①

WORKSHOP REPORT
NUCLEAR TECHNIQUES
FOR MINE DETECTION RESEARCH

JULY 22-25, 1985

LAKE LUZERNE, NEW YORK

Sponsored by

BELVOIR RESEARCH AND DEVELOPMENT CENTER

Ft. Belvoir, Virginia

Approved for public release. Distribution unlimited

Prepared by

Robert B. Moler

WORKSHOP REPORT
NUCLEAR TECHNIQUES IN MINE DETECTION RESEARCH

JULY 1985

Sponsored by the U.S. Army

Belvoir Research and Development Center

Prepared by
Robert B. Moler

A-1

TABLE OF CONTENTS

CONTENTS (cont'd)

LIST OF FIGURES

LIST OF TABLES

REPORT ON THE MINE DETECTION WORKSHOP

INTRODUCTION

The purpose of the workshop was

The United States Army Belvoir Research and Development Center sponsored a workshop, held in July 1985, to investigate the use of ionizing radiation techniques for detecting land mines and, in particular, to identify technological advancements that would alter the assessment of the prior workshop held in March 1973 (Coleman et al., 1974).

The workshop participants were tasked with making specific recommendations of techniques that merited study and to identify those areas that required further investigation in order to clarify the feasibility or practicality of the recommended tecnniques.

Although emphasis was to be placed on ~~the~~ application of developed or emerging technology to the problem of the detection of buried land mines, the detection of concealed explosives in the context of security was also ~~to be~~ considered. In the latter category, the automatic detection of explosives in luggage and hand-carried items received the greatest attention. Lesser attention was given to detecting explosives concealed within a building's structure. → (to p 3)

The question of the use of radiation tecnniques for the detection of explosives concealed on a person was briefly considered and dismissed as being infeasible within any reasonably practical constraints of exposure.

The workshop participants recognized that their considerations could not be comprehensive either in coverage or technical depth of the technology considered. In order to minimize the former limitation, a major portion of the workshop was devoted to largely uncritical exploration of technology within the limitations stated earlier. In this way, many ideas were advanced, their possible applicability explored, and ideas to enhance their potential encouraged. Criticism was discouraged, although recognition of technical limitations is inevitable when improvements are being sought.

It was recognized that combinations of techniques offered the possibility of achieving capabilities beyond those obtainable from any single method. Such combinations actively were sought, particularly combinations that could take advantage of components that would be present for a different method.

Following a general agreement on a list of techniques that merited further examination, the chosen techniques were subjected to critical examination that attempted to assess their practicality, what improvement(s) could be expected over any earlier embodiments of the technique, and to what degree the technique might meet the general requirements that had been set forth earlier in the workshop. In the process of this examination, critical technical issues were raised and practical problems were identified. To the extent possible, the panel explored the critical technical issues, but, more importantly, the need for and extent of additional feasibility studies were delineated.

Finally, the techniques that were identified as having promise were considered one final time in order to develop a consensus on the priorities that should be attached to the feasibility studies and the general level of effort that was recommended as being likely to be adequate to resolve the critical issues.

OPERATIONAL EXPECTATIONS AND REQUIREMENTS

([illegible])

Three particular explosives detection scenarios were considered, and the requirements for each were explicitly discussed by panel ~~the~~ members ~~of the~~ panel. The first of these, the detection of buried, nonmetallic, anti-vehicular (AV) mines, was the area of greatest concern and was given the greatest emphasis by the panel. The other two, detection of anti-personnel (AP) mines and detection of explosives in luggage and packages, were considered in ~~much~~ less detail.

Mine Detection Operational Requirements

For a mine detector to have any practical utility, it must be able to carry out its function effectively. That is, it must meet the user's needs to a sufficient degree that the device will be employed. The above definition is intentionally vague because any effort to provide strict quantification to the problem usually leads to requirements that are so stringent that they could not be met by any technically feasible system.

The panel approached the problem of requirements by discussing what they viewed as the minimal requirements of a system that would result in a meaningful accomplishment. In particular, the approach was to identify system limiting characteristics that would result in an impractical or unusable system. The following system characteristics are the author's interpretation of these considerations and judgments, and they do not necessarily represent the consensus of the panel. The primary focus was the antivehicular (AV) mine, and the system envisioned was a vehicular-mounted mine detector. In addition, an anti-personnel (AP) mine detector was discussed in the context of a vehicular-mounted unit, as well as a portable, hand-held unit. Not discussed was the possibility of a walk-behind, self-propelled, cart-mounted system or other conceivable intermediate forms of both AV and AP mine detectors.

Vehicular-Mounted AV Mine Detector

Forward Speed

Desired: 3 mph (4.4 fts^{-1}, 1.34 ms^{-1})
Minimum Useful: 0.5 mph (0.73 fts^{-1}, 0.23 ms^{-1})

Scanned Width

Desired: 10 ft (3.05 m)
Minimum Useful: 6 ft (1.83 m)

Power Requirements

Desired: 5 kilowatts
Maximum Practical: 100 kilowatts

AV Mine Detection Probability

Desired: 99 percent
Minimum Practical: 90 percent

False Response Rate

Desired: less than 1 per 0.25 mile
Maximum Practical: 1 per 100 yards

Mine Burial Depth for 90-Percent Detection

Desired: 8 inches
Minimum Useful: 2 inches

Environmental Capabilities

Temperature Range: -20°F to 120°F
Humidity Range: 5 percent RH to 97 percent RH

Soil Variations

Desired: arid, sandy soil to wet humus
Acceptable: detector-specific to a soil type and moisture content

Less emphasis was placed on the identification of the desired characteristics of an anti-personnel mine detector. The scan rate and other characteristics were considered only briefly, and then only to note what had been accomplished in the past and the degree to which such characteristics had been considered acceptable. It was noted that AP mines, by their very nature, were shallowly buried and, consequently, the need for soil penetration could be relaxed. Because most AP mine detectors had been conceived as portable units, the scan rate, of necessity, would be less than for a vehicular-mounted detector, but no quantification was attempted.

In addition to these operational requirements for specific detection methods, other expectations must be included. For example, in the instance of the use of fast neutrons, considerations of personnel safety, both during operation and when the system is not operating, play a significant role. For any system employing radiation sources, the release of the material as a consequence of an accident or an unavoidable hostile action requires attention. Although of lesser concern, in the use of intense machine x-ray sources, appropriate attention must be paid to the protection of the operator and individuals who may be nearby.

Because of the nature of the problem being addressed, the use of a hand-held system was not considered to have credibility, particularly in view of the speed requirements. Consequently, most of the considerations dealing with operational requirements are premised on a vehicular-mounted system.

The third scenario considered is that of detecting explosives whose illegal introduction into a building is being attempted. The operational requirements are less well defined in this instance because there is no single agency responsible for building security, and, furthermore, the range of possible scenarios is quite large so that the operational requirements may be dependent on the details of a particular building, its use, and the perceived needs of the agency responsible for the security of the building. The panel considered that the most useful approach to this problem was to avoid specific requirements and to consider only the potential applicability of a specific technology to a general expectation. This expectation was that a detection system ought to be able to detect a modest quantity of commercial or military explosives (less than a few pounds) in a package or a hand-carried item (e.g., briefcase), and that such a detection system should not impose a serious constraint on the traffic into a building. In meeting these constraints, a lower assurance of detecting explosives, compared to the AV mine situation, would likely be acceptable.

General Characteristics of Explosives and AV Mines

Table 1 provides some information on the characteristics of military explosives. Table 2 provides information on commercial explosives. In the latter case, there are large differences among the available materials; consequently, it is quite difficult to generalize. Although nitrogen is an important component in most commercial explosives, few other common characteristics are found.

The characteristics of naturally occurring materials play an important role in the ability to detect explosives. Some techniques are very sensitive to these parameters. Neutron techniques in general are highly sensitive to the hydrogen content of the soil, while x-ray methods are particularly sensitive to the soil density. Table 3 provides some general characteristics of some naturally occurring materials.

The use of x-ray techniques is of great significance in explosives and mine detection. Table 4 provides absorption coefficients for intermediate energies for a number of military explosives and explosive mixtures. Data for x-ray energies below 300 keV would have to be calculated from the absorption coefficients of the individual elements, weighted for their relative abundance in the particular material.

Table 1. Composition of Military and Commercial Explosives

	Wt%						
	Density	C	H	N	O	Pb	Density
RDX (Cyclotrimethylenetrinitramine)	1.8	16.2	2.7	37.8	43.2		0.05
TNT (Trinitrotoluene)	1.6	37.0	2.2	18.5	42.2		0.035
AN (Ammonium nitrate)	∼1.5	0.0	5.0	35.0	60.0		0.08
Pb azide	4.8	0.0	0.0	29.0	0.0	61	0.0
Pb styphnate	3.0	16.6	0.2	0.7	25.8	48	0.006
HMX (Cyclotetramethylenetetranitramine)	2.0	18.2	3.0	42.4	36.4		0.06
NG (Nitroglycerine)	1.6	15.9	2.2	18.5	63.4		0.04
EGDN (Ethyleneglycoldinitrate)	∼1.4	15.8	2.6	18.4	63.2		0.04
PETN (Pentaerithritoltetranitrate)	1.75	15.7	2.6	18.4	63.2		0.044

Table 2. Characteristics of Principle Commercial Explosive Compositions

Explosive	Composition	Specific Gravity	Comments
Dynamites	NG/EGDN and wood flour	.75 - 1.1	Often contain AN.
Gelled slurries	AN in saturated AN solution and sensitizers	1.1 - 1.3	Sensitizers include flake Al, glass microballoons, chemicals such as $H_3CNH_3NO_3$ and $CH_2OHCH_2NH_3NO_3$
Emulsions	AN in saturated AN solution, emulsified with ~3 percent oil and sensitizers	1.1 - 1.0	Microballoons and flake Al are principle sensitizers
Boosters	TNT, PETN, HMX, AN	1.7 - 1.8	Highly variable compositions with TNT as base

Table 3. General Characteristics of Natural Materials

Material	Wt%					H
	Density	C	H	N	O	Density
Wood	<1	44.0	6.2	Low	49.0	~0.06
Water	1	0.0	11.0	0.0	89.0	0.11
Soil	1.1-1.5	Low	0.1-6	Low	High	0.001-0.06
Rocks	~2-3	Low	0.0	Low	High	

Table 4. γ-Ray Absorption Coefficients for Explosive Compounds and Compositions, 0.015 to 0.125 MeV, cm^2/g

Explosive	Density g/cc	0.015	0.060	0.080	0.100	0.125
HMX	1.90	1.368	0.187	0.169	0.159	0.149
RDX	1.82	1.355	0.185	0.168	0.157	0.148
TNT	1.59	1.266	0.183	0.166	0.156	0.147
NC a/	1.66	0.996	0.184	0.169	0.159	0.150
NG	1.59	1.480	0.186	0.168	0.157	0.147
Comp B (60/40) b/	1.67	1.333	0.186	0.169	0.158	0.149
Amatol (80/20) c/	1.46	1.470	0.191	0.173	0.161	0.152
Lead azide	4.80	82.70	2.552	1.216	3.900	2.640
Lead styphnate	3.02	75.10	2.40	1.220	3.516	2.460
Mercury fulminate	4.00	123.9	2.92	1.630	3.890	2.617
Tritonal (80/20) d/	1.70	2.61	0.202	0.174	0.156	0.149
KDBNF e/	1.98	1.31	0.185	0.168	0.157	0.148
Delay Comp (Type 2) f/	3.00	--	3.52	1.644	0.952	0.665
Black Pdr g/	1.88	29.21	0.310	0.218	0.181	0.163

a/ $(C_{12}H_{14}N_6O_2)n$

b/ RDX/TNT

c/ NH_4NO_3/TNT

d/ TNT/Al

e/ $KC_6H_4N_4O_6$

f/ 59-percent $BaCrO_4$, 14 percent $KClO_4$, 9 percent Zi/Ni (70/30) alloy, 17 percent Zr/Ni (30/70) alloy

g/ 74-percent KNO_3, 16 percent C, 10 percent S

Technological Advancements Potentially Applicable

Three recent technical advances potentially significant for AV mine and explosives detection were identified by the panel. They were: (1) a high-intensity, linear scanning x-ray source with a total scan range of nearly 3 m; (2) miniature 14-MeV neutron generators with relatively high output, capable of prolonged, continuous operation and having pulsed operation capability; and (3) portable computer systems capable of information and imaging processing that exceeds the capability of large fixed computer systems of a decade ago.

