THE SENSITIVITY STUDIES OF A LANDMINE EXPLOSIVE DETECTION SYSTEM BASED ON NEUTRON BACKSCATTERING USING MONTE CARLO SIMULATION

by

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This paper carries out a Monte Carlo simulation of a landmine detection system, using the MCNP5 code, for the detection of concealed explosives such as trinitrotoluene and cyclonite. In portable field detectors, the signal strength of backscattered neutrons and gamma rays from thermal neutron activation is sensitive to a number of parameters such as the mass of explosive, depth of concealment, neutron moderation, background soil composition, soil porosity, soil moisture, multiple scattering in the background material, and configuration of the detection system. In this work, a detection system, with BF_3 detectors for neutrons and sodium iodide scintillator for γ-rays, is modeled to investigate the neutron signal-to-noise ratio and to obtain an empirical formula for the photon production rate $R^i_{(n,\gamma)} \quad Sf_G f_M f(d,m)$ from radiative capture reactions in constituent nuclides of trinitrotoluene. This formula can be used for the efficient landmine detection of explosives in quantities as small as 200 g of trinitrotoluene concealed at depths down to about 15 cm. The empirical formula can be embedded in a field programmable gate array on a field-portable explosives' sensor for efficient online detection.

Key words: explosive, land mine detector, thermal activation, moderator, Monte Carlo

INTRODUCTION

The use of neutrons for detection and characterization of explosives has been extensively studied [1-3] especially for the detection of concealed explosives in vehicles [4], air cargo [5], and for humanitarian demining [6-8].

The choice of moderator and the design of an optimal configuration is crucial to the efficacy of an anti-personnel landmine detection system where the buried explosive is small (typically <300 g of trinitrotoluene (TNT), cyclonite (RDX), *etc*.) and 10-15 cm deep. Such a system uses the signature from thermal backscattered neutrons to detect and characterize explosives. This is an important application of thermal neutron activation analysis (TNAA) as, according to UN estimates, there are over 110 million anti-personnel mines in 64 countries and over 26000 people a year become victims.

Essentially the use of neutrons is through scattering by fast neutrons or by activation by thermal neutrons; in both cases, the radionuclides formed emit characteristic gamma rays which can be used as a signature to identify constituent elements of explosives such as hydrogen, carbon, oxygen, and nitrogen. For the detection of antipersonnel landmines, the thermal neutron backscattering (TNB) method is used.

The Monte Carlo N-particle code MCNP5 [9] has been extensively used to model a landmine detection system [10-12] based on thermal neutron activation and detection of the back-scattered neutron and gamma radiation for the detection of a concealed explosive. It is thought [7] that the neutron backscattering using ^{252}Cf or ^{241}Am-^{9}Be radio-isotopic sources are appropriate only for shallow arid soils and lack the required sensitivity for the effective detection of small quantities (sub-kilogram) in landmines. Thus D-D driven inertial electrostatic confined fusion (IECF) devices have also been developed producing 10^7 D-D neutrons per second stably which have been shown to effectively detect the gamma rays of 10.83 MeV emitted by N atoms from 800 g melamine (plastic) explosives over a measurement time of 1500 s. Baysoy and Subasi [11] have carried out a detailed Monte Carlo simulation and have shown that a landmine system us-

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ing neutron backscattering could detect a small cylindrical landmine distinguishing down to <300 g TNT explosive from other nearby substances until a burial depth of 15 cm in limestone with a scanning speed of 9.6 m^2 per minute.

Experiments have also been carried out for TNT of mass 1000, 520, and 200 g using ^{252}Cf for 900 s counting time [13] with a helium detector for neutrons and a NaI detector for gamma rays and it is reported that the 10.8 MeV gamma rays give 0.53 0.06 counts per second per kilogram compared with MCNP result 0.62 0.07 counts per second per kilogram.

The objective of this work is to:

– carry out a simulation of a landmine explosive detection system with ^{252}Cf source and BF_3 and NaI detectors, for a small quantity (~<200 g) of TNT,
– estimate neutron detection efficiency in BF_3 detectors based on the $B(n, \alpha)$ reactions,
– estimate gamma production in concealed explosives from radiative capture reactions for subsequent gamma detection, and
– develop an empirical formula for the γ signal, as a function of the explosive mass and the depth of concealment, at the NaI detection system. This formula can be embedded in a field programmable gate array (FPGA) for the use in a field-portable explosives' sensor.

