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Full Length Research Paper

Design of an explosive detection system to investigate the luggage of aircraft passenger based on neutron-gamma technique

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In this study an explosive detection system to investigate luggage of air travelers by the Monte Carlo N-Particle Transport code (MCNP5) has been designed. Concrete as a commonly shielding material was the main part in the designed system. Pulsed neutron generator with 14.1 MeV neutrons was used as a neutron source. Two time gates were used in gamma detection process. The lead was used as a secondary gamma rays shielding material for the sake of background reduction. The equivalent dose outside the designed system was less than the accepted level. Gamma signals from different weights of explosives 1.833, 1.173, 0.815 and 0.399 kg at different detector positions were calculated. The results show that the designed system can be provide a reasonable values of signal-to-background ratio from the explosive basic elements constitute, C, O and N.

Key words: 14 MeV neutron, design, explosive, gamma radiation, lead, Monte Carlo calculation, neutron irradiation.

INTRODUCTION

The detection of explosives and threat materials inside packages and luggage of an aircraft passenger has become an essential requirement that must be faced with a comprehensive technical solution, in order to preserve life and property, especially in light of the growing phenomenon of terrorism in recent days. The detection and identification of explosives by neutron and gamma-ray interrogation has been investigated for over six decades (McFee et al., 2013). Prompt gamma-ray neutron activation analysis (PGNAA) offers an on-stream, non-destructive, relatively rapid method for the determination of elemental composition of bulk samples on conveyor belts (Jiaxin et al., 2011). The objectives of this type of inspection are to look for explosives in objects as small as a briefcase and as large as a truck and marine shipping container (Tsahi and Dan, 2007). The technique is based upon bombarding a sample with neutrons and measurement of the prompt gamma-ray spectrum emitted from the elements in the sample via fast neutrons inelastic scattering and/or thermal neutron capture (Nasrabadi et al., 2011; Runkle et al., 2009). There are extensive existing literatures on the designs of

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neutron-induced gamma-ray detector systems for material composition analysis, including many papers on the detection of explosives. The existing literatures comprehensively discuss most aspects of the system design, including, source design, source pulsing optimization, shielding design, detector design and positioning and sample presentation. The references of these literatures can be found in Koltick et al. (2007). The basis, however, is always the same: Look for the elemental signatures and deduce from them the presence or absence of explosives (Tsahi and Dan, 2007). The basic problem that face this technique are that, the principal elements which constitute explosives and illicit drugs (H, C, N and O) are present also in the benign materials, but with different concentrations. A certain concentration level of nitrogen is a good indicator of explosives, the combinations of oxygen, hydrogen and carbon should be considered since some common compounds such as melamine and silk contain high concentrations of nitrogen similar to explosives (Hee-Jung et al., 2006). In addition, the background associated with gamma signals which can mask these signals should be reduced to an acceptable level.

The work in the field of explosives detection needs to be more in the nature of a scoping study. In this study, we will work on the detection of explosives through a more realistic design. MCNP5 program will be used to simulate an explosive investigation system based on neutron-gamma technique to check the luggage of aircraft passenger with a shielding method to reduce the background of gamma rays.

DESIGN OF EXPLOSIVE DETECTION SYSTEM

The Monte Carlo N-Particle Transport code (MCNP5) has been used for the present simulations (MCNP X-5, 2003). Calculations were performed using the neutron source as a fixed point isotropic source with continuous nuclear cross-section data based on the ENDF/B- VI.

A D-T pulsed neutron generator operating at 10^8 neutrons per second has been simulated. The generator was used to emit 14 MeV fast neutrons to get the gamma ray signals as a result of the interaction of fast neutrons with carbon, oxygen and nitrogen present in an explosive material (FNA). Gamma ray signals from nitrogen can be obtained as a result of the interaction of the thermalized neutrons with nitrogen atoms present in the explosive material (TNA). Using a D-T neutron generator as a high energy neutron source has some advantages which can be found in Ref. (Koltick et al., 2007; Reda, 2011; Farhad and Masoud, 2014). The neutron collimator was designed in a cone shape. The emitted neutrons have spread in the form of a cone to confirm that the whole checked luggage or bag was irradiated with neutrons.

The radiation shielding is an integral part of any radiation facility to minimize the radiation exposure. The shielding can serve the purpose for attenuation of gamma and neutron up to an acceptable level by a single material, compounds or mixture of the elements (Vishwanath et al., 2013). Concretes are the most commercially commonly used materials at various facilities in the field of radiation shielding. Therefore, on the basis of cost, the main part of the shielding of the designed system was made of ordinary concrete. The elemental composition of the used ordinary concrete can be found in Vishwanath et al. (2013).

