Feasibility of Fast Neutron Analysis (FNA) for Detection of Buried Landmines

Bubble Technology Industries Inc.

Contract Scientific Authority:
A.A. Faust
Defence R&D Canada – Suffield

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Contract Report
DRDC Suffield CR 2004-201
June 2004
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31278 Highway 17
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Contract Number: W7702-02-R912/001/EDM

Contract Scientific Authority: A.A. Faust (403-544-5362)

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Abstract

Recognizing the Canadian success in developing a landmine sensor based on neutron interrogation (Minescan), DRDC has undertaken steps to improve the basic technology behind Minescan by, for example, replacing the isotopic radiation source with an electronic source (a neutron generator) in order to reduce unwanted radiation exposure to operational military personnel. The physical principles governing the operation electronic neutron generators offered a new range of operational modes, thus this contract was designed to assess the full potential of the electronic source by assessing its capability to do fast neutron interrogation in addition to the thermal neutron interrogation currently used by Minescan. These studies have led us to the conclusion that it is not feasible to try to make use of FNA as a complementary technique to TNA to enhance the detection of buried landmines based on the existing electronic source in the ILDS head. In essence, the scattering of radiation from the ground is so intense that it masks all the desired FNA signals from the mine itself. The only method to reduce the effect of the soil is to use the tagged neutron approach. However, this implies a completely different electronic source and, likely, a differently designed head. Thus, the potential use of fast neutron activation to detect landmines will require a completely new system design, including a different type of neutron generator, different head and different (faster) detectors. The detailed results reported should prove useful in discouraging international funding agencies from pursuing FNA and FNA-augmented TNA for landmine detection. In addition, photoneutron detection was investigated as a potential complementary process to FNA and TNA. Experiments conducted indicated that the detection of nitrogen by measurement of emitted photoneutrons is possible, although the experimental apparatus used was not optimized. While the practical realization of \((\gamma, n)\) techniques as fieldable landmine detectors may be difficult, the promising results from these early experiments indicate that this, till now unstudied approach, may yield valuable information.
Executive summary

**Background:** Recognizing the Canadian success in developing a landmine sensor based on neutron interrogation (Minescan), DRDC has undertaken steps to improve the basic technology behind Minescan by, for example, replacing the isotopic radiation source with an electronic source (a neutron generator) in order to reduce unwanted radiation exposure to operational military personnel. The physical principles governing the operation electronic neutron generators offered a new range of operational modes, thus this contract was designed to assess the full potential of the electronic source by assessing its capability to do fast neutron interrogation in addition to the thermal neutron interrogation currently used by Minescan.

The detection of explosives by the use of neutron interrogation has been studied for many years. However, these studies were mainly focused on the detection of explosives in luggage in airports or examinations of unearthed, unexploded ordnance (UXO). For these applications, the use of fast neutron interrogation was the preferred technique. The reactions that were utilized for this technique were neutron inelastic scattering – \((n, \gamma)\) – or induced reactions – eg. \((n, \gamma)\), \((n,p\alpha)\), etc. One of the principal objectives in fast neutron interrogation was to measure the relative concentrations of several relevant elements, e.g. C, N, O, H, Cl, etc., in order to search for the fingerprint that indicates the presence of an explosive. This putative capability could make it an attractive complementary technology to TNA.

In general, the detection of a landmine buried in the ground is much more difficult than detecting explosives in luggage because of the shielding of the soil and the presence of the ground itself. Also, a fieldable system that must operate under various adverse environmental conditions is very much tougher to develop than one that sits in an air-conditioned airport. Thus, the incorporation of fast neutron interrogation to complement the thermal neutron technique requires a comprehensive re-assessment of the whole technology, starting from fundamental physics principles.

The complimentary process to \((n, \gamma)\) is \((\gamma, n)\), known as photoneutron production. Photoneutron detection is a potential complementary process to FNA and TNA. 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. If a suitable energy sensitive neutron detector were used, the spectrum of emitted characteristic neutrons might be used to identify the nucleus. The main components of soil have \((\gamma, n)\) thresholds that are higher than for nitrogen. \(^{28}\)Si has a threshold of 17.2 MeV and \(^{16}\)O has a threshold of 15.7 MeV. Meanwhile, \(^{14}\)N has a threshold of 10.5 MeV. Thus, by using a photon source with endpoint energy below 16 MeV, it may be possible to detect N in soil.

**Principal results:** A detailed research programme is reported that considered a wide variety of factors, such as: replacing the existing low-resolution NaI detectors by high-resolution Germanium detectors, modifications to the existing shielding design, effect of the incident neutron energy spectrum, and the volume effect of the soil at different landmine burial depths. Of all the possible signatures that might be utilized in the use of fast neutron
activation, the most promising appears to be the 4.44 MeV gamma ray from carbon, from the viewpoint of signal strength and minimum interference from other unwanted radiation. Unfortunately, there is a competing reaction from oxygen that produces the identical gamma ray. Since the soil in many parts of the world is essentially composed of SiO₂, separating the large amount of O in the soil from that in the explosive would be very challenging.

As the carbon content of the explosive seems to be of limited potential in the landmine detection scenario, the nitrogen component was again considered. There are four nitrogen peaks that had no interfering oxygen lines, but even so it was found that the contribution due to a simulated explosive is swamped by the background contribution from the soil.

The only method to reduce the effect of the soil is to use the tagged neutron (also know as associated particle) approach. However, this implies a completely different electronic source and, likely, a differently designed head. Thus, the potential use of fast neutron activation to detect landmines will require a completely new system design, including a different type of neutron generator, different head and different (faster) detectors. Such a program would be a significant technical challenge, at the very leading edge of all three technologies.

The (\(\gamma, n\)) experiments indicated that the detection of nitrogen by measurement of emitted photoneutrons is possible. The high background count rate due to the available experimental apparatus made collection of good data difficult. However, this approach is worth further investigation. A new series of experiments should be undertaken with an optimized experimental apparatus to reduce unwanted background.

**Significance of results:** These studies have led us to the conclusion that it is not feasible to try to make use of FNA as a complementary technique to TNA to enhance the detection of buried landmines based on the existing electronic source in the ILDS head. In essence, the scattering of radiation from the ground is so intense that it masks all the desired FNA signals from the mine itself.

These detailed results should prove useful in discouraging international funding agencies from pursuing FNA and FNA-augmented TNA for landmine detection. Up till now, little detailed analysis has been conducted specifically aimed at mine detection geometries and scenarios. Most experimental R&D has been in the laboratory without having to contend with any of the complicating factors described in this paper. In recent years, the International Atomic Energy Agency (IAEA) has funded a US team attempting to develop a landmine detection system based on both fast and thermal neutron interrogation. The investigators have suggested that an extremely basic experimental system can be simply configured by optimization to adapt it for landmine detection. We have shown that there are numerous important technological issues associated with the application of neutron interrogation to the buried land mine problem which must be addressed in before that system would be suitable for landmine detection.

The only method to reduce the effect of the soil is to use the tagged neutron approach. How-
ever, this implies a completely different electronic source and, likely, a differently designed head. Thus, the potential use of fast neutron activation to detect landmines will require a completely new system design, including a different type of neutron generator, different head and different (faster) detectors. Such a program would be a significant technical challenge, at the very leading edge of all three technologies.

While the practical realization of $(\gamma, n)$ techniques as fieldable landmine detectors may be difficult, the promising results from these early experiments indicate that this, till now unstudied approach, may yield valuable information.

**Future work:** While the potential for FNA and FNA-augmented TNA for landmine detection has been shown to be limited, the Scientific Authority anticipates a new role may be found in vehicle bomb detection, where the challenges posed by the significant interference caused by soil would not be present. This new programme would modify and develop the second generation prototype TNA so that it would provide the Canadian Forces three modes of operation in theatre: TNA for landmine detection (current), TNA/FNA/Associated-Particle-FNA for bulk material detection and identification in a portal screening scenario, and as a stand alone UXO analysis system (useful for identifying potential chemical fills). The physics behind each of these modes of operation is understood, so the work will be in establishing the limits of the spectroscopy and the practical implementation of the selected designs.

