OPTIMIZATION OF THE ^{252}Cf-BASED EXPLOSIVE DETECTION SYSTEM BY MONTE CARLO SIMULATION

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Abstract

Optimization of the ^{252}Cf-based Explosive Detection System (EDS) was performed using Monte Carlo simulation. Heavy water, light water and polyethylene were used as moderators with lithium carbonate and lead as neutron and gamma ray shielding materials, respectively. The thicknesses of the moderators and of the neutron and gamma ray shielding materials were optimized to obtain the maximum thermal neutron flux at the center of the inspection cavity and the minimum total dose at the outer surfaces of the EDS's walls. Detection sensitivity, the required source strength and the maximum total doses of the EDS were then estimated.

Keywords: Monte Carlo simulation, optimization, explosive detection system, ^{252}Cf source

Introduction

It was not until the crash of Pan Am flight 103 in Scotland in 1988 that the air aviation industry installed Explosive Detection System (EDS) as security equipment. X-ray imaging was the only system employed beforehand for checking for weapons, such as guns and knives, concealed in the luggage. Because of the aforementioned tragic incident, the United States Government, through the Federal Aviation Administration (FAA), seriously began looking for equipment that could accurately detect explosives. The FAA contracted with Science Application International Corporation (SAIC) to research and develop an EDS which uses a nuclear technique called "Thermal Neutron Analysis (TNA)" (Shea *et al.*, 1990). SAIC started to build two machines for use and testing at San Francisco and Los Angeles airports. Once the test results satisfied the requirements of the FAA, another six machines were ordered from SAIC for use at five other domestic and overseas airports. In 1995, the FAA requested SAIC to design the TNA- based Small Package Explosive Detection System (SPEDS) for checking carry- on luggage in airports (Brown and Gozani, 1996). This system is a compact and low cost EDS which is able to detect 200 g of C- 4 explosive concealed

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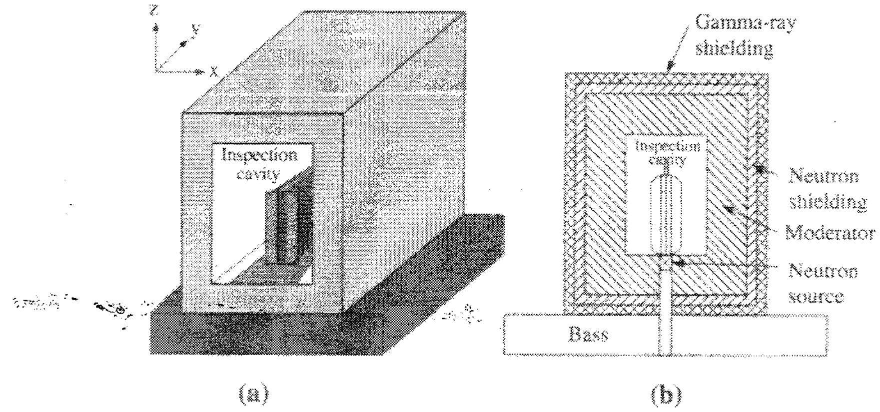
in the luggage. We are interested in designing a TNA- based EDS similar to SPEDS for checking briefcases or small bags at the entrance of sensitive areas such as VIP offices or meeting rooms. Since this work is a preliminary study, the design is a simple or idealized version of the EDS which can be modified toward a practical model later. The design of such an EDS involves optimization of the types and dimensions of its components.

The compact and low cost TNA- based EDS uses fast neutrons from a radioactive source as media to detect nitrogen (N), an important elemental component of all explosives. These neutrons will slow down when passing through the elemental components of the inspected object and become thermal neutrons before being captured by ^{14}N. The nuclei of ^{14}N will become the excited compound nuclei of ^{15}N*, before releasing 10.8 MeV characteristic gamma rays while returning to its' ground state. Detection of many such gamma rays is a clue to the possible existence of explosives concealed inside the inspected object.

