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TECHNICAL REPORT

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NUCLEAR AND ATOMIC METHODS OF MINE DETECTION

by

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ABSTRACT

This report summarizes the results of a project to provide technical review and analysis, developmental assessments, and studies of current and new technology applicable to the detection of landmines using nuclear and atomic techniques. Additionally, technical support for new research initiatives was provided in the form of independent analytical studies that sought to verify expectations and predictions for a range of techniques, including neutron capture, γ-ray induced reactions on nitrogen (an important element in military explosives), neutron elastic and inelastic scatter, γ-ray nuclear resonance scattering on nitrogen, x-ray backscatter imaging, dual energy x-ray Compton scattering, and nuclear magnetic resonance.

For relatively mature technologies such as x-ray backscatter imaging, thermal neutron capture, and the reaction of nitrogen with 13.6 MeV γ-rays, plans for laboratory testing were reviewed and plans for field tests were developed.

The project had its principal focus on x-ray backscatter imaging, particularly the optimization of the technique, the development of appropriate x-ray sources capable of scanning a 3 meter wide search path, and the development of detectors and collimators capable of withstanding the field environment. A unique type of x-ray generator was proposed that could meet the scan rate requirements. It consisted of a single 3 m long cylindrical anode with 150 grid controlled cathodes. The technical specification of this tube were developed. A laboratory demonstration of the feasibility of this concept was carried out by an associate contractor.

Although several nuclear techniques are currently being developed, x-ray backscatter imaging remains the technique with the greatest potential for achieving a respectable capability for detecting buried mines using equipment that will be reasonable in size, mass, power consumption, complexity, ruggedness and field operability.

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FOREWORD

This project was performed for the Countermine Research Group of the Countermine Technology Division of the Department of the Army's Belvoir Research, Development, and Engineering Center under Contract DAAK70-89-C-0002. Dr. Thomas Broach is the head of the Countermine Research Group. The Contracting Officer's Technical Representative at the initiation of the project was Mr. Edward Ostrosky. Ms. Elaine Boncyk was COTR during the major part of the project. Ms. Charlotte Voltz was COTR during the last half year of the project.

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NUCLEAR AND ATOMIC METHODS OF MINE DETECTION

1 INTRODUCTION

Background

The landmine has played an important role in land warfare since its introduction in World War I. Its use was greatly expanded during World War II, particularly with the introduction of the plastic mine and a wide range of anti-personnel mines. Mines took on greater significance in the Korean war and had a considerable impact during the Vietnam conflict because of the widespread use of improvised mines having an array of trigger mechanisms.

The increasing impact of the use of mines has prompted military establishments to seek means of countering mines either by neutralizing them without detailed knowledge of their location or by detecting them individually and avoiding or neutralizing them.

Although neutralization is possible in general, it is not always practical. Explosive breaching has been the favored method of clearing a path through a mine field but it is a logistics burden. In the Persian Gulf war the nature of the burial medium (sand) made the plow a practical technique. Other techniques have been explored, but few have achieved much success.

Among detection methods, success has been achieved only using metal detectors to detect metal cased mines, which are not a dominant fraction of mines in practice. The non-metallic ("plastic") mine has foiled all detection schemes except the time honored method of painstakingly slow probing with a stick or the tip of a bayonet. Numerous detection methods have been explored in considerable depth. They include just about every known physical phenomenon that could have some detectable interaction with a mine, and a few (dowsing, for example) that might raise eyebrows among scientists and engineers. Not surprisingly, atomic and nuclear techniques have enjoyed a substantial level of attention, primarily because they tend to be applicable to the one aspect of a mine that is to some degree unique - the explosives with which they are filled. Generally, the other identifiable characteristics of a mine have features in common with many other materials.

It is useful to state the characteristics of military explosives and to indicate why they tend to form a unique set. All military explosives of interest are organic chemicals[1]; that is, they contain only carbon, oxygen, nitrogen and hydrogen. Consequently, the average atomic number in these materials is approximately 6, just as it is in most organic materials.

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[1]Initiating explosives such as lead azide are not included because they are invariably used in very small amounts - rarely exceeding 0.1 g.

In contrast to the vast majority of organics familiar as every day materials (sugar, for example), military explosives are unusually dense, with specific gravities that are no lower than 1.6 (TNT) and can be as high as 2.0 (HMX). One other chemical characteristic is important - a high nitrogen content. TNT and PETN have nitrogen contents of 18.5% and 18.4% respectively by weight, similar to a few other common organic materials such as leather, wool, silk and nylon. RDX and HMX have nitrogen contents of 37.8% and 42.4% respectively - far greater than most common organic materials (melamine excepted).

The presence of both nitrogen and hydrogen in these molecules gives rise to magnetic resonance signatures that are characteristic of each of the explosive molecule types. The coupling of hydrogen dipole and nitrogen quadrupole resonances lead to resonance characteristics that are, apparently, unique to these explosives.

These explosives have a variety of physico-chemical characteristics that are important to other (non-nuclear) approaches to detection, but these will not be discussed.

The goal of this project was mine detection and hence some notion of the general characteristics of a mine is required. Because mines come in an array of shapes, sizes and purposes some further limitation is needed. The most significant difference among mines is based on their intended target. Thus mines are labeled as either anti-personnel or anti-vehicular types. Two other significant characteristics of mines were used to define the mines: (1) whether the mines are metal cased or plastic cased; and (2) whether the mines are buried or placed on the surface. This project was focused on the detection of anti-vehicular mines. Its main emphasis was on the detection of buried, plastic cased, anti-vehicular mines, not only because these mines are the most difficult to detect, but also because they represents a major fraction of the present and anticipated future threat.

Some notion of what would constitute meaningful mine detection in the operational sense was required in order to limit the efforts to areas that could sensibly be regarded as potentially applicable. The operational requirements that were adopted were those published in the *Workshop Report on Nuclear Techniques for Mine Detection*[2]. Some of the important desired characteristics are; (1) forward speed - 3 mph, (2) scanned width - 3 m, (3) detection probability - 99%, (4) false response rate - less than 1 per 0.25 mile of forward travel, (5) mine burial depth for 90% detection - 8 inches, and (6) power requirement - 5 kW. The workshop report also listed minimum (or maximum) useful values of these parameters also. Of these, two stand out; (1) an allowable maximum power of 100 kW and (2) a minimum burial depth of 2 inches.

It was considered desirable to achieve the forward speed and scan width at the expense of higher power and smaller depth of burial, and to accept less stringent detection and false response criteria (90% detection probability, and 1 false response per 100 yards).

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[2]Moler, Robert B., ed., *Workshop Report - Nuclear Techniques for Mine Detection*, Lake Luzerne, New York, July 22-25, 1985; Belvoir Research and Development Center, July 1985.

Objectives

The objective of this project was to provide technical management support to the Countermine Technology Division of Belvoir Research, Development and Engineering Center in the areas of nuclear and atomic detection techniques. This objective encompassed the review, analysis and evaluation of the theoretical basis of developmental and proposed techniques, analysis and evaluation of experimental data supporting current developments, and review of technical developments, particularly advances in technology, that have the potential of advancing the state of the art in mine detection. This objective was accomplished by carrying out the following tasks.

1. Review and analyze current mine detection methods involving nuclear and atomic techniques. This analysis will include reviewing technical reports, technical support during site visits, analysis of results and recommendations, resolution of technical problems, and preparation of program reviews and presentations.

2. Evaluation of new concepts using technically competent and objective analysis. This will include discussions of the methods used in calculations, results and interpretations of calculations and finally, a recommendation regarding the potential of the technique.

3. Review the advances in technology that have occurred over the past few years and identify those that have a potential for mine detection. Conduct a more extensive analysis as warranted, and develop preliminary test plans for such.

4. Provide technical support for new research initiatives. Carry out independent analytical calculations verifying the expectations and predictions included in the statement of work for such new research initiatives. Provide technical support at contractor's facilities during the initial research and development planning.

5. Review and develop test plans for more mature nuclear and atomic techniques, then evaluate progress and recommend systems for further development.

Approach

BRDEC initiated a major effort in photon backscatter imaging following the recommendation of the Workshop Panel. This became the major current development in the area of nuclear and atomic methods of mine detection. During the course of this project, several other developments were undertaken in conjunction with the Defense Advanced Projects Agency (DARPA) and these developments, which advanced rapidly, necessitated substantial efforts in reviewing reports, analysis of results and other activities. The principal means of providing objective review and analysis of these projects was to maintain close contact with the technical personnel directly charged with carrying out the studies. To this end I had numerous technical discussions with the respective principal investigators. Such discussions were in conjunction with contract technical review meetings and site visits in addition to frequent telephone conferences.

In addition to the mine detection developments of BRDEC and DARPA other agencies such as the FAA have undertaken a wide range of developments directed toward *explosives* detection. These developments impinge on the mine detection efforts, because nearly all nuclear and atomic methods of mine detection are predicated on the characteristics of the explosives in the mine. Direct access to the FAA contractors was restricted and the availability of developmental results were limited, hence detailed review and analysis of these results could not be carried out. Nevertheless it was possible to analyze the techniques for their potential applicability to mine detection based on an evaluation of the basic physical principals involved. These various activities along with careful review of reports submitted to BRDEC and DARPA provided the basis for a thorough analysis of results as they became available. These results were provided to BRDEC in the form of Monthly Reports or informal letter reports when a special situation arose.

An interesting and gratifying result that arose from the efforts to encourage new ideas, that were made by BRDEC, was the number of new and technically worthy ideas that were submitted for consideration. Because many of these new ideas had never been given serious consideration in the past, the level of technical analysis required often became substantial. Again, it proved most rewarding to work directly with the originators of the new ideas to develop a thorough understanding of the technique and then to carry out an independent assessment of the technique. In all instances the emphasis was on the technical feasibility of the method rather than the practicality of the method using current technology. Technical feasibility was defined as the ability to detect a medium sized mine (about 5 lbs of RDX) buried to a depth of about 3 inches and to do so with at least 90% probability and with a low probability of generating false signals with commonly occurring clutter material. If the technique passed this test then a closer examination of the practicality of implementing the technique was carried out. This analysis involved reviewing the state of the art of the technology involved and what advances would be required to achieve full scale implementation.

