Large Plastic Scintillation Detectors for the Nuclear Materials Identification System

J.S. Neal, J.T. Mihalczo, M. T. Hiatt, J. D. Edwards
Oak Ridge National Laboratory
P. O. Box 2008, Oak Ridge, Tennessee 37831-6010, USA

ABSTRACT

Future measurements with the Nuclear Materials Identification System require large, on the order of one meter by one meter, detectors for increased sensitivity. As the container to be interrogated or the distance gets larger, increased detector size is required for increased sensitivity. Large liquid and fast plastic scintillation detectors are being designed to meet experiment requirements. Large scintillation detectors present challenges for the optimization of light collection efficiency and uniformity. Design variables that affect light collection include, but are not limited to, (1) photomultiplier size, number and placement, (2) scintillator length, thickness, and light attenuation length, and (3) reflective coating reflection coefficient of scintillator walls. We have calculated light collection efficiency and uniformity for fast plastic detectors using two codes for modeling the optical properties of scintillators. Based on these calculations, we have completed our design and acquired a large plastic detectors for testing.

INTRODUCTION

Future applications of the Nuclear Materials Identification System (NMIS) [1] will require detectors that are significantly larger than those previously used. Typical NMIS measurements have utilized fast plastic scintillator detectors on the order of 6x6 inches square and liquid scintillators on the order of 6 inches in diameter. New applications include large, 1x1 meter square fast plastic scintillator detectors used as portal monitors for passive measurements and as large area detectors for active interrogation of large sealand containers. These large detectors present new challenges for the optimization of light collection efficiency and uniformity and ensuing effects on the detectors' timing resolution.

Design variables that affect light collection include, but are not limited to, (1) photomultiplier (PMT) size, number, and placement, (2) scintillator length, thickness, and light attenuation length, and (3) reflective coating reflection coefficient of scintillator walls. The scintillator dimensions and material properties were considered fixed by other constraints. PMT size was dictated by the scintillator slab thickness. Our design goal was then to achieve adequate detection uniformity while minimizing the number of PMTs. Preliminary calculations indicated the need for at least 2 opposing PMTs.

COMPARISON OF CALCULATIONS AND MEASUREMENTS

Two computer codes, DETECT2000 and MCNP-PoliMi, were used for modeling the optical properties of the proposed 1x1 meter square detector.

DETECT2000

DETECT2000 [2] is the object-oriented C++ version of DETECT [3], a Monte Carlo model of optical systems with an emphasis on scintillation detectors. The code generates scintillation photons in specified portions of the scintillator, tracks each photon in its path through components and interactions with surfaces, allows for the absorption and re-emission by a wavelength-shifting component, and records the fate (absorption, escape, or detection) of each photon. Additional information for each photon includes decay and delay times, total elapsed time to detection, number of reflecting surfaces encountered, last coordinates and whether or not the photon was wavelength shifted.

Using DETECT2000, the detector was modeled as a 1x1x0.08 meter plastic scintillator slab, wrapped with a reflective metal coating with a reflection coefficient (RC) of 1.0. While a more realistic RC for a metal coating would be approximately 0.9, the actual detector uses a thin layer of surrounding air as the reflective coating. For these calculations, we considered the modeled reflection coefficient adequate for finalizing our design. The scintillator's properties are presented in Table 1.

Table 1. Scintillation properties for the modeled detector.

Density	1.02-1.05 g/cc
Emission Maximum	425 nm
Activator	POPOP
Refractive Index	1.58
Intensity relative to Anthracene	65%
Photoelectron Yield	10000 photons/MeV
Attenuation Length	4 m
Decay Time	2.1 ns
H/C ratio	1.1

Two, opposing PMTs were modeled using nominal dimensions and characteristics for the XP4312 PMT, a 3-inch, linear focused fast PMT. The quantum efficiency of the PMTs was not modeled, but instead set to 1. The source was modeled as a point source of photons with a wavelength of 425 nm, centered in the thickness dimension, at various locations across the 1x1 meter face. Figure 1 presents a contour plot of the calculated values of the percentage of generated photons that were counted by the detection surfaces.

