Appendix N

NEUTRON TECHNOLOGIES (PAPER I)

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INTRODUCTION

Detection of landmines using nuclear techniques has been studied extensively since the late 1940s. Nuclear techniques look at either a return radiation, which is characteristic of explosive components that are infrequently found in soil (e.g., nitrogen or carbon), or an intensity change of a noncharacteristic scattered radiation, which is a function of a parameter that differs between soil and explosives. Noncharacteristic radiation methods are essentially anomaly detectors; that is, they detect inhomogeneities in the medium and inclusions in addition to mines. Virtually every conceivable nuclear reaction has been examined, but after considering a number of factors (many of them linked)—including selectivity, sensitivity, probability of detection, false alarm rate, soil absorption, time to make a detection, limitations due to fundamental physics, and technical limitations (size, weight, power, present and future availability of sources and detectors)—only a few have potential for mine detection. Probably the most thorough examination of nuclear reactions for landmine detection is the report by Coleman et al. [1] sponsored by the U.S. Army Mobility Equipment Research and Development Center (now called the Night Vision and Electronic Sensors Directorate). A workshop was held in 1985 to revisit the conclusions of the Coleman report in light of advances in technology and to identify any nuclear

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[1] This paper is based on research conducted at the Canadian Centre for Mine Action Technologies, under the sponsorship of the Canadian government (Defence R&D–Suffield).

techniques that should be developed for mine detection [2]. Experts concluded that the most promising nuclear technologies were, in order, x-ray backscatter imaging, thermal neutron capture gamma rays, neutron thermalization (moderation), and differential collimated photon scattering (now called x-ray lateral migration). Coleman did not do an explicit ranking of reactions; however, the top three techniques are the same for both studies. Moler did a further reassessment in 1991 [3] in light of research that had been done as a result of his 1985 report. His conclusions remained the same. Other reviews have included nuclear methods in the context of unexploded ordnance and landmines, [4] military demining [5], and humanitarian demining [6], all with conclusions similar to those of Coleman and Moler.

The following discussion is restricted to reactions that involve excitation by, or emission of, neutrons. For a neutron reaction to be potentially adaptable to handheld antipersonnel mine detection, it must have a large cross section and be amenable to using very efficient detectors, so that relatively weak sources can be used. This allows a decrease in size and weight of shielding for electronics and personnel. The only feasible reaction in this category is neutron moderation. We shall nevertheless look at the other neutron reactions. Although humanitarian demining is mainly concerned with the detection of antipersonnel mines, in some scenarios handheld use is not required and in others, such as supply route proving, vehicle-mounted detection of antitank mines may be needed.

NEUTRON REACTIONS

Because of range limitations in the soil and mine, the number of neutron reactions can be dramatically reduced by eliminating those that involve charged particle excitation or detection. The remaining reaction classes are neutron excitation/photon detection (neutron capture gamma rays, neutron inelastic scattering gamma rays, neutron activation); neutron excitation/neutron detection (neutron moderation, neutron elastic resonance scattering, neutron inelastic scattering); and photon excitation/neutron detection (photoneutron emission).

Neutron Capture Gamma Rays (Thermal Neutron Analysis)

Many of the materials in soils and landmines emit gamma rays when thermal neutrons are captured. Most research since the early 1950s has concentrated on the 10.835 MeV transition in nitrogen because bulk nitrogen is indicative of the presence of explosives,[2] there are virtually no nearby competing reactions except the weak 10.611 MeV transition from ^{29}Si, and it is sufficiently isolated so that low energy resolution NaI(Tl) detectors may be used. (High-resolution intrinsic Ge detectors are an alternative, but they are much more expensive for similar efficiency and less suitable for fieldable systems because they are less rugged, microphonic, more prone to neutron damage, and must be cryogenically or electromechanically cooled.) It has been estimated from experiments and modeling [7] that neutron capture detectors could be used in a scanning role (95-percent probability of detection [PD] with false alarm rate [FAR] of less than 1 per 500 meters at speeds of at least 10 km per hour). This is contradicted by other independent analyses [3,8].

Researchers have used a variety of isotopic and electronic sources and detectors. For confirmation detection, high-intensity sources (greater than 10^8 neutrons/second) are required. Performance results from low-intensity source systems, where silicon interference limits performance, cannot easily be extrapolated to those with high-intensity sources, where pulse pileup is the limiting factor.