Many of the x/γ-ray based mine detectors considered in the past relied on a single source, whether an isotopic source or an x-ray generator. Even when imaging was considered, the constraints imposed by available sources severely restricted the options that were reasonable to consider. An x-ray source that could produce an intense beam and that could scan in a linear fashion along a line of a meter or more in length would allow for consideration of a number of promising approaches, particularly with respect to imaging.

These possibilities take on added significance when considered in the light of the substantial advances that have been made in computer technology, particularly in the areas of image processing and artificial intelligence. Advanced image processors, operating in real time, presently are available, and they are sufficiently small and low enough in power consumption that their successful application to the problem of mine detection must be considered assured. Combined with image recognition and other improvements in software that appear to be available in the near term, these systems provide an impetus to consider in a new light detection methods designed to provide imaging information.

Although neutron-based techniques have been extensively explored, the limitations of available sources play a constraining role in a number of instances. The development of high-intensity, sealed tube sources that have a substantial operating life and that may be pulsed at relatively high speed were thought to be a technological advance with substantial implications for mine detection, particularly if combined with some method of imaging and image processing.

TECHNIQUES RECOMMENDED FOR FURTHER STUDY

Within this section are discussed techniques that were considered by the panel to be worthy of further study and analysis. Each is discussed in considerable detail, particularly with respect to the anticipated limitations and the technical advances that would be required in order to achieve a practical system. The techniques are considered in order of the priority assigned to them by the panel, vis a vis:

- X-Ray Backscatter Imaging;
- Thermal Neutron Capture Gamma Ray Analysis;
- Neutron Thermalization; and
- Differential Collimated Photon Scattering.

The potential for development of a dual (or multiple) energy scanning x-ray source that would produce a real-time image suitable for interpretation and the identification of a mine buried to a moderate depth (less than 5 inches) was judged to be high. The further development of such a system into a field-worthy instrument appeared to be a formidable undertaking but technically feasible.

The use of thermal neutron capture gamma ray analysis was considered to have considerably less potential than the x-ray imaging approach, but several technical advances suggested that it had a moderate development potential. If it could be shown to achieve the major mine detection goals, then its further development into a fieldable instrument was viewed as substantially less risky than the x-ray imaging system.

Neutron thermalization was judged to have very low potential for meeting the goals for a general-purpose mine detector; however, it was observed that there were certain circumstances in which it could function effectively, particularly in desert regions. Because its development appeared routine compared to the two higher potential instruments, a modest effort to define its capabilities and limitations was recommended.

The technique described as Differential Collimated Photon Scattering is, in many ways, the ultimate extension of multiple-energy, x-ray backscattering techniques. Although this technique has a significant technical potential, the inherent technical risk was judged to be very high because no prior experiments could be extrapolated with confidence to predict the advantages of the technique.

X-Ray Backscatter System

The use of x-ray backscatter has been studied, and several prototype detectors have been developed for field study. Also, the field has been reviewed extensively (Roder and Van Konynenberg, 1975). The available data indicate that backscattering is limited to mines buried no more than a few inches. At greater depths, the higher energy x-rays required for penetration produce scattered x-rays, which are primarily a function of density; therefore, they provide little information about the presence of the mine. For a surface mine, a very low-energy x-ray source would be highly sensitive to the change in atomic number represented by a mine; but even a minimal soil covering would hide the mine. Thus, a medium-energy source represents the best compromise between depth of burial and detection capability.

The observed backscatter for the geometries of interest are largely the result of multiple compton scattering, although there are geometries in which single compton scattering is a major component. Because multiple scatter represents a majority of the information relevant to the presence of a low-atomic-number inclusion of limited size in a semi-infinite medium of higher-atomic-number, a low-energy source provides the greatest information content for surface-emplaced or shallowly buried mines. However, at burial depths of 2 inches or more, the penetration of the x-rays is low, absorption is high, and few of the observed backscattered x-rays are from the mine. A higher x-ray energy then becomes important in order to permit greater depth of penetration, a result that is achieved only at the expense of a decrease in the ratio of mine-scattered x-rays to soil-scattered x-rays. Consequently, the use of x-ray energies in excess of a few hundred keV appears to lack any advantage. Furthermore, this conclusion also has the consequence that mines buried deeper than about 4 or 5 inches will be effectively undetectable by x-ray methods.

One of the most serious of the problems that has limited the use of backscattering has been the inability to develop a practical means to overcome height sensitivity. This problem arises because the intensity of the detected x-ray is very sensitive to the distance between the source and the surface. Irregularities in the surface, caused by depressions, clods, rocks, and/or other features, make impractical the setting of a specific detector threshold to signal the presence of a mine. A variety of schemes have been advanced for solving the height sensitivity problem. One approach used a backscatter beta source. This scheme worked in the absence of vegetation, but even a few leaves confounded the results. Operating two identical detectors, separated vertically by a few centimeters, would, in principle, provide height information over a limited height range if both the detectors and source are collimated. The most direct approach is to employ two different energy sources sequentially. Because the x-rays from a higher energy source penetrate further, they will exhibit a different dependence on height than will x-rays from a lower energy source whose scattering is nearer the surface.

The use of an ultrasonics device similar to that used in automatic focusing cameras was suggested also, but it was observed that it probably would suffer from the same problems as the beta backscatter system. (NOTE: In the context of neutron backscatter, the workshop panel had considered the ultrasonic technique without arriving at this negative conclusion.)

Another means of providing height compensation is to operate two detectors, one of which has an x-ray filter. Choosing an appropriate combination of x-ray source and x-ray absorber results in the two detectors having different responses to height variations. The difference arises because of the change in the backscatter spectrum that is, itself, a consequence of the change in the angle between source and detector.

Earlier embodiments of the backscattering idea used various combinations of collimated sources and collimated detectors. The most elaborate schemes proposed the use of collimated sources and either collimated detector arrays or collimated, position-sensitive detectors. These approaches generally were limited to very slow scanning because of the inability to achieve the required source intensity. None accomplished the task of reducing height sensitivity to an acceptable level.

The study completed by SAI as a consequence of the Mine Detection Workshop held in 1973 (Ginaven et al., 1973) indicated that an imaging system might be capable of accomplishing most of the detection goals if the image were to be presented to an operator for analysis. This possibility appeared worthy of further exploration in light of several recent developments.

The primary requirements for an imaging photon scattering mine detector are adequate intensity and a geometry that produces an image that has a high probability of being recognizable as a buried anti-vehicular mine. Also, the problem of height sensitivity must be overcome, although for visual detection the problem is not expected to be as severe as it would be for a purely automatic alarm device.

The potential value of an imaging system was demonstrated in work carried out by Jacobs et al. (1979). The system employed a well collimated source and an uncollimated detector. Imaging was achieved by rastering the source/detector assembly. Because the source was collimated, the backscatter signal primarily was a measure of the first scatter. In the absence of either geometry or density variations, the presence of a lower-atomic-number inclusion in the path of the primary beam will result in a reduction of the photoelectric absorption part of the attenuation process and, consequently, an increase in the number of multiple scattered photons that escape from the surface and are potentially detectable.

This process is quite similar to the processes that occur in the usual mine detection geometries, in which an uncollimated or partially collimated source is used, because of the need to maximize the source flux. If detector collimation is employed, the geometry is highly sensitive to height variation. By contrast, the collimated source geometry will be less sensitive to height variations, particularly if the detector area is large. Because of the increased attenuation path at small angles with respect to the surface, the flux will decline rapidly at large angles, and, consequently, a detector area that is moderately large may exhibit a substantially reduced height sensitivity.

If incident intensity and efficient detection of backscattered radiation were the only criteria, the system would be relatively uncomplicated technically, although still representing a substantial developmental challenge. However, as shown in several studies (Coleman, 1971), an uncollimated detector will result in very poor discrimination. This expectation was demonstrated by Jacobs _et al._ (1979). The reason for this is that subsurface features whose effective change in absorption and scatter are smaller than the value of absorption and scatter resulting from variations in the surface from an ideal plane will be masked. In order to overcome this difficulty, a means of imaging the surface is required. Jacobs _et al._ (1979), achieved this by using a second lower energy x-ray source to form a second image. The essential procedure was to form two separate images, one at the x-ray energy from a 50-kVp tube source and the second at 100 kVp. Because the lower energy scatter is very dependent on surface features, the surface features could be removed by a weighted difference of the two signals. They suggest a generalization of the procedure to form "tomographic" backscatter images as a function of depth by employing multiple x-ray energies.

Obviously, the use of more than a single energy in the scan greatly complicates the x-ray source and the image processing. It also decreases the intensity available. The fact that a difference signal is being produced puts added stress on the need for statistical precision in the individual images and suggests the need for an increase in intensity. Nevertheless, the potential for mine detection, particularly mines buried to no more than about two inches, is great. The required image processing is already available in compact form, and an appropriate x-ray source is a likely possibility based on existing scanning x-ray sources.

The dual energy differential backscatter imaging has the added advantage that it provides some additional height compensation at the same time that it compensates for scattering from an irregular surface, thus making subsurface features detectable.

Although this procedure does provide some height compensation, the change in intensity as a function of height still represents a serious problem because, if a difference signal is being recorded, the individual signals have a different geometric variation as a function of height. Consequently, it may be necessary to provide some other method of height compensation to normalize the signals at each energy prior to providing the difference signal that results in the subsurface image. This is particularly likely if the height variations are large, as they were not in the work of Jacobs, et al.

In order to make such an x-ray backscatter imaging system practical, several requirements must be met. First and foremost is a source capable of producing a high-intensity scanning beam that would make a reasonable forward rate possible. The characteristics of such a source can be estimated roughly as follows.

The forward velocity must be no less than 3 mph (1.35 ms^{-1}) and cover a width of 10 feet (3 m). This is a scanned area of 4.08 x 10^4 cm^2 s^{-1}. If the scanning beam had a size equivalent to 1-cm-x-1-cm, the line scan rate would have to be 134 per second, or a single line scan time of 7.5 ms.

If the spot size were increased to 2-cm-by-2-cm, then the line scan rate would be 67 x s^{-1}, and a single scan would occur in 15 ms, resulting in a dwell time of 100 μs per pixel.

An existing medical x-ray source (Cann, 1985) that uses an electron beam to scan a target that is 3 m in extent has a single scan time of 50 ms and operates at a scan rate of 17 s^{-1}. This x-ray source operates at 130 kV at a beam current of 800 mA. In principle, the scan could be continued indefinitely. So long as the beam current of 800 mA is not exceeded, the scan rate can be increased, limited only by the beam sweeping electronics.

Assuming a collimator on the source that results in an approximately 2-cm-x-2-cm source size at a source-to-surface distance of 15 cm, there would be about 5 x 10^9 photon incidents on each pixel. Based on prior studies, the average fractional intensity of the total backscatter is about 10^{-3}. Using an uncollimated, large-area detector, perhaps 0.1 of this flux could be detected. Because no elaborate information processing is required, the 100-μs per pixel given above is quite adequate for any desired processing.

If the source must provide two energies, as is expected, then the constraint of changing the high voltage further burdens the source intensity, scan rate, and image processing time. (NOTE: In a later section [Differential Collimated Photon Scattering], the use of multiple energies in a similar geometry is discussed. Although it was not explicitly applied to the ideas discussed in this section, the potential is apparent and was mentioned in passing by Jacobs et al. in their 1979 report.) It was plausibly assumed that the use of two separate x-ray sources of different energies would be impractical even if separate x-ray detectors for high and low energy x-rays were postulated. Consequently, the scanning source would be required to operate at twice the scan rate and to "fly back" to its origin for each scan in order to provide constant scan line spacing.

For a pixel size of 2 cm, the location of the two pixels interrogated by the same x-ray energy might be separated by 4 cm. A significant change in material (soil) properties might occur in this distance; consequently, a line averaging scheme might be needed prior to subtraction of the two energy-separated images.

Various schemes for averaging alternate scans prior to subtraction are conceptually simple and easy to implement. Optimization of them and the subtraction algorithm is far simpler based on experimental data and was not pursued by the panel.

Based on this dual-energy concept, the total photon intensity incident on each pixel area would be 2 x 10^9, the detected intensity would be about 2 x 10^5 per second, and each pixel would be observed for 50 usec. If there are 150 pixels per line and the width of an image is 50 cm (50 total scan lines), the total number of image elements is only 7500. Because the total number of photons per pixel is small, the total memory requirement is very modest. On the other hand, each line in the image must be shifted by one line every 15 ms. Obviously, the processing of the corresponding pixels from succeeding scans must be done in parallel, a procedure that is well established.