Additional studies of the $(\gamma, n)$ technique will be undertaken to fully explore the potential of the approach for landmine detection.

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FEASIBILITY OF FAST NEUTRON ANALYSIS (FNA) FOR DETECTION OF BURIED LANDMINES

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# TABLE OF CONTENTS

1. INTRODUCTION 1
2. BACKGROUND ON FAST NEUTRON INTERROGATION 3
3. SELECTION OF POTENTIAL RELEVANT REACTIONS 4
4. PRELIMINARY STUDIES FOR QUALITATIVE ASSESSMENTS 6
5. MORE QUANTITATIVE ASSESSMENTS OF SIGNAL TO BACKGROUND 26
6. FULL SIMULATION OF TNA HEAD GEOMETRY 30
7. MODIFICATIONS TO NEUTRON SOURCE AND SHIELDING FOR SIGNAL ENHANCEMENT 37
8. REPLACEMENT OF NaI BY Ge 38
9. SYSTEM PERFORMANCE USING THE MODIFIED HEAD WITH A Ge DETECTOR SYSTEM 40
10. EFFECT OF DETECTOR COLLIMATION 41
11. LOCALIZED VOLUME EFFECTS 43
12. MINE BURIAL DEPTH 45
13. EFFECT OF CHANGING NEUTRON ENERGY 47
14. COMPARISON OF FNA ON LUGGAGE AND LANDMINES 48
15. RE-EXAMINATION OF NITROGEN 50
16. USE OF TAGGED NEUTRONS 53
17. POSSIBILITY OF (γ,n) REACTION FOR DETECTION OF LANDMINES 54
18. EXPERIMENTAL MEASUREMENTS OF GAMMA-RAY SPECTRA USING 14 MeV NEUTRONS 55
19. CONCLUSIONS 56
20. REFERENCES 58
List of Figures

Figure 1: Carbon 4.44 MeV 7
Figure 2: Nitrogen 5.11 MeV 8
Figure 3: Nitrogen 2.31 MeV 9
Figure 4: Oxygen 6.92 MeV 10
Figure 5: Oxygen 6.13 MeV 11
Figure 6: Attenuation Of 14 MeV Neutron In ANSI Soil 12
Figure 7: Neutron Fluence VS Depth 13
Figure 8: Neutron Direction Tally 14
Figure 9: Total Gamma Spectrum (14 MeV n on ANSI soil [10% Water]) 16
Figure 10: Total Gamma Spectrum (14 MeV n on ANSI soil [20% water]) 17
Figure 11: Total Gamma Spectrum (14 MeV n on ANSI soil [40% water]) 18
Figure 12: 14 MeV n on ANSI soil w/20% water 1 cm below ground 19
Figure 13: 14 MeV Neutron on N – Total gamma spectrum 20
Figure 14: O (n, gamma) Gamma Spectrum 21
Figure 15: Si (n, gamma) Gamma Spectrum 22
Figure 16: Al (n, gamma) Gamma Spectrum 23
Figure 17: C (n, gamma) Gamma Spectrum 24
Figure 18: 14 MeV Neutron on H – Total gamma Spectrum 25
Figure 19: Spectra From Pure Samples 27
Figure 20: Measured Carbon Spectrum 28
Figure 21: Simulated Carbon Spectrum 28
Figure 22: Simulation of 7L Mine Filled With C4 Explosives and Soil 29
Figure 23: TNA Monte Carlo Head Mock-up 31
Figure 24: Measured DREO Spectra 32
Figure 25: Simulated DREO Gate-Off Spectrum 33
Figure 26: Spectra Before And After Adjustment of Photon Weight 34
Figure 27: Measured Spectrum With NaI Detectors 38
Figure 28: Stimulated Spectrum With NaI Detectors 39
Figure 29: Simulated Spectrum With Ge Spectrometers 39
Figure 30: Simulated Spectra For C4 Mine, No Mine and Pure Carbon 40
Figure 31: Effect Of Soil Volume On Detector Count Rate Above 4.5 MeV 42
Figure 32: Effect Of Localized Soil Volume On Detector Count Rate 44
Figure 33: Spectra With Carbon Mine At Various Depths 45
Figure 34: Spectra With Carbon Mine and Varying Soil Density 46
Figure 35: Spectrum With 11 MeV Neutrons And Buried C4 Mine, Ge Detector Used. 47
Figure 36: Bare C4 Explosive, Carbon And Oxygen Peaks 49
Figure 37: C4 Explosive Sitting On Ground, Carbon and Oxygen Peaks 49
Figure 38: Bare C4 Explosive, Region Of Nitrogen Peaks 50
Figure 39: Bare C4 Explosive, Region of Nitrogen Peaks 51
Figure 40: C4 Explosive Sitting On Ground, Nitrogen Peaks 51
Figure 41: C4 Explosive Sitting On Ground, Nitrogen Peaks 52
Figure 42: Landmine Detector With Tagged Neutrons 53
1. INTRODUCTION

About 10 years ago, one of the Scientific Authorities (J. E. McFee) published a report \(^{(1)}\) that set the direction for the use of neutron interrogation for the detection of buried landmines. He proposed the concept of fusion of data from several detection technologies in order to achieve an acceptable false alarm rate for a practical landmine detector system. Central to this concept was the development of a special sensor \(^{(2)}\) based on thermal neutron interrogation to be deployed as a confirmatory sensor for detecting the strong presence of nitrogen, which is an essential ingredient of all explosives. At this time, DND has accomplished this objective. Through a series of contracts, a neutron interrogation sensor—called Minescan—has been developed \(^{(3)}\) as the confirmatory sensor of a suite of sensors comprising a unique land-mine detection system, known as the Improved Landmine Detection System (ILDS). The completion of the ILDS has put Canada in a leadership role in terms of peace-time military demining. Other countries are copying the Canadian concept of data fusion and are trying to build similar systems to the ILDS for their own military use.

ILDS makes use of four landmine detection technologies. Three of these are well-developed technologies and the sensors were purchased from various suppliers globally. However the fourth sensor, Minescan, is a new development and the sensor has resulted directly from the DND sponsored R&D program. Minescan exists only in Canada; the IP is owned by DND.

Recognizing the Canadian success in developing a landmine sensor based on neutron interrogation, other countries have expressed interest in buying the sensors \(^{(4, 5)}\) or building better sensors \(^{(6)}\) with Canadian assistance. DND has already undertaken one step \(^{(7)}\) to improve the basic technology behind Minescan by replacing the isotopic radiation source with an electronic source, in order to reduce unwanted radiation exposure to operational military personnel. It now wishes to assess the full potential of the electronic source (a neutron generator) by assessing its capability to do fast neutron
interrogation in addition to the thermal neutron interrogation currently used by Minescan. This development will help to maintain Canada’s technological lead in the field of landmine detection.
2. BACKGROUND ON FAST NEUTRON INTERROGATION

The detection of explosives by the use of neutron interrogation has been studied for many years (e.g. see reference 8). However, these studies were mainly focused on the detection of explosives in luggage in airports or examinations of unearthed, unexploded ordnance (UXO). For these applications, the use of fast neutron (e.g. 14-MeV) interrogation was the preferred technique. The reactions that were utilized for this technique were neutron inelastic scattering—(n, n’γ)—or induced reactions—e.g. (n, pγ), (n, αγ) etc. One of the principal objectives in fast neutron interrogation was to measure the relative concentrations of several relevant elements, e.g. C, N, O, H, Cl, etc., in order to search for the fingerprint that indicates the presence of an explosive.

In general, the detection of a landmine buried in the ground is much more difficult than detecting explosives in luggage because of the shielding of the soil and the presence of the ground itself. Also, a fieldable system that must operate under various adverse environmental conditions is very much tougher to develop than one that sits in an air-conditioned airport.

