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Detection of anti-personnel landmines using neutrons and gamma-rays

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Abstract

New technology is needed to assist and accelerate the international effort to remove or neutralize millions of abandoned anti-personnel landmines that litter many former conflict areas around the world. Methods that employ neutrons and gamma rays to detect or identify landmines are now being investigated as part of this effort. A discussion and review of these methods is presented.

Keywords: Antipersonnel landmines; Humanitarian demining

1. Introduction

Abandoned landmines are a serious humanitarian problem in many parts of the world today (Monin and Gallimore, 2002). According to a recent estimate they now number more than 100 million and affect more than 70 countries. The number of persons accidentally killed by landmines each year is believed to exceed 25,000 and an even larger number are maimed. Many of the victims are women and children. Most of the casualties are caused by small plastic anti-personnel mines which are difficult to detect using the technology now available. New technology is being sought to alleviate this problem and progress is reviewed regularly, for example at meetings such as the recent international conference held in Brussels in September 2003 (Sahli et al., 2003). Among the new ideas that are now being considered for landmine detection are methods that take advantage of the penetrating powers of neutrons and gamma rays. A coordinated research project on the development of nuclear-based methods to aid Humanitarian Demining (HD) was initiated by the International Atomic Energy Agency in 1999 and is now producing results (IAEA, 1999, 2001, 2003). In this paper, we focus on work in progress in this field, both within and beyond the IAEA project.

2. Detection and neutralization of landmines

Landmines include anti-tank mines (ATM) and anti-personnel mines (APM). ATM are typically about 5 kg or more in mass while APM are much smaller, often less than 300 g. In order for a landmine to be detonated by the weight of the targeted agent (vehicle or person) acting on the earth directly above the mine, the top of the mine (or an extension) has to be within a few cm of the ground surface. When buried deeper than this the mine might be "temporarily safe", because the force exerted on it is reduced (by transmission through the soil) to a level that is insufficient to actuate the detonator. However, deeply buried mines must also be detected and removed because soil movement by natural or other causes can make them a hazard later on. ATM are easier to detect than APM because they are much larger. The real problem is to detect APM reliably and quickly. If this can be done then detecting ATM should

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be relatively easy. We therefore concentrate on the detection of APM only.

APM are a product of military technology, therefore it is appropriate that humanitarian demining (HD) should begin by considering the methods and countermeasures that the military have devised to deal with these mines. To be specific, suppose that we have a minefield in open country, such as farmland, and that ground cover (vegetation) is either minimal or has been removed in advance. In HD the objective will be to remove or neutralize all APM to a specified depth, say 30 cm below ground level. In military demining the objective may be different, perhaps simply to clear a safe path through the minefield as quickly as possible. One approach that is employed by the military is to use a suitably protected vehicle to propel simple but rugged mechanical devices such as rotating flails, rollers or ploughs across the minefield. These devices destroy, detonate or disable APM in situ, ahead of the vehicle, or sweep them into berms alongside the resulting "safe" path in the case where a plough is used. Equipment that may be damaged in this procedure can usually be repaired or replaced at little cost or delay. These methods are effective but cannot be relied upon to neutralize more than about 90% of the APM in their path. This may be satisfactory for military purposes, where a small number of casualties are considered inevitable and acceptable. It is not acceptable for HD: mechanical clearing may sometimes be used, but only as a preliminary step prior to landmine detection.

Mine detection is usually based on the detection of some kind of anomaly that might be associated with the presence of an APM in the ground. Different types of anomaly may be targeted, ranging from visible evidence of recent physical disturbance of the surface to evidence of unusual variations in physical properties of the ground, such as dielectric constant, thermal or electrical conductivity or chemical or nuclear composition. A summary of landmine detection methods is presented in Table 1. Section A of the table shows methods that are established and already in use (largely as a result of military interest). Section B shows emerging (new) methods that are not yet widely employed.

The best-known APM detection instrument is the metal detector, which is based on electromagnetic induction and on the assumption that almost all landmines contain at least a small amount (>10 g) of metal. Metal detectors can be made very sensitive and therefore reliable for detecting even such small amounts of metal. However, problems obviously arise if other metallic items are also present in the ground, for example shrapnel pieces or other forms of metallic debris. In some cases, for example when detecting APM of low metal content in former conflict regions, the number of responses from metallic debris may exceed those from landmines by a factor of more than 100. Since all responses have to be investigated this obviously reduces the rate at which APM can be cleared and also increases the cost of their removal.