There are two important conditions for optimization of the TNA- based EDS. (1) The system must have high enough thermal neutron flux distributed throughout the inspection cavity to initiate the emission of the 10.8 MeV gamma rays and (2) the system must not generate too high radiation in the vicinity of the EDS so that it is safe for operation in public. These two conditions will give the required specifications for the neutron source, radiation detectors, the neutron moderator and the shielding materials of the EDS. In this work, the types and dimensions of the moderators and the shielding materials of the TNA- based EDS are optimized by using Monte Carlo simulation. The maximum total dose, detection sensitivity and source strength of the EDS are then estimated. The computer code used in this simulation is MCNP-5 (X-5 Monte Carlo Team, 2003) which requires cross- sectional data for nuclear interactions between neutrons and gamma rays with matter as the input of the code. The Evaluated Nuclear Data File B-VI is used in the simulation to provide such data. The following sections will present the geometry of the simulation model, the components of the simulation model, the simulation results and discussion, and the conclusion.

Geometry of the Simulation Model

The simulation model has a shape of a rectangular box with the inspection cavity located at the center of the box, as shown in Figure 1(a). In Figure 1(b), the box's walls are made up of three layers of different materials with a moderation material as the innermost layer surrounding the inspection cavity. The second and third layers are neutron and gamma ray shielding materials, respectively. The inspected



(a) (b)

Figure 1. **Simulation model of the EDS: (a) three dimensional view showing a briefcase inside the inspection cavity, (b) front view showing components of the EDS and layers of the EDS's walls**

objects, such as briefcases or small bags, can enter the inspection cavity on a conveyor belt that moves through the entrance and exit of the inspection cavity. There are two doors (not shown in Figure 1), with the same layers as the EDS's walls, at the entrance and exit of the inspection cavity. The entrance and exit doors will open and close automatically when the object to be inspected is outside and inside the inspection cavity, respectively. Dimensions of the inspection cavity in X, Y, and Z directions are 40 × 80 × 60 cm^3.

Components of the Simulation Model

The simulation model has five important components, namely, a neutron source, a gamma ray detector, a moderator, neutron shielding and gamma ray shielding. The following sections will briefly describe these components.

Neutron Source

^{252}Cf is used as a source to generate fast neutrons and gamma rays for the EDS. It is a point source with the Watt fission energy spectrum which provides fast neutrons with the most probable energy of 0.7 MeV and an average energy of 2.1 MeV. However, it also provides neutrons with higher energies, some as high as 5.5 MeV (Hussein and Waller, 2000; Knoll, 2000). This source is surrounded by a cylindrical lead shield of 10 cm radius and 7 cm height. It is embedded inside the moderator just below the bottom of the inspection cavity as shown in Figure 1(b).

Gamma Ray Detectors

In a real EDS, various types of detectors are used to detect various radiations, but in a simulation, tallies are used to represent those detectors. Since we are interested in simulating two types of radiation quantities, namely, the thermal neutron flux distributed in the inspection cavity and the gamma ray and neutron doses distributed at the outer surfaces of the EDS's walls, F4 and F2 tallies are used to represent the former and the latter, respectively. Dimensions of the gamma ray detector used in this simulation are 7.62 × 7.62 cm^2.

Moderator

In this simulation, three types of moderator are used, namely heavy water, light water and polyethylene. These moderators will slow down and reflect fast neutrons emitted from the neutron source, creating thermal neutrons distributed throughout the inspection cavity. However, some of the fast neutrons may escape from the inspection cavity, reducing the probability of fast neutrons being thermalized in the inspection cavity. Therefore, in the simulation, the thicknesses of the moderators are varied until an optimized condition is achieved or until the highest thermal neutron flux is obtained inside the inspection cavity.

Neutron Shielding Material

As mentioned in Section 3.3, some of the fast neutrons may escape from the inspection cavity and will eventually arrive at the outer surfaces of the EDS's walls, resulting in a neutron dose on the surfaces. We need to prevent the escape of these neutrons to reduce this dose as much as possible. This can be done by putting a neutron shielding material as the second layer of the EDS's walls. To avoid the problem of interference between secondary gamma rays, resulting from interactions between neutrons and the inspected object, and gamma rays resulting from interactions between neutrons and the neutron shielding material, Li_2CO_3 is used as the neutron shielding material of the EDS. In this simulation, the thickness of Li_2CO_3 is varied until the optimized condition is achieved or until the lowest level of neutron doses at the outer surfaces of the EDS's walls is obtained.