Defence R&D Canada (DRDC) and Bubble Technology Industries (BTI) have been developing a thermal neutron analysis (TNA) detector as a confirmation sensor on a teleoperated, multisensor vehicle-mounted mine detector (Improved Landmine Detector Project [ILDP]) since 1994 [9]. To be usable for confirmation mine detection, a TNA detector must be carefully designed with its role specifically in mind. This was done, paying particular attention to electronic and shielding design. The production version is based on an intense ^{252}Cf source and four NaI(Tl) detectors. The sensor head is roughly a cube with 0.6-m sides and has a mass of about 216 kg. The electronics consume about 200 watts. A prototype 14.8 MeV DT [deuterium/tritium] neutron generator-based version, with a roughly 10-percent-

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[2] Explosives in landmines contain about 18–38 percent nitrogen by weight; soil contains less than 0.07 percent.

larger sensor head, consuming 1 kW, has been built and is currently undergoing testing [10]. Preliminary tests supported by calculations suggest that it should perform at least as well as the isotopic TNA—and possibly better. The lab (nonproduction) isotopic source prototype TNA has functioned well as a part of ILDP and in standalone tests in stringent climatic conditions, including in temperatures from –20°C to +40°C, snow, rain, dust, and extreme dryness.

Only the nonproduction prototype isotopic source DRDC TNA has had its performance quantified. The production version is currently undergoing testing and is expected to perform at least as well. In nonblind testing at DRDC-Suffield, it was found that the TNA can confirm the presence of a variety of surface-laid or shallowly buried antitank mines in a few seconds to a minute, depending on the explosive mass [9]. It is also capable of confirming the presence of antitank mines buried to a depth of 20 cm and shallow, large (greater than 100 g nitrogen) antipersonnel mines in less than five minutes. Limited blind testing conducted by the Institute for Defense Analyses as part of the 1998 Ground Standoff Mine Detection System trials showed that the prototype was capable of a PD/probability of false alarm (PFA) of 0.79/0.00 at Aberdeen Proving Ground, Md., and 1.00/0.32 at Socorro, N.M. [11]. The TNA is capable of better performance; however, the laboratory prototype tested was not intended to be a rugged, fielded system, and environmental conditions were unfavorable at both sites (temperatures from +35°C to +40°C). More significantly, software and hardware shortcomings, which have since been rectified in the production version, decreased performance.

The Canadian TNA program appears to be the only currently active one. Present research and development (R&D) involves detector and signal-processing improvements to decrease count times and increase sensitivity. These are expected to be incremental improvements. Extensive system characterization, planned for this year, is essential for both the isotopic- and neutron generator–based detectors. A preliminary study, started in September 2002, is investigating the feasibility and benefits of adapting the Canadian TNA detector system to combine TNA with fast neutron analysis (TNA/FNA).

Numerous experimental and modeling studies and reviews since the 1950s and experience with the Canadian TNA all point to the fact that TNA is feasible only for vehicle-mounted confirmation detection of antitank and large antipersonnel mines. In spite of occasional claims, a practical, lightweight, and person-portable system is unachievable, based on the physics, as opposed to the technology. No order of magnitude breakthroughs are expected.

Neutron Inelastic Scattering Gamma Rays (Fast Neutron Analysis)

In this method, fast neutrons excite soil and mine nuclei by inelastic scattering. As the nuclei de-excite, they emit characteristic gamma rays. The only practical source at present is a 14.8 MeV DT neutron generator. At that energy, nitrogen cross sections are much smaller than for thermal neutron capture gammas and offer no clear advantage over the latter. Production of 4.44 MeV photons from $^{12}C(n,n'\gamma)$ has a large cross section, but organic and carbonaceous material will cause false alarms.[3] Efficient, robust detectors, such as NaI(Tl), lack sufficient energy resolution to distinguish 4.44 MeV photons from Si and O background gammas, and, as stated above, Ge detectors are not practical.

The main claimed advantage for the neutron inelastic scattering gamma ray method is that it could be used to discriminate explosives from organic soil materials by measuring the C:H:O concentration ratios in the interrogated volume [12]. Given the cross sections, it seems that the time required to obtain sufficiently accurate ratios for reliable discrimination would be much longer than TNA interrogation times. Further, repeated studies since the late 1950s have consistently concluded that landmine detection through neutron inelastic scattering gamma production is not at present practical with available sources and detectors. Given these elements, it is difficult to see any advantage over thermal neutron capture.