Simulations were implemented in two stages. In the first stage (Figure 1), the concrete material was used as a neutron source housing with dimensions 150 cm × 150 cm × 50 cm height. Neutron source was put at a distance 30 cm under the surface of the concrete box and 5 cm above the head edge of the collimator cone. The neutron collimator opening at the surface of concrete box is 49.5 cm in diameter. Concrete walls on the right and the left are 72.25 cm in thickness each; with a separation distance between them 100 cm. Five idealized detectors were designed into the system to detect gamma ray emitted from the investigated luggage. Each detector having a cylindrical geometry (radius 6.35 and length 20 cm) was surrounded by a 5 cm lead shield cylinder. The distance between the five detectors and the surface of the neutron housing box is 50 cm. The concrete shield above the detectors was 67.3 cm in thickness. The distance between entry and exit points of the investigated object is 150 cm in length.

The detection of an explosive was simulated using a block of TNT with variable weights ($C_7H_5N_3O_6$; density, 1.63 g cm^{-3}). The TNT block was placed at the center of the investigation system. FTn card (Special Treatments for Tallies) was used with a special treatment TMC a b. This means that, the tally scores are made as if the neutron source was actually a square pulse starting at time a, and ending at time b. The values of a and b in the special treatment TMC are 100 shakes and 1000 shakes, respectively (1 shake=10^{-8} s), that is, the neutron generator was turned on for a time interval 10 µs. Tally time card Tn was divided into three time bins (10^2, 10^3 and 10^4 shakes). Therefore, gamma rays were registered in detectors through two different time gates, 10 µs (neutron generator, turn on) and 100 µs (neutron generator turns off). The gamma spectra were measured with and without explosive by a tally type 5.

RESULTS AND DISCUSSION

Figure 2 shows the gamma spectra registered in detectors D_1, D_2 and D_3 without and with a block of TNT of weight 1.833 kg, 15 cm × 15 cm by 5 cm thickness (as a result of the system design symmetry, detectors D_4 and D_5 not included in the discussion). Figure 2a shows the gamma spectra registered in detectors through the time gate of neutron generator turn on. As shown in figure, for all detectors, no obvious difference between gamma spectra with and without explosive. This means that, secondary gamma rays produced from neutron interaction with elements constitute the shielding materials of the designed system mask gamma signals produced from neutron interaction with elements constitute the explosive materials. Figure 2b shows the gamma spectra registered through the time gate of neutron generator turn off. As shown in figure, for all detectors, there is a gamma signal at 10.829 MeV as a result of the interaction of neutron with nitrogen present in explosive. The nitrogen element does not present in shielding materials of the designed system, which confirm that the shielding materials affect the detectors explosive identification.

A major challenge that the detector face in our detection system is the secondary gamma rays produced as a result of neutron interaction with system shielding materials. Therefore, a shielding from shielding should be inserted to prevent these secondary gamma rays from arriving to detectors.