Thus, the incorporation of fast neutron interrogation to complement the thermal neutron technique requires a comprehensive re-assessment of the whole technology, starting from fundamental physics principles. Having worked on the detection of landmines by neutron interrogation for almost 10 years, BTI was in a strong position to carry out this work.
3. SELECTION OF POTENTIAL RELEVANT REACTIONS

Although the detection of explosives in general by neutron interrogation is not exactly the same as the current challenge of detecting landmines, the basic nuclear reactions that can be used are identical. However, in the case of landmines, certain of these reactions may not be applicable because of interference from competing reactions due to the soil (surrounding the mine) or the explosive signal may be too weak relative to the high background generated by the soil under neutron interrogation.

Comprehensive listings of all possible nuclear reactions for mine detection by neutron and photon interrogation can be found in a report by Coleman et al.\(^{(10)}\) These authors have even commented on the relative applicability of these reactions for mine detection. These authors did not feel that the method was promising.

A later paper that was considered closer to our task of assessing the applicability of fast neutron interrogation was published by Vourvopoulos et al.\(^{(9)}\) This group selected 5 reactions in 3 elements (the best of all possibilities) as the basis of their fast and thermal neutron interrogation system for explosives. They provided data for gamma-ray spectra, measured with HPGe and BGO detectors, and showed that all three elements could be observed by the use of fast neutron interrogation. The capability of detecting three elements is desirable since this increases the specificity for detection of explosives relative to other materials (e.g. wool, melamine, etc.). These authors even provided a proposed irradiation protocol involving bursts of fast neutrons at specific time intervals in order to obtain gamma ray spectra from three different nuclear interrogation techniques: fast-neutron interrogation (prompt gammas), thermal-neutron interrogation (gammas immediately following the neutron pulse) and neutron activation of elements (delayed gammas). Despite the fact that these investigations pertained primarily to the detection of explosives in luggage, UXO, etc, the apparent success of the proposed methodology made it a reasonable starting point for our investigations. Consequently, our task can be viewed as determining whether these reactions are still applicable when the explosive is
buried in the ground—i.e. will these same gamma rays still be observable against the signals generated by the ground itself?
4. PRELIMINARY STUDIES FOR QUALITATIVE ASSESSMENTS

From the viewpoint of neutron transport, the primary effect of the ground is to moderate the initial monoenergetic 14 MeV beam producing lower-energy neutrons\(^{(11)}\). Since most neutron cross sections are decreasing with increasing energy in the region around 14 MeV (due to increasing competition from charged-particle emission), the effect of neutron moderation coupled with a larger cross section (for lower energy neutrons) could, in principle, lead to increased gamma-ray yield for the reactions of interest. The magnitude of this effect would depend on the shapes of the cross-section curves.

Cross sections for the reactions of interest that were published by Vourvopoulos et al, \(^{(12)}\) did not go above 10 MeV for unknown reasons. Thus, we extracted the latest cross sections from END F/B files to provide the quantitative data base for assessing the impact of ground moderation.

These cross sections are shown in Figure 1 to Figure 5. It is clear that the C (n, n\(^{'}\)) reaction to the 4.44 MeV state and the O (n, n\(^{'}\)) reaction to the 6.13 MeV state are the most promising from the viewpoint of strongest gamma-ray signals for fast neutron interrogation. Unfortunately, the potential use of oxygen may be limited due to the large quantity of oxygen in soil (e.g. SiO\(_2\)).

Preliminary Monte Carlo calculations were made to understand the general behaviour of 14 MeV neutrons impinging on soil. For these calculations, a line beam was directed along the central axis of a (large) cylinder of ANSI soil having a diameter of 50 cm and length of 170 cm. Figure 6 and 7 show respectively the attenuation of the 14 MeV beam and the calculated neutron fluence as a function of depth. Figure 7 was interesting in that the neutron fluence actually increased with depth and peaked at 10 cm. The magnitude of the increase (~35%) was larger than one might have expected and further calculations were made to confirm its validity. These studies showed that the increase was real and was due to backscattered neutrons (see Figure 8) along with the fact that these neutrons
Figure 1: Carbon 4.44 MeV

Gamma Production Cross Section

Carbon 4.44 MeV
Figure 2:  Nitrogen 5.11 MeV

Gamma Production Cross Section

Nitrogen 5.11 MeV
Figure 3: Nitrogen 2.31 MeV

Gamma Production Cross Section
Nitrogen 2.31 MeV
Figure 4: Oxygen 6.92 MeV
Figure 5: Oxygen 6.13 MeV

Gamma Production Cross Section

Oxygen 6.13 MeV
Figure 6: Attenuation Of 14 MeV Neutron In ANSI Soil
Figure 7: Neutron Fluence VS Depth
Figure 8: Neutron Direction Tally
subtended a large scattering angle, increasing their interaction probability (i.e. large neutron fluence relative to neutron current \(^{(13)}\)).

Calculations were next done to assess the complexity of the gamma-ray spectra from fast neutron activation to determine important gamma-ray components. For these calculations, the ground was represented by a cylinder of ANSI soil 1 m radius and a thickness of 1m. A layer of air 1 cm thickness covered the top of the soil cylinder. The neutron beam was 2 mm in radius and directed co-axially into the cylinder. Detector planes were placed at different depths in the soil cylinder to score photon energies as they traverse the detectors. Soil moisture was varied from 10% water (representing common moisture concentration) to 40% water (very wet soil).

Figure 9 to Figure 11 show the gamma-ray spectra obtained. It is seen that the spectra are very complex with numerous lines extending up to 13 MeV. Figure 12 is an attempt to identify the source of these gamma rays. Si and O produce dominant peaks in the spectra. Peaks from N and H are also evident. Of course, H becomes more prominent as the moisture is increased. Many of the peaks are summations of several possible gamma rays and it is not clear which reactions produce gamma rays up to 13 MeV.

To clarify the relative importance of the various component spectra, we decided to replace the ANSI soil with pure components (all at identical atom densities) that are of interest for our studies: N, O, Si, Al, C and H. These results are given in Figures 13-18.

Examinations of these results, taking into consideration the total anticipated mass of the various materials in a typical landmine and detected with NaI detectors (as in the existing TNA head), we came to the general conclusion that it would be difficult to detect N (because of its weak lines relative to other interference), carbon would be a good candidate because of the strong 4.44 MeV line, and O (through the 6.13 MeV gamma ray) might be detectable provided that the interference from SiO2 can be minimized.
Figure 9: Total Gamma Spectrum (14 MeV $n$ on ANSI soil [10% Water])
Figure 10: Total Gamma Spectrum (14 MeV n on ANSI soil [20% water])
Figure 11: Total Gamma Spectrum (14 MeV n on ANSI soil [40% water])
Figure 12: 14 MeV n on ANSI soil w/20% water 1 cm below ground
Figure 13: 14 MeV Neutron on N – Total gamma spectrum
Figure 14: O (n, gamma) Gamma Spectrum
Figure 15: Si (n, gamma) Gamma Spectrum
Figure 16: Al (n, gamma) Gamma Spectrum
Figure 17:  C (n, gamma) Gamma Spectrum
Figure 18: 14 MeV Neutron on H – Total gamma Spectrum
5. MORE QUANTITATIVE ASSESSMENTS OF SIGNAL TO BACKGROUND

To have a more quantitative assessment of the influence of the soil on the gamma rays from fast neutron activation, a second series of Monte Carlo calculations were performed. Here, we assumed a 7 liter mine (in the form of a cylinder 30 cm diameter and 10 cm thick) as a standard reference and the objective was to determine the intensity of the gamma rays from fast neutron activation relative to signals from the surrounding soil. To eliminate complication due to interference from the thermal and epi-thermal neutron capture, it was decided to use a neutron lower energy cutoff of 4 MeV; this still enables all inelastic neutron reactions of interest to take place.

Partly as a check on the validity of the calculational process itself, we redid the calculations (for the 7 L mine) with 14 MeV neutrons using pure samples (C, N, O, Al and Si) assuming they have the same atom density. Figure 19 shows the gamma ray energy spectra (in 50 keV bins). The 4.44 MeV peak from carbon is very prominent with no large expected interference from major soil constituents (e.g. oxygen). Nitrogen has no high peaks and those that are present are generally interfered with by oxygen and/or silicon peaks. These results confirm the general observation from earlier calculations that carbon may be a promising candidate for fast neutron activation.

