Principles and Applications of Neutron-based Inspection Techniques

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Abstract. Neutron based explosive inspection systems can detect a wide variety of substances of importance, for a variety of purposes from national security threats (e.g., nuclear materials, explosives, narcotics) to customs duties, shipment control and validation, and for protection of the environment. The inspection is generally founded on the nuclear interactions of the neutrons with the various nuclides present and the detection of resultant characteristic emissions. These can be discrete gamma lines resulting from the thermal (n,γ) neutron capture process or inelastic neutron scattering (n,n′γ) occurring with fast neutrons. The two types of reactions are generally complementary. The capture process provides energetic and highly penetrating gamma rays in most inorganic substances and in hydrogen, while fast neutron inelastic scattering provides relatively strong gamma-ray signatures in light elements such as carbon and oxygen. In some specific important cases, though, unique signatures are provided by the neutron capture process in light elements such as nitrogen, where unusually high energy gamma rays are produced. This forms the basis for key explosive detection techniques.
The detection of nuclear materials, both fissionable (e.g., ^{238}U) and fissile (e.g., ^{235}U), are generally based on the fissions induced by the probing neutrons and detecting one or more of the unique signatures of the fission process. These include prompt and delayed neutrons and prompt and delayed gamma rays. These signatures are not discrete in energy (typically they are continua) but temporally and energetically significantly different from the background, thus making them readily distinguishable.
The penetrability of fast neutrons as probes and the gamma rays and fission neutrons as signatures make neutron interrogation applicable for large conveyances such as cars, trucks and marine containers.
The neutron-based techniques can be used in a variety of scenarios and operational modes. They can be used as stand-alones for complete scans of objects such as vehicles, or for spot-checks to clear (or validate) alarms indicated by another inspection system such as high energy x-ray radiography. The technologies developed over the last decade are now being implemented with good results. Further advances have been made over the last few years that increase the sensitivity, applicability and robustness of these systems.
The principle and applications of neutron based inspection techniques using accelerator based sources are reviewed.

1. Introduction

Non-intrusive inspection (NII) of objects of all sizes, from luggage to shipping containers, and from postal parcels to trucks, is a vital component of any national and international security in all port of entries: land, sea and air. This has gained paramount importance in the last two decades. In addition to the security aspects, these inspections can have great value in commerce, customs and the protection of the environment.

The backbone of NII was, is, and will probably be for the foreseeable future, the x-ray radiography. There is a large and increasing base of x-ray systems with ever improving capabilities. However x-ray radiography provides basically an areal density shadow-gram of the object, requiring almost always human interpretation and judgment about shapes as distinguishing features between threat and benign materials. Unfortunately most of the current threats do not possess specific discernable shapes. What distinguish them are their chemical and consequently, their elemental compositions. Thus NII that can determine such compositions are essential to the success of the inspection mission. To be effective, inspection technologies need to be sensitive, material specific, rapid, flexible and automatic (independent of human interpretation).

Neutron based techniques provide automatic detection of a wide array of threats: explosives, chemical agents, nuclear materials and devices, other hazardous materials, drugs, etc. They

achieve this feat through the production of characteristic elemental gamma rays from nuclear reactions, primarily thermal neutron capture and/or inelastic scattering of fast neutrons. Charge particle accelerators, generating copious numbers of neutrons are essential sources for these techniques.

2. Material Composition

Each threat (and most other targeted materials), e.g., explosives, chemical agents, nuclear fissile, etc., differs from benign materials in its chemical and hence elemental composition. This difference makes the 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 phosphorous, sulfur and fluorine are present in certain nerve agents.

Military and homemade explosives are typically rich in nitrogen and oxygen and "poor" in hydrogen and carbon. Cement, coal and minerals are distinguished by the presence of the desirable elements and many undesirable ones. Common nuclear fissile materials are ^{235}U and ^{239}Pu and a common fissionable element, ^{238}U. These are all "elemental features" of materials. In general, elemental features can be expressed by the absolute values of the elemental densities, ratio of these densities, or by other functional relationships that afford better material discrimination.

Table I below summarizes very briefly the key elemental signatures of various materials of interest, nuclear reactions that may be used to detect the elements, and specific nuclear signal that identifies the elements (mostly discrete, but sometimes also continuum) gamma rays.

TABLE I: KEY ELEMENTAL FEATURES AND SIGNATURES.