The technology involved in the application of nearly all the nuclear and atomic techniques has evolved significantly in the last 10-20 years and in some cases these advances have a direct impact on the potential of a technique previously dismissed as impractical. This is particularly the case for high power x-ray and high energy bremsstrahlung sources. It also occurs in imaging and data fusion where computer technology has made rapid strides. In many other technical areas substantial advances have been made. In order to assess the degree to which such advances may impact mine detection, some idea of the type, nature and degree of the advance has be known. This is a daunting problem because it implies a comprehensive knowledge of all the fields involved and the ability to relate them to all the techniques of mine detection. No such comprehensive assessment was carried out, but many areas were reviewed in a limited way. To a large extent technological advances were chosen because they appeared to be able to improve the potential of an existing technique. In a few cases the technological advance appeared to make a previously dismissed technique potentially practical. In a small number of cases, the technological advance was reviewed in an effort to see if it could be applied to mine detection in some meaningful way. The knowledge of the existence of advanced technology came from many sources - technical journals, trade journals, discussions with contractors, conversations with colleagues engaged in research (probably the most fruitful source) and on one occasion a newspaper article.

During the course of this project several research initiative have been identified. Each of these initiatives required the development of a statement of work supported by comprehensive analytical calculations. Such calculations became an integral part of the development. In most cases technical support was continuous during the developmental phase of the contract and often was provided at the contractor's facilities. Early involvement in the research and development planning was significant in achieving a high degree of cooperation, understanding of potential difficulties, and the selection of available options for their resolution.

Among the relatively mature atomic and nuclear techniques of mine detection are photon backscatter and thermal neutron capture gamma-ray emission. Over the course of this project these two techniques have been given careful consideration in order to formulate test plans. In the former case these planned tests were developed in concert with the contractor and BRDEC personnel following extensive evaluation of results. These analyses and test results led to recommendations for systems development such as the use of plastic scintillator detectors, development of a prototype multiple cathode x-ray tube, and the development of a push-cart anti-personnel mine detector based on photon-backscatter.

2 ACCOMPLISHMENTS

Review and Analysis of Current mine Detection Methods.

This task evolved as new initiatives were identified and research and development projects initiated. Initially only one project involving a nuclear or atomic technique was being studied - x-ray backscatter imaging. This was the approach considered to be the most promising nuclear technique by the 1985 Workshop panel. Later this technique became known as photon backscatter.

The photon backscatter project was initiated with the award of a contract to the University of Florida. Dr Alan Jacobs of the Nuclear Science Center is the Principal Investigator.[3] The project continues, but with a somewhat different technical emphasis than the one contemplated by the Workshop panel.

The early phases of the photon backscatter project involved a complex effort to carry out theoretical analysis while at the same time beginning a difficult experimental program. A major effort was required to review the theoretical calculations. Additional review of the experimental apparatus and recommendations with regard to it were provided. One of the most significant areas was that of the detectors to be used in gathering experimental data. Initially I had suggested that a standard gadolinium oxysulfide fluorescent screen would be the most suitable choice because it was used in many direct viewing and video x-ray inspection systems designed for immediate review (so called, real time radiography.) Experimental results revealed that these screens were entirely unsuitable for the purpose because of a long (milliseconds) secondary fluorescence. For experimental studies a useful expedient was a small NaI(Tl) crystal.

The early studies (using the NaI(Tl) crystal) revealed the desirability of incorporating detector collimation, and cast doubt on the usefulness of the original dual energy approach. Very careful review and analysis of these results were required before the major change in direction that they implied could be recommended. Several site visits were made in order to observe the experimental arrangement that led to these results and to discuss their physical basis. Further considerations led to a recommendation that the single energy collimated detector approach should be continued and that work involving the use of uncollimated detectors and dual energy should not be continued except for certain well defined experiments that would verify the original findings under conditions favorable to the use of uncollimated detectors and dual energy. It was subsequently demonstrated that even under the most favorable conditions, an uncollimated detector operated in the dual energy mode was not competitive with a collimated detector and single energy operation

[3]Jacobs, Alan M., *Landmine Detection by Scatter Radiation Radiography*, University of Florida, Department of Nuclear Engineering Sciences, Gainesville, Florida, Department of the Army Contract DAAK-70-86-K-0016, Final Report January 1988 and Contract DAAK70-986-K-0033, Final Report February 1991.

in terms of the ability to detect a buried mine. This result was confirmed by theoretical analysis using the computer program developed earlier.

The detectors continued to represent a difficult problem. One effort involved the use of a different type of fluorescent screen - screens based on calcium tungstate. This type of screen had been used for medical imaging for decades until supplanted by gadolinium oxysulfide which is a more efficient converter of x-ray to light. Calcium tungstate has the advantage of having a very fast (μsec) fluorescent decay time. A simple conical light reflecting cone was constructed so that a circular screen could be mounted at its large end and a photodetector mounted at its small end. This unit was crudely calibrated at Imatron's facilities in California and found to be sufficiently sensitive for use in the backscatter program. Although subsequent measurements using a much more efficient light collector and a photomultiplier demonstrated that the system could function adequately, it appeared that a better expedient would be to use a commercially available large area plastic scintillator.

The advantages of the scintillator were manifold; they can be quite large, they are very rugged, they are easy to manufacture, and they are relatively inexpensive when manufactured in moderate quantities. I recommended that plastic scintillators be procured for subsequent experimental studies involving current mode data collection. This recommendation was followed and four plastic detectors were purchased from New England Nuclear. The detectors were standard NE-102 plastic 2 inches thick and 12 inches square.

Work with these detectors in the current mode revealed an unexpected result. The data appeared to be much noisier than had been the case either for the small NaI(Tl) detector or for the similar area calcium tungstate screen. Observation of the detector in the pulse mode revealed that large pulses were occurring at the rate of about 500 per second; that is, about half the rate at which the current was being sampled. These large pulses had a total energy content that was a significant fraction of the energy of all the x-ray pulses (average energy of about 40 keV) that were recorded during the integration time of a few milliseconds. Consequently each image pixel had a significant probability of having its total intensity significantly increased as a consequence of the presence of one of these large pulses. For images of mines buried at a depth of 5 cm or more, this random image noise severely reduced the detectability of the mine.

Studies were carried out at UF and at BRDEC to determine the origin of the pulses. The observations could be explained if the detectors had been contaminated with an alpha emitting isotope, but this possibility was emphatically denied by the manufacturer. A difference in the spectra recorded with the detector flat and edge up demonstrated that the source was external. A local source of energetic γ-rays was eliminated by carrying out the experiments in a parking lot far removed for the laboratory. The orientation results and the energy spectra for the two orientations are consistent with the source being cosmic ray background.

In order to eliminate this source of background it was decided to discriminate against these energetic pulses by detecting them in the pulse mode and rejecting the sample in which it had occurred. Because the soil box is not moved to the next position until a valid sample has been recorded, the sampling can be retried as often as needed to achieve a valid result. This caused the total time needed to record a single image to be increased by a few seconds.

This expedient will not work for the high intensity scanned beam, but in this case the total backscatter intensity is so large that the cosmic ray background intensity will be negligible in comparison. Despite this fact it seemed expedient to continue to explore the possibility of developing a large area detector based on the use of calcium tungstate fluorescent screens because of the low background and negligible weight that they possess.

During the course of the UF project BRDEC began a complementary in-house project whose object was to verify the UF results and to expand those results to include different soil compositions, moisture variations, and a variety of surface variations as well as the presence of natural objects such as rocks and pieces of wood, and manmade metallic objects. It was also decided to concentrate on the multiple plastic detector mode rather than the single NaI(Tl) detector.

Numerous difficulties had to be overcome to achieve a functioning system, not the least of which was the presence of significant instability in the voltage and current of the very old x-ray unit that was available. Other problems that were addressed and overcome included serious head leakage and a misaligned source spot. With the x-ray machine functioning adequately, the x-ray detection system could be checked. A problem was encountered with the use of the 3 inch diameter NaI(Tl) detectors which were found to be the result of exceeding the count rate limitations of the system.

Despite the multiple problems, the system achieved operation and began collecting data on buried mines. It was decided to concentrate on the use of the large area plastic detectors with collimation to study the detection of buried mines. The system was configured so that up to four detectors could be arranged around the source in a symmetrical array. Because the detectors operate from a single high voltage supply, matching the gain and discriminator level proved somewhat difficult. The system does not have in place the cosmic ray pulse rejection feature implemented at UF, but because the plastic detectors are very efficient, the problem poses a limitation only at burial depths of about 7.5 cm.

I provided extensive consultation as this system was brought on line and assisted on several occasions in resolving problems. In addition I provided a suggested research plan that was intended to complement the work at UF and provide additional information on the limitations of the backscatter approach.

Two important project were initiated as part of the overall effort to develop a field operable backscatter system: 1) A project by Imatron[4] to implement a scanned electron beam x-ray source based on the Imatron heart scanner; and 2) A project by Bio-Imaging Research[5] to develop a fast pulsed multiple cathode x-ray source based on the triode gun.

The Imatron project, which is on-going, anticipates the development of a scanned electron beam source with a width of about 1 meter. The unit will be a complete system because it will include collimators and detectors as well as data collection, recording, and display subsystems. The complete unit will be mounted on a flat bed truck trailer and will be capable of being exercised at the Sandia test track. Technical requirements for this developmental unit were prepared by SSI for incorporation into the statement of work.

Imatron proved to be highly capable of adapting their scanning technology to the needs of the linear scanning mine detector. They demonstrated that both the current and voltage could be achieved while scanning at a linear rate nearly a factor of 2 greater than that used in their other scanners. In addition they were able to tailor the electron beam so that it maintained a 1 mm by 9 mm image on the anode over the full width of the scan. This achievement was demonstrated with an existing circular scanner, but over a small range (≈ 20 cm.)

Achieving the required beam size on the ground was a significant challenge because of the complex nature of the collimator that is involved when a continuous scan is being used. Although the proper collimator design is easy to envision, it is quite difficult to design a reasonable approximation of the ideal system that is also manufacturable.

Because the x-ray source will operate at up to 80 kW, thermal analysis is a critical issue. The thermal problem is exacerbated by the problem of beam turn around at the end of each sweep. Because the beam must slow down during this turn around time a significant amount of time is spent with the beam focused on a small area. For this and other reasons, the beam path was configured as an elongated figure eight. This allowed the scan lines on the ground to be parallel for a fixed vehicle speed, and for the turn around region to be large enough to dissipate the energy deposited without an excessive temperature rise.

Because control of the scanning electron beam is essentially empirical, that is, the magnetic fields in the various focusing and scanning magnets are programmed stepwise based on actual measurements and no continuous feedback is used to control the location of the beam precisely, changes in the local value of the earth's magnetic field could cause

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[4]Rand, Roy E., *Continuous Anode X-ray Source*, Imatron, Inc. Department of the Army Contract DAAK70-88-C-0011, Bimonthly Reports from September 1988 to present.

