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Detection of anti-personnel landmines by neutron scattering and attenuation

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Abstract

Four methods for employing neutrons to detect abandoned small anti-personnel landmines are presented and discussed. The techniques used are based on measurements of effects due to the scattering of neutrons on the hydrogen content of the landmine.

Keywords: Antipersonnel landmines; Humanitarian demining; Neutron scattering

1. Introduction

A large fraction of the landmines that were deposited in post-second-world-war conflicts and then abandoned are small (<300 g) antipersonnel landmines (APM) of plastic construction and low metal content. The low metal content makes these APM difficult to detect by conventional methods based on metal detection. Furthermore, when detected in this way they are indistinguishable from metal debris which often litters sites of former conflicts where the abandoned landmine problem is particularly acute. Three factors can contribute to making neutron scattering useful for detecting this particular type of APM. Firstly, there is the fact that the hydrogen content of plastic APM is relatively high. The atom percentages of hydrogen in typical plastics and explosives are 55–65% and 25–35% respectively. Secondly, for neutron energies below about 3 MeV, the total neutron cross section of ^{1}H (the proton) is significantly higher than that of other nuclides that are commonly found in the soil or in metal debris. Thirdly, n–p elastic scattering, which is the dominant process in the interaction of neutrons with protons at these energies, has two unique features: the average energy loss per scattering by the neutron is large (50%), which makes hydrogen a good neutron energy moderator; and the angle of scattering of the neutron (in the laboratory frame) cannot exceed 90°. We have explored three different approaches that exploit these characteristics: firstly, neutron energy moderation as a hydrogen (and therefore APM) "signature"; secondly, the enhanced attenuation of low-energy neutrons by hydrogen; and thirdly, use of the unique neutron angular distribution in n–p scattering as another signature for APM detection. Before describing work based on these three different approaches we first discuss some general considerations that are important to the development of APM detectors based on the use of neutrons.

2. Development of APM detectors—general considerations

It would be a help if some real (disabled) APM could be made available in the laboratory as test objects for use in the development of APM detectors. Since this is not possible (for security reasons), except at official test sites, we have had to use suitable alternatives. A

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Table 1
Landmine test objects

Designation	Description
M1	Nylon disc. Mass 69 g. Diameter 70 mm. Length 17 mm.
M2	Hexogen cylinder. Mass 135 g. Diameter 60 mm. Length 33 mm. (Composition: 3.67 g (H), 21.9 g (C), 51.1 g (N), 58.3 g (O))
DLM2	TNT simulant sealed in a polymethylmethacrylate container. Container diameters: 80 mm (outer). 70 mm (inner). Container lengths: 34 mm (outer). 22 mm (inner). Mass of container 100 g. Mass of TNT simulant 100 g. Composition of TNT simulant: 17.3 g graphite + 23.9 g oxalic acid crystals + 58.8 g cyanuric acid. Elemental composition of container: [H:C:N:O] = [4:2:0:1]. reference (IAEA, 2003).

"standard" dummy landmine, DLM2, was eventually designed by the IAEA Coordinated Research Project (CRP) that sponsored this work (IAEA, 1999) and thirteen replicas of this design were constructed and distributed among CRP members. The characteristics of DLM2 are summarised in Table 1, together with those of some other test objects that we used prior to DLM2 becoming available.

A variety of considerations might be regarded as relevant guides in the development of new APM sensors (Sahli et al., 2003) or, more specifically, new sensors based on a particular type of technology such as nuclear technology (IAEA, 1999, 2001, 2003). Besides the obvious requirement that the detector must function effectively and reliably within whatever limitations are specified by its designers, other requirements that might be considered necessary or desirable are, for example, that the sensor should be: not too expensive; simple to operate; light enough to be man-portable; and non-intrusive, in other words be capable of operation without resting on, or disturbing in any way, the ground in which it is looking for landmines. After consulting with some experts (Joynt, 2001) who are actively involved in mine clearing we believe that additional requirements such as these should not be taken too seriously, at least in initial investigations of the possibilities offered by nuclear technology. The main objective should instead be to complete a proof-of-principle test to determine whether a new idea or technique is viable for landmine detection in any reasonably realistic demining context. We therefore consider here different approaches to landmine detection regardless of whether they can be implemented in a hand-carried instrument, for example, or whether they can only be implemented from a mine-protected vehicle because they are too heavy to carry or require mechanical intrusion into the soil which might set off an explosion.