Gamma Ray Shielding Material

When neutrons interact with the inspected object, the moderator and the shielding materials, characteristic secondary gamma rays are generated. These gamma rays may escape from the inspection cavity in the same manner as neutrons, causing a certain gamma ray dose on the outer surfaces of the EDS's walls. We also need to prevent these gamma rays from escaping the inspection cavity. This can be done by putting a gamma ray shielding material as the third layer of the EDS's walls. For the same reason as in Section 3.4, i.e. to avoid interference between secondary gamma rays, resulting from interactions between neutrons and the inspected object, and gamma rays resulting from interactions between neutrons and the gamma ray shielding material, lead is used as a shielding material. In this simulation, the thickness of lead is varied until the optimized condition is achieved or until the lowest level of gamma ray doses at the outer surfaces of the EDS's walls is obtained.

Simulation Results

Three types of simulations were performed in this work: (1) simulation of the distribution of thermal neutron flux in the inspection cavity, (2) simulation of radiation doses at the outer surfaces of the EDS's walls and (3) simulation of detection of the 10.8 MeV gamma rays by a gamma ray detector. All these simulations were carried out by using a PC with 866 MHz Pentium III processor. To obtain the statistical uncertainty lower than 5%, each simulation took about 6 - 8 h of CPU time. The results of these simulations will be discussed in the following sections.

Distribution of Thermal Neutron Flux in the Inspection Cavity

For the simulation of the thermal neutron flux distribution, the thicknesses of neutron shielding and gamma ray shielding materials were kept constant at 0.5 and 5.0 cm, respectively, while varying the thicknesses of moderating materials, from 20 to 60 cm with steps of 5 cm. Simulation results show that thermal neutron fluxes increase with the moderator's thickness, with heavy water giving the highest value of flux as shown in Figure 2. Polyethylene gives about the same values of thermal neutron fluxes as light water, reaching the highest value when its thickness approaches 35 cm as shown in Figure 3. However, the flux value for polyethylene with a thickness of 20 cm is only about one percent lower than that for polyethylene with a thickness of 35 cm.

Gamma Ray and Neutron Doses at Outer Surfaces of the EDS's Walls

In this simulation, the primary and secondary gamma rays and neutron doses are simulated by keeping the thicknesses of the moderators constant while varying the thicknesses of the neutron and the gamma ray shielding materials. The simulation results show

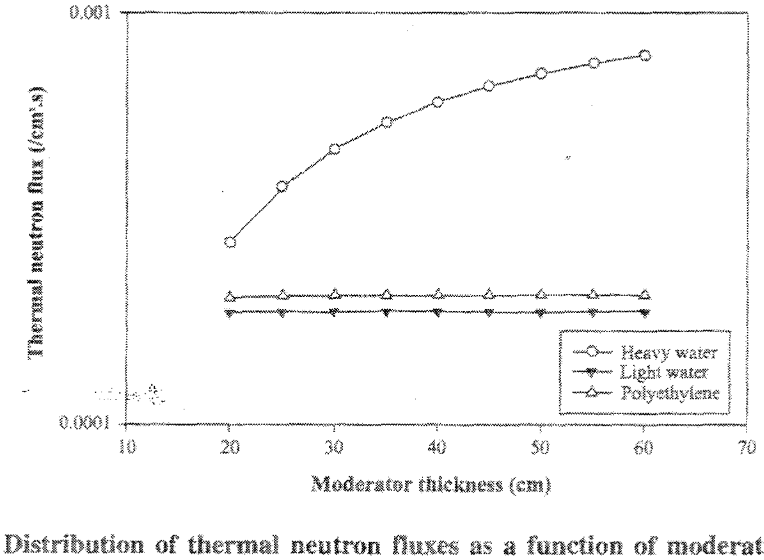


Figure 2. Distribution of thermal neutron fluxes as a function of moderator thickness when heavy water, light water and polyethylene are used as the moderators

that, for each moderator type and thickness, the primary gamma ray dose is about 100% lower than the secondary gamma ray dose but about 100% higher than the neutron dose.

Figure 4 shows a semi-logarithmic plot of the secondary gamma ray and neutron doses (in units of pico Sievert per source particle) as a function of moderator thickness at the outer surfaces of the EDS's walls in X, Y, and Z directions when using polyethylene as a moderator. Both of them decrease with moderator thickness, with the gamma doses decreasing faster than the neutron doses. Similar phenomena are also observed in gamma ray and neutron doses at the outer surfaces of the EDS's walls when using heavy water and light water as moderators.

