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The use of artificial neural networks to distinguish naturally occurring radioactive materials from unauthorized radioactive materials using a plastic scintillation detector

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HIGHLIGHTS

- Energy windowing is used to distinguish naturally occurring from unauthorized radioactive.
- High enriched and depleted uranium, Pu-239, and Cs-137 are used as unauthorized radioactives.
- Energy windows are obtained for four unauthorized radioactive materials.
- An artificial neural network is used for processing the energy windowing outputs.

ABSTRACT

Distinguishing naturally occurring radioactive (*e.g.* ceramics, fertilizers, etc.) from unauthorized materials (*e.g.* high enriched uranium, Pu-239, etc.) to reduce false alarms is a prominent characteristic of radiation monitoring port. By employing the energy windowing method for the spectrum correspond to the simulation of a plastic scintillator detector using the MCNPX Monte Carlo code together with an artificial neural network, the present work proposes a method for distinguishing naturally occurring materials and K-40 from four unauthorized sources including high enriched uranium and Pu-239 (as special nuclear materials), Cs-137 (as an example of dirty bombs), and depleted uranium.

KEYWORDS
Energy windowing
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Gamma ray detection

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1 Introduction

Prevention of the transport of radioactive materials, and locating the stolen or lost radioactive materials as well, can play key roles in national and global security. An important security project in each country may therefore include the installation of radiation monitoring ports in border controls, airports, and other places. The main task of such facilities is to detect and to prevent any unauthorized transportation of radioactive materials, whilst the traffic of authorized materials should remain unaffected.

Due to the high relative sensitivity, low-cost manufacturing, and high resistance to extreme environmental conditions such as temperature and humidity changes, plastic scintillation detectors such as polyvinyl toluene (PVT) are appropriate candidates to be used in radiation monitoring ports (Siciliano et al., 2005). Owing to the low atomic number, and their low densities as well, the plastic ingredients represent significantly poor detection resolution compared with HPGe and NaI detectors. Developing a method to improve the detection features of monitoring systems based on plastic scintillators is therefore of high importance. Energy window is a simple method for distinguishing authorized (such as ceramics, fertilizers, etc.) from unauthorized (such as enriched uranium, plutonium, etc.) radioactive materials (Ely et al., 2008). This method is considered to be more efficient than the net counting method which involves the disadvantage of taking into account the background radiation before and after passing the vehicle through the port.

In the present study, energy windows have been stablished for a plastic scintillator. By using an artificial neural network, the presence or absence of unauthorized radioactive materials have been determined. In the energy window method, the entire spectrum is divided into small windows in order to provide comparing the count rates in each window. For example, to discriminate between the enriched uranium and naturally occurring radioactive materials, using two energy windows is recommended: one

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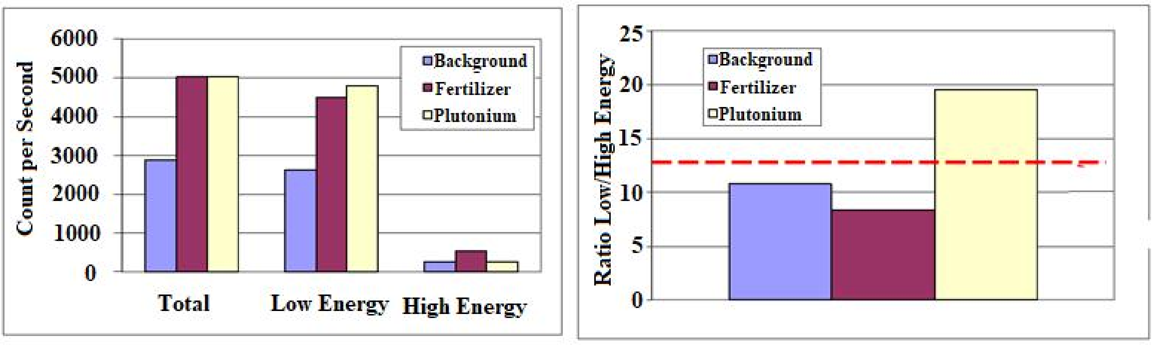

Figure 1: Energy window method used for two different samples: Pu-239 and fertilizer (Ely et al., 2008).

dedicated for energies lower than 200 keV and the other for higher energies (Ely et al., 2003). However, for identification of more than two materials, more windows, and consequently more complicated methods are required. Figure 1 shows an example of using the energy window method for detecting Pu-239. In the net counting method, the system alarms for both samples which means that it categorises both Pu-239 and fertilizer as unauthorized materials.