Material [Reference]	Key Elemental Features	Usable Nuclear Reactions	Available Signatures
CONTRABAND Explosives [2]	Elemental Density (g/cc) Relatively high O Relatively high N Relatively low C Relatively low H	 (n,n´γ) (n_α,γ) and (n,n´γ) (n,n´γ) (n,γ)	 6.130 MeV 10.80, 5.11, 2.31, 1.64 MeV 4.43 MeV 2.223 MeV
Drugs (Cocaine/Heroin) [2]	Relatively high C Relatively high H Relatively low O Low-medium Cl (for HCl-drugs)	(n,n´γ) (n_{th},γ) (n,n´γ) (n_{th},γ) and (n,n´γ)	As above As above As above 6.110 MeV and other strong lines for Cl
MINERALS Cement [1]	Ca, Si, Fe, Al, Mg	(n_{th},γ)	Specific capture γ-rays, e.g., 6.420 MeV for Ca 4.934 MeV for Si 7.630/46 MeV for Fe, etc.
Coal [1]	C (high concentration) H, S ,Si, Al, Fe, Ca, K, Na, Ti	(n_{th},γ), (n,n´γ) (n_{th},γ)	Specific capture (or inelastic) γ -rays, e.g., 4.945 MeV (n,γ) and 4.43 MeV (n,n´γ) for C, 2.223 MeV for H, 5.420 MeV for S, etc.
NUCLEAR [3]	^{232}Th, ^{233}U, ^{235}U, ^{239}Pu, ^{240}Pu	(n_{th},f), (n,f), (γ,f) secondary, (n,γ), (n,n´γ)	N_p, n_d, γ_p, γ_d; total/coincidence; Very high density

3. Relevant Nuclear Reactions

The main neutron nuclear reactions that affect the inspection process are divided into two main groups. Reactions that affect the neutron transport and hence the penetration in the cargo material, such as elastic scattering (n,n) (see for example, Figure 1) and thermal neutron capture process (n_{th},γ). Reactions that generate the elemental signatures (mostly discrete characteristic gamma rays) are primarily thermal neutron capture (n_{th},γ) and fast neutron inelastic scattering (n,n'γ) (see for example, Figure 2), which takes place only if the neutron energy is higher than the nuclear level it excites ("threshold" reaction). These reactions form the basis of "neutron in-gamma out" group of NII techniques. In a few cases [2] the high energy structure of the neutron elastic scattering is employed to get some elemental information; this group of techniques falls in the "neutron in - neutron out" type of inspection. The detection of fissionable materials involves "neutrons in - neutron and gamma out".

The total (mostly elastic scattering) cross sections of neutrons in most organic elements: hydrogen, carbon, nitrogen and oxygen over broad energy range from thermal (1e-8 MeV) to 10 MeV are shown in Figure 1. The most influential element on neutron transport and in particular, its penetration, is hydrogen. This is because of the large energy loss (up to 100%, and on average 50%) a neutron can suffer in a single collision with a hydrogen atom. Thus intense neutron sources are required to inspect full-size cargo containers or trucks heavily loaded with hydrogenous materials such as food stuff. On the other hand metallic and general industrial products are much more transparent to fast or even to thermal neutrons.

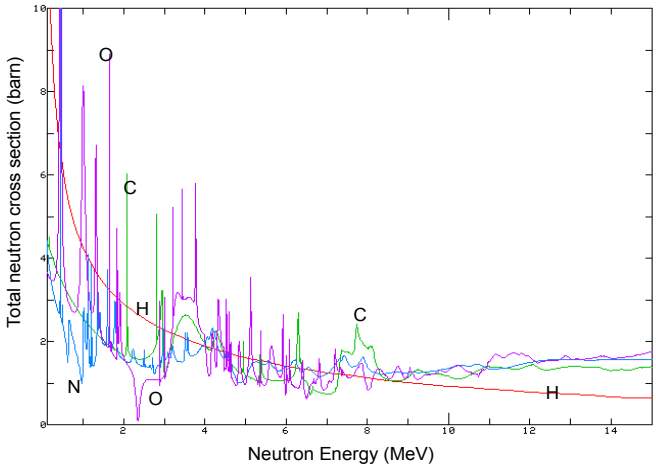


FIG. 1. Neutron total cross section of light "organic" elements.