3. APM detection by neutron energy moderation

The neutron energy moderation method is a hydrogen-sensing technique that has been used for many years to measure the moisture content of agricultural land and for oil well logging. It was also considered for landmine detection more than ten years ago (Orphan, 1992). It depends on the fact that dry sand will normally contain very little hydrogen, hence an 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 (Brooks et al., 2003). 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. We have called the detectors of this type that we have developed HYdrogen Density Anomaly Detector (HYDAD) detectors. Two sub-types have been developed, HYDAD-H for hand-held operation and HYDAD-VM for a vehicle-mounted landmine detector.

3.1. The HYDAD-H hand-held detector

Fig. 1 is a schematic diagram of the hand-held HYDAD-H system. It consists of a fast neutron source S (AmBe or ^{252}Cf) attached to a slow neutron detector D (^{3}He-filled proportional counter in this example) and some electronics (not shown). The detector is effectively 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 (e.g. in the dummy landmine or other test object). Thus, the detector count rate passes through a maximum as the system is scanned along a horizontal line close to the sand surface, passing directly over the test object (see Fig. 2(a)). With the help of suitably designed "contrast-enhancing" electronics this count rate is converted into an audible beep rate that increases from $<0.3\,s^{-1}$ to more $>3\,s^{-1}$ (Fig. 2(b)) as the detector is scanned from a distant off-mine position to directly above the test object. A battery-powered, hand-held prototype version of HYDAD-H has been tested in out-of-doors conditions. More details, including movie clips showing the detector in operation during these tests are available at 〈http://www.phy.uct.ac.za/hydad〉.

Results obtained using HYDAD-H and other similar systems (IAEA 1999, 2001, 2003; Bom et al., 2003; Viesti et al., 2003; Csikai et al., 2003) indicate that this type of detector is 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 is fundamental and impossible to overcome. However it is possible to extend the range of the method to depths greater than 10 cm in dry sand by using a modified geometry, HYDAD-VM, as explained below.

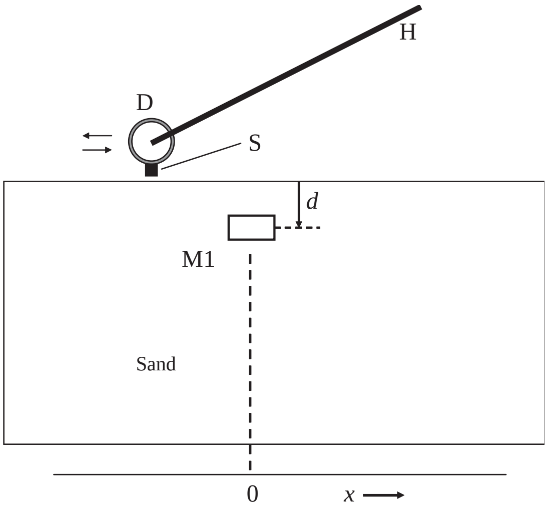

Fig. 1. Schematic diagram of the HYDAD-H hand-held APM detector showing: test object (M1); fast neutron source (S); slow neutron detector (D); and carrying rod (H).

3.2. The HYDAD-VM vehicle-mounted detector

Fig. 3 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 positions at which a metal detector registers a positive response. Each paint spot has to be checked afterwards using one or more confirmation sensors. At the moment this is done by foot-bound personnel using hand-held metal detectors, probing sticks or sniffer dogs. 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. The neutron source and detectors will be kept well out of reach of any blast that might occur during the insertion of the spike. After the spike is safely in position, as shown in Fig. 3, a neutron source (AmBe) will be lowered into it and a symmetric array of six or more slow neutron detectors will be lowered carefully to a position just above ground level. Laboratory and out-of-doors 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 a