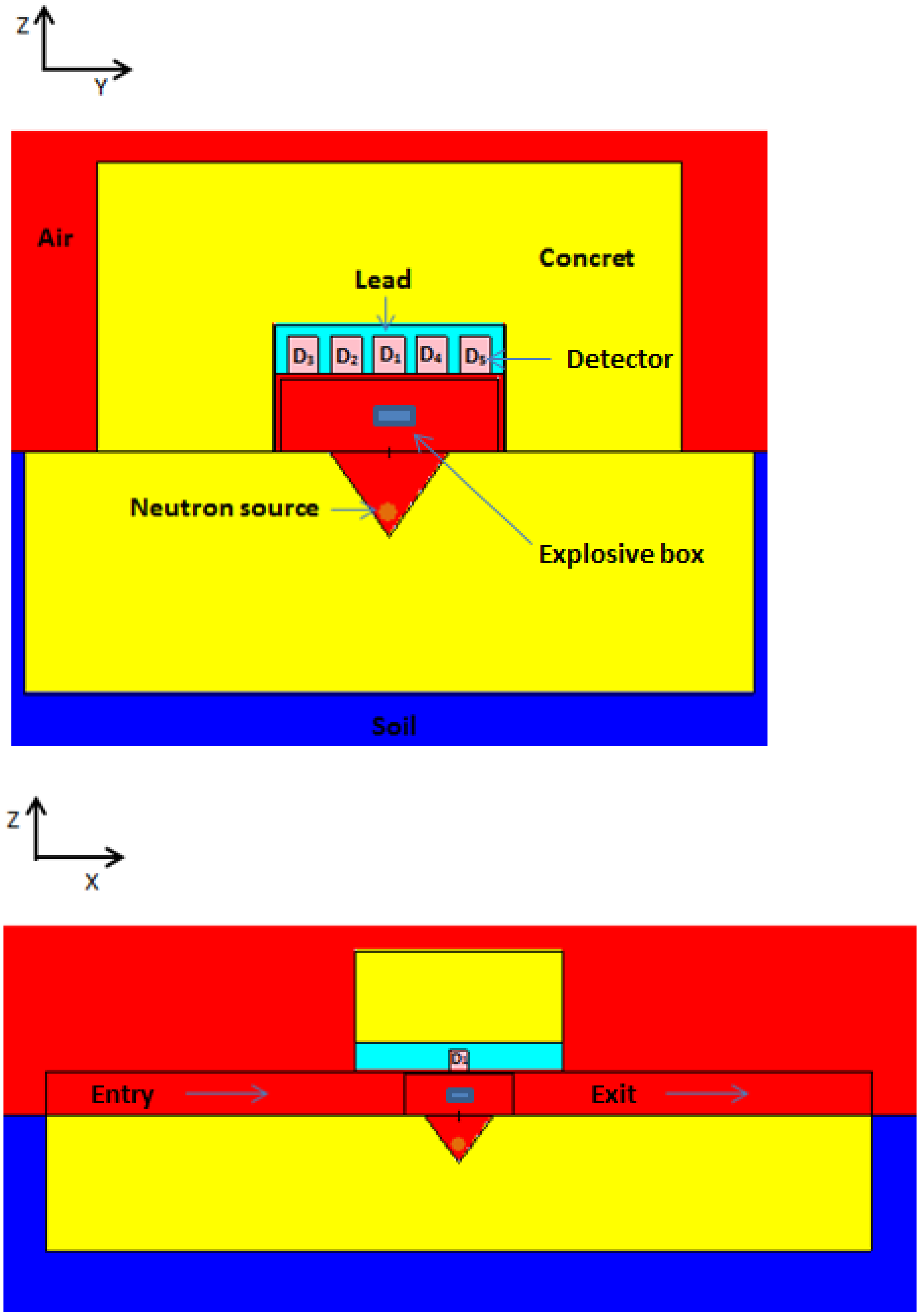


Figure 1. Vertical cutoff view (YZ and XZ cross-section) for explosive detection system shielding design (dimensions are not to scale).

The second stage of our simulations (Figure 3), a variable thickness of lead layer was put as an internal cover for the concrete shield at the expense of the concrete thickness.

Figure 4a and b shows a comparison of the gamma rays (background) registered in detector D_1 at different lead layers 0, 1, 3, 5, 7, 9 and 11 cm in thickness. The detection was through the time gate of a neutron generator, turn on and turns off, respectively. The effect of lead inner shielding was noticeable in reducing the background peaks. Table 1 presents the flux of interested peaks (turn on gate) for a 0 cm lead shielding (Φ_B (0 cm)) as a comparison with the same peaks at the different studied thicknesses of lead shielding (Φ_B (t cm)). The table also shows the percentage ratio between the fluxes of gamma peaks for the different thicknesses of lead shielding with respect to those at 0 cm lead shielding.

