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THE DETECTION OF BULK EXPLOSIVES USING NUCLEAR-BASED TECHNIQUES

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ABSTRACT

The status of nuclear-based techniques for the detection of bulk explosives presently under investigation by the US Federal Aviation Administration (FAA) is reviewed. These include thermal neutron activation (TNA), fast neutron activation (FNA), the associated particle technique, nuclear resonance absorption, and photoneutron activation. The results of comprehensive airport testing of the TNA system performed during 1987-88 are summarized. From a technical point of view, nuclear-based techniques now represent the most comprehensive and feasible approach for meeting the operational criteria of detection, false alarms, and throughput.

I. INTRODUCTION

In 1986 we presented a rationale for the detection of bulk explosives based on nuclear techniques that addressed the requirements of civil aviation security in the airport environment.[1] Since then, efforts have intensified to implement a system based on thermal neutron activation (TNA), with new work developing in fast neutron and energetic photon reactions. In this paper we will describe these techniques and present new results from laboratory and airport testing.

Based on preliminary results, we contended in our earlier paper[1] that nuclear-based techniques did provide sufficiently penetrating probes and distinguishable detectable reaction products to achieve the FAA operational goals; new data have supported this contention.

II. CHARACTERISTICS OF NUCLEAR-BASED EXPLOSIVE DETECTION TECHNIQUES

Nuclear-based detection techniques probe the screened items with penetrating radiation, notably neutrons and photons. An array of detectors positioned near the screened item senses the high-energy gamma-ray reaction products induced by the probe (see Fig. 1). The intensity, energy, and spatial distribution of the detected radiation; their relationship to the probing radiation; and any additional information concerning the object are used to determine the presence or absence of an explosive.

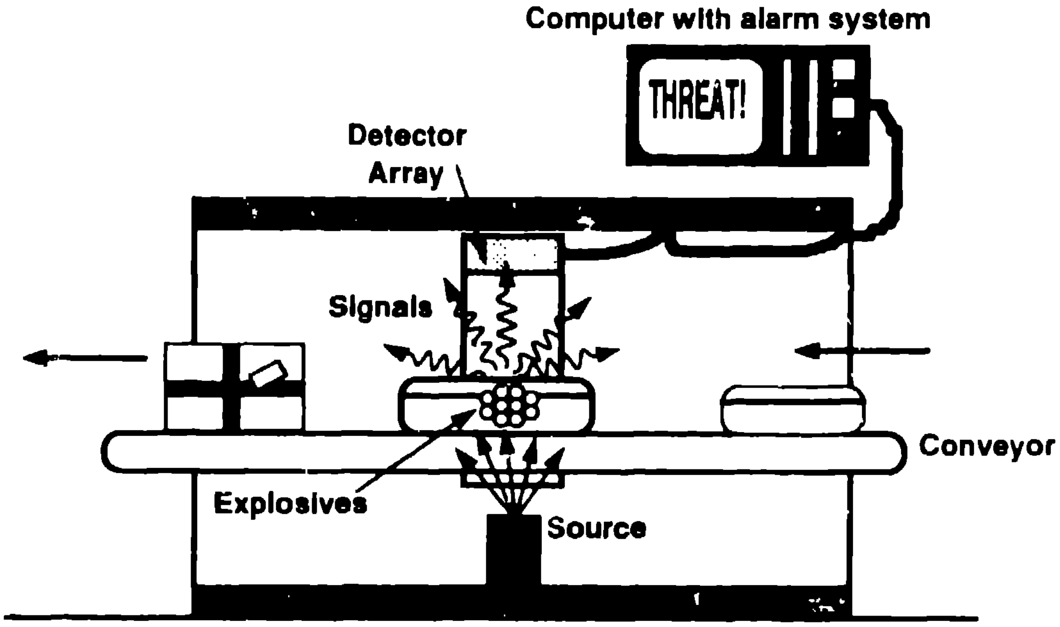

Fig. 1. Explosive-detection schematic.