It has been implied that a neutron inelastic scattering gamma ray detector for landmines can be easily constructed from components used in other roles, such as coal slurry analysis [12]. However, quite the opposite is true. Experience with TNA for mine detection shows that detector systems must be purpose-built for the role with intense

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[3] Explosives in landmines contain about 16–37 percent carbon by weight; soils contain about 0.1–9.0 percent.

neutron sources and carefully designed shielding. The intensity of sources required precludes the use of the associated particle technique to acquire position information. There may be some advantages to combining TNA with FNA, such as adding a carbon detection capability to the nitrogen capability of TNA. However, this must be done in a purpose-built design. DRDC has recently initiated a feasibility study to examine if the DRDC/BTI neutron generator source TNA can be modified to provide an FNA capability.

Changing the neutron energy to 6 MeV has the advantage of producing a 5.10-MeV nitrogen gamma with no interfering gammas from soil. Currently, there are no sources of 6-MeV neutrons, and a feasibility study to determine if one could be constructed is recommended.

Neutron Activation

Fast neutrons can activate materials in soils and mines through a number of reactions. These materials can be detected by measuring characteristic gamma rays from their radioactive daughters. Half-lives of these radioactive components vary from milliseconds to days. Silicon and oxygen account for the dominant gamma rays from soil, but detecting a lack of these materials is equivalent to detecting voids. The $^{14}N(n,2n)$ reaction will produce characteristic 511 keV gamma rays, but they are much weaker in intensity than the gammas from silicon. A series of experiments from the 1950s through the 1970s verified that the nitrogen signal is far too weak to be usable for practical scan/dwell times. Silicon voids were detectable but only with very intense neutron generators (about 2×10^{10}) neutrons/second, five minute irradiation) and at very slow speeds. These results are limited by the physics and preclude the development of a practical detection system.

Neutron Moderation

This method involves irradiating an area with fast neutrons and detecting subsequently moderated and returned slow neutrons. Explosives contain 2–3 percent hydrogen by weight, while soils may contain 0-percent to more than 50-percent hydrogen. Thus the presence of an anomaly in the measurement of hydrogen density may be used to imply the presence of a mine. Measurement of the albedo signal (ratio of number of slow neutrons returned from the soil to the number of incident fast neutrons) is then used as an indicator of the presence of a mine. The large cross sections make it amenable in principle to handheld operation and detection of antipersonnel mines. The chief limiting factor in the signal-to-clutter ratio (SCR) is hydrogen in groundwater. The hydrogen densities of the soil and the mine are equal, and mines cannot be detected when the gravimetric percentage of water is between 18 and 27. Other factors that affect the SCR are ground surface irregularities and detector height variations. In practice in the past, these combined factors have rendered this detection technique, using nonimaging detectors, useless in all but the driest of conditions. One method of reducing false alarms from all of the above sources is to spatially image the neutrons coming from the ground.

The U.S. Army sponsored research in neutron moderation detection of landmines from the early 1950s through the early 1990s. Isotopic sources, such as Po-Be and Cf, with typical outputs of 10^6 neutrons/second, were used as well as accelerator sources employing different reactions yielding 1.1 MeV, 2.8 MeV, and 14.8 MeV neutron energies. Detectors have included BF_3 and ^3He proportional counters and ^6LiI crystals wrapped in Cd. All previous research has been nonimaging. A few research groups are currently involved in neutron moderation studies involving simulation and experiment. Researchers active in this area include Frank Brooks's group at the University of Capetown, South Africa [13]; Carel W.E. van Eijk's group at the Delft University of Technology in the Netherlands [14]; and Julius Csikai's group at the Institute of Experimental Physics, University of Debrecen, Hungary. For neutron moderation to be useful, imaging must be employed to reduce the high FAR. None of the previously mentioned work involves developing imaging systems.