The established methods listed in section A of Table 1 are considered insufficient for HD because they are too slow and therefore too expensive to use when a high clearance efficiency ($>99.6\%$) is required. New techniques based on the emerging methods listed in section B of Table 1 are viewed as possible answers to this need. HD systems of the future will probably be multi-sensor systems incorporating two or more different methods of which at least one is a new method (section B). A possible HD system could for example consist of a metal detector and/or ground penetrating radar as the primary sensors (or sweep sensors) plus one or more confirmation sensors. Ideally it will operate as follows. The sweep sensors scan the whole of the minefield thoroughly, quickly and without missing any APM. A number of "false positives", due for example to metallic debris or other artefacts, may be recorded in the primary scan. The confirmation sensors examine only those regions in which the sweep sensors have registered a positive response. Their function is to provide independent information that can be combined with that from the sweep sensors to eliminate false positives without discarding any true positives, in other words APM. The APM candidates that survive beyond this stage are then exposed by digging and removed if they do indeed prove to be APM.

Table 1
Landmine detection methods

(A) Established methods	(B) Emerging methods
Metal detection (electromagnetic induction)	Infra red
Ground penetrating radar	X-ray backscatter
Sniffer dogs	Nuclear quadrupole resonance
Probing sticks	Laser-induced breakdown spectroscopy
	Smart probing sticks
	Artificial nose
	Rats, bees, elephants ....
	Neutrons and gamma rays

3. Neutron and gamma methods for APM detection

Nuclear-based methods presently constitute only a small part of the endeavour to provide new APM sensors and are not yet recognised as strong contenders for this role (Sahli et al., 2003). The IAEA coordinated research programme (CRP) mentioned earlier has encouraged studies of nuclear methods and is supported by participants from universities and research institutions in 18 different countries (see Table 2). These studies are being carried out by a variety of methods, including computer modelling and simulation, experimental work in laboratories and out-of-doors and field tests (IAEA, 1999, 2001, 2003). The effects of factors such as different minefield environments, soil types and moisture content of the soil are also being considered. In order to facilitate comparisons of results obtained by different methods and different groups a standard dummy landmine, known as DLM2, was designed and developed by CRP members (IAEA, 2003). DLM2 consists of 100 g of innocuous TNT simulant sealed in an acrylic container (mass 100 g) of diameter 80 mm and height 34 mm. Thirteen replicas of DLM2 were constructed and have been distributed among CRP members.

We confine further discussion to work on nuclear-based methods for which results are now available from both simulations and experiments. This work can be grouped under four headings that correspond to different approaches to APM detection: neutron-induced gamma emission; neutron energy moderation; neutron and gamma attenuation; and fast neutron backscattering. Work is also in progress on other methods, for example gamma backscattering and gamma-gamma coincidence imaging (IAEA, 1999, 2001, 2003).

3.1. Neutron-induced gamma emission

Participants from eight of the countries listed in Table 2 are involved in the development of APM detectors based on this approach. Neutrons of energy 14 MeV from a d-T source (see Fig. 1) penetrate the ground and interact with nuclei that they encounter in the soil and in objects buried in the soil. Interactions such as neutron inelastic scattering and neutron radiative capture lead directly to gamma emission with an energy spectrum characteristic of the target nuclei involved. Neutron-induced reactions that produce radioactive products can also lead to the delayed emission of characteristic gamma rays. Gamma rays are detected by a bismuth germanate (BGO) scintillator. The pulse height spectrum from the BGO is analysed to identify the nuclei and hence the elemental constituents that produced the gamma rays and to determine their relative proportions. It is thus possible to identify explosives from their chemical composition which is indicated by the elemental concentration ratios (H:C:N:O) determined from the analysis of the pulse height spectrum. This provides a signature for identifying APM or other explosive objects, with excellent discrimination against metallic debris and other artefacts.