The most important signature generating reactions are the neutron capture reactions (n,γ). Their magnitude is generally inversely proportional to the speed of the neutron, thus they are highest for low-energy neutrons. Most elements with a very few exceptions have useable capture cross sections. This reaction forms the basis for most of the material specific inspection techniques as is indicated in the third column of Table 1.

A complementary reaction to the (n,γ) reaction is the neutron inelastic scattering (n,n' γ) which occurred only when the neutron energy is higher than the specific nuclear level, and a γ ray with energy corresponding to this level is generally emitted. Figure 2 shows the cross

section to generate (directly or in steps, via intermediate nuclear levels) the most important gamma rays in fast neutron scattering: 4.43 MeV for carbon, 1.64, 2.13 and 5.11 MeV for nitrogen and 6.13 MeV for oxygen. The (n,n´γ) complements the (n,γ) reactions in that it has higher values for those elements, like carbon and oxygen, where the latter is very small.

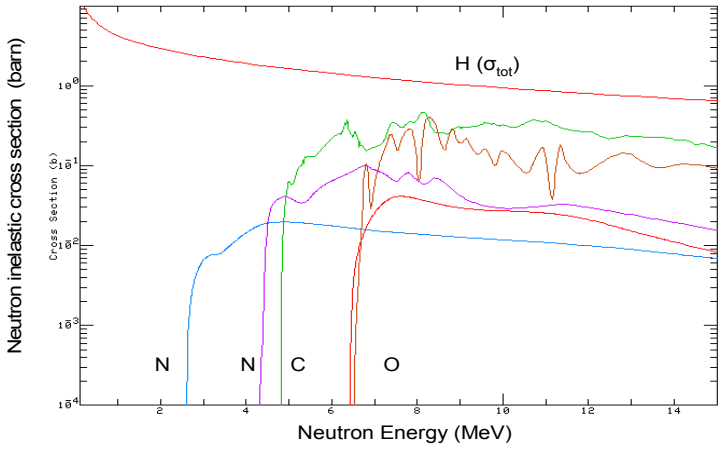


FIG. 2. Neutron inelastic cross section of "organic light" elements (H total cross-section is provided as a reference).

The detection of fissile (^{233}U, ^{235}U, ^{239}Pu) and fissionable materials (all fissile materials plus ^{232}Th, ^{238}U, ^{240}Pu, etc.) is governed by the fission cross sections (Figure 3). The values of the neutron fission cross sections for these materials cover more than two orders of magnitudes from about 1 to 700 barns. The fissile materials are fissioned very effectively by thermal neutrons, while all fissionable materials are fissioned by fast neutrons with cross sections of the order of 1 to a few barns.

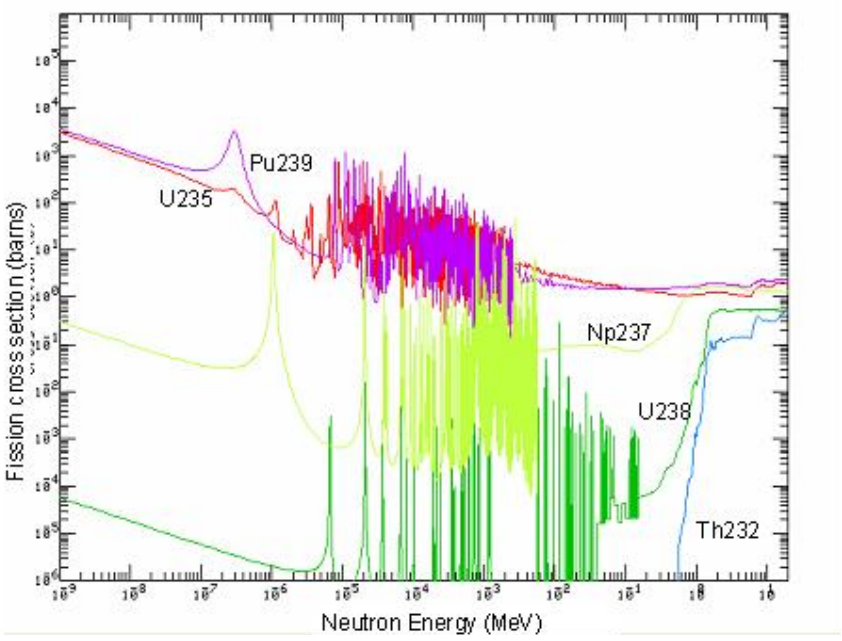


FIG. 3. Neutron fission cross section of fissionable isotopes.