The detector for this scheme must satisfy a number of significant requirements. It must be relatively sensitive if a high statistical inference is to be achieved. Also, it must cover a large size, i.e., it must be approximately equal in efficiency over the full scan range. These requirements potentially may be met by a variety of detectors or detector systems. Because the backscatter radiation consists of low-energy photons, fluorescent screens in conjunction with photodiode arrays are a possible choice. Such combinations have been used in other applications. There is insufficient information available to determine the practical potential of this choice.

Types of detectors that were considered potentially useful included plastic scintillators, liquid scintillators, and Xenon-filled gas scintillation counters, as well as long cylinders coated internally with fluorescers and viewed by a pair of photomultipliers.

Another possible choice consists of a detector/photodiode array, where the detector itself is some form of scintillator. Although the use of photomultipliers is possible, the advent of low-noise amplifiers for photodiodes have rendered them obsolete for most applications.

The detectors whose characteristics are best known for applications similar to the imaging backscatter mine detector are the solid, crystalline scintillators $BiGeO_4$ and $CdWO_4$. Both exhibit the desirable characteristics of high efficiency and low afterglow, the latter being particularly important for high scan rate operation in which detector current is measured and digitized. A single detector 3m long is unlikely to be practical, although a Xenon-filled gas scintillation detector with photomultipliers at each end might be feasible. The more likely approach would use an array of detectors spaced along the source. The detector response function as a function of location of the source would correct for response variations. A relatively small number of detectors would be sufficient for complete coverage.

Whether a pulse-counting detector or a current mode detector is employed is based on the x-ray intensity available, but current mode was considered to be a better choice if the available x-ray intensity could be made sufficient, which seems likely. There appeared to be no advantage to the use of crystal scintillators, and the consensus was that the simplest systems, such as a fluorescent screen or plastic scintillator/photodiode array, would be preferred.

The panel considered the differential x-ray backscatter imaging approach to have a substantial possibility for application to the mine detection problem and to be the most promising of the techniques explored during the workshop.

A feasibility study of the technique would answer a number of the elementary questions that are still outstanding. Such a study should address the following questions:

1. What are the optimum x-ray energies that yield high detection probability over a range of burial depths?

2. What is the largest practical pixel size that will result in a high detection probability?

3. What is the variation of intensity with height, and can it be compensated for effectively?

4. What are the practical requirements for x-ray source intensity, detector size, detector efficiency, and other initial system parameters?

5. What range of soil parameters can be tolerated by the system?

6. What type of expected artifacts (rocks, roots, scrap metal, clods, holes, etc.) will result in false alarms?

These are generic questions that must be answered in a general way before a more detailed design and development program could be embarked upon.

The dual energy differential backscatter technique has some inherent limitations. The scan rate (area per unit time) as a mine detector will be limited by a number of system parameters, several of which will be quite resistant to substantial improvement. The x-ray source is the primary limitation. In the scanning system discussed, a continuous power dissipation of about 10^5 watts is projected. This relatively large power is dissipated in a liquid-cooled target with an area of 300 cm^2, a value that is achievable with present technology; however, an order of magnitude increase appears to be out of reach.

An x-ray source of this type will present formidable practical problems for a field device. In addition to the power handling requirement, there is the necessity of maintaining a high vacuum in a large volume. The existing x-ray source uses active pumping to achieve the required vacuum. It is unlikely that the sealed tube approach will be feasible for this source. Even if much larger power handling capability were possible, the beam handling problems would be severe, and accomplishment of it in a transportable system is likely to be a formidable prospect.

Perhaps the most limiting area is the requirement of operator interpretation of the changing image field. Although image analysis and recognition carried out by a computer and software conceivably will replace the human operator, this transition cannot be expected within the foreseeable future, particularly if a transportable system is involved. Interpretation in real time is a considerable problem, even though it is a necessity for practical applications. Consequently, the panel recognized that such a system would have to be remotely operated in order to ensure the safety of the operator and interpreter.

Thermal Neutron Capture Gamma Ray

Detection of nitrogen based on the 10.8-MeV from the $^{14}N(n,\gamma)^{15}N$ reaction is a technique that has received a great deal of attention beginning in the 1950s. The method has always been viewed as being an attractive technique because it seemed to be substantially more specific for explosives than alternative approaches. In the historical review prepared by SAI (Coleman et al, 1974), all the available data were examined. This review was not encouraging, but it did lead to some questions about the validity of these early results and also led to a new experimental study carried out using a 50-cm^3, high-resolution Germanium detector.

This study, done by SAI, employed an extremely favorable geometry in which the source was 1 inch above the surface, with the mine consisting of 9 pounds of NH_4NO_3 buried 1.5 inches below the ground. The detector was shielded and collimated so that its field of view was restricted to a relatively small solid angle centered on the mine. Although not stated, a detector of this type would be likely to exhibit a resolution of less than 2 keV at 1.33-MeV and a resolution of less than 6 keV at 10.8-MeV. The spectra presented by SAI appear to have a resolution of about 50 keV. This is not explained in the text of the report.

Orphan has re-examined these results and presents calculations based on the use of a $BiGeO_4$ detector (see attachment). These calculations are in general agreement with the earlier results obtained with a Ge detector. In either case, the detection capability would appear to be sufficiently good to make the claim that thermal neutron capture gamma ray analysis would be a viable option for detection of nitrogen and, hence, explosives.

The assessment is mitigated by the following observations: (1) the total count rate capability of the detectors considered is limited by inherent detector time constraints and preamplifier/amplifier time constants to values that are relatively small, less than 3 x 10^5/s, and cannot exceed 1 x 10^5/s without introducing significant pile-up effects. Given a detector system that is highly collimated, the data of Coleman <u>et al</u>. (SAI, 1974), implies a spectrum total count rate to total nitrogen 10.8-MeV gamma peak count rate in excess of 3 x 10^3. The earlier data of Powell and Matthews (1973), using a large (5-in. diameter by 4-in. length) NaI(Tl) scintillator, a 30-lb high-explosives sample, and an idealized geometry (an 8-in. thick lead collimator) resulted in a spectrum total count rate to nitrogen 10.8-MeV peak total count rate in excess of 1.5 x 10^4, and a ratio of 0.5 for the counts in the nitrogen peaks to the background counts under the peak. However, this value must be tempered by the possibility that the high reported value came about because of a lack of adequate shielding between the ^{252}Cf source and the detector. If this count ratio is adjusted for the greater efficiency of a 3-in.-x-3-in. BGO detector, a spectrum total to nitrogen peak count rate of 3000 is obtained. For an absolute count rate limit of 3.0 x 10^5, then in the 0.2-s sweep time required, the total counts expected in the nitrogen peak area would be about 20. Based on a count rate of 300,000/s, a pulse pile-up and peak-shape discrimination system with a resolution of 0.1-μs would contribute 5 to 10 counts per second to the region. This value is consistent with the data of Powell and Matthews (1971).

Although the use of BGO has advantages because of its high efficiency, its lower resolution would seem to pose an additional problem. Because the peak is broad, pile-up background will contribute twice the number of events that would be seen with NaI(Tl). The large NaI(Tl) scintillator used by Powell and Matthews had sufficient resolution to resolve the 10.8-MeV full energy and first escape peaks from the background, although the existence of a background at all is a serious limitation. The lower resolution of a BGO detector will make compensation for this inevitable background more difficult. It seems reasonable to assume that the background in the region of the 10.8-MeV peaks will have a significant impact on the ability to detect a mine. Thus, a signal-to-background ratio of 1:1, with a nitrogen-derived count of 20, would be inadequate because a threshold of more than 30 would be required to avoid almost continuous alarms. Even at this discrimination level, the number of alarms would be entirely unacceptable. Moreover, such a level would have a high miss rate (about 10 percent). V. Orphan was of the opinion that the signal observed in the 10.8-MeV region was free of background, but this was not the view of the panel as a whole.

The most significant improvement relevant to the detection of explosives through the detection of the 10.8-MeV gamma ray from the capture of thermal neutrons by ^{14}N is the development of electronic techniques that permit NaI and BGO scintillators to operate at rates 4 to 5 times the upper limit possible in 1973. This increase has a significant impact on the potential of the technique. Based on a maximum rate of 10^5 s^{-1} and a peak-to-total ratio of 1:1000, using a large (4-in.-x-5-in.) NaI(Tl) detector, a total of 25 counts would be recorded, of which about 12 would be in the full energy peak. Such a result was judged by Reynolds et al. (1974), as not likely to be developed into a practical system. If a count rate of 3×10^5 s^{-1} is now practicable, as is assumed, the total count would be about 75, of which about 38 would be in the full energy peak.

If the peak-to-total ratio is as low as 1:3000, as seems possible, the above values would be reduced by a factor of 3. Thus, it is reasonable to conclude that if a peak-to-total ratio of 1:1000 is achievable with either a NaI or BGO detector, a system to detect nitrogen in explosives might be technically feasible. Even so, there would be formidable difficulties in the path to a practical system because of shielding problems. If the requirement of a 1:1000 peak-to-total ratio can be achieved only at the expense of collimation, the overall problem is exacerbated.

The panel reviewed the possibility of developing a practical system of mine detection with a degree of scepticism, but agreed that, in view of some recent developments, it could not be ruled out as a possible method. Although the additional data provided by SAI does modify the negative judgment arrived at by earlier studies, it does not provide a strong case, and practical feasibility of the method remains marginal at best in the judgment of the panel.

There is a second thermal neutron capture reaction in ^{14}N: the $^{14}N(n,p)^{14}C$ reaction. This reaction has a large cross-section. Unfortunately, it produces no gamma rays, and the beta radiation from ^{14}C has a half-life of more than 5000 years. In any event, beta rays have such low penetrability in matter that they could not be detected. This panel unanimously agreed that this possibility should be dismissed from consideration.

In order to clarify some of the unanswered questions regarding the practical feasibility of the thermal neutron capture gamma ray technique, a carefully designed program would need to be carried out. This program would focus on setting up an experimental procedure that could replicate with a reasonable degree of precision typical field environments. It is particularly important that buried mines (or simulants) be arranged so that they can be removed and replaced with soil in a systematic and repeatable way.

Critical questions to be answered are the maximum neutron flux requirements, the signal-to-background ratio achievable, statistical adequacy of the information, and the effects of mine type, burial depth, soil type, soil moisture content, and geometry (height variations) on the ability to provide high assurance of the presence of a mine without excessive false alarm response.

The recognized limitation of this technique is the neutron flux necessary to produce a sufficient signal to result in an alarm with low false alarm probability. This requirement is intimately connected with the detector ability to operate at a very high pulse rate with reasonably high efficiency at the 10.6-MeV photon energy of the gamma ray from ^{15}N, and to have an adequate resolution to provide the required signal-to-background ratio. The latter is dependent on the electronic pulse pile-up discrimination, along with the intrinsic response time characteristics of the detector. All of these parameters interact in a complex manner that can be predicted, but there are sufficient variations in the estimates made for each of the parameters to preclude a precise calculation of the overall result.

The intense source of neutrons required for this technique represents an additional area of concern. Such a source (about 10^{10} s^{-1} of 14-MeV neutrons) is extremely hazardous. Although the neutron flux is completely absent when the machine is not activated, in normal operation personnel would have to be excluded from a substantial area (more than 50-m radius), and the system probably would require a remotely operated vehicle.

Materials exposed to the neutrons would become activated so that eventually the vehicle and ancillary equipment would have a significant level of radioactivity. Aluminum and copper would pose potential hazards after prolonged (8 hours), continuous exposure to the neutrons being generated. This problem could be dealt with if the technique proved to be technically feasible and practical.

Neutron Moderation

Compared to typical soils, explosives contain a relatively high percentage of hydrogen. This has led to an interest in the use of neutron techniques that exploit the fact that hydrogen efficiently scatters and thermalizes fast neutrons. Several devices have been employed to study the effect of replacing soil with a quantity of explosives (1,2). These have been either adaptations of existing neutron logging devices or specially designed devices. The operating principle is straightforward. A detector sensitive to thermal neutrons (usually a BF_3 or ^3He filled gas proportional counter) is placed near, but shielded from, a source of fast neutrons. As the device passes over the ground, the thermal neutron albedo from the ground changes with the hydrogen content of the material beneath the neutron source. This simple approach has been shown to exhibit a number of significant limitations. In the first case, a strong height sensitivity is apparent. Several methods to overcome this problem have been explored. The use of beta radiation backscattering proved inappropriate because leaves and other low-density vegetation are equally as effective at producing a signal as soil, and changes in soil composition also change the backscatter intensity. The panel considered the use of a simple sonar device (such as found in some cameras), but was unable to determine if a similar reflection problem might not occur. The use of low-energy x-rays ($\sim$50 keV) was thought to be a better choice because it could penetrate low-density vegetation and would not penetrate soil significantly. No data relating to the use of x-rays for this purpose was presented by any of the panel members, although the principle itself was considered to be sound, and data on x-ray backscatter at x-ray energies below 100 keV is available. An x-ray backscatter mine detection research program carried out by Industrial Nucleonics in 1973 (Thompson, 1973) attempted to overcome the height sensitivity of the x-ray backscatter technique by using a pair of detectors, one of which has a Europium filter (k absorption edge 48.5 keV). In the geometry used, both the spectrum and the total intensity of backscattered x-rays varies with height. Consequently, the two detectors had responses as a function of height that were appreciably different and could be used for height compensation. This technique could be applicable to the neutron moderation technique.

