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Monte Carlo simulation of portal detectors of a steel factory. Comparison of measured and simulated response

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Abstract

Metal scrap is widely used in steel production. Millions of tons of scrap metal are traded each year worldwide; hence, both national and international authorities have shown an increasing interest in the probing and detection of radioactivity contamination in scrap metal. In order to minimize and/or avoid economical losses and material contamination, portal monitors have been installed at the entrance point of installations of many steel industries. Portal monitors typically consist of large organic scintillation detectors. The purpose of this study is to simulate such detectors and compare simulation results with experimental measurements in order to understand, calibrate and effectively use the detectors' response. Monte Carlo simulations of these systems demonstrate the assumptions that have to be made for optimal matching of measured and simulated results. As it was reported in previous studies, we observed a difference between measured and experimental values next to the light guide. In this work, we propose a transition area near the boundary surface of the scintillator and the light guide; this results in a good qualitative and quantitative agreement of measured and simulated results. This study will also define a guideline for later portal monitor simulations and a reliable estimation of the portals' efficiency.

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Keywords: Monte Carlo; Portal; Simulation; Organic scintillators; Response; Scrap metal

1. Introduction

Metal scrap is actively traded worldwide as a valuable resource. Increasingly more steel is produced from scrap metal due to its availability and the resulting energy savings. However, there is always the possibility of radioactive contamination of the scrap metal. In order to prevent accidental melting of contaminated scrap and hence to avoid economical losses and factory contamination, steel industries have been installing portal monitors at the entrance point of their installations. Yet, there is always the possibility of smelting scrap metal with low concentration of radioactive materials or shielded sources.

The determination of the minimum detection limits (MDL) of homogeneously contaminated scrap metal or of shielded sources embedded in scrap metal loads is currently an important topic of research and investigation [1]. Furthermore, the estimation of the radiological risk for both workers and public in the case that a non-detectable radioactive source enters the manufacturing process is of great interest. In order to address the aforementioned, therefore, one has to study first, the response of the detectors used in such applications.

The detectors typically used in portal monitors are made of polyvinyltoluene (PVT) and polystyrene. These are low-cost organic scintillating detectors and they can be easily mass-produced. Furthermore, they have reduced sensitivity to damage or gain drifts resulting from temperature changes and they are best suited for efficient gamma-ray detection such as in primary portal monitors, when large numbers of vehicles need to be scanned.

The purpose of this study is to simulate the response of a plastic polystyrene scintillator based on a set of

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measurements obtained from a portal monitor. The effective simulation and understanding of the detector response is crucial for determining its MDL and assessing the possible radiological risk for both workers and public.

2. Materials and methods

2.1. Measurements

The measurements were taken with a polystyrene portal's monitoring detector. Each portal monitor consisted of 2 scintillating detectors. For the dimensions of the scintillating detectors and the measurements, the lid of the portal monitor had to be opened. The dimensions of the polystyrene scintillating detector were found to be $15 \times 89 \times 3.8\,\text{cm}^3$. Based on the technical specifications, the scintillating detector consists of a 79 cm-high scintillating part (i.e., $15 \times 79 \times 3.8\,\text{cm}^3$) and a 10 cm-high light guide (i.e., $15 \times 10 \times 3.8\,\text{cm}^3$), the latter being between the scintillator and the photomultiplier tube (PMT); these two parts result in a total height of 89 cm, which is identical to the dimensions measured.

First, a background measurement was taken. Then, we placed a 0.46 μCi ^{137}Cs source at several positions directly on the scintillating detector. We chose 3 positions lengthwise (at $x = 1$, 7.5 and 14 cm) and 9 positions height-wise (at $y = 0$, 10, 20, 30, 40, 50, 60, 70 and 84.5 cm) as shown in Fig. 1. For each source position the count rate (counts per second (cps)) probed by the detector was recorded. The portal monitors are set to measure counts from 22 up to 144 keV (voltage discriminator settings). It is noted that these values are not precise but rather approximate ones derived from the "voltage to energy" relationship of the voltage discriminator.

Finally, the background measurement was subtracted from the actual measurements at all source positions.

2.2. Monte Carlo simulations

Simulation of the detector was carried out with a set of Monte Carlo simulations. The tool used for the Monte Carlo simulations was the MCNP4C2 code of the Los Alamos National Laboratory. The simulated geometry is identical to that shown in Fig. 1 (i.e., scintillator, light guide and source positions). An input file was generated for each source position. The edge positions, at $x = 1$ and 14 cm, were only simulated once due to the symmetry of the problem. The tally used for the simulation was the standard f8 of the MCNP code (pulse height tally). Each simulation was done with 10 million particles, a number considered sufficient to give results with good statistics, due to the apparent simplicity of the problem. The output extracted from the results was the count rate in the 22–144 keV energy range normalized per starting photon.