[5]Rodebaugh, Raymond F., *Dual Energy X-Ray Backscatter System*, Bio-Imaging Research, Inc. Lincolnshire, IL; Department of the Army Contract DAAK70-88-C-0027, Monthly Reports September 1988 through March 1990.

the beam to miss the anode entirely. This problem required that the entire beam line be shielded from external fields.

Despite the complexity of the system, the design was completed and verified in most aspects. Presently, completion of a test unit is dependent on the availability of sufficient funding to procure major hardware items.

This system is particularly complex and required a substantial effort to review and verify many of the important results and calculations involved. Several site visits were involved that allowed detailed questioning of the Principal Investigator and his team. Those details of the electron beam scan that could be demonstrated on an existing circular scanner were observed and the stated results verified.

The development of a simpler x-ray source has been a priority from the initiation of the backscatter project. SSI proposed that an x-ray source that achieved scanning by pulsing a sequence of x-ray tubes would be more nearly practical than the highly complex electron beam scanner. Two approaches to this idea were considered: 1) a sequence of small ($\approx$ 2 cm diameter) x-ray tubes that incorporated cathode structures that permitted the electron beam to be interrupted very rapidly (few μs); and 2) a single cooled cylindrical anode in a housing in which grid controlled cathodes could be mounted at 2 cm intervals. A detailed technical analysis of these possibilities were developed along with technical requirements. This analysis and the technical requirements were incorporated into a statement of work that led to a competitive procurement.

A contract was awarded to Bio-Imaging Research (BIR). They reviewed the state of the art for miniature x-ray tubes capable of operating at anode potentials greater than 100 kV and concluded that a major development program would be necessary to achieve the requirements. A similar analysis indicated that the use of a single anode and multiple pulsed cathodes would be a superior approach. At a meeting at BIR to review these results BIR proposed to proceed with the development of a laboratory demonstration unit consisting of three or four cathodes capable of being switched from "zero" current to 1 ampere of current within less than 5 μs.

I provided substantial input into this development including the choice of cathode (dispenser cathodes) and grid material (Buckbee-Meers electroformed mesh) as well as test procedures. Within the limits of the scope of the project this development was very successful. A tungsten coated copper anode along with three grid controlled cathodes were mounted in a single vacuum housing. After some optimization this x-ray triode achieved turn on times of less than 2 μs and turn off times of less than 5 μs. During the on times, currents in excess of 1 ampere at a cathode to anode potential of 105 kV were demonstrated. Sequential pulsing of the cathodes was achieved with each cathode being active for about 100 μs.

This development achieved substantially all of its goals and laid the groundwork for the development of a prototype system capable of being incorporated into a field testable system. Presently, further development has been suspended because of funding limitations.

I provided reviews and analyses of other nuclear and atomic techniques that were in development. The two most important of these were the thermal neutron analysis (TNA) method being developed by SAI International Corporation[6] (SAIC) and the gamma, neutron method being developed by Titan/Spectron Corporation[7] (Titan), both under the sponsorship of the Defense Advanced Research Projects Agency.

The TNA method relies on the interaction of a thermal neutron with nitrogen which results in the instantaneous emission of gamma rays. In a small fraction of cases a unique 10.6 MeV gamma ray is emitted. This high energy gamma ray is unique to nitrogen and the technique is specific for the presence of nitrogen if no other processes generate signals at this energy. Numerous analyses of this technique have been made in the past and all tend to indicate that the combination of low sensitivity for detection of the 10.6 MeV gamma ray, its low probability of being emitted and the very large background of lower energy gamma rays make practical implementation of the technique improbable.

Improvements in detector technology and particularly improvements in pulse pile-up rejection[8] have allowed the technique to approach its theoretical limitation. This limitation is set by the maximum rate of gamma ray interaction in the detector, which limits the intensity of the neutron source, and makes greater sensitivity to nitrogen achievable only by increasing the number of detectors viewing the irradiated area. Despite the considerable advances that had been achieved, upon re-analysis I concluded that the system still could not achieve the minimal requirements of a practical mine detector.

Another nuclear technique that is capable of achieving moderately specific detection of nitrogen is based on the $^{14}N(\gamma,n)^{13}N$ reaction. This approach is predicated on the availability of a reasonably compact 13 megavolt electron accelerator with a total beam power capability about 25 kW. Dr. R. Bruce Miller of Titan believed that such a power source could be developed and proposed that this reaction would be specific for the detection of nitrogen.

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[6]Brown, Doug and Patty Jurgens, *Feasibility Study of Neutron Activation Techniques for Mine Detection*, SAI International Corp. Project #1-088-07-255, Department of the Army Contract DAAK70-88-C-0031.

[7]Clifford, Jerome R., et al, *Mine Detection Using Energetic Photons -Basic Research Effort*, TITAN/SPECTRON Development Laboratories, Department of the Army Contract DAAK70-88-C-0033, Final Report October 1989.

[8]Pulse pileup occurs when two gamma rays are absorbed by the detector in a time period that is too short for the electronics to distinguish them as separate gamma rays. Thus individual 7 MeV and 3.6 MeV gamma rays that are absorbed in a NaI(Tl) detector within a time of 3 μs will appear to be a single 10.6 MeV gamma ray. For NaI(Tl) the total number of gamma ray interaction per second is determined by the required minimum time between interactions. The maximum rate is about $3 \cdot 10^5$ per second.

I reviewed the original idea and pointed out some potential limitations. The most significant limitation is the fact that ^{13}N produced by the reaction has a 10 minute half-life. It decays by emission of a positron which can only be detected by its subsequent 511 keV annihilation radiation. In a typical landmine detection scenario, only one second is available for detection and only 1/1000 of the ^{13}N atoms produced will decay.

Titan was awarded a contract to develop the technique and proceeded to explore the principal using available laboratory accelerators and detectors. Also they developed a computer program that would permit exploration of a wider range of conditions than could be studied experimentally within the time and resources available.

A number of important results emerged from this theoretical and experimental study. The most important difficulty that was revealed was that copper underwent a γ,n reaction to produce ^{63}Cu with characteristics so similar to that of nitrogen that the two are indistinguishable; consequently, a mass of copper will produce a false signal that no modification of the technique can eliminate. A second problem uncovered was that phosphorous also exhibited the same reaction. Phosphorous is less of a false alarm problem because it is highly unlikely to occur in a concentrated mass, but its presence in soil as a consequence of natural occurrence or the use of fertilizers and pesticides raises the background counting rate and thus makes the detection of a given mass of nitrogen more difficult. There are numerous other reactions that occur, but they give rise to isotopes with half-lives of one second or less. For the first 2 seconds after irradiation, the count rate is very high and precludes detection of nitrogen. As was originally anticipated, the detector must pass over the irradiated region several seconds after the irradiation has occurred. This can be accomplished by aiming the gamma ray beam several meters ahead of the vehicle.

The γ,n reaction has some interesting properties that suggest rather unique ways of exploiting the irradiation/detection process. Because of the relatively long half-life of ^{13}N (10 minutes) it is possible to separate the irradiation procedure from detection. One such scheme consists of an irradiator mounted on a hovercraft which is followed by a several small robotic detector vehicles designed not to activate an antivehicular mine. Their size and simplicity make them expendable. Furthermore, the detector can be designed to achieve relatively good spatial resolution so that the mine location can be specified within 5-10 centimeters.

Presently Titan is in the process of mounting the recently developed compact linear accelerator on a vehicle along with the detector array. This test system will be able to scan only a limited path width, but should be able to carry out more or less realistic studies of the efficacy of the system.

An interesting idea put forth by the workshop panel involved the use of Compton scattering of x rays in a well defined geometry to detect the occurrence of a significant difference in atomic number at a given depth beneath the surface. This scheme requires the use of two or more x-ray energies and an array of highly collimated detectors so arranged that the view of each detector would be limited to a different depth in the soil. For a homogeneous soil, mono-energetic x-rays and no multiple scattering, the depth and average atomic number of each scattering volume can be inferred independent of the density of the soil or the height of the source and detectors above the soil. Even if multiple scattering is taken into account, energy discrimination in the detectors was thought to be able to reduce the effect to acceptable values.

SRS Technologies[9] undertook to explore this general approach based on the use of Bragg scattering in a bent crystal to generate a mono-energetic x-ray beam from a standard x-ray machine. It became clear quite soon that this technique could not achieve the required intensity and SRS decided to attempt to detect mines by dual energy Compton scattering using a filtered bremsstrahlung source.

Prior to this change I had carried out an approximate analysis of multiple scattering assuming mono-energetic fan beam sources and a detector array for imaging. This analysis showed clearly that there would be a significant contribution from multiple scattering in all of the detectors even if high resolution germanium detectors were used. Making a quantitative estimate of such multiple scattering is very complex and was not attempted, but the qualitative results suggested that for the most optimistic situation, up to 1/10 of the recorded counts would be the result of multiple scattering. This was less optimistic than the expectation put forth by SRS.

After abandoning the mono-energetic x-ray source approach, SRS carried out a careful study in which a highly collimated source and detector were used in a well defined geometry. The dual energy feature was achieved by setting two energy windows in the spectrum observed by a single detector. In this arrangement the calculations carried out by UF of multiple scattered flux into a collimated detector could be used to infer the ratio of multiple to single scattered x-rays. This result suggested that for a scattering volume at a depth of about 6 inches, about 1/4 of the observed counts were the result of multiple scattering. Although significant in itself, because it greatly affected the ability of the procedure to detect the critical difference between the atomic numbers of soil and explosives, the use of a broad energy spectrum had a more devastating effect.

The key feature of the use of two discrete mono-energetic x-ray sources is that both height variations and density variations can be eliminated from the equations used to calculate atomic number. Because the x-ray absorption coefficients are dependent on the energy of the x-rays, the original approach is not valid if the monoenergetic x-rays are replaced by two energy bands. In fact, the equations become highly sensitive both to height and density variations. Although the density variations were not explored experimentally, it was demonstrated that height variations of as little as 0.5 cm resulted in a change of the

[9] Short, Michael A., Eric J. Bonner and Michael R. Fallon, *Countermine Research Program: Non-Metallic Mine Detection*, SRS Technologies project UR90-033, Department of the Army Contract DAAK70-89-C-0004, Final Report January 1990.

calculated atomic number parameter equal to that resulting from the replacement of soil by an equal volume of explosive. Calculations demonstrated that similarly small variations in density of the soil would be indistinguishable from the presence of a mine.