THE MODEL

For a preliminary analysis, a configuration shown in fig. 1 is modeled to map the neutron and photon fluxes and associated reaction rates from thermal neutron activation of a small (~200 g) sample of TNT. The system consists of an anisotropic ^{252}Cf source, labeled „S" placed in a capsule in a moderator (borated wax: $\rho = 0.947$ gcm^{-3} with weight fractions: H 0.14, C 0.83, B^{10} 0.01, B^{11} 0.02) with the BF_3 tubes, the sodium iodide (NaI) detector, the soil (limestone $\rho =$ 2.71 gcm^{-3} with weight fractions: carbon 0.12, oxygen 0.48, and calcium 0.40) and the concealed explosive.

The radioisotope californium ^{252}Cf, an intense spontaneous fission is taken as the source with an emission of 2.31 10^7 neutrons per second [14]. The BF_3 region is modeled as a cylindrical tube of radius 1.5 cm, length 30 cm filled with gas of density 2.567 10^{-3} gcm^{-3} (weight fractions: B^{10} 0.143368, B^{11} 0.006568, F^{19} 0.85).

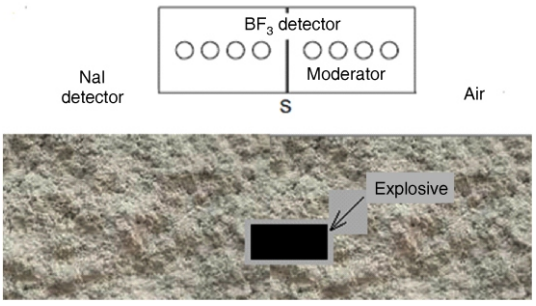

Figure 1. Landmine detection system modeled with MCNP5

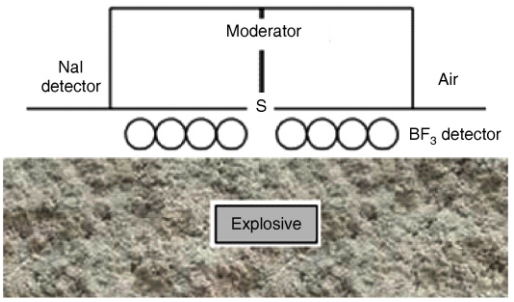

Figure 2. Landmine detection system with BF_3 tubes placed below the moderator

A NaI scintillator detector is used with radius 3.9238 cm and length 5 cm.

In the second model, shown in fig. 2, the BF_3 tubes are placed outside the box of moderator for reasons that will be explained in the following sections.

METHODOLOGY

Monte Carlo simulation was carried out to determine the neutron flux ϕ using the F4 tally of MCNP and subsequent reaction rates.

Alpha production reactions (n, α) for neutron detection

Neutron detection in the BF_3 detector takes place by the following nuclear reaction in the gas

$$^{10}_{5}\mathrm{B} \; ^{1}_{0}n \quad ^{7}_{3}\mathrm{Li} \; ^{4}_{2}\mathrm{He} \qquad (1)$$

for which the MCNP FM14 tally is used as follows

$$FM14 \qquad {}^{(BF_3)}_{n,\alpha}\phi(r,E,\Omega)\mathrm{d}V\mathrm{d}E\mathrm{d}\Omega \qquad (2)$$

where $\Sigma^{(BF_3)}_{n,a}$ is the macroscopic cross-section in BF_3 for the n, α reaction, V – the region volume, E – the neutron energy, and Ω – the solid angle.

Radiative capture reactions (n, α) for photon detection

Commonly used explosives contain hydrogen (2-4 wt. %), carbon (9-37 wt. %), oxygen (8-50 %) and nitrogen (13-70 wt. %) *e. g.* TNT has a mass composition: H (2.2 %), C(37.02 %), O(42.26 %), and N(18.5 %).

Thus, the detection, and subsequent characterization of an explosive require determination of atomic densities of H, C, O and N. The following fast and thermal reactions are thus important for characterization.