Nuclear interrogation involves detecting reaction products from target isotopes that are reliably and sufficiently present in all explosives. The discriminating features of explosives are summarized in Table I according to their specificity and sensitivity as a basis for detection. The universal occurrence of these same elements in nonexplosives, however, limits the attainable level of detection sensitivity, and, invariably, increases the probability of false alarms.

TABLE I

DISCRIMINATING FEATURES OF EXPLOSIVES

Characteristic Feature	Specificity
Total nitrogen	High
Nitrogen density	High
Oxygen density	High
N:H, N:C, and N:O ratios	Very high
Trace metals	High
Total density	Moderate
Physical shape	Low

The FAA operational criteria will limit the choice of techniques to those probing reactions that can meet the criteria in a practical way. No single factor determines the applicability of a specific reaction to the complex problem of explosive detection, but any choice of reactions must consider the availability, cost, size, and shielding requirements for a particular nuclear probe. The induced radioactivity in the contents of luggage and the potential exposure to the public are also important considerations in selecting appropriate probes.

III. TECHNIQUES PRESENTLY UNDER INVESTIGATION

A. Neutron Probes

1. Thermal Neutron Activation Explosive Detection System (TNA/EDA) --- Science Applications International Corporation (SAIC), Santa Clara, California. This technique detects and images the 10.8-MeV gamma ray produced in nitrogen by the prompt radiative capture of thermal neutrons. The concept was originally investigated by the Westinghouse Corporation, Pittsburgh, Pennsylvania, who demonstrated its feasibility to the FAA with checked baggage and air cargo.[2] The technique detects and images only nitrogen and is sensitive to backgrounds from other interfering elements that also emit high-energy gamma rays. It remains the most thoroughly tested of all explosive detection techniques and sets the standard for comparison with other techniques.

In the SAIC version, the neutron source is either the radioisotope ^{252}Cf or an electronic neutron generator with a peak neutron intensity of 5×10^8 n/s. Fast neutrons from the source are slowed down by hydrogenous moderating materials that make up the walls of the interrogating cavity to create a cloud of low energy neutrons. The overall size of the system is determined by the requirements for sufficient moderating material to produce a high neutron flux in the interrogating cavity, plus additional shielding to reduce radiation exposure to personnel (see Fig. 2). The neutrons diffuse into the screened object to produce characteristic gamma rays that are promptly emitted following neutron capture. The SAIC detector array consists of up to 80 NaI(Tl) inorganic scintillators arranged in two C-shaped rings, with a ^{252}Cf source in the gap of each C-ring. In the electronic neutron generator design, the rings are collapsed into one ring, with the single generator source displacing the detectors to each side.

