Appendix A

Nuclear-based Explosives Detection Systems

Thermal Neutron Analysis (TNA)

Sponsor: Federal Aviation Administration (FAA) Technical Center through contractual relationship with Science Applications International Corp. (SAIC).

Status: Testing of one preproduction unit is under way at JFK Airport, New York, one unit was recently checked out in Miami, one is at Dunes, one at Gatwick and two more are to be delivered to FAA shortly for installation at selected airports in the United States and abroad.

Funding: $12 to $15 million R&D funding over 4 years from FAA Technical Center, plus about $5 million private funding, plus $15 million for the six preproduction units FAA bought for airport demonstration.

Basic Operating Principle and Goals of Concept

When a neutron strikes a nucleus, there is a certain probability that it will be absorbed. This process is often accompanied by the emission of a high energy gamma ray whose energy is characteristic of the nucleus. The amount and type of some specific elements present in a sample inspected by neutron radiation can be inferred from a measurement of the intensity and energy of these gamma rays. The TNA concept depends on this principle for the identification of nitrogen in explosives.

An item of luggage is moved through a "bath" of thermal (i.e., slow) neutrons generated by a radioactive source or an electronic neutron generator (particle accelerator). In the current design, the isotope californium-252 is used. The capture of a neutron in nitrogen results in a high-energy gamma ray produced through the reaction

$$^{4}\mathrm{N} + \text{thermal neutron} = {}^{5}\mathrm{N} + 10.8\ \mathrm{MeV}\ \text{gamma.}$$

The signals from an array of gamma-ray detectors are analyzed to give a rough spatial distribution of nitrogen. Figure A-1 demonstrates the principle of operation of TNA.

The currently tested version of TNA was designed, following FAA performance specifications, to detect a minimum mass of nitrogen, equivalent to a certain quantity of plastic explosives. It has limited spatial resolution and detects primarily nitrogen, not oxygen or carbon; although hydrogen, chlorine, and some other elements could, in principle, be detected to enhance performance. Because only nitrogen is currently specified by the device and because of the system's difficulty in dealing with nitrogen background from innocent materials, the false-alarm rate is higher than desired. This has become an important issue for the current TNA hardware. Further, the sensitivity (probability of detection for a given quantity of explosives) is limited. Sensitivity can, indeed, be increased by lowering thresholds, but a concomitant rise in the false alarm rate results. This situation can be improved, according to the system's designer, by using TNA or other techniques to measure other elements present and by other system modifications.

Technical Description

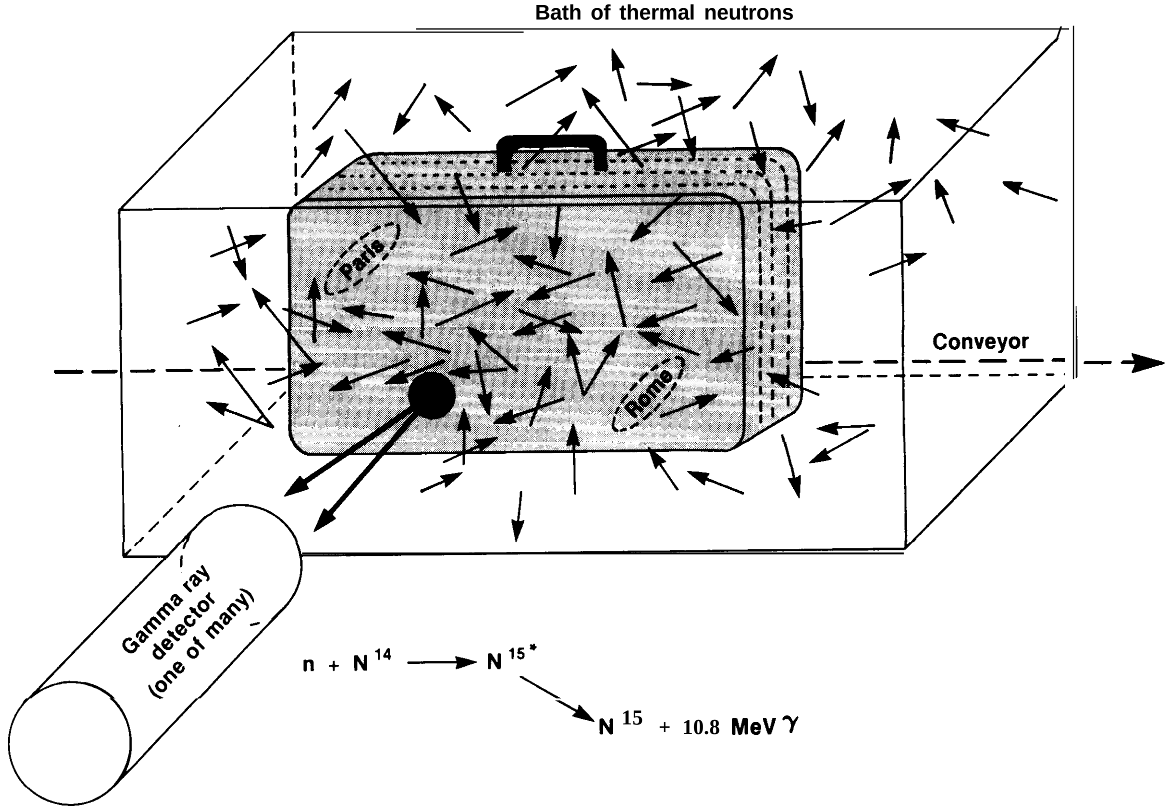
The current TNA equipment is represented by engineered preproduction units that are being tested at airport sites. They are being modified and upgraded in accordance with experience gained in a real operating environment. For instance, an x-ray system has been combined within the TNA set-up in an attempt to reduce the false alarm rate. The combined TNA/x-ray system is generally referred to as the "XENIS' system.