SRS suggested that these difficulties could be overcome by generating an image of the area under scrutiny, but this approach would involve a very great complexity in the detector array even if a scanning x-ray beam were to be employed. In any event the height variation problem and density variations would persist, and multiple scattering would result in substantially increased variations in the value of the atomic number parameter, greatly diminishing the ability of the system to detect the presence of a mine. In order to carry out the required measurements, the many detectors must operate in the pulse counting and energy discrimination mode. Because of count rate limitations, and the need for high precision in the individual results, the rate of scan would be extremely low, requiring several minutes to explore a 1 m^2 area. As a consequence of these severe limitations it was recommended that this project not be continued.

I participated in numerous program reviews and assisted in the development of presentations, particularly presentations of the photon backscatter program. In addition I attended several DARPA quarterly reviews and provided overall assessments of the projects being described at these meetings.

<u>Evaluation of New Concepts</u>

I have evaluated a wide range of new concepts during the course of this project. Many of these were the direct result of the New Concepts Symposia that were sponsored by BRDEC. Some of these concepts merit discussion because of their uniqueness or their apparent promise. Among these are:

1. $^{14}N(\gamma,n)^{13}N$ (10 s $t_{1/2}$ positron emission) with 511 keV γ-ray detection,
2. $^{14}N(\gamma,2n/2p)^{12}N/^{12}C$ (11, 20 ms $t_{1/2}$ 16 MeV positron emission) with bremsstrahlung detection,
3. Pulsed fast neutron elastic scattering with time of flight neutron detection,
4. Dual energy Compton scattering with energy selective detection,
   Gamma-ray nuclear resonance scattering with gamma-ray resonance detection,
6. Pulsed fast neutron inelastic scatter with energy selective neutron detection,
7. Direction resolved pulsed fast neutron inelastic scatter with time gated gamma ray detection, and
8. Longitudinal magnetic resonance with resonance RF detection using SQUID technology.

Each of the above techniques was analyzed in substantial detail and a report on the analysis was submitted. These analyses were carried through, often in conjunction with the original authors of the new concept. Serious limitations uncovered by the analysis were discussed with the author and potential solutions considered. These reports described the techniques and approaches used in the analysis and provided detailed results were such results had a major impact on whether the concept appeared to have sufficient potential to merit recommending it for further study. Numerous other concepts were presented to BRDEC for consideration, but those not in the above list had such severe technical and theoretical limitations that there evaluation was limited to addressing an overriding issue that would preclude their successful implementation. Finally there was a group of other submitted "new" concepts that were minor variations of techniques that had been examined in considerable detail in past studies and which could be confidently set aside based on the results on those studies. The results of the analyses of the above concepts are briefly described below.

Gamma, Neutron Reaction - Detection of 511 keV Radiation

Nitrogen is known to undergo the $^{14}N(\gamma,n)^{13}N$ reaction beginning at a γ-ray energy of about 10 MeV. The reaction cross-section (probability) has a significant peak at about 16 MeV and falls to a minimum value at about 25 MeV. The low value of the threshold for the onset on the reaction is nearly unique for low atomic number elements such as carbon, oxygen, nitrogen, aluminum and calcium and the apparent cross-section is relatively large. But these reactions have not been studied extensively and there is considerable uncertainty concerning the details of the many possible reactions.

The reaction product, ^{13}N is a positron emitter with a halflife of 10 minutes. It emits no γ-rays directly. Detection depends on the fact that a positron will annihilate with an electron to produce two oppositely directly 511 keV γ-rays. These relatively low energy γ-rays can be detected efficiently so long as they are not absorbed by a significant layer of soil (roughly 10 cm.)

Implementation of this technique is based on a number of assumptions and presuppositions all of which needed to be examined. The major questions were: 1) is the production of ^{13}N sufficiently unique to make it diagnostic for the presence of a high nitrogen content in a small volume?; 2) What combination of source intensity, and detector efficiency will be required to meet the minimum search rate requirement?; 3) Will secondary reactions that produce isotopes with halflives greater than a few seconds generate so much γ-ray background that the essential nitrogen generated 511 keV γ-ray signal will be swamped?; 4) What type of detection scheme will result in the required detection efficiency while achieving adequate localization of the detected mine?; 5) Are the anticipated characteristics of the accelerator such that it meets the mass, volume and power requirements and is there adequate prior demonstration that the required device can be developed?

The initial analysis indicated that the most of these questions could be answered positively on the basis of information available in the published literature or by relatively simple calculation. It was apparent that the most serious interference would arise from oxygen with a threshold of about 16 MeV and that operation with a γ-ray energy below this value would be essential.

Calculating the production of ^{13}N using a bremsstrahlung γ-ray source requires a convolution integral. Because the details of the energy dependence of the cross-section were poorly known and the bremsstrahlung intensity depends on the details of the target, only a conservative approximation was calculated. To carry out the approximate calculations the following assumptions were made: highly efficient detection of 511 keV γ-rays (for example a 7.5 cm thick $BiGeO_4$ detector) and a detector area of 700 cm^2 (somewhat smaller than the largest mine); a large mine buried to a depth of 10 cm ($\approx$4 in). For a detection system advancing at the 3 mph rate, the minimum statistical requirements would be met with a beam current of 200 μa.

Estimating the production of interferences arising from secondary reactions was possible only in a qualitative way. It is known that fast neutrons will thermalize and be absorbed in a few milliseconds, and that most of the potential products had short halflives. Consequently, it was estimated that detection would have to be delayed by at least 1 second following irradiation. Most other reaction would be γ,n reactions on heavy elements with atomic numbers greater than 30. The natural abundances of such elements in ordinary soil is very low and this source of interferences was considered to be unimportant.

The detectors needed to meet efficiency requirements seemed to be a weak point in this concept. Because the detectors must be efficient detectors of 511 keV γ-rays, a large area of high density material such as NaI(Tl) or $BiGeO_4$ would be required. An array of such detectors could be used to localize a mine, but operated individually, the overall detection efficiency is compromised. Furthermore the necessity of scanning a path that is up to 4 m wide implies the use of a very large number of detectors. Efficient detection also implies operating in the pulse counting mode with energy discrimination, which would be quite a complex operation if more than 100 detectors are needed to cover the width of the path. However, it was concluded that the use of large arrays of detectors in numerous unrelated scientific projects demonstrated that the essential requirements could be met in a practical, if somewhat costly manner.

The area in which the greatest uncertainty arose was the reasonableness of the assertion that a moderately compact linear electron accelerator could be developed that would meet the stated mass, volume and power requirements. The basic design of the proposed accelerator was compared to existing laboratory designs. Despite the uncertainty in extrapolating these designs to the proposed accelerator, the design appeared to be sufficiently conservative in approach, and the individual components sufficiently well established for operation in other applications, that the development risk was not excessive.

Overall this concept appeared to have a relatively high potential for achieving the goal of detecting medium and large buried anti-vehicular mines at the required area scan rate. It appeared likely that the developed system would be complex even though it would meet the general system requirements. Because no well defined operational requirements had been developed this issue could not be addressed, but it was clear that considerable attention would have to be given to making the system practical for field use and for minimizing the need for field maintenance and repair. Further development of this concept was recommended.

Gamma, 2 Neutron Reaction - Detection of Bremsstrahlung Radiation

For γ-rays with an energy of 25 MeV or greater ^{14}N undergoes a reaction in which two neutrons are knocked out resulting in the production of ^{12}N. This isotope is virtually unique in its decay properties, having a half-life of only 11 milliseconds. In addition to its unique half-life (and closely related to it) is the fact that this isotope decays by emission of a very energetic (16 MeV) positron. The uniqueness of this isotope and its potential for explosives detection was originally explored by Luis Alvarez, its discoverer. Its detailed exposition as a new concept was carried out by Professor W. Peter Trower.

The features of this reaction that make it unique are the decay half-life and the energy of the beta (positron) decay. All of the elements likely to be found in soil in significant amounts will react with energetic γ-rays to produce radioactive isotopes. The vast majority of these isotopes produced by γ,x reactions in soil elements have half-lives that are greater than a few seconds. This difference in half-life results in an inherent detectability difference of a factor of several hundred. For similar concentrations and reaction cross-sections of nitrogen and a competing element the "activity" (proportional to the number of atoms created divided by the half-life) during the 10-20 ms following irradiation will be nearly 100 times greater for ^{12}N than for such competing isotopes as ^{39}Ca. Considering equal areas of interrogation, ^{40}Ca (the parent of ^{39}Ca) would have a much lower concentration in soil than the apparent concentration of nitrogen in a comparable area in which a mine had been buried. Thus, if a detector capable of responding in this time period is activated a millisecond after a γ-pulse has ended and records for 10-20 ms, a large increase in intensity will be recorded if a volume of soil is replaced by a mine.

The second feature of importance, the high energy of the emitted positron, provides a means of discriminating the presence of ^{13}N decays from other competing positron emitters. The highest energy positron is from ^{39}Ca with an energy of 5.5 MeV. If a detector is capable of rejecting bremsstrahlung with an energy less than 5.5 MeV, then no competing reaction would be detected.

Calculations indicated that a γ-ray source capable of generating bremsstrahlung with a maximum energy of 50 MeV at a beam current of 20 μa (1 kW of power) would produce sufficient ^{13}N to meet the statistical requirements of explosives detection. The generation of such energetic γ-rays using the usual electron beam impinging on a target of tungsten would generate a narrow beam that would irradiate an area of less than 1000 cm^2 at a distance of 2-3 m. Consequently some means of scanning the beam would be necessary. The beam size and required area coverage (3+ m wide by 1.4 m/s forward rate) implies that about 50 regions (pixels) will be interrogated each second and hence about each interrogation is carried out in 20 ms.

High energy γ-rays generate a plethora of fast neutrons, and these in turn will interact with available elements to produce both capture γ-rays and delayed γ-rays. Fortunately, thermalization occurs very rapidly and hence a delay of about 1 ms is sufficient to eliminate prompt gamma rays. These fast neutrons do create another problem - potential interactions in the detector.

The detector requirements in this system are rather demanding. Because some energy discrimination is required, the detection mode must be pulse counting. In order to collect data with acceptable statistical significance at the required rate, the detector and supporting electronics must be exceptional fast. To illustrate this; if the background is as low as 1000 counts in 20 ms, the total number of counts required to achieve assured detection of a mine would be about 1500 counts. Consequently the count rate at the beginning of the 20 ms counting period might be as high as 10^5/s. In addition to the high counting rate that is required, the detectors should not respond to neutrons. As mentioned above, fast neutrons will be produced in abundance and would generate an overwhelming signal in most fast detectors. For example plastic scintillators contain substantial hydrogen and the n,p scattering reaction would result in a background signal intensity that could saturate the detector. If the saturation is sufficiently large, recovery could be so slow that the important nitrogen signal could not be observed. Techniques to mitigate this effect include making the detector inactive for the first several milliseconds and employing a detector insensitive to neutrons. The latter is the preferred choice and a liquid fluorocarbon scintillator was proposed for initial investigation.

