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Neutron-Activated Gamma-Emission: Technology Review

by Marc Litz, Christopher Waits, and Jennifer Mullins

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14. ABSTRACT This report describes the technical basis for the technology in place using neutron-activated gamma-backscatter techniques. Commercially available systems are used. The details of the capabilities and differences in these systems can best be compared when the technical details are understood. The choices between types of electronic neutron generators are described. The types of γ -detectors are described and compared. The analysis techniques that produce the results within minutes are compared for accuracy, reliability, statistical validity, and speed of acquisition. The potential for use in three identified concept of operations (CONOPS) are described.					
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Contents

List of Figures	v
List of Tables	vi
Executive Summary	vii
1. Introduction	1
2. Background	3
2.1 Interactions of Neutrons with Matter	3
2.2 Materials for Absorption and Detection of Neutrons	5
2.3 Interactions of Neutrons with Explosives	6
2.4 Gamma Emission from Neutron Induced Reactions	7
2.5 X-ray Backscatter Analysis Techniques.....	13
3. Sources of Neutrons	15
3.1 Radioisotope-induced Neutron Sources	15
3.1.1 Gamma-induced Sources of Neutrons, (γ , n) Reactions.....	15
3.1.2 Alpha-induced Sources of Neutrons (α , n) Reactions.....	16
3.1.3 Spontaneous Fission (SF) Producing Neutrons from Isotopic Sources	16
3.2 Neutron Generation from Accelerators	17
3.2.1 Compact Accelerators	17
3.2.2 Spallation Sources	20
3.3 Neutron Generation from Reactors	20
4. X-ray Detectors	21
4.1 Scintillation Detectors	22
4.2 Solid State Detectors	22
5. Monte-Carlo Simulation	24
6. Safety Issues	27

7. Evolution of the Technology	29
7.1 Areas for Improvement	29
7.2 Big Changes that Can Make a Difference	30
8. Summary and Conclusions	30
9. References	32
List of Symbols, Abbreviations, and Acronyms	35
Distribution List	37

List of Figures

Figure 1. A variety of techniques are deployable to locate, identify, and remediate against the use of high explosives (<i>I</i>). The block diagram shows concepts used for bulk detection.....	2
Figure 2. Fast neutrons are compared to slow neutrons in the way they interact with a nucleus. Neutrons are captured after they have been slowed by scattering.....	4
Figure 3. Neutron cross section (barns) for materials with best stopping power. Gd has the largest known cross section of 1×10^7 barns. Cross section for capture of neutrons is generally reduced as the energy of the neutron increases.....	6
Figure 4. The density relationship between the major organic contributors (N, C, and O) of explosives allow the discrimination between benign and significant materials.....	8
Figure 5. Materials identification using neutron activation yields gamma radiation that can be detected using x-ray detectors. The materials of interest are identified for the different industrial and military applications (explosives, mining, special-nuclear-materials [SNM], and chemical warfare [CW]).....	9
Figure 6. It is useful to identify three temporal regimes for detection of gamma ray backscatter from materials. These include the (I) prompt, (II) radiative capture, and (III) die-away time periods.....	10
Figure 7. Neutron capture is an inelastic scatter interaction that occurs more often with low/thermal neutrons. The neutron energy absorbed is reemitted as gamma energy in a prompt reaction.....	11
Figure 8. Nuclear reactions used in compact accelerators use the D-D and D-T reactions.....	18
Figure 9. Cross section for the interaction in units of neutrons generated per mC thrown at a target.....	19
Figure 10. Generic neutron tube schematic.....	19
Figure 11. X-ray spectra showing number of counts vs. gamma energy. The resolution of the measurable lines varies with detector.....	21
Figure 12. Response of solid-state detectors compared to NaI (most sensitive).....	23
Figure 13. Geometry defined in MCNPX to simulate the γ -spectra collected by NaI detectors (cell 6) from target (cell 3).....	24
Figure 14. Doubling distance of target reduces signal by factor of four. The neutron induced gamma spectrum of the AN target located 15 (red) and 30 cm (purple) from NaI detector.....	25
Figure 15. The gamma line at 4.43 MeV indicates carbon in the two explosive targets, each of 1000cc. The resolution of the energy bins shown is 62.5 keV in these simulations. The signal strength is 10 times reduced when buried in sand.....	26
Figure 16. Dose rate as a function of distance from the ENG running at a typical 2×10^7 neutrons per second.....	27

Figure 17. Radiation dose (mRem) is displayed. By separating out the powers of ten (orders of magnitude) of radiation levels, it is easier to show the insignificance of the radiation produced in ENG. Source: <http://www.nrc.gov/images/about-nrc/radiation/factoid2-lg.jpg>.28

List of Tables

Table 1. Nuclear reactions of interest for the detection/identification of explosives.	7
Table 2. Examples of elemental compositions of some threats and common benign materials (concentration of the elements is given in weight %).	9
Table 3. Element, gamma emitted(keV), and cross section (barns) is listed. These gammas can be identified in the x-ray backscatter results. From IAEA Neutron Database, Appendix I. Prompt Gamma from Thermal Neutrons.	12
Table 4. Measured peaks from the most abundant elements in explosives.	13
Table 5. Characteristics of neutron induced analysis techniques on materials.	14
Table 6. Gamma induced neutron generation has been measured in these decaying isotopes.	16
Table 7. Common nuclear reactions for deuteron accelerators.	17
Table 8. Major interactions with neutrons in the human body.	28

Executive Summary

Neutron-activated gamma-emission technology was first described as a useful materials identification process in 1970s. Compact accelerators are used to generate neutrons, which then interact with atoms independent of their elemental composition (carbon, nitrogen, oxygen, etc.). During this process, the atomic nuclei are stimulated by the neutrons to emit gamma radiation. Detecting this gamma radiation enables us to count the photons tagged with the energy emitted by the gamma radiation. Thus, we can use the captured gamma energy to identify an element, where the intensity correlates to the amount of material present.

Advances in technology have enabled accelerators compact enough to fit in a suitcase weighting <50 kg that have a power consumption of <100 W and can operate on batteries for a full day. Solid-state gamma detectors and scintillation detectors have become mechanically robust and reliable. Available neutron flux levels and gamma detection sensitivity enables statistically valid results and unambiguous identification of target materials in a 2-ft range within 5 min. Associated particle imaging (API) techniques have enabled time-mark and direction-tagging of the neutrons so that the location of the gamma emission (distance and angle) can be located within 5-cc volumes.

Further, materials can be identified in a few seconds if the neutron generator is within a foot of the target and if photon detectors surrounded the target volume. However, this is not realistic in many operational scenarios, so the limited number of detectors, covering a small solid-angle, limits the speed of the identification process to a few minutes. Neutrons are emitted isotropically from the neutron generator, and gammas are emitted isotropically from atomic nuclei. The combination produces signals that decrease as $1/\text{radius}^4$. In this case, if the neutron source and gamma detector are removed to twice the distance from the target, then the signal will drop by a factor of 16. Another characteristic that can add time to identifying materials is the mass of the target of interest. As the mass increases, the time to detect decreases linearly. The limitations to the technology are proximity between the target and the system, and detection sensitivity.

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1. Introduction

Protection of military forces and infrastructure are primary among the missions of the Joint Improvised Explosive Device Defeat Organization (JIEDDO). The process of protection can include threat (1) detection, (2) location, (3) verification, (4) identification, and (5) neutralization. The purpose of this report is to provide a technical review of neutron-activated gamma-backscatter techniques relevant to these missions. The technique has been proven useful in identifying organic materials hidden from sight. The level of effectiveness could have a significant impact on the movement of transportation convoys. It is our goal to evaluate whether timely, efficient, and cost-effective tools are available to reduce detection uncertainties. In addition, we would like to determine what would be available for explosive material detection and/or verification application in less than one year.

Regular terror attacks in foreign countries and potential attacks in the U.S. have led towards a heightened awareness of technologies that can have a significant impact on the identification of explosives. Standoff detection is still difficult because of source strength limitations in public environments and return signal strength compared to background. Operational concepts are critical in determining choice of hardware, analysis process, and information content to be relayed to Soldier. The non-intrusive, highly penetrating qualities of neutron sources are qualities to be exploited; however, optimal system configurations cannot be made until the application and concepts of operation (CONOPS) can be identified. An example of a practical CONOPS would be that Soldiers in convoy on roadways detect a potential threat through awareness of their surroundings. They locate a potential threat and need a positive ID before they can proceed. The feature identification required to verify a threat for this operation includes material composition, relative concentrations, and material density. Backpack-sized systems are being developed that are silent until a critical threshold of material is reached.

Many processes are applicable to materials identification. A variety of techniques are deployed to locate, identify, and remediate against the use of high explosives (*I-4*). The block diagram in figure 1 shows typical use scenarios. X-rays and electromagnetic systems are often used a first-line interrogation tool. This is because such tools produce (1) more directed radiation, in quantities that are safer and easier to use, and (2) a faster response than neutron and higher energy gamma-based sources. Unfortunately, they often lack the resolution and penetration to accurately identify suspect materials with a high probability of success.

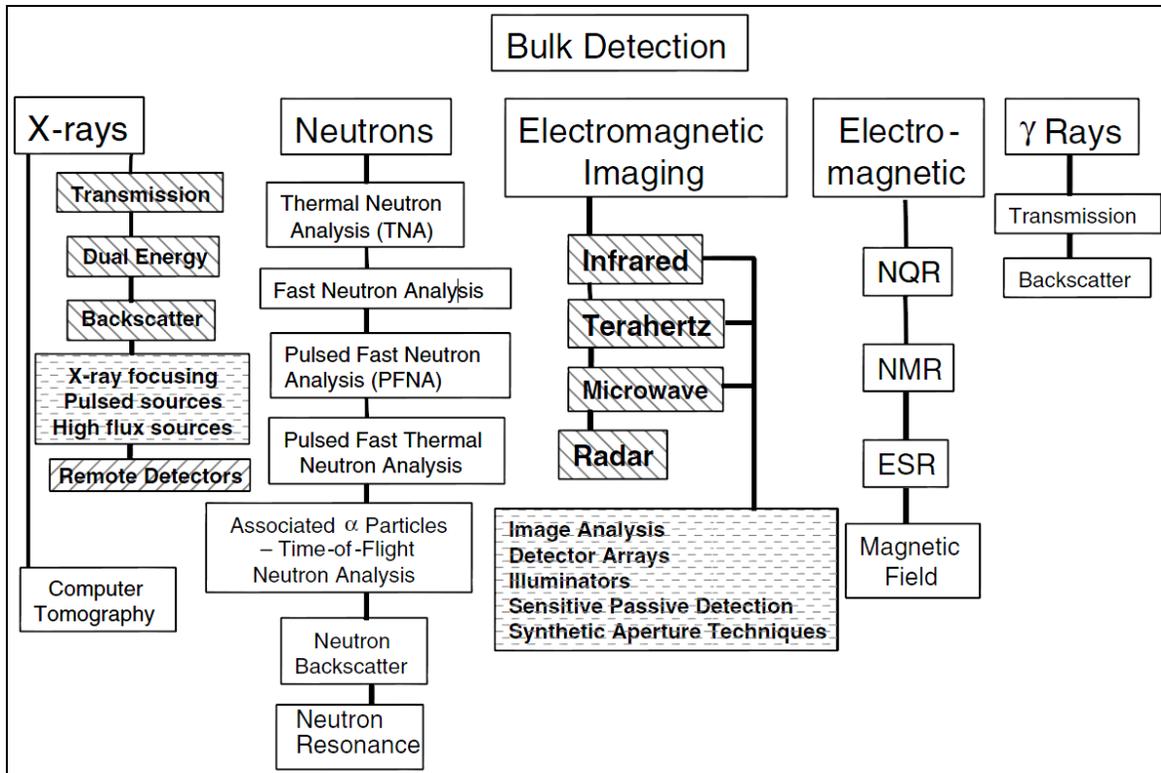


Figure 1. A variety of techniques are deployable to locate, identify, and remediate against the use of high explosives (1). The block diagram shows concepts used for bulk detection.

Explosives contain relatively high ratios of nitrogen and oxygen compared to carbon and hydrogen. These organic materials emit characteristic gamma radiation between 2 to 10 MeV, a point at which neutrons scatter from the nucleus in inelastic collisions (like in a car crash, where energy goes into forms other than just mass and velocity). Thus, neutron-activated gamma emission can be used to detect and identify threat materials based on the gamma energy spectrum. The key components to this technique are the (1) neutron source, (2) gamma detector, (3) spectrum analysis, and (4) decision algorithm. Section 2 begins with an introduction of how neutrons interact with matter. Section 3 describes techniques for neutron production and the devices available to produce them. Section 4 continues with the detectors used to measure x-rays generated by neutron activation of materials. Section 5 tabulates and explains the algorithms and techniques available to understand x-ray backscatter results using numerical simulation. Safety issues are of great interest to users and are calculated in section 6. Ideas to increase target distance and reduce measurement time are discussed in section 7. Section 8 provides summary of the state of the art.

