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Full Length Research Paper

Numerical evaluation of a landmine detection system based on the neutron back scattering technique

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This paper describes an anti-personnel landmine detection system, which is based on the neutron back-scattering technique. It consists of a point-like isotopic neutron source (252Cf, 2,31 × 107 n/s), eight BF3 detectors and a neutron moderating and shielding block made from borated paraffin (3 wt%). It was modeled and tested by carrying out Monte Carlo calculations (MCNP-4C2 Code). The tests were performed in some troublesome conditions which include long burial depths for a landmine, higher humidity levels in the formation and existence of some plastics-like substances in the scanning area near a mine. Use of the neutron moderator behind the BF3 detectors increased the counting statistics and improved the S/N ratio. The system could detect a small cylindrical land mine (<300 g) until a burial depth of 15 cm in limestone and also worked well in distinguishing trinitrotoluene (TNT) from the other nearby substances. However, the presence of moisture in limestone in the level of 5% limited its applicability. Scanning speed of the system was calculated as 9.6 m2/min on an even land surface. The calculations revealed that it would be worthwhile to construct and test such a simple and fast practical system for detecting nonmetallic land mines in a laboratory environment.

Key words: Neutron backscattering, landmine, BF3 detectors, 252Cf, MCNP.

INTRODUCTION

A metal detector, by itself, is not efficient enough to detect a small anti-personnel land mine (APL) with low metal content. However, applying a combination of two methods may be more efficient. A metal detector integrated with a nuclear technique is an alternative. We know that there are some sophisticated nuclear techniques proposed for this purpose (IAEA, 1999; Hussein et al., 2000; Brooks et al., 2004a, b). Among them, the neutron backscattering technique (NBS) is widely used because it is the fastest, simplest and most easily applicable (Bom et al., 2006, 2008). Therefore, it may be cooperated with a metal detector in an APL detection system. It bases on counting the neutrons scattered back from a formation irradiated with fast neutrons and practically consists of a portable fast neutron source, a single or a series of the BF_3 or ^{3}He detectors and a neutron moderating and shielding block.

The narrow beam scan (NBS) technique has been tested several times in mine detection for the last ten years, either in laboratory experiments or in calculations based on a Monte Carlo code. Brooks et al. (1999, 2001) from the University of South Africa were the first experimenting it in the laboratory environment. Later, for example, Hussein et al. (2005) in Canada tried the ^{3}He detector and the ^{252}Cf source in their calculations and actual experiments, Datema et al. (2001, 2004) constructed the Delft University Neutron Backscatter Landmine Detector (DUNBLAD) in Netherlands, using again a ^{252}Cf source together with eight ^{3}He detectors in their set up, and recently, Ochbelagh and his group in Iran (2007) investigated the effects of various moderator materials on backscattered neutron flux. In these works, they all commonly pointed out the importance of using a moderating and shielding block around the detector to enhance the number of thermal neutrons due to a land mine and to protect the operator of the system from hazardous radiation, respectively. Therefore, they used an adequate material, such as heavy water, polyethylene or paraffin in the construction of this block to moderate the fast neutrons. Additionally, boron has been used either as a separate layer in the block or a constituent in a mixture (borated paraffin) to stop the moderated

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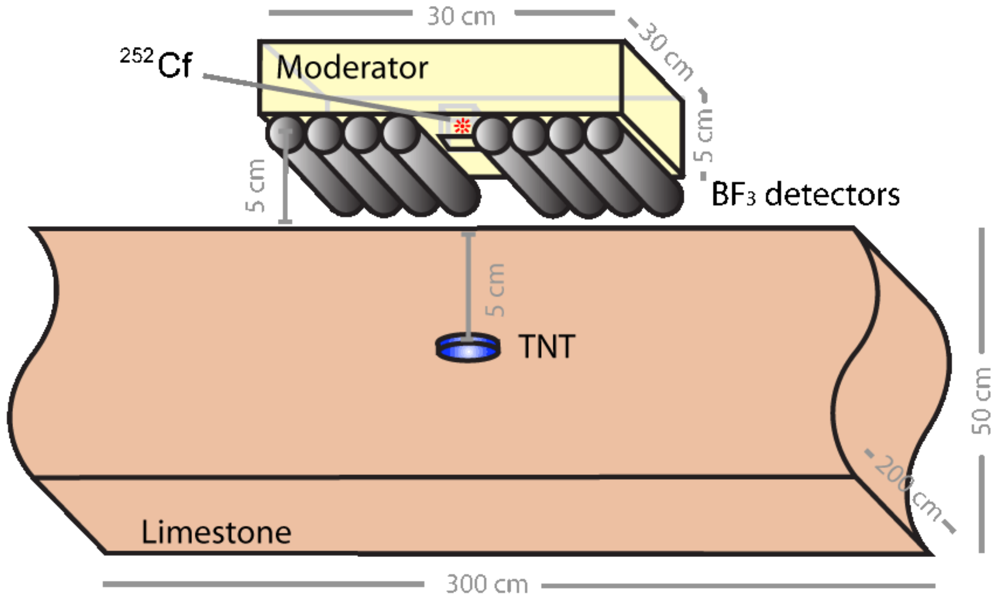