A major concern with this technique is its practicality. A 50 MeV accelerator is a massive device in most possible implementations. A very high frequency linac could result in a relatively small version, and the proposed racetrack microtron has the potential of being reduced in volume and mass to an acceptable system. Nevertheless there were numerous potential limitations to the system than would have to be overcome. Despite the limitations that were apparent the technique had considerable technical promise that if realized would make the advances in technology needed for practical implementation a worthwhile goal. Consequently a modest effort to investigate this technique was recommended.

Fast Neutron Elastic Scattering

Neutrons undergo a variety of reactions with nuclei. For neutron energies of a few MeV, elastic scattering is the dominant process, and most common elements such as carbon, oxygen, nitrogen and silicon exhibit a number of elastic scattering resonances with quite large cross-sections - often greater than several barns.[10] Neutron scattering has a particularly simple form because it can be analyzed as a strictly classical billiard ball collision process. If the incident neutron energy is know the energy of the scattered neutron is precisely defined by the mass of the isotope with which it collided and the angle between the incoming and out-going directions.

In order to make use of this phenomenon a detector capable of resolving the relatively small differences in energy between neutrons scattered from carbon, nitrogen and oxygen must be available. Because detectors that depend on measuring the energy deposited generally are not capable of such energy resolution most neutron studies rely on time of flight detection. In this scheme the differences in velocity among neutrons scattered from different isotopes is determined by recording the time required for a well defined pulse of constant energy neutrons to reach the detector. The precision of the energy determination is a complex combination of incident neutron energy spread, time spread of the neutron pulse, angular divergence of the neutron beam, the area of the detector, and surface roughness (height variations) in the irradiated area.

The neutron source is generated by a beam of protons with very precise energy. There are only two nuclear reactions considered suitable for this type of source, and of these the $^{6}Li(p,n)^{6}Be$ reaction is the more suitable for high intensity applications. Only a highly stable accelerator such as a Van de Graaff or a feedback controlled cyclotron can meet the stability requirements. Although the intensity requirements cam be met in principal, to do so would require the development of a compact cyclotron with a beam current more than one hundred times greater than is routinely achievable with existing machines.

The presence of a mass of explosive buried beneath the surface of soil will generate a unique time of flight record under ideal circumstances. For mono-energetic neutrons in a very short pulse (0.1 ns) irradiating a small area (10 cm^2), and an ideal time of flight neutron detector, the observed time history would reveal the presence of all the major elements and isotopes, their location in depth from the surface and their approximate concentrations. As a simple example, neutrons scattered from silicon atoms located at the soil surface would be the first to arrive at the detector. These silicon scattered neutrons would have an intensity proportional to the surface concentration of silicon. Neutrons scattered from sub-surface silicon would form a continuous (in time) signal that decreased in intensity as a function of their TOF because of attenuation, but would be present until sharply terminated at the surface of the explosive (which contains no silicon.) Neutrons

[10] The Barn is the nuclear equivalent of an interaction coefficient. By definition one Barn is 10^{-24} cm^2. Typical nuclear reactions involving charged particles such as protons or electrons or γ-rays will have cross-sections measured in millibarns or microbarns. Thermal neutrons interactions by contrast can exhibit cross-sections of hundreds or even thousands of barns. Elastic neutron scattering is intermediate with a cross-section of about 0.5 b for many isotopes. For the low atomic number isotopes of carbon, nitrogen, and oxygen there are distinct scattering resonances in the range of 0.5 MeV and 5 MeV that have cross-sections as large as 10 b.

that penetrate the mine, once more encounter silicon and hence the TOF record shows an abrupt increase in intensity at the appropriate time, which will decrease to background levels at a time representing a depth at which only a negligible number of neutrons are able to make the round trip. Similarly, neutrons scattered from oxygen in the soil will appear in the TOF record significantly later than silicon scattered neutrons. Neutrons scattered from nitrogen and carbon have lower velocities and will appear later yet. When these elements are present in discrete layers at different distances from the source and detector, the TOF record becomes quite complex.

The complex TOF record described above is further complicated by the lack of precision that is inherent in each of the critical aspects of the neutron production, scattering and detection processes. Thus, rather than observing the onset of silicon scattering as a sharply defined abrupt increase in neutrons detected, the increase occurs over a time of several nanoseconds and is complicated by statistical scatter because of the limited number of detected neutrons. This resolution limitation has a substantial impact on the functioning of the system. In general it guarantees that carbon and nitrogen scattering cannot be distinguished and that even their presence will be difficult to detect because of variations in oxygen concentration below the layer where carbon and nitrogen are present. These limitations would place much higher demands on source intensity and detector efficiency in order to reduce their impact, but even if no limitations were present in this regard, the inherent limitations appeared to assure a low probability of successful implementation for the technique.

Further analyses of the potential for development of the scanned, pulsed mono-energetic neutron source suggested that such a development was not likely in the reasonable future. Similarly, the required detector does not exist and the possibility of developing an appropriate detector rested on a vaguely described conjectural approach.

Despite the considerable appeal of the fundamental physics of this concept[11], its successful implementation was considered to be very unlikely and the development of the advanced equipment needed for practical application was seen as improbable in the foreseeable future. Consequently the concept was not recommended for further development.

Dual Energy Compton Scattering

A Compton scattering system involving multiple detectors and energies was discussed in the 1985 Workshop report. The panel considered the idea to have merit but concluded

[11]Dr. Henry Gomberg of Penetron, Inc., the originator of the concept, carried out some simple idealized laboratory experiments in which he was able to observe the C, N, and O scattering peaks, but not resolve the C and N peaks. A sophisticated peak fitting computer program was used to resolve the C and N peaks, but it depended on *a priori* information such as expected peak locations and widths, information that would not be available in the mine detection scenario.

that the dual energy scattering system pioneered by Dr. A Jacobs to be a much more practical approach. Some of the difficulties recognized were the complexity of having the large array of detectors needed to provide the three dimensional scans, the complexity of the source and detector collimation, and the very large isotopic sources needed to provide the mono-energetic γ-rays that would be required.

A considerable simplification of this approach would involve interrogating the same volume through the same ray path with two different energies. A straightforward analysis shows that if the soil has constant composition and the scattering volume has constant properties as a function of location, a parameter that is independent of the soil density and the height of the source/detector above the soil surface can be derived from the intensity measurements at the two energies. A substantial difficulty with this approach is the ability to supply the very intense mono-energetic sources required and to achieve the high speed detection and energy discrimination critical to meeting the area scan requirements.

Dr. Ferril Losee of SRS, Inc. presented the above system in the context of the use of a curved bent crystal diffraction system that could achieve the necessary mono-energetic x-ray sources. Additional potential approaches involved the use of a scanned electron beam to generate characteristic fluorescence x-rays and the use of isotopic sources. The necessity of achieving good energy resolution was recognized and the use of liquid nitrogen cooled Ge crystal detectors was suggested.

The approach was to arrange a source and detector in a 90° (or 45°) geometry. Both the source and detector are highly collimated so that a narrow beam of x-rays penetrates the soil to a soil volume beneath a buried mine that is common to the line of sight of the detector collimator. A narrow beam of scattered x-rays originating from this common volume of soil would be detected. Because the energy of the scattered x-rays would be well defined, energy discrimination would largely eliminate background from multiple scattering. With two energies undergoing scattering (either simultaneously, or better yet alternately), and assuming an unchanging composition for the soil, a parameter "R" called the ratio of ratios, could be defined that would be a constant regardless of density and height variations. If a volume of explosive replaced the soil in either the entrance or exit path for the x-rays, a substantial change in the value of "R" would occur because of the change in average atomic number.

Clearly there are a number of processes that impact the potential viability of this scheme - the most important being the ability to supply the intense mono-energetic x-ray sources required. Two other issues were the fraction of detected x-rays in the energy window that would be the result of multiple scattering and variations in "R" that would occur as a consequence of inhomogeneities in the composition of the soil. These latter could be the result of small rocks or other intrusions in the path of the x-rays entering or emerging from the soil.

The x-ray intensity requirement is a complex interaction of the absorption of x-rays (primarily dependent on the depth of the scattering volume), the size of the area being interrogated, the energy resolution required and the number of detected x-rays needed to meet statistical requirements. Because multiple scattering would be much greater if a fan beam of x-ray was used, a higher intensity would be needed in this configuration than for a scanned beam as used in the simple backscatter approach. These various options were analyzed and compared to the mono-energetic x-ray output projected to be available for a curved bent crystal monochromator. The characteristics of the monochromator were those claimed to have been measured by SRS for their newly developed efficient graphite monochromator. Although a fan beam would be used, and two monochromators and detector sets would be involved, a single bremsstrahlung source with a power of about 5 kW would suffice to cover a path width greater than 1 m. The most troublesome issue was the potential for a significant fraction of the detected x-rays to be the result of multiple scattering. Because no available computer program was able to deal with the geometry involved, only approximate calculations could be carried out, but these indicated the possibility of substantial multiple scattering in the energy windows involved. The problem would be worse for the low energy detector and for a scattering volume at a depth of 6 inches, might contribute as much as 50% of the detected x-rays. The situation worsens as the energy resolution of the detectors is relaxed in order to accept a higher fraction of the scattered x-rays.

Despite these reservations, the system appeared to have merit, and did not involve the complex accelerators for x-ray and γ-ray generation needed in the backscatter imaging and nuclear reaction approaches. It was concluded that this new concept merited further study and a recommendation to this effect was made to BRDEC, with the constraint that such a study should be limited to a carefully designed feasibility investigation.[12]

Gamma-Ray Nuclear Resonance Scattering

A little know phenomenon in nuclear physics is nuclear resonance absorption of gamma-rays. Just as with scattering of visible photons by atoms, the scattering of γ-rays involved in the Mossbauer effect, the interaction can occur only if the energy of the photon is a precise match to the energy of the corresponding energy level in the atom or nucleus. In the case of the Mossbauer effect, the γ-ray energies are such that nuclear recoil during emission is small enough that an atom in a crystal lattice will not be displaced, and the recoil mass can be the entire crystal thus eliminating the energy loss. For energetic γ-rays the nuclear recoil momentum is much larger and cannot be constrained by the weak forces in a crystal lattice, consequently, the emitted γ-ray has an energy that is significantly less that the energy level in the nucleus. In essence no energy overlap occurs and resonance absorption will not occur except in unusual circumstances.