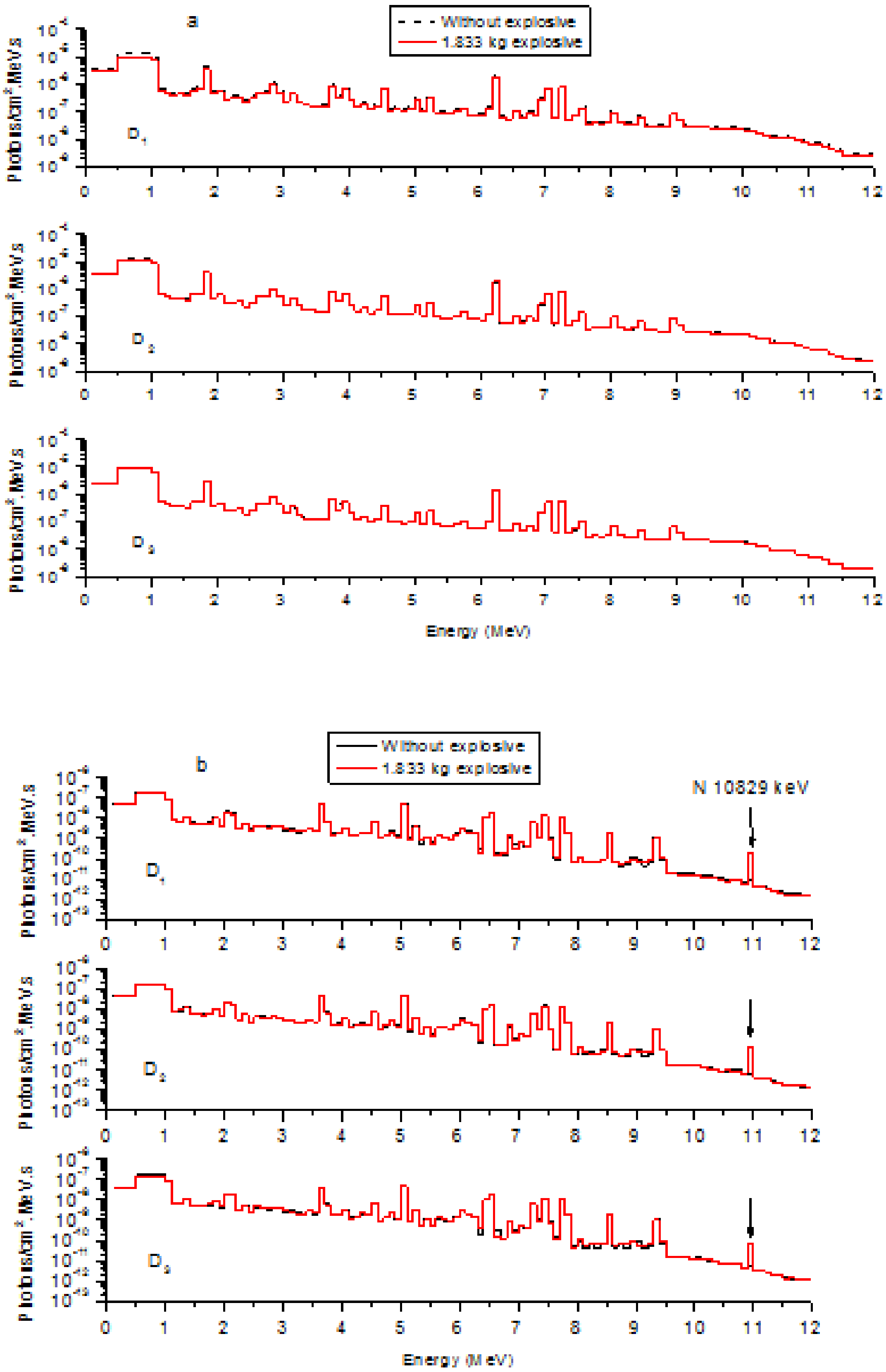


Figure 2. Gamma ray spectra accumulated through detectors D_1, D_2 and D_3 over time gates of neutron generator, turn on (a), and turn off (b), respectively. Gamma spectra were measured without and with a block of TNT of weight 1.833 kg.

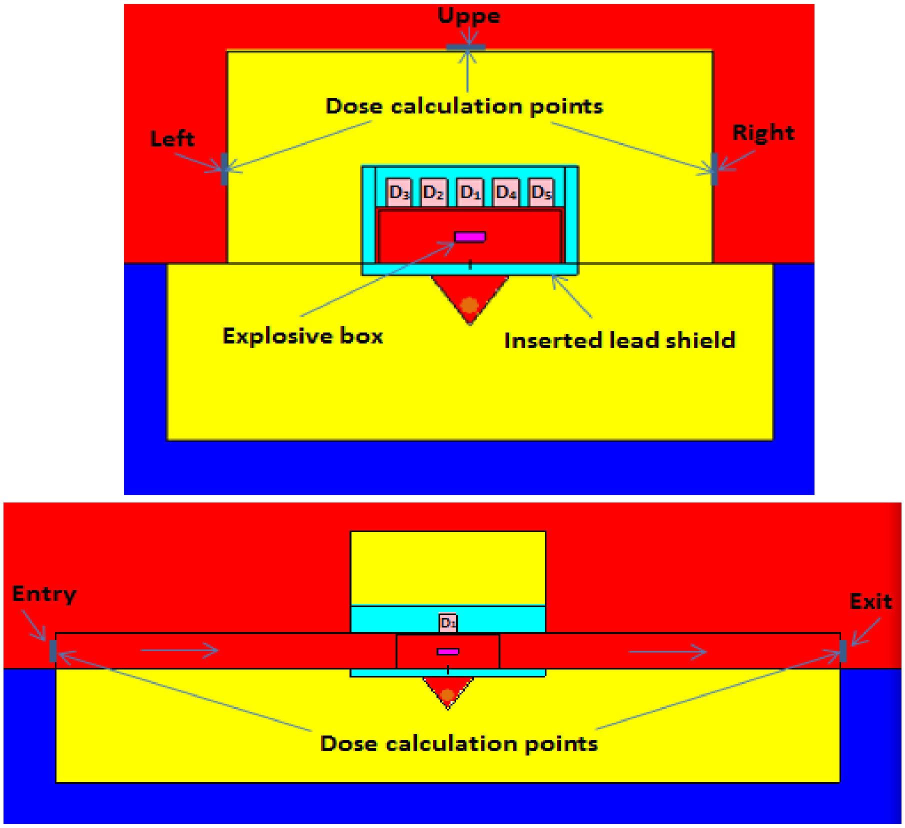


Figure 3. Vertical cutoff view (YZ and XZ cross-section) for explosive detection system shielding design with inserted lead shield (dimensions are not to scale). Points where the dose was estimated are also indicated. All considerations are as in Figure 1.