The californium source is of moderate strength (approximately 80 millicuries or 3 x 10^9 alpha particles/see and 3.5 x 10^8 neutrons/sec[1]). It is contained in a small, double-walled capsule of a common industrial design. The capsule was exposed to a blast from a substantial explosive charge and maintained its integrity. Radiation from the shielded system, near its surface, has been examined and found to be comparable to the natural background level of radiation exposure. The environmental threat of the system has been assessed by the Nuclear Regulatory Commission (NRC) and found to be within Environmental Protection Agency and NRC exposure guidelines.

The source exposes baggage on a conveyor belt to a "bath' of neutrons inside a shielded cavity. The baggage is surrounded by an array of gamma-ray detectors, which send their data to a computer. The software, in turn, transforms the data into" a spatial distribution, giving a rough image of the nitrogen content of the object. The system also records various other data used as input to algorithms that distinguish objects that contain explosives from "clean" ones. The details of the analysis algorithms have not been examined by OTA. Generally speaking, the system utilizes artificial intelligence techniques based on neural networks and permit the system to learn from experience. Many pieces of baggage, including both items containing explosives and clean ones, are observed by the

[1]A curie is 3.7x 10^{10} disintegrations/sec

Figure A-l—Sketch of Apparatus for Thermal Neutron Analysis of Nitrogen



SOURCE: Lee Grodzins, 1990.

system in order to learn the distinguishing characteristics of the "bad" objects.[2] There is a continual upgrading process in refining the decisionmaking algorithms. The add-on x-ray system is used to reduce the number of false alarms by determining whether the nitrogen image (provided by TNA) overlaps with the two-dimensional image of density (given by the two-view x-ray system used). The details of the correlation of these data have not yet been examined by OTA.

Status

The current version of the TNA device was developed by SAIC under FAA Technical Center sponsorship during the last 5 years. SAIC was selected by a competitive procurement process in 1985. The current device was designed to satisfy performance specifications set down by FAA at that time. These demanded, among other things, a baggage handling rate of 10 per minute (6 seconds per bag) and automated detection. The devices were tested against these criteria at SAIC's laboratories at Santa Clara, CA, as well as at San Francisco (SFO) and Los Angeles (LAX) Airports in 1987 and 1988, where the system was accepted by the FAA as meeting these specifications. These tests were not done independently, but were designed and conducted jointly by the FAA and SAIC, in the presence and with the concurrence of FAA consultants. This test was performed somewhat in the manner of some Department of Defense weapons acceptance tests, and there is currently considerable controversy over their significance.

Since that time, the FAA has ordered 6 preproduction units from SAIC for actual airport testing at a cost of about $15 million. This price includes SAIC's participation in operations, maintenance for 1 year, and installation, including the x-ray adjunct. The last of these units are scheduled to be delivered to the FAA when their destinations are determined. Currently, three of these units are operative, one at Trans World Airlines (TWA) at JFK Airport in New York, one at Gatwick Airport, near London, and one at United Airlines at Dunes Airport in the Washington, DC area. A fourth is being refurbished after a year's operation at Miami International Airport at Pan American Airways. The Kennedy system routinely operates about 5 hours per day, during which time most of the foreign flights leave New York. It examines about

[2] The original selection algorithm was based on SAIC's lost luggage stock. Later it was amplified by the experience gained at Los Angeles and San Francisco airports. The system is currently using the experience it is gaining at various sites to refine its decisionmaking capability.

350 bags per day, primarily the interline transfer bags from other flights. This selection was based on logistic considerations (i.e., where the system could be physically placed in the TWA baggage handling area), and is the limiting factor on the testing of the system's throughput capacity. The Miami system was located at a baggage transfer point and the Gatwick and Dunes units are located in the main concourse in front of the check-in counters.

