22 Detection of Explosives and Other Threats Using Accelerator-Based Neutron Techniques

T. Gozani

Ancore Corp, an OSI Systems Company, 2950 Patrick Henry Dr., Santa Clara, CA 95054, USA
tsahi@ancore.com

22.1 Introduction

Neutral particles, in particular neutrons and photons, are very suitable for probing deeply and nonintrusively into sealed objects. The main reasons are their good penetration, which makes available two- (and sometimes three-) dimensional radiographic images, and, very importantly in the case of neutrons, the elemental/material information they provide.

Nonintrusive inspection of objects of all sizes, from luggage to shipping containers and from postal parcels to trucks, is a vital component of any national security, from aviation to land and sea ports of entry. The paramount importance of these inspections is more obvious in the era after the 11th of September 2001, as the spectrum of threats is wider and the probability of occurrence more real.

To be effective, inspection technologies need to be sensitive, material-specific, rapid, flexible and automatic. Currently used inspection technologies such as x-ray radiography and vapor/trace detectors are severely deficient in this respect.

Neutron-based technologies, on the other hand, provide accurate, rapid and automatic detection of a wide array of threats: explosives, chemical agents, nuclear materials and devices, other hazardous materials, drugs, etc. The nuclear-based techniques achieve these feats through the production of characteristic elemental gamma rays from nuclear reactions, primarily thermal-neutron capture and/or inelastic scattering of fast neutrons. Small charged-particle accelerators, generating copious numbers of neutrons, are essential sources for these techniques.

22.2 Characterization of Threats

Each threat, for example explosives, chemical agents or fissile nuclear material, differs from benign materials in its chemical and hence elemental composition. This difference makes nuclear, and especially neutron-based, techniques a unique tool for detecting the presence of concealed threats amongst benign cargo.

Many of the threats are made of the basic four "organic" elements: hydrogen, carbon, nitrogen and oxygen. Additional elements found in significant amounts are, for example, chlorine in some explosives, drugs and blister chemical agents, while phosphorus, sulfur and fluorine are present in certain nerve agents. Common fissile nuclear materials are ^{235}U and ^{239}Pu. Examples of elemental compositions of various threats and common benign materials are provided in Table 22.1. The table shows that explosives are typically rich in nitrogen and oxygen and "poor" in hydrogen and carbon. In general, elemental features can be expressed by their absolute values, by ratios of elements or by other functional relationships that allow better material discrimination.

Table 22.1. Examples of elemental compositions of some threats and common benign materials (concentrations of the elements are given in weight %)

Threat	C	H	N	O	P	F	Cl	S	N/H	N/C
Explosives										
C4	21.9	3.6	34.4	40.1	0	0	0	0	10	2
TNT	37	2.2	18.5	42.3	0	0	0	0	8	1
PETN	19	2.4	17.7	60.8	0	0	0	0	7	1
AN (ammonium nitrate)	0	5	35	60	0	0	0	0	7	∞
Chemical agents										
Sarin	34.3	7.1	0	22.9	22.1	13.6	0	0	0	0
VX	49.5	9.7	5.2	12	11.6	0	0	12	1	0
CA (H-Cyanide)	44.5	3.7	51.8	0	0	0	0	0	14	1
HD (mustard gas)	30.2	5	0	0	0	0	44.6	0	0	0
Phosgene	12.1	0	0	16.2	0	0	71.7	0	NA	0
Common benign										
Water	0	11.1	0	88.9	0	0	0	0	0	0
Paper	44	6	0	50	0	0	0	0	0	0
Plastic	86	14	0	0	0	0	0	0	0	0
Salt	0	0	0	0	0	0	60	0	NA	NA

22.3 Nuclear Reactions and Signatures

Detection of elements relies on the ability of the neutrons to efficiently interact with them, that is, to have a high enough interaction cross section, and the fact that the interaction results in the emission of detectable gamma rays, and in a few cases neutrons.

The nuclear interactions most employed for inspection and real-time assay are neutron capture and inelastic scattering. The signature emission in the former is the gamma rays from deexcitation of the $A + 1$ nucleus created

in the reaction (A is the atomic mass). Inelastic neutron scattering leaves the scattering nucleus in an excited state, and its deexcitation leads to the emission of characteristic gamma rays.