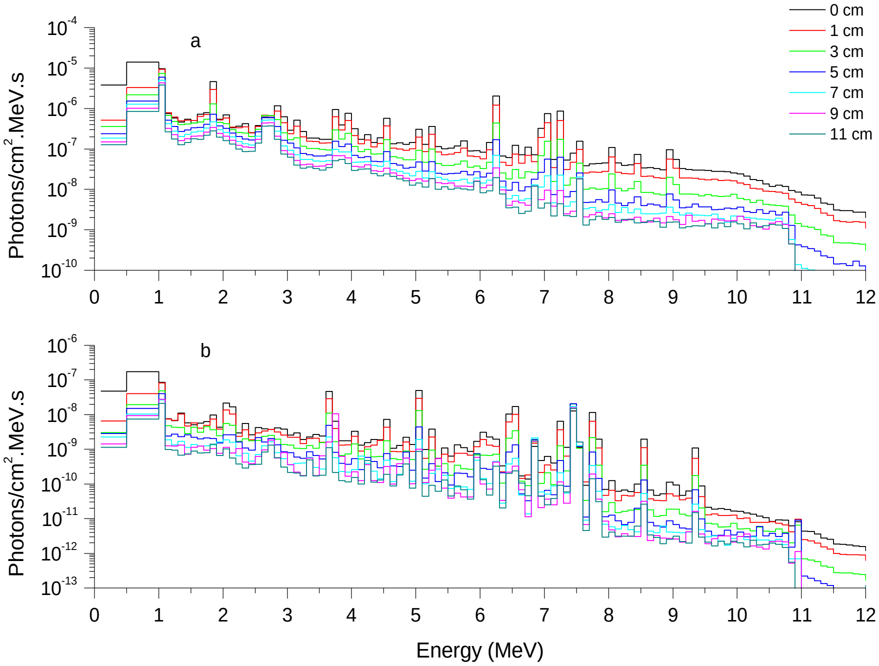


Figure 4. Gamma ray spectra accumulated through the detector D_1 over time gates of neutron generator, turn on (a), and turn off (b), respectively. Gamma spectra were measured with inner lead shielding 1, 3, 5, 7, 9 and 11 cm in thickness.

Table 1. The flux of interested peaks in gamma background spectra for different inner lead shielding layers, in addition, the percentage ratio of peaks. The data for detector D_1 in case of turn on time gate.

Energy (MeV)	0 cm	1 cm	3 cm	5 cm	7 cm	9 cm	11 cm
4.5	5.74E-7	3.73E-7	1.68E-7	8.54E-8	4.95E-8	3.33E-8	2.42E-8
6.2	2.02E-6	1.21E-6	4.4E-7	1.68E-7	6.95E-8	3.37E-8	1.94E-8
7	7.52E-7	4.44E-7	1.55E-7	5.58E-8	2.17E-8	9.46E-9	4.56E-9
7.2	8.56E-7	5.03E-7	1.74E-7	6.22E-8	2.26E-8	9.42E-9	4.46E-9
***Percentage Ratio=[Φ_B (t cm)/ Φ_B (0 cm)] × 100**							
4.5		64.98	29.27	14.88	8.62	5.80	4.22
6.2		59.90	21.78	8.32	3.44	1.67	0.96
7		59.04	20.61	7.42	2.89	1.26	0.61
7.2		58.76	20.33	7.27	2.64	1.10	0.52

*t is the lead thickness.

Table 2. Dose values (µSv/hr) around the final system design at right or left surface, upper surface and entry or exit point (Figure 3). ICRP dose equivalent factors for neutrons and photons have been used.

Position	Dose		
	Neutron	Gamma	Total
Right or left surface	2.38	0.245	2.625
Upper surface	1.99	0.193	2.183
Entry or exit point	2.58	0.024	2.604

The values of percentage ratio show that the peaks dramatically decrease with lead thickness increase. The preferred lead thickness in our present work was 7 cm lead thickness on the base of the comparison between the thickness increase and the percentage ratio decrease. The final design assures the attainment of highest signal at the lowest background.

The dose values around the final designation of the system (Figure 3), with inner lead 7 cm in thickness, are given in Table 2. The flux-to-dose rate conversion factors for neutrons and photons were obtained using the International Commission on Radiological Protection (ICRP) data included in the MCNP5 program, and the DE and DF tally cards were used to convert from particle flux to human biological dose equivalent rate. The dose values obtained in Table 2 are lower than the accepted limit recommended by ICRP-26 (25 µSv h^{-1}) for occupational exposures (Reda, 2011; ICRP, 1977).