Table 2
Participating countries

Australia	Austria	Canada
Croatia	Egypt	Germany
Hungary	Italy	Japan
Netherlands	Russia	Slovakia
Slovenia	South Africa	Sweden
UK	USA	Vietnam

IAEA coordinated research project on humanitarian demining

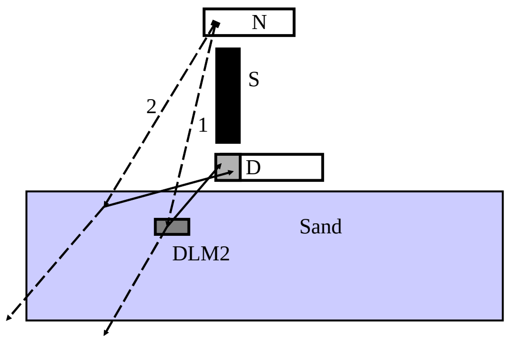

Fig. 1. Schematic diagram of a neutron-induced gamma system for APM detection showing: dummy APM (DLM2); sealed tube d-T neutron generator (N); shadow shield (S); and BGO scintillation detector (D). Events 1 and 2 illustrate examples of neutron elastic scattering in DLM2 and in the sand, respectively. The associated gamma ray is detected in D in both examples. Dashed (continuous) lines show neutrons (gamma rays).

One example of this approach is the PELAN system (Pulsed ELemental Analysis using Neutrons) developed by the University of Western Kentucky and the Scientific Applications International Corporation (SAIC) in the USA (Vourvopoulos et al., 2003). PELAN employs a commercially-available sealed-tube d-T neutron generator that provides 14 MeV neutrons in bursts (pulses) of duration about 10 μs, separated by about 90 μs. Two time gates are used to select two distinct and different pulse height spectra from the BGO detector: firstly the spectrum due to gammas detected during the neutron pulse; secondly the spectrum due to gammas detected between pulses. The first spectrum is due primarily to prompt gammas from the inelastic scattering (n, n′γ) of fast neutrons or from reactions (n, $x\gamma$) induced by fast neutrons. The second spectrum arises from two sources: firstly from radiative capture (n, γ) of thermal neutrons, which is delayed by the time (>10 μs) required for fast neutrons to thermalize; and secondly from the relatively slow radioactive decay of gamma emitters produced by neutron capture. The two spectra constitute a more structured "element signature" than that obtained without time gating. This enables element concentration ratios to be determined with better accuracy and therefore enhances the capability of the system for identifying explosives.

Another version of the neutron-induced gamma approach is the nanosecond neutron analyser (NNA) developed by the Khlopin Radium Institute in St. Petersburg, Russia (Kuznetsov et al., 2003). This system employs the associated-particle neutron-tagging technique which is well known in nuclear physics (Fig. 2). The specially-constructed sealed-tube d-T neutron generator of this system incorporates a semiconductor detector to register the α-particle that is emitted in coincidence with the 14 MeV neutron from the $^3H(d,n)^4He$ reaction. Since the directions of the α-particle and neutron are almost directly opposite to one-another (to conserve linear momentum) detection of the α effectively defines a "kinematically collimated cone" for the associated neutron direction. When the BGO crystal detects gammas from neutron inelastic scattering, for example, and a suitable time-delayed coincidence is observed between it and the α-detector then one can infer that the inelastic scattering occurred at some point within the cone. The nanosecond coincidence requirement therefore selects inelastic scattering events within a well-defined target region and discriminates very effectively against background gammas that originate from neutron interactions at points outside the cone or deep into the ground (see Fig. 2). The resulting pulse height spectrum from the BGO detector therefore exhibits a good signal-to-background ratio and is well suited for full spectrum analysis leading to element ratio data and hence explosive identification. A prototype NNA instrument that incorporates nine separate α-detectors in a 3×3 matrix has been constructed (Fig. 3). This allows nine different kinematically-collimated neutron beams to be investigated simultaneously. It is estimated that a production model of this system should be able to identify a landmine equivalent to DLM2 at a depth of up to 5 cm in dry soil from a measurement requiring about 30 s. Other APM detector systems that are based on the associated particle technique are described by Lunardon et al. (2003) and by Maglich et al. (2003).

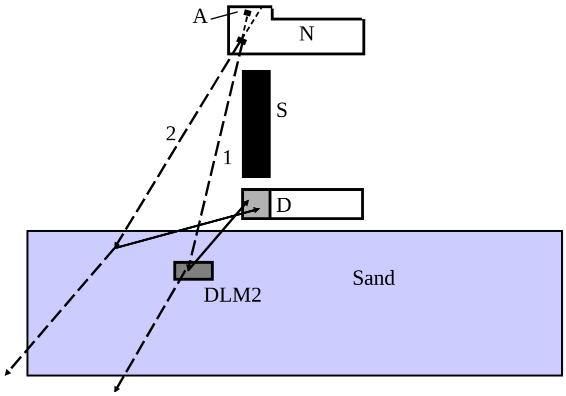

Fig. 2. Schematic diagram of an associated-particle system for APM detection. Details are the same as for Fig. 1 except for the sealed tube d-T neutron generator N, which incorporates an α-particle detector A. Light dashed lines show the α-particles associated with events 1 and 2. Note how the associated particle coincidence selects event 1 and discriminates against event 2.