4. Observed Signatures

The observed signature, i.e., the characteristic gamma rays resulting from the appropriate neutron interactions are generally mono-energetic gamma rays. However as detected by the external detector, the physical processes occurring in the detectors make the observed signatures usually more complex requiring optimal electronics, hardware and appropriate algorithm to convert the observed signatures to the correct decision of presence or absence of the targeted material. The processes that complicates the observed signatures are photo-effect, Compton scattering and pair production in addition , the inherent limitation of the energy resolution and the presence of various radiation backgrounds..

Figure 4 shows a typical spectrum of a lightly loaded truck with bulk explosives (ammonium nitrate based) at different distances from the inspection system. This spectrum is taken with multiple 10 cm cube NaI scintillation detectors. This type of detector is the most commonly used in neutron based inspection systems, because of its good energy resolution, good detection efficiency, reasonable availability in large sizes and quantities, and reasonable cost. Under some special conditions higher resolution detectors like Ge may be used. Figure 5 shows a long TNA spectrum measurement of soil taken with a medium-size Ge detector, showing clearly the many elemental lines. With the advent of new, high efficiency, better resolution detectors such as the rare earths halides, e.g., $LaBr_2$, neutron based systems may start using these powerful detectors as their availability grows and prices decline.

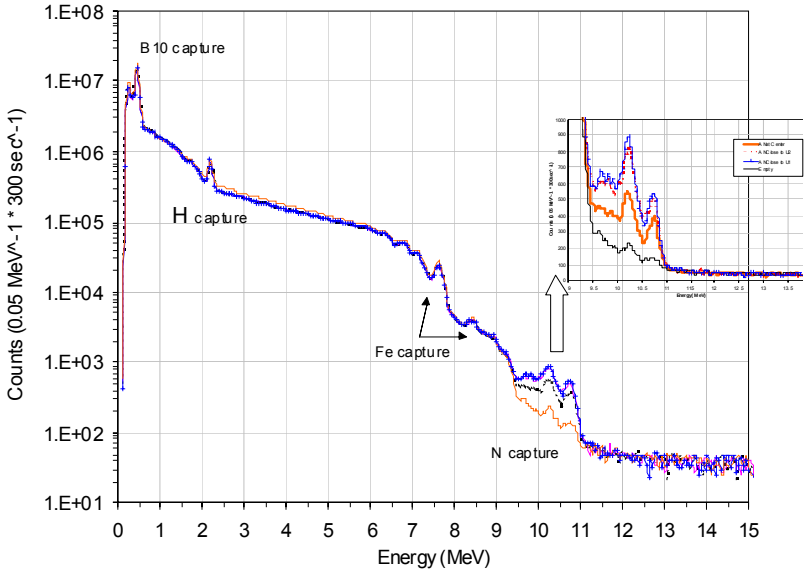


FIG. 4. TNA spectrum of explosive at different distances from the inspected side of truck. (Key signatures are the 10.8 MeV N(n,γ) and 2.2MeV H(n,γ); the Fe peaks are due to truck and other structural materials present.)

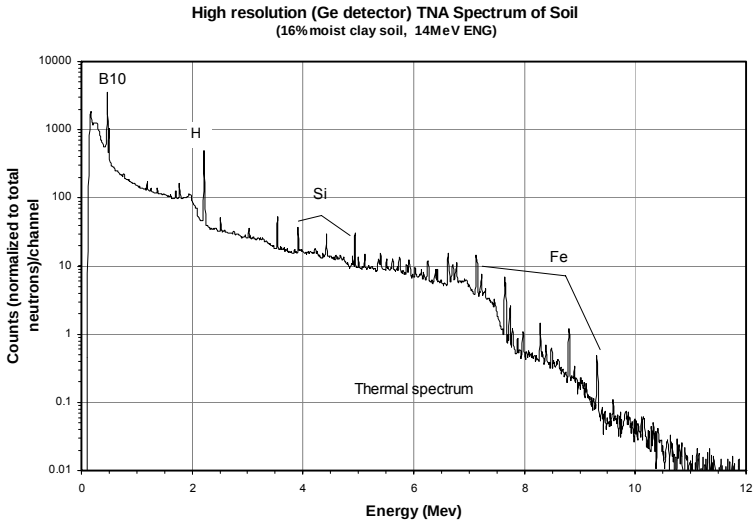


FIG. 5. High resolution TNA spectrum of soil.