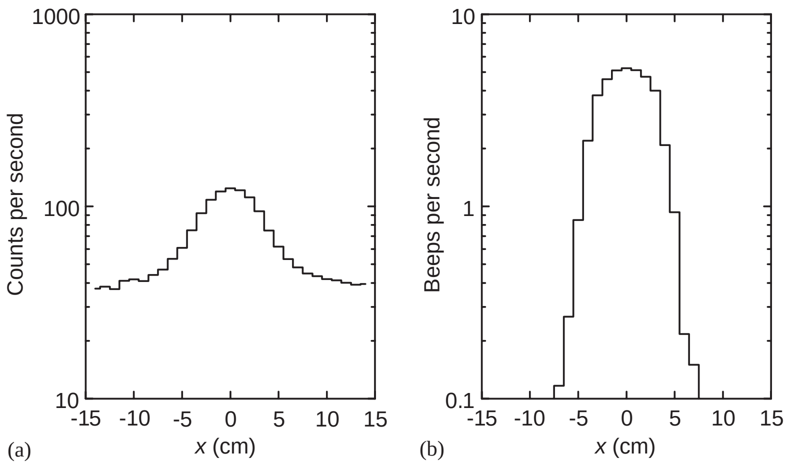

Fig. 2. (a) Detector count rate and (b) contrast-enhanced beep rate, as a function of the horizontal displacement x of the HYDAD-H detector D from the test object M1 (see Fig. 1), buried at a depth $d = 19$ mm.

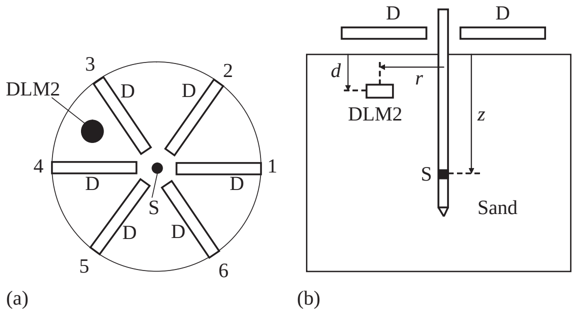

Fig. 3. Schematic diagram of the HYDAD-VM APM detector system showing: dummy APM (DLM2); the hollow spike containing an AmBe neutron source (S); and the symmetrical array of six identical slow neutron detectors (D). (a) Plan view. (b) Vertical section through the centre.

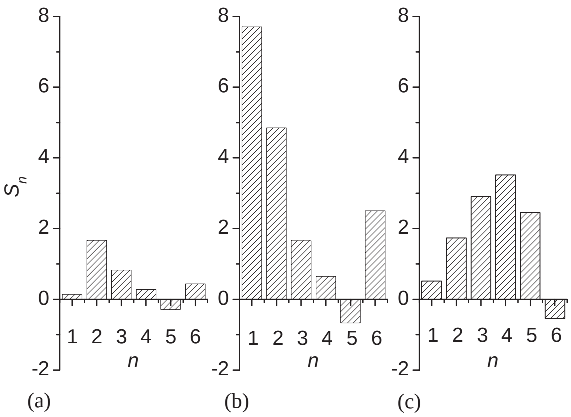

Fig. 4. Plots of the deviation parameter S_n (Eq. (1)) as a function of detector position n (see Fig. 3) obtained from 1 min count measurements made using the AmBe source at depth $z = 30$ cm and: (a) no test object in the sand; (b) DLM2 below detector 1, at $r = 10$ cm, $d = 11$ cm; and (c) DLM2 below detector 4, at $r = 10$ cm, $d = 24$ cm.

group of adjacent detectors will exhibit count rates that are significantly higher than those from the other detectors.

