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Tsahi Gozani[a]; Richard E. Morgado[b]; Chris C. Seher[c]
[a] Science Applications International Corporation, Sunnyvale, CA [b] Los Alamos National Laboratory, Los Alamos, NM [c] Department of Transportation Federal Aviation, Administration Technical Center, Atlantic City, NJ

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NUCLEAR-BASED TECHNIQUES FOR EXPLOSIVE DETECTION

Tsahi Gozani
Science Applications International Corporation
Sunnyvale, CA

Richard E. Morgado
Los Alamos National Laboratory
Los Alamos, NM

Chris C. Seher
Department of Transportation
Federal Aviation Administration Technical Center
Atlantic City, NJ

ABSTRACT

The status of bulk explosive detection techniques based on nuclear interrogation methods is reviewed. The desirable characteristics of an operational system capable of meeting the requirements for civil aviation security are compared with what can be expected from nuclear-based techniques. The comparison is limited to those techniques that utilize penetrating neutron and photon probes on the target elements of explosives most likely to be encountered in the airport scenario. The physical properties of a relevant group of explosives are surveyed for unique characteristics that could provide detectable signatures to nuclear-based techniques. A survey of the accessible reactions and their relative detection sensitivities are tabulated for a selection of practical interrogating probes. Some results obtained with systems currently under development are reported.

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1. INTRODUCTION

Approximately three quarters of a million passengers board airplanes daily at the 600 major airports that service the United States. They either check in or carry on roughly two million articles of luggage.[1] Although the probability that any one item might contain an explosive is small, the consequences of an explosive reaching the aircraft are obviously unacceptable to the public. Thus any system intended to detect explosives in cargo and checked-in or carry-on luggage must have a very high probability of detection (PD) while simultaneously minimizing the probability of false alarms (PFA). Unfortunately, the small amounts of explosives that must be detected against the large background of innocuous contents found in the average suitcase requires that a compromise be made between achievable detection and false alarm rates. False alarms arise from several causes including, among others, instrumental limitations, inadequate statistics, and materials that, within the capabilities of a particular system, mimic or subvert the explosive response. As many as 7500 passengers a day would have to be detained for further interrogation as a result of every percent PFA. It is estimated that

the additional annual cost of each percent PFA could range between $1 and $2 million.[2] Whether or not this level of cost and inconvenience is operationally acceptable, it nevertheless clearly emphasizes the need to achieve the lowest possible system PFA. In addition to performance, any candidate system must also present the prospect of achieving the practical, technical and operational requirements imposed by the managers of civil aviation security.

Acceptable response to the explosive threat to civil aviation requires detection techniques that are highly sensitive, specific, rapid, and nonintrusive. Detection techniques have been investigated for a variety of approaches based on different technologies that measure one particular physical property, preferably unique, common to the majority of explosives. To date, a comprehensive solution that meets the operational criteria has not been found. Experiences with the various approaches have, however, provided more insight into the difficulties of the problem. It has become increasingly apparent that the determination of only one physical parameter of explosives is insufficient. To approach unequivocal detection with a minimum of nuisance alarms, a number of unique, physical parameters must be mesaured, such as density, spatial distribution, and partial elemental composition. A family of techniques based on nuclear interactions is capable, in principle, of simultaneously providing this detailed information in the allowed minimum time. In the

following paper we review the current status of the application of these techniques to explosive detection systems (EDS).

In the active nuclear-based techniques described in this paper, the screened luggage is probed by highly penetrating radiation, notably neutrons or energetic x-rays (bremsstrahlung) from electron accelerators. The high-energy gamma-ray reactions produced by the interactions of the primary radiation probe with the nuclei of the target object are sensed by an array of detectors positioned near the luggage. The intensity, energy, and spatial distribution of the detected radiations, their relationship to the primary radiation, and any additional information concerning the object can help to determine the presence or absence of explosives.

In order to appreciate the capabilities of nuclear-based techniques, it is necessary to consider the physical characteristics of explosives as well as the basic nuclear reactions from a nuclear point of view. This is attempted in the following sections, which also describe the desirable characteristics of an operational EDS and give several examples of experimental and prototypical nuclear-based explosive detection systems.

2. DESIRABLE CHARACTERISTICS OF AN OPERATIONAL EXPLOSIVE DETECTION SYSTEM

The Federal Aviation Administration Office of Civil Aviation Security has issued guidelines for what it considers desirable

characteristics of an operational system for bulk explosive detection.[3] These characteristics include

- Checked baggage and air cargo threshold quantities of a few pounds for various explosives;
- One-half pound threshold quantities for passengers and carry-on luggage;
- Screening rate of 6 seconds per item;
- Detection efficiency in excess of 95%;
- False-alarm probability of 1% or less for checked baggage and air cargo, and 2% or less for passengers and carry-on baggage;
- Detection independent of specific explosive configuration;
- Nonintrusive in order to protect privacy;
- Nonhazardous to contents, passengers, operating personnel and environment;
- Reliable, easily maintained, and operable by relatively unskilled personnel;
- Nonburdensome financially to airlines, airports, and passengers;
- Occupy smallest possible volume with lightest possible weight.

The nominal amount of explosives of concern to the FAA is a few pounds of dynamite and a somewhat smaller amount of C-4 in checked baggage and air cargo. The quantity of concern for passengers and

carry-on baggage is one-half pound. In order to screen the multitude of items on any passenger airplane without any unwarranted delay, a peak screening rate of 10 items per minute is a desirable goal. The maximum physical dimensions of checked luggage that must be accommodated by the detection system are 81-cm x 66-cm x 40-cm (32" x 26" x 16") and an average weight of 30 kg. The average density would then be <0.2 g/cm^3 with fluctuations between voids (0.001 g/cm^3) and metals (3 g/cm^3).