In order to compare the simulated and experimental count rates, the simulated results normalized per starting photon were multiplied by the photons emitted from the ^{137}Cs source per second.

3. Results and discussion

First, we checked our simulations through comparison between the count rate obtained from the measurements and the count rate derived from the MCNP outputs. This was done at the source position $x = 7.5$ cm, $y = 50$ cm, that is, in the middle of the detector and 50 cm away from the PMT.

The resulting simulated spectrum is shown in Fig. 2. The highlighted gray area shows the energy window defined by the detector's discriminator. In that energy window, the MCNP calculated count rates are found to differ as much as 20% from the corresponding experimental ones. However, Fig. 2 suggests that a small difference in the energy window could significantly affect the results. For example, a 15–160 keV simulated window has an output of 760 cps which is 3.8% lower than the measured value of 790 cps. A 22–144 keV simulated window, though, has 635 cps which is 25% lower than the measured value. Based on these findings and since the manufacturer of the voltage discriminator states that the "voltage to energy level" relationship is approximate, we consider the agreement between the calculated and measured results to be satisfactory. Therefore, in the response diagrams

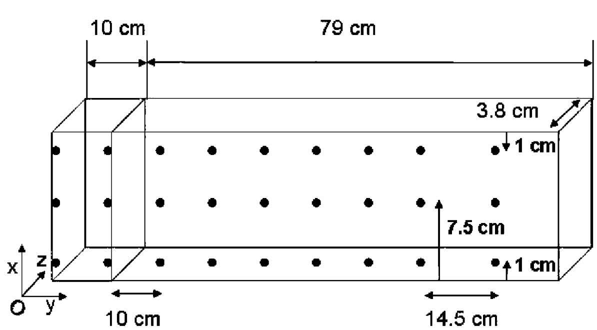

Fig. 1. Detector configuration. The black dots represent the positions of the source during the measurements.

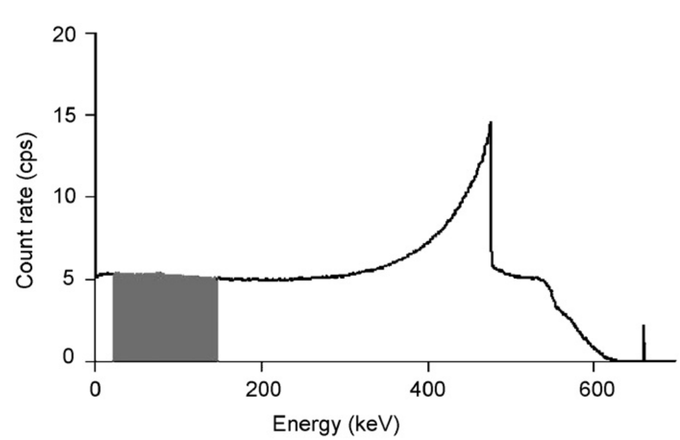

Fig. 2. Simulated energy spectrum for the ^{137}Cs source at $y = 50$ cm. In gray, the discriminator energy window.

that follow, all simulation results are normalized to the measured ones at the $x = 7.5$ cm, $y = 50$ cm source position.

Fig. 3 shows the measured and simulated count rates in the middle of the detector. Although there is a satisfactory agreement between measurements and simulated results for distances greater than about 35 cm from the PMT, there are distinct differences between data and simulations at smaller distances. The measured count rates start to drop off earlier. It appears that the detector is less efficient in the region near the light guide.

This phenomenon has also been observed and reported by other researchers, but no clear physical explanation has been proposed yet [2]. It has been assumed that it is probably related to the light collection efficiency or to the different reflection factors of the light guide and the scintillator.

In this study, we consider a "transition area" in the detector volume, right next to the light guide. In that area only a percentage of the events in the detector volume are recorded as counts. In order to find out the starting point of such a transition area and to determine its length in the y dimension, we considered the position at which the experimental data started to deviate from the calculated ones (Fig. 3). The proposed transition area was therefore considered to start 35 cm away from the PMT end and to finish at the light guide, i.e., $y = 10$ cm. For our simulations in the transition area, we divided the volume of the scintillator between $y = 10$ and 35 cm into 5 equal pieces called transition layers. In each layer a different percentage of occurring events were considered in the simulated count rates. The function that simulated the response of the detector in the transition area is shown in Fig. 4.