Fig. 4 shows results obtained from some test measurements made in dry sand using an AmBe source (8×10^5 n s^{-1} into 4π) at a depth $z = 30$ cm (see Fig. 3). Counts C_n were recorded for each detector position n over a period of 1 min. A "baseline" reference count C_b was then estimated by locating the two lowest adjacent values of C_n and averaging them. The deviation S_n of each count from the baseline was then determined, in units of the standard deviation, from the following equation

$$S_n = (C_n - C_b)/(C_n + C_b)^{1/2}. \quad (1)$$

Fig. 4 shows plots of S_n as a function of detector number (position) n obtained under three different conditions: (a) with no test object present; and, (b) and (c), with DLM2 in position at radius coordinate $r = 10$ cm. In (b) DLM2 was below detector 1 at depth $d = 11$ cm. In (c) it was below detector 4 at depth $d = 24$ cm. It is clear that a simple criterion such as $S_n > 3$ will be sufficient to determine, from this measurement, whether an object such as DLM2 is present and, if so, to locate the object to within a few cm. Tests of this type have demonstrated that 1 min of counting in the geometry of Fig. 3 will be sufficient to detect the DLM2 dummy landmine to a precision of 3 or more standard deviations ($S_n > 3$), at depths d up to 30 cm and within a radius $r = 20$ cm of the spike.

4. APM detection by 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. 5 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. Neutron and gamma count rates are

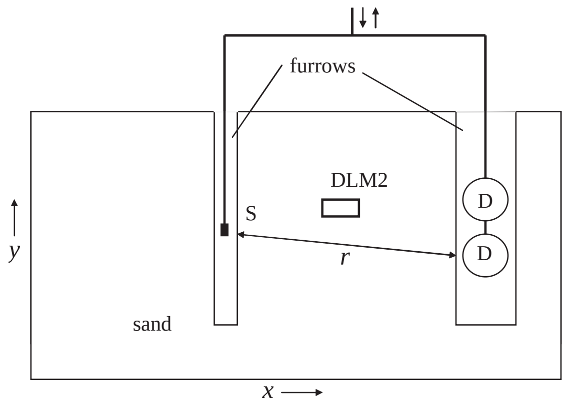

Fig. 5. Schematic diagram of the HYRAD APM detection system showing: the neutron source (S); NE213 liquid scintillator detectors (D); and dummy APM (DLM2).

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. Let the numbers of neutrons and gammas emitted per unit time by the source be N_{on} and $N_{o\gamma}$, respectively. For each detector the majority of neutrons and gammas detected will be those that travel directly from the source to the detector without interacting in the sand. Considering only these neutrons and gammas, the numbers counted per unit time are given by

$$N_n = \Omega\ \varepsilon_n\ N_{on} \exp\left(-\mu_n\, r\right) \tag{2}$$

and

$$N_\gamma = \Omega\ \varepsilon_\gamma\ N_{o\gamma} \exp\left(-\mu_\gamma\, r\right), \tag{3}$$

where r is the thickness of sand between the source and detector, Ω is the solid angle subtended by the detector at the source, ε_n and ε_γ are the efficiencies of the liquid scintillator for detecting neutrons and gammas, respectively, from the source and μ_n and μ_γ are the linear attenuation coefficients of the sand for these neutrons and gammas. The ratio of the neutron and gamma counts $R = N_n/N_\gamma$ is therefore given by

$$R = (\varepsilon_n N_{on}/\varepsilon_\gamma N_{o\gamma})\ \exp\left[(\mu_\gamma - \mu_n)r\right]. \tag{4}$$

For homogeneous media the coefficients μ_n and μ_γ depend linearly on the density ρ of the sand between the source and detector hence Eq. (4) may be rewritten

$$R = (\varepsilon_n N_{on}/\varepsilon_\gamma N_{o\gamma})\ \exp\left[(f_\gamma(Z) - f_n(Z,A))\rho r\right], \tag{5}$$

where $f_\gamma(Z)$ 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 detectors for detecting these radiations. Eq. (5) 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. (5) 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 (Brooks et al., 2003). 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.

5. APM detection by 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 timing or even using a continuous-spectrum source without making any timing measurements (Csikai et al., 2003). In principle it should be possible to adapt these techniques for APM detection but further work still needs to be done to demonstrate that this is actually feasible.

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, 2001; 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 APM 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 and 6.50 MeV). This can be used to achieve better penetration of neutrons through the soil, making deeper lying mines accessible.