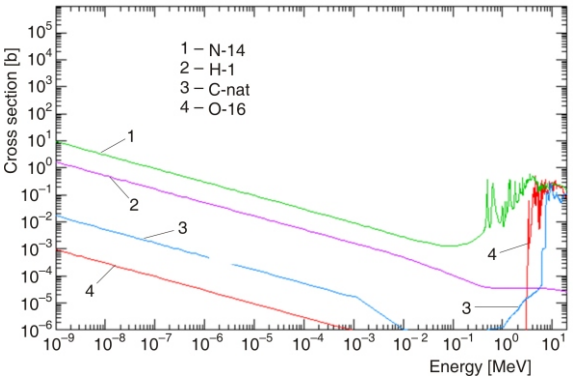

Figure 3. Radiative capture cross-sections, T = 300 K (MCNP ENDF/B-6 cross-section)

Fast (inelastic) reactions (cross-sections C: 200-400 mb*, N: 430 mb, O: 474 mb [13], as seen in fig. 3)

$$^{12}_{1}\mathrm{C}\ ^{1}_{0}n(14\,\mathrm{MeV}) \qquad ^{12}_{6}\mathrm{C}\ ^{1}_{0}n\ \ \gamma(4.4\,\mathrm{MeV}) \quad (3)$$

$$^{14}_{7}\mathrm{N}\ ^{1}_{0}n(14\,\mathrm{MeV}) \qquad ^{14}_{7}\mathrm{C}\ ^{1}_{0}n\ \ \gamma(5.1\,\mathrm{MeV}) \quad (4)$$

$$^{16}_{8}\mathrm{O}\ ^{1}_{0}n(14\,\mathrm{MeV}) \qquad ^{16}_{8}\mathrm{O}\ ^{1}_{0}n\ \ \gamma 6.1\,4\,\mathrm{MeV}) \quad (5)$$

Important thermal radiative capture reactions with significant cross-sections, as seen in fig. 3, are

$$^{1}_{1}\mathrm{H}\ ^{1}_{0}n(\mathrm{thermal}) \qquad ^{2}_{1}\mathrm{H}\ \ \gamma(2.2\,\mathrm{MeV}) \quad (6)$$

$$^{14}_{7}\mathrm{N}\ ^{1}_{0}n(\mathrm{thermal}) \qquad ^{15}_{7}\mathrm{N}\ \ \gamma(10.8\,\mathrm{MeV}) \quad (7)$$

For the (n, γ) reactions, the cross-sections for C and O are much lower than those for H and N. This work thus focuses on these two reaction rates, the subsequent γ production and the eventual detection in the NaI scintillators.

The radiative capture reaction rates in the explosive for both hydrogen and nitrogen are tallied as follows

$$FM24 \qquad {}^{H}_{n,\gamma}\phi(r,E,\Omega)\mathrm{d}V\mathrm{d}E\mathrm{d}\Omega \quad (8)$$

$$FM34 \qquad {}^{H}_{n,\gamma}\phi(r,E,\Omega)\mathrm{d}V\mathrm{d}E\mathrm{d}\Omega \quad (9)$$

where $\Sigma^{i}_{n,\gamma}$ are the radiative capture reactions for hydrogen (i = H) and for nitrogen (i = N).

Photon flux in the explosive material: an empirical formula

The photon flux in the explosive medium is from radiative capture reactions and from photon scattering in the medium. This becomes the "source" term of photons which must undergo multiple scattering or capture in the surrounding medium before emerging from the ground and being detected in the scintillators. The source term is quantified in this work to form a basis for an empirical formula which can later be developed as a function of mass and depth of concealment.