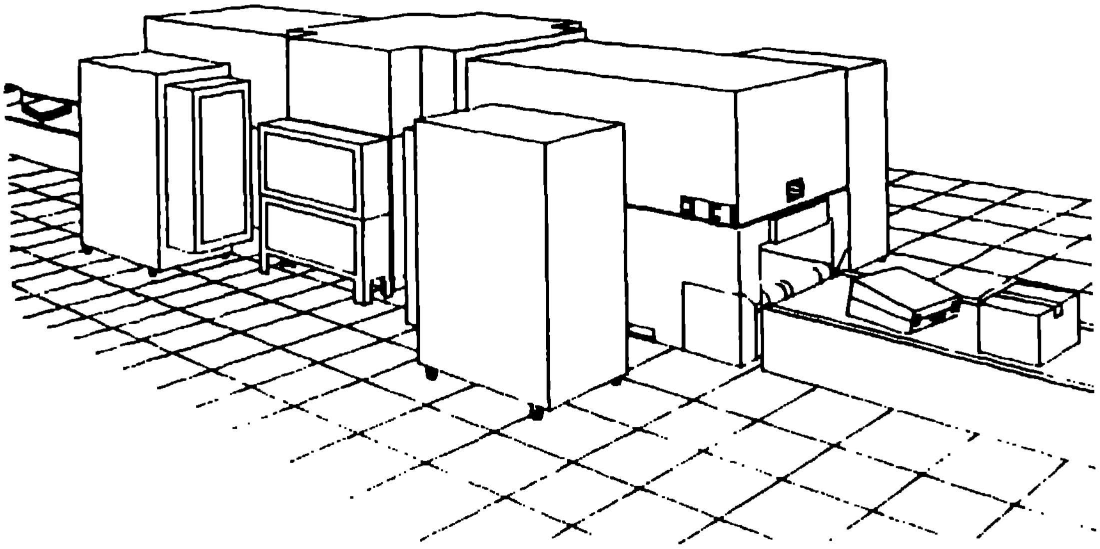

Fig. 2. SAIC explosive-detection system.

Figure 3 depicts the typical gamma-ray spectra obtained from a luggage sample with and without a threat amount of explosive simulant. These spectra are characterized by a large background of low- and intermediate energy gamma rays arising from suitcase contents and from cavity construction materials. The construction materials were carefully selected to minimize backgrounds, and corrections for the remaining backgrounds are applied to each detector. Additional corrections are applied to the high-energy gamma rays from chromium, chlorine, and nickel that interfere directly with the gamma rays from nitrogen.

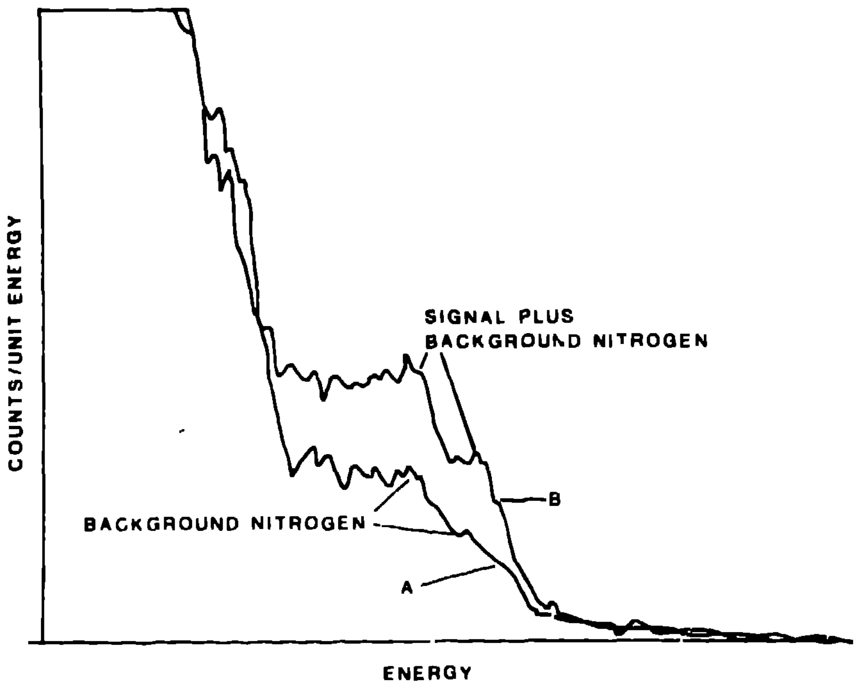

Fig. 1. Linear spectrum of high-energy region (a) without and (b) with 1-kg C-4 simulant.

High-speed analog-signal-processing electronics were developed to measure precisely the energy of each gamma ray at the data rates necessary to meet the system throughput requirement. The detected gamma-ray signals are converted into pulses suitable for computer processing. If a predetermined set of conditions is fulfilled (such as a localized region of high gamma-ray rate from nitrogen), the system's alarms indicate the possible presence of an explosive threat.