2. Background

The neutron (neutral) and the proton (positively charged) are the sole components of the atomic nucleus. The neutron's lack of charge differentiates the way it interacts with matter when compared to other particles. Interaction with the nucleus through absorption and scattering events is the only important flux reducing mechanism for neutrons passing through matter.

Neutrons can be produced by fusion processes in stars, by the spallation processes of cosmic rays in the atmosphere, and by the process of spontaneous fission in large mass isotopes. No other natural source of neutrons is known. In certain light isotopes, the "last" neutron in the nucleus is weakly bound and is released when the compound nucleus is formed following an α -particle bombardment decay, as in $\text{Be}^9 + \alpha \rightarrow \text{C}^{12} + \text{n}$ and $\text{Be}^9 + \alpha \rightarrow 3\text{He}^4 + \text{n}$. Chadwick (5) made use of the naturally occurring α -emitter polonium-210, which decays to lead-206 with the emission of a 5.3-MeV α -particle, to isolate and identify the neutron in 1932.

2.1 Interactions of Neutrons with Matter

Neutrons carry no charge and do not interact with charged particles. Neutrons are usually absorbed by the nucleus, creating secondary radiation along the way. Secondary radiation is typically composed of heavy charged particles or scattered nuclei from neutron-induced nuclear reactions. The neutron interactions are energy dependant: slow (<0.5 eV) versus fast neutrons. The forms of neutron interaction with matter are as follows:

1. Elastic scattering (energy conserved in the kinetic energy of the colliding particles) (n,n')
2. Inelastic scattering (prompt energy lost to other reactions) (n,n' γ)
3. Absorption with gamma emission (n, γ)
4. Absorption with proton emission (n,p)
5. Absorption with fission of the nucleus, leaving various remnants (n,r)

Elastic scattering with nuclei is similar to the collision of two billiard balls. The kinetic energy loss (speed loss) per collision depends strongly on the mass of the nucleus the neutron is hitting: if the nucleus is large, the incoming neutron will lose practically no energy. Hydrogen (light nucleus, proton only) rich material such as polyethylene is, therefore, often used to slow down fast neutrons. The reaction is denoted as X(n,n')X type. Elastic scattering dominates for slow neutrons.

Inelastic scattering occurs when the incoming neutron has a sufficient kinetic energy (usually >100 keV for heavy nuclei and greater than some MeV for light nuclei) to put the nucleus being hit in an excited state, which decays in a very short time to its ground state (less than 10^{-12} s),

releasing the energy difference as a γ -ray of characteristic energy (also called “prompt” γ -ray). The incoming fast neutron continues with a reduced kinetic energy. The reaction is, therefore, of the $X(n,n'\gamma)X$ type. Inelastic scattering dominates for fast neutrons.

Nuclear reactions occur with the production of charged particles or additional neutrons, usually starting from a threshold energy, often a few MeV. A nuclear reaction often has as the consequence of activating the material, i.e., the nucleus becomes radioactive. This radioactivity can be short lived (e.g., lasting milliseconds or seconds). If the nuclei decay emits γ -rays, these are denoted as delayed γ -rays. Examples are nuclear reactions of the $X(n,\alpha)Y$, $X(n,p)Y$, $X(n,2n)Y$ type. Neutron capture does preferentially take place when the neutron has sufficiently low energy or resonance interactions. This type of reaction is denoted as the $AZ(n,\gamma)A+1Z$ type.

Elastic scattering from light nuclei (interaction type 1) producing ionization tracks is common for the detection of *fast neutrons*. Proton emission and creation of radionuclide (interaction type 4) is most useful for the identification of *slow neutrons* ($<1/2$ eV). Direct neutron detection is complicated by the fact that these interactions are most often measured in more complex environments that include gamma and alpha reactions as well.

The types of interactions are illustrated in figure 2. The lightning bolt indicates a nuclear reaction. Prompt and delayed gammas have different energies, but both are useful in the identification process. Neutrons interact differently with every nuclide depending in neutron energy, and to some extent, atomic number (Z). Absorption is an exponential process suggesting inelastic scattering as the dominant mechanism.

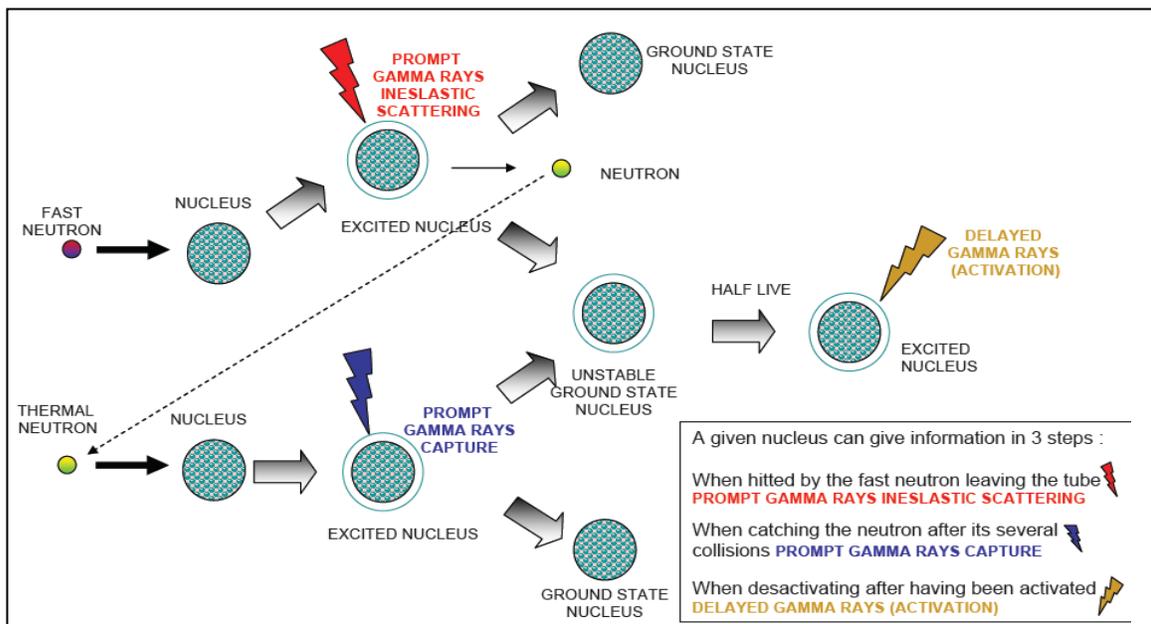


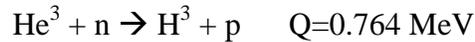
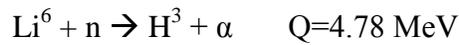
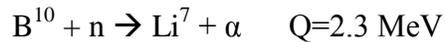
Figure 2. Fast neutrons are compared to slow neutrons in the way they interact with a nucleus. Neutrons are captured after they have been slowed by scattering.

2.2 Materials for Absorption and Detection of Neutrons

The most commonly used techniques to identify slow neutrons involve the following:

1. Elastic scattering with absorber nuclei leads to thermal neutrons (n, n') reactions.
 - Heavy nuclei only absorb partial energy (n, n').
2. Neutron induced nuclear reactions lead to radiative recapture ($n, n'\gamma$) reactions.
 - Hydrogen acts as a moderator and captures ($n, n'\gamma$).
3. Scatter leaving energy manifests as recoil nuclei.
 - Activation foils can be used (n, r).
4. Inelastic scatter for heavy nuclei leaves nuclei in excited states, and then emits a γ (n, γ) reaction.

Matter is relatively transparent to neutrons. Because of their high capture cross section for neutrons (23), the following materials are found in slow neutron detectors where these nuclear reactions take place:



Cd^{110} has 22 kbarn capture cross section

Gd^{157} has 255 kbarn (largest) capture cross section

The elements above represent the largest cross sections on the periodic table. Gadolinium-157 has the largest known neutron cross section of any element, followed by helium-3. The neutron scattering cross section for these materials is shown in figure 3. Boron-10 is relatively inexpensive, has a large capture cross section, and is commonly used in radiation safety shielding. The 1-eV neutrons in lead (Pb) have a large cross section of ~8 barns compared to 1000 barns for boron-10, whereas the 10-MeV neutrons in Pb have a cross section of 35 barns compared to 2 barns in boron-10. Paraffin absorbs neutrons in the $\text{H}^1 + n \rightarrow \text{H}^2 + \gamma$ reaction (and the reverse is also true when gamma exceeds 2.2 MeV). Neutron absorption by nuclei within 100 μs is typical.

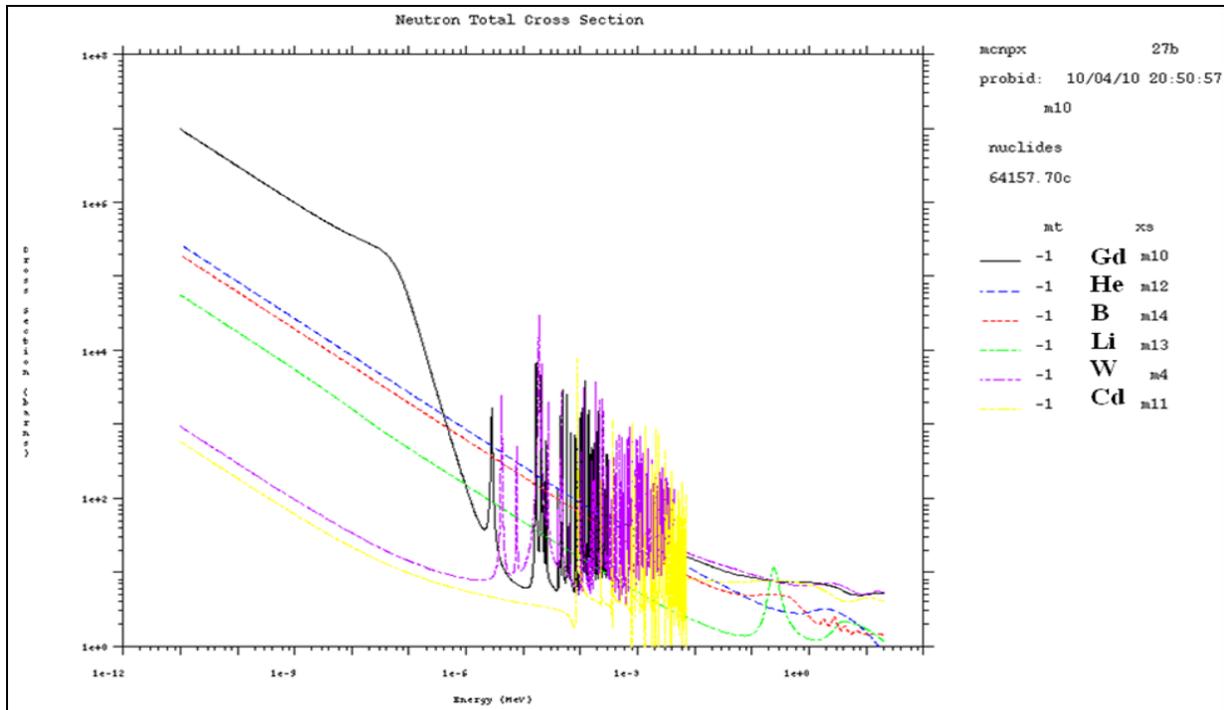


Figure 3. Neutron cross section (barns) for materials with best stopping power. Gd has the largest known cross section of 1×10^7 barns. Cross section for capture of neutrons is generally reduced as the energy of the neutron increases.

2.3 Interactions of Neutrons with Explosives

In Iraq, the typical explosives found in improvised explosive devices (IEDs) are military type high-density explosives that can be identified by their organic content. Neutron activation of organic materials (such as hydrogen, oxygen, carbon, and nitrogen) creates γ -ray signatures that can be identified with gamma detectors. The ease of identification is dependent on the strength of the explosive's signal compared to the background signal. The signal-to-noise ratio is dependent on distance and mass of the explosives, as well as detector sensitivity and size.

A selected set of gamma signatures are shown in table 1 (26). The elements shown are the one most relevant to high explosives buried in earth. Overlaps in gamma-spectral-line signal create conflicts in signal recognition, and therefore, add uncertainty to the measurement. If the intensity is small, low signal strength can be overcome by a longer dwell time that allows count accumulation and generation of better statistics. Additional time may be difficult for operational use, but is a useful tradeoff if accuracy is required. The following reactions are common and particularly useful in identifying explosive material.

Table 1. Nuclear reactions of interest for the detection/identification of explosives.