3.2. Neutron energy moderation

The neutron energy moderation method is based on a hydrogen-sensing technique that has been used to measure the moisture content of agricultural land and for oil well logging for many years. It was also suggested for landmine detection more than 10 years ago (Orphan,

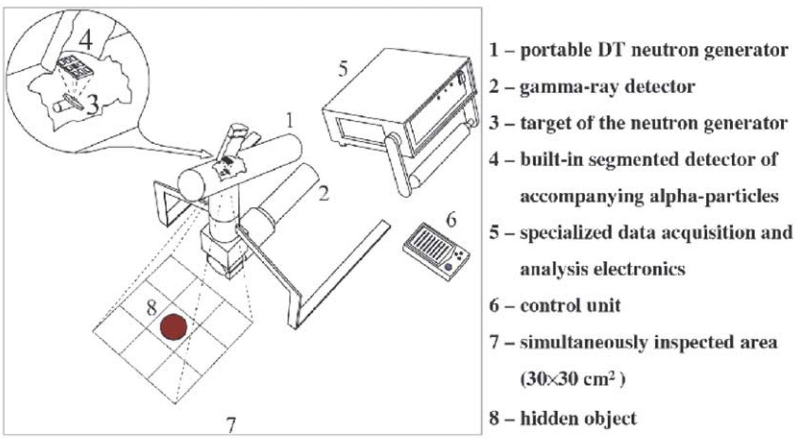

Fig. 3. Schematic diagram of the prototype NNA system of Kuznetsov et al. (2003).

1992). The method depends on the fact that dry sand will normally contain very little hydrogen whereas the hydrogen content of a plastic APM will typically be in the range 40–50 atom-percent (25–35 atom% in the explosive and 55–65 atom% in the plastic). Thus a typical APM buried in dry sand constitutes a significant hydrogen anomaly and this anomaly can be detected by observing the moderation of fast neutrons to thermal or epithermal energy. In practice the presence of moisture in the sand will limit the effectiveness of this method and will therefore restrict its use to situations in which the soil is relatively dry. There are likely to be many situations requiring mine clearing where moisture in the soil will limit or exclude the use of the method, but also many other situations in which moisture does not present a problem and where it might therefore be useful.

Participants from 10 of the countries listed in Table 2 are involved in the development of APM detectors based on neutron energy moderation. Some of the instruments that have been developed and tested are: Delft University Neutron Backscattering LAndmine Detector (DUNBLAD) from the Netherlands (Bom et al., 2003); Detection and Imaging of Anti-personnel Landmines by Neutron Backscattering Technique (DIAMINE) from a collaboration based in Italy, Slovakia, Belgium, Germany and Croatia (Viesti et al., 2003); and HYdrogen Density Anomaly Detector (HYDAD) from South Africa (Brooks et al., 2003). As an example of this method we present some further details about HYDAD systems, with which we happen to be particularly familiar.

Fig. 4 is a schematic diagram of a hand-held HYDAD system, HYDAD-H. It consists of a fast neutron source (AmBe or ^{252}Cf) attached to a slow neutron detector (^{3}He-filled proportional counter in this example) and some electronics (not shown). The detector is insensitive to the fast neutrons and gamma rays emitted from the source but highly sensitive to the slow neutrons (thermal and epithermal) that result from n–p scattering in the dummy landmine DLM2. Thus the detector count rate increases as the system is scanned along a horizontal line close to the sand surface, passing directly over DLM2. With the help of suitably designed electronics this count rate is converted into an audible beep rate that increases from about 0.3 s^{-1} to more than 3 s^{-1} as the detector is scanned from a distant off-mine position to directly above DLM2. More details about HYDAD-H, including movie clips showing the detector in operation, can be seen at the website <http://www.phy.uct.ac.za/hydad>.