Testing of the final designation of the system was carried out. Different weights of explosives 1.833, 1.173, 0.815 and 0.399 kg were put in the center of the system cavity, respectively. Figure 5 (a, b and c) shows gamma spectra registered in detectors D_1, D_2 and D_3, respectively, in case of a neutron generator turn on, without and with the different weights of explosives. There are an obvious difference in gamma peaks of the interested elements C and O compared with the spectrum without explosive.

In case of neutron generator, turn off, Figure 6 (a, b and c) for detectors D_1, D_2 and D_3, respectively, shows that the signal of N in gamma ray spectra for the investigated weights of explosive (1.833, 1.173, 0.815 and 0.399 kg) can be easily distinguished from a spectrum of gamma ray without explosive.

As shown in Figures 5 and 6 the decrease in explosive weight meets by the decrease in gamma signal. In practice, the detection of explosive is efficient when the flux of considerable gamma ray signals (C, O and N) in present of explosive Φ_E, increases considerably in comparing with the same gamma signals in absent of explosive Φ_B (flux of background). Therefore, the signal-to-background ratio SBR (Φ_E/Φ_B) as an analyzed method for explosive detection gives the required decision for explosive identification.

Figure 7 (a, b and c) shows the SBR for C, O and N gamma signals collected in detectors D_1, D_2 and D_3, respectively, for different explosive masses. There is an obvious increase in SBR with explosive mass increase for all detectors.

For the sake of comparison, Table 3 shows the SBR of gamma signals of interested elements C, O and N

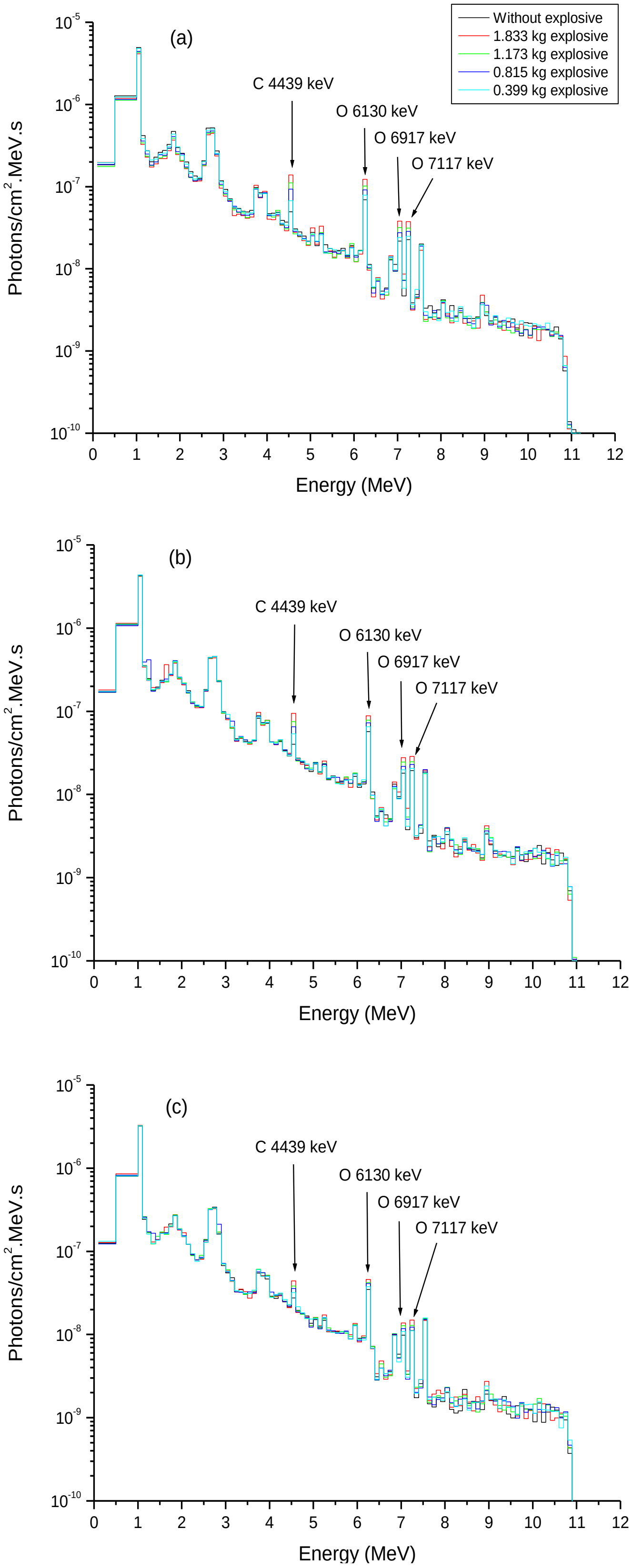


Figure 5. Gamma ray spectra accumulated through detectors D_1 (a), D_2 (b) and D_3 (c), over time gate of neutron generator, turn on. Gamma spectra were measured without and with explosive of weights 1.833, 1.173, 0.815 and 0.399 kg.

