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Organic liquid scintillation detector shape and volume impact on radiation portal monitors

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A B S T R A C T

We have developed and tested a radiation portal monitor using organic liquid scintillation detectors. In order to optimize our system designs, neutron measurements were carried out with three organic liquid scintillation detectors of different shapes and sizes, along with a ^{3}He radiation portal monitor (RPM) as a reference.

The three liquids tested were a 7.62 cm diameter by 7.62 cm length cylindrical active volume organic liquid scintillation detector, a 12.7 cm diameter by 12.7 cm length cylindrical active volume organic liquid scintillation detector, and a 25 cm by 25 cm by 10 cm "paddle" shaped organic liquid scintillation detector. Background and Cf-252 neutron measurements were recorded to allow for a comparison of neutron intrinsic efficiencies as well as receiver operating characteristics (ROC) curves between detectors.

The 12.7 cm diameter cylindrical active volume organic liquid scintillation detector exhibited the highest intrinsic neutron efficiency (54%) of all three liquid scintillators. An ROC curve analysis for a heavily moderated Cf-252 measurement showed that using the 12.7 cm diameter by 12.7 cm length cylindrical active volume Eljen EJ309 organic liquid scintillation detector would result in the fewest needed detector units in order to achieve a near 100% positive neutron alarm rate while maintaining a better than 1 in 10,000 false alarm rate on natural neutron background. A small number of organic liquid scintillation detectors could therefore be a valid alternative to ^{3}He in some RPM applications.

1. Introduction

The continuing loss and theft of nuclear material poses a threat to global security. The International Atomic Energy Agency maintains the Incident and Trafficking Database that compiles reported incidents and interdictions of nuclear and other radioactive material out of regulatory control [1]. The nuclear nonproliferation regime uses a complement of nuclear security, physical protection, and international safeguards while striving to minimize the number of radiological material thefts and to maximize the likelihood of recovering these materials in a timely manner. Radiation portal monitor (RPM) systems constitute one of the nuclear nonproliferation mission's tools. These systems are widely deployed to screen flows of people and goods for concealed nuclear and radiological material. Common applications for RPM systems include, but are not limited to, screening vehicles at international border crossings, cargo containers at international shipping ports, and luggage at airports. While the range of applications is broad, the operating principle of RPM systems remains the same. The systems use radiation detectors to acquire gamma-ray and neutron count rates. The entity passing through the RPM will be further investigated if either of these radiation count rates exceeds an alarm threshold set above expected background radiation count rates.

A high neutron capture cross-section and excellent gamma-ray discrimination capability have established ^{3}He-gas filled proportional counters as the neutron detector of choice for nearly all deployed RPM systems [2–3]. The long-term potential of a supply shortage of ^{3}He-gas [4] has spurred the development of alternative neutron detectors for various applications, including RPM systems, but also safeguards instrumentation. Examples of alternative neutron detectors include pulse shape discrimination capable plastic [5] and liquid [6] organic scintillation detectors, as well as boron tri-fluoride proportional counters [7], boron coated straws [8–9], and many others [10–11].

The Detection for Nuclear Nonproliferation Group (DNNG) at the University of Michigan has developed pedestrian and vehicle RPM systems using liquid organic scintillation detectors, which are also being investigated as a ^{3}He replacement technology in nuclear

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safeguards instrumentation, such as neutron coincidence well counters [12–13] and radiation imaging systems [14]. The DNNG RPM prototypes were extensively tested at experimental RPM benchmark campaigns organized by the European Commission's SCINTILLA project. These benchmark campaigns were conducted at the ITRAP facility at the Joint Research Centre in Ispra, Italy, and were designed to follow the established ANSI standard for RPM testing [15]. DNNG successfully participated in the two SCINTILLA benchmarks in 2014 [16–19].

While different detector materials possess certain intrinsic properties, in practice, the overall performance of a detector material will also depend heavily upon the shape and volume of the detector. Several studies were performed to optimize the use of ^{3}He in RPM systems [20–21]. The initial design goals for a traditional RPM include maximizing the system's neutron detection efficiency while minimizing the amount of costly ^{3}He utilized in the design. Such optimization studies have not yet been shown for organic liquid scintillation detectors. An ideal liquid scintillation detector RPM would maximize system neutron detection efficiency while minimizing cost, thus minimizing the number of detector cells. The scintillation light readout, typically a photomultiplier tube (PMT), dominates the cost of a liquid scintillation detector. In this new study, experimental results comparing three organic liquid scintillation detectors of different size and shape are compared with experimental results for ^{3}He proportional counters. These studies can be useful in choosing detector shape and size for future RPM designs that are optimized for cost and neutron detection efficiency.