Figure 1. Experimental setup.

Table 1. Densities and compositions of the materials used in simulations*

Material (density in g/cm^3)	Elemental mass fraction												
	H	^{10}B	^{11}B	C	N	O	Na	Al	Si	K	Ca	Fe	Pb
TNT (1.65)	0.02			0.37	0.19	0.42							
Limestone (2.71)				0.12		0.48					0.4		
B-paraffin (0.947)	0.14	0.01	0.02	0.83									
Polyethylene (0.92)	0.14			0.86									
B-Polyethylene (0.94)	0.62	0.02		0.28		0.08							
B-Pb-PE (3.80)	0.02	0.02		0.11		0.04			0.01		0.01		0.8
Boric acid (1.465)	0.02	0.04	0.15			0.79							
Wood (0.5)	0.06			0.55	0.04	0.35							
Granite rock (2.5)	0.01					0.56	0.01	0.04	0.32	0.02	0.03	0.01	

*Data were taken from Hussein et al. (2005); Maučec and de Meijer (2002); Gujrathi and D'Auria (1972).

(thermal) direct neutrons of the source going to the detectors.

Some authors also proposed using a graphite or beryllium reflector on the source and a cadmium cover on the neutron detector to increase the fast neutron flux on the mine and to stop the thermal neutrons from the moderating block, respectively (Datema et al., 2002; Ochbelagh et al., 2008). However, they were usually left out in the models since their effects were minimal.

In this work, we aimed to design a mine detection system which would lead us to the construction of an actual device. We assessed the conclusions drawn from the previous works and applied the NBS technique. In the following are the optimizing and testing calculations of our system carried out by the Monte Carlo method.

MODEL FOR THE EXPERIMENTAL SETUP

The experimental setup as used in our model calculations is schematically depicted in Figure 1. It shows the landmine (TNT) buried in the formation (limestone) along with the neutron source and the detector assembly located horizontally under the neutron moderating and shielding block right above it.

The neutron source was a point like ^{252}Cf isotope (10 μg, 2.306 × 10^7 n/s) which has an energy spectrum very similar to the fission spectrum of ^{235}U. So, a Watt Fission Spectrum was adopted instead of the ^{252}Cf spectrum using the coefficients provided by the MCNP Code (Briesmeister, 2000). As a landmine, TNT (1.65 g/cm^3) was used in a cylindrical geometry, 3.5 cm in radius and 2 cm in height, and it was buried 5 cm deep in pure limestone in a container (300 × 200 × 50 cm). Neutrons scattered back from the formation irradiated with fast neutrons were counted by eight BF_3 tubes (1.5 cm in radius and 30 cm in length), each containing BF_3 gas enriched to 97% in B^{10} in a pressure of 250 Torr.

As shown in Figure 1, eight BF_3 tubes were placed horizontally, side by side, under the moderator block in two identical groups 5 cm apart from each other to allow for inserting the neutron source between them. Densities and chemical compositions of the materials used in the structure of the mine detection system are presented in Table 1.