Results obtained using the DUNBLAD, DIAMINE and HYDAD-H systems indicate that the neutron moderation method based on the geometry of Fig. 4 will be suitable for detecting APM buried to depths up to 10 cm in dry sand, less effective over moist sand and unsuited for operation over "wet" sand, that is sand containing more than about 10% (by mass) of water. The moisture-related limitation appears to be fundamental and impossible to overcome. However, it is

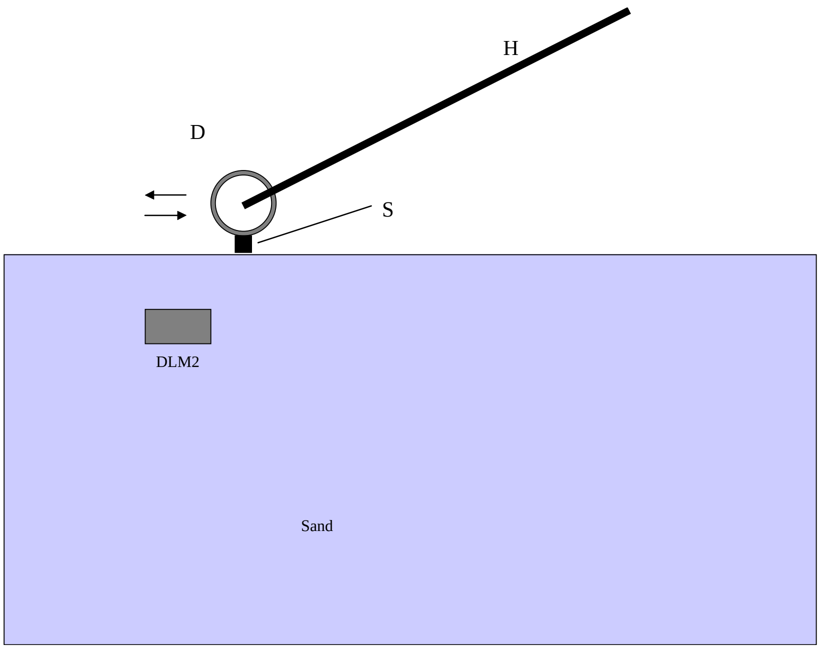

Fig. 4. Schematic diagram of the HYDAD-H hand-held APM detector showing: dummy APM (DLM2); fast neutron source (S); slow neutron detector (D); and carrying rod (H).

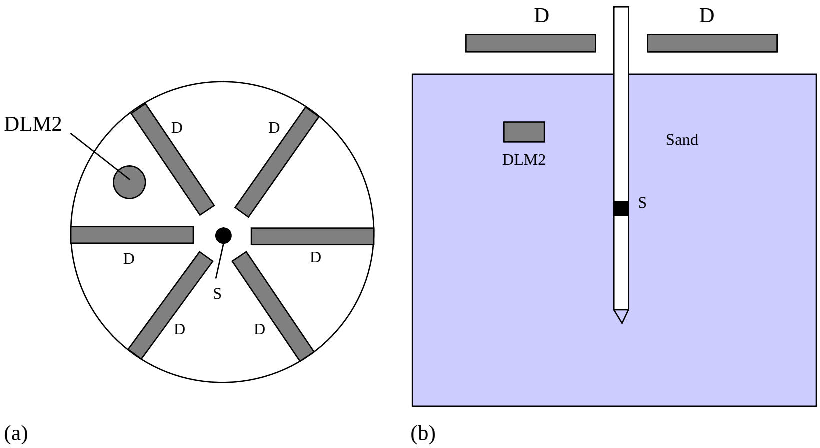

Fig. 5. Schematic diagram of the HYDAD-VM APM detection system viewed (a) from above and (b) in a vertical section, showing: dummy APM (DLM2); the hollow spike containing an AmBe neutron source (S); and the symmetrical array of six identical slow neutron detectors (D).