The fast neutron interactions with materials provide the characteristic gamma rays due to the inelastic neutron scattering. These gamma rays are unfortunately always accompanied by a background originating from the neutron interactions with the detector material itself (whether it is NaI, Ge, BGO, etc.) as seen in Figure 6. If one is able to separate these interactions by the time of occurrence (as in the PFNA case [4]) one can get very clean signature spectra as shown in Figure 7.

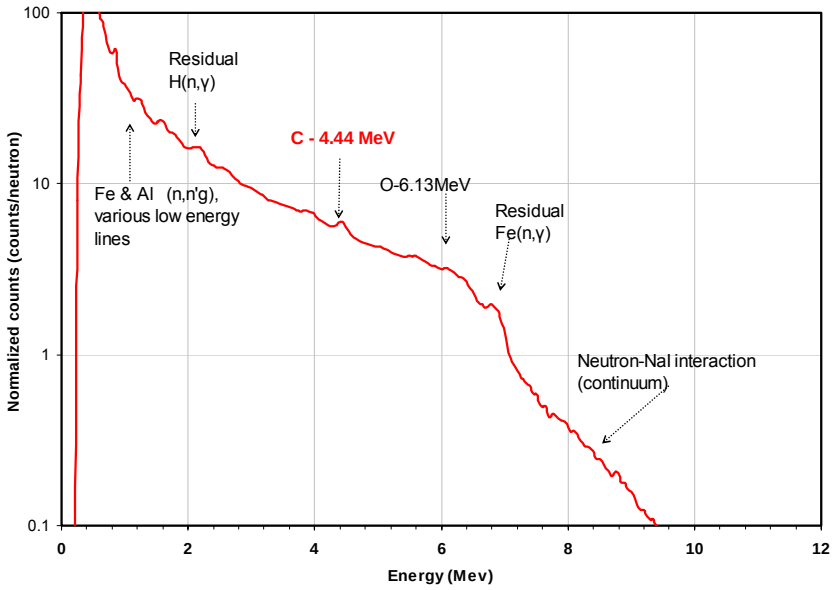
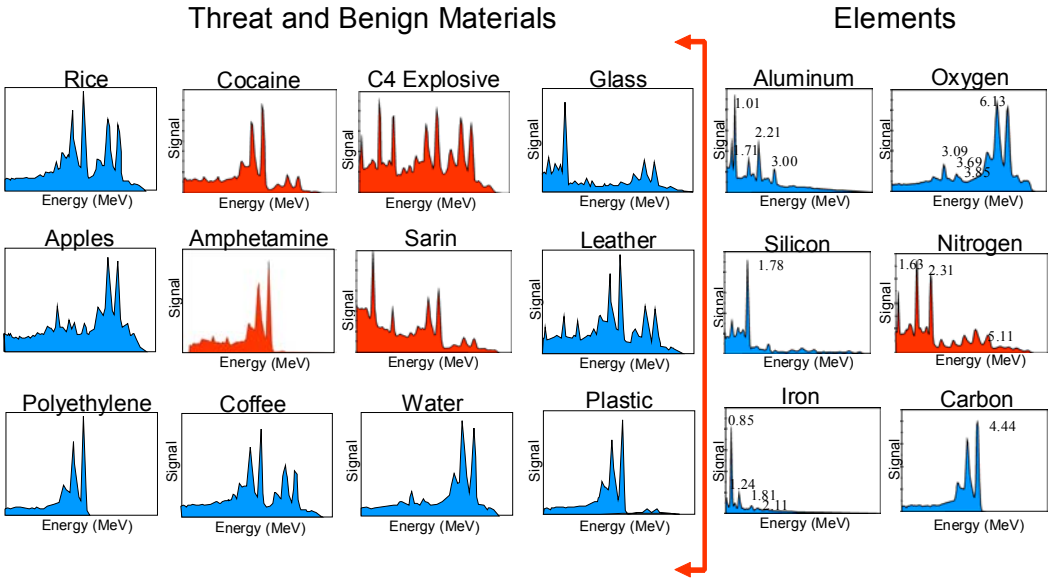


FIG. 6. 14 MeV induced FNA spectrum.



The elemental signals combine to give unique material signatures.

The target data base can be continually updated.

FIG. 7. Neutron inelastic gamma ray spectra as measured in the PFNA lab by 10 cm x 10 cm x 10 cm NaI for a few elements and compounds (some measured and some simulated.