2 Methodology

The present study aims to incorporate the energy window method for identification of five different radioactive materials: high enriched uranium and Pu-239 (as special nuclear materials), Cs-137 (as an example of dirty bombs), depleted uranium, and K-40 (as a natural material).

Due to the unavailability of high-enriched uranium, Pu-239, and depleted uranium as well, gamma ray sources which emit photons comparable with those of the mentioned materials have been used. Because of a clear peak at 186 keV, Co-57 which emits photons with the energy of 122 keV can be considered as an acceptable alternative for U-235. Pu-239 emits gamma rays with energies range between 330 to 420 keV and can therefore be replaced by Ba-133 emitting gamma rays of 356 keV. As an alternative for depleted uranium, which emits photons of 766-1001 keV following the decay, Co-60 (emitting gamma rays of 1173 and 1332 keV) has been used.

In order to compare the results of simulations with those of measurements, the identical sources have been used. In addition, identifying gamma-ray contaminations which naturally exist in the soil as the main factor of background counts is vital. This information is required to be used in simulation of the background spectrum utilizing MCNPX 2.6 code. In order to simulate background radiation, the sources and their corresponding activities discussed by Ryan (Ryan, 2012) have been used.

The gamma ray sources used to simulate the background radiation, and their corresponding activities as well, have been listed in Table 1.

Although the background source activities may vary slightly in different energy regions, the overall spectrum shape remains unchanged. Owing to the fact that almost all natural radioactive materials contain (on the order of a few percent) the mentioned sources, it can be concluded that the spectra corresponding to the natural materials are similar to the background spectrum. Figure 2 clearly shows that though the background spectrum is similar to that of the natural material, it differes from the spectra correspond to the non-natural materials

Table 1: Materials used to simulate the background radiation.

Source	Specific activity (Bq per kg)
K-40	42.27
Ra-226	10.67
Th-232	4.97
Th-234	12.74

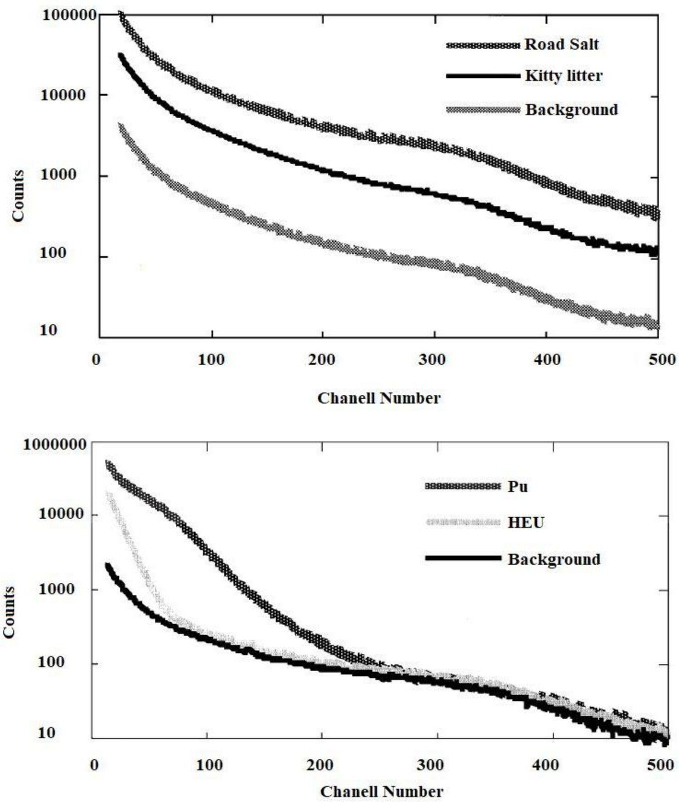

Figure 2: The gamma ray spectra correspond to natural and unauthorized materials (Ely et al., 2003).

Table 2: The range of energy windows obtained through simulations.