The neutron capture cross section (for which the common symbol is $\sigma(\mathrm{n}, \gamma)$) is in general (except for strong resonances in some elements) inversely proportional to the velocity (and hence the square root of the energy) of the neutron. Thus the lower the energy, or the more "thermalized" the neutrons are, the higher the cross section. In principle, all types of nuclei undergo thermal capture, though with vastly different cross sections. Oxygen is practically undetectable through capture (cross section 0.0002 barn; 1 barn $= 1 \times 10^{-28}\,\mathrm{m}^2$), and carbon also has a very low cross section (0.0035 barn), while hydrogen, nitrogen and most metals are readily detectable through this process. The neutron cross sections for hydrogen and nitrogen are 0.33 and 0.07 barn, respectively. The cross sections for metals are in general higher. The branching ratios (i.e., the percentage of deexcitations leading to the detected gamma rays) are 100% and 14% for H (2.2 MeV) and N (10.8 MeV), respectively. A typical thermal-capture spectrum is shown in Fig. 22.1 (lower curves) and discussed there as part of the conventional

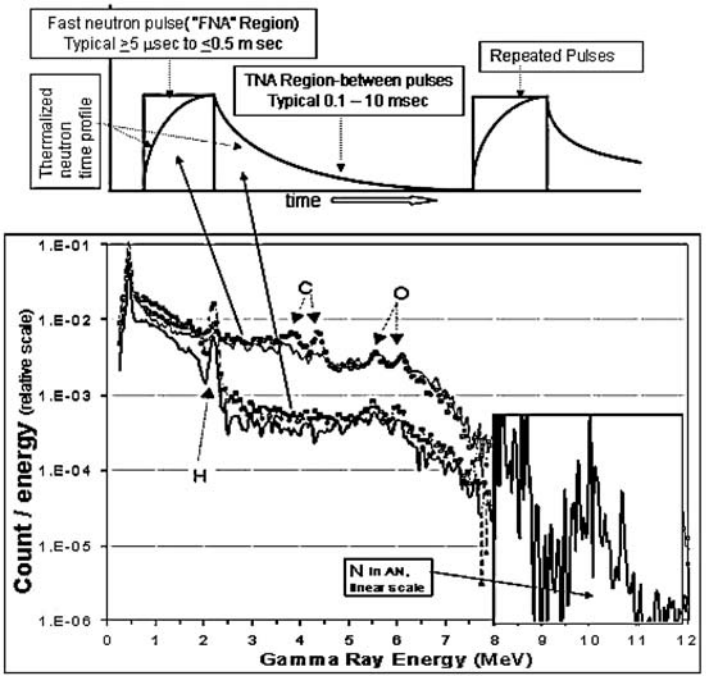

Fig. 22.1. Principles of conventional pulsed-neutron inspection (PNI), utilizing a combination of FNA and TNA techniques. The lower two curves represent the TNA spectra

pulsed-neutron technique. The main features in these spectra are the hydrogen line at 2.22 MeV and nitrogen line at 10.8 MeV (along with their single-escape peaks, which are 0.511 MeV lower).

The inelastic processes have thresholds below which the specific reaction cannot take place. These are approximately 2.6 MeV for nitrogen, 4.8 MeV for carbon and 6.4 MeV for oxygen. The cross sections for these interactions, symbolized by $\sigma(\mathrm{n}, \mathrm{n}'\gamma)$, are generally much lower than $\sigma(\mathrm{n}, \gamma)$. They range from less than 10^{-3} to a few barns. Fortunately, the values of $\sigma(\mathrm{n}, \mathrm{n}'\gamma)$ for the organic elements are among the highest, between 0.05 and 0.5 barn. The behavior of these cross sections as a function of energy and the resulting gamma ray signatures (as detected by NaI scintillation detectors) are shown in Fig. 22.2.

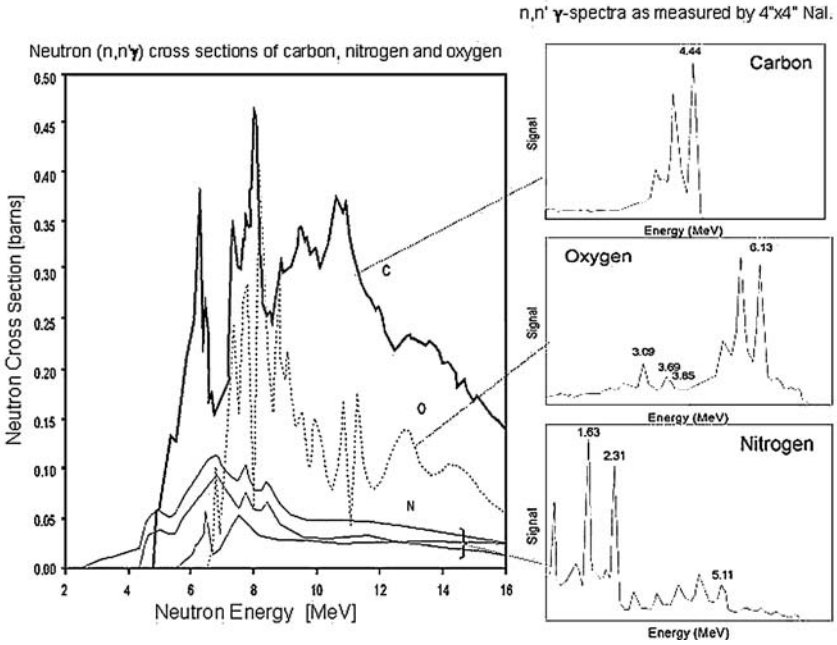

Fig. 22.2. Neutron inelastic cross sections in organic elements (carbon, nitrogen and oxygen) and the resulting gamma ray signatures, as detected by a $10 \times 10 \times 10\,\mathrm{cm}^3$ sodium iodide detector

22.4 Accelerator-Based Neutron Sources

A wide variety of neutron sources can be used as part of nonintrusive material-specific interrogations. When the main nuclear process is neutron capture (n, γ), all accelerator-based sources are usable, as the neutrons are slowed down

in the system, and most of the reactions take place when they are fully thermalized. The selection of the source is then determined by the available intensity, total cost (and cost per neutron), energy of the neutrons (in general, the lower the better), etc. When fast-neutron reactions are the whole or part of the interrogation process, the energy, energy resolution and time structure, in addition to intensity, cost and size, are very critical in the selection process.