No one technique has thus far been able to approach the operational characteristics described above, and it is now generally agreed that a combination of techniques will be required. Nonnuclear systems under investigation have achieved detection efficiencies in excess of 90% in the laboratory but are plagued by high nuisance alarm rates and long screening times. In order to achieve the required screening rate, the articles must be passed through the system at an average speed of the order of 16 cm/s. Although a single nuclear-based system should achieve the required screening rate, an alternative scheme could also be considered for less-sensitive systems. Since most of the items will not contain suspicious material, it has been suggested that two similar systems, one operating in the fast-scan mode and the other in a slow-scan mode,[4] would significantly improve throughput. The fast-scan system would meet the operational requirement for throughput while the slow-scan system would acquire more detailed information for a longer period of time on those items

that alarm the fast-scan system. The total throughput rate would be essentially unaffected provided the fast-scan system does not produce a burdensome nuisance alarm rate. This approach, requiring two systems may be justifiable only if the overall nuisance alarm rate is substantially reduced.

Nuclear-based techniques are inherently nonintrusive so that privacy of the luggage contents is insured. The thermal neutron technique[5] which has concluded extensive testing as a breadboard system has also been demonstrated to be nonhazardous to luggage contents but requires the necessary personnel shielding in order to reduce external radiation to acceptable levels. This pre-prototype system used a large radioisotopic neutron source. Although reliability and operational simplicity are not meaningfully defined for this breadboard configuration, it has been successfully transported and operated under adverse conditions without major difficulty. It is expected that the prototypes currently under development will provide similar attributes whether based on isotopic neutron sources or electronic neutron generators.

It is relevant to point out that antihijacking procedures before 1984 cost over $100 million per year to implement at an approximate cost of 45 cents per inspection. Measures added since 1984 and especially in 1986 have considerably increased the cost. The capital cost of a typical x-ray inspection system is $40K and operational costs per unit vary between $100 and $300K per year. It would not be

extravagant to expend the same order of magnitude in dollars on an explosive screening system in order to prevent the loss of one fully loaded, wide-body passenger plane.[2] Because operation costs would also dominate an operator-based sysetm, a high degree of automation would be required to offset the likely higher capital costs. Nuclear techniques are well suited to automation as considerable experience in computer-controlled data acquisition and monitoring has been gained in similar on-line systems.[6]

3. RELEVANT PROPERTIES OF EXPLOSIVES

The ability to develop an EDS that meets the rigid guidelines listed above requires a thorough understanding of as many properties of explosives as are relevant to the specific techniques. These properties may include physical, chemical, nuclear, and electromagnetic as well as geometric considerations.

Despite the plethora of explosive types, a general classification into six major groups with minor variations within each has been proposed.[7] The proposed classification scheme includes

- Nitroglycerine-based dynamites,
- Ammonium nitrate-based dynamites,
- Military explosives,
- Homemade explosives,
- Low-order powers, and
- Special purpose explosives.

Nitroglycerine-based dynamites are the most common form of explosives. The basic composition includes equal amounts of nitroglycerine and ethylene glycol dinitrate (EGDN) plus a desensitizing absorber in the form of cellulose and either sodium or ammonium nitrate.

A large number of ammonium-based dynamites are replacing nitroglycerine-based dynamites in popularity. Commonly referred to as slurries or water gels, two general types are distinguished: cap-sensitive and cap-insensitive types. The former consists of aluminum, ammonium nitrate, ethylene glycol, and water while the latter contains wax or fuel oil and water.

Military explosives include Composition-4 (C-4), TNT, and picric acid. C-4 is composed of cyclotrimethylene trinitramine (RDX) and a plasticizer.

Homemade explosives are diverse, limited only by the creativity of the perpetrator. Ammonium nitrate (fertilizer) and fuel oil are the most available constituents.

Low-order powders (black and smokeless) are problematic when assembled in pipe-bomb configurations and have been used extensively in that form. Black powder contains potassium nitrate, carbon, and sulfur. Smokeless powder is primarily pure nitrocellulose or a mixture of nitrocellulose and nitroglycerine.

Special-purpose explosives include detonating cords, blasting caps, and primers. The explosive entities are PETN, lead azide, lead styphnate, mercury fulminate, and blasting gel.

The density and major elemental composition of relevant explosives are listed in Table 1. Table 1 clearly indicates that the most unique signature of explosives is the high concentration and density of nitrogen. Nitrogen weight fractions range from 15 to 35%, with 20% as a typical value. The nominal density is 1.6 g/cm^3 and ranges between 1.25 to 2.0 g/cm^3 or more. Other significant signatures are the relatively low hydrogen and carbon contents. Except for the ammonium nitrate-based explosives, the hydrogen weight fraction of explosives is around 2 to 3.5%, compared with 11 to 14% in polyethylene, alcohol and water, and 5 to 6% in wood products. The relatively low carbon weight fraction is approximately 15 to 30%, with most in the 20-25% range, compared with twice that amount in wood-derived products. Explosives are also rich in oxygen with weight fractions in the 40-60% range. Hence, the ratios of nitrogen to hydrogen and carbon can be exceptionally high for explosives, while the nitrogen to oxygen ratio is exceptionally low.

Explosives, for the most part, are relatively high density, low-Z materials. High-Z materials are not universally present, although their presence in the form of sodium, mercury, aluminum, lead, sulfur, and potassium in trace amounts would serve as an additional indicator in those explosives that possess them.

Finally, most explosives must have a minimum propagation thickness or diameter in order to be effective. The minimum propagation thickness entails a sizable contiguous body of explosive in the other

TABLE 1

Physical Properties and Compositions of Relevant Explosives

Material	Physical State	Nominal Density (g/cm^3)	Percent Weight Composition				
			H	C	N	O	Other
Nitroglycerine	Liquid	1.6	2.2	15.9	18.5	63.4	-
Ammonium nitrate	Solid	1.7	5.0	0.0	35.0	58.0	-
Black powder	Solid	1.7-1.95	0.5	11.0	10.5	36.0	10% S, 29% K, 0.5% Ash
Nitrocellulose (9-14% N)	Solid	1.50-1.7	2.4	24.3	14.1	59.2	-
PETN	Solid	1.76	2.4	19.0	17.7	60.7	-
TNT	Solid	1.5-1.6 (cast)					
		1.63-1.64 (pressed)	2.2	37.0	18.5	42.3	-
C-3	Putty-like Solid	1.58-1.62	2.9	22.8	32.8	41.6	-
C-4	Putty-like Solid	1.64-1.66	3.6	21.9	34.5	40.2	-
Composition B	Solid	1.71	2.7	24.4	30.5	42.7	-
Lead styphnate	Solid	3.02	0.7	15.4	9.0	30.8	Pb:44.24
Tetyrl	Solid	1.57-1.71	1.8	29.3	24.4	44.6	-
Dynamite	Solid	1.25	4.0	14.0	15.-20.	59.0	Na:10.0
Trinitroanisole	Solid	1.41	2.1	34.6	17.3	46.1	-
Trinitroxylene	Solid	1.60	3.5	42.4	16.5	37.6	-
Picric acid	Solid	1.76	0.1	31.4	18.3	48.9	-
Cordite	Solid	1.66	-	-	13.1	-	-
Lead azide	Solid	4.48	-	-	28.9	-	Pb:71