In the simulations, a Personnel Computer (PC) version of the

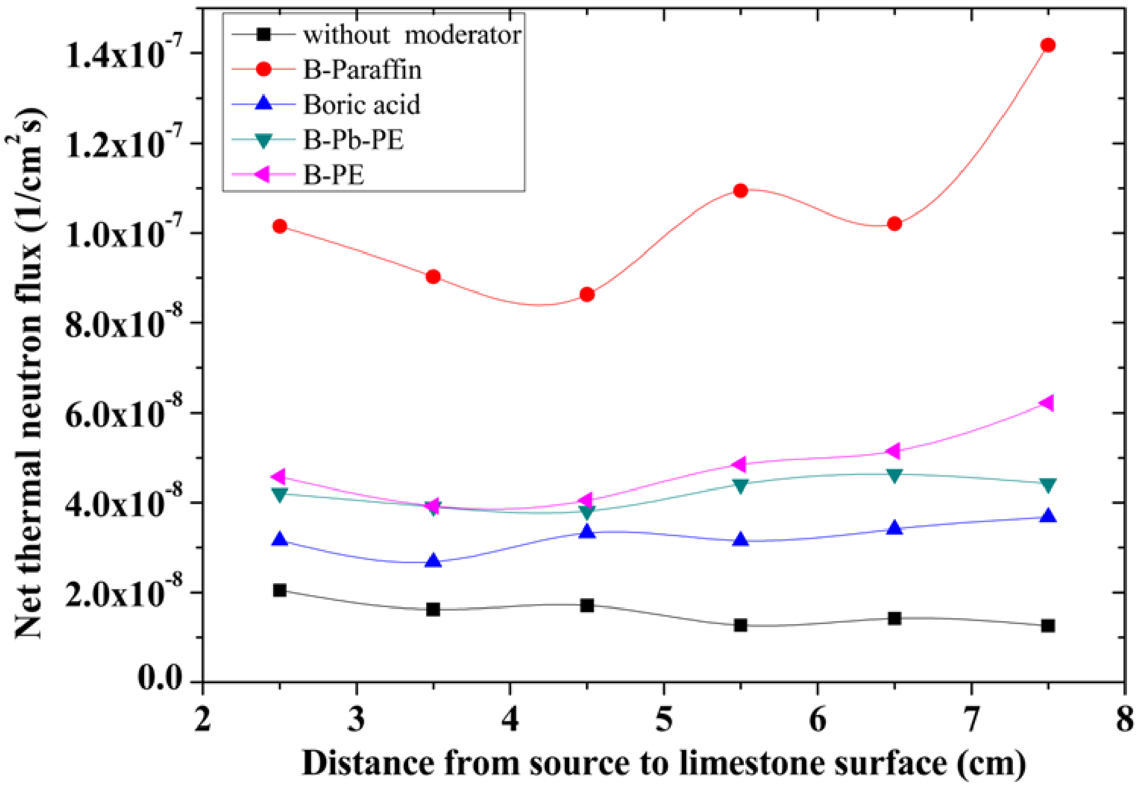

Figure 2. Variation of the net thermal neutron flux to the BF_3 tubes for some moderating and shielding materials with the distance between the source and the land surface.

Table 2. The net neutron fluxes in the detectors for some B-paraffin blocks having the same thickness (5 cm) but different surface areas.

Size (cm)	Net thermal neutron flux (0.025 eV) ($1/cm^2s$)	Net neutron flux (0-1 keV) ($1/cm^2s$)
5 x 5 x 5	3.881×10^{-8}	9.509×10^{-7}
10 x 10 x 5	6.842×10^{-8}	1.167×10^{-6}
20 x 20 x 5	1.098×10^{-7}	1.428×10^{-6}
20 x 30 x 5	1.268×10^{-7}	1.467×10^{-6}
30 x 30 x 5	1.430×10^{-7}	1.478×10^{-6}
40 x 40 x 5	1.582×10^{-7}	1.514×10^{-6}
60 x 60 x 5	1.580×10^{-7}	1.547×10^{-6}

Monte Carlo particle transport code (MCNP 4C2) was used, and 10^7 neutrons were traced. For the cross sections interested ENDF/B-VI and ENDF/B-VII libraries were utilized. Each calculation performed on a PC (2.26 GHz, Dual core Intel CPU) lasted roughly one hour.