Element	Reactions	Neutron Energy	Reaction Type	Energy (MeV)
H	${}^1_1\text{H}(n,\gamma){}^2_1\text{H}$	Thermal	Prompt	2.23
C	${}^{12}_6\text{C}(n,n'\gamma){}^{12}_6\text{C}$	Fast (>5 MeV)	Prompt	4.43
N	${}^{14}_7\text{N}(n,\gamma){}^{15}_7\text{N}$	Thermal	Prompt	2.31
N	${}^{14}_7\text{N}(n,n'\gamma){}^{14}_7\text{N}$	Fast (>3 MeV)	Prompt	5.11
N	${}^{14}_7\text{N}(n,2n){}^{13}_7\text{N}$	Fast (14 MeV)	9.9-m activation	
O	${}^{16}_8\text{O}(n,n'\gamma){}^{16}_8\text{O}$	Fast (>7 MeV)	Prompt	6.13
O	${}^{16}_8\text{O}(n,p){}^{16}_7\text{N}$	Fast (>9 MeV)	7.1-s activation	7.12
Cl	${}^{35}_{17}\text{Cl}(n,\gamma){}^{36}_{17}\text{Cl}$	Thermal	Prompt	
Cl	${}^{35}_{17}\text{Cl}(n,n'\gamma){}^{35}_{17}\text{Cl}$	Fast (>3 MeV)	Prompt	
Cl	${}^{35}_{17}\text{Cl}(n,p){}^{37}_{17}\text{S}$	Fast (14 MeV)	Activation (4.9 min)	

2.4 Gamma Emission from Neutron Induced Reactions

A variety of technologies (described in section 1) have been studied with the goal of identifying bulk explosives. Most of the techniques provide imaging information based on the density of the package. The interpretation of imaging requires humans in the loop. Neutron activation provides elemental material composition, eliminating the need for a human in the loop. Density and mass can be identified if sufficient counts are collected by a gamma detector. The more data collected, the further from the detector the target can be located. The probability of identification increases with time.

Gamma rays, which are emitted from radioactive nuclei that form after neutron bombardment, provide a unique gamma-energy spectral signature for each element. Techniques that measure transmitted, attenuated, or scattered neutrons can provide imaging, as well as information about elemental composition. Being electrically neutral, neutrons do not interact strongly with matter. The penetrating nature is an asset for screening cargo and luggage; however, the inconvenience, expense, and hazards of radioactive, accelerator, and reactor neutron sources limit their application to settings in which human exposure can be prevented with certainty. Safety is discussed in more detail in section 6.

Neutrons bombard the nuclei of unknown materials. The neutrons are scattered or absorbed by the nuclei, emitting gammas of specific energies, depending on the neutron initial energy and the specific nucleus. Analysis of the emitted gammas can provide material composition and density of the unknown material.

For explosives identification, the organic elements of carbon, nitrogen, oxygen, and hydrogen are the most useful markers. The ratio of abundance in the sample is essential in the identification process, as our environment contains much of these organic nuclei. All the organic elements resonate at their characteristic frequency, but H absorbs neutrons to a much larger extent than the other elements. The statistical nature of gamma emission, the variation of gamma attenuation with distance and the presence of organic clutter (in food, fertilizer, dirt road, etc.) makes it

difficult to use signal strength only. The ratio of signal strengths from the organic materials has a significant impact in differentiating one explosive material from another with enhanced reliability. The large nitrogen content in explosives becomes obvious when the elemental ratios are separated out in a three-dimensional (3-D) space map, as shown in figure 4.

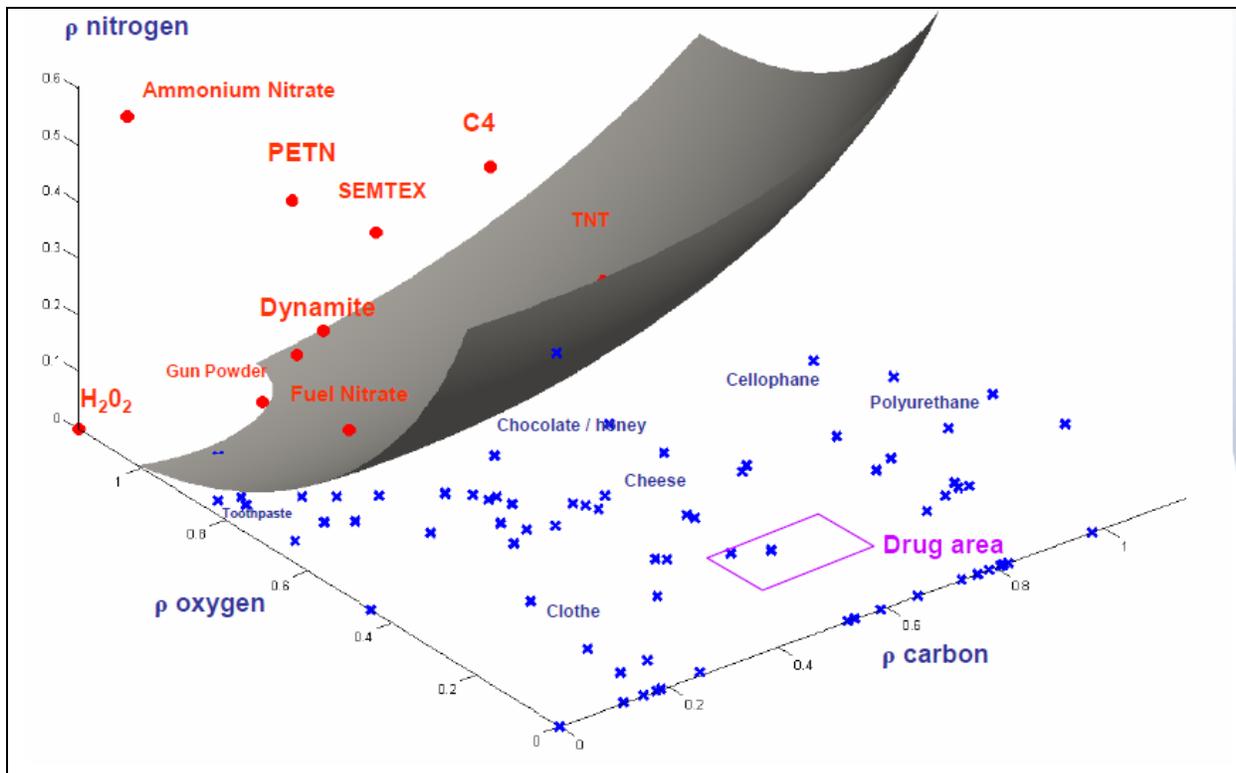


Figure 4. The density relationship between the major organic contributors (N, C, and O) of explosives allow the discrimination between benign and significant materials.

The periodic table shown in figure 5 illustrates which elements are useful in industrial, chemical safety, and nuclear weapons identification applications. The techniques associated with neutron activated gamma-emission are not limited to research groups, or newly investigated compounds. The mining industry is the largest user of this tool. By defining the purity of raw materials mined from the ground in real time on conveyer belts, they can save time and money in mixing the correct quality and mixtures of materials without having to store the materials first.

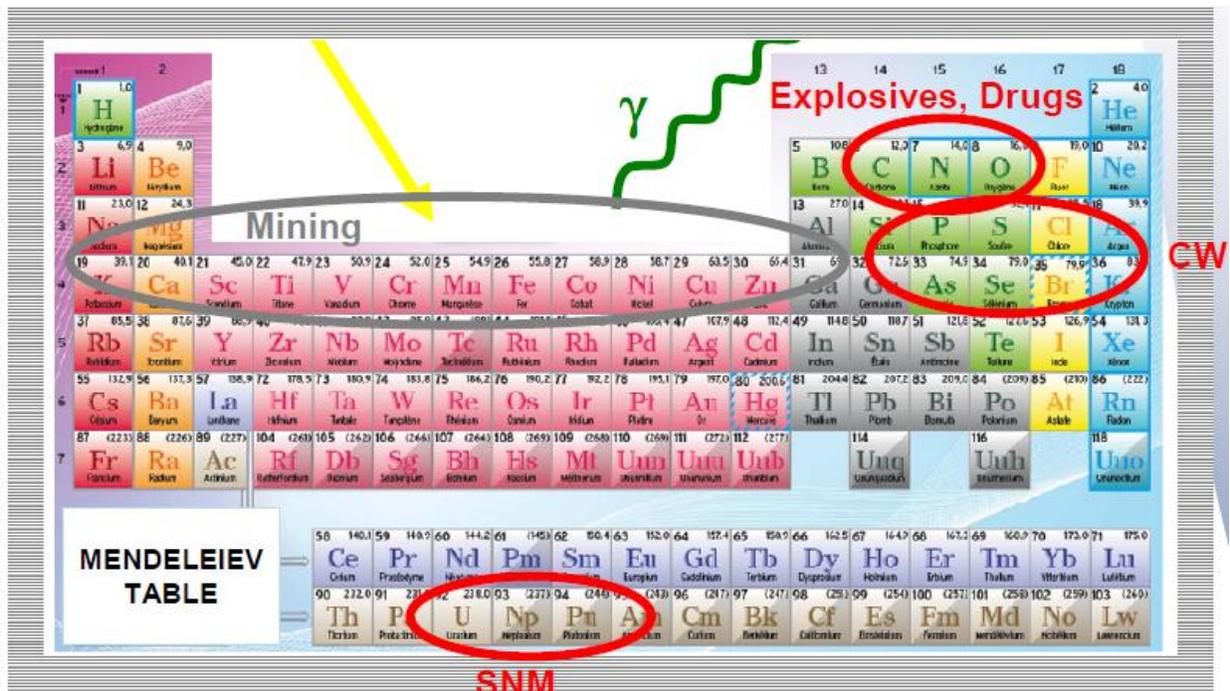


Figure 5. Materials identification using neutron activation yields gamma radiation that can be detected using x-ray detectors. The materials of interest are identified for the different industrial and military applications (explosives, mining, special-nuclear-materials [SNM], and chemical warfare [CW]).

The real-time characterization of materials is one of the properties of interest for the de-mining application. Differentiation of false alarms from real threats is another important characteristic in the battlefield. The false alarm rate can be reduced by comparing the elemental ratios. The intensity of signal from each element is dependent on distance, statistics, time on target, and detector sensitivity/background; however, the ratios of elemental composition are one of the best indicators of material content, as shown in results in table 2.

Table 2. Examples of elemental compositions of some threats and common benign materials (concentration of the elements is given in weight %).

	C	H	N	O	Cl	N/H	N/C
Explosives							
C4	21.9	3.6	34.4	40.1	0	10	2
TNT	37	2.2	18.5	42.3	0	8	1
PETN	19	2.4	17.7	60.8	0	7	1
AN	0	5	35	60	0	7	∞
Benign							
Water	0	11.1	0	88.9	0	0	0
Paper	44	6	0	50	0	0	0
Plastic	86	14	0	0	0	0	0
Salt	0	0	0	0	60	0	0

Direct neutron detection is not used for identifying organic explosive materials. Gamma rays are generated as a result of neutron interaction with the nucleus. Boron detectors are the most common type used if direct measurement of the neutron must be made, because the neutron capture cross section is so large in the $B^{10} + n \rightarrow Li^7 + \alpha$ reaction.

As discussed in section 2.1, there are a variety of ways that neutrons interact with matter (figure 6). The first differentiation is comparing prompt reactions to delayed interactions. The prompt reactions that occur in materials during the neutron pulse are a result of inelastic scattering. The signal-to-noise ratio is lower during the delayed period compared to the prompt response because of the concurrent neutron flux hitting the detector. Pulsed neutron sources are used to increase the signal-to-noise ratio during periods of time when the neutron beam is off. Shielding the gamma detector from the isotropic emissions of neutrons is difficult and requires dense materials, adding weight to the system.

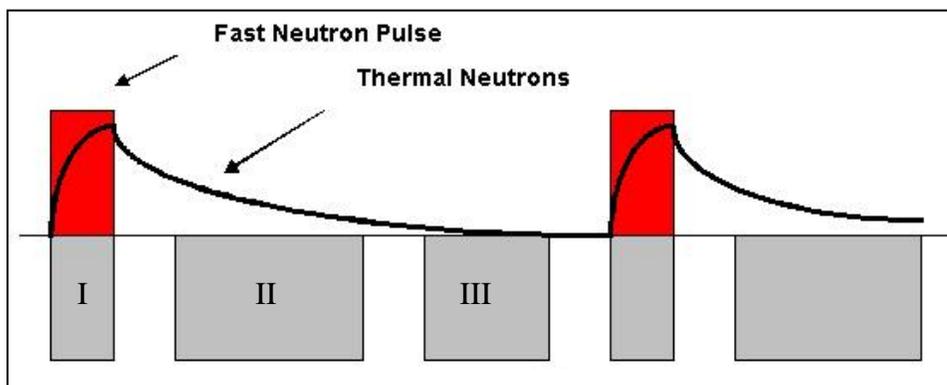


Figure 6. It is useful to identify three temporal regimes for detection of gamma ray backscatter from materials. These include the (I) prompt, (II) radiative capture, and (III) die-away time periods.