two dimensions. This information could be useful to a detection technique without making specific assumptions of the actual shape of the explosive.

The physical and compositional features of explosives are summarized in Table 2 according to their specificity and usefulness as a basis for a detection technique.

Any nuclear detection technique would necessarily involve reaction products from the above-mentioned target isotopes that are reliably present in sufficient quantities in all explosives. The high-percentage weight compositions of these isotopes suggest which

TABLE 2

Signature	Specificity
Total nitrogen	High
Nitrogen density	Very High
N/H, N/C, N/O	Very High
Small quantity of metals (Na to Pb)	High
Total density, ρ	Med-Low
Shape	Low

reactions are accessible to a particular choice of interrogating probe and energy for a prescribed level of PD. The universal occurrence of these same elements in nonexplosives will limit the level of detection selectivity and, invariably, additional information will be required beyond simply sensing the presence of any one essential element. However, even the most comprehensive laboratory solution may not be capable of meeting the operational criteria. These criteria will limit the choices of techniques to those probes and reactions that have a reasonable chance of meeting these criteria in a practical way.

4. CHARACTERISTICS OF ACCESSIBLE NUCLEAR REACTIONS

The most promising nuclear techniques for an EDS are active interrogations in which a beam of neutrons or high-energy photons probe the object. The interrogating probe must be able to penetrate the surrounding, possibly high-Z, materials with high efficiency. On the other hand, the probe must be reasonably well-coupled to the predominantly low-Z materials that constitute explosives. These apparently contradictory requirements are reasonably met by neutrons and photons in a practical way. Despite the fact that reaction cross sections are measured in tens of millibarns (one millibarns = 10^{-27} cm^2), the available probe intensities, the percent weight atomic compositions of explosives, the low levels of competing backgrounds, and high detection efficiencies can overcome the apparent smallness of the reaction cross sections.

The reaction products must also be high-energy, penetrating radiations that are distinct from competing backgrounds and capable of being detected with high efficiency. At the practical probe energies envisioned here, the nuclear reaction products are invariably high-energy gamma rays whose spectra are directly identifiable with the nuclear isotopes from which they originated. With a detection system of modest energy resolution, the gamma rays can be distinguished from natural backgrounds and characterized according to energy.

A variety of nuclear reaction channels are accessible depending on the probe energy and specific target nuclei. Table 3 lists the reactions relevant to the energies and target isotopes under discussion here. The usefulness of any one reaction for explosive detection will depend on many factors: backgrounds, detector requirements, feasible probe intensities, and practical requirements such as cost, reliability, complexity, and required space.

Table 3 demonstrates the large variety of reactions and production sensitivities (as expressed by the reaction cross sections in the table, but also depending on the branching ratios and lifetimes which are not included in the tabulation) for all the major elements that are present in explosives.

Radiative capture of thermal neutrons occurs to some extent in all the target elements of explosives although only hydrogen and nitrogen present sufficient cross section to provide a detectable

TABLE 3

Accessible Nuclear Reactions for Neutron or High-Energy Photon Interrogation

No.	Isotope	Probe Energy*	Reaction	Cross Section (mb)	Detectable Products	Comments
1	^{1}H	n_{th}	$^{1}H(n_{th},\gamma)^{2}H^{*}$	332	2.223-MeV γ	Requires moderating material low in H--imaging candidate
2	^{1}H (and ^{10}B)	n (slowing down spect.)	thermalization absorption	(2-8) x10^{4}	n_{th}	
3	^{2}H	γ(>2.2 MeV)	$^{2}H(\gamma,n)^{1}H$	3	fast neutrons	Low energy threshold
4	^{2}H	n(14 MeV)	$^{2}H(n,2n)^{1}H$	75	fast neutrons	Isotopic abundance 0.015%
5	^{12}C	n_{th}	$^{12}C(n_{th},\gamma)^{13}C$	3.4	1.26-, 3.68-, 4.95-MeV γ	Requires carbon-free moderating material
6	^{12}C	n(14 MeV)	$^{12}C(n,n'\gamma)^{12}C^{*}$	100	4.43-MeV γ	Imaging candidate
7	^{12}C	n(14 MeV)	$12C(n,p)^{12}B^{*}$	2	13.4-MeV β 4.3-, 7.7-MeV γ	
8	^{12}C	n(14 MeV)	$^{12}C(n,\alpha)^{9}Be^{*}$	114	1.1-, 2.4-, 3.1-MeV γ	
9	^{12}C	γ(>19 MeV)	$^{12}C^{x}(\gamma,N)^{11}C$	2	511-keV γ	Positron emission; $T_{1/2}$ = 20.3 min.-- Imaging candidate
10	^{13}C	n_{th}	$^{13}C(n_{th},\gamma)^{13}C$	1	8.2-MeV γ	Isotopic abundance 1.11%

[x] At higher photon energies other reactions become possible; for practical reasons our table is limited to electron accelerators with energies less than 20 MeV.