A DRDC/BTI team has been developing a neutron moderation imager based on a large scintillation screen and wavelength shifter optical fiber readouts for mine detection since 2000 [15]. A proof-of-concept detector is nearly constructed, and preliminary testing will be completed by the project's end in March 2003. The DRDC/BTI imager will be 50 cm × 50 cm, with a mass of roughly 13 kg and a power consumption of 10 watts. Various other imaging technologies can be investigated, but these, together with clever packaging, will likely lead to only incremental decreases in mass and power. There is little published data on measured PD and FAR, which are largely a function of how long one is willing to count. It is unlikely that performance will dramatically improve over the estimates from simulation studies [14]. These showed that images of suitable fidelity could be made of antipersonnel and antitank mines. Detection of a small antipersonnel mine (PMA2) with a PD/PFA of 0.98/0.02 could be achieved in about 6 seconds at a 5-cm depth in sand with 10-percent water. At a depth of 10 cm, the time increases to 21 seconds. For a small antitank mine (500-g explosive, 7-cm diameter, 7-cm height [cylinder]) at a 5-cm depth in sand with 10-percent water, the detection time decreases to 0.4 seconds. It appears that detection in environments with water contents between 10 percent and 20 percent may be possible.

Neutron moderation imaging may have potential for quick confirmation or slow scanning of antipersonnel mines in soils with moisture content less than or equal to 10 percent and possibly between 10 percent and 20 percent. A prototype Canadian instrument will be ready by March 2003, and its performance will be extensively characterized in summer 2003. No other countries appear to be actively investigating neutron moderation imaging at this time, although the Delft group recently reported having a design for an imaging detector based on position-sensitive ^{3}He tubes. Although the Canadian instrument could use a distributed array of low-intensity, point ^{252}Cf sources, better performance will be achieved with a uniform continuous source. Although none is available at present, such a source is being developed by DRDC and will be installed in the detector by March 2003. A further improvement might be gained by employing a distributed pulsed neutron source. The thermal decay constant for explosives is significantly different than that for either wet or dry soil. Measurement of the decay constant for each pixel could significantly improve the contrast between mine and soil, particularly in wet soil. Richard Craig of Pacific Northwest National Laboratory is developing a nonimaging detector based on this method. Distributed, wide area pulsed neutron sources do not exist, but DRDC and BTI have some design concepts, and a funding proposal to develop one has been submitted.

Neutron Elastic Resonance Scattering

In light elements, such as those in explosives and soil, the cross sections for elastic scattering of neutrons in the keV to MeV range exhibit resonances as a function of neutron energy. Each element has a characteristic set of resonance energies and intensities. Because the resonances are generally narrow and sit on a broad continuum component of the cross section, it is necessary to use an accelerator, such as a Van de Graaff, to produce monoenergetic neutrons. This is not practical in the field. Broad-spectrum sources (e.g., fission sources) are practical, but the resonance component of the cross section is generally much smaller than the continuum component, which is common to both explosive and soil materials. Thus, no measurable difference is observed between the target and background. Experiments conducted in the early 1950s using a carbon target, a continuous source, and a carbon filter confirmed this. High-energy-resolution detectors, such as time-of-flight (TOF) detectors or ^{3}He ionization chambers, are unlikely to assist in resolving the continuum component from the resonance component. TOF detectors are too large and inefficient. Recoil broadening is much greater than the resolution of either detector type and hence averages over the narrow resonances. The detector resolutions are also greater than or equal to the resonance widths. This leads to the inability to resolve resonances from the continuum to which all elements contribute. Thus, several close resonances in O and N cannot be distinguished from each other or the continuum, and the two narrow carbon resonances cannot be distinguished from the continuum. This makes the method nonspecific, and there appear to be no productive avenues for further research in this area.

Neutron Inelastic Scattering

When neutrons scatter from certain nuclei, they can lose energy by exciting the nucleus from its ground state to an excited state. In principle, the nucleus can be detected by detecting an excess of neutrons with an energy that is lower than the incident energy by the difference between the ground and excited states. Carbon's large cross section to the 4.4-MeV level makes it the most likely candidate, although a carbon detector is prone to false alarms from organic materials and carbonaceous soil. Nitrogen, which would be more specific to explosives, has cross sections that are about three to eight times smaller. The only practical monoenergetic source is a 14.8-MeV neutron generator. In principle, scattered continuous fission spectra could be unfolded to reveal the peaks in the inelastic scattering neutron spectrum, but the continuum of neutrons from direct and multiple scattering, including inelastic scattering from low-lying states, in background material nuclei would make this method impractical. Neutrons are around 10 MeV for carbon and 7–13 MeV for nitrogen. The only practical detectors in this range are TOF systems, which are inefficient and large. For scanning, neutron fluxes of 10^{11} neutrons/second would be required, while for confirmation, 10^9 neutrons/second would likely be adequate. At present, there are no advantages—and some disadvantages—to this technique over neutron inelastic scattering gamma rays. Any system would be too large and heavy for humanitarian demining.