Having selected carbon as a good potential explosives component to investigate, the next step in the simulations was to generate more representative spectra under more realistic geometry. Thus the 7 L landmine was put into soil and a NaI gamma-ray detector added. The soil volume was 80 cm in diameter and 40 cm thick, with the landmine placed on axis 10 cm below the surface. This somewhat small soil configuration results in an over estimate of the relative effect of the landmine. The NaI detector was modeled as a 5 cm thick detector slab surrounding the sides and top of the soil volume. The resolution of the NaI detector was modeled as FWHM = 0.06√E. The “measured” detector response was obtained by using an “MCNP F8 photon tally.” This rather unrealistic detector
configuration was used to reduce the computational time to get quick relative results for the presence of a landmine in the soil. The D-T source was modeled as a line beam along the axis of the mine.

The modeled response of the NaI detector was first checked against experiment by simulating a 3”x3” crystal looking at a pure carbon sample and comparing the simulated spectrum with a measured spectrum obtained using a PuBe neutron source ($^9$Be($\alpha$, n)$^{12}$C* gamma emission). The results are shown in Figure 20 (measured) and Figure 21 (simulated). The simulated spectrum has a somewhat better peak-to-valley ratio than the measured spectrum. However, the simulation is quite adequate for the present purpose.

The simulated spectra for the soil with and without (mine filled with soil in the simulation) a landmine present are shown in Figure 22. The carbon in the landmine clearly stands out in the 4.44 MeV peak. The replacement of soil (high oxygen content) by the mine (lower oxygen content) can be seen in the spectral region from 5 to 7 MeV which is dominated by oxygen peaks.

Figure 19: Spectra From Pure Samples
Figure 20: Measured Carbon Spectrum

Figure 21: Simulated Carbon Spectrum
Figure 22: Simulation of 7L Mine Filled With C4 Explosives and Soil
6. FULL SIMULATION OF TNA HEAD GEOMETRY

With the possibility that the carbon \((n, n'\gamma)\) reaction could be applicable for fast neutron interrogation, we began new calculations using a full mock-up of the TNA head as shown in Figure 23.

We also made many experimental measurements at DRDC-Ottawa using the actual head in order to have data to check the absolute (i.e. quantitative) validity of the Monte Carlo simulation. Three of these spectra are shown in Figure 24. The two top spectra were obtained using the NiPVC calibration plate (on the surface of a large sand box) and in the normal detector “gate on” mode which accumulates data only over the time period 10 \(\mu\)s to 80 \(\mu\)s following an accelerator pulse. This restricts the gamma rays to those from thermal neutron capture and from neutron activation.

The top curve was obtained with an accelerator output of \(2 \times 10^8\) n/s, while the central curve was for an output of \(1 \times 10^8\) n/s. The shapes of these curves at the higher energy end differ slightly, indicating a small effect from pulse pile-up. The lower curve was obtained without the use of gating so that both fast and thermal neutron activation are measured. This measurement was made for 7.3 kg of fertilizer (simulated landmine) and output of \(1 \times 10^7\) n/s. The same irradiation time (10 min) as for the above experiments was used. Analyses of these data indicate that the total counts in the lower spectrum was about half of the 1E8 spectrum. This implies that roughly 20% of the gate-off spectrum (fast + thermal) is collected during the gate-on (thermal) mode, while the remaining 80% is collected during the accelerator pulse. Since the pulse period is 10 \(\mu\)s while the gate-on period is 80 \(\mu\)s, the instantaneous count rate during the pulse is 32 times higher than the gate-on mode. This would account for the increased pile-up in the 1E7 gate-off spectrum.
Figure 23: TNA Monte Carlo Head Mock-up

This figure intentionally removed by Scientific Authority.
Since these experiments did not involve carbon (fertilizer contains N, but no carbon), no comments on detectability of carbon can be made from these data. However no obvious features of N can be seen in the “gate-off” spectrum, which is in line with our expectations from such a simple interrogation protocol.

We then performed Monte Carlo simulations of these experimental conditions using the TNA head mock-up. For these calculations, the low energy cut off was reduced to $10^{-8}$ MeV to include the effect of thermal neutrons. Calculations were done with and without a neutron lifetime cut-off of 10 µs so that in-pulse, gate-off and gate-on (difference) spectra could be produced. Figure 25 shows the simulated gate-off spectrum without the mine. The surprising difference between the simulated and measured gate-off spectra is that the simulated gate-off spectrum does not show the roll over starting at ~7 MeV, which is quite obvious in the measured spectrum.
Investigations into the cause of this discrepancy revealed that the problem was related to the use of the F8 detector tally. Data dump of the neutron scattering and photon production parameters at collision points showed that while the neutron simulation was being done properly, the weights assigned to photons were incompatible with their treatment in the F8 detector tally. This problem only arises in the case when photon weights exceed unity. By judicious choice of weights and correcting for them at a later stage of the computation, we were able to circumvent this computational oddity of MCNP.

Figure 25: Simulated DREO Gate-Off Spectrum
The results after making these corrections to the photon tally appear to be good as evidenced in Figure 26, which shows the new results versus the original results from Figure 25. The new spectrum now displays the roll-off at ~7 MeV as expected.

A comparison between the improved simulations and the experimental results is given in the table below. Because the simulations and experiments use different energy bins and the simulations give combined results for all six detectors, both sets of results were normalized to counts / keV bin width / source neutron. Counts are given for distinct energies and count rates for spectrum integrals at the experimental D-T generator rate.
### Table

**Comparison of Experimental and MCNP Count Rates**

#### No Mine, Gate Off

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<td>0.089</td>
<td>6.1E-10</td>
</tr>
<tr>
<td>&gt;2</td>
<td>8 kcps/detector</td>
<td>14 kcps/detector</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>&gt;0</td>
<td>1.0 Mcps/detector in-pulse @ 1E7 **</td>
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#### No Mine, Gate On

<table>
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<tr>
<th>E (MeV)</th>
<th>c/n/50 keV</th>
<th>c/n/keV</th>
<th>900 min MCNP *</th>
<th>DR030104</th>
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<td>3.0</td>
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<td>8.0E-8</td>
<td>63.9</td>
<td>4.4E-8</td>
</tr>
<tr>
<td>5.0</td>
<td>9.1E-6</td>
<td>3.0E-8</td>
<td>27.6</td>
<td>1.9E-8</td>
</tr>
<tr>
<td>7.0</td>
<td>2.4E-6</td>
<td>8.0E-9</td>
<td>10.3</td>
<td>7.1E-9</td>
</tr>
<tr>
<td>10.5</td>
<td>6.4E-8</td>
<td>2.1E-10</td>
<td>0.022</td>
<td>1.5E-11</td>
</tr>
<tr>
<td>&gt;2</td>
<td>25 kcps/detector</td>
<td>18 kcps/detector</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>&gt;0</td>
<td>290 kcps/detector @ 1E8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Subtraction of in-pulse from gate-off.

** Assumes 10% duty cycle

There is generally reasonable agreement between simulations and experiment. However, the simulations still show an over response in the high energy region (see gate-on data in the table at 10.5 MeV). The gate-on response for the nitrogen peak at 10.8 MeV could
not be determined by these simulations (900 min runs) because statistical fluctuations in this region mask the difference between the mine and no-mine results.

In examining our data, we found that the simulated in-pulse results with and without a mine show no significant difference between the spectra in the region of the carbon peak at 4.4 MeV. This observation was initially puzzling.
7. MODIFICATIONS TO NEUTRON SOURCE AND SHIELDING FOR SIGNAL ENHANCEMENT

To improve the fast neutron (in-pulse) performance of the landmine detector for finding carbon, the TNA head design was modified (in the simulation) [text removed from original report by Scientific Authority] Still no difference could be seen between the simulated spectra with and without the mine buried at various depths.
8. REPLACEMENT OF NaI BY Ge

As another step to improve the capability of seeing the landmine, the NaI detectors were replaced in the simulation by Ge spectrometers of the same size. The resolution of the Ge spectrometers was set to be relatively poor (~4 keV at Co-60 1.3 MeV) to allow for compromises that would have to be made in the resolution to achieve high count rates. Figure 27, 28 and 29 show spectra for a mine buried at 10 cm under different conditions.