There is significant synergy between the detection of many different substances, SNM and other fissionable materials. A properly designed non intrusive system for explosives and other substances can in principle be augmented to detect also fissionable materials. The most distinctive property of the latter is the fissionability, which provides a host of useable signatures (see Table II). The fission signatures are not characterized by discrete lines, but are more continua of exponentially declining spectra as a function of increasing energy with multiple particles. The temporal behavior of some of these signatures is heavily used in the detection, specifically the delayed neutrons and delayed gamma rays, which are detectable well after the source neutron burst, that caused the fission, is shut-off. The prompt neutrons from thermal fission are detected by the time decay of the thermal neutron population ("Die Away Time"). Under some conditions the unusually high multiplicity of the prompt neutrons and/or prompt gamma rays can be used as a distinct indication of the presence of a fissionable isotope.

TABLE II: KEY DETECTABLE SIGNATURES OF FISSION [3,5].

Fission signature	^{235}U	^{239}Pu	^{238}U
No. of Prompt neutrons/fission	≈2.8	≈3.2	≈2.9
No. of delayed neutrons/fission	0.015	0.006	0.044
No. of prompt and delayed γ rays /fission	≈6.7	≈6.7	≈7.2

5. Examples of Neutron-based NII

Over the last two decades, several neutron based systems were built and some were successfully deployed as standalones or more often in combination with high-energy x-ray

radiography. The systems incorporated the physics principles discussed above with the practical constraints of the inspection world, where space is limited and throughput is paramount. There is a substantial body of data and literature on these systems, a small part of which is included in this paper and its references.

Figure 8 shows a gantry consisting of a 14 MeV neutron generator based, dual-head system for inspecting vehicles, from passenger cars to full size trucks, and marine shipping containers for bulk explosives, drugs, and many hazardous substances or even for cargo material verification [6].

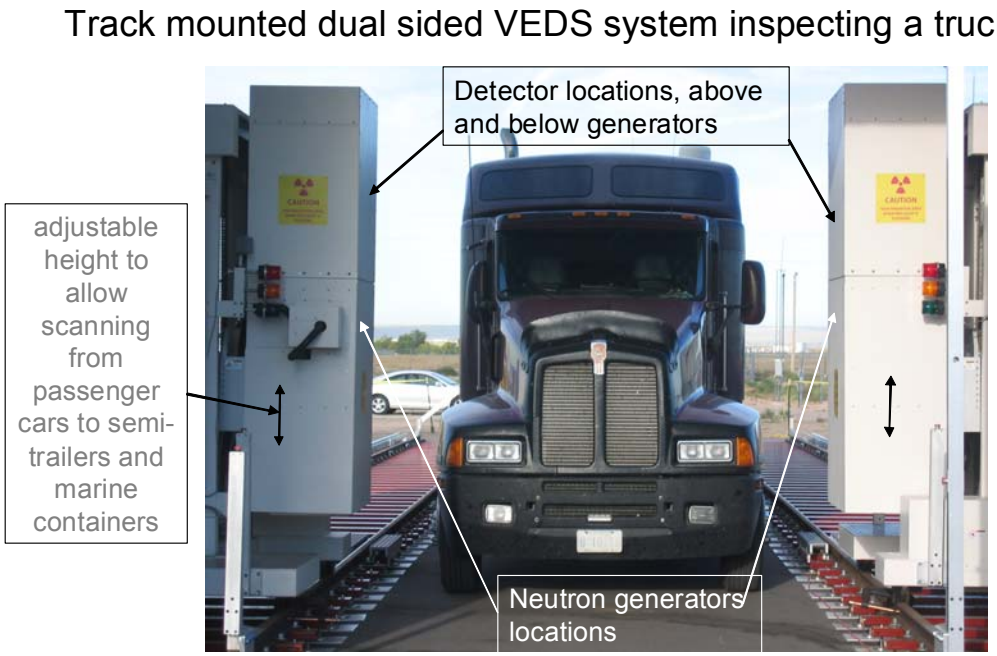


FIG. 8. Dual Sided VEDS (Vehicle Explosive Detection System).

A variant of this system was augmented to include the detection of SNM by the highly sensitive Differential Die Away Analysis (DDAA [7,8]). An example of the DDAA response to SNM in various locations within a truck loaded with metallic cargo is shown in Figure 9. The SNM was readily detected regardless of its location.