The other major problem is the fact that soil hydrogen content is so highly variable that it spans the range of explosives and extends significantly beyond it. The explosives RDX and TNT contain 2.7 percent and 2.2 percent, respectively, of hydrogen. By contrast, an arid, sandy soil might have a hydrogen content of 10^{-3} percent, while an organic soil following a rain might have a hydrogen content of 5 percent.

Early efforts to use neutron moderation as a means of discriminating explosives buried in soil were unsuccessful. Van Konynenburg and Roder, 1970, report that a bowl of water (11-percent hydrogen), buried 2 inches below the soil level, could not be detected, although surface moisture changes were readily detected.

In a recent study reported by Buhts, Malone, and Cooper, 1985, two different mines were buried to depths of 2 cm, 4 cm, 6 cm, and 8 cm. The hydrogen content of four specimens of soil ranged from 1.5 percent to 2.5 percent. All of the data were recorded with the source/detector in contact with the soil, thus removing any variation in results attributable to height. Twelve individual random traverses across the location of a mine were made, each traverse beginning 4 feet from the mine and terminating 4 feet beyond the mine. Using only the data at a distance of 2 feet or more from the mine, some useful information regarding the variation in recorded counts (and, hence, average soil hydrogen content) can be developed. This data is essentially the background hydrogen variation that can be expected for a typical moderately dry soil. The data have been collected and are plotted as a histogram of frequency versus counts falling within 50-count intervals (see Figure 1). Based on this data, the variation in expected counts is very high. Thus, the probability that the

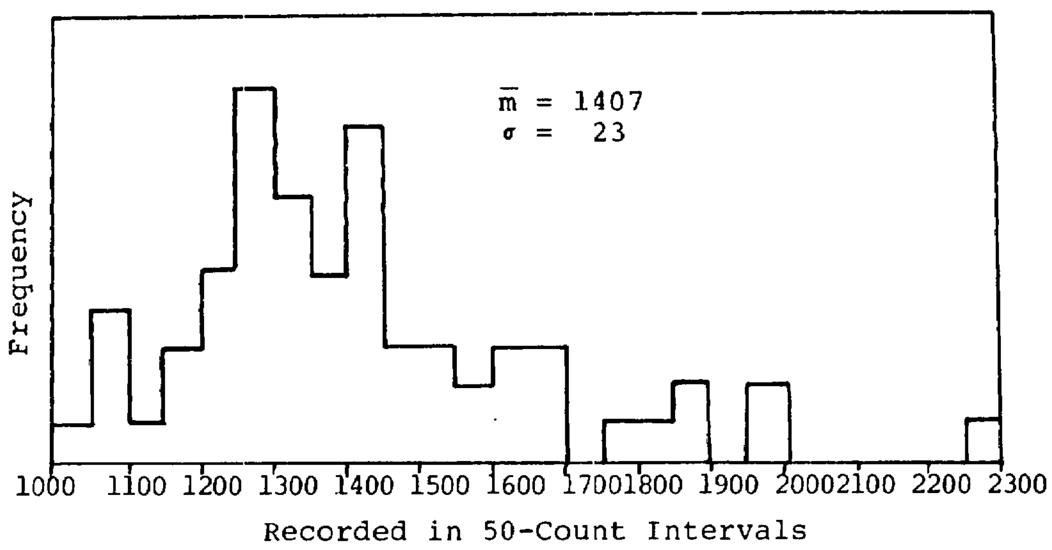

Figure 1. Distribution of Counts in 50-Count Intervals for Data Recorded in Undisturbed Soil

recorded counts will exceed 2100 in the absence of a mine is about 0.135 percent.

The number of counts for one mine (VS-16), buried to a depth of 1 cm, was 2277 and 2308 for two trials. When this mine was buried at 2 cm, the counts for two trials were 1991 and 1966. At 4-cm burial, the nine trials gave results that ranged from 1595 to 1741. Deeper burials resulted in an average count of 1542 at 6 cm and 1254 counts at 8 cm. These latter two results are most likely entirely the result of the soil and not the mine itself, based on a simple calculation of the known thermalization lengths for fast neutrons in water and adjusting for the effective average density of water in the soil.

If the soil conditions of this study prevailed in most situations, then if a missed detection probability of 5 percent is tolerable (i.e., a one-sided deviation of 1.6σ), then a threshold of 2260 could be set. The probability of producing a false positive is then about 0.7 percent, perhaps an acceptable result. If the interrogated area is 1 ft^2, there would result one false alarm for each 1400-ft^2. For the 2-cm burial, the results are much worse. For a miss probability of 5 percent, the detection threshold would have to be set at 1908 counts. Consequently, the probability that a false alarm would occur is the probability that the counts in an unmined area would exceed the mean by 2.1σ, or about 1.6 percent. This is equivalent to one false alarm for every 63 ft^2 interrogated. For a second mine (Pt-Mi-Ba), even for a burial depth of 1 cm, the false alarm rate for any reasonable detection probability would be high because the two recorded counts were 1938 and 2033.

In practice, the soil moisture content could be higher than the values observed in this study, and, hence, the background counts would be higher, a result that would make the detection of a mine under any conditions problemmatical.

If the soil becomes saturated, then the mine acts as a hydrogen deficit. In this case, the mine would be detected as a count decrease. Although such a possibility was recognized, it did not appear likely that this situation would be commonly encountered.

A second serious problem is the presence of puddles of water and the rapidly changing moisture content after a rain storm. In this situation, the system is essentially unusable because no level can be established.

The possibility of discrimination based on shape was discussed, but there seemed to be little likelihood that this additional information, if it could be obtained, would substantially alter the unfavorable results obtained in these two studies. Consequently, the panel was unenthusiastic about the prospects of this method.

The anticipated limitations of the neutron moderation technique did not encourage the panel to recommend further extensive exploration of the technique; however, it was recognized that in dry, sandy soil, the method could be an efficient means of detecting mines. A very modest program to explore this possibility was recommended. Also, it was thought that some additional study to define the limitations of the method in other soil types might be useful to place the method's limitations in perspective.

Differential Collimated Photon Scattering

In the backscatter geometry ordinarily used for mine detection, multiple scattering dominates the information-bearing return signal. The energy usually is relatively low in order to maximize the signal, and single scatter cannot be separated from multiple scatter. If, on the other hand, the system is configured so that a collimated beam is incident normal to the surface, and a collimated detector interrogates a volume at a specific level below the surface, and if the energy is sufficiently large that the single scatter peak can be separated from a multiple scatter peak, then a direct measure of the density of the volume interrogated is obtained, so long as the attenuations of the incident beam and the single scatter beam remain constant. Unfortunately, this latter condition is unlikely to be met in any practical mine detection scenario. A way to overcome this limitation is to have a series of collimated detectors, arranged in a vertical array, each interrogating a different volume. If the array contains a number of small detectors, then there will be one detector that will receive a return signal while the one just above it will record no signal because its interrogation volume is air only. The detector that records a signal will measure the density of the soil in its interrogated volume. From this datum the attenuation for the incident beam and single scatter beam for the next lower volume can be calculated, assuming that the density is constant over the volume. This procedure could continue to as great a depth as desired so long as the lowest detector receives an adequate single scatter flux.

The above scheme functions as desired so long as the average atomic number in the soil remains constant over the volume being interrogated. If a significant shift occurs, such as having a thin surface layer that is high in organic matter above a lateritic soil that has a high iron content, for example, then a more complex scheme using two energies would be required. The second energy would be a relatively low energy. Combining the two results would, in principle, provide a measure of both the average atomic number and the density. In practice, this method will not function well because the lower energy x-rays will produce single and multiple scatters that will not be separated. Because the inference of atomic number is dependent on the single compton scatter, the multiple scatter component will largely obviate the general possibility of achieving the desired result. Although the multiple scatter component contains information on both atomic number and density, the source of the multiple scatter is not well characterized, and the data will be the average of a much larger volume than that of the intersection of the source irradiation and detector volumes in the soil.

If the effect of a varying soil atomic number can be ignored by assuming that its variation is small, the system required to implement the idea described would be a large undertaking. Instead of a single column of detectors, each with a focusing collimator and a single focusing source, this arrangement would have to be duplicated many times in order to cover an adequate width. A rough estimate suggests that a vertical array of eight detectors, each 2 cm in diameter, might suffice for a single column. This array would have to be duplicated at 5-cm intervals over a width of about 2 meters. Thus, some 240 detectors and 40 sources would be required.

The technical difficulties are quite large in other respects. For a 400-keV source photon penetrating 10 cm of soil undergoing a 120^{0} compton scatter, and the resultant 200-keV photon then penetrating 15 cm of soil, the probability that the original photon will result in a detected event is about 3×10^{-8} for a soil of density 1.5g cm^{-3}. If detection must occur in about 0.25 s, and at least 100 events must be recorded to achieve reasonable statistical precision (zero background and the occurrence of a positive signal for a mine from several contiguous locations are assumed as the means of achieving low false alarm), then the source flux at the intersection point would have to be 1.3×10^{10} s^{-1}. If the source were 10 cm above the surface, the total distance would be 20 cm. Assuming an irradiated area of 3 cm^2, the total source strength would have to be 1.6 x 10^{13} s^{-1} (about 400 Curies). A ^{137}Cs source of this size could be achieved, and a source of about 100 Ci could accomplish the same end if an efficient focusing collimator could be fabricated. Forty such sources would be required, resulting in a minimum source strength of 4000 Curies. Shielding such a system would result in a substantial mass and considerable complexity.

Alternatively, several x-ray tubes operating at the normal upper limit of about 320 KVP, heavily filtered to produce a peak at about 250 keV, might be a possibility.

In either case, the source required would present formidable difficulties. Although the panel agreed that such a system was theoretically possible, the members considered that it had lesser promise than did the alternative method of dual energy backscattering discussed earlier.

A feasibility study to assess this concept could be carried out using a single collimated source and collimated detector. The major question to be answered is whether this concept will achieve the discrimination suggested for it. Prior to carrying out an experiment, an analysis of the operation of the system should be done based on the substantial body of data already available for scattering of x-rays from soils. These experimental data and the known scattering cross-sections would allow an essentially complete assessment of the fundamental potential and anticipated limitation of the method.

As pointed out above, the number and size of the individual source is a matter of concern. Although individual sources apparently can meet the requirement, the system would be complex. Meeting a minimal speed requirement would be difficult with any combination of sources and detector. The statistical demands would be relatively severe in order to minimize false alarms. Although the scheme seems to solve the height sensitivity problem, the problem of response to other objects remains as a potential source of false alarms.

OTHER TECHNIQUES CONSIDERED

None of the following techniques were considered to have sufficient promise to merit further experimental or analytical study. In most instances, it seemed unlikely that even substantial advances in technology would alter this negative evaluation. In a few cases, notably x-ray fluorescence, it was thought that the possibility existed that a substantial advance in technology could alter the negative assessment, but that such an advance was not presently foreseeable.

Fast Neutron Reaction Techniques

Fast neutron techniques were reviewed in light of advances in neutron source availability and the applicability of advances in signal processing.

The development of highly reliable, small, sealed tube d-t, 14-MeV neutron generators provided the impetus for this re-evaluation. It was speculated that improvements in signal processing would result in an advantage for fast neutron reaction techniques, but no specific role for advanced signal processing was presented.

Several earlier studies on fast neutron reactions were pointed out, and it was agreed that reactions that used oxygen as the target nucleus were inappropriate because of the ubiquitous nature of the presence of oxygen at concentrations comparable to those common to explosives. The consensus was that oxygen was inapplicable as a means of signaling the presence of explosives.