Extensive laboratory optimization measurements were followed by an intensive period of airport testing (June 1987 March 1988), which included measurements with both the radioisotopic and electronic neutron sources. Tests to detect simulated bulk and sheet explosive simulants at the operationally required throughput rate were performed at the San Francisco and Los Angeles International Airports in California on both domestic and International baggage sets. The results of the tests are summarized in Table II

TABLE II

AIRPORT TEST RESULTS FOR THE TNA EXPLOSIVE DETECTION SYSTEM

FOR MORE THAN 30,000 SCREENED ITEMS

Item	Probability of Detection (%)	Probability of False Alarm (%)
Luggage	90-96	3-8
Cargo	90-95	1-4

The range of PD and PFA values results from variations in performance due to the contents of the luggage items as a function of the destination and the season of the year. The trade-off in PD vs PFA to match a particular situation is programmed into the system decision-making process.

A disturbing result of the airport tests was the large fraction of items, particularly in the international sample, that contained more than one threat equivalent of nitrogen (see Fig. 4). This illustrates the need to measure other independent, distinguishing features besides nitrogen to reach the lowest possible PFA. To achieve this, SAIC determined a large number of discriminants, the most significant of which are the average density of each bag, the neutron flux attenuation in the bag, and the spatial distribution of nitrogen.

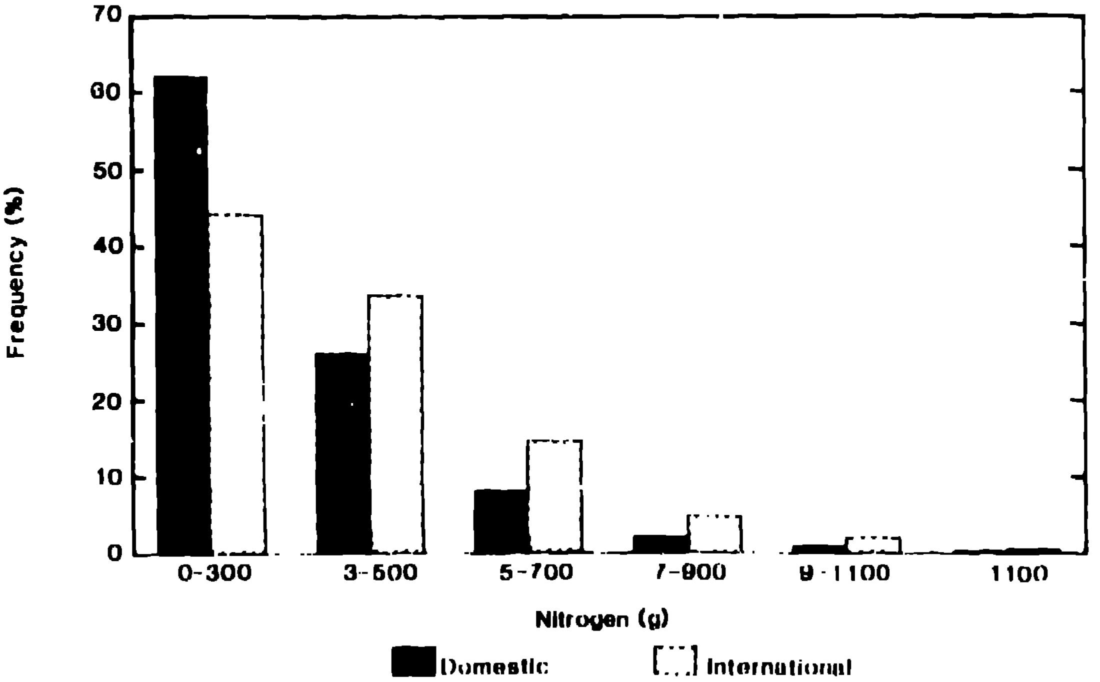

Fig. 4 Domestic vs international nitrogen distribution

The TNA technique has successfully achieved the FAA operational criteria of PD, PFA, and throughput. Presently, SAIC is designing and modeling improved and more compact versions based on both types of neutron sources. More importantly, the success of TNA has demonstrated the efficacy of nuclear-based techniques and has provided the basis for consideration of other techniques.