TABLE 3 (cont)

Accessible Nuclear Reactions for Neutrons or High-Energy Photon Interrogation

No.	Isotope	Probe Energy*	Reaction	Cross Section (mb)	Detectable Products	Comments
11	^{13}C	γ(>5 MeV)	$^{13}C(\gamma,n)^{12}C$	2	fast neutrons	Low threshold
12	^{14}N	n_{th}	$^{14}N(n_{th},\gamma)^{15}N^*$	75	10.8-MeV γ ~ 5.5-MeV coincident γ's	Free from background; imaging candidate
13	^{14}N	γ(>11 MeV) γ(>30 MeV	$^{14}N(\gamma,n)^{13}N$ $^{14}N(\gamma,2n)^{12}N$	2 0.1	511-keV γ 511-keV γ	e^+ emission; $T_{1/2}$ = 10 min. e^+ emission; $T_{1/2}$ = 10 ms)
14	^{14}N	n(14 MeV)	$^{14}N(n,n'\gamma)^{14}N^*$	400	several γ's between 1.5 - 5-MeV γ	
15	^{14}N	n(14 MeV)	$^{14}N(n,\alpha\gamma)^{11}B^*$	100	4.44-MeV γ	Imaging candidate, requires carbon free moderating material
16	^{14}N	n(14 MeV)	$^{14}N(n,p\gamma)^{14}C^*$	40	6.73-, 6.09-MeV γ	
17	^{14}N	n(14 MeV)	$^{14}N(n,d\gamma)^{13}C^*$	50	3.68-MeV γ	
18	^{14}N	n(14 MeV)	$^{14}N(n,2n)^{13}N$	6	511-keV γ	Positron emission; $T_{1/2}$ = 10 min.--Imaging candidate, high Cu background
19	^{16}O	n(14 MeV)	$^{16}O(n,n'\gamma)^{16}O^*$	250	6.13-MeV γ	Imaging candidate
20	^{16}O	n(14 MeV)	$^{16}O(n,p)^{16}N^*$	40	6.13-MeV γ	Activation - $T_{1/2}$ = 7 seconds Imaging candidate
21	^{16}O	n(14 MeV)	$^{16}O(n,\alpha)^{13}C^*$	300	8.2-MeV γ	
22	^{16}O	γ(>16 MeV)	$^{16}O(\gamma,n)^{15}O$	1.3	511-keV γ	Positron emission; $T_{1/2}$ = 122 seconds. Imaging candidate

signal. The signal from hydrogen is severely debased by the background hydrogen signal from the moderating and shielding material necessarily present in any thermalizing system. We will return to the radiative capture process in nitrogen further on.

High-energy gamma rays from the inelastic reactions of 14-MeV neutrons occur in all target elements except hydrogen. The cross sections for these reactions are an order of magnitude larger than radiative capture processes. We will describe an interesting application of this reaction in section 5.3.

High-energy photon probes are required to photoactivate the target elements of carbon, nitrogen, and oxygen. Particularly important are the photoneutron reactions leading to positron emission, each with the characteristic half-life of the parent isotope. The subsequent annihilation of the positron produces back-to-back 511-keV gamma rays. Detection of the coincident gamma rays provides imaging as well as isotopic determination from the characteristic half-life. Photoactivation threshold energies are, however, high: 10.5 MeV for nitrogen, 15.7 MeV for oxygen, and 18.8 MeV for carbon.

No single factor determines the applicability of a specific reaction to the complex problem of explosive detection. The selection of a particular reaction would depend to a large degree on the availability, cost, and size of the required probe source and its shielding requirements. Among the neutron sources to choose from are the spontaneous fission source, ^{252}Cf, and electronic neutron

generators that utilize the D-D and D-T fusion reactions. Energetic photon probes are most readily produced by electron linear accelerators.

The reaction product must also be considered when probe energies are sufficient to induce radioactivity. If the reaction product is radioactive with a half-life that is considerably longer than the dwell time of the luggage in the irradiation zone (6 seconds, at most), then the overall system sensitivity will be greatly reduced. Thus those positron-emitting reactions with $T_{1/2}$ of a few minutes or longer will most likely be unacceptable. The induced activity in the luggage and the potential radiation exposure to the public are also important considerations in selecting appropriate reactions.

If one considers the FAA requirements along with the state-of-the-art, the most promising family of nuclear reactions for the near term is the thermal neutron capture gamma-ray group. More commonly referred to as the Thermal Neutron Activation (TNA) technique, the reactions in Table 3 that fall into this category include numbers 1, 5, 10 and mainly, 14. These TNA techniques belong to the family of Prompt Neutron Gamma Activation Analysis (PGNAA) methods that have been thoroughly researched in the last several decades. In the most recent decade, great strides have been made in their industrial implementation for full on-line elemental analysis, especially in the coal and mineral industries.[6] Four full-fledged prototypical explosive detection systems based on the TNA are currently being built for the FAA by Science Applications

International Corporation (SAIC) and Westinghouse Corporation. The basic attributes and some performance results for these systems will be described below. We also include a brief description of a high-energy photon interrogation technique and the associated particle time-of-flight technique for 14 MeV inelastic neutron reactions. reactions.

5. CURRENT DEVELOPMENTS

5.1 Westinghouse TNA, Pittsburgh, Pennsylvania

The thermal neutron activation technique has been under development at Westinghouse Corporation since 1977 for the FAA.[5] In its breadboard version, the system has undergone the most extensive field testing to date of any explosive detection technique at airports where both checked baggage and air cargo have been screened. The results are encouraging and indicative of the level of sensitivity and selectivity that can be obtained when three physical parameters are determined, namely, the quantity and density of nitrogen and its spatial lumpiness. It has served an important function in demonstrating that a nuclear technique based on the detection of nitrogen is a viable concept and can reasonably approach a number of the FAA technical and operational requirements for an EDS.

In its present form, the technique utilizes the radiative capture of thermal neutrons on nitrogen and detects the 10.8 MeV gamma rays produced in this process. The cross section for this reaction is

75 millibarns and 14% of the neutron captures result in a ground state transition gamma ray at 10.8 MeV. The neutron source is 400 micro- grams of the spontaneously fissioning isotope, ^{252}Cf, emitting 10^9 neutrons per second with an average energy of 2.3 MeV. The fission neutrons are thermalized in a high-density polyethylene cavity with inner dimensions capable of handling large suitcases. The estimated maximum thermal neutron flux in the cavity is 1.6×10^5 neutrons/cm^2-s.