With the incorporation of the proposed transition area, our simulated count rates were found to be in satisfactory agreement with experimentally measured count rates qualitatively and quantitatively, throughout the volume of the detector (Fig. 5).

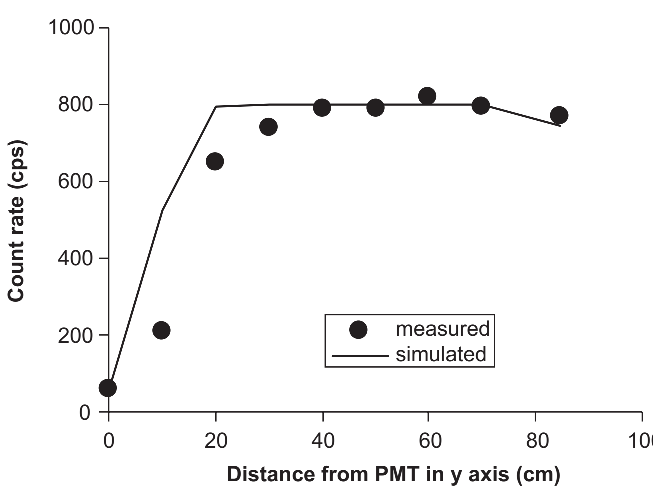

Fig. 3. Measured and simulated responses for the source positioned in the middle of the detector. The simulated count rates are normalized to the measured one at the position $y = 50$ cm.

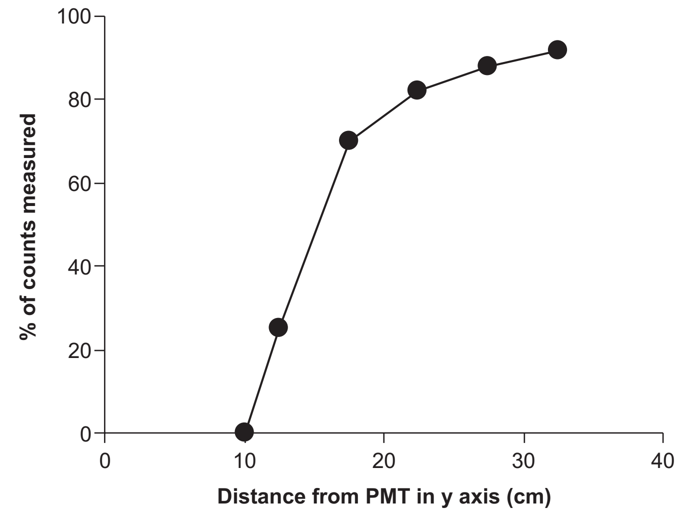

Fig. 4. Modeled response of the transition area. The dots represent the % of the counts to be considered in each transition layer. The light guide (0%) is from $y = 0$ to 10 cm.

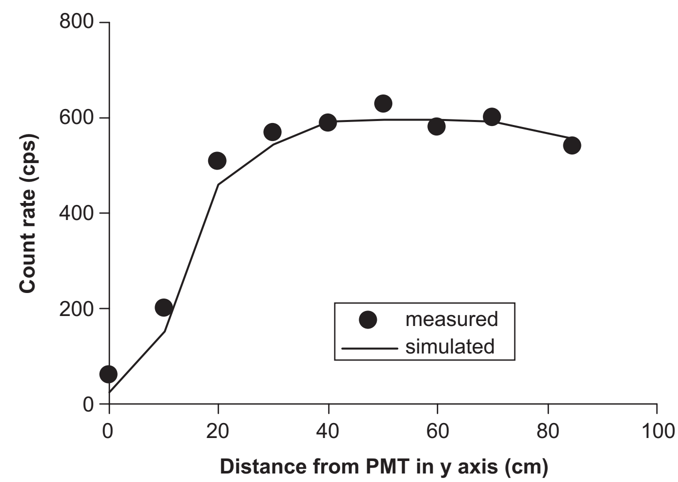

Fig. 5. Measured and simulated count rates for the source positioned at the edge of the detector ($x = 1$ cm) with incorporation of the proposed transition area.

In this study, we have found out and report that the MCNP code is a good tool for modeling large organic scintillators accurately. Differences between experimental and simulated values are most likely due to the approximate relationship of the voltage to energy level of a voltage discriminator.

As it was indicated in earlier studies, we also observed a difference between simulated and experimental values in the region next to the light guide of an organic scintillation detector [2]. In order to study this phenomenon we propose a transition region right next to the light guide. This results in a satisfactory agreement between measured and simulated results throughout the volume of the detector. Further work also needs to be done with other detectors and with a variety of sources in order to fully investigate the full merit of the proposed solution.

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