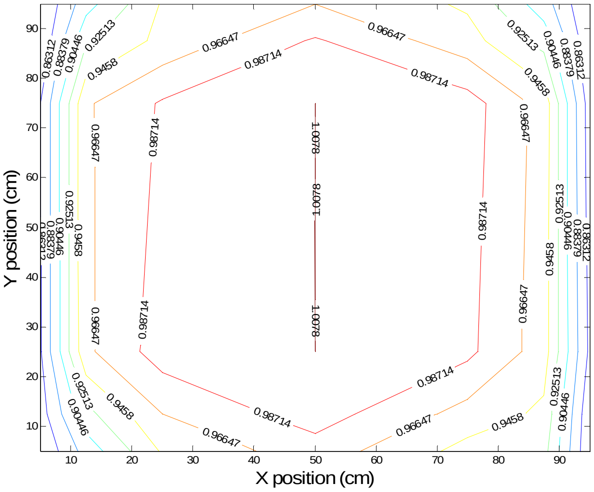

Figure 1. Contour plot of calculated values of detected photons using the DETECT2000 code.

Using a Na-22 source, the uniformity of the actual 1x1 meter plastic slab, shown in Figure 2, was measured. The anode signals of the opposing PMTs were matched for timing and gain and then summed. The summed signal was used as input for a constant fraction discriminator and a timer/counter. Background subtracted values are plotted in Figure 3 as a contour plot.

Figure 2. 1x1 meter plastic scintillator detector with a 3.75x3.75 inch plastic scintillator detector resting on top.

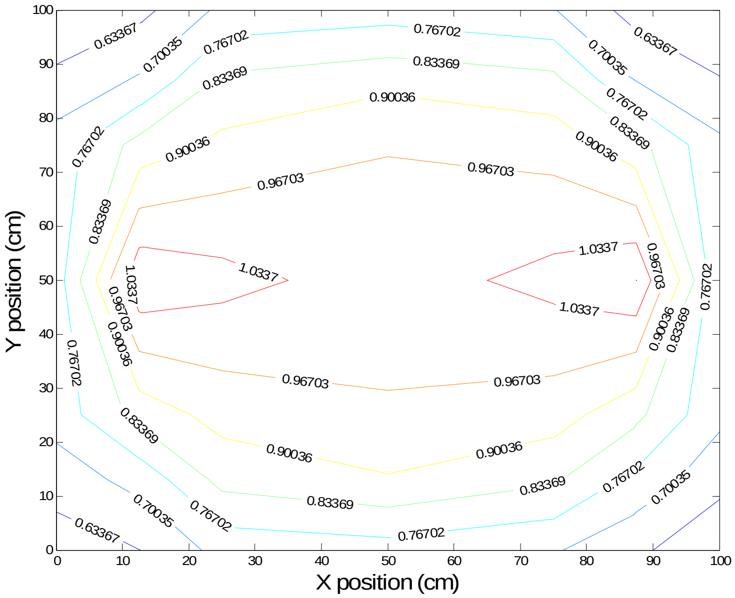

Figure 3. Contour plot of measured values of detected photons. The PMTs are located on the left and right sides of the figure, centered.

In addition to uniformity calculations, DETECT2000 was used to calculate (1) the percentage of photons counted as a function of RC (ratio of the reflected power to the power incident on the surface), Figure 4, (2) the distribution of the total elapsed time from scintillation excitation to the end of the photon history, Figure 5, (3) the mean flight time for counted photons for RC=1, Figure 6, (4) the distribution of the number of contacted surfaces for counted photons for reflection coefficient=1, Figure 7, and (5) the mean number of encountered surfaces for counted photons versus RC of the outer surface of the detector, Figure 8.