Table 22.2 lists possible accelerator neutron sources for interrogation systems. Four categories of sources are included: accelerator-based low-energy (<150 kV, which includes the important class of sealed-tube (d, T) neutron generators), accelerator-based medium-energy (0.5–2 MV), accelerator-based "high-energy" (>2 MV) and others (for example based on photoneutron production employing an electron linac).

Table 22.2. Accelerator-based sources for neutron-based inspection techniques

Nuclear Reaction	Strength (typical) (n/s)	Neutron Energy (MeV)	Neutron Spectrum	Pulsing Capabilities (pulse width)	Typical Repetition Rate	Possible Applications
Accelerator-based: low-energy (<150 kV)						
Sealed tube						
(d, D)	10^6–10^8	3.2	Narrow	>µs	DC–10 kHz	TNA/FNA, fissile detection
(d, T)	10^8–10^9	14	Narrow	>µs	DC–10 kHz	TNA, FNA, fissile detection
Accelerator-based: medium energy (>500 kV–2 MV)						
Electrostatic, RFQ						
(p, Li)	10^8–10^{10}	0.15–1	Narrow	DC–ns; µs	RFQ, 180 Hz	TNA/FNA fissile
(d, Be)	10^9–10^{11}	Variable	Broad	DC–ns; µs	RFQ, 180 Hz	PFNA, fissile
Accelerator-based: "high"-energy (>2 MV)						
Electrostatic						
(d, D)	10^9–10^{11}	Variable	Mono-energetic	ns	1–10 MHz	PFNA, fissile
Electrostatic, cyclotron						
(d, Be)	10^9–10^{12}	Variable	Broad	ns	1 MHz	NRA
Others						
Medium-energy (E< 10 MeV) electron linac, using bremstrahlung photonuclear reaction with a converter						
(γ, Be), (γ, D)	10^9–10^{11}	Broad, "Fission-like"		µs	180 Hz	TNA, fissile

22.5 Generic Neutron Inspection Technologies

Three generic neutron-based inspection techniques can be readily identified: TNA, FNA and NRA. They and their main "derivatives," such as PNI, PFNA and API, are briefly described in textual form in the appendix of this chapter and in numerous articles (see e.g. [1, 2], which include a comprehensive bibliography). Table 22.3 takes a different look at the same three techniques, however, from the point of view of the element detected. It elucidates, the fact that hydrogen can be directly detected by TNA through the (n, γ) process and by NRA through the energy dependence of the neutron elastic-scattering process. Oxygen, carbon and nitrogen can be determined by the FNA and NRA techniques. Nitrogen, however, can also be detected by the TNA process. The ability of the probing neutrons to create a certain fingerprint and its strength depend greatly on the neutron interaction cross section with the chemical element of interest, as discussed in Sect. 22.3.

22.6 Time-Dependent Effects

The TNA technique is the only one that can use either low-cost radioisotopic neutron sources, such as ^{252}Cf, or an accelerator-based electronic neutron generator (ENG). All other techniques require a charged-particle accelerator to generate neutrons. The ENG offers the flexibility of being switched on and off or repetitively pulsed. The latter brings forth the possibility of separating the fast-neutron-induced signals and background from those induced by thermal neutrons. These sources are typically pulsed at 100 to 5000 pulses per second with a corresponding time between pulses of 10 to 0.2 ms and with a typical pulse width of 5 to 500 µs. All the fast-neutron interactions are confined within the pulse. Following the pulse, only the thermal neutrons are present (decaying with a characteristic time constant of the system called the neutron thermal "die-away" time), resulting in a better signal-to-background for neutron capture gamma ray spectroscopy.

ENGs are usually low-voltage (50–150 kV) deuteron accelerators based on the cascade principle (see Box 3). In the most common form, the accelerator tube, target and ion source are all in a small sealed tube. The targets are typically made of tritiated titanium (or scandium) coated on a copper substrate. The most prolific neutron-generating nuclear reaction at low accelerating voltages is (d, T), which generates 14 MeV neutrons. A vehicular explosive detection system employing such a neutron generator is described in Sect. 22.7.