- measured gate-on spectrum with NaI detectors
- simulated gate-off spectrum with NaI detectors
- simulated gate-off spectrum with Ge spectrometers.

The measured and simulated spectra for NaI detectors (under different conditions!) show similar general shape for gamma-ray peaks. The simulated Ge spectrometer spectrum shows the dramatic improvement in the spectrum that comes with greatly improved resolution.

Figure 27: Measured Spectrum With NaI Detectors
Figure 28:  Stimulated Spectrum With NaI Detectors

Figure 29:  Simulated Spectrum With Ge Spectrometers
9. SYSTEM PERFORMANCE USING THE MODIFIED HEAD WITH A Ge DETECTOR SYSTEM

In Figure 30, the 4.44 MeV carbon peak is shown for three cases: no mine, a mine filled with C4 explosive, and a mine filled with pure carbon at a density of one. The mine is at a depth of 10 cm. The pure carbon mine was included to facilitate the study of the spectrum dependence on the carbon density in a mine. Even under these optimized conditions for the neutron source, neutron shielding and detector resolution, a C4 mine is still not detectable, although an explosive with higher carbon may be marginally.

We were surprised at the intensity of the 4.44 MeV peak in the spectrum when there was no mine present. Upon investigation, we found that this was due to a fast neutron reaction in oxygen which results in the emission of an alpha particle and hence a 4.44 MeV gamma-ray from the resulting carbon nucleus. Though this is a very low probability reaction, the large amount of oxygen in the soil results in a very significant 4.44 MeV peak which interferes with the detection of carbon via this gamma ray.

Figure 30: Simulated Spectra For C4 Mine, No Mine and Pure Carbon
10. EFFECT OF DETECTOR COLLIMATION

The possibility of adding collimation to the detector system was investigated to see if the contribution of the soil to the measured spectrum could be reduced. To do this the soil volume in this simulation (surrounding the 7 L mine) was varied to determine the contribution from various parts of the soil. Since carbon makes no contribution to the spectrum above 4.44 MeV, the gross effect of the soil can be determined by integrating the spectrum above this energy. In the simulation, the soil volume was initially defined by a hemisphere. The radius of this hemisphere was reduced from 80 cm to 55 cm. The results showed that there was no effect on the number of photons detected above 4.5 MeV.

Below a radius of 55 cm, particle tracking problems occurred because the same spherical radius is used to define parts of the TNA head in the simulation. The simulation of the soil volume was therefore changed to a cylinder and its radius and height (soil depth) varied. The results showed that changes in the soil depth from 45 cm to 20 cm (bottom of mine at 20 cm) had no effect on the detector response. The results for varying the cylinder radius is shown in Figure 31. An effect does occur when the radius is reduced below 35 cm. However, since the detector centerlines of the TNA head are located at a radius of 28.75 cm, these results indicate that any collimation which does not mask the mine will not have a significant effect on the background count rate due to the soil.

In the simulations to determine the effect of collimation by varying the soil volume, the reduction of the soil radius was observed to have two effects. Primarily it reduces the detector response by reducing the volume in which inelastic neutron scattering in the soil can take place. A secondary effect is that for a soil radius less than the detector ring radius it reduces the attenuation of gamma-rays that are produced in the remaining soil volume.
Figure 31: Effect Of Soil Volume On Detector Count Rate Above 4.5 MeV
11. LOCALIZED VOLUME EFFECTS

In an attempt to understand the relative impact of soil volumes in the vicinity of the mine on the 4.44 MeV gamma ray, we studied the change in the counting rate as a soil volume is located at different positions. In these calculations, the modified TNA head was 5 cm above an infinite ground and Ge detectors were assumed (as per Section 9). For simplicity, the localized soil volume was represented by a 7 L mine. To assess the contribution from this volume it was filled by either soil or pure carbon to simulate the neutron scattering properties of the soil without creating any gamma rays above 4.5 MeV. The impact of the soil volume was assessed by noting the decrease in counts above 4.5 MeV due to the carbon mine relative to the counts when the mine was assumed to be filled with soil. The ratio of this increase relative to total counts without the mine (i.e. infinite soil) would give the percentage change due to the soil volume at that particular location.

Unfortunately we found that computation times were too excessive to achieve statistically meaningful results. To permit more rapid running of a large number of desired soil locations, the six discrete detectors were replaced by an annular detector 8 cm wide and 5 cm thick (and using an F6 energy deposition tally to replace the F8 detector tally). Results for the annular detector are shown in Figure 32, along with some longer runs (900 min) for the six detector configuration to confirm the results of the simplified model. These data show that the detector response (count rate above 4.5 MeV) to the localized volume located at a depth of 10 cm (the depth used previously to determine the detectability of a mine) is about 2-3 percent of that due to the entire soil volume. Thus, even though the yield of the 4.44 MeV gamma from carbon is ten times that from oxygen, this is offset by the low detector response to the mine volume at that location plus the background contribution from oxygen in the soil and in the neutron shielding material in the landmine detector.
Figure 32: Effect Of Localized Soil Volume On Detector Count Rate

![Graph showing the effect of localized soil volume on detector count rate. The graph plots mine offset (cm) on the x-axis and response relative to total soil volume (%) on the y-axis. Different data points represent different conditions, such as Det-Depth00, Det-Depth05, Det-Depth10, AnnularDet-Depth00, AnnularDet-Depth05, and AnnularDet-Depth10.]
12. MINE BURIAL DEPTH

To further investigate the effect of mine location, simulations (using six detectors and F8 tally) were done for different burial depths of a pure carbon mine. The sensitivity to burial depth is shown dramatically in Figure 33. While a carbon mine can be easily seen on the surface, it is almost indistinguishable from the ground (no mine) even at a depth of 5 cm.

Another way of studying the role played by the soil is to put the carbon filled mine at a depth of 10 cm and to vary the density of the surrounding soil. The results are shown in Figure 34. As the soil density is increased there is a progressive competition of the contribution of carbon to the 4.44 MeV peak from oxygen in the soil, resulting in only a small change in the peak height.

Figure 33: Spectra With Carbon Mine At Various Depths
Figure 34: Spectra With Carbon Mine and Varying Soil Density
13. EFFECT OF CHANGING NEUTRON ENERGY

Figure 33 showed that a pure carbon mine would be easily detectable at the surface of the ground but it is only marginally detectable when buried 10 cm due to the oxygen interference at 4.44 MeV. At 14 MeV the neutron cross section contributing to this gamma-ray is increasing as a function of energy for oxygen while decreasing for carbon. By decreasing the neutron energy to below 12 MeV the oxygen contribution can be eliminated entirely. A simulation was run at a neutron energy of 11 MeV for a C4 mine buried 10 cm to see whether optimizing the neutron energy would make a C4 mine detectable. The results in Figure 35 shows that the C4 mine still cannot be detected even with Ge detectors because of background due to other O and N reactions. The use of other signal enhancement techniques may help.

Figure 35: Spectrum With 11 MeV Neutrons And Buried C4 Mine, Ge Detector Used.
14. COMPARISON OF FNA ON LUGGAGE AND LANDMINES

Since FNA appears to be so successful in the detection of explosives in luggage, yet has been found to be almost inapplicable for landmine applications, we felt it would be instructive to compare the results from the two scenarios more directly. We started by modeling a bare one pound sample of C4 explosive (little bigger than the size of a hockey puck) uniformly irradiated by a beam of 14 MeV neutrons. The ring of Ge detectors was used in these simulations. The beam extends beyond the C4 sample (out to a 60 cm diameter) to simulate a collimated beam that might be used in luggage monitoring. Because of the increased access around a single piece of luggage the shielding of the detector system from the neutron source can be greatly improved. Figure 36 shows the main carbon and oxygen region of the gamma-ray spectrum. The peaks due to the oxygen 6.13 MeV and carbon 4.44 MeV gammas stand out clearly.