Nitrogen, on the other hand, is present at high levels in explosives of military utility. The concentration in RDX is 37.8 Wt% (highest), and in TNT it is 18.5 Wt% (lowest). For RDX in particular, the nitrogen content is high compared to most naturally occurring substances. For TNT, the nitrogen content is comparable to that in protein, but the density is substantially higher. Thus, nitrogen appears to be a reasonably likely signature for these explosives.

Various fast neutron reactions were considered (NOTE: These reactions and others were reviewed in considerable detail in Coleman, et al. (1974). Among the more likely were the $^{14}N(n,2n)^{13}N$ and the $^{14}N(n' \gamma)^{14}N$. The first of these reactions results in a positron-emitting nuclide with a 4-s half-life. A secondary emission of very low abundance is a 6.4-MeV gamma ray. The latter is detectable with good efficiency, but three serious problems mitigate against practical application of the reaction. First is the reduction in speed engendered by the necessity of recording events for a significant fraction of a half-life. The second problem is the very large background resulting from gamma rays from thermal capture. Even using high-resolution detectors, the large background present represents a substantial problem in distinguishing the desired gamma ray. Third, in addition to the general background caused by compton scattering in the detector, there are gamma rays from thermal capture in iron and silicon that will be indistinguishable from the gamma rays from ^{13}N. Because these thermal neutron capture reactions have a large cross-section compared to the fast neutron reactions of interest, the detection of nitrogen by this means appeared unpromising.

In the case of the second reaction, only the prompt radiation from the excited states of ^{14}N would be useful. The most abundant gamma ray lines are 2.31 MeV and 1.63 MeV. However, there are numerous other nuclides that would produce similar gamma rays upon being irradiated with neutrons. The objections raised above would apply to this reaction also.

Several earlier studies were discussed, and it was pointed out that the presence of copper resulted in a strong interference for detection of ^{13}N because ^{14}Cu has large production cross-sections and decays by positron emission, as does ^{13}N. The 2.3-MeV gamma ray from the $n,n'\gamma$ reaction is strongly interfered with by similar energy gamma rays from many other inelastic scattering reactions and also from gamma rays resulting from neutron capture.

This technique appeared to offer little potential, and no new or emerging advance in technology seemed likely to be so directly relevant as to change the negative consensus of the panel.

Neutron Inelastic Scattering

Among the isotopes of nitrogen and oxygen that are major constituent atoms in most explosive molecules, several undergo inelastic scattering reactions with fast neutrons. These reactions, particularly $^{12}C(n,n'\gamma)^{12}C$ and $^{16}O(n,n'\gamma)^{16}O$ produce strong gamma rays that might be used to identify the presence of a mine. Unfortunately, a strong gamma-producing reaction with nitrogen does not exist. The panel considered that the use of inelastic scattering did not show significant promise as a technique, primarily because the use of carbon or oxygen as the element to be detected was not specific to explosives.

This judgment is well attested to by the results achieved in several earlier studies. In particular, the work carried out by TNC showed that using carbon as the identifying signature led to many false alarms because of the presence of wood or organic material in the soil. Oxygen proved to be even less specific--most soils are composed primarily of the oxides of silicon and aluminum and calcium carbonates.

TNC used a large collimated, anticoincidence-shielded NaI(Tl) detector, and, later, a Germanium detector shielded only from direct fast neutrons. With this system, the 4.44-MeV gamma ray from $^{12}C(n,n'\gamma)^{12}C$ was prominent, but the background from many other inelastic scatter gamma rays and capture gamma rays was very intense also. In a practical application, the background dominated the spectrum, and the carbon line became a minor feature. A small quantity of wood lying on the surface resulted in a signal comparable to a large AV mine buried to 1 inch. Although the signal could be increased using a more intense source, the count rate limitations in the detector would not allow this approach to make the system practical, even if the problem of false alarms from wood or other carbon sources could be overcome.

Improvements in signal processing have resulted in substantial increases in count rate capabilities but fall far short of the factor needed. Furthermore, the fast neutron intensity required also is beyond present technology. Based on the TNC results, it would require a count rate capability of more than 10^6 s^{-1} and a pulsed neutron source of 10^{13} neutrons per pulse, with a pulsing capability of 10 s^{-1} (an average of 10^{12} neutrons/s). Neither capability is presently available or likely to be developed in the near future.

Photon Inelastic Scattering

Inelastic photon scattering can be considered in several contexts. In the simplest mode, various reactions may be considered. As with fast neutrons, the most likely approach involves reactions with nitrogen. Among these reactions are $^{15}N(\gamma,n)^{14}N$ and $^{14}N(\gamma,n)^{13}N$. The latter reaction produces the same 10-min half-life nucleus that was found to be unsuitable for detection of nitrogen with fast neutrons as a source. Essentially, the same objections will occur with inelastic scattering because nearly all of the nuclides that undergo n,2n reactions undergo γ,n reactions and with similar cross-sections.

A second possibility is to use lower energy photons to produce the $d(\gamma,n)p$ reaction. The photon threshold for this reaction is sufficiently low that very few nuclides will undergo inelastic scattering reactions. The neutrons thus produced have relatively low energy (less than a few MeV), will thermalize rapidly, and will produce capture gamma rays on reaction with ^{14}N. The detection of nitrogen through its capture gamma rays was discussed in an earlier section. In this section, the point of interest is the possibility of producing the required neutrons through the $d(\gamma,n)p$ reaction. This issue was discussed in detail by A. Barshall in the report of the 1973 Workshop (1). The major obstacle was considered to be the mass and power requirements of the gamma ray source (betatron) that would be required to achieve the necessary neutron production.

Although substantial progress has been achieved in betatron and electron linear accelerator technology, particularly the development of the wave-guide technique that permits the head itself to be separated from the mass of the generator, the necessary power is a substantial barrier. The consensus was that this approach did not merit additional study in comparison with the similar approach using a fast neutron generator with thermalization taking place in the soil.

An objection not discussed explicitly, but obvious, is that neutron production is dependent on the presence of hydrogen in the soil. In arid soils, the neutron production would be low and would make the detection of explosives substantially more difficult, and might make it impossible.

Neutron Reaction Using A Pulsed Neutron Source

The combined pulsed neutron experiment (CPNE) is an approach to bulk soil analysis that takes advantage of a variety of neutron-based techniques. Its purpose is to carry out such an analysis remotely. A pulsed 14.4-MeV neutron source allows a large number of independent measurements to be taken. The system operates as follows: a short (a few tens of microseconds), intense pulse of deuterons is accelerated to about 100 keV of energy and strikes a target containing tritium. The resulting d-t reaction provides a burst of up to 10^9 14.4-MeV neutrons. These fast neutrons undergo a variety of reactions. Following the burst of 14.4-MeV neutrons, a detector measuring the die-away of epithermal neutrons allows a determination of the hydrogen content of the surroundings. Simultaneously with this measurement and before a significant reduction of the neutron intensity has taken place, the energy of gamma rays produced by fast neutron inelastic scattering is recorded. After a suitable time period has passed (about 400 microseconds), most neutrons have reached thermal energies and are being lost due to neutron capture. The prompt gamma rays from neutron capture are recorded in this interval. At the same time, a gross gamma ray count rate measurement determines the rate of loss of thermal neutrons to provide an additional measure of the total neutron capture cross-section of the material. This procedure is repeated at a rate up to 100 Hz (usually limited to about 10 Hz).

The advantage that this method has over the use of a continuous source is that fast neutron reactions can be separated from thermal neutron capture reactions. A second advantage lies in the ability to turn off the neutron source when the system is not being used, thus eliminating the large shield that usually is required for isotopic neutron sources. An important disadvantage is that the 14.4-MeV neutrons that are generated are much more difficult to shield than the lower energy isotopic neutrons, thus placing a greater emphasis on safety during operation and probably requiring increased shielding for the operator.

The fundamental problems of using the CPNE approach are similar to those already discussed in connection with fast neutrons. These problems and others introduced by the pulsed neutron technique itself are so severe that it seems unlikely that the advantages of the CPNE approach would mitigate them sufficiently to make the likelihood of success a serious possibility, except that there is some consideration that using the CPNE approach in its thermal neutron capture gamma ray mode may have a greater possibility. However, Powell and Matthews (1973) have largely resolved this issue in the negative, as discussed below.

The total neutron output of an optimized d-t generator can be as high as $10^{11}s^{-1}$, but perhaps would be less by a factor of 100 in the pulsed mode ($\sim 10^{9}$ neutrons/pulse). Furthermore, the higher neutron energy compared to that from a ^{252}Cf isotopic source results in the neutrons being thermalized further from the neutron source. This causes a reduction of the thermal neutron intensity at the location of a mine. The combination of these two factors is likely to result in a signal-to-background ratio somewhat less favorable than would be obtained for a lower energy neutron source. The use of a pulsed source has a further, perhaps serious, problem. Because the detector is active for only a fraction of the time for a given number of gamma rays per second recorded, the count rate in the detector must be increased by the fraction of time that the detector is active, resulting in a requirement for an extremely large counting rate. Powell and Matthews (1973) vividly illustrated this problem. In the continuous mode of operation, no discernible N peak can be found. An approximate calculation based on average thermalization times in moderately wet soil suggests that the ratio of total counts to N prompt gamma ray counts in a 5-in.-x-4-in. NaI detector would be about 20,000. Thus, assuming a limit of 2.5 x 10^{5} counts/s and a duty cycle of 25 percent, the number of counts due to N would be about one in the 0.25-s period available for detection. This technique has a modest potential if a detector that combines high detection efficiency and high count rates (10^{6}/s) were available. Given such a detector, the pulsed neutron technique has the potential of competing with a continuous fast neutron source because of the reduction in gamma background from inelastic scatter reactions. It does not appear that this modest improvement offsets the general loss of intensity. Furthermore, the greatly increased technical requirements for the detector do not appear to be achievable with any existing or potential detector system.

The use of plastic scintillators is unlikely to be effective because of the steep slope of the efficiency-versus-energy curve. The use of an efficient detector at a count rate of 2 x 10^6 s^{-1} might be possible. Using the data of Powell and Matthews and extrapolating to BGO, a 10^9 burst of neutrons integrated from about 50 microseconds after the pulse to 1 millisecond after the pulse would produce about 100 counts in the full energy and first escape peaks. The background counts from all events are difficult to estimate but would arise primarily from pile-up. (The description of the experiments of Powell and Matthews does not indicate a shield was placed between the ^{252}Cf source and the detector, although such an oversight does not seem likely.) Based on extrapolation from experimental data and calculation, a value between 50 and 150 is about as precise as the estimate can be made. At the lower value, the system has a modest possibility of feasibility, while at the upper end of the range the feasibility is marginal. However, this is predicated on the existence of an efficient detector capable of operating at count rates exceeding 10^6 s and having essentially negligible pile-up (i.e., a light decay curve of less than 100 nanoseconds). Such a detector does not exist, and such a development is not evident in the immediate future (5 to 10 years).

X-Ray Fluorescence Detection of Lead

The potential for lead detection as a means of confirming the presence of a detonator was considered. (Note: Military fuzes (detonators) use either lead styphnate or lead azide as the initiating charge. A typical fuze contains 50 to 100 milligrams of lead.) Although free machining brass and a number of aluminum alloys contain up to 2-percent lead, the possibility of locating a concentration of lead in an area already considered suspect was thought to have merit. An earlier study by SAI was reviewed for applicability. This study was aimed at the use of other heavy metals ("taggants") deliberately introduced into commercial detonators because of the severe problem of false alarms resulting from the abundance of lead-containing items expected to be found in checked luggage--the problem being addressed.

Miller, et al. (1978), concluded that, for 100 mg of heavy metals present in a 1-cm^2 area, the source/detector requirements for detection within a few seconds were quite severe.

For typical luggage, the average thickness, density, and atomic number would be less than for soil; hence, the backscatter intensity would be less than for soil. In the more favorable luggage situation, the backscatter-to-fluorescent radiation intensity ratio was more than 10^5:1. Miller, et al., concluded that, in order to meet the constraint of 90-percent detection assurance in a few seconds, 10 detectors of 10-cm^2 area each, capable of operating at 10 times presently achievable rates of 10^5 s^{-1}, would be required. The detectors also must maintain a resolution of 80 to 100 eV, requirements that can be achieved only with Germanium detectors cooled to about 100°K.