Total dose values can be obtained by adding the primary and secondary gamma ray doses of each case to their neutron doses.

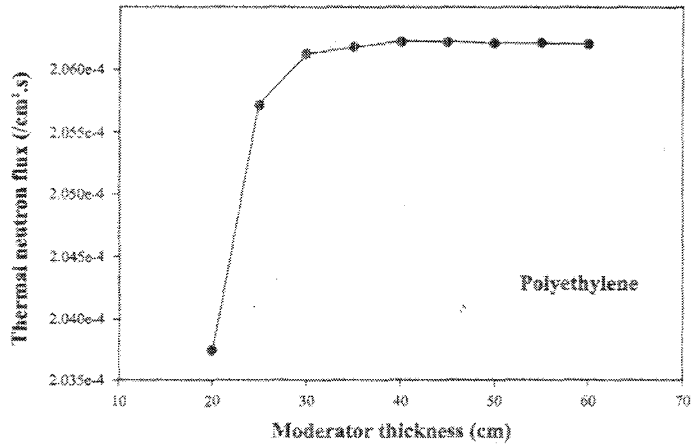


Figure 3. **Distribution of thermal neutron fluxes as a function of moderator thickness when polyethylene is used as the moderator**

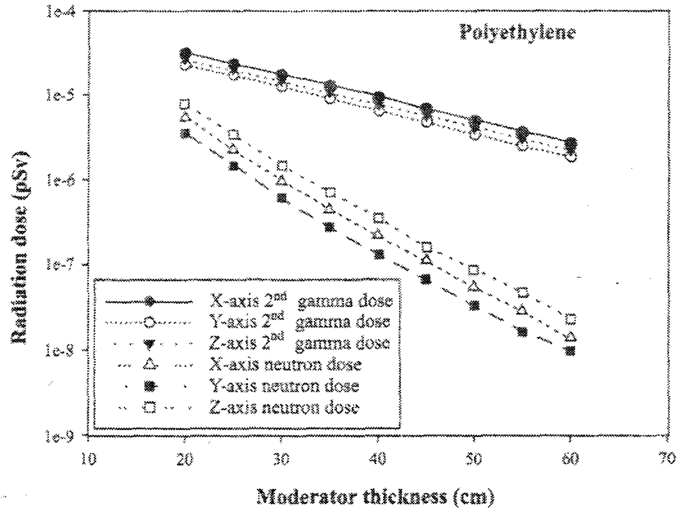


Figure 4. **Semi-logarithmic plots of radiation doses as a function of moderator thickness in X, Y, and Z directions when using polyethylene as a moderator**

Figure 5 shows a linear plot of the total doses as a function of the moderator thickness at the outer surfaces of the EDS's walls in X, Y, and Z directions with polyethylene as a moderator. All of them decrease very quickly with moderator thickness. At a thickness of 35 cm, the total dose in X direction is about 50% higher than those in Y and Z directions, which have about the same values. The same phenomena occur in the total doses when using other types of moderators.

If plotted on a semi-logarithmic plot in a certain direction for all three moderators, total doses at the outer surfaces of the EDS's walls can be compared. Figure 6 shows comparisons of total doses for heavy water, light water and polyethylene in X, Y, and Z directions, respectively. It is interesting that heavy water, which has the highest moderating power, also has the highest radiation shielding power. Polyethylene, which has the second highest moderating power, has about the same radiation shielding power as light water.

Effect of the Neutron Shielding Thickness on Gamma Ray and Neutron Doses

In an attempt to investigate how gamma ray and neutron doses behave when the thickness of neutron shielding material is varied, MCNP code was used to simulate this behavior by varying the thickness of Li_2CO_3 while keeping the thicknesses of the moderator and gamma ray shielding materials constant. The thickness of Li_2CO_3 is varied in three steps from 1 to 5 cm while keeping the thicknesses of polyethylene and lead constant at 35 cm and 0.5 cm, respectively. Figure 7 shows a semi-logarithmic plot of the gamma ray and neutron doses as a function of Li_2CO_3 thickness at the outer surfaces of the EDS's walls in X, Y, and Z directions when using polyethylene as a moderator. Both gamma ray and neutron doses decreased, about 10% when Li_2CO_3 thickness increased from 1 to 5 cm.