A number of simulations were carried out to optimize the structure, shape and size of the constituents in the APL system. First, various materials as proposed by the others were tested to use in the construction of the moderating and shielding block. Figure 2 shows the results of the Monte Carlo calculations carried out in this work for the moderator blocks of the same size (30 × 30 × 5 cm), but different compositions. In these calculations, all the other parameters of the detection system concerning the source, the detector assembly and the landmine (size, position, etc.,) were all kept constant. It is clearly seen that the net number of thermal neutrons (the difference between the counts in the detectors taken with and without TNT in limestone, $N-N_0$) increased nearly five times for the block of borated paraffin with respect to that without any moderator, and it was almost insensitive to the changes of the distance between the source and the land upper surface. The calculation also showed that using 3% (weight per cent) Boron in the mixture rose the S/N ratio ($N-N_0/N_0$) from 1.005 to 1.05, about 10 times with respect to its value when no-moderator was used. Hence, a B-paraffin block was used in the experimental layout, and the spacing between the source and the soil surface was set at 7.5 cm considering that the land surface could be uneven.

The size of the B-paraffin block was determined in accordance with the neutron flux calculations in the detectors carried out in two steps; first by changing its thickness and then its surface area. Figure 3 and Table 2 present the results of these simulations, respectively.

Consequently, a borated-paraffin block with a surface area of 30 × 30 cm^2 and a thickness of 5 cm was used on the neutron detectors as predicted by the simulations.

TEST OF THE PERFORMANCE OF THE MODEL SETUP

The performance of the APL detection system designed in this work was tested in some extreme, troublesome conditions. These imply larger burial depths for a landmine, higher humidity levels in the formation and existence of some plastics-like substances close to a mine.

Figure 4 indicates how the thermal neutron flux at the neutron detectors changed when the burial depth of TNT in limestone was increased. It exhibits the clear discrepancies between the counts taken with and without

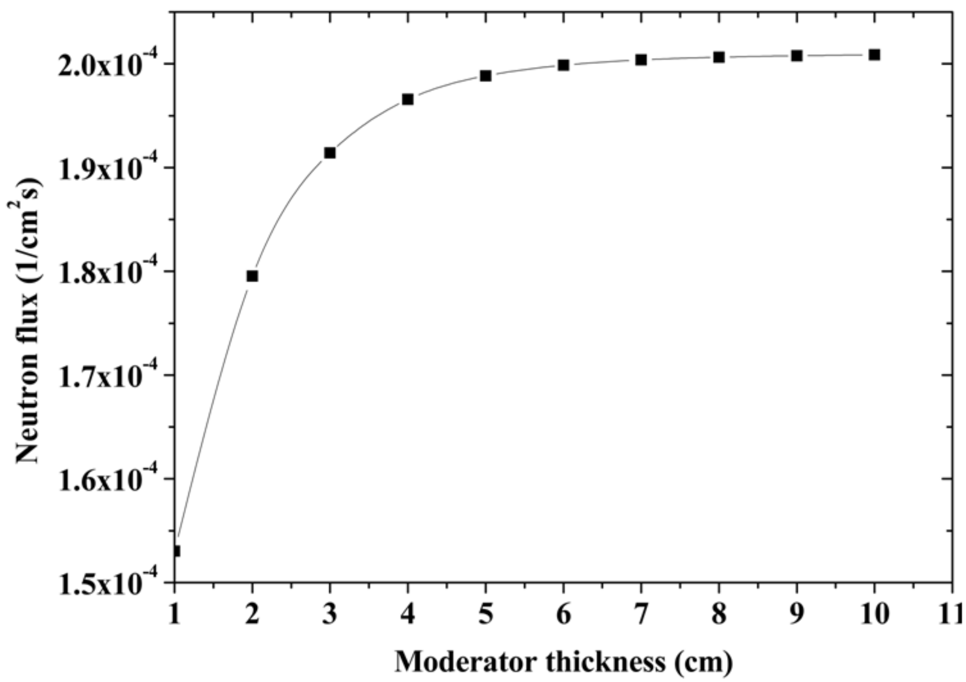

Figure 3. Effect of the moderator thickness on the neutron flux (0 to 1 keV) at the BF_3 detectors.