2. Data analysis methods

2.1. Pulse shape discrimination

Organic liquid scintillation detectors possess pulse shape discrimination (PSD) capability that allows for the detection and distinction of neutron and gamma-ray interactions [22–24]. Interactions in the detector result in the creation of pulses of visible light. For neutron interactions a larger percentage of the total light is found in the tail of the pulse. When one plots the pulse tail integral versus the pulse total integral, distinct bands, correlating to neutron and gamma-ray interactions, become visible. The degree to which these bands are separated determines the quality of the PSD and is often expressed with a figure of merit (FOM), as shown in Eq. (1) below.

$$\mathrm{FOM} = \frac{\mathrm{Centroid_N} - \mathrm{Centroid_G}}{\mathrm{FWHM_N} + \mathrm{FWHM_G}} \tag{1}$$

where the centroids and full width half maxima (FWHM) come from the fitted Gaussian distributions of the neutron and gamma-ray distributions when histogramming the tail-to-total integral ratios from all detected pulses. The FOM depends strongly on how the user defines the range of the tail integral, which is optimized for each detector. Fig. 1 shows the histogrammed tail-to-total pulse integral ratio for a tail integral start time of 40 ns past the pulse maximum. The tail integral start time of 40 ns past the pulse maximum resulted in a high FOM for all three organic liquid scintillation detectors used in these studies. The tail integral length for all detectors was 220 ns, and the total pulse acquisition window width was 600 ns.

The goal of the PSD analysis is to ultimately determine a discrimination curve for the tail integral versus total integral plot. Above this curve all pulses are labeled as neutron interactions and below this curve all pulses are labeled as gamma-ray interactions in the detector. An algorithm developed by DNNG was used with ^{252}Cf mixed neutron and gamma-ray data to automatically determine the individual PSD curves for the three different organic liquid scintillation detectors used in this study [25]. This algorithm performs the charge-integration PSD method and divides the dataset into subsets using linear slices. The points of the PSD curve are computed by finding the point of minimum misclassification of photons and neutrons for the two fitted Gaussian distributions for each data subset. The PSD plots and discrimination curves obtained with this algorithm are shown in Fig. 2.

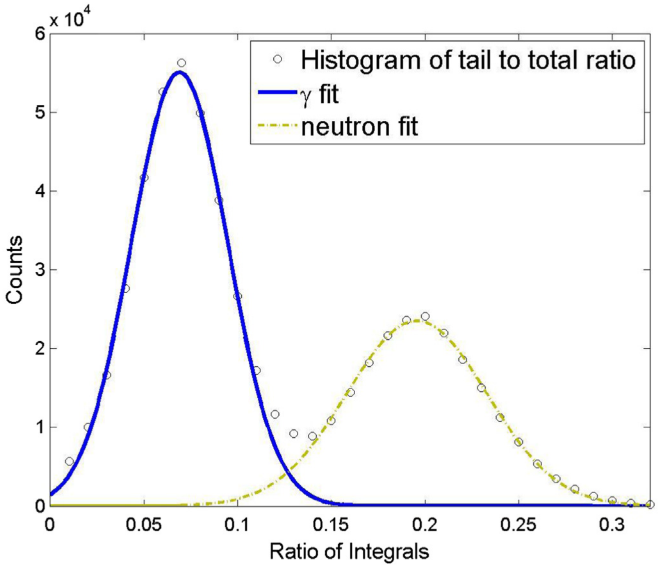

Fig. 1. Tail-to-total pulse integral ratio histogram showing the separation of gamma (blue, left) and neutron (yellow, right) fitted Gaussian distributions for ideal tail integral starting positions for ^{252}Cf data acquired with the 25 cm by 25 cm by 10 cm BC501A paddle-shaped organic liquid scintillation detector. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.2. Receiver operating characteristics curves

The size and shape of the detector affect the pulse shape discrimination (PSD) performance and intrinsic neutron efficiency of the detector. These parameters ultimately determine the number of detectors, and thus system cost, of the RPM system. Fig. 3 compares gamma ray count rates as a function of time for two detectors of different sizes as a ^{137}Cs gamma-ray source repeatedly travels past the DNNG RPM at a velocity of 2.2 m/s and a distance of 100 cm. The difference in observable signal to background ratio for these two detectors is apparent.

A receiver operating characteristics (ROC) curve can be used to determine the exact number of detectors of a given size needed to achieve a desired false alarm rate while also maintaining a high detection probability for some fixed minimum detectable activity. A false alarm for a RPM is defined as the system registering a neutron alarm in the absence of any neutron source other than variable natural background radiation.

For a given radiation background environment and a specific radiation source, one can compute the probabilities of false alarming versus positive detection for a range of user defined alarm levels [26]. Given Poisson distributions with means μ_{BG} and μ_{SIG} for neutrons detected from natural background and the source to be detected, the probabilities of a true positive alarm P_{TP} and a false positive alarm P_{FP} are functions of the chosen alarm level, t_n, as shown in (Eqs. (2) and 3).

$$P_{FP}(t_n, \mu_{BG}) = e^{-(\mu_{BG})} \sum_{i=t_n}^{\infty} \frac{\mu_{BG}^{i}}{i!} \tag{2}$$