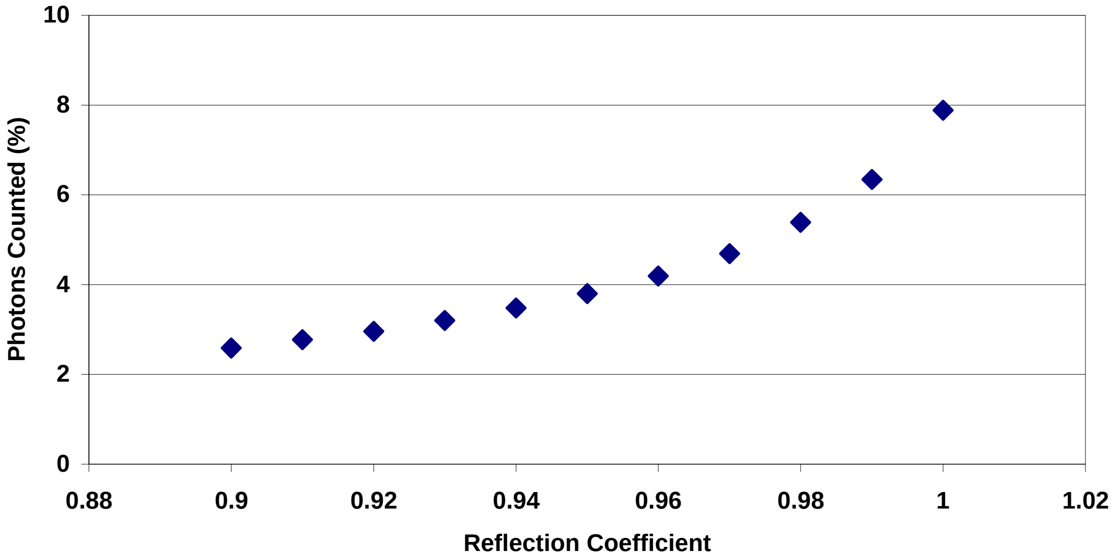

Figure 4. Plot of percentage of photons counted versus the reflection coefficient of the outer surface of the detector.

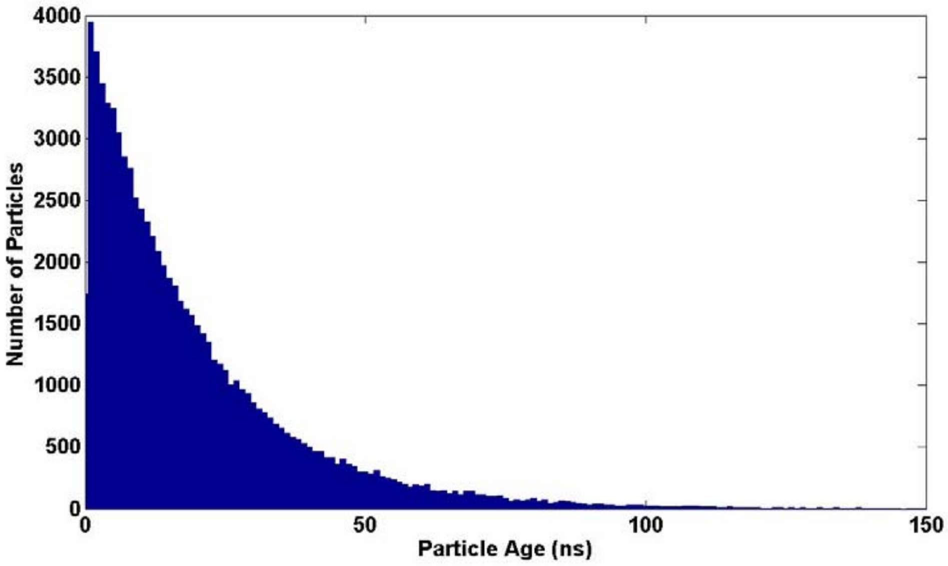

Figure 5. Distribution of the total elapsed time from scintillation excitation to the end of the history for relection coefficient=1.