The mine detection scenario would allow some modification in this pessimistic assessment. In particular, the source of fluorescence excitation could be collimated, resulting in a less severe backscatter-to-fluorescence radiation ratio. The detector then could be collimated so that it observes only the relatively small volume being interrogated by the source. If the irradiated area is about 2 cm^2, this arrangement would reduce the backscatter-to-fluorescence radiation ratio by a substantial ratio. An approximate calculation based on data published by Roder and Van Konynenburg (1975) suggests that the ratio would be about unity in the case of 100 mg of lead buried at 2 cm if the lead is irradiated by a source with an average energy of 90-kV (about 250 kV peak). To be useful, such a system would have to record a minimum of 100 lead x-rays in a period of 10 s, or approximately 10 counts per second. In the event that a backscatter-to-fluorescence ratio of 10 could be achieved, the detector would have to operate at a rate of only 100/s, a value readily achieved.

The major practical difficulty with this approach, assuming that the technical problems are solved or solvable, is that the location of the fuze must be known with exquisite precision. If the fuze location is known only approximately so that an area of 10-cm-x-10-cm had to be viewed, the detection problem becomes very severe. In this case, the whole area might be irradiated and viewed with either a single uncollimated detector or an array of collimated detectors. The technical problems rapidly become substantial if a reasonable time of interrogation is maintained.

In the case of a single uncollimated detector, the background-to-fluorescence ratio could be more than 500, and the total number of counts would have to be 5 x 10^4, or a count rate of 50,000 s^{-1}. A second problem is the large changes in background that occur because of height, soil density, and burial depth variations. Because the detection of the lead k and k x-ray fluorescence will depend on a background subtraction, these variations will have a very significant effect.

These effects could be reduced by using a highly specific source energy. Baker and Moler (1972) used the 88.2-keV gamma ray from

^{109}Cd. The energy of this gamma ray is only 0.1 keV above the lead k absorption edge and made possible the separation of the lead x-ray fluorescence lines (particularly the k_β lines) from the backscatter radiation in this open collimated system. They considered the possibility of producing an x-ray generator source of similar quality by secondary fluorescence, but the practical possible fluorescers are limited to thorium and uranium, both of which would produce abundant backscatter in the region of the lead x-rays. It was considered that thorium might be marginally acceptable. The additional background resulting from scattering of the primary x-ray beam by the secondary fluorescer was not considered, but, unless additional filtration is used, it will contribute significantly to the backscatter spectrum.

Although the panel concluded that x-ray fluorescence was worthy of further study in the role of a verification method if it could be used in conjunction with a technique such as x-ray backscattering by employing the same equipment, a number of issues were raised that needed clarification. R.B. Moler was charged with re-evaluating the ideas in light of the work done earlier by Baker and Moler (1971) and the extensive study of Miller, et al. (1978). The preceeding evaluation is the result of this further analysis. It concludes that the potential applicability of the x-ray fluorescence method is very low and does not merit additional experimental studies. This negative evaluation is a consequence of the difficulty of achieving an adequate fluorescence-to-backscattering ratio for a practical geometry, and the related result that to overcome the signal-to-background problem involves the use of an intense, highly specific (and unavailable) x-ray source and the ability to locate the lead of a fuze to within about 1 cm. This latter criterion seems to be impractical in a system where the vehicle would have to come to a halt and the x-ray source and detector positioned precisely in order to carry out the required verifications.

Based on these considerations, it does not appear likely that the use of x-ray fluorescence would be a practical means of verifying the presence of a mine, unless the location of the fuze could be found precisely so that a collimated source could be used.

Accelerated Particles

The use of accelerated particles was considered by the panel, but it was concluded that it had little relevance to the problem. This judgment was based on the observation that charged particles penetrate soil to a very limited extent, even if accelerated to an energy of 100 MeV. Neutral particles (excepting neutrons) of similar energy are immediately converted to charged particles upon entering soil (or after passage through a short distance in air) and penetrate a short distance before being stopped.

In addition to their lack of penetration, no nuclear reaction or other interaction was suggested that could be used to identify explosives.

The panel was unanimous in concluding that the use of accelerated particles offered no identifiable possibility for explosives detection.

OTHER POSSIBLE TECHNIQUES

Several other techniques were discussed by the panel, but the conclusion in each case was that they have little potential. A few of the more important ones are summarized here.

n,2n and n,p Reactions on Carbon, Nitrogen, and Oxygen. Fast neutrons produce n,2n reactions on the principle isotopes of carbon, nitrogen, and oxygen. All the isotopes produce only positron radiation with half-lives much too long to be useful for mine detection (the shortest, ^{15}O, has a half-life of 2.1 minutes). If the anihilation radiation is used for detection, a similar result from a copper reaction results in a high false alarm rate.

The (n,p) reactions in ^{16}O, ^{15}N, and ^{12}C lead to short half-life isotopes that emit high energy gamma rays. The $^{16}O(n,p)$ reaction produces ^{16}N with a 7.3-s half-life and 6.5-MeV gamma ray. This reaction was dismissed because soils are likely to contain about the same fraction of oxygen as explosives. The $^{15}N(n,p)$ reaction produces short-lived ^{15}C, with 0.55-MeV gamma rays, but the cross-section and abundance of ^{15}N are so low that the reaction offers no possibility of being useful.

The $^{12}C(n,p)$ reaction leads to ^{12}B. The latter decays rapidly to an excited state of ^{12}C, which emits a 4.4-MeV gamma ray. Although this reaction has been used to detect mines, the natural occurrence of carbon largely obviates its usefulness. The panel could find no practical means of making this a feasible method of explosives detection.

Tagging of Explosives. Although this technique is apparently feasible, it offers no solution to the problem of detecting enemy mines. For obvious reasons, its further consideration was dropped.

Nuclear Magnetic Resonance. This subject was raised, but because it is not a radiation technique, it was not considered to be within the purvue of the panel. It was briefly discussed in the context of detection of explosives in the luggage/package scenario. The technique was considered to hold out little promise because of a number of difficulties such as the lack of a strong signal, difficulty of achieving a uniform magnetic field, interference by metal, and ease of shielding.

REFERENCES

1. Baker, S.A., and R.B. Moler, (1971), "Exploratory Design, Engineering, and Operational Development of a Pilot Model Lead Detection System," IITRI-V6119-13, Final Report, Contract No. J-LEAA-010-71 (1971).

2. Buhts, R., P.G. Malone, and S.S. Cooper, "Preliminary Evaluation of a Prototype Neutron-Thermalization Detector for Plastic-Cased Mines," unpublished draft report (1985).

3. Cann, C., (1985), private communication.

4. Coleman, W.A., "Calculation on the Sensitivity of the X-Ray Field Backscattered from Soil Due to Subterranean Material Deficiencies," Report BRL-R-1537, U.S. Army Ballistic Research Laboratories (1971).

5. Coleman, W.A., R.P. Ginaven, and G.M. Reynolds, "Nuclear Methods of Mine Detection," Final Report, U.S. Army Contract DAAK02-73-0139, Report No. SAI.74.203.LJ, Science Applications Inc., La Jolla, CA, 92037.

6. Jacobs, A.M., B.C. Towe, and J.E. Harkness (1979), "Backscatter X-Ray Radiography: Medical Applications," SPIE 206, (1979), 129-134.

7. Powell, J.E., and J.W. Matthews, (1971), "The Detection of High Explosives by Capture Gamma Ray Techniques," Report SC-RR-71-0450, Sandia National Laboratories.

8. Roder, F.L., and R.A. Van Konynenberg, (1975), "Theory and Applications of X-Ray and Gamma Ray Backscatter to Landmine Detection," U.S. Army Mobility Equipment Research and Development Center, Report No. 2134, Fort Belvoir, VA, March 1975.

9. Thompson, M.L., (1973), "Advanced Experimental Model AP Detector (Gamma Ray), Industrial Nucleonics Final Report, Contract DAA.K02-72-C-0619 (1973).

10. Van Konynenberg, R.A., and F.L. Roder, (1970), "Evaluation of the Dresser-Atlas Road Logger as a Detector of Road Disturbance," Technical Memorandum, U.S. Army Mobility Equipment Research and Development Center, Fort Belvoir, VA, June 1970.

APPENDIX I

LIST OF PARTICIPANTS

ARO WORKSHOP
MINE DETECTION METHODS USING IONIZING RADIATION

22-25 JULY 1985

ARO WORKSHOP ON
NUCLEAR TECHNIQUES FOR MINE DETECTION RESEARCH

July 22-25, 1985
Lake Luzerne, New York

Participants

Dr. Harold Berger
Industrial Quality
9832 Canal Road
Gaithersburg, MD 20879
301/948-0332

Dr. Robert Brooke
U.S. Army
Fort Belvoir Research
and Development Center
Attn.: STRBE-ND (R. Brooke)
Fort Belvoir, VA 22060
703/664-2775

Major Robert Buhts
U.S. Army Instructor Group
Clarkson University
P.O. Box 312
Pottsdam, NY 13676
315/268-7705

Dr. Chris Cann
Department of Radiology
University of California
San Francisco, CA 94143
415/666-5026

Dr. Monte Davis
Georgia Institute
of Technology
1207 Reeder Circle, N.E.
Atlanta, GA 30306
404/874-7472

Mr. Samuel Helf
U.S. Army, Retired
55 Sherwood Drive
Morristown, NJ 07960

Dr. Robert B. Moler
The Aerospace Corporation
955 L'Enfant Plaza, S.W.
Suite 4000
Washington, D.C. 20024
202/488-6088

Dr. Victor Orphan
Science Applications
International Corporation
10401 Roselle Street
San Diego, CA 92121
619/458-3713

Ms. Betty Persons
Workshop Coordinator
Battelle Columbus Laboratories
505 King Avenue
Columbus, OH 43201
614/424-4596

Dr. Fredrick Roder
U.S. Army
Fort Belvoir Research
and Development Center
Attn.: STRBE-ND (F. Roder)
Fort Belvoir, VA 22060
703/664-2775

Dr. Jeff Stokes
IRT Corporation
3030 Callan Road
San Diego, CA 92121
619/450-4343

Dr. Richard Van Konynenburg
MC L-396
Lawrence Livermore
National Laboratory
P.O. Box 808
Livermore, CA 94550
415/422-0456

APPENDIX II

EXPECTED DETECTION PROBABILITY FROM PGNAA MINE DETECTION SYSTEM

13 SEPTEMBER 1985

Prepared by
Science Applications International Corporation
10401 Roselle Street
San Diego, CA 92121

Appendix II

Science Applications International Corporation

September 13, 1985

Dr. Robert Moler
12003 Bobwhite Drive
Catharpin, Virginia 22018

Dear Bob:

Enclosed is a brief report describing the results of the PGNAA for mine detection feasibility calculation performed by our Sunnyvale Division (T. Gozani, et al). I've added a few spectra from our recent FAA proposal (explosives in luggage) which help demonstrate the feasibility of using lower resolution but higher efficiency detectors than IGe to discriminate the N 10.8 MeV gamma-rays. A quick cross check of the Sunnyvale count rate numbers with estimates derived from the 1974 SAI PGNAA measurements at Ft. Belvoir using a large Ge (Li) reveals excellent agreement (considering the large uncertainty in these count rate estimates).

Please give me a call if you have questions or comments. Thank you for your patience — sorry this took so long.

Best regards,

SCIENCE APPLICATIONS INTERNATIONAL CORPORATION

V. J. Orphan
Corporate Vice President

VJO/b

enclosure

10401 Roselle Street, San Diego, California 92121, (619) 458-3700

Other SAIC Offices Albuquerque, Ann Arbor, Arlington, Atlanta, Boston, Chicago, Huntsville, La Jolla, Los Angeles, McLean, Palo Alto, Santa Barbara, Sunnyvale and Tucson

Expected Detection Probability from PGNAA Mine Detection System

The key factor in the estimation of the mine detection probability is the number of 10.8 MeV gamma rays detected when the detector array passes over a mine. This is a complicated function of source strength, number and type of detectors, mine size and depth, etc., which is too complex to present in closed analytical form. To estimate the count rate, then, a numerical integration of count rate was done on a computer. In general, the parameters chosen for the calculation were those used in Mynatt(1). That is, soil composition and density, mine size, and neutron flux were the same as in that paper. A 10^9n/sec fission source (~415 μgms of ^{252}Cf) is assumed and this is calculated (quite conservatively) to result in 10^{-4}n/cm^2/sec per source number/sec or 10^5 n_{th}/cm^2 sec at the depth of the mine (5 cm). Figure 1 shows a perspective view of the system. A linear array of 9 detectors is swept over the surface of the soil; the figure shows the relative position between the mine and the array at three different times. Note that for simplicity of the calculation, the height of the array above the soil is taken to be the same as the buried depth of the mine (5 cm); this, of course, is not a requirement. Figure 2 shows the top view of the system. The source of neutrons is located 20.32 cm (8 inches) to one side of the array (and is 2 cm higher off the ground). The mine is a 25 cm x 25 cm x 10 cm solid, which happens to pass under one end of the array rather than the center. The detectors used are 7.62 cm (3 inches) in diameter, spaced with 10 cm between centers.