The NRA technique requires either the use of variable-energy (0.5–5 MeV), high-resolution, monoenergetic neutron beams and any sensitive neutron detectors, or a broad-energy (e.g., white-spectrum) neutron beam with a high-resolution neutron spectrometer using the neutron time-of-flight (ToF) technique. The implementation of a variable-energy neutron beam is very

Table 22.3. Basic nuclear-physics characteristics of neutron-based techniques

Element	Generic Technique	Nuclear Reaction	Neutron Energy Range	Effective Cross Section (barn)	Practical Fingerprint (γ-rays or neutrons)
H	TNA	(n, γ)	Thermal	0.33	2.2 MeV γ-ray
H	FNA	(n, n$'\gamma$)	$\leq$14 MeV	0	None
H	NRA	(n, n)*	0.1–5 MeV	10–2	Change in total neutron σ vs. energy
C	TNA	(n, γ)	Thermal	3.5×10^{-3}	Very weak 4.93 MeV γ-ray
C	FNA	(n, n$'\gamma$)	$\leq$14 MeV	$\sim$0.2–$\sim$00.45	4.43 MeV γ-ray
C	NRA	(n, n)*	0.1–5 MeV	A few barns, with a few resonances	A few resonances and other structure in σ
N	TNA	(n, γ)	Thermal	0.011	10.8 MeV γ-ray
N	FNA	(n, n$'\gamma$)	$\leq$14 MeV	0.02–0.1	5.11, 2.31, 1.64 MeV γ-rays
N	NRA	(n, n)*	0.1–5 MeV	A few barns; very few and very narrow resonances	Weak signature
O	TNA	(n, γ)	Thermal	2×10^{-4}	None
O	FNA	(n, n$'\gamma$)	$\leq$14 MeV	0.1–0.4	6.13 MeV γ-ray
O	NRA	(n, n)*	0.1–5 MeV	In excess of 10 barns, many strong resonances	Very strong signature
Cl	TNA	(n, γ)	Thermal	33	6.11 MeV and other strong γ-rays
Cl	FNA	(n, n$'\gamma$)	$\leq$14 MeV	0.15–0.3	1.76, 1.22, 3.16 MeV and other γ-rays
Cl	NRA	(n, n)*	0.1–5 MeV	Weak, low-E_n resonances	Weak signature
"Metals" (Al, Si, Fe etc.)	TNA	(n, γ)	Thermal	0.1–10	Numerous strong γ-rays with generally medium to high energy
"Metals" (Al, Si, Fe etc.)	FNA	(n, n$'\gamma$)	$\leq$14 MeV	0.1–2	Generally very narrow and dense resonances
"Metals" (Al, Si, Fe etc.)	NRA	(n, n)*	0.1–5 MeV	2–5	Si strong; others have weak signatures

* (n, n) signifies an elastic scattering interaction of a neutron.

difficult, and thus the second approach is the one studied. The neutron ToF technique requires that the neutron generation be in the form of very narrow pulses, typically of the order of 1 ns, and with the time between pulses long enough that all neutrons belonging to a pulse vanish before the next pulse is generated. For a flight path of 5 m and the neutron energy range of interest, this time is of the order of 500 ns, entailing a repetition rate of 2 MHz or less.

Similar temporal behavior of the neutron production is required for the PFNA technique, though for completely different reasons. The ns pulsing of the monoenergetic (in the range of 7.5 to 9 MeV) neutron beam in the PFNA technique both results in a superior signal-to-background ratio (by separating the two) and allows the determination of all the local elemental densities. More detailed discussion of the PFNA system is given in Sect. 22.8.

22.7 Conventional Pulsed-Neutron Inspection (PNI) – Example of an Accelerator-Based Nonintrusive Inspection System

This technique was developed in the early 1960s for oil logging, nuclear-reactor start-up and the detection of nuclear materials. With this technique one can separate the (n, γ) reactions (TNA), which continue to occur after the fast neutrons have stopped being injected into the system, from the mixture of (n, n$'\gamma$) (i.e. FNA) and TNA reactions taking place during the pulse. This is shown in Fig. 22.1. A sequence of neutron pulses, roughly 5 μs wide or wider (depending on the allowable duty factor, the available intensity and the neutron "die-away" time constant of the system), is injected into the inspected item. The spectrum of the gamma rays produced during the pulse is measured, typically using high-efficiency NaI (sodium iodide), BGO (bismuth germanate oxide) or, sometimes, high-resolution Ge (germanium) solid-state detectors. Figure 22.1 shows spectra collected over many 14 MeV neutron pulses (upper curves in the spectra box), which are dominated by the fast-neutron interactions, as manifested by the presence of the oxygen and carbon inelastic lines. The materials inspected here were paper (indicated by a square marker), as a benign material, and ammonium nitrate (AN), as an explosive (smooth lines). Note that the carbon lines in AN (which does not have carbon) are very weak, representing background from shielding materials.