Gamma rays are detected by two 6 x 8 matrix arrays of scintillation detectors positioned on 4-in centers on each side of the interrogating cavity. Each of the 96 detectors is a cylinder (2-in x 15-in) of NE110 scintillator, coupled to a 2-in photomultiplier tube. Organic scintillators such as these are characterized by very fast light pulses (<5 ns risetime), but with reduced energy resolution and detection efficiency compared with slower inorganic scintillators. The high speed is required to handle the high counting rates from background gamma rays from the source and from neutron cpatures in the cavity materials. Some crude imaging is affected by the collimating effect of the detector geometry that preferentially detects Compton scattering events along the long axis of the scintillator cylinder.

Calibration of the detectors is maintained by stabilizing the location of the Compton edge of the 2.22-MeV gamma ray from radiative capture in hydrogen. Gain stabilization of all 96 detectors is automatically maintained to a precision of $\pm 0.3\%$. An additional

NaI(Tl) detector is included to provide improved energy resolution in order to estimate the effect of backgrounds from interfering materials.

The screening phase of operation requires that the 10-second sum of the counts within an energy window located near the Compton edge of the 10.8-MeV gamma ray for all detectors exceed a predetermined threshold. The initial threshold is determined by measurements of explosive simulants in the amounts prescribed by the operational criteria. Screened objects that do not exceed the threshold count are cleared for boarding. Objects that exceed the threshold are held for 30 seconds at each of four different positions as required to cover the entire area of the object. These measurements determine the nitrogen density distribution in the suspect object by producing a crude image of the individual detectors that exceed a second predetermined threshold. A clustering criterion is applied to the data and a decision is rendered.

The system tractor-trailer has been successfully transported to airports for field testing. Performance has been measured with over 8000 actual airline checked bags and air cargo. FAA-defined simulated explosives were attached to the outside of approximately 20% of the samples. Using a four-stage algorithm with crude imaging information and a 19-second processing time, a PD of 98.1% and a PFA of 1.6% were demonstrated for the air cargo sample. Post-test analysis provided algorithm that yielded even better

detection and false alarm rates and operational modes where the average processing time might be reduced to around 9 seconds.

The most recent measurements of checked baggage in early 1985 yielded a PD of 96.3% and a PFA of 4.3%, revealing a 50% increase in total nitrogen counts from checked baggage as compared with air cargo. The average processing time per smaple was 30 seconds. Post-test analyses of the data has led to improved performance and prospects for a reduced processing time.

Westinghouse is currently in the first phase of an FAA-funded project to produce two improved versions of the TNA systems, one based on a radioisotopic neutron source and a second system incorporating an electronic neutron generator. The new system will incorporate markedly improved moderating cavity designs, better detectors with increased efficiency and better spatial and energy resolution, and reduced processing time approaching 10 bags per minute. Both new systems are scheduled for airport testing in Summer 1987.

5.2 Science Applications International Corporation Advanced ATNA, Sunnyvalue, California

5.2.1 Introduction

An Advanced TNA system has been studied and is now being designed and constructed by Science Applications International Corporation (SAIC) for the FAA. The ATNA attempts to incorporate most of the attributes of the TNA technique without

precluding the future incorporation of even more advanced nuclear or other synergistic techniques.

The basis for any TNA system is shown schematically in Fig. 1. Neutrons from a radioisotope, e.g., ^{252}Cf, or an electronic neutron generator, are slowed to create a cloud of low-energy thermal neutrons. The neutrons interact with the variety of nuclei in the luggage and produce characteristic high-energy gamma rays that are detected by an external array of detectors. The detector processing electronics converts the detected signals into pulses suitable for computer processing. If a predetermined set of conditions is fulfilled, such as a high count rate from nitrogen, the system alarms to indicate the possible presence of an explosive threat.

5.2.2 Basic Features of ATNA

The SAIC ATNA incorporates many important features, both nuclear and technical:

- Efficient inorganic scintillators capable of resolving closely spaced high-energy gamma ray lines.
- An efficient array of these scintillators.
- An optimal cavity design to obtain reasonably uniform thermal neutron flux. Interrogation volume exceeds the largest allowable piece of luggage. The entire luggage content is interrogated with minimal background interference, commensurate with the inherent detector characteristics.

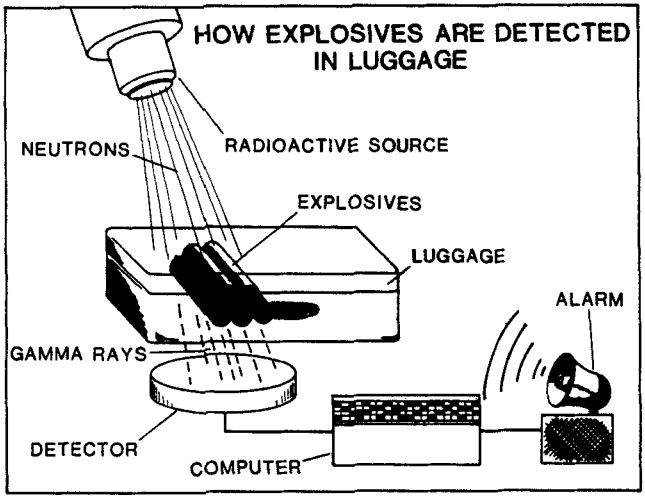

FIGURE 1
Thermal neutron activation schematic.

- Reduced neutron flux variations.
- Industrial isotopic sources with long half-lives or reliable neutron generators with sufficiently long target lives.
- Composite radiation shielding for reduced overall weight while assuring that dose rates are well below the requirements of the US Nuclear Regulatory Commission.
- Modular design to facilitate transportation and mechanical maintenance.
- Self-diagnostics to stabilize electronics and annunciate and identify malfunctions.

- Capability of scanning a continuous flow of luggage although prototype design only calls for manual luggage handling.
- Fully automatic operation. The system does not depend on operator experience or interpretation. Decisions are made by a flexible yet simple decision-making module that allows variable thresholds, utilizes simple image reconstruction, and nas the ability to learn from an expanding data base while incorporating all available a priori information.