Nitrogen-14 is one of the few isotopes in which there is a way around the difficulties

[12]Dr. Losee was no longer employed by SRS, Inc. when the development contract was awarded. Dr. Michael Short undertook to carry out the project. The results of his work have already been described.

described above. For this isotope there is an energy level at 9.172 MeV. It is known that ^{13}C undergoes a resonance reaction with protons to produce ^{14}N with the simultaneous production of this 9.172 MeV γ-ray. Furthermore, all of the momentum of the protons must be transferred to the excited ^{14}N atom that results from the fusion of the proton with the ^{13}C atom. This fast moving atom decays with the emission of the 2.311 MeV γ-ray. Because the emission is isotropic, and momentum conservation is involved, γ-rays emitted in the forward direction have a higher energy than those emitted in the back direction. At an angle of about 40° from the forward direction, the energy of the emitted γ-ray is such that it precisely overlaps the 9.172 MeV energy level of ^{14}N. This concept originated with Israeli physicists at the Soreq Nuclear Research Laboratory, Yavne, Israel.[13] This group along with another group headed by Richard E. Murgado at Los Alamos National Laboratory[14] have made important advances in its application.

If a beam of γ-rays of precisely the correct energy is incident on a sample containing nitrogen, a small fraction of the incident γ-rays will be resonantly absorbed, producing a dip in the intensity of the beam. Of the γ-rays absorbed, a fraction will be re-emitted isotopically. The isotopically scattered 9.172 MeV γ-rays will be detectable at other locations with a suitable detector.

The major barriers to this technique are the difficulty of achieving sufficient intensity of the correct energy γ-ray and detecting the γ-rays with adequate efficiency. Clearly these are related problems because more initial intensity reduces the need for detection efficiency and efficient detection reduces the demands on source intensity. The intensity of the γ-ray source is limited by the proton beam current and the amount of power that can be dissipated by the target. If a thin layer of pure ^{13}C is deposited on a thick copper or tungsten target, the power is limited only by the evaporation of the carbon from the target. In general this limit is not reached because the proton beam current that can be achieved is relatively small. Currents of about 100 μa are achieved (250 W) and currents of 1 ma (2500 W) have been suggested as attainable.

If a high resolution detector is employed, background events can be minimized, and multiple scattering will be minimized. But high resolution detectors do not have high efficiency. An alternative is to use a resonance detector in which nitrogen in the detector interact with the resonant γ-rays, but this approach is possible only in the restricted case in which the transmitted beam is detected.

For mine detection, only those 9.172 MeV γ-rays resonantly scattered out of the soil are available for detection and these have an energy below the nitrogen resonance.

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[13]Vartsky, D. and M.B. Goldberg, unpublished reports to the US Federal Aviation Agency, 1985.

[14]Murgado, Richard E., *The Feasibility of Detecting FAA-Threat Quantities of Explosives in Luggage and Cargo Using Nuclear Resonance Absorption in Nitrogen*, Los Alamos National Laboratory, Advanced Nuclear Technology, Phase I Final Report (October 1989).

Detecting these γ-rays can be done using an ordinary NaI(Tl) crystal, but because of the poor resolution of the detector, a significant background of scattered γ-rays will occur. The use of a high resolution detector such as cryogenic Ge would largely eliminate the problem at the expense of considerable complication and a lower detection efficiency. Analysis suggested that the use of high efficiency moderate resolution detectors would be the superior choice. In either case the maximum possible source intensity would be necessary in order to meet the area scanning requirement for practical mine detection.

This concept is quite unique. Its specificity for nitrogen is equal to or superior to that of any other nuclear technique, and the energy of the accelerator needed to generate the resonant γ-rays is quite modest compared to the other γ-ray based methods. If a moderately thick ^{13}C target is used, the energy of the proton beam needed to be controlled only to a limited extent. Because the source beam will be a curved fan (assuming that collimation is used to restrict the output to the correct energy), a path width of up to 2 m can be achieved without any beam scanning requirements.

The analysis suggested that the source intensity, detection efficiency, background reduction and mine localization could all be met with a system that involved a power of only a few kilowatts. It was concluded that this system had significant potential and further study was recommended.

Pulsed Fast Neutron Inelastic Scattering-Energy Selective Neutron Detection

For neutrons with an energy approximately greater than 6 MeV, one of the prominent reactions that occurs is inelastic nuclear scattering. The reaction (schematically A(n,n')A* leaves the nucleus in an excited state and results in the prompt emission of characteristic γ-rays. Because only well defined nuclear levels can be excited, if the incident fast neutrons are mono-energetic, the inelastically scattered neutrons also are monoenergetic. Because isotopes such as ^{14}N, ^{16}O, and ^{12}C have distinct nuclear energy levels, they are readily detected and quantified by recording the intensity of their characteristic γ-rays or inelastically scattered neutrons. Detecting the γ-rays is the classic approach, but because energy spectroscopy is required to distinguish among the myriad of g-rays of similar energy, and all suitable detectors and the associated electronic processing circuits are limited in the rate at which they can process signals, this approach is relatively slow. In general, the neutron output is restricted to an intensity of about 10^7/s. The useful γ-rays occur only during a very brief period of about 50 μs following the neutron pulse, but as the neutrons thermalize they continue to generate capture γ-rays for at least 500 μs. Even at a neutron pulse rate of 1000/s detecting a large mass of nitrogen may require several minutes.

This severe limitation can be removed in principal by detecting the inelastically scattered neutrons assuming that the neutron pulse is very fast - less than 1 μs. Because they had developed an intense very fast (50 ns) 14 MeV neutron source Drs. Nardi and

Brzosko[15] proposed a system in which these diagnostic inelastically scattered neutron groups would be used to detect and localize a mass of explosives based on the presence of nitrogen and carbon.

Although a time of flight system could be used, the fastest such detectors have extremely low efficiency and for a system in which the incident neutron has an energy of 14 MeV, and the scattered neutrons have energies in the range of 5 MeV to 10 MeV, the time resolution must be less than one nanosecond even for a detector several meters from the soil surface.

The TOF spectrum will be highly complex, even more so than was the case for lower energy neutron elastic scattering, because often there are several energy levels in each isotope that can be excited by MeV neutrons. Because interactions can occur at any depth for many isotopes, particularly the abundant isotopes Si, O, Ca and Al, recognizing the features representing the presence of nitrogen and carbon and distinguishing then is very difficult. This difficulty is further complicated by the fact that each pulse of neutrons lasts about 25 ns, a value large in comparison to the time of arrival differences in the neutron TOF spectrum. Also there exists structure within each neutron pulse that is not reproducible from pulse to pulse. An analysis of a typical TOF spectrum made it clear that it was impractical to resolve this complex spectrum and that the difficulty was such that it bordered on being inherently impossible.

An alternative neutron detection scheme is to develop an energy selective detector. For a conjectural detector having high efficiency and a time response of a few nanoseconds, and designed to respond only to $\approx$ 7 MeV neutrons from nitrogen, the current output in the presence of nitrogen would be a sharply increasing current at the appropriate time after a pulse followed by a decreasing signal as the neutrons scattered from more distant nitrogen atoms. For a fixed thickness, the signal should terminate abruptly after the neutrons pass through the explosives. Even this scheme is complicated by the structure in the neutron pulse and the presence of other neutrons groups close in energy to the nitrogen scattered neutrons.

Nardi and Brzosko have carried out calculations based on the energy levels and cross-sections for neutron inelastic scattering on the light elements, particularly carbon, oxygen and nitrogen and have concluded that the there is sufficient separation in energies to make specific detection of the presence of nitrogen feasible. The diagnostic neutrons from nitrogen have an energy of 10.4 MeV. A strong oxygen peak occurs at an energy of 11.3 MeV. Their calculations do not include the effect of scattering, which would degrade the sharpness of the calculated peaks and generate a substantial general background. To take advantage of these neutron scattering peaks, an efficient detector with an energy resolution of a few hundred KeV would be required.

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[15]Brzosko, J.S., and V. Nardi, *Hunter System for Land Mines Detection - Nuclear Method*, Avogadro Energy Systems, Inc., Final Report, Department of the Army Contract DAAH01-C-0516 March 1990.

No detector is know that will meet the above requirements. Although moderately high neutron detection efficiency can be achieved using n,p scattering, achieving adequate energy resolution is difficult at best and always results in a substantial sacrifice of efficiency. The claim that such a detector could be developed is not supported by any analytical or experimental evidence.

A further complication that mitigates against the practical development of this scheme is the necessity of collimating the fast neutrons in order both to minimize the variation in the return time of a single neutron group and to achieve adequate localization of the mine. This is not a simple problem for 14 MeV neutrons and has yet to be achieved without introducing many lower energy neutrons into the collimated beam. Finally the pulse rate of the present neutron generator is only one pulse per second, and this must be increased by a factor of at least 100, a substantial problem.

On careful analysis, the fundamental difficulties involved in implementing this technique were found to be substantial; that is, difficulties such as the inherent complexity of the inelastic neutron spectra and the presence of multiple elastic scattering contributing an irreducible background to the spectrum would be present. Furthermore the developmental difficulties appeared to be severe. These included the necessity of increasing the neutron production pulse rate by a factor of 100, collimation of the neutron source and developing a scanning procedure capable of sweeping the beam across a 3 m path. Finally the system rested on the development of a neutron detector for which no analytical or experimental evidence could be adduced, but whose claimed characteristics would be beyond the present state of the art by a startling amount. It was concluded that this concept did not merit developmental support.

Direction Resolved Pulsed Fast Neutron Inelastic - γ-Ray Detection

A different approach to the use of pulsed fast neutron inelastic scatter was investigated by A. H. Aitken of Consolidated Controls Corp.[16] In the reaction $^3H(^2H,n)^3He$ (usually described as the DT reaction), the two product are a 14.4 MeV neutron and a 4 MeV ^3He nucleus. The neutron and ^3He particles travel in opposite directions and hence if the direction of the ^3He can be defined, then the direction of the neutron will be known. This approach is known as the associated particle method and has been used in the past in a simple arrangement. Consolidated controls developed a superior associated particle detector that permitted neutrons with a relatively large angular spread to be determined.