Figure 37 shows the spectrum from the same one pound of C4 explosive but this time it is sitting on the ground. Also shown in this figure is the spectrum from Figure 36. Its peaks appear as small bumps along the energy axis. The contribution of C4 to the total spectrum is swamped by the contribution from the soil. The total count rate with the soil present is 150 times that obtained with the bare C4 explosive. A luggage or package monitoring system using FNA has to deal with only tens of pounds of added material contained in the luggage/package itself, not the hundreds of pounds that contribute to the masking of the signal when dealing with explosives in the soil.
Figure 36: Bare C4 Explosive, Carbon And Oxygen Peaks

Figure 37: C4 Explosive Sitting On Ground, Carbon and Oxygen Peaks
15. RE-EXAMINATION OF NITROGEN

The initial evaluation of possible peaks for use in FNA strongly pointed to carbon. However for 14 MeV neutrons, the peak at 4.44 MeV from carbon has too much interference from an oxygen peak at the same energy. Are there nitrogen peaks which are not interfered with by oxygen peaks that are of sufficient intensity to be useful? The six nitrogen peaks of highest intensity are at 1.635, 2.313, 3.684, 5.106, 6.727 and 7.028 MeV. The ones at 3.684 and 5.106 have interfering oxygen peaks (full energy or escape) leaving four possibilities. Figure 38 and 39 show portions of the simulated spectrum covering these four energies for a bare C4 sample (see above). Figure 40 and 41 show the result obtained when the C4 sample is placed on the ground. Again we see that the contribution due to C4 is swamped by the contribution from the soil.

Figure 38: Bare C4 Explosive, Region Of Nitrogen Peaks
Figure 39: Bare C4 Explosive, Region of Nitrogen Peaks

Figure 40: C4 Explosive Sitting On Ground, Nitrogen Peaks
Figure 41: C4 Explosive Sitting On Ground, Nitrogen Peaks
16. USE OF TAGGED NEUTRONS

The equivalent to a tightly collimated beam of neutrons can be obtained by tagging the neutron to the associated alpha particle created by the D-T reaction thus providing information on the neutron direction and hence the ability to select the soil volume (defines a cone) contributing to the measured spectrum. A final set of simulations was done for such a tightly collimated beam (parallel beam of 9 cm radius) of 14 MeV neutrons directed at a landmine in the ground. This beam also represents perfect shielding of the detectors from the neutron source since only tagged gamma-rays are counted. The results obtained for the 4.44 MeV peak for pure carbon and C4 mines are shown in Figure 42. These results show that under these ideal conditions the explosives are clearly detectable. This approach however represents a major technological program. Although such accelerators are claimed to be in existence, \(^{14}\) their capabilities and limitations need to be properly assessed. Then, there is the need to conceive of an entire landmine detection system that will incorporate the accelerator, the detector system and the head itself with a view towards developing a first prototype for testing.

**Figure 42:** Landmine Detector With Tagged Neutrons
17. POSSIBILITY OF $(\gamma, n)$ REACTION FOR DETECTION OF LANDMINES

Photoneutrons may offer an alternative approach for detection of landmines. The main components of soil have $(\gamma, n)$ thresholds that are higher than for N. $^{28}$Si has a threshold of 17.2 MeV and $^{16}$O has a threshold of 15.7 MeV. Meanwhile, $^{14}$N has a threshold of 10.5 MeV. Thus, by keeping the bremsstrahlung end-point below 16 MeV, it may be possible to detect N in soil.

In the original project plan, an electron accelerator at MevX had been identified as the machine for performing some $(\gamma, n)$ experiments. This machine was known to scientists at DRDC-Ottawa. However, during the execution of the contract, we contacted MevX regarding the use of their machine for the work. We were informed that their machine only went up to 10 MeV. They had an old machine that went up to 25 MeV, but it was not working and required serious service. We were advised to approach NRC, who had a 35 MeV machine.

We contacted NRC and they were keen to help with the proposed experiment. Their available time and schedule for doing the experiment precluded performing the comprehensive set of measurements that we wished to do. Thus, a preliminary set of experiments, done over a couple of days, was planned and carried out. Appendix A describes these experiments in greater detail.

The results from the NRC $(\gamma, n)$ experiments indicated that the detection of nitrogen by measurement of emitted photoneutrons is possible. The high background count rate due to the tungsten collimators made collection of good data difficult. However, this approach is worth further investigation. A new series of experiments should be undertaken with changes to the collimator and window components to reduce unwanted background.
18. EXPERIMENTAL MEASUREMENTS OF GAMMA-RAY SPECTRA USING 14 MeV NEUTRONS

Some experimental measurements were made to check the validity of the results obtained by Monte Carlo calculations. The required experimental equipment was located at DRDC-Suffield at the time suitable for performing these experiments. Furthermore, the Scientific Authority had just purchased a large Ge detector prior to the planning of these experiments.

Thus, it was decided to perform these experiments at DRDC-Suffield, in collaboration with the Scientific Authority. Arrangements were made to assemble the necessary experimental equipment, and two scientists from BTI went to Suffield in October, 2003, to join the Scientific Authority’s staff in conducting the experiments.

A succinct summary of the experiments is given in Appendix 2.

The tests done at Suffield showed that the amount of interference from oxygen is close to that predicted by MCNP. There was some disagreement between the measured and predicted ratio of the 4.44 MeV carbon peak area to that from oxygen at 6.11 MeV. This may be due to differences between the experimental set-up and the idealized geometry used in the MCNP simulation. However, the experiments broadly confirm the interference of the 4.44 MeV line by oxygen and that FNA does not appear attractive for detection of buried landmines unless one goes to the extent of using tagged neutrons.
19. **CONCLUSIONS**

These studies have led us to the conclusion that it is not feasible to try to make use of FNA as a complementary technique to TNA to enhance the detection of buried landmines based on the existing electronic source in the ILDS head. In essence, the scattering of radiation from the ground is so intense that it masks all the desired FNA signals from the mine itself.

Of all the possible signatures that might be utilized in the use of fast neutron activation, the most promising appeared to be the 4.44 MeV gamma ray from carbon, from the viewpoint of signal strength and minimum interference from other unwanted radiations. Unfortunately, there is a competing reaction from oxygen that produces the identical gamma ray. Despite the fact that the oxygen reaction has very low probability, the much larger amount of oxygen in soil (compared to the carbon in the landmine) makes this contaminant a major problem. The only method to reduce the effect of the soil is to use the “tagged neutron” approach. However, this implies a completely different electronic source and, likely, a differently designed head. Thus, the potential use of fast neutron activation to detect landmines will require a completely new system design, including a different type of neutron generator, different head and different (faster) detectors. Such a program would be a significant technical challenge, at the very leading edge of all three technologies.

The experiments done at DRDC-Suffield were not as extensive as we would like. There were discrepancies between the measured and predicted ratios of the 4.44 MeV from carbon and the 6.11 MeV gamma ray from oxygen. It is likely that the discrepancy is due to actual versus idealized interrogation geometries. Nevertheless, the experimental results confirm the interference of the 4.44 MeV carbon line from the competing reaction in oxygen.
The experiment done at NRC indicated that the detection of nitrogen by the \((\gamma, n)\) process is a distinct possibility. However, much more experimentation is needed to confirm this possibility.
20. REFERENCES


21. Appendices
Photoneutron Detection of Land Mines

NRC Linac Experiments

2003 September

On 2003 September 09-10 tests were done on the NRC linac in Ottawa to determine if the gamma-n reaction in nitrogen is a possible means for detecting land mines. Of the major soil constituents only nitrogen and silicon have non-zero gamma-n cross section below 16 MeV. Initial estimates showed the bremsstrahlung produced by even a modest beam current at an electron energy of 16 MeV would generate sufficient photoneutrons in both nitrogen and silicon for both to be easily detectable. The outstanding question was whether there would be sufficient difference in the strength of their signals to make a buried land mine detectable from the surrounding ground.