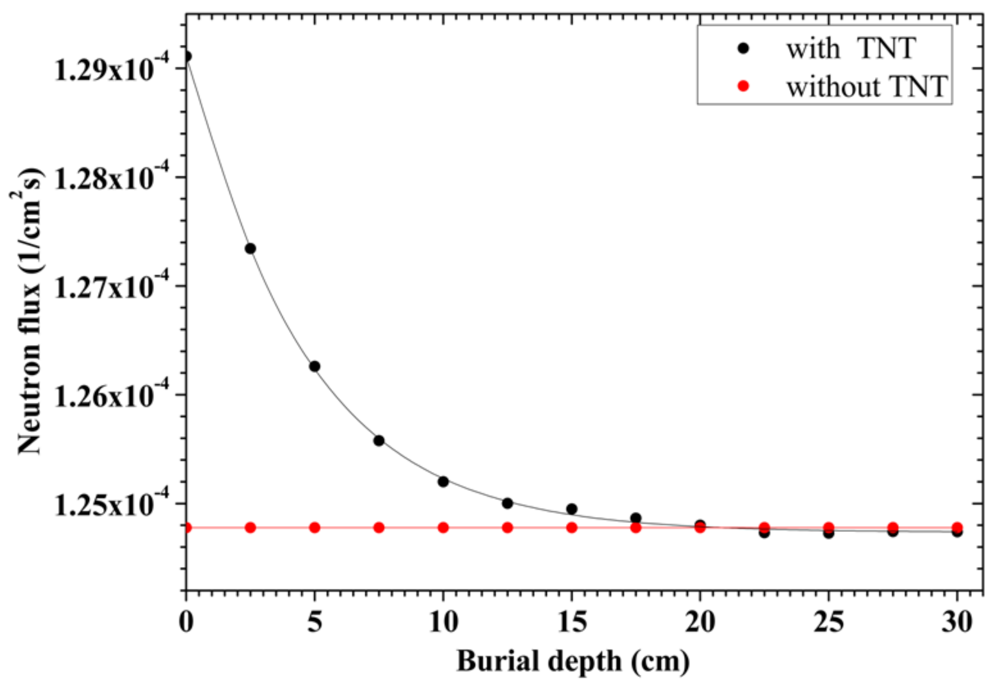

Figure 4. Backscattered neutron fluxes at the BF_3-detectors for TNT as a function of the burial depth.

TNT until a depth of 15 cm. Although the absolute difference seems to be very small, for example, about 1% for a depth of 5 cm, it should be noted that, considering the neutron source strength (~10^7 n/s) and the whole surface area of the detector assembly (~24 × 30 cm^2), this amounts to a total number of ~10^4 net neutrons which is very good for a measurement.

Existence of moisture in a formation involving a landmine has an undesirable effect in the application of NBS technique. This is because a wet soil contains lots of hydrogen molecules, which would compete with a mine in scattering the fast neutrons. That is, if the humidity in the formation is at a level to scatter more or less the same number of the incident fast neutrons as the

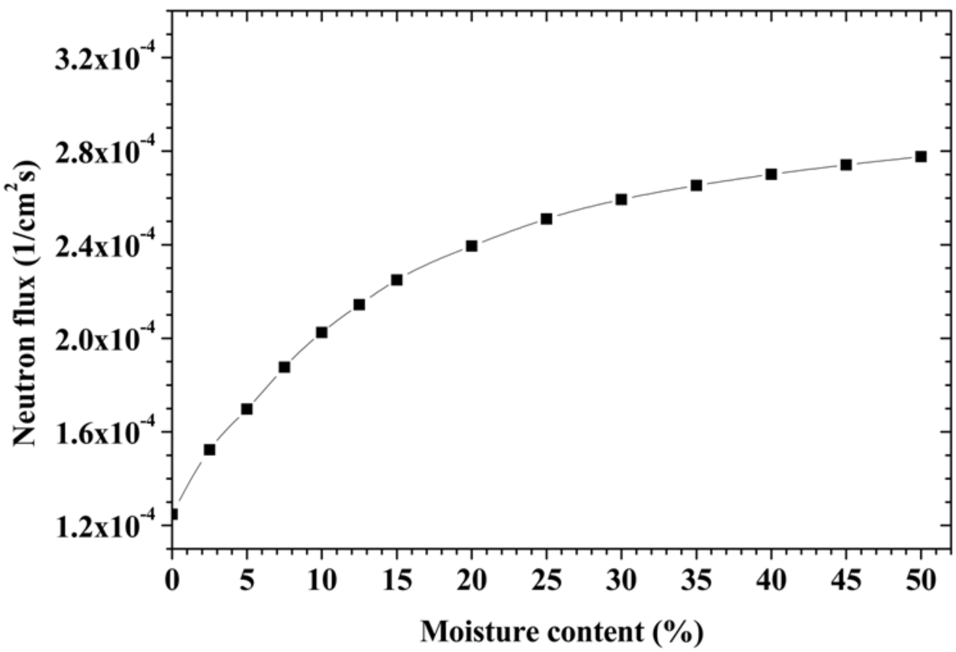

Figure 5. Neutron fluxes at the BF_3- detectors as a function of the humidity level in limestone.