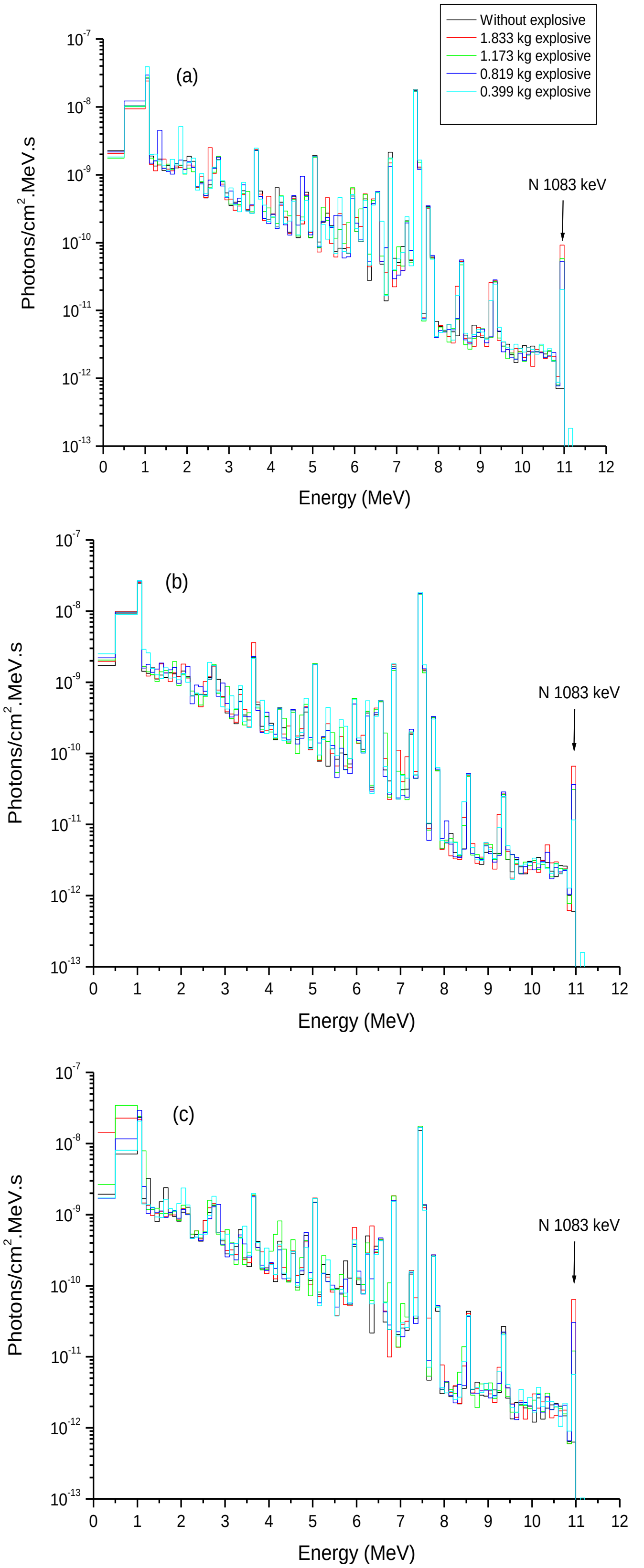
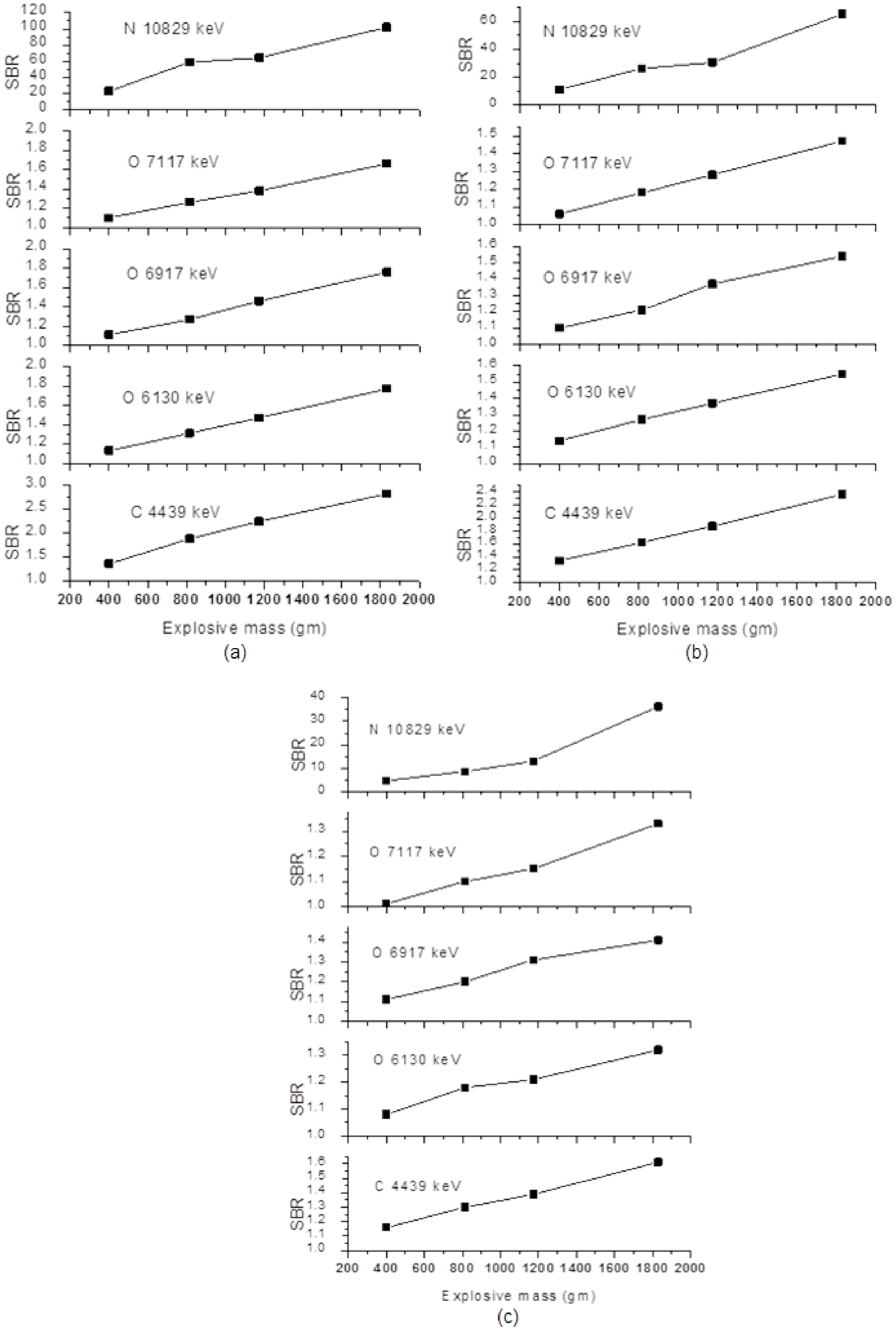