The initial experimental layout for this test is shown in Figure 1. Figure 2 shows the configuration for the detector electronics. Two neutron detectors were used. One was a conventional BF3 detector. The other was a ZnS scintillator which included LiF as a converter to generate alpha particles which are detected by the ZnS. Either detector could be connected to the oscilloscope, the MCA or the counter/timer. A LiF/YAP scintillator was also available but it was not used in these tests.

With an electron beam energy of 16 MeV and a thick aluminum brems target (the one normally used) the beam current had to be reduce to a nominal 0.1 μA from the initially proposed 1 μA to reduce the response of the neutron detectors to the gamma flash from the beam pulse. The gate delay was set to 20 μs to allow for recovery from the gamma flash and the gate width was set to 100 μs (its maximum).

With this configuration significant neutron count rates (hundred per second) were seen in both the ZnS and BF3 detectors without a sample present. To reduce the number of background neutrons the tungsten collimators were opened to their maximum position. This reduced the neutron count rates by about 20%. Tungsten has a very large gamma-n cross section with its peak cross section (~400 mb) located at ~13.5 MeV. It was also noted that aluminum has a gamma-n cross section of about 1 mb in the 15-16 MeV region. The aluminum brems target was replaced by a graphite brems target which reduced the neutron count rates by a further factor of 2.5.

With this configuration measurements were done with the urea, sugar and crushed gravel samples. No observable difference could be seen between the samples, though all gave results about 20% higher than the case with no sample. The effect of the samples was probably due to the scattering of neutrons being generated in the collimator.
To eliminate the neutrons still being generated in the tungsten collimator, the graphite brem target was moved downstream of the collimator with the resulting layout as shown in Figure 3. The table on which the equipment was mounted was lowered to reduced any possible neutron contribution from its steel structure and the brem target and the sample mounted on wooden blocks.

With this new layout the beam current had to be reduced by a further factor of ten to 7.5 nA to reduce the detector response to the gamma flash. The gate delay was also increased to 30 μs. Neutron count rates were now about a factor of four lower than they had been in the previous configuration. However, no large difference could be seen between when the urea sample was present and when it was not.

A lead beam dump (the lead gamma-n cross section is even larger than that of tungsten) which was situated ~3 m from the experimental setup was removed. This reduced the neutron count rates by ~20%.

At this point the question of brems production in the accelerator beam line or the end window was considered. The end window consists of titanium 0.005” thick. A measurement was done with no brem target or sample present. An additional sheet of 0.005” titanium was then placed at the end of the beam line and the measurement repeated. This increased the neutron count rate by 80%. This sheet of titanium was then moved downstream of the collimator and the measurement repeated. This location for the titanium had no effect on the neutron count rate.

It was concluded that with the setup in Figure 3 the neutron background was primarily due to brem generated in the titanium beam line end window which produced photon neutrons in the tungsten collimator. This was confirmed by temporarily closing the collimator slightly which resulted in an increase in the count rate by a factor of ~4.

As it was not possible to remove the tungsten collimator in the time available it was decided to proceed with the measurements with the Figure 3 configuration. The counting times were increased to improve statistics. The pertinent sample data and the measured results are given in Table 1 below.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Weight (oz)</th>
<th>BF3 Counts*</th>
<th>ZnS Counts*</th>
<th>Integ Beam Cur (Coul)</th>
<th>Norm</th>
</tr>
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<td>12183</td>
<td>1978</td>
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<td></td>
</tr>
<tr>
<td>Urea</td>
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<td>12819</td>
<td>2182</td>
<td>2.28E-6</td>
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</tr>
<tr>
<td>Crushed Gravel</td>
<td>55</td>
<td>13098</td>
<td>2256</td>
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<tr>
<td>Sugar</td>
<td>33</td>
<td>12811</td>
<td>2253</td>
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<td>5.7</td>
</tr>
<tr>
<td>Soil (dry)</td>
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<td>13224</td>
<td>2213</td>
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<td>8.4</td>
</tr>
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<td>13272</td>
<td>2296</td>
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<tr>
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<td>58</td>
<td>13162</td>
<td>2178</td>
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<td>6.3</td>
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<tr>
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<td></td>
<td>12465</td>
<td>2156</td>
<td>2.30E-6</td>
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</tr>
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</table>

* All counts were for 300 s.
Also included at the end of the table is a column labeled Norm. This was obtained by normalizing the BF3 counts to the integrated beam current, subtracting from that the average of the two normalized BF3 counts for no sample, and then normalizing to unit sample weight.

The internal consistency between the crushed gravel, coarse sand and fine sand would be expected as all three should be basically silica. Ideally the sugar result for Norm should be zero as both carbon and oxygen have zero photoneutron cross section below 16 MeV. The sugar result represents the contribution due to the scattering of neutrons originating outside the sample.

The two results which stand out from the others are the urea and the soil. The urea result is encouraging in that a high gamma-n response is desired. The high soil result could reflect the heavy (high clay) nature of this soil sample with a consequent high alumina content. This soil result indicates that this method for detecting land mines might be problematic in a clay soil environment.

The results of these tests indicate the results desired but are far from definitive. The high background count rate makes interpretation difficult. Two measures could be taken to improve the experimental setup. The first is to remove the tungsten collimator assembly and thus eliminate this major background source. Repeating these tests with this enhancement would be worthwhile. The second would be change the beam line end window to either Be or some plastic material. This would be only a minor improvement relative to removing the collimator, and its significance could be determined only once the collimator is removed by repeating the test done here by adding an extra titanium sheet.
Figure 2
APPENDIX 2
Gamma Ray Spectra From Inelastic Neutron Scattering

DRES D-T Neutron Generator Experiments

2003 October

On 2003 October 03 gamma-ray spectral measurements were done at DRES to investigate the feasibility of using FNA in land mine detection. The samples used were the six samples used in the NRC linac experiments in 2003 September augmented by three additional samples. The sample data is given below in Table 1. Using the D-T neutron generator from the TNA land mine detector system, the samples were irradiated with 14 MeV neutrons. The gamma-ray spectra were collected using the DRES Ortec HPGe detector with the X-COOLER.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Chemical Comp</th>
<th>Weight (oz)</th>
<th>C Weight (oz)</th>
<th>O Weight (oz)</th>
</tr>
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<td>Urea</td>
<td>CH₄N₂O</td>
<td>29</td>
<td>5.8</td>
<td>7.8</td>
</tr>
<tr>
<td>Sugar</td>
<td>C₁₂H₂₆O₁₁</td>
<td>33</td>
<td>14.</td>
<td>17.</td>
</tr>
<tr>
<td>Crushed Gravel</td>
<td>SiO₂</td>
<td>55</td>
<td></td>
<td>29.</td>
</tr>
<tr>
<td>Coarse Sand</td>
<td>SiO₂</td>
<td>53</td>
<td></td>
<td>28.</td>
</tr>
<tr>
<td>Fine Sand</td>
<td>SiO₂</td>
<td>58</td>
<td></td>
<td>31.</td>
</tr>
<tr>
<td>Dry Soil</td>
<td>SiO₂ &amp; Al₂O₃</td>
<td>38</td>
<td></td>
<td>17.</td>
</tr>
<tr>
<td>1 L 2-stroke Oil*</td>
<td>~CH₂</td>
<td>32</td>
<td>27.</td>
<td></td>
</tr>
<tr>
<td>20 L Diesel Fuel*</td>
<td>~CH₂</td>
<td>640</td>
<td>549.</td>
<td></td>
</tr>
<tr>
<td>19 L Water</td>
<td>H₂O</td>
<td>670</td>
<td></td>
<td>596.</td>
</tr>
</tbody>
</table>

* Assumed density 0.9 g/ml

The hardware arrangement for the detector, D-T generator and the steel shadow shield (to protect the detector from the direct neutron beam) is shown in Figure 1. Samples were located at mid height in front of the shadow shield by stacking empty sample containers to attain the appropriate height. The neutron generator conditions for the measurements were 70 kV and 50 μA giving a source strength of ~ 4x10⁷ n/s.

The electronics configuration is shown in Figure 2. Three spectra were collected simultaneously in the Canberra Multiport II MCA: the gated in-beam inelastic scatter spectrum (mca3), the gated out-of-beam (n, n'γ) spectrum (mca4) and the total ungated spectrum (mca2). The total spectrum count rate in-beam was ~5 times the out-of-beam value.