Since neutrons have no charge, they only interact with the nucleus of an atom, not with the electrons. The most common type of neutron-induced reaction is the neutron capture reaction (see figure 2). This occurs most often when a thermal neutron (<1 eV) is completely captured in the nucleus, creating an isotope of the atom. The next most common interaction occurs from low energy neutrons, where a neutron fuses with the nucleus. In this way, a compound nucleus forms in an excited state. The excited compound nucleus will very quickly decay to a more stable state through emission of one or more gamma rays (also known as prompt gamma rays). The new state of the compound nucleus yields a radioactive nucleus, which will beta decay into an excited state of another radioactive nucleus, which will then decay by emission of one or more gamma rays (also known as characteristic delayed gamma rays). These interactions are illustrated in figure 7. The emission rate depends on the half-life of each radioactive nucleus. The half-life of radioactive nuclei can range from nanoseconds to billions of years.

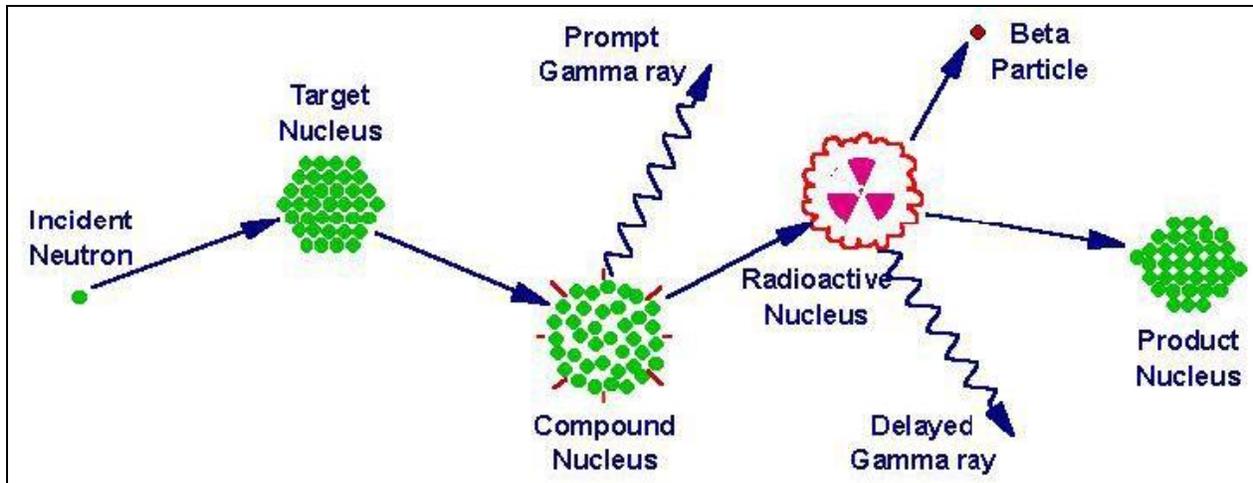


Figure 7. Neutron capture is an inelastic scatter interaction that occurs more often with low/thermal neutrons. The neutron energy absorbed is reemitted as gamma energy in a prompt reaction.

The energy of the gamma radiation emitted by specific nuclei after neutron capture by nuclei has been studied at great length, and tables have been developed that enable identification of a nucleus. When a thermal neutron (<1 eV) is captured by a nucleus, the gamma emitted is unique in energy compared to that emitted by nuclei of another atoms. The gammas emitted by a nucleus of the most relevant atoms in explosives and clutter are shown in table 3. The cross section (σ) for interaction of thermal neutrons with the atom as a function of emitted gamma is also shown in the table. The hydrogen nucleus is the most attenuating/absorbing of the nuclei listed, having the largest cross section compared with other atoms shown. This is because the hydrogen is composed of only one proton and has a great affinity for the incoming neutron, making the system more stable.

The table of emitted gammas described in table 3 is a result of meticulous measurement on accelerators (6–8, 13, 14, 16, 17) using high-sensitivity detection systems in shielded rooms. In a practical real-world environment, the target atoms are not isolated. They are mixed in with other materials that are euphemistically described as clutter. The multiplicity of gamma lines because of background noise and overlap of nearby lines makes identification of the absolute intensity difficult. The most identifiable gamma lines from buried explosives are shown in table 4.

Table 3. Element, gamma emitted(keV), and cross section (barns) is listed. These gammas can be identified in the x-ray backscatter results. From IAEA Neutron Database, Appendix I. Prompt Gamma from Thermal Neutrons.

Element	Thermal gamma (keV)	σ_{total} (b)	Intensity rank
H	2223.24835	0.3326	
	6250	0.000492	
B	477.595	716	
C	4945.301	0.00261	
	1261.765	0.00124	
	3683.920	0.00122	
C	0.998 7	0.00137	
N	1678.24(3)	0.00625(9)	
	1681.17(4)	0.00130(4)	
	1884.85(3)	0.01450(18)	5
	1999.69(3)	0.00321(5)	
	2520.45(4)	0.00425(8)	
	2830.80(5)	0.00133(4)	
	3531.98(5)	0.00686(12)	
	3677.80(5)	0.01140(15)	7
	4508.69(6)	0.01290(21)	6
	5268.98(7)	0.0237(4)	1
O	5297.66(15)	0.0167(3)	2
	5533.25(8)	0.01570(25)	3
	5561.95(8)	0.00863(15)	9
	6322.30(9)	0.0149(3)	4
	7298.90(10)	0.00772(16)	10
	8310.17(13)	0.00336(9)	
	9149.24(17)	0.00133(6)	
	0829.10(21)	0.0107(4)	8
	870.68(3)	1.75(11)E-4	
	1087.71(3)	1.51(9) E-4	
Si	2184.38(4)	1.75(11)E-4	
	3272.11(7)	3.53(25)E-5	
Si	1273.38(3)	0.0289(6)	4
	2092.91(3)	0.0330(6)	3
	3538.98(5)	0.1180(20)	1
	3660.73(6)	0.00705(21)	7
	4933.83(7)	0.1120(23)	2
	5106.60(10)	0.0065(3)	8
	6379.75(11)	0.0210(6)	5
	7199.02(13)	0.0127(4)	6

Table 4. Measured peaks from the most abundant elements in explosives.

Element	E_{γ} (MeV)	Capture	Prompt
N	10.8	(n, γ)	
N	5.11		(n,n' γ)
N	2.31	(n, γ)	
N	1.64	(n, γ)	
N	10.8	(n, γ)	
N	10.3		
Fe	7.63	(n, γ)	
H	2.2	(n, γ)	
Si	3.9	(n, γ)	
Si	4.2	(n, γ)	
Si	4.9	(n, γ)	(n,n' γ)
O	6.13		(n,n' γ)
C	4.43		(n,n' γ)
H	2.23	(n, γ)	

The measured peaks must be compared to the background environment. A sample from simulation shows that the error of carbon is large compared to the other elements. This is because the prompt emission from the carbon atom occurs while still in recoil and Doppler shift is significant. The abundance of carbon (therefore, the multiple locations within the field of view) contributes to the errors in absolute magnitude.

2.5 X-ray Backscatter Analysis Techniques

A variety of analysis techniques exist for neutron-activated x-ray-backscatter. The choice of technique is highly dependent on the application space (22). Analysis techniques are compared in table 5. Slower neutrons have a higher cross section for absorption than fast neutrons. Neutron absorption by an atom with gamma emission is denoted as (n, γ) interaction.

Table 5. Characteristics of neutron induced analysis techniques on materials.

#	Technique Name	Probing Radiation	Main Nuclear Reaction	Detected Radiation	Sources	Primary and Secondary Detected Elements
1	TNA (Thermal neutron analysis)	Thermalized neutrons	(n,γ)	Neutron capture γ-rays/prompt & delayed neutrons and γ rays for SNM ²	²⁵² Cf, also accelerator based sources (ENG ¹)	Cl, N, SNM**
						H, Metals, P, S
2	FNA (Fast neutron analysis)	Fast (high energy, usually 14 MeV) neutrons	(n,n'γ)	γ-rays produced from inelastically scattered neutrons	ENG based on (d,T)	O, C (N)
						(H) Cl, P
3	FNA/TNA	Pulsed neutron source; fast neutrons during the pulse, thermal neutrons between pulses	(n,n'γ) + (n,γ)	During pulse (FNA), after pulse (TNA)	μs pulsed ENG based on (d,T)	N, Cl, SNM
						H, C, O, P, S
4	PFNA (ns Pulsed fast neutron analysis)	Nanosecond (ns) pulses of fast neutrons	(n,n'γ)	Like FNA w/TOF ³ /prompt & delayed neutrons and γ rays for SNM	ns pulsed (d,D) accelerator with E _d ~6 MeV	O, C, N, Cl, Others, SNM
						H, Metals, Si, P, S, Others
5	API (Associated particles inspection)	14 MeV neutrons in coincidence with the associated α-particles	(n,n'γ)	Like FNA in delayed coincidence with α	(d,T)	O, C, N
						Metals
6	NRA (Neutron resonance absorption)	Nanoseconds pulsed fast neutrons (0.5-4 MeV), broad energy spectrum	(n,n)	Elastically and resonantly scattered neutrons	Accelerator based ns pulsed (d,Be) or (d,D) w/angular correlation, with E _d ≥4 MeV	H, O, C, N
						(Others)

¹ENG: Electronic Neutron Generator – can be based on neutron production processes such as (d,D), (d,T), (d,Be), (p,Li), (p,Be).

²SNM: Special Nuclear Materials –e.g., fissile isotopes ²³⁵U and ²³⁹Pu.

³TOF: Neutron Time of Flight method.

Thermal neutron analysis (TNA) is by far the most commonly used because it is the least complex in implementation. The lower energy neutrons from californium-252 (0.7–4 MeV) and deuterium-on-deuterium (D-D) electronic neutron generators (ENG) (2.5 MeV neutron output) are most applicable. Slower neutrons have a higher cross section for absorption by atoms than do fast neutrons.

In fast neutron analysis (FNA), x-rays are produced from inelastic scattered (n, n'γ) neutrons. Pulsed fast neutron analysis (PFNA) is technique that allows the separation of fast neutrons from slow/thermal neutrons. The fast neutrons occur in inelastic collisions denoted as (n, nγ), while the thermal neutrons are generated after multiple collisions from the original fast neutron. The higher energy 14.1-MeV neutron flux from deuterium-on-tritium (D-T) ENG are not absorbed by atoms until many inelastic collisions occur, at which point their energy has been knocked down to thermal-energy levels. Naturally, the delayed signal from the thermal/slow neutrons can be measured with less background if separated in time from the neutron pulse. This noise reduction

capability can make a difference when high spectral resolution, excellent statistical estimations, and detailed analysis are required.

Associated particle imaging (API) is a technique that appears to be most useful because both location and atomic ratios can be identified from unknown materials. Location is measured by tagging the time and direction of emitted neutrons. By measuring alpha particles that are emitted at 180° to the neutron, time and direction can be tagged for each neutron. Distance of interaction is deduced from the time-of-flight (TOF) information. Angle of emission is deduced from the gridded alpha detector behind the neutron converter.

API can be added on D-T accelerators. The nuclear reaction in a D-T tube is ${}^2_1\text{D} + {}^3_1\text{T} \rightarrow {}^4_2\text{He}$ (3.5 MeV) + n_0 (14.1 MeV). The accelerated deuteron (one proton and one neutron) hits the tritium (one proton and two neutrons) target, creating an alpha particle/helium atom (two protons and two neutrons) and an energetic neutron. (No alpha radiation is emitted in D-D reactions.) The alpha and neutron are emitted 180° from each other. An alpha detector located behind the “forward direction” identifies the time and direction of the alpha, providing information for time-tagging the emitted neutron and its direction. After the neutron interacts with the target atom, the emitted gamma is captured. The location of the target atom can be identified by using the direction from the alpha-correlated neutron and the TOF of the captured gamma.

Neutron resonance analysis (NRA) is another analysis technique, which requires variable energy neutrons (white spectrum). Neutron TOF is measured using short (ns) pulses in order to discriminate the pulse-to-pulse timing. A more expensive and larger source of neutrons is required to perform this (n, n) reaction analysis.