possible to extend the range of the method to depths greater than 10 cm in dry sand in the following way (Brooks et al., 2003). Fig. 5 shows a modified HYDAD geometry, HYDAD-VM, designed for operating from a mine-protected vehicle (MPV) such as those used by the South African company Mechem for mine clearing operations in Southern Africa. These MPV can operate safely over land containing APM and are equipped with trailing arrays of metal detectors that drop paint spots onto the ground to mark each position at which a metal detector registers a positive response. Each paint spot has to be checked afterwards using one or more confirmation sensors. In the proposed method a device that is controlled from within the MPV will be used to drive a hollow metal spike vertically into the ground, to a depth of about 40 cm, at or close to the paint spot. If the spike were to trigger an explosion and be damaged during this operation then it could be easily and cheaply replaced. After the spike is in position, as shown in Fig. 5, a neutron source (AmBe) is lowered into it and a symmetric array of six or more slow neutron detectors is lowered carefully to a position just above ground level. Laboratory tests have confirmed that the count rates from the six detectors will be similar if the soil is dry and homogeneous and does not contain any hydrogen-rich object. However, if an object such as DLM2 is present within about 20 cm of the spike then one detector or two adjacent detectors will exhibit count rates that are significantly higher than the other detectors. Test measurements made using an AmBe source that provided $8 \times 10^5\,\mathrm{n\,s^{-1}}$ into 4π have demonstrated that one minute of counting in this geometry will be sufficient to detect the DLM2 dummy landmine to a precision of 3 or more standard deviations, at depths up to 30 cm and within a radius of 20 cm of the spike.

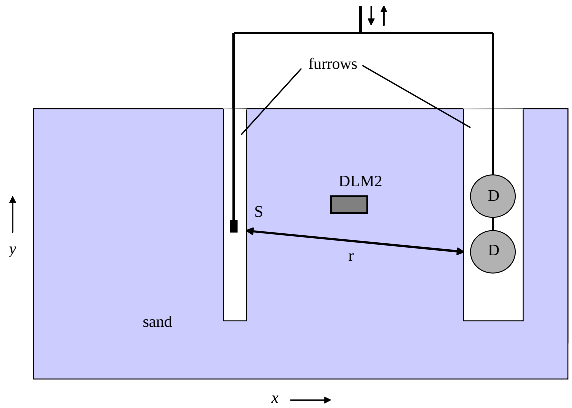

Fig. 6. Schematic diagram of the HYRAD APM detection system showing: the neutron source (S); NE213 liquid scintillator detectors (D); and dummy APM (DLM2).

3.3. Neutron and gamma attenuation

This method, which we refer to as HYdrogen RADiography (HYRAD), is based on a principle similar to that of the neutron-gamma transmission method (NEUGAT) of Bartle et al. (1990). It combines neutron and gamma transmission radiography so as to optimise sensitivity for detecting hydrogen. Suppose that the region to be examined lies between two furrows, each about 40 cm deep. Fig. 6 presents a schematic diagram of the system. A source (^{252}Cf) of neutrons and gammas is suspended in one furrow and an array of two or more detectors (NE213 liquid scintillators) in the other. The source and the detectors are coupled together by means of a rigid frame and move up and down (in direction y) in the furrows while advancing relatively slowly along the furrows (direction z). The NE213 detectors are equipped with pulse shape discriminators to identify and count fast neutrons and gamma rays in separate channels. The ratio R of neutron counts to gamma counts is measured as a function of the source position (x, y, z) for each detector.

Suppose that the medium between the two furrows consists entirely of dry sand. Then for either detector we can show (Brooks et al., 2003) that

$$R = K \exp\left[(f_\gamma(Z) - f_n(Z, A))\rho r\right], \tag{1}$$

where K is a constant, r is the thickness of sand between the source and detector, ρ is the density of the sand and $f_\gamma(Z)$ and $f_n(Z,A)$ are functions of the atomic and nuclear composition of the sand, the neutron cross sections of the nuclei in the sand, the energy spectra of the neutrons and gammas emitted by the source and the energy thresholds imposed by the detector for detecting these radiations. Eq. (1) shows that R will be independent of ρ and r if $f_\gamma(Z) = f_n(Z, A)$. This condition can be achieved (approximately) in practice through control of the respective energy thresholds of the NE213 detectors. Thus provided only that the atomic composition of the sand is uniform, the count rate ratio R is not affected by the presence of any voids in the sand or variations in thickness or degree of compaction. However, the presence of an object of different atomic composition between the source and detector affects the exponent of Eq. (1) and hence R. A hydrogen-rich object like DLM2 reduces R because it increases the neutron attenuation and reduces the gamma attenuation relative to that of the sand that it displaces. A high-Z object has the opposite effect, leading to an increase in R over that observed with no object present. Simultaneous measurements of $R(x, y, z)$ for two or more detectors can thus be used to detect and identify both low-Z objects and high-Z objects and also to locate their positions.

