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Minimum Detectable Activity Estimates for a Germanium-Detector Based Spectroscopic Portal Monitor

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Abstract

The Minimum Detectable Activity (MDA) for identification is one of several important performance measures for Advanced Spectroscopic Portal Monitors (ASP) given in ANSI N42.38 (draft) to determine the effectiveness of the ASP. In most spectroscopic applications, the samples are counted for a sufficiently long time to achieve the required minimum detectable activity or until the measured activities are within the desired statistical limits. However, in the ASP, the counting time is defined by the transit time of the vehicle or container through the portal field of view. For the specified transit speed and field of view, this gives a data collection time of a non-distributed source of 3 to 8 seconds. The performance criteria for a specified nuclide are stated in terms of the minimum detectable activity and in addition, at that stated activity limit, the number of false negatives must be less than 5 %, while the number of false positives in the same situation must be less than 1 in 1000. This low number of false negatives and false positives defines where the threshold for declaration of detection or identification should be set. This threshold must be based on some parameter derived from the spectrum, but is not necessarily only the activity of the nuclide. In addition, it is not desirable to use the concept of "blank" MDA, as used in sample counting, (which would correspond to measuring the background when the portal was unoccupied), because changes (normally suppression) to the background count-rate occur because of the presence of the vehicle and its cargo. Ideally, therefore, this parameter must be determined dynamically from the actual spectrum collected and compared to the threshold to determine if the nuclide is present.

To determine the MDA for the ORTEC ASP, the detection parameter threshold was determined by modeling the portal monitor performance using measured efficiencies of the germanium detectors at the geometries specified in ANSI N42.38 and specifying the maximum number of false negatives and false positives to be as required in the standard. Then the parameter value was calculated on measured spectra for the geometries and measurement conditions (speed and distance) and for a range of nuclide activities. Using these measurements, a function can be determined relating the parameter value and the activity. From this function, the activity at the parameter threshold can be determined, which is the portal MDA for the tested geometry.

Results are shown for ^{133}Ba, ^{137}Cs, ^{60}Co , and ^{241}Am for the ORTEC HPGe portal. These MDA predictions are compared to the requirements of ANSI N42.38.

Justification

The minimum quantity of radioactive material that can be detected and identified in an Advanced Spectroscopic Portal Monitor with the desired precision is one of the major design considerations for the detector size and placement, as well as the number (or total efficiency) of detectors. The identification can be based on one peak or on several peaks and energy regions. In addition, the identification must satisfy the false negative and false positive requirements. None of the standards developed to date (e.g., ANSI N42.38 draft) include any methodology for calculating this value. To accommodate the requirements, a method has been developed to estimate the minimum quantity able to be identified, where the identification is based on the peak quality of the nuclide peaks in the portal spectrum. The method is based on empirically determined detector efficiencies, the required false negative and positive rates, and the mean identification peak parameter for repeated portal occupancies of a range of nuclide activities. The identification of a nuclide relies on the peak quality value and not directly on the counts in the peak region above a "background" spectrum.

Introduction

The Advanced Spectroscopy Portal (ASP) program is a DNDO activity aimed at the improvement of radiation portal monitors (RPM) of many types: cargo, passenger vehicle, rail, pedestrian, and vehicle mounted. The objective is to improve the ability of the portals to not only detect but also identify radionuclides passing by the detectors. An additional objective is to improve nuclide identification in situations where several nuclides are present which might confuse, intentionally or otherwise, an RPM into failing to report the actual nuclides. In particular, correct identification of natural, medical and nuclear materials is of high importance, whether the nuclides are seen singly or in multiplies; shielded or unshielded.

ORTEC participated in the first round of ASP testing, supplying a prototype cargo portal system for evaluation at the Nevada Test Site (NTS) in the summer of 2005. As a consequence, a model for prediction of the monitor performance was developed.

Equipment

The prototype cargo portal system detector configuration is shown in Fig. 1 and described more completely in previous works [1, 2]. The system consists of two radiation sensor panels (RSP) of 6 detectors each on each side of the traffic lane for a total of 24 high purity germanium (HPGe) detectors. Testing was carried out over several weeks on a complete system at NTS and additional tests were done on a single RSP at the ORTEC facility in Oak Ridge, TN.

Figure 1 Prototype Cargo Portal on test site. Photo courtesy of National Nuclear Security Administration/Nevada Site Office

All HPGe detectors used were PROFILE GEM™ type, with crystal dimensions of 85 mm diameter and 30 mm long. The performance of all of the individual detectors, being nearly identical, could be easily predicted with a model of a single detector.

The choice of detector length and diameter was based on Monte-Carlo efficiency modeling which was subsequently validated by experiment. The choice was made in such a way as to make a reasonable compromise between number of detectors, the sensitivity and uniformity of response across the portal detection zone. The length/diameter ratio combined with the number and spacing of detectors determine the uniformity of response within the zone. The initial choice of 6 each 85 mm x 30 mm detectors per panel was made with the major emphasis on sensitivity and detection zone uniformity.