3. Sources of Neutrons

3.1 Radioisotope-induced Neutron Sources

3.1.1 Gamma-induced Sources of Neutrons, (γ , n) Reactions

A number of reactions with γ are known to create neutrons (7, 8). A configuration commonly used is a cylindrical vessel, containing a cylinder of radioactive isotope emitting gammas, surrounded by a target material of heavy water (D_2O) or Be^9 . Gamma radiation, with an energy exceeding the neutron binding energy of the nucleus, can eject a neutron. Two example materials are beryllium and hydrogen, with their decay products:

- ${}^9\text{Be} + \gamma \rightarrow n + 2 {}^4\text{He}$ for $\gamma > 1.7 \text{ MeV}$
- ${}^9\text{Be} + \gamma \rightarrow n + {}^8\text{Be}$ for $\gamma > 1.3 \text{ MeV}$
- ${}^2\text{H}(\text{d}) + \gamma \rightarrow n + {}^1\text{H}$ for $\gamma > 2.26 \text{ MeV}$

The γ emissions of decaying isotopes that bombard the heavy water and beryllium are known to generate neutrons, yielding the flux as shown in the last column of table 6. The largest flux of neutrons comes from antimony-124. However, sodium-22 is a more commonly available isotope.

Table 6. Gamma induced neutron generation has been measured in these decaying isotopes.

Isotope	E_γ	Target	E_n	10^6 n/Ci-s
Na ²⁴	2.76	D ₂ O	0.27	2.7
Na ²⁴	2.76	Be ⁹	1.0	2.4
Ga ⁷²	2.5	D ₂ O	0.16	0.64
Ga ⁷²	2.5	Be ⁹	0.32	1.04
La ¹⁴⁰	2.5	D ₂ O	0.151	0.062
La ¹⁴⁰	2.5	Be ⁹	0.75	0.041
Sb ¹²⁴	1.67	Be ⁹	0.024	3.2

3.1.2 Alpha-induced Sources of Neutrons (α, n) Reactions

Neutrons are produced when alpha particles impinge upon isotopes of lithium, beryllium, carbon, and oxygen. These nuclear reactions can be used to construct a neutron source by mixing a radioisotope that emits alpha particles, such as radium or polonium, with a low atomic weight isotope, usually in the form of a mixture of powders of the two materials. Typical emission rates for alpha reaction neutron sources range from 10^6 to 10^8 neutrons per second. As an example, a representative alpha-beryllium neutron source can be expected to produce approximately 30 neutrons for every one million alpha particles. The useful lifetime for these types of sources is variable, depending upon the half-life of the radioisotope that emits the alpha particles. The size and cost of these neutron sources are comparable to spontaneous fission sources.

Usual combinations of materials are as follows:

- plutonium-beryllium (²³⁹Pu⁹Be),
- americium-beryllium (²⁴¹Am⁹Be),
- americium-lithium (²⁴¹Am⁷Li), and
- radium-beryllium (²²⁶Ra⁹Be).

The neutron initiators of early nuclear weapons used a polonium-beryllium layer separated by nickel and gold until a neutron pulse was desired.

3.1.3 Spontaneous Fission (SF) Producing Neutrons from Isotopic Sources

The most common industrial/commercial neutron isotope is ²⁵²Cf (9). A government program for production of californium is centered at Oak Ridge National Laboratory (ORNL) high-flux-reactor (HIFR). Californium is used to start up new power reactors and provides a continuous neutron flux for industrial use (i.e., logging, oil). The price of a typical ²⁵²Cf neutron source is

\$20,000. The spontaneous fission neutron spectrum of ^{252}Cf from 0.2 to 7.0 MeV has been measured (10) using TOF techniques. Proton recoils in emulsions were used to study the higher energy neutrons. The measured neutron spectrum can be described by the empirical relation:

$$N(E) \propto \exp^{-0.88E} \sinh[2E]^{1/2}, \quad (1)$$

where $N(E)$ is the number of neutrons of energy E per unit energy interval and E in units of MeV.

3.2 Neutron Generation from Accelerators

Particle accelerators are used to accelerate charged particles. The energetic charged particles can then be used to generate neutrons. A deuteron (d) is composed of a proton and a neutron, in comparison to a single proton for hydrogen atom (6, 77, 28). The D-D reaction can occur with accelerating energies as low as 50 keV deuterons even though the binding energy for the neutron and proton in the deuteron is 2.2 MeV. This low energy interaction is possible because the coulomb barrier is small for these single-particle atoms. Some of the common deuteron interactions with a high yield of neutrons are shown in table 7. Tritium (t or ^3H) is composed of a proton with two neutrons. The deuterium-tritium (D-T) reaction yields a 14.1-MeV neutron, higher than the D-D reaction neutron of 2.5 MeV.

Table 7. Common nuclear reactions for deuteron accelerators.

$\text{H}^2 + d \rightarrow \text{He}^3 + n$ (2.5 MeV)	(D-D reaction)
$\text{H}^3 + d \rightarrow \text{He}^4 + n$ (14.2 MeV)	(D-T reaction)
$\text{Li}^7 + d \rightarrow \text{Be}^8 + n$	
$\text{Be}^9 + d \rightarrow \text{Be}^{10} + n$	

The most common compact accelerators now use the D-D reaction to produce a 2.5-MeV neutron and a D-T tritium target for a 14-MeV neutron. The Be^9 interaction with deuteron is the highest yield. Beryllium however, is a hazardous carcinogenic compound in most forms (20).

While neutrons are emitted isotropically, the energy varies with angle (15). The interaction energy ($Q=3.98$ MeV for D-D) is conserved but the outgoing neutron energy (E_n) energy varies as

$$3Q=4E_n - E_d - 2\cos\theta(2E_d E_n)^{1/2} \quad (2)$$

Incoming deuteron energy (E_d) remains constant, but E_n varies with angle. When $\theta = 90^\circ$, $E_d = 1$ MeV then $E_n = 3.2$ MeV for D-D reaction. This is defined as an exothermic reaction, positive Q , because the kinetic energy of the products is greater than the kinetic energy of the input reactants $d+H^2$.

3.2.1 Compact Accelerators

Several manufacturers of compact neutron sources have developed industrial products for the geological needs of the logging and oil well industries (12). The neutron generators are used to

identify the geological surroundings through the identification of the organic materials present. It is precisely these organic material identifying capabilities that make the neutron activation technique useful for organic material composition in IEDs.

The two nuclear reactions commonly found in compact neutron accelerators are the D-D and the D-T type (figure 8). The D-D is a deuteron (p,n) thrown at (accelerated towards) another deuteron, stationary target. The cross section for interaction is shown in figure 9. The neutron emitted from the D-D reaction is a 2.5-MeV neutron. The D-T event occurs when a deuteron (p,n) is thrown at a tritium (p,n,n) target. The cross section for interaction is about 1.2×10^{11} neutrons generated for each mC of 150 kV accelerated D (16). The cross section curve increases to an exponential flattop after 150 kV as shown in figure 9. The neutron emitted from the D-T reaction is a 14-MeV neutron (13). The D-T generated 100 times more neutrons per coulomb of charge than the D-D reaction. These devices are commercially available from Thermo-Scientific Inc. (U.S.), EADS-Sodurn (FR), DelMar Ventures Inc. (Russian), and Adelphi Laboratories (U.S.). Many research ideas are being pursued and are discussed in section 7.

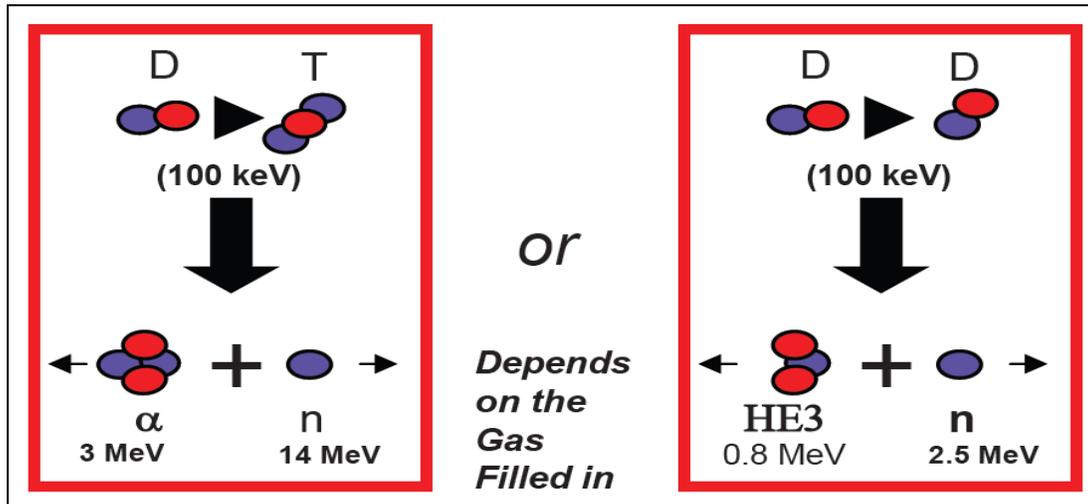


Figure 8. Nuclear reactions used in compact accelerators use the D-D and D-T reactions.

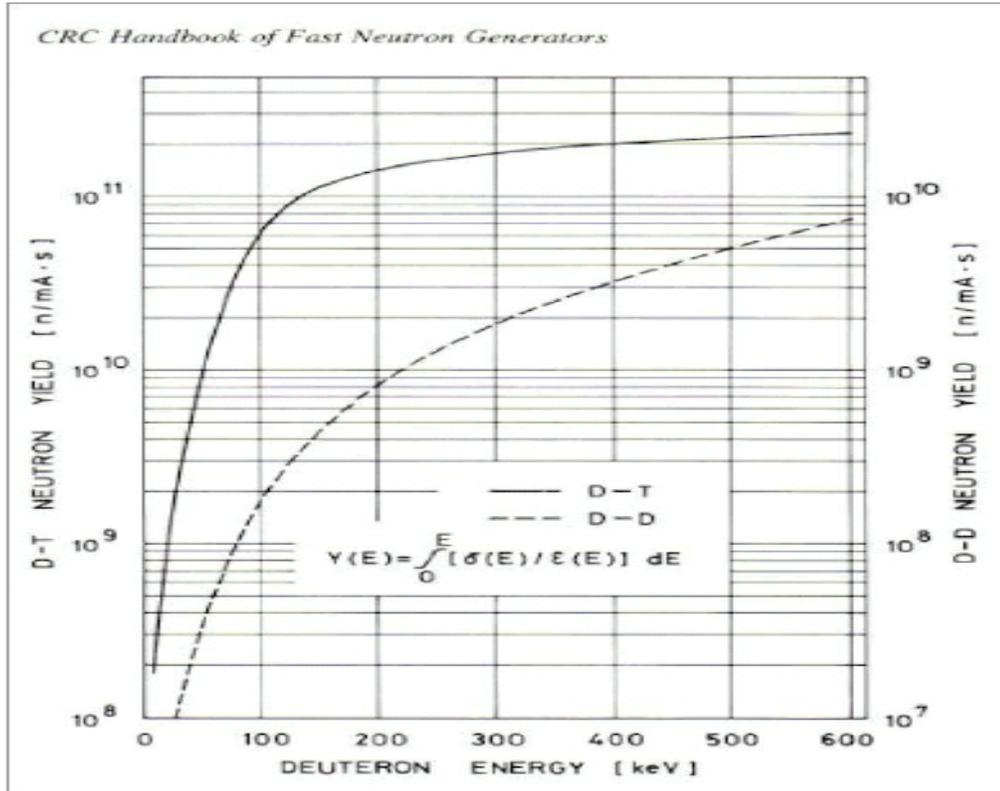


Figure 9. Cross section for the interaction in units of neutrons generated per mC thrown at a target.

The compact accelerator is composed of the (1) ion source, (2) accelerating region, and (3) target section. The ion source is often a low pressure gas, cold cathode source (penning trap) requiring crossed electric and magnetic fields to contain the ions until they are accelerated from the cathode region. The schematic of a generic neutron tube is illustrated in figure 10.

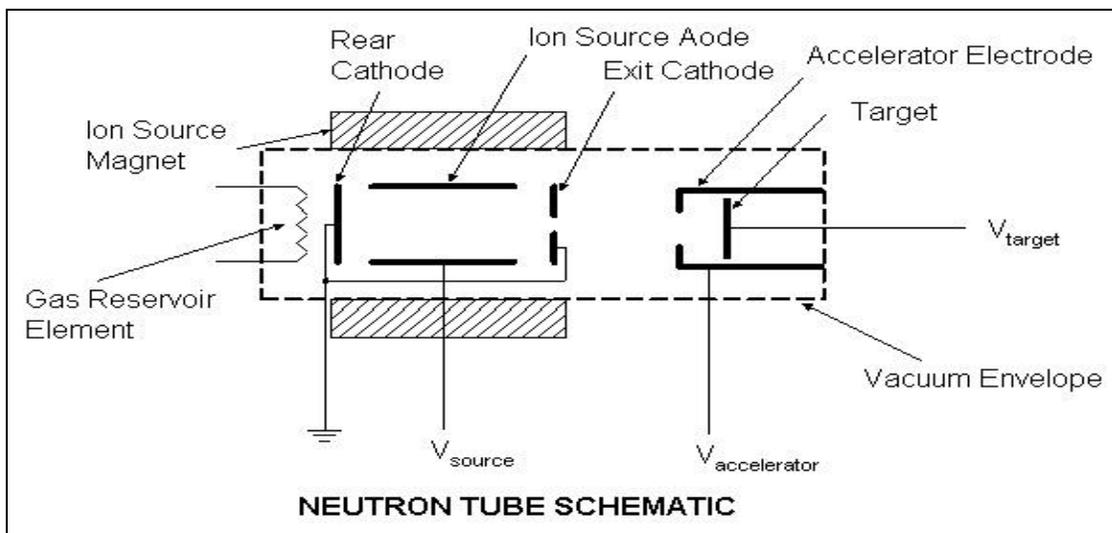
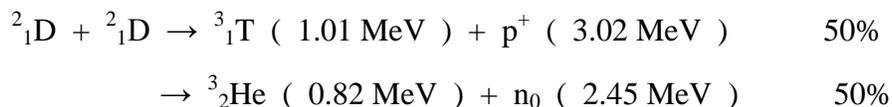


Figure 10. Generic neutron tube schematic.