The spectra after the pulse are solely due to (n, γ) reactions and the weak, delayed oxygen activation (from O(n, p)N, which β-decays, with a half-life of 7.5 s, to ^{16}O, giving the same gamma rays as from inelastic scattering on ^{16}O). The spectra are characterized by the strong capture line of hydrogen and, in case of the explosive, the unique high-energy gamma ray (10.8 MeV) from capture in nitrogen. The observation of this line is the first and the primary indication of the presence of explosives (or fertilizers – which can be

used as explosives). The other elemental lines and spectral features in this technique are used to eliminate or confirm the presence of explosives. The technique is effective for detection of the bulk amounts of explosives that are typical for vehicle bombs.

Vehicle explosives detection systems (VEDS) are being used in various parts of the world.

22.8 PFNA – Example of a High-Performance Accelerator-Based Nonintrusive Inspection System

22.8.1 Introduction

Pulsed fast-neutron analysis (PFNA [3]) is a technique which uses a collimated pulsed beam of fast neutrons to excite the nuclei of common elements in bulk materials. The primary interactions of interest for contraband detection are gamma ray emissions following inelastic scattering of the fast neutrons with carbon, nitrogen and oxygen (and any other element present). Direct imaging of the elemental content of the material is accomplished by using a time-of-flight (ToF) technique to identify the position of the interactions, and gamma ray spectroscopy to identify the elemental gamma rays (see Figs. 22.3 and 22.4). The ratios of elemental signatures, or other combinations are used to identify contraband.

22.8.2 PFNA Nanosecond Pulsed-Neutron Production System

The cargo inspection system application of PFNA requires a beam of monoenergetic (with resolution $\Delta E/E$ <1%) neutrons in an energy range of about 7 to 9 MeV, which can be raster scanned across the face of an inspected object such as a truck or cargo container. The required neutron beam is produced using a deuteron (^{2}H) beam in excess of 75 μA, with higher current desirable, from an NEC Pelletron tandem (models 9SDH-2 and 10.5SDH-4 are being used). An injector/buncher system was also developed for PFNA by NEC [4]. The ion source for this system is the Toroidal Volume Ion Source (TORVIS), which was an adaptation of a Brookhaven National Laboratory design by Prelec and Alessi [5]. The negative ions are accelerated to 80 keV and analyzed in a 90° dipole magnet before entering the bunching system. The 2.5 or 5 MHz double-drift buncher is designed to achieve a bunching efficiency of around 40% and a pulse width of 1 ns FWHM and 2 ns FWTM when the beam achieves its full energy (about 6 MeV). The fully accelerated deuteron beam enters a self-cooled deuterium (D_2 gas) target and produces neutrons via the d(D, n)^{3}He reaction.