5.2.3 Gamma-Ray Spectroscopy

The most important physical quantity determined by any active nuclear-based technique is the gamma-ray spectrum produced by the interaction of the probing radiation with the interrogated luggage. Examples of spectra measured in the SAIC laboratory ATNA system are depicted in Figs. 2, 3, and 4. The gamma-ray spectrum produced by 1 kg of C-4 simulant in a "typical", large, full suitcase is depicted in Fig. 2 with the log scale for the ordinate covering five orders of magnitude. This spectrum demonstrates the basic difficulty of the TNA method, namely, weak lines of interest (i.e., in the nitrogen region) superimposed on an intense, lower-energy background. However, it also illustrates the ability of the ATNA system to separate the signal gamma rays from the intense background. This is demonstrated more clearly on a linear scale in Fig. 3 for the high-energy portion of the spectra with and without the C-4

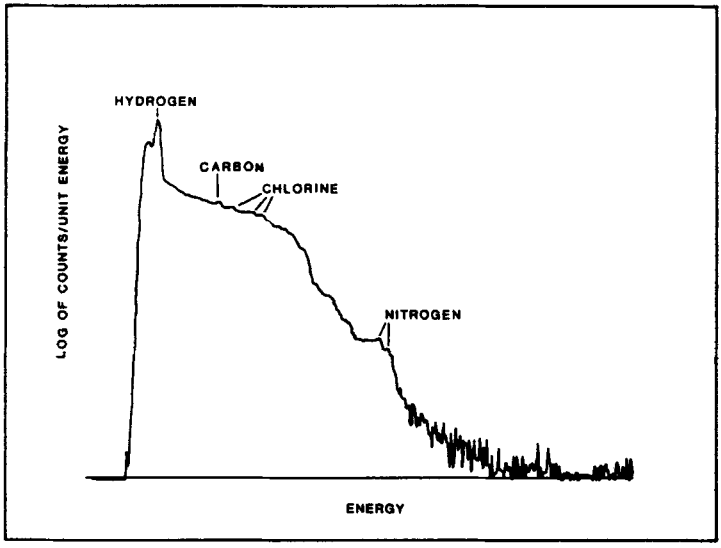

FIGURE 2
Log spectrum of 1 kg C-4 simulant in typical suitcase.

simulant. The nitrogen signal from the C-4 is significantly higher than the nitrogen signal from the suitcase contents and from the air. The medium-energy part of the spectrum is dominated by suitcase material, in this case the chlorine from PVC, as illustrated in Fig. 4. The capability of performing spectral analysis under the difficult conditions prevailing during the short measurement time greatly facilitates the ATNA in reducing the false alarm rate.

The nitrogen count rate in the total detector array during the screening time of 6 seconds or less is a very important indicator of the possible presence of an explosive. Figure 5 depicts total array

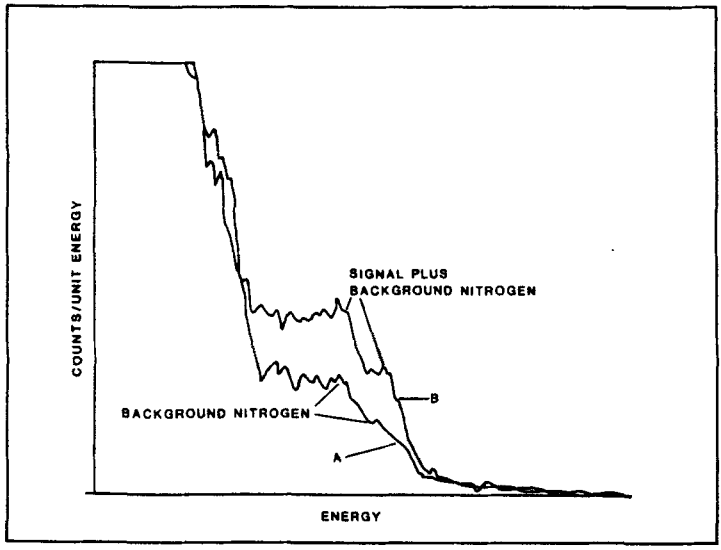

FIGURE 3
Linear spectrum of high-energy region (A)
without and (B) with 1 kg C-4 simulant.

count rates versus position for a packed suitcase. This is a most demanding test of the explosive detection capability based on count rate, since the explosive in the suitcase would yield a significantly higher count rate than the explosive alone. While this specific case allows the computer to clearly discriminate in 6 seconds between an explosive and a nonexplosive, using the total counts other cases would not. In those cases more complex data reduction and decision-making techniques are required.

5.2.4 System Performance

In the final analysis an explosive detection system has to be measured against the performance and other operational criteria

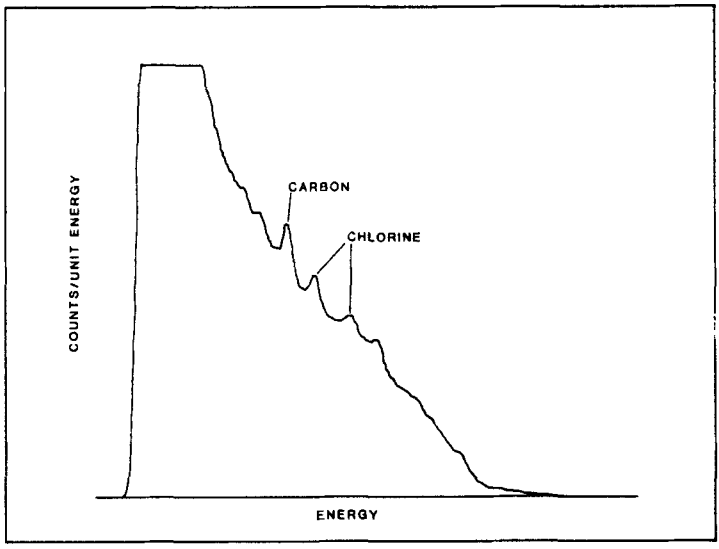

FIGURE 4
Linear spectrum of medium energy region.