* 1 mb = 10^{-31}m^2

RESULTS

Neutron (n, α) reactions for detection

The $B(n,\alpha)$ reaction cross section and the neutron flux in a BF_3 detector, was obtained from both configurations viz figs. 1 and 2 for a small amount of TNT (127.307 g) [11] to estimate the sensitivity with the depth of concealment. It is understood that if such a small amount is detectable, then larger amounts will be easier to detect. For the configuration of fig. 1, it was found that the noise is exceedingly high and masks the contribution of the explosive. This is due to the small neutronic contribution in the flux, of explosive material (especially hydrogen) concealed in the limestone ground material, and thus a significant portion of the scattered neutron flux from the ground is received in the BF_3 detectors after being thermalized in the moderator. Thus, in the presence of a small amount of explosive, the difference in the thermalized flux masks the signal of interest. Thus, the simulation was performed for the BF_3 tubes placed before the moderator. In this case, the low-energy flux (E 0.625 eV) in one of the counters (closest to the source on the left side), shown in fig. 4 clearly differentiates the signal down to a depth of about 30 cm. All results are simulated for 4 M neutrons and have a relative error less than 1 %. The computer time was of the order of 10 minutes on an Intel(R) Core(TM) i7-2620M CPU @ 2.70 GHz, 8 GB RAM and 32-bit Operating System. Similar results are obtained for the other 7 tubes. The resulting count rate from the $B(n,\alpha)$ reaction, spread over 2-14 % increase depending on the concealment depth, is shown in fig. 5.

The configuration of fig. 1 is thus good only for a very large mass of concealed explosive as shown in fig. 6 for 2.598 kg TNT (cylinder CY radius 5 cm) at a depth of 15 cm. From this simulation, it is clear that of

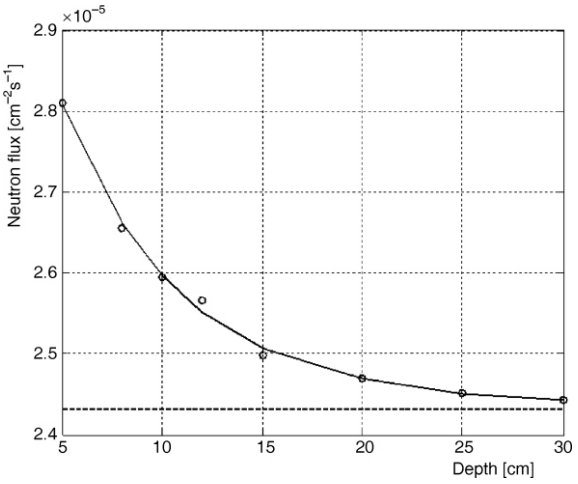

Figure 4. Neutron flux (E 0.625 eV) in BF_3 tube

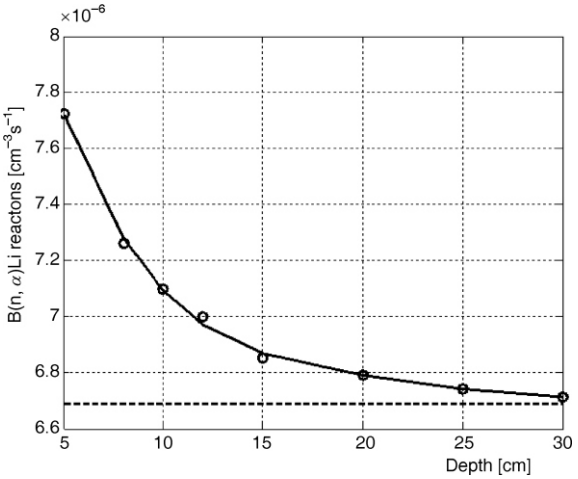

Figure 5. B(n, α) reaction rate in BF_3 detector

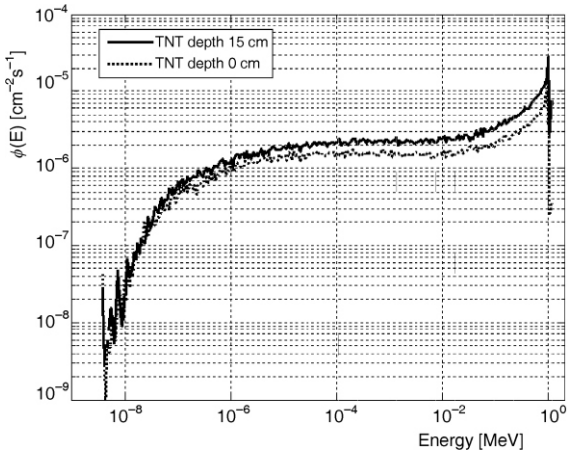

Figure 6. Neutron flux in BF_3 detector

the difference in the low-energy flux is very small compared with that for the high-energy flux, hence yielding a low-quality detection signal.