Figs. 6 and 7 display results (Drosg, 2001) obtained from Monte Carlo simulations (code MCNPv4B) of the MNBRP system. Comparisons are shown of the spectra of back-scattered neutrons observed from dry soil at a scattering angle of 150°. The incident neutron energy was 2.35 MeV. The dashed histograms show the spectrum obtained with no test object embedded in the soil. The solid histograms show spectra obtained with the test object M2 (see Table 1) buried at cover depths of 7 cm (Fig. 6) and 22 cm (Fig. 7). The peak at the upper limit (2.03 MeV) of these spectra is due to neutrons that are back-scattered by the higher Z components of the soil. The shadowing effect referred to is the attenuation

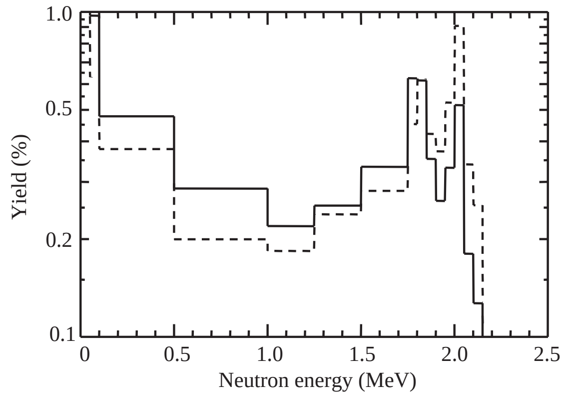

Fig. 6. Results obtained from a Monte Carlo simulation of the MNBRP APM detector. A comparison is shown of the back-scattered neutron spectra obtained at angle 150° for 2.35 MeV incident neutron energy, without (dashed line) and with (solid line) the test object M2 embedded in the sand at a cover depth of 7 cm.

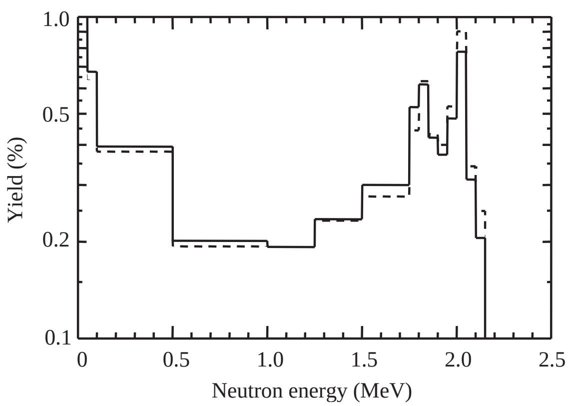

Fig. 7. Same as Fig. 6 but for a cover depth of 22 cm.

of this peak that results from the displacement of soil by M2 and the removal and energy-degradation of neutrons by the (low Z) constituents (in particular hydrogen) in M2. The effect is strong (> 40%) at cover depths of 7 cm or less, as can be seen in Fig. 6, and drops to about 10% at a depth of 22 cm (Fig. 7).

Experimental tests (Drosg, 2001) have confirmed the results predicted by these simulations and have also demonstrated that the shadowing effect can be strongly enhanced, if nanosecond timing is available. Nanosecond timing makes it possible to use neutron time-of-flight (“time slicing”) to select neutrons that are backscattered from a specific depth in the medium and thus to discriminate against neutrons scattered by soil above and below the landmine, thus reducing background very effectively. For example, in tests made using a pulsed neutron beam and a test object similar to DLM2 at a cover depth of 14 cm, time slicing increased the shadowing effect from 18% to 53% (Drosg, 2001).

Recent Monte Carlo simulations (code MCNPv4B) of deep-lying mines ($\leqslant$80 cm sand cover) which took time slicing into account confirmed expectations

- that the shadowing effect does not decrease much when increasing the soil cover, as already suggested by the experiment (Drosg, 2001), and
- that the backscattered neutron intensity drops exponentially with the depth of the mine.