The state of progress in the development of high-efficiency neutron spectrometers in the 7–13 MeV range should be examined to determine if development is feasible and practical.

Photoneutrons

If incident gamma-ray energies exceed the Q-value for neutron production, neutrons will be emitted with energies approximately equal to the gamma-ray energy minus Q-value minus the energy of the excited state in which the resultant nucleus is left (a correction for the nuclear recoil is required). Detection of neutrons without energy discrimination has been attempted using a bremsstrahlung beam whose endpoint energy was slightly higher than the 10.5 MeV ^{14}N threshold. It failed because of the strong background of neutrons from silicon. Detection of ^{13}C and ^{2}H is also possible; if an incident energy of 6 MeV were used, only those two isotopes would be excited. However, this would be prone to false alarms from organic materials and carbonaceous soils, and down-scattered fast neutrons from water would dominate the response.

If a suitable energy-sensitive neutron detector were used, the spectrum of emitted characteristic neutrons might be used to identify the nucleus. The normal detectors in the 100 keV to few MeV range are proton recoil and TOF. The former generally has poor energy resolution due to uncertainties in unfolding its flat response to monoenergetic neutrons. The latter is very large if reasonable energy resolution is desired. A high-resolution, fast neutron spectrometer based on a ^{3}He ionization chamber has been used for photoneutron spectroscopy in this energy range [16] and was proposed in this role for mine detection [4]. These instruments are no longer manufactured, but DRDC has such a detector. Plans are under way to repeat the previous bremsstrahlung threshold experiments over mines and soil at various endpoint energies from 6 to 14 MeV in the near future. A Linac will be used as a source and a ^{3}He ionization chamber, proton recoil counters, and threshold energy bubble detectors will all be used for comparison.

The required gamma-ray energies are too high for isotopic sources and a bremsstrahlung source, such as a medical Linac, is the only practical alternative. Thus, a detector based on photoneutron spectroscopy would be too big for humanitarian demining. It might be feasible for a limited role as a confirming detector for route proving, but it is not likely to offer any advantages over neutron capture gamma rays.

SUMMARY AND R&D RECOMMENDATIONS

Among neutron reactions, only neutron capture gamma rays have so far led to fielded systems. However, because of the physics, these detectors are vehicle-mounted and are restricted to detecting antitank and large antipersonnel mines; they are not practical for detection of small antipersonnel mines. The only neutron technology that may be feasible as a handheld detector of small antipersonnel mines is neutron moderation imaging. Such detectors would function in a confirmation or slow scanning mode and would not work in very wet soil. R&D on TNA and neutron moderation imaging is presently concentrated in Canada.

No neutron-based technologies will provide an order of magnitude improvement in detection speed or efficiency. Modest research programs in selected aspects of neutron moderation imaging, neutron capture gamma rays (TNA), neutron inelastic scattering gamma rays (FNA), and TNA/FNA combinations may be warranted for mine detection. These should complement, rather than compete with, existing R&D programs.

Specific suggestions follow. Estimated person years (PYs) and funding follow each project item in parentheses. These should be treated as rough order of magnitude estimates only.

Desirable R&D for humanitarian demining (detection of anti-tank/large antipersonnel mines for route proving):

- A feasibility study to determine if a practical 6-MeV neutron generator could be constructed for FNA (1 PY, $200,000).
- Design and construction of a practical 6-MeV neutron generator (subject to positive outcome from feasibility study) (6 PYs, $5 million).
- Feasibility study to determine whether high efficiency and resolution neutron spectrometers in the 7–13 MeV range could be developed (1 PY, $200,000).
- Design and construction of high efficiency and resolution 7–13 MeV neutron spectrometers (subject to positive outcome from feasibility study) (5 PYs, $200,000).

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