It is thus clear that the detection system based on fig. 1 cannot differentiate on the basis of either mass of explosive or depth of concealment.

To estimate the increase in neutronic detection signal as a function of explosive mass, concealed at a depth of 5 cm, a number of MC runs were made with 0.4 M neutrons and it was found (fig. 7) that a 30 % increase in the low-energy flux in the BF_3 counters is observed for a mass increase from about 140 g to 1200 g, while the higher energy fluxes (0.625 eV-1 MeV) decrease (fig. 8) with an increase in mass, and the higher energy flux (1-14 MeV) slightly increases. The net increase in the neutron count rates is of the order of 30 % as seen in fig. 9.

Radiative capture reactions for γ detection

In addition to the mere detection of an explosive, its identification is accomplished by the signature photons emerging from the thermal neutron activation of constituent elements. Thus, from MC simulations of

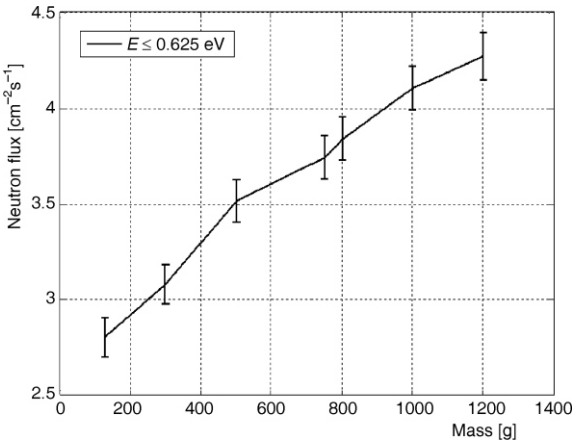

Figure 7. Neutron flux in one BF_3 tube for "low" energies

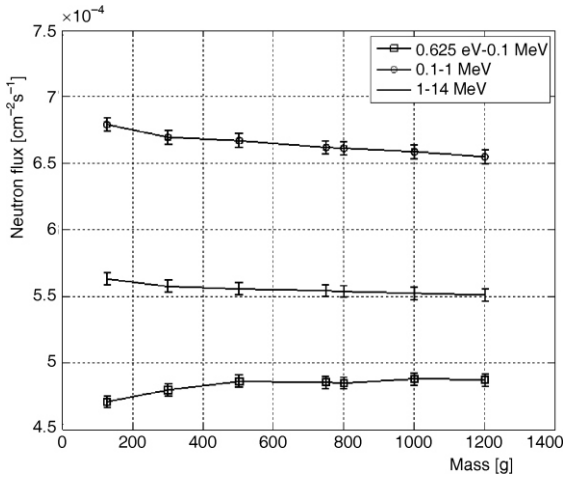

Figure 8. Neutron flux in one BF_3 tube for high energies

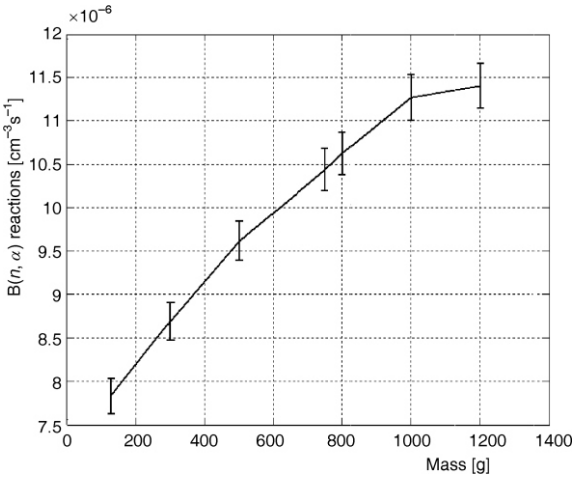

Figure 9. Reaction rates B(n, α) for configuration of fig. 2

the photon emissions, in a coupled n-γ simulation, the capture reaction rates were obtained as shown in figs. 10 and 11 for the two reactions: N^{14} (n, γ)N^{15} and H^1 (n, γ)H^2. It was found that there is a maximum reaction rate close to the surface where slowing down is the dominant effect; after this point the attenuation causes the reaction rate to decrease.