The target is usually composed of a thin film made of a metal such as titanium, scandium, or zirconium, which is deposited on a copper or molybdenum substrate (14). Titanium, scandium, and zirconium form stable chemical compounds called *metal hydrides* when combined with hydrogen or its isotopes. These metal hydrides are made up of two hydrogen (deuterium or tritium) atoms per metal atom and allow the target to have extremely high densities of hydrogen. This is important to maximize the neutron yield of the neutron tube. The gas reservoir element also uses metal hydrides as the active material. All MF Physics neutron tubes are designed such that the gas reservoir element and the target each incorporate equal amounts of deuterium and tritium. In these mixed gas tubes, both the ion beam and target contain 50% deuterium and 50% tritium. This allows the tubes to have very stable neutron yields over their operational life.

The reactions that take place in a D-D tube have equal branching ratios. Therefore, only half the time will the API technique produce the desired neutron for the analysis technique:



The additional location information available from the APUI technique is significant. It permits 3-D spatial identification of target atoms; eliminates the need to gather information about the background environment, saving operational time and offers better signal-to-noise ratios and better statistical figures in the final results.

3.2.2 Spallation Sources

Fragments of material (spall) are ejected from a target because of impact from a heavier/fast moving particle. Protons (or, in some cases, heavy ions) are accelerated to collide with a heavy (high Z) metal atom such as tungsten or uranium. Protons at the Los Alamos Nuclear Science Center (LANSCE) are produced in an accelerator, and then stored in a ring where the 800-MeV protons are liberated 20 times a second in 1- μs bursts. Each proton generates about 20 neutrons. The 27-MeV energy deposited in the spallation target per neutron is small compared to the energy produced in a reactor (about 5 times as much) per neutron. The flux expected from the Spallation Neutron Source (SNS) at Oak Ridge is $\sim 10^{17}$ n/cm²/s as compared to the existing LANSC) 800-MeV protons' 10^6 n/cm²/s per pulsed, which only occurs a few times a day.

3.3 Neutron Generation from Reactors

The primary output of a uranium-based nuclear reactor is neutrons. The largest flux reactor, specially designed for this purpose, is the Oak Ridge National Laboratory's HIFR located in Oak Ridge, TN. The neutron flux is 10^{15} n/cm²/s. The largest university operated reactor is located at University of Missouri Research Reactor (MURR) Center (11). The neutron flux is 10^{14} n/cm²/s. Over half of the medical isotopes in use in the United States come from this reactor.

4. X-ray Detectors

Detection of photons, packets of energy with no rest mass and no electrical charge, is measured as wavelength, frequency, or energy. Energy, expressed in units of electron volts (eV), is commonly used in nuclear detection, typically thousands or millions of electron volts, keV and MeV, respectively. X-ray photons and gamma-ray photons of the same energy are identical. However, they are generated in different ways. Gamma rays originate in processes in an atom's nucleus. Each radioactive isotope that emits gamma rays does so in a unique energy spectrum, as in figure 11, which identifies an isotope. X-rays originate in interactions with an atom's electrons.

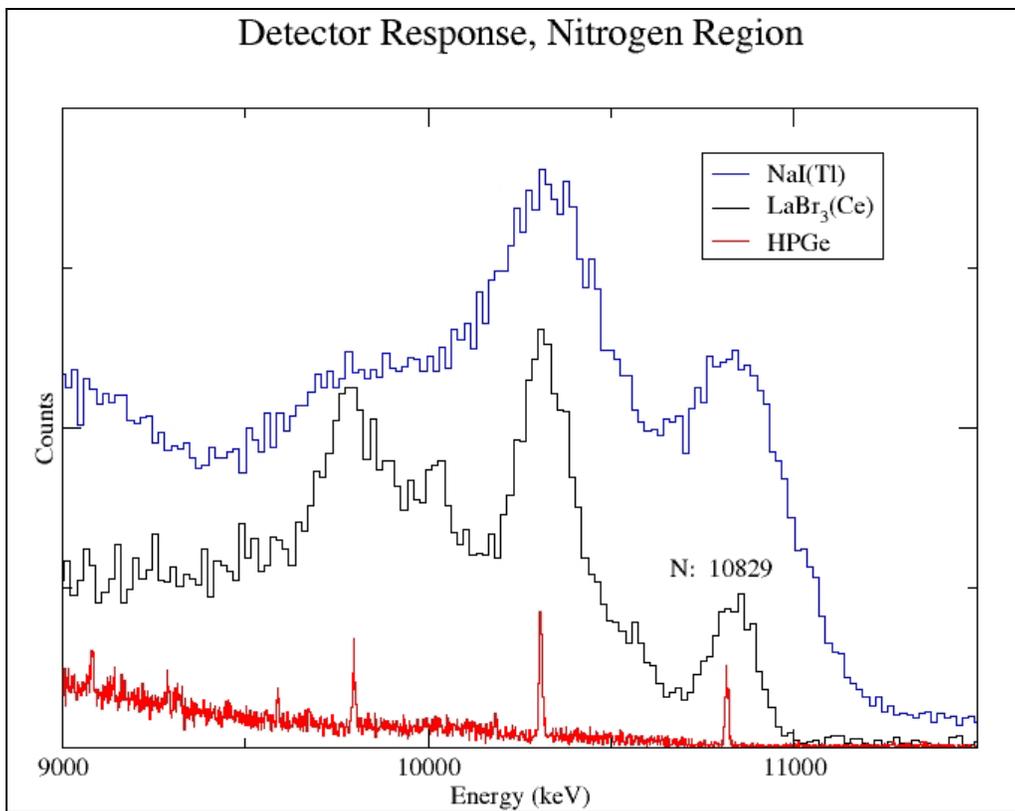


Figure 11. X-ray spectra showing number of counts vs. gamma energy. The resolution of the measurable lines varies with detector.

Detectors require a signal-to-noise ratio high enough to permit detection. Noise is caused by natural background radiation. Detector sensitivity is primarily determined by (1) detection efficiency and (2) spectral resolution. Efficiency refers to the signal strength a detector can output to a recording device. Radiation intensity (e.g., number of photons per unit of area) diminishes with distance and typically falls-off as $1/\text{distance}^2$. As the location of detector gets farther from radiation source, or reduces size (aperture) the efficiency decreases. Spectral

resolution refers to the sharpness of peaks in a gamma-ray spectrum. A perfect detector would record a spectrum as vertical “needles” because each radioactive isotope releases gamma rays only at specific energies. Since detectors are not perfect, each energy peak is recorded as a Gaussian curve. The narrower the curve, the more details available to identify the radiation source.

4.1 Scintillation Detectors

X-rays enter a scintillation material, which emits an optical photon because of x-ray interaction with the electron shells. The optical photon is collected by a photomultiplier tube, which creates a burst of electrons from the burst of optical photons. The electrical pulse is measured for height. The height of the electrical pulse is related to the number of optical photons collected (and therefore the number of x-rays hitting the scintillator). The energy deposited in the scintillator corresponds to the number of photons generated and the x-ray energy.

Common scintillation materials are made of crystal, plastic, or liquid. Sodium iodide (NaI) is a crystal that has been used since the 1950s and is one of the most common scintillating materials. It is very sensitive (compared to other scintillators) and inexpensive, but is also hygroscopic (absorbs water) so it must be sealed to protect it from water in the atmosphere. Lanthimum bromide (LaBr) is a more recently identified scintillator material. It is more expensive because it is newer, but it is at least two times more sensitive than NaI. More importantly it has a narrower spectral line width (21).

Gamma lines from nuclear transitions are a less than an eV wide. However no detector can measure gamma lines with that level of accuracy for reasons of electronic noise and optical-to-electrical conversion inefficiencies. A comparison of line width is shown in figure 11. The line width of NaI is about 7% at 661 keV, which is larger than that of LaBr at about 3%, and compared to 1% for high-purity germanium (HPGe).

Polyvinyl toluene (PVT), a plastic used in radiation detectors that can be fielded in large sheets at low cost, is efficient but has poor resolution. It is an organic material composed of low atomic number (*Z*) materials. It is not as efficient at converting radiation because it stops less of the radiation. It can detect radiation, but peaks from gamma rays of different energies blur together, which can make it impossible to identify an isotope. It is inexpensive in large quantities and sizes.

4.2 Solid State Detectors

HPGe counters are the most commonly used solid-state detectors. A volume of germanium is doped with n and p regions to form a diode p-n junction. They have excellent spectral resolutions, but require cryogenic cooling to reduce noise in the device. These detectors are expensive and heavy, have a small detector area, and must be cooled to extremely low temperatures with liquid nitrogen, making them less than ideal for use in the field.

A more recent solid-state device made of cadmium zinc telluride (CZT) has been found to be more versatile than HPGe because it does not require cooling to be effective. It is considerably less expensive than HPGe and has a relatively high atomic number, high density, and wide bandgap. CdZnTe detectors with energy resolution of 3.45% (full width at half maximum [FWHM]) at 59.54 keV at room temperature have been developed for x-ray fluorescence analysis. The sensitivity of CZT is greater than HPGe, but the spectral line widths are greater than HPGe. In figure 12, these characteristics are shown and compared to the NaI scintillator discussed earlier.

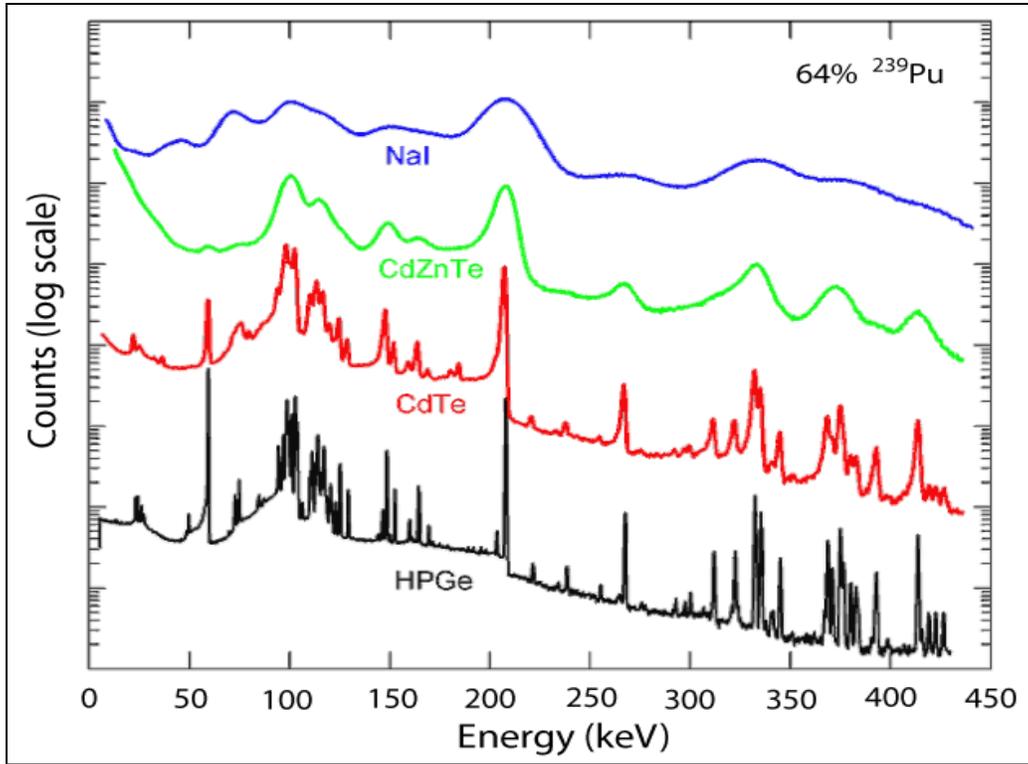


Figure 12. Response of solid-state detectors compared to NaI (most sensitive).