Table 1 shows the result of this calculation for a particular case. The mine depth was chosen to be 5 cm, and BGO was chosen as the detector type. The table shows the count rate per second in each detector at three different mine positions (Z is the distance between the detector center line and the midline of the mine), and, in the final column, the gamma rays counted in each detector if it takes ¼ of a second to sweep over the three positions (or 0.083 sec per position, namely 6.75 miles/hr scanning speed). Note that this table shows only the three middle positions; a substantial count rate still results from when the mine is further away (one way to get an estimate of this is to look at

---

1. Mynatt, F.R., Alsmiller, R.G., Jr., and Williams, L.R., "A Study of Mine Detection by Means of Neutron—Induced Gamma Rays", Nucl. Tech. 12, 239 (1971)

the count rates in detector 3, which is 30 cm away from the edge of the mine; it still contributes about 13 counts in 0.25 seconds). Thus, this 400 counts in 0.25 seconds is a conservative (under)estimate of the expected number of counts for this situation. Doubling the mine depth to 10 cm (but leaving the detector height at 5 cm above the soil) would reduce this by a less than factor of 10, to about 40 counts per 0.25 seconds.

Table 1. Mine buried at 5 cm depth (t = 5 cm)

	Det #	Counts per second in detector at			Total counts in 0.25 sec
		Z = -12.5 cm	Z = 0 cm	Z = 12.5 cm	
	1	8.9	15.8	16.7	3.4
	2	16.0	29.6	29.7	6.3
	3	32.5	64.2	58.6	12.9
	4	76.3	164.2	129.5	30.8
	5	175.4	403.8	275.7	71.2
Mine Position	6	257.5	593.6	386.2	103.1
	7	259.1	588.0	374.9	101.8
	8	178.4	392.4	254.2	68.8
	9	83.3	169.5	123.2	31.3
	Total	1087.3	2421.1	1648.7	429.8

Notes: Detectors are 7.62 cm (3") diameter by 10.2 cm (4") long BGO scintillators. Source is located 20.32 cm off the line of the detector array at position number 5; mine is located 10 cm under array at positions 6 through 8.

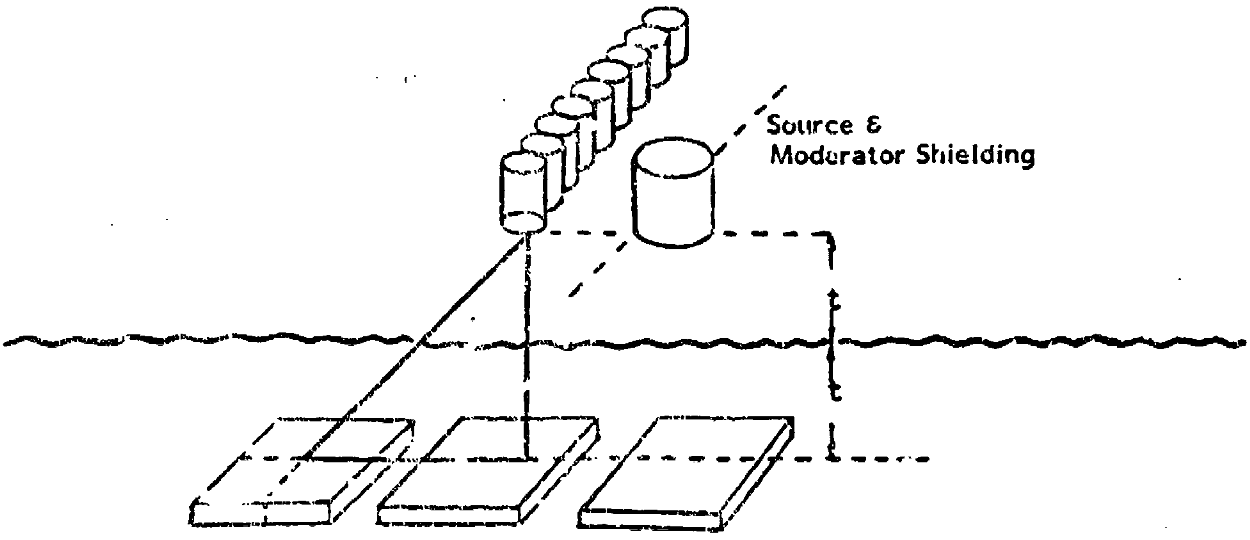

Figure 1: Perspective view of detector array. Soil thickness and height of system above soil were taken as the same distance for simplicity.

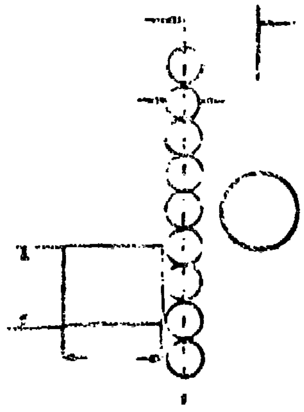

Figure 2: Top view of system (source and detector assembly). Position of mine used in calculation is shown.

The excellent signal-to-background of the N (n,γ) line at 10.8 MeV was demonstrated by the SAIC measurements(2) in 1974 using the experimental arrangement shown in Figure 3. The Ge(Li) spectrum shown in Figure 4 clearly reveals the 10.8 MeV gamma-ray peaks (full energy, single-escape and double-escape) and conclusively demonstrates that high energy capture gamma-rays from Si do not provide any significant interference. The absolute count rate of 10.8 MeV gamma rays from the "mine" at the surface was about 2.8±0.4, 8.6±0.3 and 11.8±0.3 net counts per minute in the full energy, single escape and double escape peaks respectively. The ability of lower resolution, but much higher efficiency NaI detectors to also detect and discriminate the 10.8 MeV N gamma-rays is demonstrated in Figure 5 which shows the N capture gamma-ray from a coal sample measured with a NaI detector.

The availability of BGO detectors, having nearly an order-of-magnitude greater efficiency than NaI at 10.8 MeV (see Figure 6) greatly improves the performance of PGNAA for explosive detection. The ability to perform spectroscopic analysis using a BGO detector is demonstrated in Figure 7. Shown are several superimposed thermal capture gamma-ray spectra measured for Fe, Cl and N (typical of explosive) samples with a 3" x 4" BGO detector. This measurement was made using a fairly tight geometry (representative of the mine detection geometry in which the source and detector are close together) of the SAIC PGNAA Coal Slurry Meter using only 10 μg of ^{252}Cf. The ability to separate the 10.8 MeV nitrogen line from encroaching Fe, Cl and other lines is quite obvious. This spectroscopic capability will greatly enhance the ability to further reduce the false alarm probability. The overall system optimization must insure that the ratio of 10.8 MeV nitrogen to lower-energy capture gamma-rays from other elements (H, Si, C, etc.) is maximized without exceeding the total detector count rate capabilities (∼ 250,000 cps).

As a cross check on the calculated count rates given above in Table 1, we also estimated the BGO detector count rate (for the detector located over the mine) using experimental data for the number of 10.8 MeV gamma-rays produced in the 1974 SAI experiment (see Figure 3). Reference 2 reports the flux of 10.8 MeV gamma-rays 30 cm above the mine was ∼20 gamma-rays/cm^2/sec. The differences in the parameters for the experiment and calculation (see Table 2) can be used to correct this 10.8 MeV gamma

---

2. W. A. Coleman, R. O. Ginaven and G. M. Reynolds, "Nuclear Methods of Mine Detection" Science Applciations, Inc Report SAI-74-203-LJ.

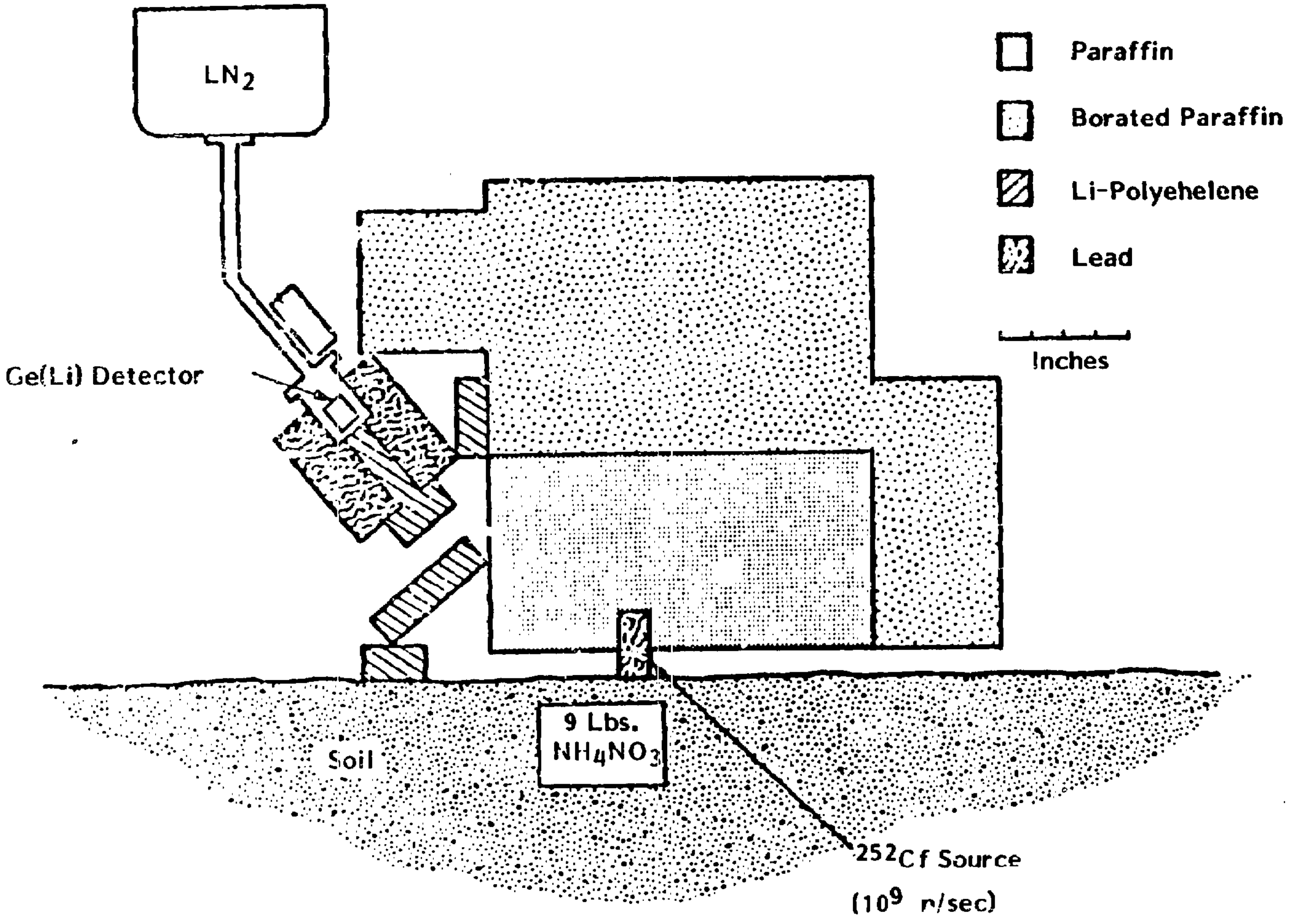

Figure 3. Experimental Setup for Outside Measurements (U)

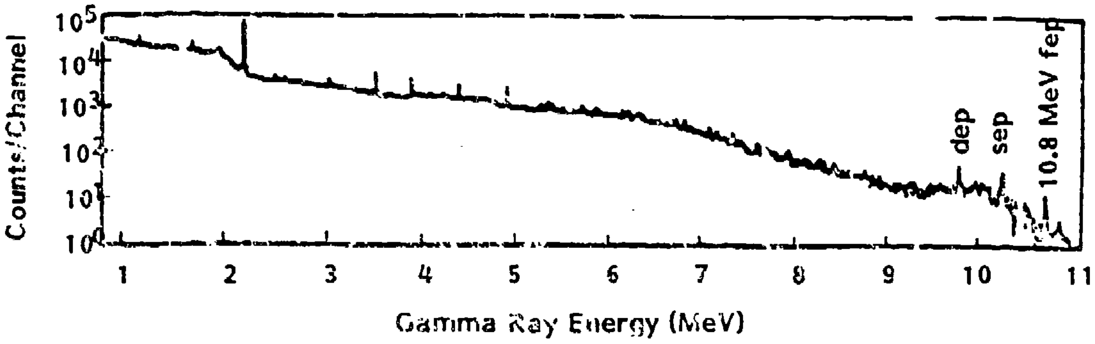

Figure 4. Gamma Ray Spectrum of 9 Pounds NH_4NO_3 Buried 1.5 Inches in Soil (Outside Measurement)