Measurements in the laboratory using dry sand have confirmed the feasibility of this method. Preparations are now being made for out-of-doors testing. Ploughing the necessary furrows should not present a problem if or when a practical system based on this method is designed. This could be done by attaching ‘‘ripper blades’’, such as are commonly fitted on bulldozers, to a mine-protected vehicle and trailing the detection system at a safe distance behind the blades to protect it from any explosions that they might trigger.

3.4. Fast neutron backscattering

Fast neutron scattering analysis (Buffler et al., 2001) is a technique that has been shown to be capable of detecting explosives in bulk media. It is most effective when a monoenergetic, nanosecond pulsed neutron source is used but can also be undertaken using a monoenergetic source that is not equipped with nanosecond pulsing or even using a continuous-spectrum source without making any timing measurements (Csikai et al., 2001). In principle it should be possible to adapt these techniques for APM detection.

Another neutron scattering method, monoenergetic neutron backscattering with resonance penetration (MNBRP) has been more thoroughly investigated by means of both computer simulation and laboratory tests and has given promising results (Drosg et al., 2002). This method makes use of two special and interesting features of neutron scattering: firstly the fact that neutrons are confined to forward angles after scattering on protons, which has the effect of making hydrogen-rich objects such as landmines appear as shadows when they are viewed by neutron backscattering; and secondly, the presence of deep minima in the neutron cross section of oxygen (the most abundant element in typical soils) at certain neutron energies (for example 2.35 MeV). This feature can be used to accentuate the shadowing effect and to achieve better penetration of neutrons through the soil. Tests and simulations have demonstrated that MNBRP should be capable of detecting landmines equivalent to DLM2 at depths up to 22 cm. Further investigations should be undertaken to determine optimum conditions for employing this method in the field.

4. Discussion and conclusions

Neutron and gamma methods are a relatively recent addition to the emerging methods for APM detection listed in section B of Table 1. As for any new technique, the development of each proposed nuclear method can be tracked and monitored through a series of distinct phases such as the following:

Phase 1—Formulation of a new idea followed by simulations and laboratory tests that demonstrate the feasibility of the method at the ‘‘proof-of-principle’’ level.

Phase 2—Construction of a prototype instrument for tests and demonstrations both in the laboratory and out-of-doors, using a dummy landmine such as DLM2.

Phase 3—Further tests of the prototype instrument using both dummy and real landmines (without detonators) under the guidance and supervision of a demining organization, preferably at a test facility operated by such an organization.

Phase 4—Final modification of the prototype instrument, if required or recommended as a result of the phase 3 tests, and then testing and adaptation for field use under the guidance and control of the demining organization.

All of the nuclear methods considered in Sections 3.1–3.3 and also the MNBRP method from Section 3.4 have already completed phase 1 successfully. PELAN (Section 3.1) has also completed phase 2 and is now undergoing trials (phase 3) at test sites in Croatia and the USA. NNA, the other associated particle methods mentioned in Section 3.1 and the neutron moderation methods of Section 3.2 (DUNBLAD, DIAMINE and HYDAD) are at various stages in phase 2. Some or all of these methods should be ready to move into phase 3 soon if decisions are taken to continue work on their development. HYRAD (Section 3.3) and MNBRP (Section 3.4) should be extended into phase 2 as soon as possible.

Phase 3 is the stage at which a method may begin to be considered a proposition by demining organizations. PELAN appears to be the only nuclear technique that has already reached this stage. The results already obtained using the other nuclear-based methods need to be examined closely to determine whether any of these methods merit further development and testing beyond phase 2. It seems possible that this may happen soon under the auspices of the IAEA.

Another question that needs to be considered is the type of APM detector that can be realised by means of each technique—will it be light enough to be carried and deployed in the same way as a hand-held metal detector, for example, or will its size or other factors dictate that it has to be mounted on a mine-protected vehicle? At the moment it seems that only the DUNBLAD, DIAMINE and HYDAD-H detectors (from the list of candidates that we have considered) may be conveniently man-portable.

In conclusion, we note that nuclear-based methods for landmine detection have not yet been recognised as ready for deployment in the field. There has nevertheless been good progress in the development of nuclear-based APM detectors so this might change soon. Some of the nuclear methods such as PELAN are already undergoing field testing and others are nearing this stage. If contacts could be strengthened between the designers of nuclear-based sensors and the demining organizations for whom the sensors are intended then both parties might benefit.

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