Choice of detector can be critical for materials detection (see section 4.1). NaI detectors are inexpensive in comparison to LaBr and Ge detectors. NaI and LaBr are crystal scintillators that require no cooling during operational use. HPGe detectors provide the best energy resolution, which makes it easy to discriminate between gamma energies that may lie very close to each other or may be overlapping. In the present application of neutron interaction, many of the resonances are as high as 11 MeV. In this case, higher Z materials are more efficient. In addition, NaI produces continuum response in 8–9 MeV (27).

5. Monte-Carlo Simulation

The neutron emission, target scatter, and gamma collection processes were simulated using MCNPX. MCNPX is a legacy code from Los Alamos National Laboratory backed by many years of validations. The code is also actively being updated with more capabilities. These simulations are useful in understanding the limitations of the process.

The geometry chosen to understand some of these limitations first included a neutron beam oriented directly above the target (explosive). In this simplified model, the neutron beam is generated above the target from the positive z -direction as illustrated in figure 13. The polygon labeled cell 5 models the high-density polymer shield that is composed of hydrogen chains. Hydrogen is a very good absorber of neutrons because the single proton in the hydrogen atom has great affinity for the neutron of the beam. The high density poly shields the gamma detector (cell 6) composed of a NaI crystal from the direct exposure to the neutron beam. The target explosive is shown as cell 3 in figure 13. The model results described vary the explosive material of the neutron emission from the ENG.

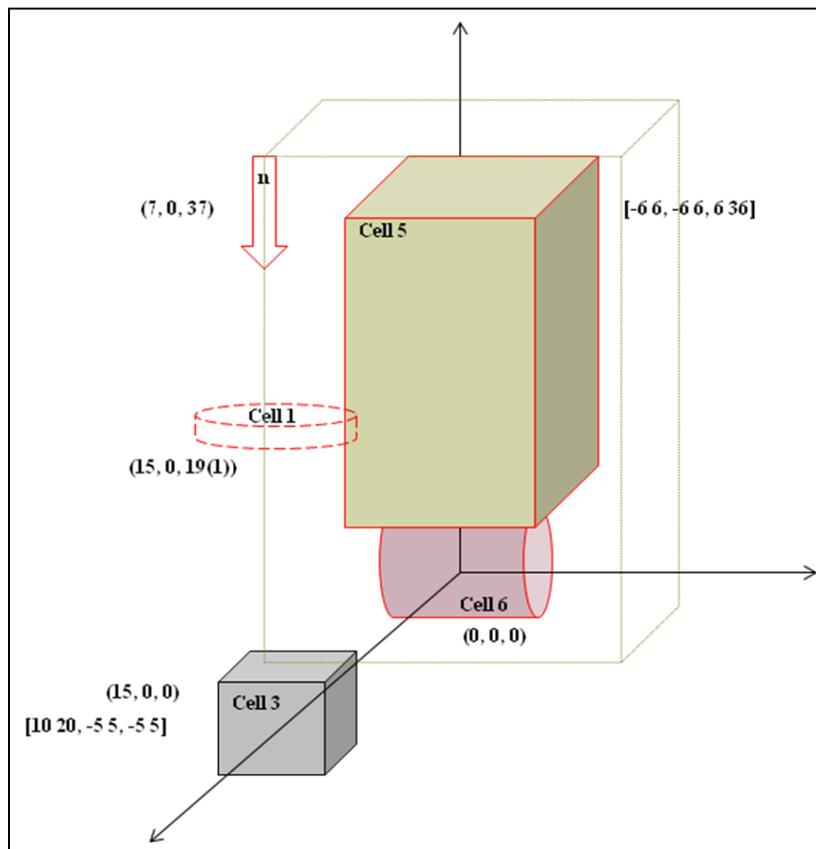


Figure 13. Geometry defined in MCNPX to simulate the γ -spectra collected by NaI detectors (cell 6) from target (cell 3).

A comparison of the gamma spectrum collected in cell 6 (NaI detector) shows that the signal-to-noise ratio is degraded with the insertion of clutter. Materials in the path between the neutrons and target explosive (cell 3) introduce noise into the gamma spectrum. Noise here is defined as signal other than from the explosive, where the goal is to define the explosive from the gamma spectrum. Clutter may be generated from material in the ground if the target is buried or larger volumes of air as the target is moved further from the neutron source and gamma detector. While the size of the gamma line intensity from the explosives does not change significantly as a result of distance or physical clutter, the noise background increases, reducing the signal-to-noise ratio. As a result, the gamma line counts of interest can be hidden in the background noise. If not hidden totally, the relative intensity is reduced compared to the background, the signal is harder to detect, and therefore, less statistically significant. The impact is that many more counts must be collected (more time) for a clean determination of the materials present in the target. As an example, the background level rises by a factor of two when the target was buried in 15 cm of sand, when compared to the air surrounding the explosive (in an aboveground measurement). For a measurement in the sand to have the same statistical validity, the collection time would have to be four times longer.

A parametric study was performed by moving the neutron beam and the target further away from the NaI gamma detector (figure 14). The result showed the expected $1/r^2$ fall-off of signal as would be expected. This parameter variation was performed in order to validate the simulation geometry.

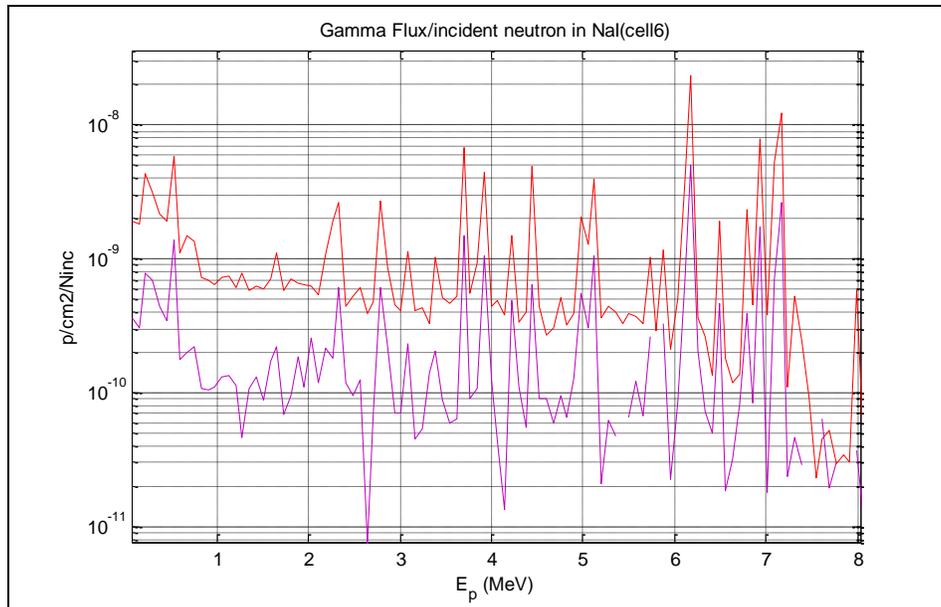


Figure 14. Doubling distance of target reduces signal by factor of four. The neutron induced gamma spectrum of the AN target located 15 (red) and 30 cm (purple) from NaI detector.

The gamma line at 4.43 MeV indicates the presence of carbon as shown in figure 15. The prompt gamma line results from the inelastic reaction $^{12}\text{C}(n,n'\gamma)^{12}\text{C}$ when neutrons have energy

greater than 5 MeV. Numerical results show the background-subtracted gamma spectra. The intensity of the carbon-indicator gamma line decreases proportional to the carbon content. Targets [C(green), C4(red), AN(blue)] are located 15 cm in (a) air and (b) sand from the NaI detector. The chemical formula for the explosive C4 is $C_3H_6N_6O_6$, which has ~14% the number of carbon atoms of a solid block of carbon. In addition, the density of the carbon (2.3 g/cc) compared to C4 (1.82 g/cc) reduces the number of carbon atoms in C4 to 0.11 that of carbon block. The calculated results of the simulation show a signal strength reduced by $2/21=0.95$, within 5% of what would be expected. The chemical formula for ammonium-nitrate is NH_4NO_3 has no carbon, so should appear as background/noise signal only.

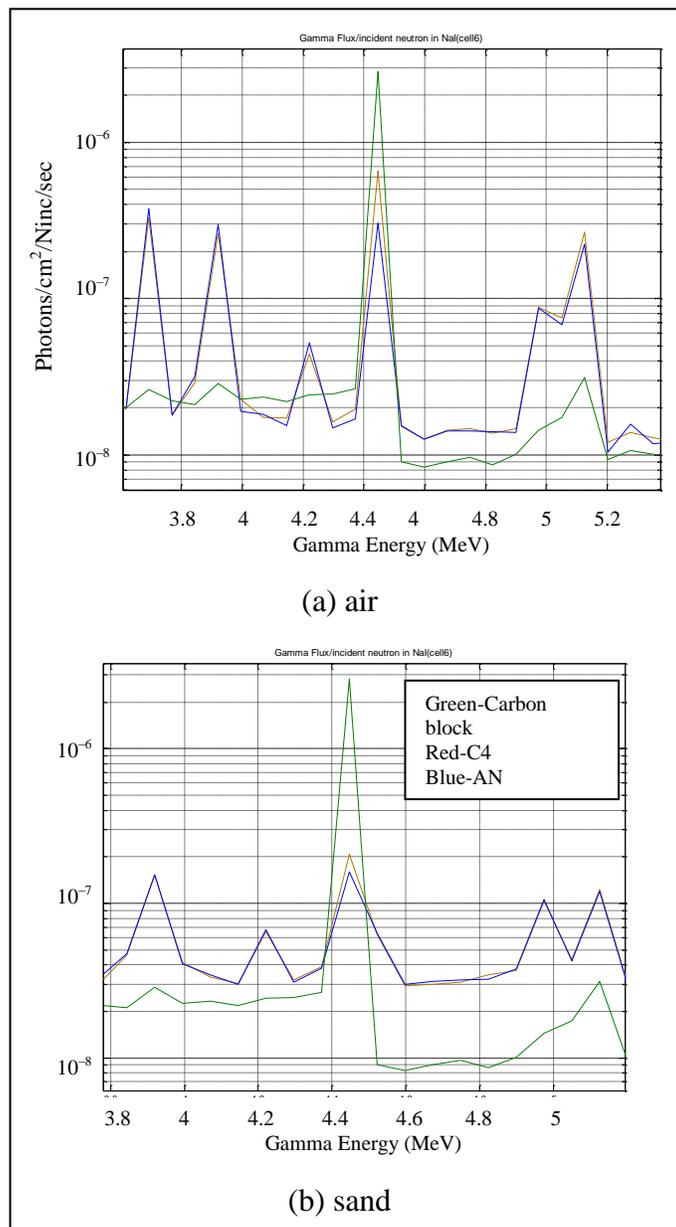


Figure 15. The gamma line at 4.43 MeV indicates carbon in the two explosive targets, each of 1000cc. The resolution of the energy bins shown is 62.5 keV in these

simulations. The signal strength is 10 times reduced when buried in sand.

6. Safety Issues

The recommended exposure limits for radiation workers is limited to 5 R/yr (50 mSv/yr) by the International Commission on Radiological Protection (ICRP). Most laboratories set lower limits based on the as low as reasonably achievable (ALARA) principle. A lethal dose is defined as a whole body dose that results in 50% mortality in 30 days. This is usually identified as 500 Rads (5 Gy).

The dose from an isotropic source reduces by a factor of four as one moves twice the distance from the source following a $1/r^2$ fall-off. The safety requirement for a flux of 2×10^7 neutrons/s is shown in figure 16. At a distance of 4 m, the dose rate falls below the criteria set by the Nuclear Regulatory Commission (NRC) for safety of the general public, a maximum of 2 mREM/hr, shown with red line in figure 16. The NRC rules also stipulate that the maximum dose a member of the general public can receive in a year is 100 mR/yr. This number is well below the typical level of level of background radiation of 360 mREM/yr accumulated by the general public from natural and manmade sources. Following the ALARA policy convention is performed if 12.5 m radius is enforced for compact electronic generators of neutrons, where the dose rate is 10 times below the legal limit.