Performance modeling

The nuclide identification scheme uses a "peak quality factor" to quantify the quality of a gamma-ray peak in the spectral data. This quality factor, Q, is defined as

$$Q \equiv \frac{G - B}{\sigma_N}$$

Where:

G represents the gross counts in a region of the spectrum centered at the gamma-ray peak energy with a width based on the FWHM,

B represents the number of background counts in the same region,

σ_N represents the uncertainty of value: G-B.

The numerator of this equation represents the signal or net counts in the peak. The denominator is the statistical error expected in the signal. Similar peak factors have been reported by others [3, 4].

The peak is determined to be present when the computed value of Q is above a set threshold value. If the peak (or peaks) for a nuclide are present and certain other isotope specific criteria are met, the isotope is judged to be present

In order to predict detection and identification performance of the cargo portal and to predict performance in a variety of other configurations, an empirical model was developed. This model calculates Q probability distributions, for nuclides positioned throughout the detection zone as a function of number and separation of detectors, vehicular speed, and collimator field of view.

The model requires the following inputs:

Fixed model input parameters
- HPGe Detector efficiency versus energy, distance and angle
- HPGe energy resolution versus energy
- Collimator field of view

Variable input parameters
- Background spectrum seen by detector
- Source type (nuclide)
- Source distance from detector
- Source speed through detection zone
- Number of detectors per RSP
- vertical position of the detectors
- One or two sided configuration
- Desired detection probability
- Desired false alarm probability

The efficiency of a single detector as a function of source position in front of the RSP is shown in Fig. 2 [2]. The positioning of the source in the collection time window can cause the maximum count to vary by ± 6%, but the total number of counts is the same over the width of the total time window used in the model. The predicted Q distributions were validated by comparing the predictions with distributions derived from data from the prototype testing.

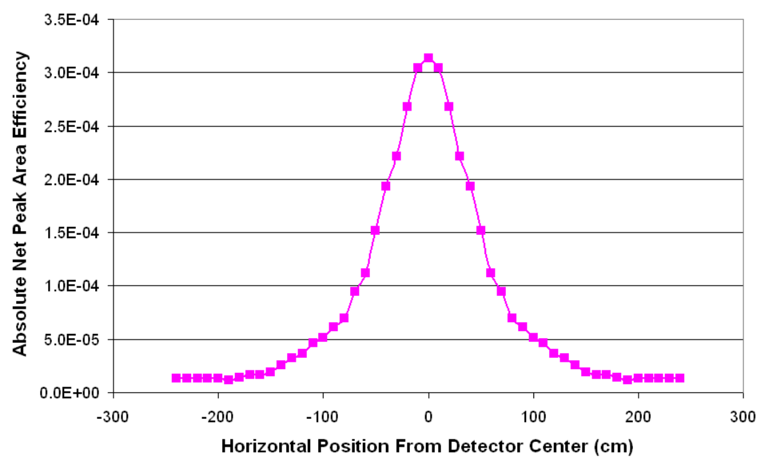

Figure 2 Modeled efficiency for 137Cs at 50 cm vertical distance from detector shield.

Using the Q probability distributions from background spectra (no source in the monitor) and from simulated nuclide peak areas, it is possible to predict the minimum amount of a specific nuclide that can be detectable and the amount needed for identification, given the requirements for false negatives and false alarms. Figure 3 shows the probability

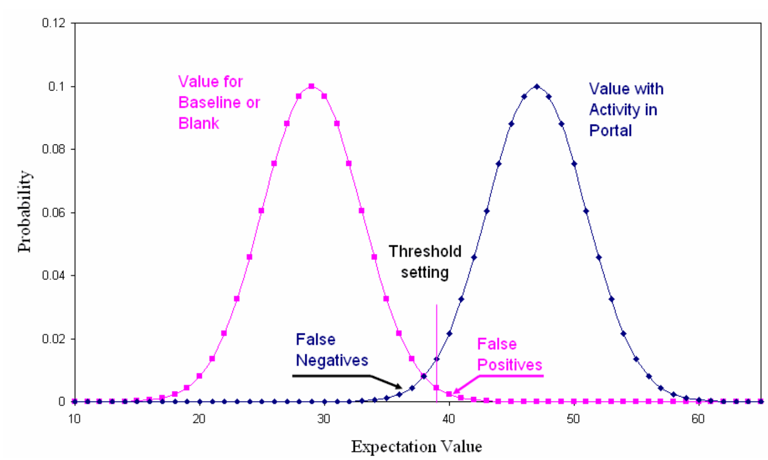

Figure 3 Gaussian distributions for base line and activity.

distribution of Q for a specific nuclide using a single gamma ray peak using the background or blank spectra. (See Ref. 5)

Integrating these curves from the minimum value to some value q, gives the total probability that Q will be below q as shown in Fig. 4. The Q calculations for the background spectra are the Blank (left most) curve.

For a false positive probability of 1 in 1000, the integral of the function is 0.999. The value of Q corresponding to this value is the threshold value for 1:1000 false positive rate because any positive indication on the background is a false positive. In Fig. 4, this is a value of 4.4. That is, for the expected distribution of Q for the background spectra, Q will be above 4.4 for 1 time in 1000 tests (occupancies). Thus the "threshold," QT, can be set at 4.4 to achieve the false positive rate. A threshold value is the value above which an identification or detection is said to have occurred.