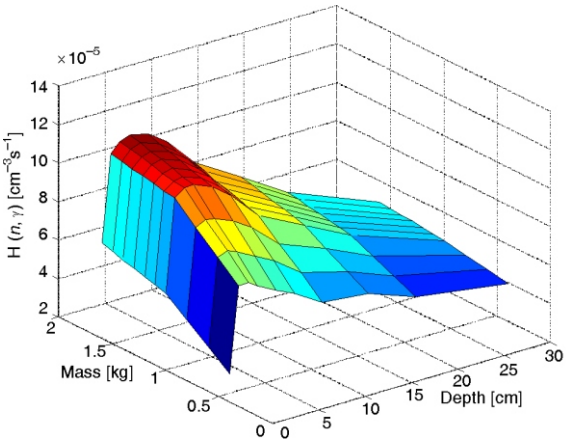

Figure 10. Reaction rate H(*n*, *γ*) in explosive

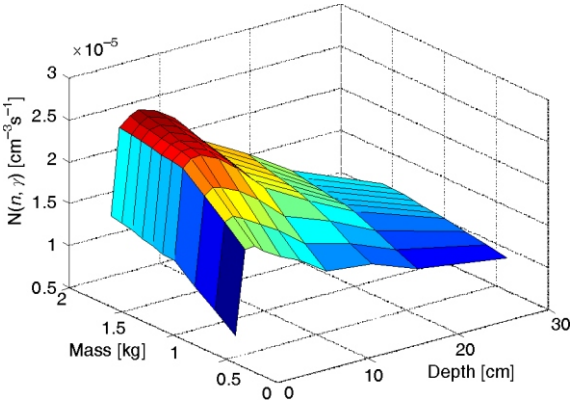

Figure 11. Reaction rate H(*n*, *γ*) in explosive

The results of figs. 10 and 11 were curve-fitted with two variables x and y representing the depth of concealment and explosive mass, respectively. The results of a linear 3rd order polynomial for

$$f(x,y) \quad \sum_{i,j} p_{ij} x^i y^i$$

were obtained with coefficients given in tab. 1 and goodness of fit quantities shown in tab. 2.

Table 2 gives the goodness-of-fit statistics used to interpret the surface-fitted polynomial with coefficients listed in tab. 1. They are: (a) the sum-of-squares due to error (SSE), (b) R^2, (c) adjusted R^2, and (d) the root mean square error RMSE. SSE measures the total deviation of response values. Table 2 shows that SSE is close to zero for both N(n, γ) and N(n, γ), implying that the fit is useful for prediction due to a small random error. Similarly R^2 ~0.78 implies that the fit accounts for about 78 % of the variation of the data are about the average while the adjusted R^2 statistic, adjusted on the basis of the "residual degrees of freedom" is a more reliable indicator with a value of 1 indicating a better fit. Finally the RMSE listed (10^{-5}, 10^{-6}), which is an estimate of the standard deviation of the random component in the data, indicates that the polynomial is of acceptable accuracy to predict both reaction rates.

Table 2. Goodness of fit for surface-fitted polynomial

Quantity	$H(n, \gamma)$	$H(n, \gamma)$
SSE	1.382 10^{-8}	7.077 10^{-10}
R-squared	0.7833	0.7845
Adjusted R-squared	0.7616	0.7630
RMSE	1.239 10^{-5}	2.804 10^{-6}

The function can thus be used as a "source term" for photon emissions from concealed explosives. For source strength of the order of 107 n/s, the total source strength is seen to increase from over 100 to 10^4 photons per second from nitrogen and from 400 to 40,000 photons per second from hydrogen, for mass in the range 100 g to over 3.2 kg as shown in fig. 12.