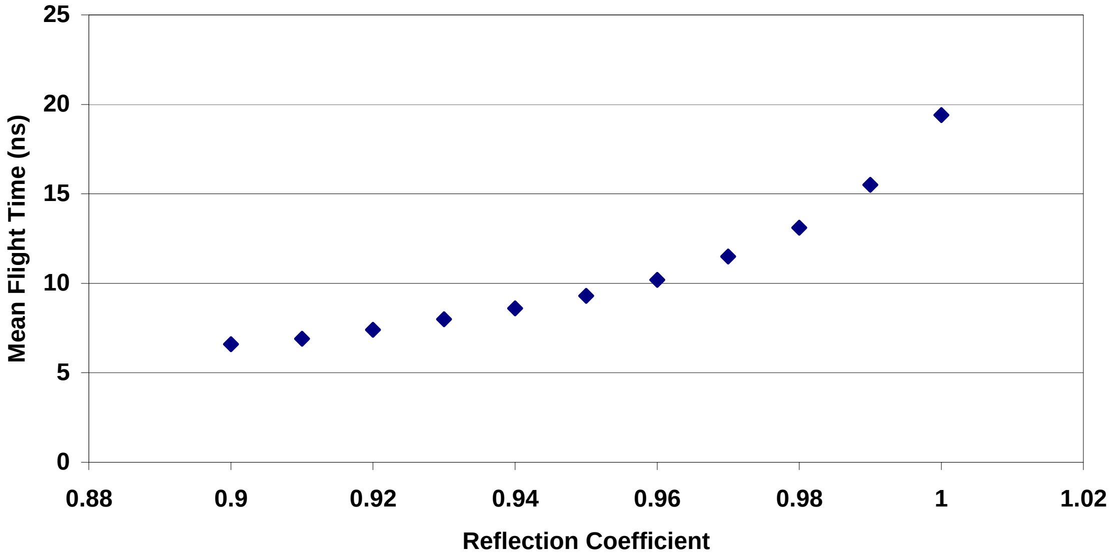

Figure 6. Plot of mean flight time for counted photons versus reflection coefficient of the outer surface of the detector.

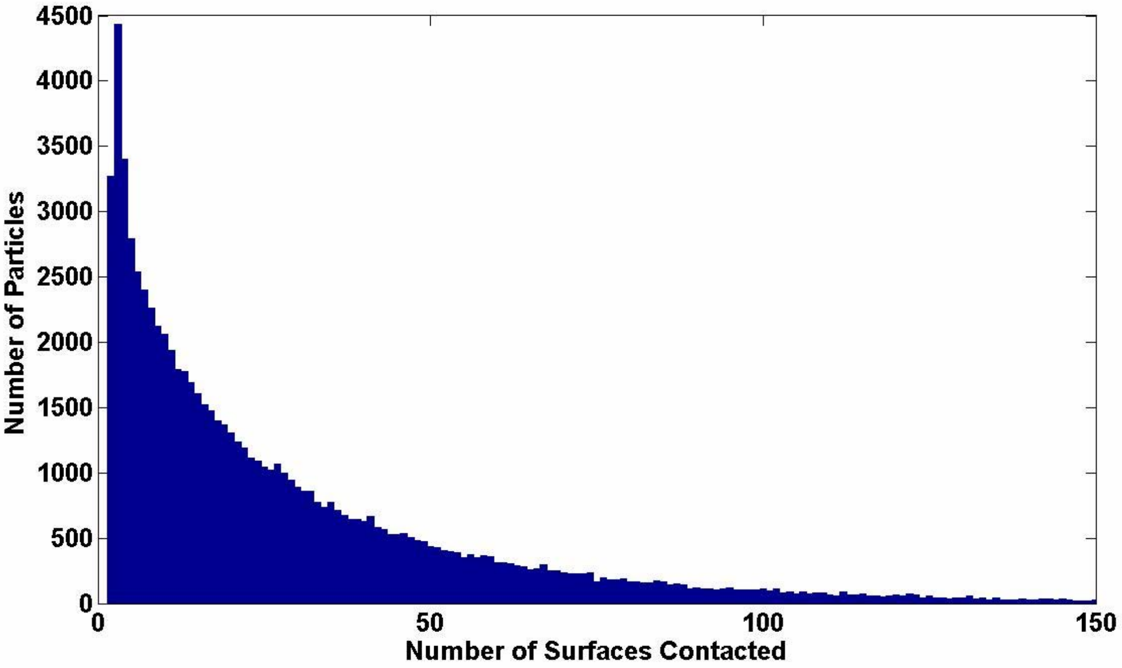

Figure 7. Distribution of the number of contacted surfaces for counted photons for reflection coefficient=1.