Figure 6. Gamma ray spectra accumulated through detectors D_1 (a), D_2 (b) and D_3 (c), over time gate of neutron generator, turn off. Gamma spectra were measured without and with explosive of weights 1.833, 1.173, 0.815 and 0.399 kg.



(a) (b) (c)

Figure 7. SBR for gamma signals of C, O and N versus explosive mass for detectors D_1 (a), D_2 (b) and D_3 (c).

Table 3. Signal-to-background for interested signals of gamma ray of the interested explosive elements for different explosive weights.

Element	Energy (keV)	Explosive mass (kg)											
		1.833			1.173			0.815			0.399		
		D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3
C	4439	2.81	2.36	1.61	2.24	1.87	1.39	1.88	1.62	1.3	1.36	1.34	1.16
	6130	1.77	1.55	1.32	1.47	1.37	1.21	1.31	1.27	1.18	1.13	1.14	1.08
O	6917	1.76	1.54	1.41	1.46	1.37	1.31	1.27	1.21	1.2	1.11	1.1	1.11
	7117	1.66	1.47	1.33	1.38	1.28	1.15	1.26	1.18	1.1	1.1	1.06	1.01
N	10829	102	65.5	36.3	64.2	30.7	13.1	58.6	26.3	8.67	22.7	11.5	4.7

registered in detectors D_1, D_2 and D_3. The table indicates that the increase in explosive mass meets with an increase in SBR and the values of SBR are higher for detector D_1 than the others detectors due to the nearest of D_1 from the explosive position. There is a degradation in the values of SBR for detectors D_1, D_2 and D_3, respectively, corresponding to far away from explosive position.

Conclusion

The designed system is consistent with safety requirements, cost limitations and material availability. The simulations performed in this study indicate that the explosive detection depends mainly on the background reduction, which depends on lead thickness in our design. The method of using the lead materials as a shielding from shielding is affecting the signal to background ratio. Two time gates enables to pick signals from the most basic elements constitute explosive. This study shows that explosive mass within the limits of 400 g can be detected through the designed system. The designed system should be tested with luggage having containment, including explosive which will be the future work.

Conflict of Interest

The authors have not declared any conflict of interest.

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