2. ***Fast-Neutron-Activation Explosive-Detection System (FNA/EDS)---Science Applications International Corporation, Santa Clara, California.*** To extend the advantages and overcome the limitations of the TNA approach, SAIC is investigating a new technique that relies on the inelastic reactions of fast neutrons (FNA) on carbon, nitrogen, and oxygen. A continuous flux of fast neutrons (14 MeV) is produced in the reaction.

$$d + T \longrightarrow {}^4He + n,$$

where a beam of deuterons (d) is accelerated at low energy (150 keV) onto a tritium (T) target, liberating alpha particles (^4He) and neutrons. Subsequent neutron collisions produce characteristic gamma rays from inelastic reactions with the main constituents of explosives. Thus, most of the characteristic components of explosives can, in principle, be detected and imaged. The overall improvement in PD and PFA can be estimated once the system's signal-to-background ratios are determined for each element.

The interrogating cavity has an inner layer of lead (Pb) that maintains the flux of fast neutrons, minimizes thermalization, and shields the detector array from gamma rays produced in the personnel shielding materials. As with TNA, the selection of construction materials with the proper neutronic characteristics is critical to the technique's success.

The required peak intensity of neutrons in FNA is expected to be lower than TNA, resulting in less shielding and an overall smaller system. The method of detection and imaging is identical to that of TNA. Increased sensitivity to explosives is predicted on the basis of the higher interaction rates of fast neutrons, while improved selectivity is expected from imaging spatially coincident multiple elements of explosives.

An FNA cavity, neutron source, and partial detector array have been assembled and operated. A systematic study is underway to determine the detector shielding required to reduce the background originating from fast neutron reactions directly in the detector and surrounding materials. The spectra of samples for individual signal elements and composite materials have been measured. Further detector, shielding, and cavity optimization are required to reduce the high-energy background continuum that compromises the overall sensitivity in the region of interest.

Laboratory measurements with test samples of luggage and explosive simulants will begin in the Fall of 1988, with airport testing scheduled for 1989.

*3. **The Associated Particle Technique***. The associated particle technique further extends the idea of FNA to produce three-dimensional images of gamma rays produced by fast neutron inelastic interactions. With support from the FAA and the US Navy, Consolidated Controls Corporation (CCC) is developing the technique for explosive detection,[3] although the technique is not limited to detecting and imaging explosives.[4-7] The Advanced Nuclear Technology Group at Los Alamos National Laboratory is extending the limits of the technique's application to the area of national security.

The technique exploits the temporal and spatial correlation between the 14-MeV neutron and its associated alpha particle (^{4}He) produced in the d-T fusion reaction described in the previous section. At low deuteron energies the alpha particle and neutron are produced back-to-back. Thus, by localizing the alpha particle, the direction of the neutron is determined (see Fig. 5). The neutron's subsequent interaction point is determined by measuring the total time between the detection of the alpha particle and the detection of the gamma ray produced in the neutron interaction.