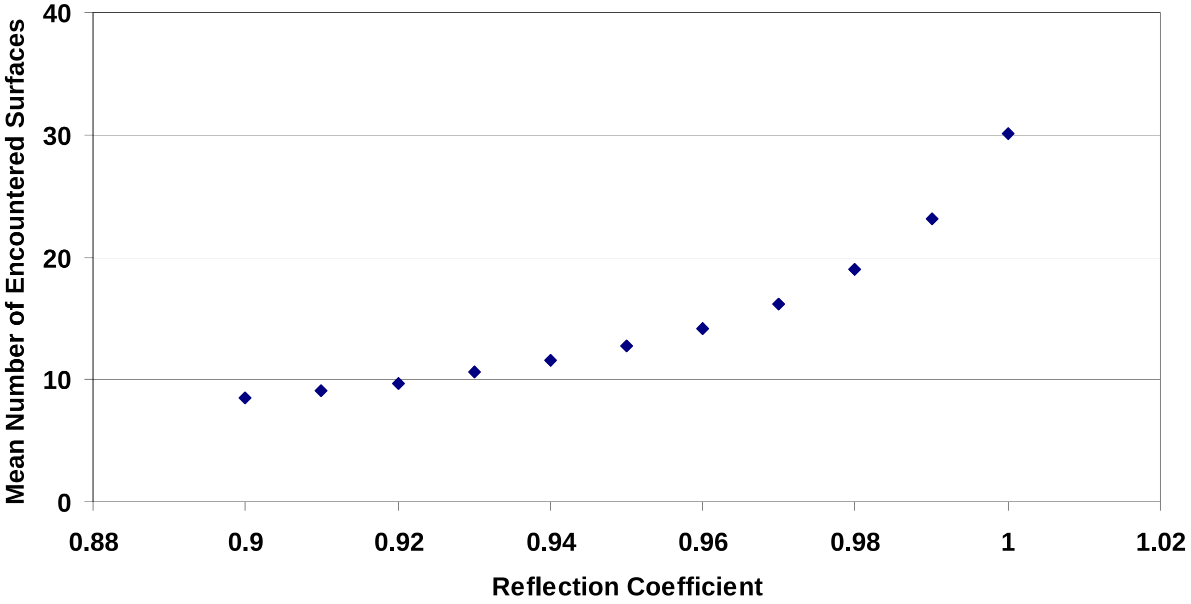

Figure 8. Plot of mean number of encountered surfaces for counted photons versus reflection coefficient of the outer surface of the detector.

Calculations using DETECT2000 demonstrate the need to consider the non-uniform collection of light as a function of position and the potentially significant contribution of photon mean flight time when modeling detector response.

MCNP-PolMi

MCNP-PoliMi [4], a time-dependent coincidence variant of the MCNP-4C code, and its post processor code were used to simulate a time-of-flight measurement using an instrumented Cf-252 source and the large plastic scintillator detector, separated at a distance of 133 cm. The MCNP-PoliMi data output reports information on the collisions that occur within the detector cell. These data must be post-processed to simulate the detector response. A post-processing code simulates light generation using a series of models:

- for neutrons in liquid: .035*e^2 + .1410*e
- for neutrons in plastic: .0364*e^2 + .125*e
- for photons in liquid: 1*e
- for photons in plastic: .9920*e + .0080

Figure 9 presents the source-detector correlated counts, normalized per Cf-252 fission, versus delay time since fission fragment detection for both the MCNP-Polimi calculation and the actual measurement. The effects of a large detector can be seen most prominently in the initial gamma peak, normally unimodal but now bimodal due to light transport time effects. This effect is not seen in the standard MCNP-PoliMi simulations since the code assumes that the generated light for a given photon or neutron is collected by the PMT photocathode instantaneously and with 100% efficiency. Light transport phenomena such as reflections, absorption, and reemission are not currently considered in the post-processing code but have been taken into account in a preliminary revision. Several experiments with large scintillators indicate that the number of counts recorded by the PMT can be modeled as a function of distance from the center of the scintillator. Using the data from these experiments, a preliminary revision of the MCNP-PoliMi post-processing code has been performed that takes into account the position of the incoming particle's interaction and modifies the light collection calculations appropriately. Currently, the best model uses a curve created from a regression of the number of counts recorded from a Cs-137 source and a Co-60 source at various points on the face of a 25 cm x 25 cm liquid scintillator to create an appropriate light collection factor. When used to model a 1 m x 1 m plastic scintillator for a time-of-flight experiment, this light collection factor was able to reduce errors in the initial gamma peak from ~300% to ~25% with slightly smaller reductions in errors over the rest of the range. Further revisions of the code using both measured data and calculated data from DETECT2000 are being undertaken to fully account for light transport effects in the scintillators. Models to account for timing effects are also under consideration.