Effect of the Gamma Ray Shielding Thickness on Gamma Ray and Neutron Doses

To investigate characteristics of the gamma ray and neutron doses when varying the thickness of gamma ray shielding material, a simulation was performed. This time the thickness of lead was varied from 0.3 to 0.5 cm while keeping the thicknesses of polyethylene and Li_2CO_3 constant at 35 and 5 cm,

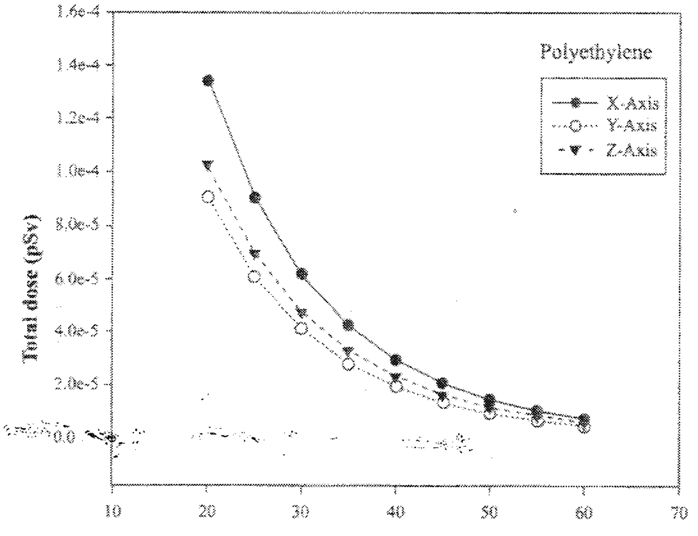


Figure 5. Linear plots of total doses as a function of moderator thickness in X, Y, and Z directions when using polyethylene as a moderator

respectively. Figure 8 shows a semi-logarithmic plot of gamma ray and neutron doses as a function of lead thickness at the outer surfaces of the EDS's walls in X, Y, and Z directions. Again, both doses decreased slightly by about 5% when lead thickness was increased from 0.3 to 0.5 cm.

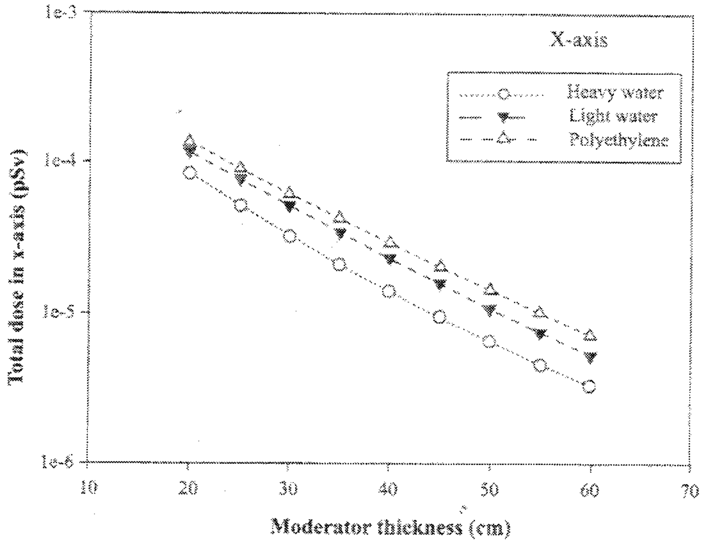


Figure 6. **Semi-logarithmic plot of the total dose in X direction as a function of moderator thickness when using heavy water, light water and polyethylene as moderators**