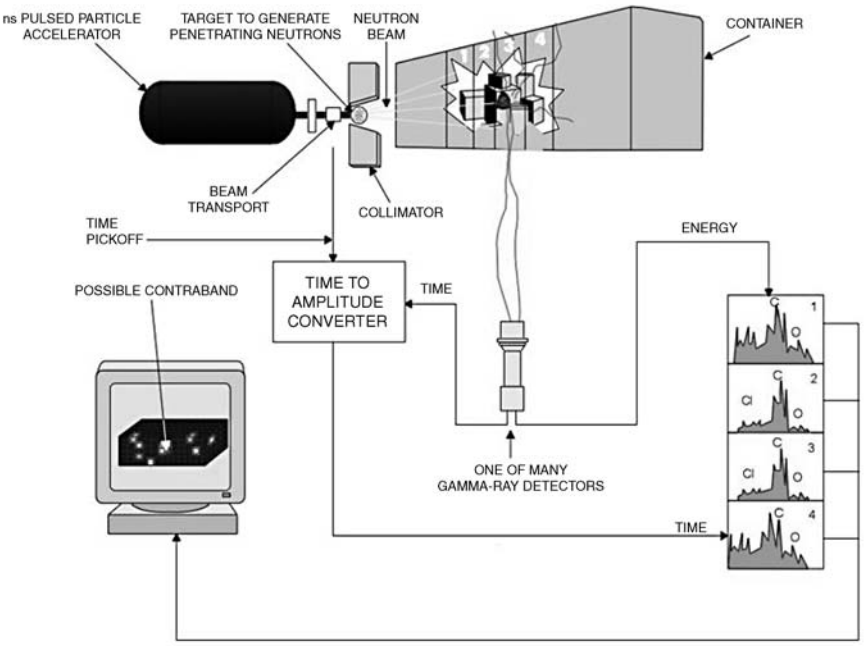

Fig. 22.3. Principle of PFNA

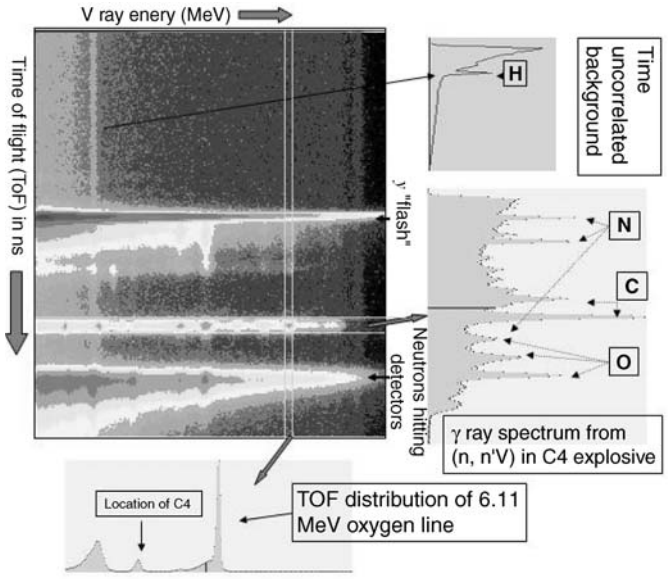

Fig. 22.4. Basic PFNA three-dimensional information – time of flight (ToF), γ-ray spectra and intensity

22.8.3 Scanning System

The oscillating neutron beam is achieved by mechanically rastering the deuteron beam and the beam line. After acceleration, the deuteron beam is taken through 90° using a dipole magnet. One unique requirement of the neutron production system is that it must not degrade the nanosecond time structure of the beam. This is done by focusing the beam to a spot, a few mm wide, near the center of the bend of the dipole. The dipole magnet, 90° beam line and gas cell are all rotated about the original beam axis to produce a vertical mechanical rastering of the beam. The 90° beam line is about 2 m long from the rotation axis to the gas cell. In operation the beam line can be rotated over a variable and wide angular range about the horizontal position. This motion is accomplished by mounting the dipole, 90° beam line components and deuterium gas cell on a platform which rotates on two bearings concentric with the beam axis. The platform and beam line hardware are shown in Fig. 22.5. The platform, magnet, vacuum hardware and counterweight weigh roughly 4500 kg. The scanning speed of the platform is adjustable. The platform is driven by a hydraulic actuator or an electric motor. The rotating and fixed beam lines are one continuous high-vacuum system employing a special high-vacuum rotary union.

The deuteron beam current deposits several hundred W of heat in the gas cell. The pressurized deuterium cell is separated from the evacuated beam drift tube by a 9 μm Havar foil and is self-supporting. The window is cooled by jets blowing deuterium gas on the interior face of the window. The deuterium is pumped through the cell in a closed-loop system and cooled with a heat exchanger. In order to not damage the window, the beam spot must be kept

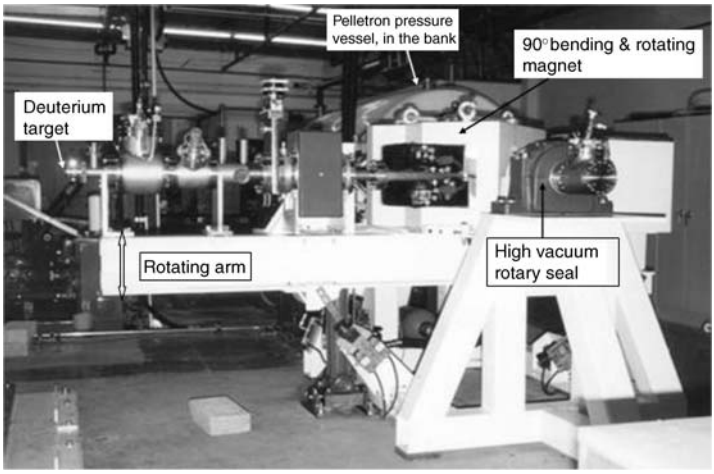

Fig. 22.5. The original PFNA scan arm, which rotates the beam line and neutron production target, before installation at Ancore's facility in Santa Clara, CA, USA

large on the window. The beam optics of the system were designed so that a proper-size spot is achieved at the gas cell when the beam is focused in the center of the bend of the dipole.

Horizontal collimation is accomplished using a fixed slot collimator. Vertical collimation is achieved by a variable collimator located at the end of the scan arm. This collimator can be adjusted to change the neutron beam cross section (the "pixel").

The uniqueness of PFNA is its ability to determine the elemental (and from that the material) content in each volume element (called a voxel) of the inspected object. The spatial information is achieved, first, by collimating the relatively forward-peaked neutron beam from the ^{2}H(d, n)^{3}He reaction. The point of interaction is provided by measuring the time of flight of a packet (or pulse) of neutrons (flying at a velocity of $\approx$4 cm/ns) from its point of creation (the target) to the time when the gamma ray detector detects the appropriate rays from the (n, n$'\gamma$) reaction. By correcting for the photon flight time, knowing the raster neutron beam angle and the position of the detector (there are more than 100 detectors distributed around the inspection tunnel), the system determines the location of the event. The spectrum of the detected gamma rays provides information on the material type at that location.