The scan time can be estimated from the source strength by accounting for (a) material attenuation f_M through the soil, (b) geometrical attenuation f_G at the detector, and (c) the detector efficiency. As an example, for 100 photons per second of 10.8 MeV from nitrogen, the material attenuation across 25 cm of limestone would reduce the intensity to ~20 %, while the geometrical attenuation for a 3.8 cm NaI window placed 6 cm above the ground would be ~10 % *i. e.* 2 photons per second would be incident at the detector. Assuming further, a detection efficiency of 0.8, would require a scan time of about 1 minute for 100 counts detected.

Empirical formula

Based on the surface fitting described, an empirical formula of the form $R^i_{(n,\gamma)} \quad Sf_G f_M f(d,m)$, i H,N is proposed where f_G = dΩ f_M = Be^{-s}, and

Table 1. Surface fitting (coefficients and confidence bounds)

Coefficient	H(n, γ)	95 % confidence bounds	N(n, γ)	95 % confidence bounds
p_{00}	1.962e-005	(–3.355e-005, 7.278e-005)	5.402e-6	(–6.631e-6, 1.743e-5)
p_{10}	7.851e-006	(3.977e-006, 1.172e-005)	1.696e-6	(8.191e-7, 2.572e-6)
p_{01}	9.949e-005	(–7.863e-005, 0.0002776)	2.157e-5	(–1.874e-5, 6.189e-5)
p_{20}	–7.131e-007	(–9.233e-007, –5.03e-007)	–1.592e-7	(–2.068e-7, –1.117e-7)
p_{11}	–1.632e-006	(–6.45e-006, 3.187e-006)	–3.14e-7	(–1.405e-6, 7.765e-7)
p_{02}	–3.614e-005	(–0.0002213, 0.0001491)	–7.878e-6	(–4.979e-5, 3.404e-5)
p_{30}	1.569e-008	(1.145e-008, 1.993e-008)	3.532e-9	(2.572e-9, 4.492e-9)
p_{21}	–3.734e-008	(–1.198e-007, 4.516e-008)	–9.149e-9	(–2.782e-8, 9.524e-9)
p_{12}	9.013e-007	(–1.161e-006, 2.964e-006)	1.929e-7	(–2.739e-7, 6.598e-7)
p_{03}	1.951e-006	(–5.844e-005, 6.235e-005)	4.275e-7	(–1.324e-5, 1.41e-5)

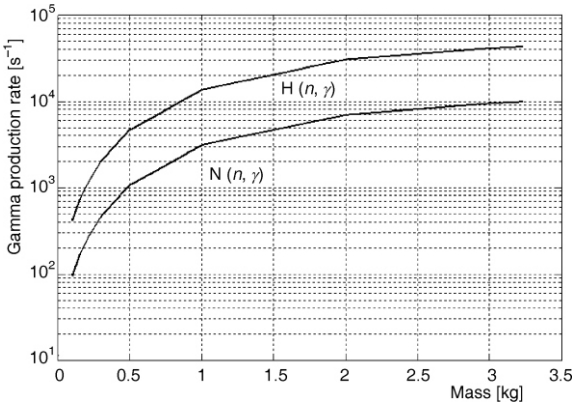

Figure 12. γ production rate from radiative capture (n, γ) in the explosive

$f(d,m)$ $_{i,j}\, p_{i,j}\, d^i m^i$, i 1, 2, 3 and j =1, 2, 3, with coefficients listed in tab. 1.

The curve-fitted reaction rates shown in fig. 13 for hydrogen and in fig. 14 for nitrogen indicate accuracy to about 10 % for mass up to about 1 kg TNT concealed down to about 10 cm in limestone.

CONCLUSIONS

The main conclusions from this Monte Carlo simulation carried out for the landmine detection system based on neutron backscattering are:

For neutron detection, the BF_3 tubes will give better detection if placed before the moderator box directly 'seeing' the ground to catch any 'softening' of the neutron spectrum from the concealed explosive.

The radiative capture increases initially with the depth and then decreases as the effect of the attenuation becomes important. There is thus an optimum depth at which a signal is maximum; this corresponds to the average track mean free path of neutrons in limestone which is of the order of 3 cm for a ^{252}Cf source.