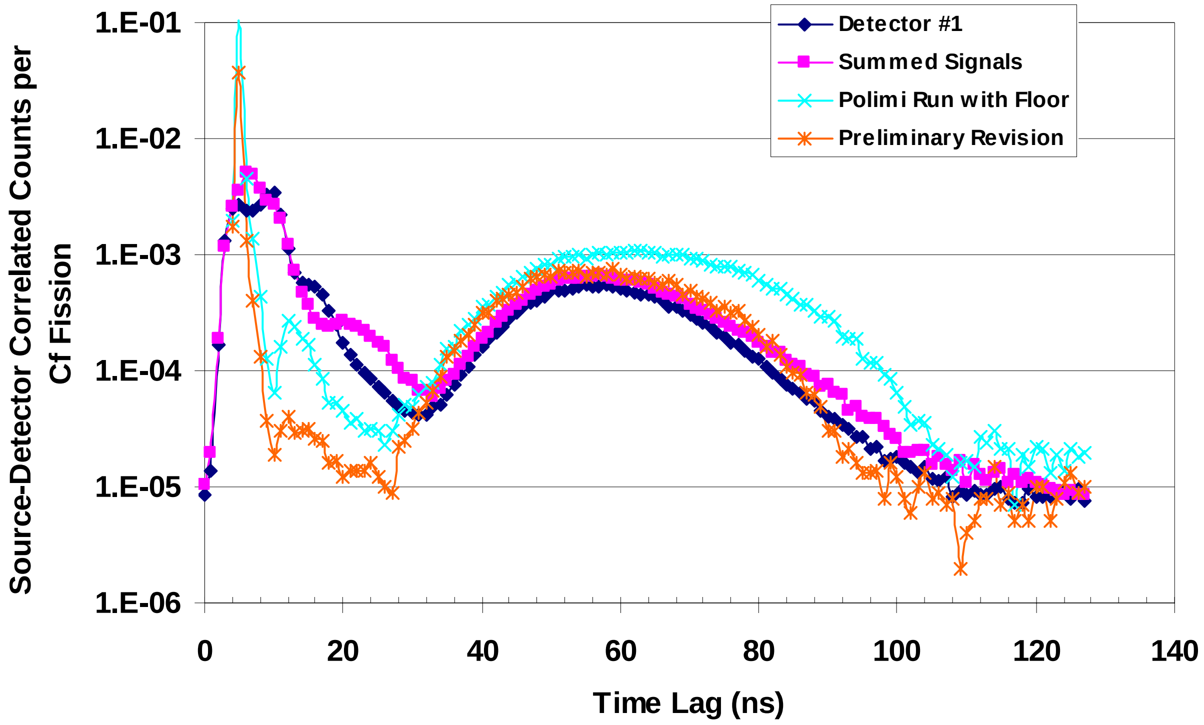

Figure 9. MCNP-PoliMi simulations and measurement results for a time-of-flight measurement using an instrumented Cf-252 source and a 1x1 meter plastic scintillator, separated by distance of 133 cm.

SUMMARY

Light detection calculations and time-dependent coincidence simulations have been made for a 1x1 meter plastic scintillator detector using the DETECT2000 and MCNP-PoliMi computer codes, respectively. Measurements of detector uniformity using a Na-22 source and of time-dependent coincidences and neutron detection efficiency using an instrumented Cf-252 source were made and compared to the calculations.

The most significant differences between measurements and simulations may be attributed to scintillation light transport effects in the large detector. The current MCNP-PoliMi post-procesor does not currently consider light transport phenomena in the detector but a preliminary revision of the code has shown great promise in successfully accounting for these effects. Ongoing efforts seek to further refine this model to obtain even more realistic light collection efficiencies. Models to account for timing effects are also under consideration. Measurements and simulations are also being made for 25x25 cm liquid scintillator detectors.

REFERENCES

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