listed in section 2. The most important performance criteria are the probability of detection (PD) and the false alarm probability (PFA). These two quantities are interrelated in a complex way. The PFA is strongly dependent on luggage contents because some nonexplosive items in luggage can have a significant amount of nitrogen. However, this information concerning the distribution of nitrogen-bearing contents is very difficult to obtain and will vary greatly from airport to airport, country to country, and season to season. The goal of the SAIC ATNA is to be as independent as possible of this distribution and to minimize the residual dependence on it, at each

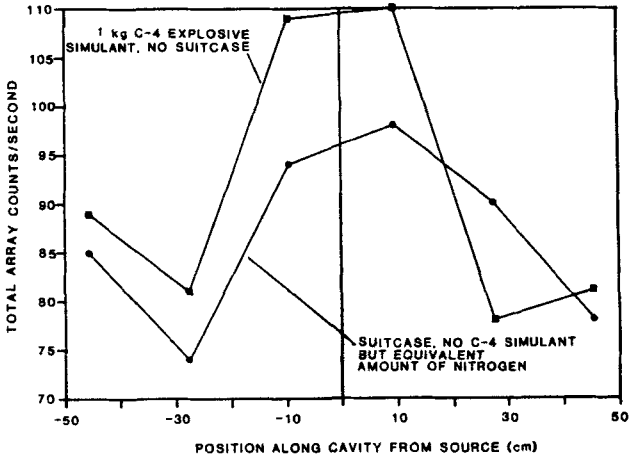

FIGURE 5
Total array count rate vs position from source for 1 kg C-4 simulant with no suitcase, and for suitcase with no C-4 simulant but with an equivalent amount of uniformly distributed nitrogen in wool.

installation, by intelligent system adjustment, e.g., by employing a rudimentary expert system.

In order to assess the performance of the ATNA, SAIC analyzed data from FAA tests made with the Westinghouse breadboard system in Philadelphia in February 1985. The selected sample consists of the luggage that had sufficient nitrogen counts to trigger a false alarm and represents the very high end of the distribution in terms of large amounts of nitrogen and other background-producing material. This distribution and the SAIC ATNA system response to the total nitrogen count threshold yielded the PD vs PFA curve labeled "Total Counts Alone" in Fig. 6. This shows that for a PD of < 92%,

reasonable PFAs are obtained, but for PDs above 92%, the PFA increases very rapidly. However, if the same database is subjected to criteria related to signal spatial distribution in addition to total nitrogen counts, much higher PDs with reasonable PFAs are achieved in measurement or scanning times as short as 6 seconds per item, as demonstrated by the curve marked "Total counts plus spatial discrimination" in Fig. 6.

These laboratory results indicate that the FAA goals outlined in a previous section are indeed attainable. The actual tests must, of course, be conducted in various airports and these are planned for Summer 1987. An overall schematic of the SAIC ATNA, which is believed to meet the required goals, is shown in Fig. 7.

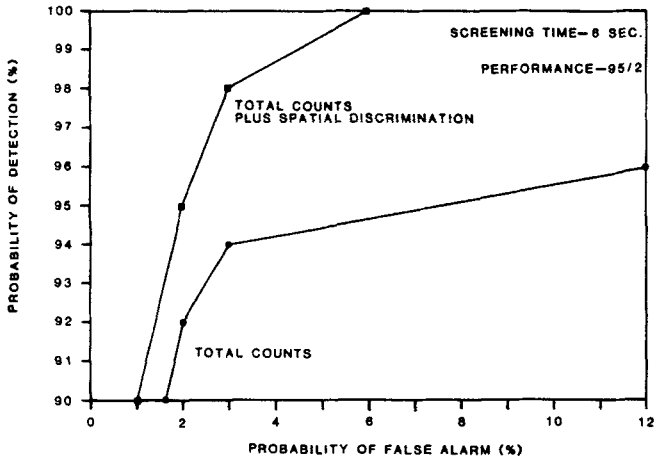

FIGURE 6
Probability of detection (PD) vs probability of false alarm (PFA) for total counts alone and for total counts plus spatial discrimination. Curves are based on a sample of Philadelphia test data.

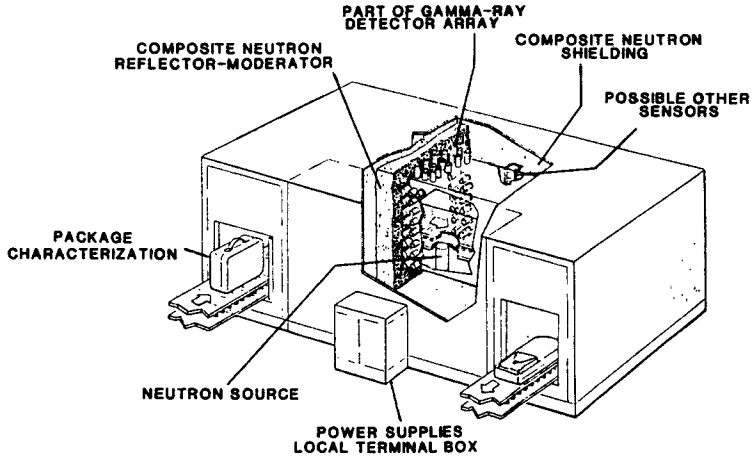

FIGURE 7
Schematic SAIC ATNA.

5.3 Associated Particle Technique

Consolidated Controls Corporation, Springfield, Virginia

Nitrogen and the other major constituents of explosives, with the exception of hydrogen, emit characteristic gamma rays when bombarded by neutrons with energies in excess of 6.5 MeV. These penetrating gamma rays range from 1.5 to 7 MeV in energy. In most cases it is not possible to separate these signals from interfering backgrounds. The associated particle technique (Fig. 8) exploits the temporal and spatial correlation between the 14-MeV neutron and its associated alpha particle produced in the D-T fusion reaction to extract these signals from the backgrounds in an ingenious manner.