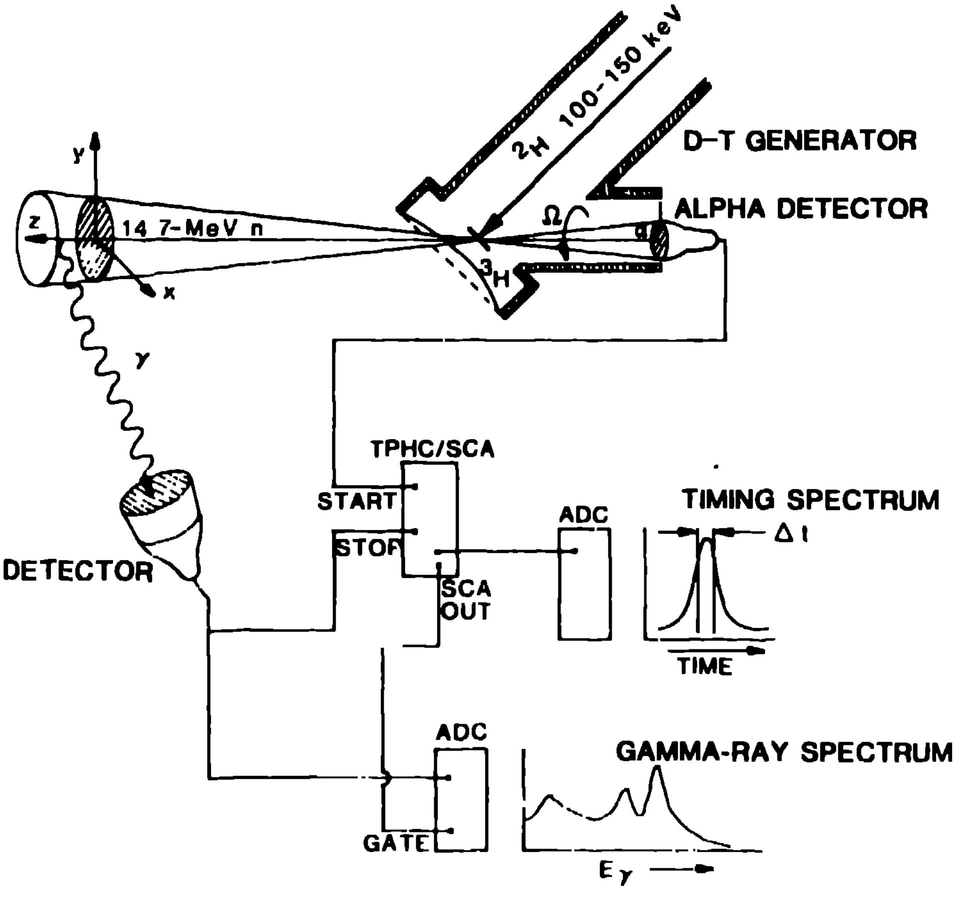

Fig. 5. Associated particle technique schematic.

The gamma-ray spectra provide unique signatures for most elements. With an appropriately characterized detector, the individual elements and their relative percent weight compositions can be determined and visualized. By binning the data according to the variation of the time-of-flight with distance from the target, images for each volume element are generated. Larger volumes are imaged by adding more alpha detectors.

The first phase of the CCC program involved detailed spectral measurements of simulated explosives and the contents of luggage. It was quickly recognized that although the sensitivity of the technique would not meet the FAA throughput requirement for a fast screening system, it was possible, with longer inspection times, to achieve lower PFAs than other techniques.

The second phase of the CCC program involved the development of a compact, sealed-tube neutron generator (STNG) with an integrated alpha detector. They succeeded in producing a 10^7 n/s source for a single-pixel system that was delivered to the US Navy in 1988.

The Los Alamos program has concentrated on the fundamental aspects of neutron intensity, beam optics, and detector timing resolution to increase the sensitivity and improve the spatial resolution of the technique. Sub-nanosecond time resolution was achieved using a plastic scintillator alpha detector and BaF_2 gamma-ray detector. A gamma-ray detector shielding study is seeking to reduce the counting rate from time-correlated and uncorrelated, neutron-induced backgrounds and is targeted for a ten-fold increase in sensitivity.

Immediate plans call for the implementation of a four-element alpha-detector array and two gamma-ray detectors. A fully operational system with a 100-element alpha-detector array and as many as 10 gamma-ray detectors (each simultaneously acquiring 128 channels of spectral data in as many as 16 time windows) is envisioned. To acquire, process, and display the copious amounts of data produced by an operational multi-pixel system, special attention must be directed to computer architecture. Los Alamos is investigating the parallel-processing capability afforded by the VME bus. The single-processor-based Valet system (developed by CERN in Geneva for high-energy, colliding beam experiments) is currently being used in the single-pixel system and is expected to be able to handle the four-element array. The system affords a large degree of flexibility in the availability of data acquisition hardware through its CAMAC interface. A demonstration of three-dimensional imaging of the elemental composition of extended objects, including explosives, is planned for late 1988.

B. High-Energy Photon Probes

The FAA has funded feasibility studies of two techniques that use high-energy photon probes to detect and image specific elemental components of explosives: nuclear resonance absorption and photoneutron activation. Both techniques are highly speculative, and work is progressing to resolve basic physics questions regarding resonance widths and reaction cross sections and to determine sources of background. The required energetic photon beams are produced either by bremsstrahlung radiation or from proton-induced reactions.