The three pieces of information: ToF, energy and intensity, collected every 10 to 100 ms (depending on the scanning speed and the size of the object), are shown in Fig. 22.4 (gray scale code: white to black indicates very high to very low intensity). This measurement was longer than the measurement done in a routine scan to show all the key physics aspects of PFNA. Figure 22.4 shows the time (abscissa) and energy (ordinate) obtained from inspection of a sample of C4 explosive placed in the middle of a marine container. It also shows a slice along the time corresponding to the location of the C4, providing the γ ray spectrum of the explosive. Also shown is an energy slice, corresponding to the oxygen signal from the explosive, showing its precise location. Capture γ rays that are the result of neutrons thermalized in the container and its surroundings, appear as a constant (time-"uncorrelated") background and can easily be subtracted. The hydrogen capture line is shown in the top right corner. The other two features of the plot are the "γ flash" created by the photons accompanying the neutron production hitting the detectors, and the second, later, broad time peak, representing the "n flash" i.e. scattered neutrons hitting the detectors. The time between these two time markers is when the PFNA information is collected. Through distributed computing and via a large number of very intensive computations, readily done in today's high-end computers, the PFNA system makes an automatic decision as to whether a threat exists and where it is, and presents it to the operator.

22.8.4 Examples of PFNA Inspection Results

The overall PFNA system configuration is shown in Fig. 22.6. All the major components are identified there. The PFNA operator screen (item 11 in Fig. 22.6) contains, in a compact way, the inspection decision.

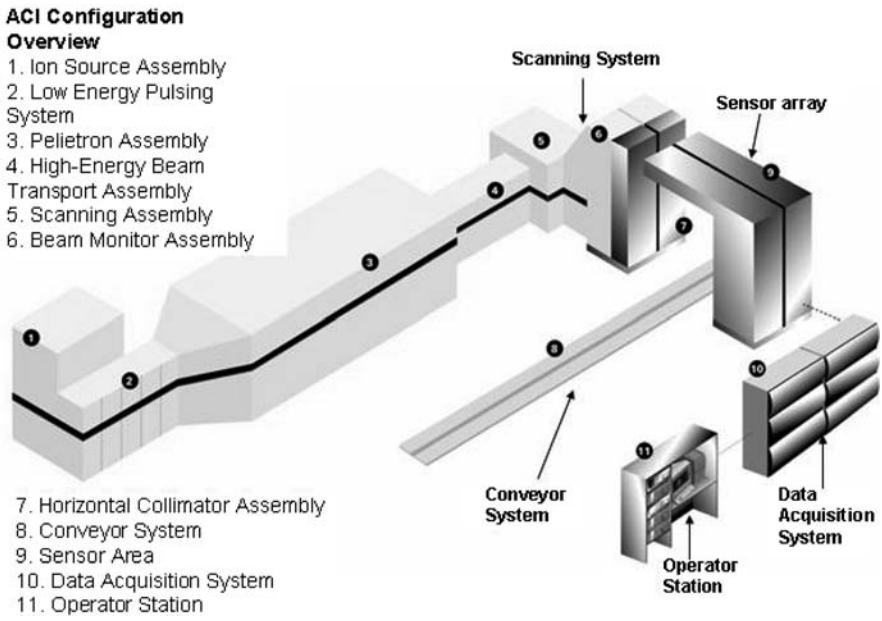

Fig. 22.6. Generic PFNA inspection system configuration with its main components

Examples of actual results are provided in Figs. 22.7 and 22.8 as an illustration of the power of PFNA inspection. Each figure shows the physical object in which the threat was concealed, the radiography image (obtained via the γ flash) of the inspected object and, finally, the PFNA decision image. Figure 22.7 shows this for a small piece of explosive in an air cargo container, whereas Fig. 22.8 does so for a large marine shipping container with concealed explosives and drugs.

22.9 Conclusions

Neutron-based inspection techniques are unique because of their great elemental (and hence material) specificity and sensitivity, and the ability to localize the threat. Particle accelerators from below 100 kV to 6 MV (or 3 MV tandems) have already played a very important role in the evolution of these