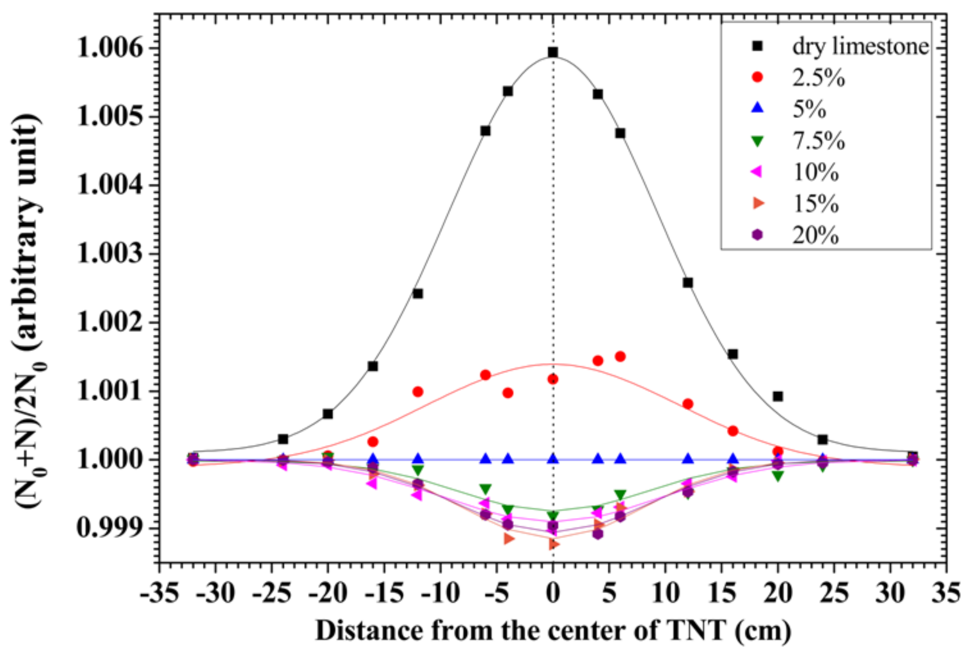

Figure 6. Distributions of the number of neutrons scattered back to the detectors for TNT buried at 5 cm depth in limestone with different water contents. Each curve in the diagram was obtained by over-scanning the upper surface of limestone horizontally along TNT under the surface by the APL detection system.

landmine does, the detection system cannot distinguish between them. Figure 5 shows the variation of neutron flux with the moisture content in limestone (without TNT). As it is expected, the neutron flux increases exponentially with the rising humidity level and almost saturates at the level of 25%.

Effect of moisture on the mine distinguishing ability of the detection system was investigated by the Monte Carlo calculations. In the simulations upper surface of limestone was over-scanned by the detection system longitudinally along TNT buried at 5 cm depth. Figure 6 indicates the backscattered neutron (0 to 1 keV) distributions around TNT at different humidity levels, which maximize over the center of the mine. Each curve in this diagram was obtained by over-scanning the upper surface of limestone horizontally along TNT under the