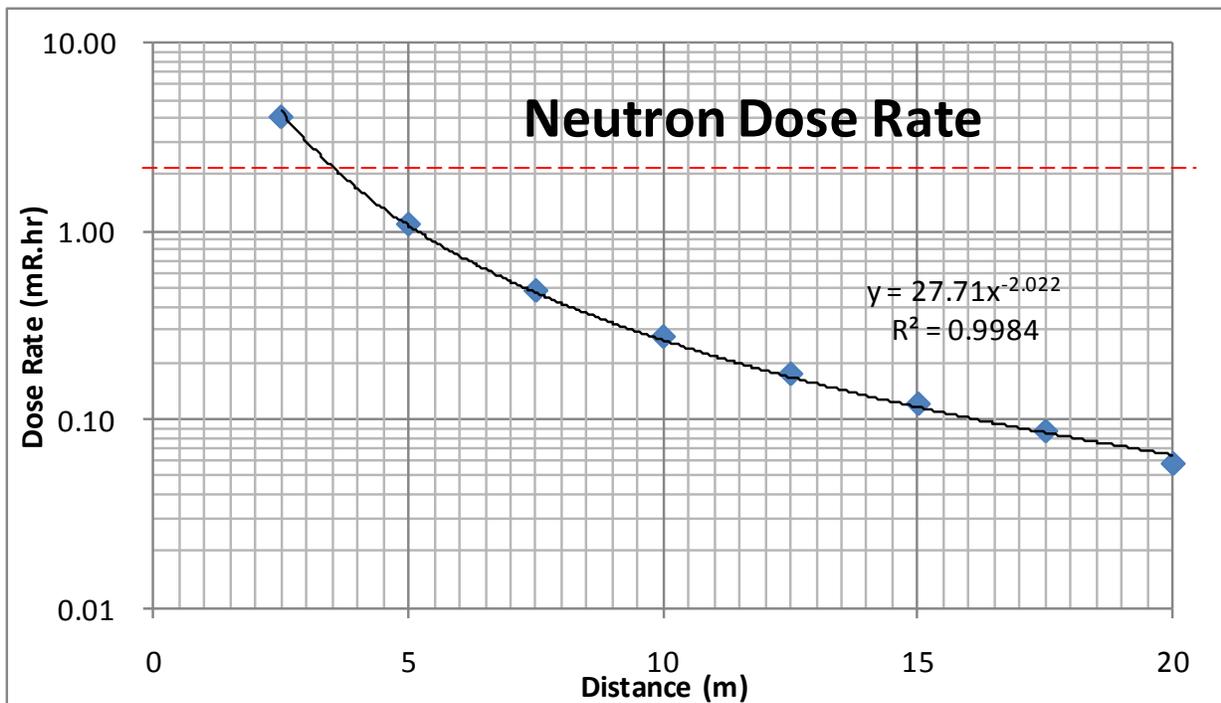


Figure 16. Dose rate as a function of distance from the ENG running at a typical 2×10^7 neutrons per second.

In the human body, the typical reactions and neutron threshold energy for interaction are shown in table 8. The human body contains approximately 68% of ^{16}O , 15% of ^{12}C , and 3% of ^{14}N . While the cross sections for interaction do not reach high levels, they represent potential soft-target weaknesses (22).

Table 8. Major interactions with neutrons in the human body.

Reaction	Neutron threshold Energy (MeV)	Half-life (min)
$^{16}\text{O} (n,2n) ^{15}\text{O}$	16.7	2.1
$^{31}\text{P} (n,2n) ^{30}\text{P}$	12.6	2.5
$^{14}\text{N} (n,2n) ^{13}\text{N}$	11.3	10.0
$^{39}\text{K} (n,2n) ^{38}\text{K}$	13.4	7.7
$^{12}\text{C} (n,2n) ^{11}\text{C}$	20.2	20.3
$^{35}\text{Cl} (n,2n) ^{34\text{m}}\text{Cl}$	13.1	32

Another example of the relevant safety parameters shows that the radiation measured 11 m from an ENG for a period of 10 min is 0.166 mrem. This level of radiation is not only barely detectable with highly sensitive detectors, but 1,000 times lower than normal background radiation received by members of the general public. Another way to look at this is that five 10-min measurements is still less than the 1-mREM dose that would be collected during a leg or arm x-ray for medical purposes. The orders of magnitude difference in radiation are shown in the bar charts of figure 17.

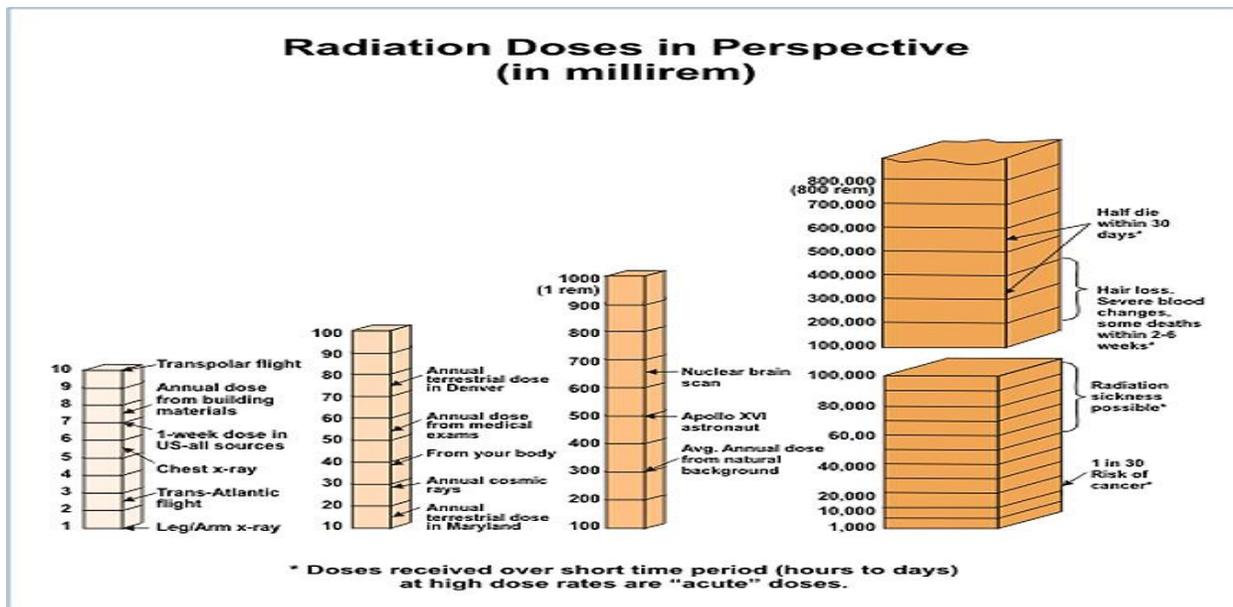


Figure 17. Radiation dose (mRem) is displayed. By separating out the powers of ten (orders of magnitude) of radiation levels, it is easier to show the insignificance of the radiation produced in ENG. Source: <http://www.nrc.gov/images/about-nrc/radiation/factoid2-1g.jpg>.

Neutron interactions in the body have been studied in order to understand the relevant parameters for safety (25). These results have guided regulation and procedure during operational use. The reactions with elements prevalent in the body are shown in table 8. The neutron energy threshold is particularly important in evaluating the threat from a 14-MeV neutron generator. Two of the six elements listed have neutron energy thresholds above 14 MeV and can therefore be considered improbable and are less significant in safety planning.

7. Evolution of the Technology

Commercial requirements for compact, low-power electronic neutrons sources became conventional in the 70s through the commercial requirements of mining and logging. Then, as the state of the art increased, increasing reliability and software tools for efficient analysis of composition and density were developed. Great savings came from identifying the composition of coal as it is mined from the ground (along the conveyer belt) to evaluate grade and composition so a fair price could be determined. In addition to the proper evaluation for price, the buyer now had a tool to identify the quality of coal during delivery. This permitted efficient burning and real-time mixing of a variety of coal qualities within a single shipment.

Materials analysis for scientific activities was the next venue that gained from the increased analytical tools and databases of information that were being developed as a result of the expanded use of the neutron technique. After 911, cargo inspection applications grew. The ever-expanding requirements for (1) deeper penetration into cargo packaging and (2) higher speed analysis/results still exceeds the capabilities of the neutron activation technique. However cargo inspection by neutron analysis is being performed on a regular basis, as a secondary tool, after x-ray analysis provides a visual image. When questionable x-ray images result, specific areas for neutron probing are identified.

7.1 Areas for Improvement

The two areas for improvement would be in (1) compact accelerator reliability/fabrication technology and (2) detector collection efficiency. Unfortunately, compact accelerator technology rarely has high priority. Investigation of micro-laser-powered dielectric particle-accelerators are underway primarily for medical applications but with interesting applications to remote sensing (30). Approaches to increasing flux are being investigated using micro-machined multi-tip cathode arrays to reach neutron flux densities of 10^{10} n/cm² (31). Additional techniques that have developed in high flux sources developed for boron neutron capture therapy (BNCT), found to be an experimental success in cancer treatment (26).

Improved flux on target can result from either a more powerful neutron emitter or a directional beam. The inexpensive approach in a D-T reaction allows for only isotropic emission. Other reactions offer some directionality; however, they require higher energy accelerators. With directional beams comes increased safety because more energy on target reduces the activity. Another path towards reducing the time it takes to get a statistically valid result is by increasing the detector area. This can be accomplished with networked sensor arrays, but no longer provides the compact system approach. The operational needs must dictate the trade-off between detector area and time to acquire valid results.

7.2 Big Changes that Can Make a Difference

Inexpensive, sensitive, and easier to use (no cryo-cooling) NaI detectors have the difficulty of low resolution (broad line width). This makes recognition and line ratio detection more difficult and time consuming. However, improved neural network algorithms are being considered to aid in this process (16). This would allow the system architecture to remain relatively inexpensive and produce better estimates with statistically valid answers in shorter time periods.

8. Summary and Conclusions

This report describes the technical basis for the technologies using neutron-activated gamma-emission techniques. Commercially manufactured systems are available today. The details of the capabilities and features in these systems can best be compared when the technical details are understood. The choices between types of electronic neutron generators are described. The types of γ -detectors are described and compared. The analysis techniques that produce the results within minutes are compared for accuracy, reliability, statistical validity, and speed of acquisition. The potential for use in four identified CONOPS are described.

The technical basis of neutron-activated γ -emission techniques relevant to at least four identified CONOPS have been crudely illustrated. The CONOPS that most likely fit the available hardware include, but are not limited to, (1) eliminate delay in logistics convoys, (2) increase reliability and speed of route/mine clearing, (3) aid dismounted-Soldier urban house-to-house clearing, and (4) provide Explosive Ordnance Disposal (EOD) materials identification. The technique of neutron-activated γ -emission has been proven useful in identifying organic materials hidden from sight. The apparent level of effectiveness could have significant impact in any one of these four CONOPS.

The neutron-activated γ -emission technique works well in the laboratory. Fitting the technical process into CONOPS in a seamless path has not been shown. The potential for successful implementation looks attractive and should be pursued. A suitcase (<100 lb) packed with an ENG and a γ -detector are sufficient to show that nitrogen-based materials are not present within

a 3–5 min period in clutter. This technique works well within 2-ft range for a suitcase-sized system that can be cost effective (\$150–300k).

Neutrons are generated in small compact accelerators. The size, reliability, and intensity are sufficiently developed to be operated reliably in the field. The operational safety of these electronic sources is well understood by the NRC. The rules of acceptable use are clear and have been defined. Members of the general public can be present as long as the sources are operated in a 25-ft radius clear zone. A 4-in long, 4-in diameter γ -detector is sufficient to gather enough data within 5 min to unambiguously identify elemental material composition, but more importantly for some CONOPS, quickly show that no hazard is present.

The next phase of this effort will compare the “ready for prime-time commercially available units,” comparing/measuring which units provide results that are timely, efficient, and cost effective in both eliminating uncertainties and identifying materials. This evaluation occurred in May 2010. The results are classified at this time. In addition, we would like to determine which commercial systems would be ready (or easily modified) for the above explosive material verification application within 6 months.

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List of Symbols, Abbreviations, and Acronyms

3-D	three-dimensional
ALARA	as low as reasonably achievable
Am	americium
API	associated particle imaging
B	boron
Be	beryllium
BNCT	boron neutron capture therapy
C	carbon
Cf	californium
Cl	chlorine
CONOPS	concepts of operation
CW	chemical warfare
CZT	cadmium zinc telluride
D ₂ O	heavy water
D-D	deuterium-on-deuterium
D-T	deuterium-on-tritium
ENG	electronic neutron generators
EOD	Explosive Ordnance Disposal
Fe	iron
FNA	fast neutron analysis
FWHM	full width at half maximum
Gd	gadolinium
He	helium
HIFR	high-flux-reactor

HPGe	high-purity germanium
IEDs	improvised explosive devices
ICRP	International Commission on Radiological Protection (
JIEDDO	Joint Improvised Explosive Device Defeat Organization
LaBr	lanthimum bromide
Li	lithium
N	nitrogen
Na	sodium
NaI	sodium iodide
NRA	neutron resonance analysis
NRC	Nuclear Regulatory Commission
O	oxygen
ORNL	Oak Ridge National Laboratory
Pb	lead
PFNA	pulsed fast neutron analysis
Pu	plutonium
Ra	radium
SF	spontaneous fission
Si	silicon
SNM	special-nuclear-materials
TNA	thermal neutron analysis
TOF	time-of-flight

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