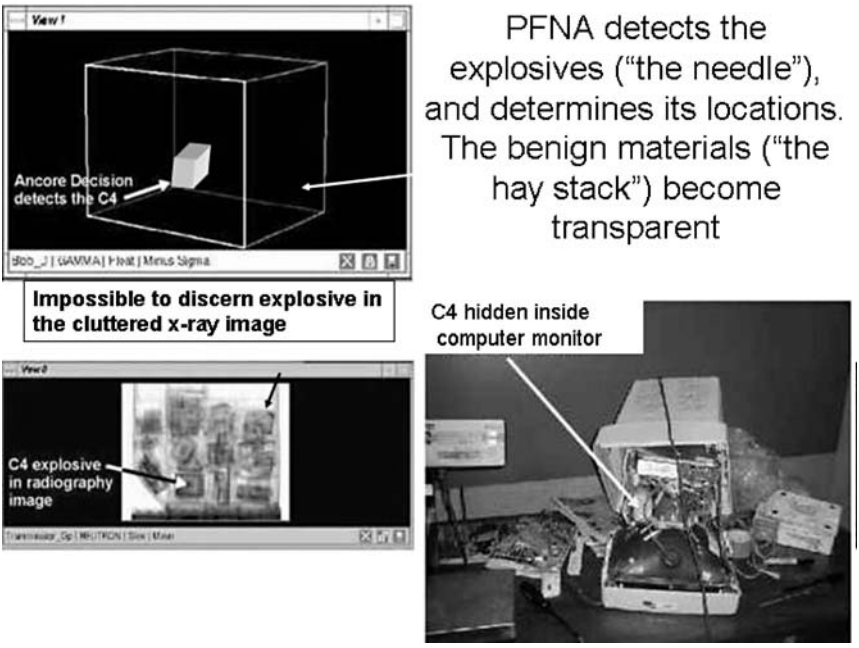

Fig. 22.7. Test results: PFNA inspection of an air cargo container loaded with computer monitors with a small concealed piece of explosive

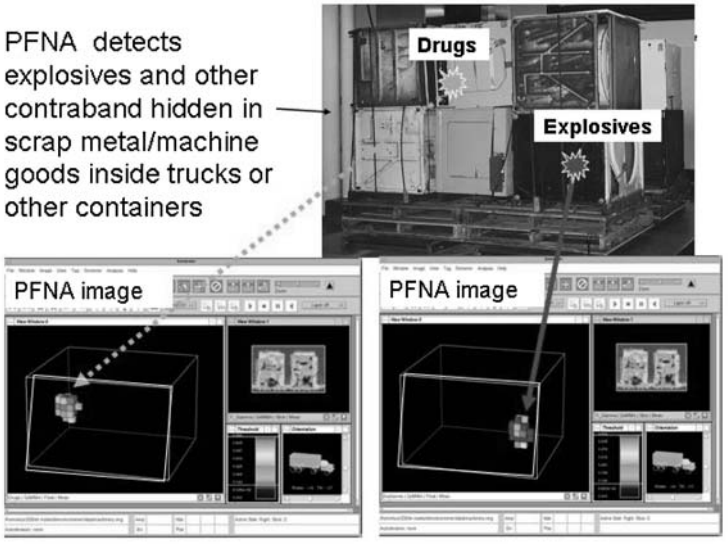

Fig. 22.8. Test results: PFNA inspection of a scrap metal shipment with hidden explosives and drugs

techniques. These accelerators will continue to increase their contribution to the inspection arena with the availability of higher-current, more compact and lower-cost machines.

22.A Appendix: Brief Description of Neutron-Based Inspection Techniques

TNA – thermal-neutron analysis. A method based on the capture of thermal neutrons by nuclei, creating high-energy gamma rays which are characteristic of the specific nuclei. Thermal neutrons are produced by slowing down fast neutrons from isotopic sources or accelerators in a specially designed moderator and in the interrogated object itself. The gamma rays are detected by an array of detectors surrounding the object. Spatial information on the interacting nuclei of interest (nitrogen, chlorine etc.) is also obtained from the detector array.

FNA – fast-neutron analysis. A method based on the interactions of fast neutrons, mostly by inelastic neutron scattering, with the nuclei of interest. Characteristic gamma rays from nitrogen, carbon, oxygen, chlorine and other elements can be measured. An array of gamma ray detectors surrounds the object to yield the spatial distribution of the elements of interest similarly to TNA.

PFNA – (nanosecond) pulsed fast-neutron analysis. A method based on fast-neutron interactions that yield characteristic gamma rays, similarly to FNA. The technique employs the time-of-flight (ToF) technique to obtain the spatial distribution of the signal. The ToF is obtained by using very narrow, about 1 ns, pulses of monoenergetic neutrons with a frequency of 1 to 10 MHz.

PNI – pulsed-neutron interrogation (an FNA/TNA combination). The interrogating neutrons are repetitively pulsed (typically 5–500 μs wide pulses, 100 to 1000 times a second). During the pulse both fast- (i.e., FNA) and thermal-neutron (TNA) reactions take place. Between pulses only thermal neutrons exist, decaying with the system "die-away" time constant (typically 0.5 to 5 ms), and pure TNA signals are obtained. PNI is uniquely suitable for detection of fissile materials. Between the repetitive pulses of fast neutrons the thermal neutrons create fissions that can be detected via the presence of prompt epithermal neutrons, delayed neutrons, and prompt and delayed gamma rays.

API – associated-particle imaging. A technique to tag source neutrons in time and direction, by the associated charged particle emitted simultaneously in the nuclear reaction that generates the neutron, for example ^{4}He and ^{3}He in the (d, T) and (d, D) neutron-producing reactions, respectively.

NRA – neutron resonance attenuation. A neutron radiography technique measuring the areal density (density times thickness) of elements present in the interrogated object. The technique takes advantage of sharp resonances

and other features in the neutron total cross section in the energy range of 0.5 to 5 MeV. Two-dimensional projections of the areal density of N, C, O and H can be obtained using fast neutrons with a broad energy spectrum, generated in narrow pulses, to perform time-of-flight neutron spectrometry.

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