If the direction of the neutron is known, then it is a simple matter to look for γ-rays returning within a small time variation to be detected and stored. The origin of these time gated γ-rays will be know within relatively narrow limits. Given enough time, a three

[16] Aitken, A. H., and C. W. Peters, *Investigation of an Improved Neutron Technology for Mine Detection Purposes*, Consolidated Controls Corp. Final Report Department of the Army Contract DAAK70-C-0028 December 1988.

dimensional map of the origin of gamma rays can be developed. Analysis of the energy and intensity of the γ-rays will permit, in principal, the recovery of the elemental composition of the soil in each volume element.

Several substantial difficulties are present in the adaptation of this technique to mine detection, but the most important is the limitation in neutron output imposed by the associated particle detector. This particle detector has a time resolution of about 0.1 μs. Hence the total number of neutrons incident on an interrogation area is less than 10^7/s. For the required advance rate of 1.43 m/s (3 mph) and a path width of 1 m, the area covered per second is 14300 cm^2. Even if a spatial resolution of 5 cm^2 is used the total number of neutrons incident on a pixel will be less than 3000. A very small fraction (<0.01) of these neutrons will react before undergoing elastic scattering. About 30 fast neutrons will scatter inelastically to produce characteristic γ-rays. Because these γ-rays are emitted isotopically, about 0.1 of them will be intercepted by a large area 100% efficiency detector. The three detected γ-rays could arise from any of the 4 or 5 abundant elements in soil and from any depth between 0 and $\approx$ 10 cm. If the depth resolution is about 2 cm, then for each resolution volume and element only 0.15 γ-rays would be detected. The γ-ray spectra that will be recorded will be very complex, because they contain several γ-rays from each element and even an efficient detector will rarely absorb all the energy from a γ-ray interaction. Consequently, to detect the presence of a specific γ-ray a detector must intercept a few hundred γ-rays of that energy.

Consolidated Controls effectively demonstrated the above considerations by operating their system in the time gated mode so that only those γ-rays originating from a specific depth would be recorded. To achieve the necessary statistical precision, the system collected data for several hours. No substantial improvement in the associated particle detector is anticipated, and therefore the system is effectively limited to an operational mode that is at least a factor of 10^3 slower than is required. Even if such an improvement were possible, the γ-ray detectors would limit the neutron intensity because they are limited to a rate of 10^5/s, which is about a factor of 100 greater than the actual operating conditions in the experiments.

Advances in the state of the art of the magnitude required could not be anticipated for the foreseeable future and consequently further development of this technique was not recommended.

Longitudinal Magnetic Resonance

Crystalline materials that contain hydrogen in their molecules exhibit RF resonances when their molecules are aligned in a suitable magnetic field. Molecules that also contain nitrogen exhibit quadrupole resonances caused by the alignment of the nitrogen atom in the electric dipole field of the hydrogen atom. RDX exhibits a relatively strong quadrupole resonance but only weak dipole resonances, while TNT has a strong dipole resonance and only a very weak quadrupole resonance. In either case if the molecule is subjected to the correct magnetic field the quadrupole and dipole resonances will have the same frequency and will interact strongly (couple). When this situation prevails T_2 the de-excitation time constant, is greatly shortened - fractions of a second instead of several seconds. The required field is relatively low, a few hundred Gauss, and can be achieved simply. This phenomenon can be taken advantage of to detect explosives in a one-sided geometry.

Quantum Magnetics has been developing various applications of nuclear magnetic resonance (NMR) and nuclear quadrupole resonance (NQR) in which the ultra-sensitive SQUID (Superconducting Quantum Interference Device) is used to sense changes in the magnetic field. They examined the potential for achieving sensitive and specific detection of military explosives and proposed that the technique of longitudinal magnetic resonance, in which the NMR and NQR resonances would be coupled and the resulting fields detected using their RF SQUID technology.[17]

The basic approach takes advantage of the time required for an aligned atom to lose alignment as a result of thermal motion. A varying magnetic field is applied to the explosives, so that some of the atoms are aligned at the correct field. The aligning field is removed and a small holding field is applied. During this period an RF pulse at the correct frequency causes a fraction of the aligned atoms to be excited, but because T_1 is very long de-excitation does not occur. The aligning field is then re-applied which causes T_1 to be very short as a consequence of the resonant interaction between the dipole and quadrupole moments and results in the emission of an RF pulse at one of the resonant frequencies of RDX or TNT if a mine is present. This sequence can be carried out in a time consistent with the desired search rate, and appears to have the sensitivity required to detect moderately small amounts (few kilograms) of explosives. The technique clearly is more sensitive for RDX than for TNT. The RF detection technology is that of the RF SQUID, which is extraordinarily sensitive in this application. Its major drawback is that it must operate at liquid helium temperature.

This technique has one major limitation for which no technical solution appears possible - it cannot detect metal cased mines. The magnetic fields and RF signals cannot penetrate the case of a metallic mine to a degree that would make detection feasible. Despite the above limitation and the apparent difficulties involved in developing this concept it is one of the most innovative approaches to explosives detection that has been presented in the past decade. The conclusion was reached that this technique had substantial potential and it was recommended that this new concept be explored in greater depth.

Review of Technological Advances Relevant to Mine Detection

Technological advances have been made in a number of fields in the past few years. Many of these advances have direct relevance to techniques of mine detection. The most

[17]Quantum Magnetics, Inc., unpublished documents submitted to BRDEC, 1990 and 1991.

obvious such case is the development of the microcomputer whose capabilities now rival those of a mainframe computer of 20 years ago. Other significant advances have occurred in the fields of electron accelerators, scanning x-ray sources and radiation detectors. In other areas the SQUID has had a major impact on the measurement of magnetic fields, and the development of very fast gas chromatography and tandem mass spectrometers has had a major impact on the potential for rapid identification of explosives vapors.

The area of rapidly scanning x-ray sources among the above is the most significant and two developments that are very important are described below.

Rapidly Scanned Electron Beam X-Ray Source

One of the goals in the medical imaging field was the development of a tomographic scanner capable of diagnosing heart conditions. Such an x-ray device would have to be able to image the heart so rapidly that it would create a stop action tomograph. Typical computed tomographs could produce single slice images of poor quality in a time of a few seconds at best. But such slow images were useless for quantitative evaluation of heart action. Workers at Imatron Corporation had set themselves the goal of achieving good images in a time of less than 0.1 s along with a number of other groups who were striving for the same result.

The Imatron group led by Dr. Douglas Boyd choose to pursue a technique in which an intense (0.5 -1.0 ampere) electron beam would be directed onto a circular target. This approach is fraught with difficulties. It was known that an intense electron beam will defocus over a short path in vacuum because of the repulsion between electrons. Imatron discovered and perfected a technique called gas focusing that allowed a well focused beam (1 mm by 5 mm focal spot) to be transported several meters without significant loss of focus. The electron beam, which has an energy of 80 kV and a current of about 0.7 amperes, is guided onto a 1+ m diameter circular target (actually a section of a conical shell) where a complete traversal occurs in a little as 40 ms. The critical element in this system is the ability to maintain the beam focus after it has exited the last magnetic quadrupole where its direction is determined. The beam then travels about 2 m in vacuum until it strikes the tungsten target where the x-rays are generated.

Transferring this technology to a line target was expected to be technically unexceptional although some additional beam manipulation would be required. The principal issue that needed to be addressed was whether the gas focusing technique would function successfully at the higher beam sweep speed, current and voltage required for the x-ray backscatter imaging system for which it was envisioned. Because the details of the gas focusing approach were unpublished, a detailed assessment could not be carried out, but a quantitative analysis suggested that the process would operate successfully at the higher sweep rate.

A detailed development and test plan was prepared for this technique. Subsequently

Imatron was awarded a contract to develop a field operable prototype with a limited scan range (1 m). An early task was to demonstrate that the needed focal properties could be maintained at the higher sweep rate and current. This was successfully achieved using an existing scanner, and a detailed design for the prototype was begun.

Fast Switching Multiple Cathode Linear X-Ray Tube

Although the scanned electron beam x-ray source was know to be capable of achieving the desired scanned x-ray beam, the large size of the vacuum chamber, the sensitivity of the electron beam scan to local magnetic field variations as well as other physical and mechanical difficulties made it very desirable to find an alternative approach to the x-ray beam scanning requirement. The use of pulsed x-ray sources was well known, and it was known that some of these high intensity sources could be pulsed rapidly for several hundred cycles before failure occurred due to overheating[18] (the anodes were not cooled.) Also it was known that a low voltage (25 kV) X-ray triode had been developed and marketed in the past although it was no longer available. These developments suggested that it would be feasible to operate a high current, x-ray generator in a fast switching mode.

Two options were considered. The first was the use of an array of pulsed x-ray tubes arranged in some geometry so that their X-ray spots formed a linear array with a spacing of about 2.5 cm. Detailed discussions with suppliers of x-ray tubes revealed that no suitable tube existed and that to achieve the stated requirements would entail a major development.

The second option, which would require specific development also, would be to arrange a linear array of switchable cathodes in a tube with a single large anode. This option would make use of technological advances in cathodes that had occurred, but would apply the in a highly specific way. The most obvious way to achieve the fast switching was to incorporate a control grid with each of the cathodes. The grid would have to control the one ampere electron beam required to be available from each cathode. A critical aspect of this approach was the recent development of the dispenser cathode, a device capable of delivering one ampere of electrons from a very small source (0.5 cm). These sources were known to have very long operating lives (several thousand hours.) The x-ray system would use a single cooled cylindrical anode. Within the same vacuum housing, cathodes with their integral grids would be spaced at about 2 cm intervals. The grids, controlled by a switching network, would switch the current from each cathode. The current would have to be switched on in a time of less than 5 μs, operate at about 1 a for 100 μs and be switched off in less than 5 μs.

[18]The author operated a 1 MV Hewlett-Packard pulsed X-ray generator at a power of 10 kW in a mode in which it was pulsed at the rate of 3 times per second for 30 seconds, at which point the temperature of the massive, but uncooled, tungsten anode was so high that the glass envelop cracked. The manufacturer rated the tube for several hundred pulses when they occurred over a period of many hours or days.

A detailed set of technical specifications and a test plan were prepared for the development and feasibility demonstration of a laboratory breadboard consisting of a four cathode unit. The test plan was designed to demonstrate that fast switching of a 120 kV 1 amp beam could be achieved and that cathodes capable of supplying a one ampere electron beam beams could be arranged in a linear array with a single anode powered by a high voltage source, and that these cathodes could be switched at the required rate without introducing serious problems. A subsequent contract issued to Bio-Imaging Research resulted in the successful development and demonstration of a 4 cathode array operated at 105 kV and 0.7 amperes with the four cathodes switched at the rate of about 70/s. Each cathode remained on for a period of 100 μs. The turn on time was about 1 μs and the turn off time was about 4 μs. At the end of each cycle a delay of 13 ms simulated the effect of the cathodes that would be present in a full array of 150 cathodes.