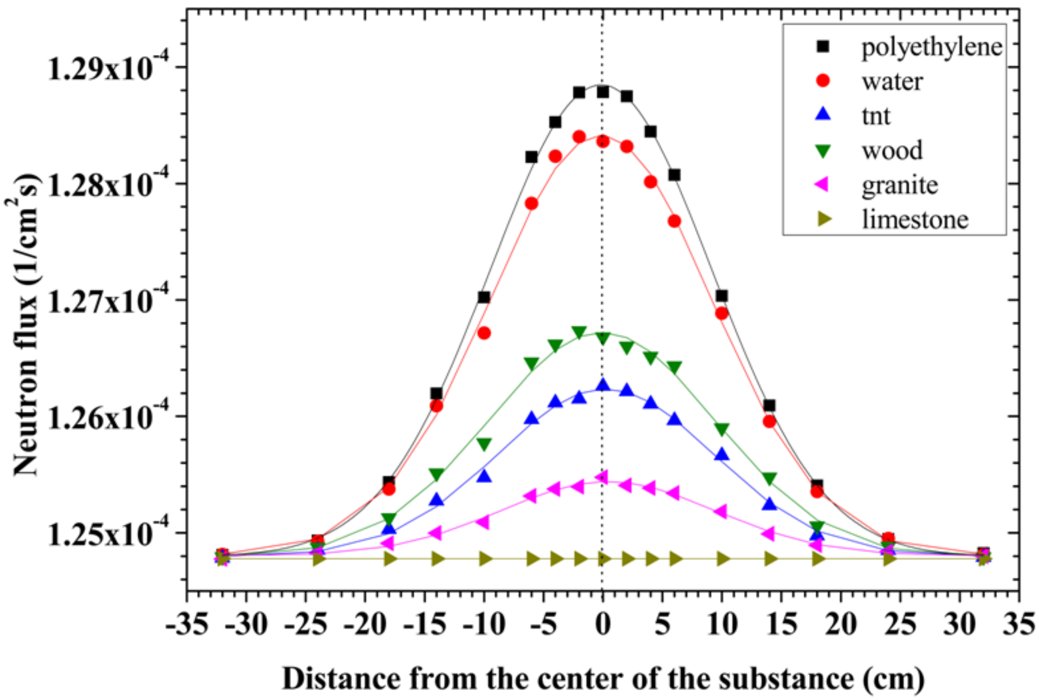

Figure 7. Distributions of the backscattered neutron fluxes due to some plastic-like substances placed in the volume of TNT at 5 cm deep under the upper surface of limestone. Each curve in the diagram was obtained by over-scanning the upper surface of limestone horizontally along the substance under the surface by the APL detection system.

Table 3. Neutron fluxes for some materials as normalized to those for TNT.

Buried object	Net neutron flux (n/cm^{2}s)	Normalized neutron flux	Maucec et al. (2002)
TNT	34	1.00	1.00
Polyethylene	92	2.70	2.53
Water	82	2.42	2.20
Wood	44	1.28	1.07
Granite rock	16	0.47	0.40

surface by the APL detection system. Clearly, TNT is normally distinguishable in limestone except for the humidity level of 5%. It is also interesting to note that if the humidity level increases beyond this level the neutrons backscattered from the volume occupied by TNT decreases below the background counting level, which manifests itself again as an anomaly in the medium.

A series of simulations was also carried out to assess the sensitivity of the system in distinguishing a landmine from some other plastic-like substances, which can exist in the formation near the mine. The neutron counting in the BF_3 tubes was calculated assuming the substances to have the same shape and equal dimensions as the landmine used and presented in Figure 7. These data as normalized to that calculated for TNT in the similar conditions are consistent with the literature values as given in Table 3. Clearly, TNT is generally distinguishable among the other materials.

RESULTS

In this work, an APM detection system based on NBS technique was modeled and tested in troublesome conditions with the Monte Carlo simulations. In the applications, limestone was used as a type of formation (soil) because it is rather common in the southern east of Turkey, which mostly suffers from the land mines buried under the land along the border.

Use of a neutron moderating and shielding block from borated paraffin (3 wt%, in the dimensions of 30 × 30 × 5 cm) behind the BF_3 detectors increased both the number of backscattered thermal neutrons counted and the S/N ratio in the measurements. So, it improved the accuracy of the measurements decreasing the uncertainties associated with the counting statistics. Furthermore, using boron loaded paraffin block instead of separate or multi-layer blocks helps in decreasing the volume and weight of the detection system which is very important in the mobile usage. The system could detect a small cylindrical land mine (3.5 cm in radius and 2 cm in height and less than 300 g in weight) until a burial depth of 15 cm in limestone and also worked well in distinguishing TNT from the other plastic-like substances in the scanning area. However, the presence of moisture in limestone in the level of 5% limited the applicability of the NBS technique for TNT. Moreover, the scanning speed of the detection system on an even land surface was calculated to be 9.6 m^2/min which is sufficient for a measurement.

The authors are aware of the facts that some assumptions made in the calculations do not reflect the actual conditions. For example, an efficiency of ~100% for the neutron detectors was too optimistic over the entire energy range of neutrons and those heterogeneities in the shape of TNT were not realistic. Nevertheless, this work has encouraged us on that it would be feasible to construct and test such a simple and fast practical system for detecting nonmetallic land mines which would be cooperated with a metal detector in a laboratory environment.

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