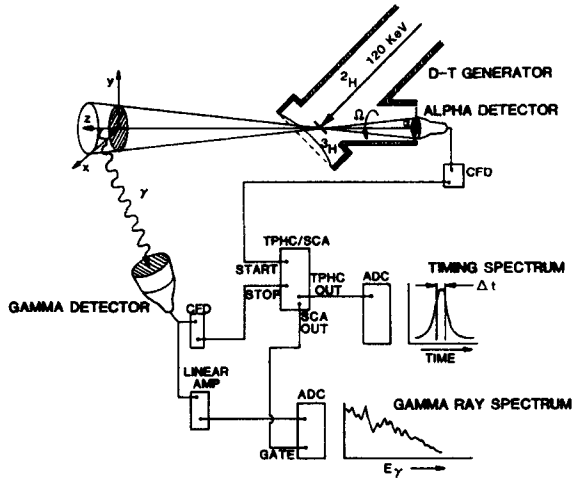

FIGURE 8
Associated particle technique schematic.

At low deuteron accelerating energies, the alpha particle and neutron are produced essentially back-to-back in the lab frame of the D-T reaction. The direction and subsequent interaction point of the neutron can be determined by detecting its associated alpha particle and the total time-of-flight as determined by a returning gamma ray produced in an inelastic interaction with a target nucleus. Typical inelastic cross sections at 14 MeV for the target elements found in explosives are several hundred millibarns.

Each time-of-flight window corresponds to a well-defined volume element along the direction of the neutron beam for which the gamma-ray spectrum is measured to determine its elemental composition

and density. The inelastic gamma-ray spectra are unique for most elements, ranging in complexity from the single gamma ray of carbon (4.43 MeV), the multiple lines associated with nitrogen and oxygen, and finally to the composite spectra of all elements found in explosives. With a properly characterized gamma-ray detector, the individual elements and their relative percent weight composition can in principle be determined.

The innovators of the technique at the Advanced Systems Division of Consolidated Controls Corporation[4] have received support from the FAA to investigate the feasibility of the technique for explosive detection. Although the feasibility has been demonstrated for four other applications,[8-11] a considerable development effort is required to extend the technique to interrogating larger volumes and to meet the FAA criteria for throughput and sensitivity.

The major effort in the first phase of the study has involved detailed spectral measurements of simulated explosives and luggage contents with the technique. The second phase has involved the development of compact sealed-tube neutron generators (STNG) with integrated multiple alpha-detector arrays. Based on the results of these phases, a prototype system will be designed and fabricated. Additional neutron generators and detectors will be incorporated in a step-wise manner, culminating in a breadboard system that will be tested in the airport environment.

5.4 High-Energy Photon Techniques

High-energy photon beams are efficiently produced by electron linear accelerators (linacs). Compact and reliable accelerators up to 25 MeV have been used for radiation therapy and nondestructive testing since the 1950s. These accelerators are characterized by high intensities, low duty factors, and variable energies. The high-energy photon beams resulting from bremsstrahlung production targets are peaked forward and can be well tailored by collimation and beam flattening to uniformly irradiate arbitrarily shaped volumes. The small focal spot, high output, and variable energy are ideal for radiographic applications, including tomography. A portable, variable-energy linac has recently been developed at Los Alamos National Laboratory for field operations up to 10-MeV (Fig. 9).

In addition to being excellent radiographic sources, linacs are also efficient producers of neutrons from the low-Z, low-photoneutron threshold elements of deuterium and beryllium. The neutrons may subsequently be moderated and used to induce radiative capture reactions in the target nuclei of explosives and interrogated during the period between accelerator pulses. Utilizing the time structure of the accelerator and the build-up time for the neutrons to reach thermal energies eliminates backgrounds that are due to prompt reactions. This technique has been successfully employed in the early 1970's to measure nuclear materials using low energy linac[12] and later in a nuclear waste management system developed at Los Alamos National Laboratory.[13]

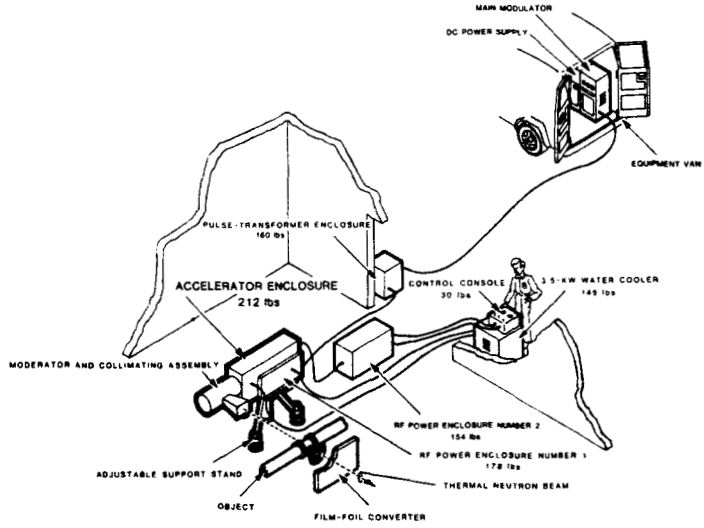

FIGURE 9
Portable 10-MeV linear accelerator.

An interesting prospect for high-energy photon probes is the photoactivation processes leading to positron emission with short half-lives and annihilation as described in the previous section. Despite the high threshold accelerating energies involved, this technique could be used to both image and identify individual target elements. However, backgrounds from positron emitters would lead to unacceptable false alarms unless additional isotopic discrimination could be achieved on the basis of half-lives. This technique warrants further investigation to determine feasibility in the airport scenario.

6. CONCLUSIONS

The rationale for applying nuclear based techniques to the problem of bulk explosive detection has been explored and the status of current and proposed applications reviewed. From a strictly technical standpoint, the techniques represent the most comprehensive and feasible approach towards meeting the operational criteria of detection and false alarm rates. Beyond feasibility, the major impediments to operational implementation appear to be cost, complexity, and size. An effective reduction in cost and complexity might be achieved with the automation and control that has come to be expected from nuclear technology. The problem of size, although common to all techniques because it is dictated primarily by the maximum dimension of the objects under interrogation, is more serious for nuclear-based techniques that require additional shielding to achieve permissable working levels of radiation.

The comprehensive airport tests planned for the second half of 1987 should provide the critical data needed to make the TNA based techniques, a keystone for airport security. However continued long term R&D effort in nuclear based techniques is required to assure improved performance and to mitigate possible terrorist counter measures.

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