*1. **Nuclear Resonance Absorption**.* Nuclear resonance absorption is observed when incident photons are strongly absorbed by a specific target nucleus at a particular photon energy corresponding to the resonance energy of the nucleus. If the width of the resonance is appropriately narrow, the fraction of the total absorption due to resonance absorption is large. This provides an opportunity to detect and image a particular isotope whose resonant absorption energy is closely matched to the probe-photon energy. It also exists for one of the isotopes in explosives, and resonance absorption of high-energy photons has been observed. In principle, a detection system functionally comparable to a concourse x-ray scanner but sensitive only to explosives is possible.

The feasibility study is determining if the level of sensitivity provided by this technique can meet the operational requirements. Monoenergetic photon beams with the precise energy for resonant absorption have been produced with proton beams via the (p,γ) reaction at Van de Graaff accelerators. The photons emanate from a geometrically small spot as a fan beam with a small angular divergence, providing for the possibility of imaging with high spatial resolution. The width of the resonance has been determined, and the required proton current for a prescribed level of sensitivity has been estimated. Targets capable of sustaining the power level have been designed and tested in a proton beam. The present effort is directed toward designing, fabricating, and testing an array of detectors that produces images of explosive simulants. The goal is to determine the spatial resolution and detection sensitivity required to detect sheet explosives.

*2. **Photoneutron Reactions**.* Photoneutron reactions involve the production of short-lived radioisotopic beta emitters predominantly by the (γ,n) (γ,p) and $(\gamma,2n)$ reactions The reaction thresholds for the elements of interest in explosives require high-energy bremsstrahlung beams (10-MeV and higher). The resulting beta emitters are detected either by coincidence detection of the two, 511-keV gamma rays following the annihilation of the positron or by the high-energy bremsstrahlung associated with the emitted positrons and electrons. Coincidence detection is inherently imaging in three-dimensions, identical to positron emission tomography scanning in the medical application. The challenge is to distinguish the source of positrons specific to isotopes of explosives from other positron emitters produced at the high photon energies required. This can be done by employing a pulsed beam of photons and interrogating in-between pulses. Isotopic determination is made on the basis of the characteristic half-life of the positron emitter.

The FAA is supporting an experimental program to determine the sensitivity of photoneutron reactions to explosive constituents and the backgrounds that may occur at the energies involved. Preliminary results indicate that there are competing reactions that provide both additional sources of detection and backgrounds.[8]

IV. CONCLUSION

Access by terrorists to new, shape-independent or non-nitrogenous explosives presents a serious challenge to all bulk-detection technologies. The development of automated detection equipment to screen passengers, baggage, and cargo for concealed explosives remains a top FAA priority. Significant progress is being made in this area through the development of the advanced bulk-detection techniques described in this paper.

The TNA system is the first truly automated explosive detection device operationally tested on airline baggage and cargo. The performance of the system and the flexibility to select detection options based on a perceived threat level have resulted in an FAA decision to purchase and deploy at least five TNA units. The plan is to deploy the systems at high-risk, Category X airports in the United States and possibly at one or two foreign airports used by US carriers. Estimated delivery is for July 1989.

Efforts are underway to improve the reliability and performance of the TNA system. These include the development of an electronic neutron source with increased output and longer lifetime and the integration of the TNA-generated nitrogen images with high-resolution x-ray images. Tests show that this correlation reduces the PFA by 50% with little effect on the PD.[9]

As the lead agency for the development of explosive-detection technology in the US, the FAA is continuing its search for new detection concepts and technologies that have prospects for greater effectiveness and reduced size, complexity, and cost than those currently under development. Toward this end, the FAA strategy has been to increase the number and technical quality of new concepts under investigation. Approximately 20 proposals have been evaluated in each of the past three years, resulting in four or more funded proposals per year. These include problem areas not addressed by bulk-detection technologies, such as screening for explosives on the person and in carry-on luggage.

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