments were determined within 1.1 % difference for all cases, except the lowest enrichment, which was determined within 15 % difference. Table 2 compares the actual test case values with estimated values.

Table 2. Comparison of test case properties with estimations made using Equations (1) and (2) and "measured" values.

	Mass (kg)			Enrichment (%)		
Case	Actual	Estimated	% Difference	Actual	Estimated	% Difference
1	9	9.2	2.2	50	50.1	0.2
2	13	12.7	2.3	10	11.5	15
3	15	15.3	2.0	90	88.9	1.1
4	17	16.8	1.2	70	69.3	1.0

CONCLUSIONS

We have described a method for the determination of uranium metal mass and enrichment based on the use of a DT neutron generator and a plastic scintillator. The analysis is based on knowledge of the neutron time of arrival and pulse heights at the detector. We showed that, in most cases, sample mass can be estimated within 2.3 %, and enrichments above 50 wt.% can be predicted within 1.1 %. The measurement can be performed using a DT neutron generator having an output of 10^8 n/s, and the measurement time would be less than 1 minute.

REFERENCES

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2. 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.

3. S. A. Pozzi, "Determination of Liquid Scintillator Response Matrix for Neutron Spectrum Unfolding," 7th International Conference on Facilities Operations – Safeguards Interface, Charleston, South Carolina, February 29 - March 4, 2004.