Among the other advances in technology that were reviewed, the compact electron linac that was proposed by Titan received the greatest attention. This development was the result of improvements in manufacturing precision for waveguides and the availability of efficient high power high frequency klystons. The compact linac would be used to generate 13 MeV γ-rays that would generate the $^{14}N(\gamma,n)^{13}N$ reaction discussed in the first part of this report. A test plan for the demonstration of a vehicular mounted linac was developed informally and provided to Dr. R. Bruce Miller at Titan who developed the concept and oversaw its realization under sponsorship of the Departments of Defense and Energy.

Technical Support for New Research Initiatives

There were three major new research initiatives during the course of this project; 1) Development of the scanning electron beam x-ray source, 2) Development of the multiple cathode x-ray source, and 3) Feasibility study on the dual energy Compton scattering technique of explosives detection. These three techniques have been discussed in an earlier section of this report, but it is appropriate to discuss how the initial statements of work were analyzed in order to verify the expectations and predictions included therein and the technical support provided during the planning phase of these new initiatives.

Scanning Electron Beam

The fundamental requirements for an x-ray source based on a high power scanning electron beam had been set forth in the original solicitation; however, numerous details of required development and testing of such a source were to be proposed by the prospective contractors. These details included demonstration of achieving the desired stability of the high voltage power supply for the voltage and current conditions required, demonstration of the achievement of beam focusing at the required beam current and sweep rate required and demonstration of the ability of the system to dissipate the 100 kW of power being absorbed by the anode without overheating. Other areas of concern were the achievement of the necessary x-ray spot size on the ground, and providing mechanical stability for such a large vacuum chamber.

A theoretical paper on the gas focusing principal had been published earlier and its predictions were in accord with the results achieved by Imatron in their medical scanner. Although the medical scanner operated at a lower scanning speed (the rate at which the beam traversed the anode) than would be required for the mine detection application, it operated at essentially the same current. Gas focusing involves both the electron beam current which is related both to the production of positive ions along the beam path and which are critical to maintaining the focused beam and to the electron beam scan rate, which must not exceed the rate at which positive ions migrate into the beam. Using the theoretical model, it was calculated that even for the factor of two greater beam scan rate anticipated, the gas focusing approach would have a significant margin of safety in terms of the ions being swept out of the beam during its drift through the scanning and focusing magnet fields, and remaining in the beam to maintain its focal properties near the anode.

This issue was critical and during the initial R&D planning a well defined demonstration of the ability to maintain focal properties during high speed scanning was required as a condition for continuation into the next task. This approach was agreed to and details of the demonstration were incorporated into the test plan. The approach was to make use of a prototype medical scanner, and to modify it so that over a limited range it would maintain focus while scanning at the required rate.

Virtually all of the other critical issues would have to be studied analytically because none of the existing equipment could be adapted to meet the severe requirements of backscatter imaging. Thus specific objectives were set up in which mechanical, thermal, thermo-mechanical, electrical and other aspects of the system design were to be analyzed using state of the art computer models and the models as well as the results obtained provided at appropriate design review meetings.

Similar planning was initiated for the scanner construction and test phase. In this phase, components would be tested as individual units before being incorporated into the system. In many instances the component such as the electron source or high voltage supply could be tested separately by incorporating it into the existing prototype medical scanner before the final system is assembled. The entire beam line (beam formation, focusing and scanning) could be proven in this manner.

Mature Nuclear And Atomic Techniques - Review and Test Planning

Two nuclear/atomic techniques had achieved sufficient maturity to warrant detailed review and planning for field testing - x-ray backscatter imaging and thermal neutron induced gamma-ray analysis (TNA). An x-ray backscatter field test unit design and construction contract has been issued to Imatron by BRDEC, but the actual construction has not begun. DARPA has contracted with GEO-Centers and its sub-contractor SAIC for the design and construction of a TNA unit. The system is expected to be available early in calendar year 1992. Field testing protocols were developed for both units.

X-Ray Backscatter Imaging

The field testable unit for x-ray backscatter imaging under construction by Imatron is designed to cover a 1 m wide path as opposed to the 3+ m path that a fully operational unit would be required to scan. The test track under construction at Sandia National Laboratories at Albuquerque, NM is designed as a pair of 1 m wide tracks in which various features will be incorporated.

The principal issues to be addressed in testing a backscatter imaging system have been explored in a limited way in the laboratory setting and include: 1) mine detectability as a function of mine size and depth of burial; 2) false alarms resulting from the presence of artifacts such as blocks of wood, rocks and voids; 3) false alarms and missed detections caused by surface roughness such as ruts and potholes; and 4) missed detections caused by height sensitivity. Obviously, most of these effects can interact in ways that could increase the probability of missed detections and false alarms, but no reasonable test protocol could expect to explore all the possibilities.

The test tracks at Sandia will consist of one smooth track in which the three sizes of mines will be buried to different depths. This track will include a number of buried and flush to the surface artifacts as well. The second track will incorporate surface roughness features in a controlled way. A vehicle will encounter ruts and bumps at irregular intervals such that front/rear and left/right as well as four way independent ruts and bumps will be encountered. This track will not include other types of artifacts.

In general these types of tests will provide a reasonable exercise of the x-ray backscatter mine detector. However, it does not account for the anticipated effects of soil composition variations. In particular it will not adequately test for the impact of high moisture content.

3 CONCLUSIONS

The US Army Belvoir Research, Development and Engineering Center initiated a renewed effort to develop useful means of detecting mines using nuclear and atomic in 1985, beginning with the convening of a Workshop in which a select small group of experts would attempt to review a wide range of methods and provide a prioritized list of that merited further exploration and development. BRDEC also initiated two Mine Detection Symposium/Workshops in which industrial organizations and universities were invited. The purpose of these symposia was to acquaint industry and universities with the nature of the problem and what approaches had been explored in the past. In addition, BRDEC issued a Broad Agency Announcement inviting the submission of White Papers and proposals in which new methods or improvements in known methods would be presented. As a result, numerous ideas were submitted.

A large number of technical proposals and white papers were reviewed, the majority of which could be shown to be technically flawed. In all cases, technical review included a careful analysis of the methodology, not only to verify that the calculations made in the proposal were correct and reasonable, but also to determine whether the technique could achieve the claims made for it. In most cases, I carried out a more thorough analysis than had been done by the authors of the proposal. Thus it was often possible to show that an aspect of the physics involved in the application a particular methodology had been overlooked and that when correctly incorporated made it unlikely or impossible in principal to achieve the results required. Among the many proposals submitted two were judged to have significant potential; x-ray backscatter imaging and dual energy Compton scattering.

X-ray backscatter imaging has become the focus of development in nuclear and atomic techniques and has progressed to the point that there is little doubt that it will function as a mine detector. Because the experimental studies have been limited to the laboratory simulation of field conditions, there is considerable uncertainty concerning the practical limitations of the technique, particularly with regard to surface clutter that will be encountered in most field applications.

Not only has X-ray backscatter imaging has received the most intensive study, but also it has resulted in the initiation of projects to develop an appropriate scanned x-ray beam. Competing techniques are under development by Imatron and Bio-Imaging Research.

Dual energy Compton scattering could not achieve any useful results as originally proposed because of severe source strength limitations. In the relatively crude form that was studied (selection of bands from a continuous bremsstrahlung source) the method is very sensitive to soil density and composition variations and is extremely sensitive to variation in height - so much so that surface roughness created by 0.5 cm pebbles caused variations as great as those expected from a mine buried less than 2.5 cm. Because of the inherent limitations of the technique no further studies were recommended.

The γ,2n reaction on ^{14}N is one of the comparatively promising techniques in the technical sense because it can detect nitrogen with good specificity and sensitivity. In the practical operational sense it is much more problematical because of the high energy γ-ray generator necessary (50 MeV), and the unique requirements for the detector. Another difficulty arises from the very fast decay (12 ms) of ^{12}N, which results in the detector recording γ-rays from the previously irradiated pixel as the beam sweeps across the path. This effect can be partially alleviated by an unfolding procedure, however this procedure assumes that the background is constant (no height variation for example.) Also it requires better statistical information because a subtraction is involved. The practical implementation of this technique is likely to be more complex than either the x-ray backscatter imaging method or the γ,n reaction on ^{14}N.

Longitudinal magnetic resonance has been analyzed and the conclusion reached that it has significant potential for non-metallic mines. It is much more speculative as a technique than any other technique than has been given serious consideration. Its potential arises from the fact that if it functions as claimed, it would be uniquely specific for explosives such as TNT or RDX. One of its major disadvantages is that it cannot detect metallic mines, and must be operated in conjunction with some other technique.

Other nuclear techniques that have been given serious attention are the thermal neutron capture/γ-ray detection approach and the γ,n/511 keV γ-ray detection approach. Development of these two methods has been sponsored by DARPA rather than BRDEC, but I have been requested to review these developments and assess the technical merits and potential of the techniques. Although the neutron capture approach method has the merit of being sensitive to nitrogen only and is ostensibly less complex than either x-ray backscatter or the γ,n approach, its capability is severely limited by the fundamental physics involved. I have not seen any convincing evidence that these limitations can be circumvented although the developer has made considerable strides. The developmental field test unit will be able to search a path width of only about 0.5 m while having a mass of about 2 tons. Its response to surface clutter, soil composition, and moisture content have not been explored except in a very superficial way.

The γ,n reaction on ^{14}N is also relatively specific. This technique has more potential than does the n-capture approach, but its engineering complications are relatively severe. The use of a 14 MeV linac in a field application appears to pose more difficulty than a large x-ray tube as required by the x-ray backscatter imaging method. The developer has made substantial strides in the development of the required linac and has carried out significant studies in the laboratory to assess the operation of the system. Although the system's response to certain clutter, notably copper, has been acknowledged and a solution proposed, other environmental problems remain to be identified.

It is difficult to arrive at an objective evaluation of the ranking of competing techniques when none have been subjected to extensive field testing that would reveal their limitations and strengths. Nevertheless, I conclude that on balance, the x-ray backscatter imaging method has the greatest potential for achieving a respectable capability for detecting buried mines using equipment that will be reasonable in size, mass, power consumption, complexity, ruggedness and field operability.

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