Window	1	2	3	4	5	6
Source	Co-57 (High enriched U)	Ba-133 (Pu-239)	Cs-137	Co-60 (Depleted U)	K-40	Background
Lower limit (keV)	30	159	392	671	1403	1522
Upper limit (keV)	158	391	670	1402	1521	2000

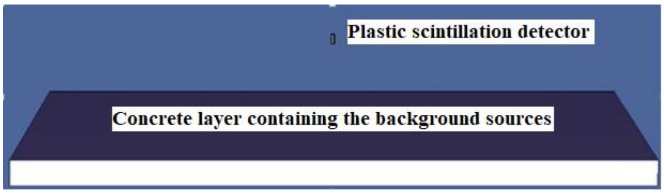

Figure 3: The detector and the concrete layer.

The detector used in the measurements is a 2 inches by 2 inches right cylinder plastic scintillation (PVT) detector. A concrete layer, a material which is commonly used in radiation monitoring ports, containing the radioactive materials (see Table 1) has been used to simulate the background radiations. The concrete layer has been considered large enough to be comparable with the size of the detector ($8{\times}8{\times}0.3$ m^3) in order to provide effective simulation of the presence of background radiation. The detector is located 1 meter upper than the concrete surface (See Fig. 3).

In order to set the energy windows, 1 microCurie of each source, including Co-57, Ba-133, Cs-137, Co-60, and K-40 have been considered at different distances from the detector (from 5 cm to 2 m in 10 cm steps). The MCNP pulse-height tally, F8, has been used for calculations.

In the absence of four unauthorized sources, the background has also been calculated. The total source counts had then been divided to the root of total background counts to obtain the energy window of each source. It arise from the fact that the sensitivity of each energy window depends on its background counts, and the maximum value correspond to each energy determines the upper limit of the energy window. However, in the case of identical counts for source and background for each energy in the simulations, this energy would represent the corresponding energy window. For each source, the energy windows for different distances have been calculated, and the mean values have been considered as the upper limit of the energy window. The lower limit of Co-57 window has been set to 30 keV to remove the noise effects. Clearly, the lower limit of the window for a source equals to the upper limit of the window corresponding to the source of lower energy. For example, for Ba-133, the lower limit of the energy window equals to the upper limit of Co-57 window.

The results obtained from simulations are listed in Table 2. Moreover, Fig. 4 shows the calculated values using F8 tally in each source energy window.

Having obtained the required energy windows, 32 different states of the presence or absence of the above mentioned sources have been considered in MCNP calculations. The results have been obtained for activities both equal or non-equal to the source activity (the lowest source activity is 1 microCurie) for different distances (randomly chosen between 10 cm to 800 cm). The results have been used to train a multilayer perceptron network (MLP).

This study aims to detect four unauthorized sources,

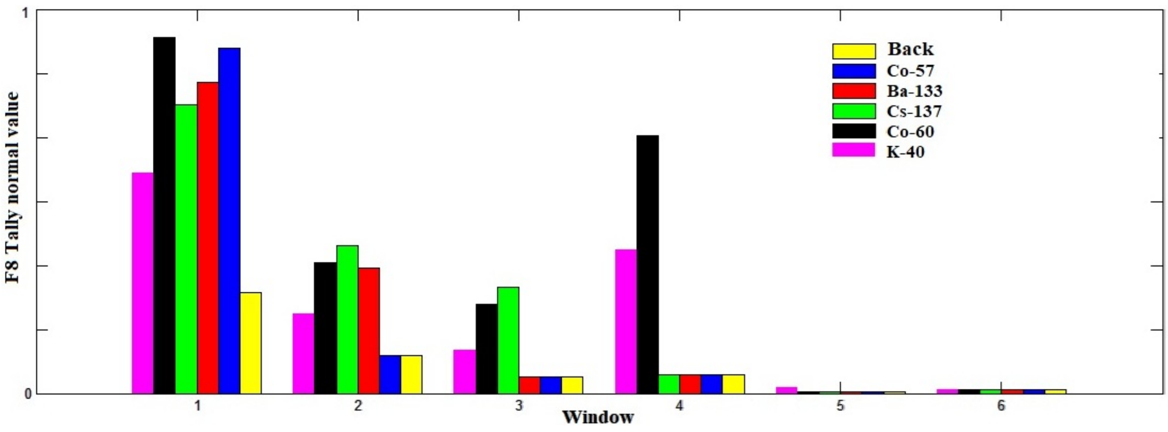

Figure 4: The normalized F8 tally for different energy windows.

where K-40 is considered as an authorized (*i.e.* safe) source. The advantage of setting separate windows is increasing the system decision-making capability which reduces the corresponding false alarms as there may exist several materials containing radioactive source. In this way, the system output can be either 1 or -1, which represent the presence (an alarm sound is played) and the absence of unauthorized sources nearby, respectively. The neural network consists of an input layer (requiring six input data), an output layer (giving one output), and a hidden layer. Figure 5 shows a schematic diagram of the network designed.