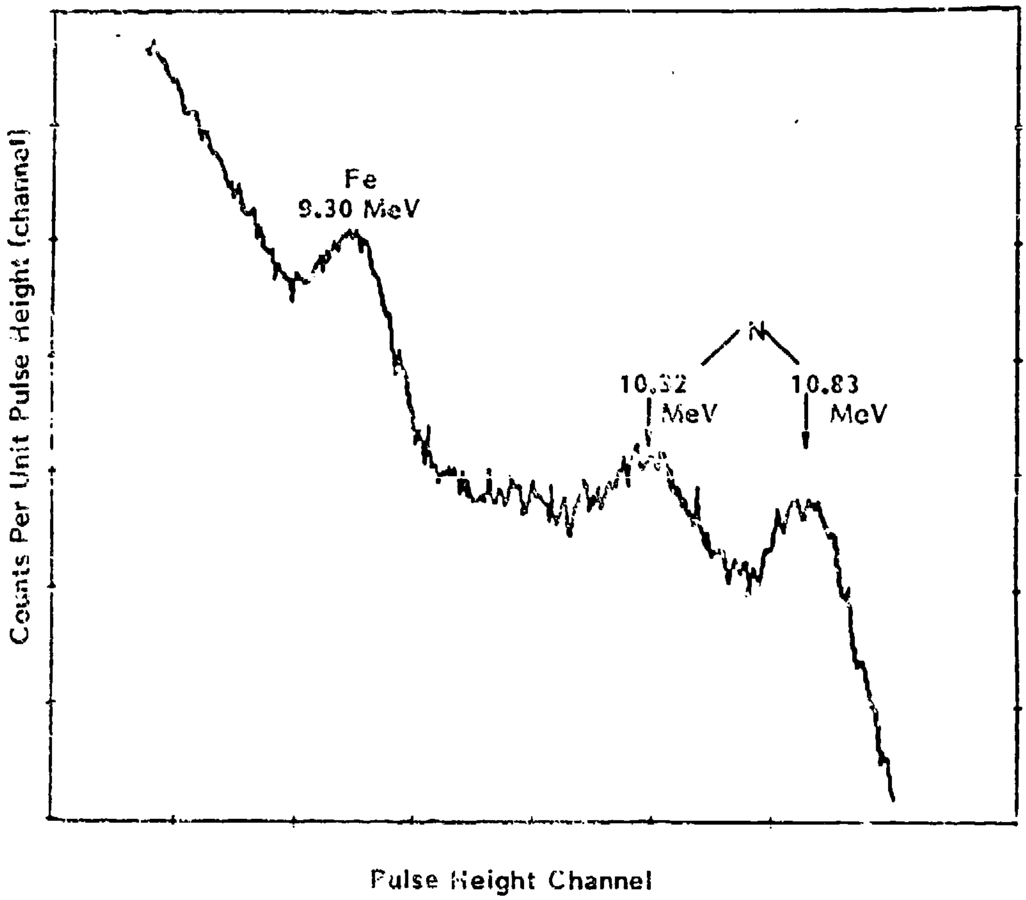

Figure 5. Pulse height distribution in the nitrogen 10 MeV region, as measured in coal using single 6" x 6" NaI (Tl) detector (10 cps/gram nitrogen)

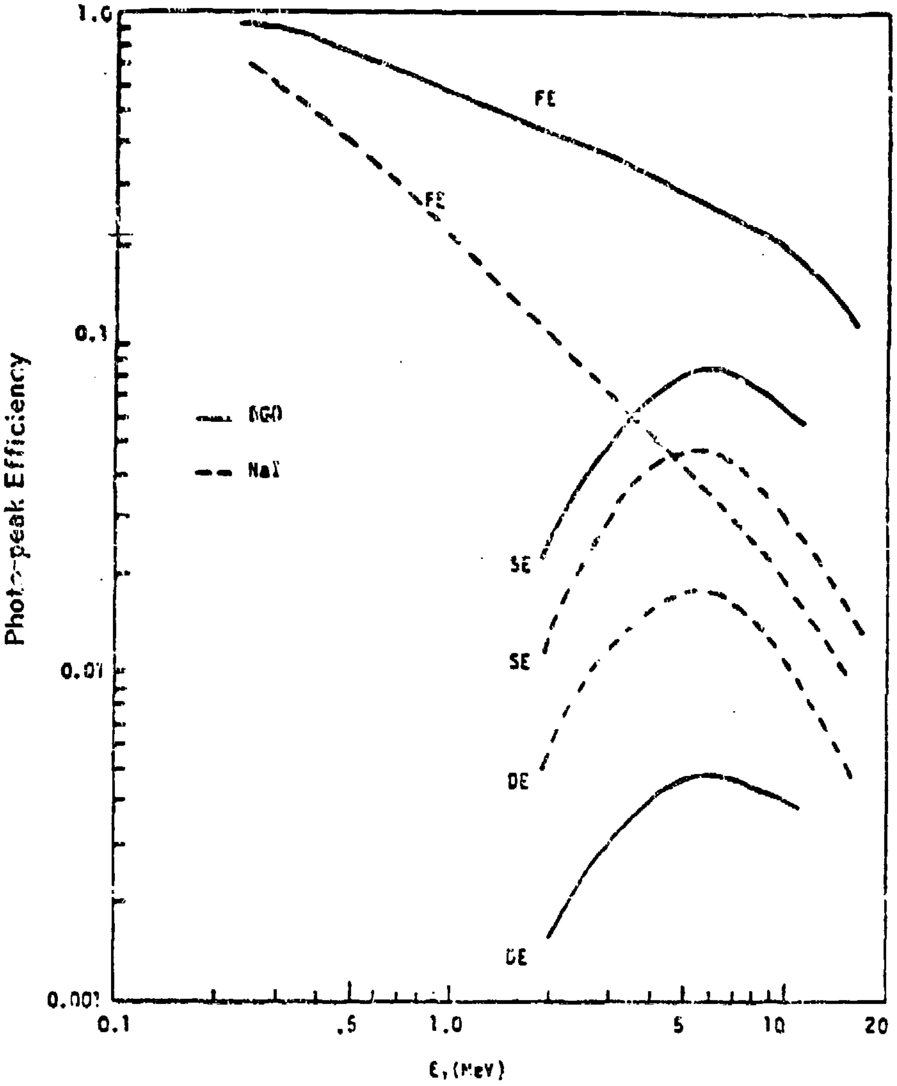

Figure 6. A comparison of the calculated efficiencies of bare 3" x 3" bismuth germinate and NaI detectors. (FE, SE, DE = full energy, single escape and double escape peak respectively.)

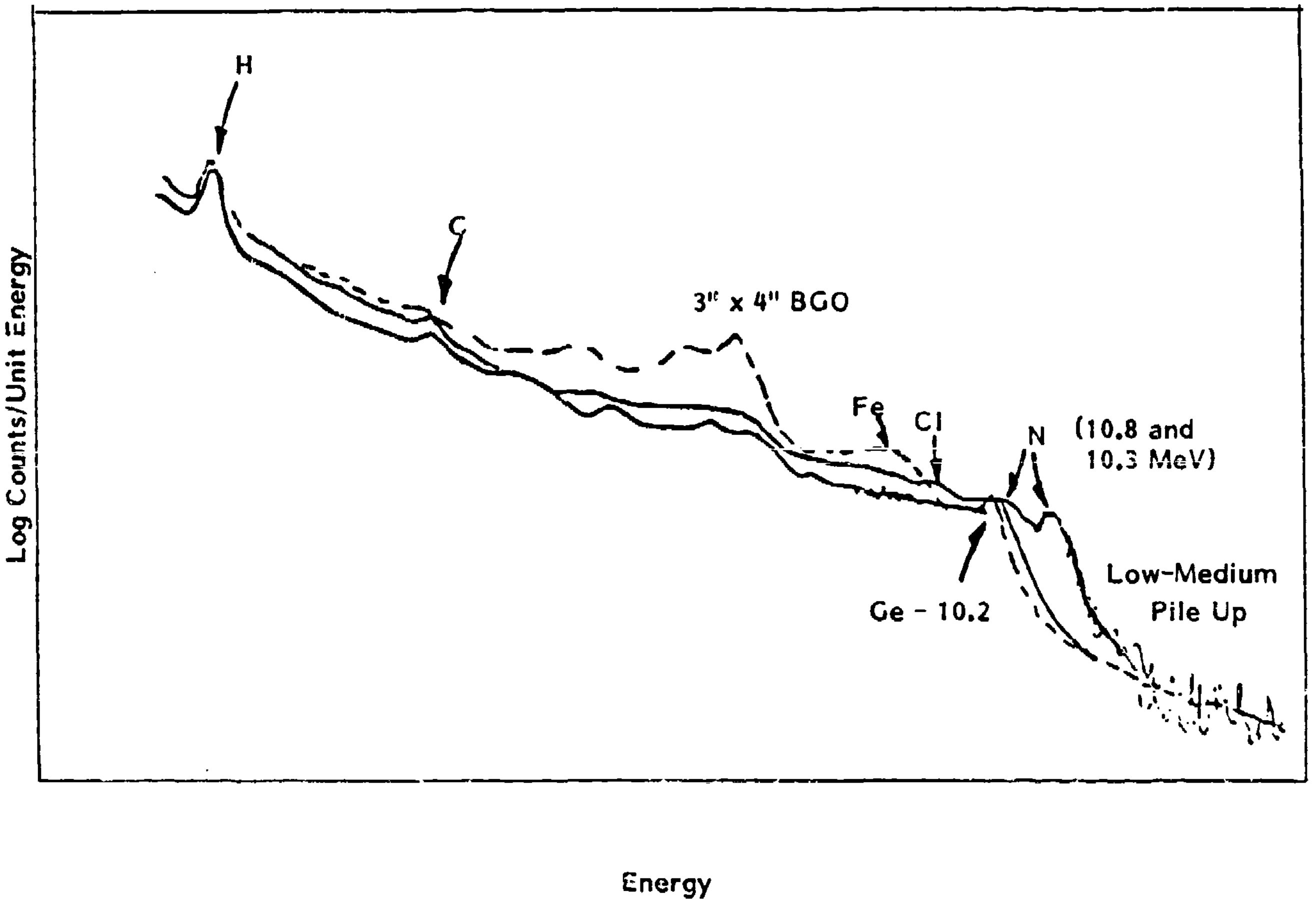

Figure 7. Thermal neutron capture gamma ray spectra as measured by BGO Scintillator for N (typical of explosive) Fe and Cl.

Table 2. Comparison of Parameters of Present PGNAA Count Rate Calculation with 1974 SAI Experiment

	1985 Calculation	1974 Experiment
Source	10^9 n/sec	10^9 n/sec
Source Distance from Mine	12.2 cm	7.6 cm
Soil over mine	5 cm	0 cm
"Detector" Distance from Mine	10 cm	30 cm
Mine Simulant	11.3 kg Nitroglycerin	4.08 kg Ammonium Nitrate
Nitrogen Weight	2.03 kg	1.43 kg

flux to obtain the flux for the BGO detector-source geometry shown in Figure 1 as follows:

$$\phi_{BGO} = \phi_{Ge} \left(\frac{7.6}{12.2}\right)^2 \left(.52\right) \left(\frac{30}{10}\right)^2 \left(\frac{2.03}{1.43}\right)$$

$$= (20\gamma/cm^2\text{-sec})\,(0.38)\,(0.52)\,(9)\,(1.41)$$

$$= 51\ \gamma/cm^2\text{-sec}$$

The 0.52 factor was obtained from an extrapolation of the experimentally determined (see reference 2) reduction in 10.8 MeV gamma-rays resulting from burying the mine 1.5 inches. The BGO detector count rate is

$$C_{BGO} = (51\gamma/cm^2\text{-sec})\,(\text{Det Area})\,(\text{Det Efficiency})$$

$$C_{BGO} = (51\gamma/cm^2\text{-sec})\,(45.6\ cm^2)\,(0.2)$$

$$C_{BGO} = 463\ \text{cps}\quad(\text{Experiment})$$

From Table 1, the calculated C_{BGO} = 590 cps. This degree of agreement, while fortuitous, since some of the approximations used are no better than a factor of two; provides some assurance that the count rate calculations in Table 1 are reasonable.