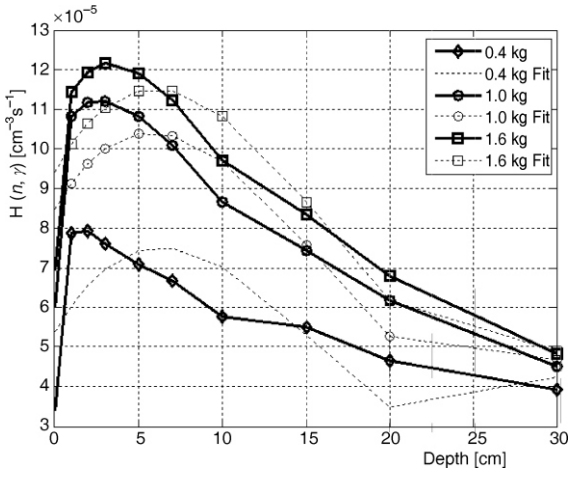

Figure 13. Reaction rates H(n, γ) per atom for MC re-runs compared with surface-fitted values

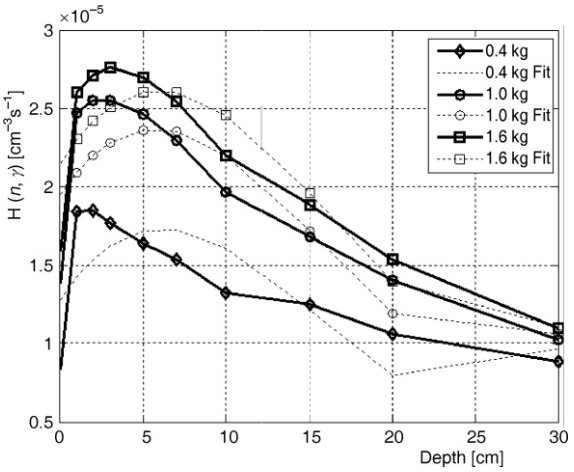

Figure 14. Reaction rates N(n, γ) per atom for MC re-runs compared with surface-fitted results

A sample as small as 127 g of TNT can be detected down to about 20 cm in limestone. The scan time for reasonable detection would be of the order of 1 minute.

An empirical formula has been given for the gamma source in the concealed explosive. This can be readily used in a field portable sensor embedded in a FPGA detection system, given the mass absorption coefficient of the soil and the solid angle geometry of the NaI detector, to conclude on the mass and depth of any concealed explosive.

AUTHORS' CONTRIBUTIONS

Modeling of the detection system and MCNP simulations were carried out by H. Khan and Z. Koreshi. Interpretation and presentation of the results were performed by H. Khan and Z. Koreshi and the research and manuscript were reviewed by all three authors.

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СТУДИЈА ОСЕТЉИВОСТИ СИСТЕМА ЗА ДЕТЕКЦИЈУ ЕКСПЛОЗИВНИХ МИНА НА ОСНОВУ НЕУТРОНА РАСЕЈАНИХ УНАЗАД ПРИМЕНОМ МОНТЕ КАРЛО СИМУЛАЦИЈЕ

У овом раду Монте Карло методом симулиран је систем за детекцију мина и скривеног експлозива као што су тринитротолуен и циклонит – применом MCNP5 програмског пакета. Јачина сигнала преносивих детектора која потиче од расејаних неутрона и гама зрачења, услед активације термичких неутрона, зависи од низа параметара као што су: маса експлозива, дубина на којој је мина закопана, модерација неутрона, састав земљишта, порозност земљишта, вишеструко расејање у земљишту и конфигурација детекторског система. Моделован је детекторски систем са BF_3 детекторима за неутроне и NaI сцинтилатором за детекцију гама зрачења, како би се испитао однос сигнал-шум при детекцији неутрона и добила емпиријска формула за брзину настајања фотона, $R^{i}_{(n,\gamma)} \quad Sf_G f_M f(d,m)$ из реакција радијативног захвата у саставним нуклидима тринитротолуена. Ова формула може се применити за ефикасно откривање експлозива чак и при малим количинама од око 200 г на дубинама до око 15 cm. Формула је обједињена у FPGA јединицу преносних детектора експлозива ради ефикасније онлајн детекције.

Кључне речи: експлозив, детектор мина, термичка активација, модератор, Монте Карло