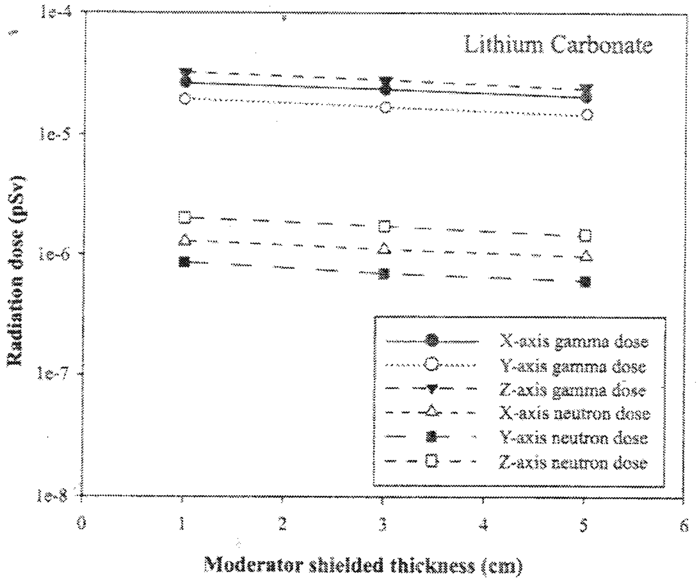


Figure 7. **Semi-logarithmic plots of gamma ray and neutron doses as a function of Li_2CO_3 thickness at outer surfaces of the EDS's walls in X, Y, and Z directions when using polyethylene as a moderator**

Simulation of the Detection of the 10.8 MeV Gamma Rays

For the purpose of the EDS source strength estimation, the detection of the 10.8 MeV gamma rays was simulated. In this simulation, TNT and RDX of various masses were put at the center of the inspection cavity for inspection. Figure 9 shows fluxes of the 10.8 MeV gamma rays detected by a gamma ray detector with TNT and RDX of 200, 500, and 1,000 g at the center of the inspection cavity. Theses fluxes are used to estimate the required EDS source strength in Section 5.

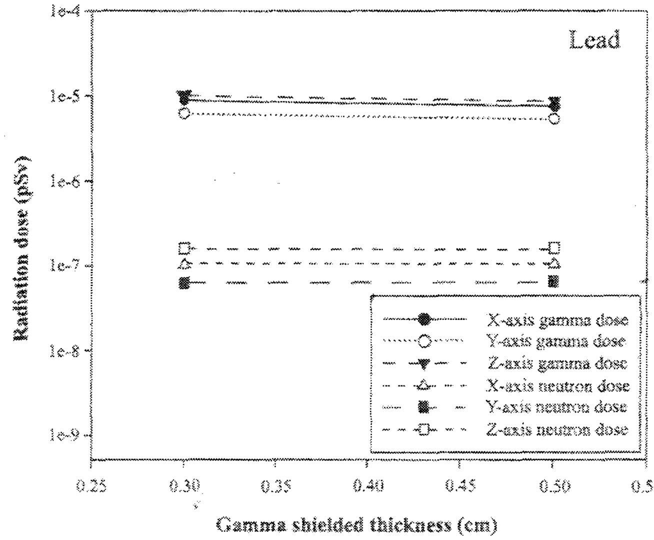


Figure 8. **Semi-logarithmic plots of gamma ray and neutron doses as a function of Pb thickness at outer surfaces of the EDS's walls in X, Y, and Z directions when using polyethylene as a moderator**

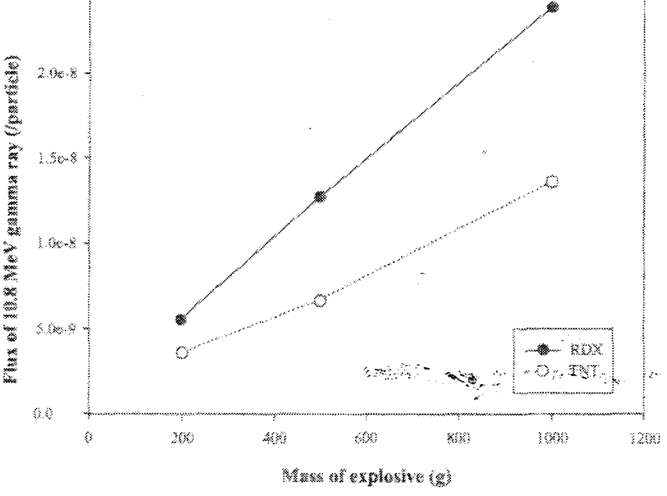


Figure 9. **Fluxes of the 10.8 MeV gamma rays detected by a gamma ray detector when TNT and RDX of various masses are put at the center of the inspection cavity for inspection**

Discussion and Conclusion

In this section, source strength and the maximum total dose estimations will be discussed, leading to the conclusion in Section 5.3.