An example of an out-of-beam spectrum obtained with the sugar sample is shown in Figure 3. This spectrum is dominated by neutron capture gamma-rays from iron. The effects of the samples on the out-of-beam spectra were primarily due to neutron capture in hydrogen, neutron
capture in silicon, the decay of N-16 produced by the (n,p) reaction in O-16, and the decay of Pb-207m produced by neutron capture in lead when shielding was added.

An example of an in-beam spectrum obtained with the sugar sample is shown in Figure 4. The peaks of interest in the spectrum are oxygen peak at 6.11 MeV (plus single and double escape peaks) and the carbon peak at 4.44 Mev. The carbon peak is Doppler broadened due to the very short half-life of the energy level leading to this peak.

Gross and background subtracted count rates for the photo peak of carbon and oxygen for a number of samples are shown in Table 2. The background subtracted data is normalized to the mass of the element present in the sample. Because of the high background count rates for the carbon and oxygen peaks, part way through the measurements lead shielding was placed around the detector to reduce the background contribution due to the room environment (the TNA system was in the room). This proved effective, however the total count rate did increase as a result of neutron interactions in the lead shield.

### Table 2

<table>
<thead>
<tr>
<th>Spectrum Number</th>
<th>Sample</th>
<th>Carbon</th>
<th>Oxygen</th>
<th>Detector Unshielded</th>
<th>Carbon</th>
<th>Oxygen</th>
<th>Background Subtracted</th>
<th>Carbon</th>
<th>Oxygen</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003-10-03-03-mca3</td>
<td>Background</td>
<td>1.45</td>
<td>0.73</td>
<td></td>
<td></td>
<td></td>
<td>0.09</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>2003-10-03-01-mca3</td>
<td>Urea (CH_4N_2O)</td>
<td>1.95</td>
<td>0.77</td>
<td></td>
<td></td>
<td></td>
<td>0.09</td>
<td>0.011</td>
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<tr>
<td>2003-10-03-02-mca3</td>
<td>Sugar (C_{12}H_{22}O_{11})</td>
<td>2.64</td>
<td>0.92</td>
<td></td>
<td></td>
<td></td>
<td>0.05</td>
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<tr>
<td>2003-10-03-04-mca3</td>
<td>1 L of 2-stroke oil*</td>
<td>2.74</td>
<td>0.70</td>
<td></td>
<td></td>
<td></td>
<td>0.04</td>
<td>0.005</td>
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<tr>
<td>2003-10-03-05-mca3</td>
<td>6 samples stacked</td>
<td>2.19</td>
<td>1.37</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2003-10-03-07-mca3</td>
<td>Background</td>
<td>0.22</td>
<td>0.30</td>
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<td></td>
<td>0.07</td>
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<tr>
<td>2003-10-03-10-mca3</td>
<td>1 L of 2-stroke oil*</td>
<td>1.99</td>
<td>0.29</td>
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<td></td>
<td>0.01</td>
<td>0.006</td>
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<tr>
<td>2003-10-03-14-mca3</td>
<td>2 sand samples</td>
<td>0.50</td>
<td>0.65</td>
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<td></td>
</tr>
<tr>
<td>2003-10-03-11-mca3</td>
<td>20 L of diesel fuel*</td>
<td>6.21</td>
<td>0.15</td>
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<tr>
<td>2003-10-03-12-mca3</td>
<td>19 L of water</td>
<td>0.49</td>
<td>2.05</td>
<td></td>
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</tr>
</tbody>
</table>

* Assumed density = 0.9 g/ml and CH_2 chemical composition.

Excluding the spectra 2003-10-03-05, -11 and -12 because the counting geometry was less well defined, the average background subtracted count rates for the carbon and oxygen peaks are 0.075 cps/oz and 0.007 cps/oz respectively. This difference of about a factor of ~10 is considerably larger than the expected factor of ~2 based on the MCNP calculated gamma yield factor of ~1.4 combined with a detector efficiency factor of ~1.4 (assuming 1/E efficiency
dependence). Additional MCNP simulations were done to see if the presence of hydrogen in the samples or different material densities could be responsible for this discrepancy. Only small changes in the ratio were found. This large difference is not reflected in the two large volume samples (20 L diesel fuel and 19 L water) which have similar geometries, atom densities and neutron moderation where the difference is a factor of ~3.

The MCNP simulations indicated that oxygen should also contribute to the 4.44 MeV peak at a rate of ~1/10 that of carbon. The “2 sand samples” results give a background subtracted count rate of 0.005 cps/oz-oxygen in the 4.44 MeV peak, which is 1/15 the average value for carbon. The 20 L water sample also shows this effect at a rate of about 1/20 that for the 19 L diesel fuel sample.

The carbon count rate observed in these tests (2×10^4 cps/n/oz) is considerably smaller than that obtained in the MCNP simulations for a FNA land mine detector system (15×10^4 cps/n/oz). The detector in the simulation was much larger than the one used in the experiments.

These experimental results can be said to be only in broad agreement with the MCNP predictions. The most significant difference is in the ratio of the count rates for the 4.44 MeV (carbon) and 6.11 MeV (oxygen) peaks. The contribution of oxygen to the 4.44 MeV peak is confirmed though it is slightly lower than predicted. The Doppler broadening of the 4.44 MeV peak decreases the advantage of using Ge spectrometers. However there are no other significant peaks in this region in the spectra, even in the “6 samples stacked” spectrum which contains a significant amount of soil material.

The conclusion reached from the MCNP simulations of a FNA land mine detector was that without tagged neutrons the 4.44 MeV peak does not provide a practical means of detecting carbon in explosives due to the contribution to this peak from oxygen and the underlying large continuum. These experimental results do agree with the prediction of significant oxygen interference in this peak.
Neutron source

1/16" steel plate sized to support neutron generator

Shadow shield made from 1" steel

Ge detector

Top of table ~6' from floor

Figure 1
Hardware Arrangement
Figure 2
Electronics Configuration
Feasibility of Fast Neutron Analysis (FNA) for Detection of Buried Landmines (U)

Contractor Report.

Defence R&D Canada – Suffield, P.O. Box 4000 Main Station, Medicine Hat, Alberta, Canada T1A 8K6

DRDC Suffield CR-2004-201

Unlimited
Recognizing the Canadian success in developing a landmine sensor based on neutron interrogation ( Minescan), DRDC has undertaken steps to improve the basic technology behind Minescan by, for example, replacing the isotopic radiation source with an electronic source (a neutron generator) in order to reduce unwanted radiation exposure to operational military personnel. The physical principles governing the operation electronic neutron generators offered a new range of operational modes, thus this contract was designed to assess the full potential of the electronic source by assessing its capability to do fast neutron interrogation in addition to the thermal neutron interrogation currently used by Minescan. These studies have led us to the conclusion that it is not feasible to try to make use of FNA as a complementary technique to TNA to enhance the detection of buried landmines based on the existing electronic source in the ILDS head. In essence, the scattering of radiation from the ground is so intense that it masks all the desired FNA signals from the mine itself. The only method to reduce the effect of the soil is to use the tagged neutron approach. However, this implies a completely different electronic source and, likely, a differently designed head. Thus, the potential use of fast neutron activation to detect landmines will require a completely new system design, including a different type of neutron generator, different head and different ( faster) detectors. The detailed results reported should prove useful in discouraging international funding agencies from pursuing FNA and FNA-augmented TNA for landmine detection. In addition, photoneutron detection was investigated as a potential complementary process to FNA and TNA. Experiments conducted indicated that the detection of nitrogen by measurement of emitted photoneutrons is possible, although the experimental apparatus used was not optimized. While the practical realization of ( y, n) techniques as fieldable landmine detectors may be difficult, the promising results from these early experiments indicate that this, till now unstudied approach, may yield valuable information.

Inelastic neutron scattering, Neutron absorption, Fast Neutron Analysis, Thermal Neutron Analysis, Explosive, Landmine, Detection