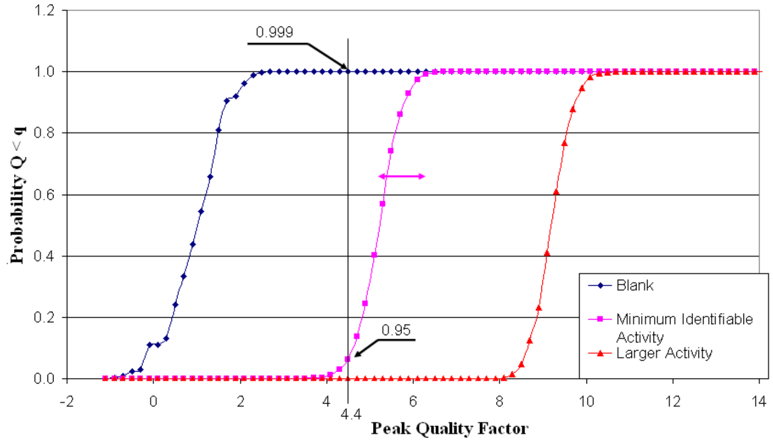

Figure 4 Example of a model generated detection probability distribution.

Using the efficiency data, the Q distribution can be calculated for any activity as shown by the Larger Activity (right most) curve in Fig. 4. With the threshold set at 4.4, the Q curves can be calculated for the activity where the cumulative probability has a value of 0.05 at a q of 4.4 corresponding to a 5% false negative rate. This activity is then the minimum identifiable activity (MIA).

Figure 4 shows the benefit of using HPGe detectors which is the separation between the probability distribution of background and typical sources is large. The large separation between the probability distributions of the source of interest and the background are due to the good resolution of the Germanium detector.

Results

The validated model can be used to calculate the MIA for a given set of conditions for nuclides for which spectra are available. The set of conditions used here are: cargo configuration with 24 detectors, spaced uniformly at 40 cm, 8 kph, FAP 1:1000 and greater than 95% Detection Probability (DP).

The MIA varies over the detection zone because of the varying distances from the source to the detector. Figure 5 shows the form of a typical detection limit (MIA) curve for the system of 24 detectors and for the source position to be at 50 and 250 cm from the detectors. This is from the closest position and the midpoint of the zone. The vertical position is from the base of the panel to the maximum active height of the cargo portal. The ^{137}Cs source is traveling at 8 kph. The MIA variation over the zone for other energies (nuclides) is similar, but the actual activities depend on the nuclide.

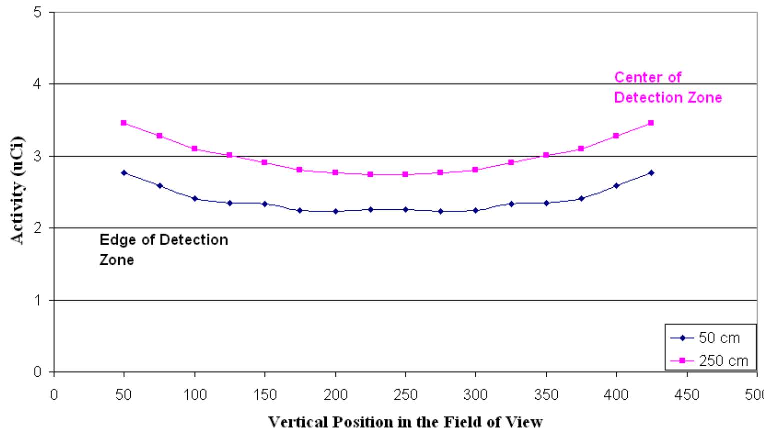

Figure 5 Variation of the Minimum Identifiable Activity over the vertical position in the field of view.

Table I shows predictions from the validated model for nuclide listed in ANSI N42.38. The first column is the nuclide. The second column is the required minimum activity for identification in the ANSI N42.38 specification. The third column for each nuclide is the Q value predicted for the required identification activity (column 2) and the last column is the minimum identification which is acheived when the Q value threshold is set for FAP of 1:1000 and DP of 95%.

Table I. Detection Limits for Some Nuclides in a 24-Detector Cargo Portal

Source	Required Identify Activity (: Ci) ANSI N42.38	Mean Q at Required Identify Activity (: Ci)	Minimum Identifiable Activity (: Ci)
241Am	47	19.20	8.77
133Ba	9	11.47	3.44
137Cs	16	14.99	3.00
60Co	7	8.02	2.29

Clearly, the 24-detector system far exceeds the ANSI requirements for these nuclides.

Conclusion

A semi-empirical model has been developed to predict the MIA for various configurations of HPGe detectors in portal monitors, handheld units and other configurations. It has been validated for a 2-sided cargo portal using data from testing at NTS and ORTEC. Using this model, the performance of 24-detector cargo portal is shown to be much better than the ANSI N42.38 requirements. Future work will concentrate further on other configurations of monitors and search instruments using HPGe detectors.

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