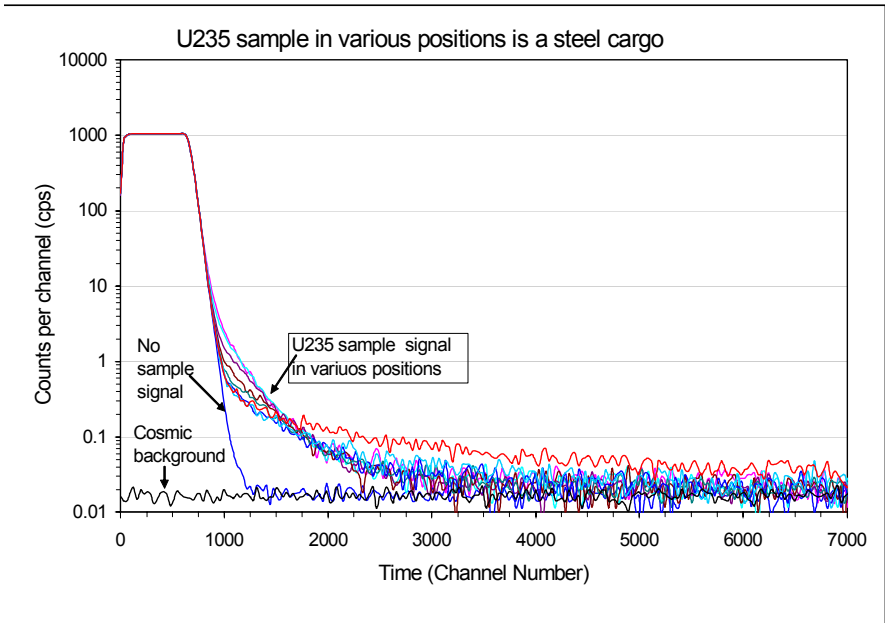


FIG. 9. Detection of SNM using Differential Die Away Analysis [7,8] carried out in a system similar to VEDS (Fig. 8).

Figure 10 shows the concept of an integrated systems approach, where the strength of each independent system is used to compensate for the weakness of the other. The prime inspection here is done by the very high-speed portal, high-energy x-ray radiography, of which alarms are based on density projection and presence of high Z materials. These alarms, the great majority of which are not real, are cleared by the lower speed but material specific neutron based inspection system. The throughputs of the two systems are matched so that the combined system has the maximum throughput. Lower cost combined systems for less demanding applications are shown in Figure 11.

Finally, a few results of the PFNA inspection system, arguably the most sensitive inspection system yet developed, for a very large variety of situations are shown. Here the detection of various targeted materials, which are hazardous to the flying public, such as flammable substances, oxidizers (represented here as paints) and drugs are shown, Whereas they cannot be located, let alone detected, in the x-ray image or by any other radiography method, the PFNA can locate and identify their presence based on prior elemental calibration and appropriate algorithms.

FIG. 10. Combined system concept: neutron based technique clears alarms made by a 6 MV to 9 MV high-throughput x-ray inspection system.

FIG.11. Examples of combined systems: ^{60}C based radiography system with ^{252}Cf based VEDS (left) and a similar combination with 4.5 MV linac based x-ray system (right).

A summary of the techniques used in the field, pilot or advanced laboratory systems is given in Table 3. Most of the applications of these techniques have been aimed at the automatic inspection of large objects such as trucks, marine shipping and air cargo containers. Some demonstrations were successfully conducted with checked and carry-on luggage, small to medium size packages, liquid containers, etc. It is hoped that in the coming years more of these techniques will find their respective places to improve the efficacy of non intrusive inspection worldwide.

TABLE III: SUMMARY OF TECHNOLOGIES USED IN NEUTRON BASED NII SYSTEMS.

#	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 $E_d \geq 4$ MeV	H, O, C, N (Others)

[1]ENG: Electronic Neutron Generator – can be based on neutron production processes such as (d,D), (d,T), (d,Be), (p,Li)), (p,Be).
[2]SNM: Special Nuclear Materials –e.g., fissile isotopes ^{235}U and ^{239}Pu.
[3]TOF: Neutron Time of Flight method.

FIG. 12. Detection of small hazardous substances (left) in air cargo container by the PFNA technique. PFNA Houston air cargo prototype system (on right) [see also this proceedings].

6. References

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