Source Strength Estimation

Reading from Figure 9, the 10.8 MeV gamma rays fluxes detected by a gamma ray detector for various explosive masses were obtained, as shown in Table 1. These fluxes increase linearly with explosive mass. By using these fluxes, the required EDS source strength S, can be estimated from the formula, $S = CPS / N_\gamma$, where CPS and N_γ are numbers of counts per second and flux of the 10.8 MeV gamma rays, respectively. Assuming the signal- to- noise ratio of 3, the required minimum flux of 10.8 MeV gamma rays detected by a gamma ray detector can be 100. Taking this value of minimum flux and choosing a reasonable counting time of 60 s, $CPS = 100 / 60 = 1.67$. For the case of inspection of 500 g TNT, the 10.8 MeV gamma ray flux, $N_\gamma = 6.64 \times 10^{-9}$ (Table 1). The above formula will then give the required source strength, $S = 1.67 / 6.44 \times 10^{-9} = 2.59 \times 10^{8}$ n/s. By using the same source strength and CPS values, the 10.8 MeV gamma ray flux for the case of RDX inspection will be the same as that of the TNT case (6.64×10^{-9}). By using this value of gamma ray flux for extrapolation in the top graph of Figure 9, the detection sensitivity for inspection of RDX will be about 230 g. The EDS's detection sensitivity for RDX inspection is more than twice that for TNT inspection. Following the same procedures, we can estimate source strengths required for inspection of 200 and 1,000 g of TNT to be 4.60×10^{8} and 1.22×10^{8} n/s, respectively. The corresponding detection sensitivities for RDX inspection of these two cases can be obtained by reading from the top graph of Figure 9, with the values of 115 and 520 g, respectively.

Maximum Total Dose Estimation

With known source strength S, the maximum total dose rate received by a control operator in one year can be estimated from a formula, $H = D \times S \times t$, where D is the absorbed dose and t is the time period that the control operator works with the EDS in 1 year ($t = 52$ w/y $\times$ 5 d/w $\times$ 8 h/d $\times$ 3,600 s/h $= 7.49 \times 10^{6}$/s). For the case of using 20 cm thick polyethylene as a moderator with neutron and gamma ray shielding materials of 5 and 0.5 cm thick, respectively, $D = 13.39 \times 10^{-6}$/pSv. Since the required source strength for the case of inspection of 200 g of TNT or 115 g of RDX is 4.60×10^{8}/n/s, the maximum total dose rate received by a control operator will be $H = 13.39 \times 10^{-18}$/Sv $\times 4.60 \times 10^{8}$/n/s $\times 7.49 \times 10^{6}$/s $= 0.046$ Sv/y. This value is well under the ICRP whole body maximum permissible dose (MPD) of 0.05 Sv/y (ICRP, 1977).

Table 1. Fluxes of the 10.8 MeV gamma rays detected by a gamma ray detector in a unit of per source neutron

Type of explosive	Mass of explosive (g)	Flux of the 10.8 MeV gamma rays (per source neutron)
RDX	200	5.51×10^{-9}
RDX	500	1.27×10^{-8}
RDX	1,000	2.39×10^{-8}
TNT	200	3.59×10^{-9}
TNT	500	6.64×10^{-9}
TNT	1,000	1.36×10^{-8}

Conclusion

The conclusions of this work are as follows. Though heavy water gives the highest moderating and shielding powers, for economic and practical reasons polyethylene is selected as the moderator of the EDS. Li_2CO_3 and lead are selected as neutron and gamma ray shielding materials. Their optimum thicknesses are 20.0, 0.5, and 5.0 cm, respectively. These thicknesses give rise to the maximum thermal neutron flux at the center of the inspection cavity of $2.04 \times 10^{-4}/cm^2$- s. The maximum total dose at the outer surfaces of the EDS's walls occurs in X direction with the value of 13.39×10^{-6}/pSv. Fluxes of the 10.8 MeV gamma rays detected by a gamma ray detector were simulated for various masses of TNT and RDX sitting at the center of the inspection cavity. It was found that for the case of 200 g TNT inspection, the 10.8 MeV gamma ray flux is 3.59×10^{-9}. With this value of gamma ray flux, the required EDS source strength is estimated to be 4.60×10^8/n/s. The corresponding EDS detection sensitivity for RDX inspection is 115 g. Using a source strength value of 4.60×10^8/n/s, the maximum total dose rate received by a control operator is estimated to be 0.046 Sv/y which is well under the ICRP whole body MPD of 0.05 Sv/y. It would be interesting to confirm the results from this simulation through actual experiments.

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