For quartz sand of density 1.59 g/cm^3 the depth dependence of the detected time-selected neutron intensity was found to be

$$I = I_o \exp(-0.13d) \tag{6}$$

with d the thickness of the sand cover in cm. With the approximation that d is the same for the ingoing and outgoing attenuation the factor 0.130 can be split into 0.039 due to the ingoing and 0.091 for the outgoing attenuation. This big difference was expected because the incoming radiation was chosen to match the energy of the resonance with minimum attenuation.

These tests and simulations therefore demonstrate that the MNBRP method, with time slicing, is intrinsically capable of detecting landmines equivalent to DLM2 at depths well beyond 22 cm. The maximum depth attainable will be limited by factors such as source intensity, measuring time available, quality of neutron beam collimation and the effects of multiple neutron scattering. Further investigations should be undertaken to study these factors and to determine optimum conditions for implementing this method in the field.

6. Discussion and conclusions

We have described four types of APM detector that depend on the characteristics of neutron–proton interactions: HYDAD-H and HYDAD-VM (Section 3); HYRAD (Section 4); and MNBRP (Section 5). “Proof-of-principle” tests based on computer simulations and laboratory experiments have been satisfactorily completed for all of these proposed detector systems. A battery-powered, prototype version of the hand-held HYDAD-H detector has been constructed and tested in out-of-doors conditions. This detector is not suitable for use in wet conditions. In dry conditions it has been shown to be reliable for detecting APM equivalent to DLM2 at burial depths up to about 7 cm, that is depths within which APM are an immediate threat to pedestrians. HYDAD-H could therefore be used to provide better protection to foot-bound mine-clearing personnel operating in dry conditions and should be field tested with this possibility in mind.

HYDAD-VM employs a modified geometry based on that of HYDAD-H and is designed to extend the range of APM detection to greater depths, for example 30 cm. Use of this detector will also be limited to dry conditions. The modified geometry requires that a pipe be driven into the ground at a point as close as possible to the position of the suspected APM that is being investigated. Since this might lead to detonation of an APM, operation of HYDAD-VM from within a mine-protected vehicle is envisaged. The neutron source and detection equipment will not be in danger in the case of an explosion since they will not be brought into position until the pipe is safely inserted in the soil. The performance of HYDAD-VM in laboratory tests indicates that 1 min of counting followed by a few seconds of data reduction will be sufficient to detect and locate an APM equivalent to DLM2 in a volume of diameter 40 cm, extending to 30 cm below ground level, or to confirm the absence of such an APM in this volume. Out-of-doors tests of HYDAD-VM are now in progress.

Work is now in progress (Brooks et al., 2003) to replace some of the hard-wired electronics of the present HYDAD-H and HYDAD-VM detectors with software that will operate on-line on a small, hand-held computer. This change also includes the addition of position sensors to enable detector responses to be recorded as a function of position during scanning and then integrated, mapped and presented in the on-line display.

The HYRAD system (Section 4) is now being prepared for testing in out-of-doors conditions. These tests will pay special attention to the effects of variability of ground conditions on the neutron and gamma transmission measurements and the impact that these effects might have on the reliability of APM detection by this method.

The MNBRP system will offer many useful advantages for APM detection if the necessary requirements for bringing it into field operation can be realised. One of the main requirements will be to obtain a high-intensity, monoenergetic neutron source of suitable energy, such as 2.38 MeV. This requirement, together with the need for neutron collimation and an efficient neutron detector are expected to dictate that this system will have to be vehicle-mounted rather than hand-held. The neutron source should ideally be a source with nanosecond timing capability in order to allow time-slicing to be used, as mentioned in Section 5.

In conclusion, computer simulations and laboratory experiments have demonstrated that each of the four proposed APM detection methods are viable, at least at the proof-of-principle level. All of these methods already appear to show promise of being useful in the role of confirmation sensor in a multisensor APM detection system. In such a role they would be used only to examine areas in which some other type of "primary" sensor such as a metal detector had previously recorded a positive response indicating a possible landmine. The MNBRP and HYRAD detectors may also have potential for use as primary sensors. Further investigations, out-of-doors and at testing facilities for APM detectors, are now required in order to determine how HYDAD, HYRAD and MNBRP detectors should be adapted for field application and to test them in this context.

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