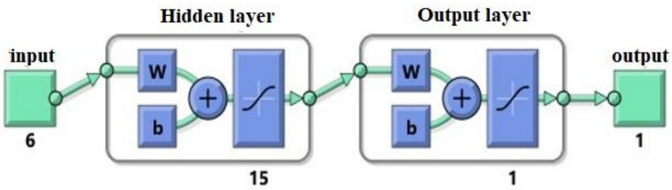

Figure 5: A schematic diagram of the artificial neural network design.

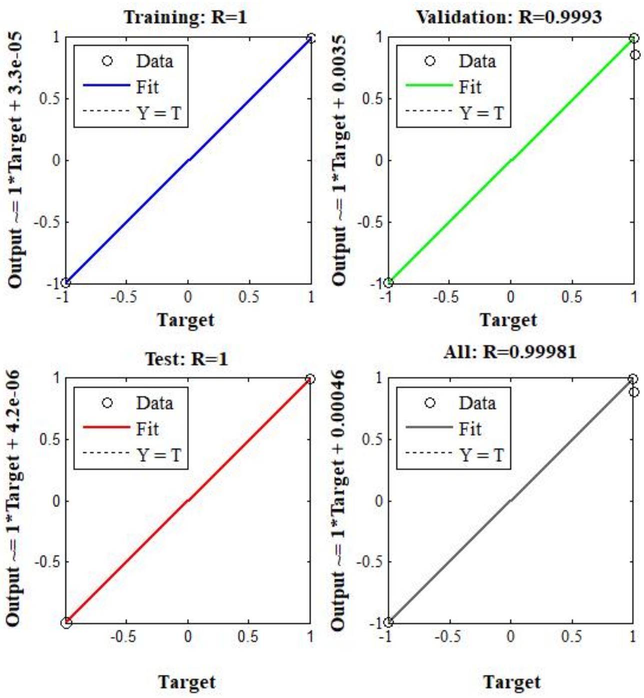

Figure 6: The regression diagram of the neural network.

The six input data are the count rates calculated for six energy windows and divided by the largest value, so that all input data remain smaller than or equal to 1. 150 data sets have been calculated to design the neural network through simulation using MCNP code, among which about 15% (22 samples) have been used for the test, about 15% (22 samples) have been considered for validation, and the others have been employed for training. The data have randomly been selected using MATLAB. These data include different combinations of sources, distances, and natural materials (*e.g.* soil samples used in the literature (Ryan, 2012)).

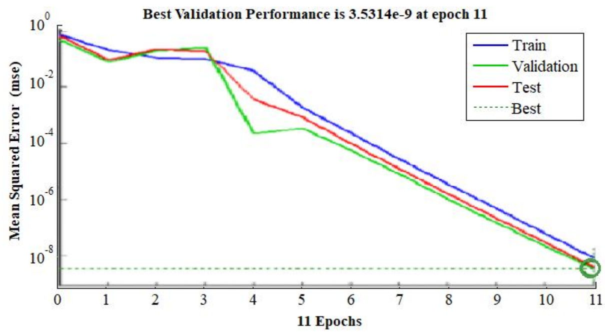

Figure 7: The system efficiency diagram of the neural network.

3 Results

The regression and the system efficiency plots are illustrated in Figs. 6 and 7, respectively. According to Fig. 6, the artificial neural network can effectively distinguish unauthorized sources from background radiation and naturally occurring materials.

4 Discussion and Conclusion

The present study proposes a method to successfully distinguish naturally-occurring radioactive from unauthorized materials using an artificial neural network with a readily available plastic scintillator based on energy windowing. In order to distinguish the sources, an independent neural network for each source is necessary. In this case, the output corresponding to each network indicates the presence or absence of each source.

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