The system is tested daily against baggage containing simulated explosives. Performance data are gathered from these tests as well as from the false alarms of real passenger luggage. The current false-alarm rate is running higher than that achieved in the "acceptance" tests for the "LAX distribution.' The XENIS system uses a two-view x-ray seamer system, built by EG&G Astrophysics Division, in tandem with the TNA device. With this combination, the false-alarm rate is lowered significantly. Any bags that do not pass the TNA/XENIS system and are still deemed suspicious, following a close examination of the data by an operator, are turned over to TWA for further action. It has been claimed by SAIC that by rerunning a suspect bag, the false-alarm rate can be lowered to a very few percent. However, SAIC also notes that this decreases the probability of detection.

The algorithm by which the system either accepts or rejects a given bag is still under development and is being modified to include the x-ray information. In the current operating version, the x-ray/TNA information match is being performed outside of and independent of the TNA analysis.

Potential and Shortcomings

The SAIC TNA is the first automated baggage inspection system and the only one that, in the view of the FAA, meets present FAA guidelines. However, the degree to which it meets these guidelines is very controversial. The impartial testing of this baggage handling system is a complex issue: many variables need to be considered. Baggage differs among airports, flights, and seasons. These differences have profound effects on system performance. Explosives also differ greatly. Various types present differing degrees of difficulty. Also, human factors are involved in how the explosives are handled for any test. Currently, there is no generally acceptable test protocol that would allow the FAA to certify that a system is "working properly", although FAA contracted with the Department of Energy's Sandia National Laboratory to propose one. The National Research Council is also looking at this issue for the FAA.

The current TNA system also has several severe shortcomings, including its high cost, which is currently estimated to be $0.75 to $1.0 million per system (depending on various assumptions including the savings due to large-scale production). SAIC claims to be willing and able to build 30 units per year, but so far has no committed orders and currently plans to build only a few beyond the past FAA purchase. The current system is massive, weighing close to 14 tons and taking up a large amount of real estate (the footprint for the TNA alone is about 12 m^2, and an additional equivalent area would be needed to add an x-ray system and baggage diverter) in an area where space is scarce and valuable. Considerable site preparation was necessary for the JFK installation. Further, the use of a radioactive source and the resulting shielding requirements present an acceptance problem. If an electronic neutron generator were used, the shielding requirement would not be reduced. To date, foreign acceptance of TNA systems has been difficult to achieve, but there are active negotiations between the FAA and some foreign airports for test systems, and, as noted, a TNA unit has been installed at Gatwick, near London.[3]

The limited sensitivity and the strong dependence of the false-alarm rate on the lower limit set for detection is one of the major issues that will determine the utility of the current version of TNA. The sensitivity, in terms of the detectable amount of explosive, was set by the FAA prior to the Pan Am 103 incident at Lockerbie, which is generally thought to have resulted from a substantially lesser amount than the original FAA specification.[4] The publicly available data taken to date on the issue of threshold sensitivity v. false-alarm rate are sparse.[5]

[3] The radiation exposure issue appears to be one of perceptions; the facts do not appear to indicate a serious problem. The operators of the TNA will be shielded to levels that are acceptable for workplace exposure, as defined by Food and Drug Administration standards (at 1 foot from the system, the radiation level is less than the permissible levels allowed for home TV sets). Residual dose rates from the baggage are very low—0.03 microSv/hr at the surface immediately after exposure. The radioactivity declines rapidly afterwards. For comparison, a resident of Leadville, CO experiences an exposure of 2.8 milliSv/yr, transcontinental airline crews experience 2.80 milliSv/yr in addition to exposures received from normal background (which amount to about 1.5-3.0 milliSv/yr, depending on location), the average human receives 0.2 milliSv/yr from potassium in food. Eating one banana per day gives a dose of 0.8 microSv/yr. From these&@ it would appear that the danger from radioactivity from TNA is not a real issue.

[4] However, there were several cases many years prior to Lockerbie in which lesser amounts of explosive were introduced aboard the aircraft cabin and produced significant damage and fatalities.

[5] At an NAS Symposium on Airline Security and Explosives Detection, Feb. 26-27, 1990, Dr. Gozani of SAIC reported that when the sensitivity was raised to maintain a 95 percent detection probability for this reduced amount, the false alarm rate rose to a high level. Since the initial writing of this report, a significant amount of new testing of the TNA/XENIS systems both at Santa Clara and at JFK has occurred. Some of these tests were run by SAIC with FAA supervision and overview, some by the FAA, and the last set by a group of independent consultants hired by the FAA, headed by Dr. Joseph Navarro of Wackenhut Securities Co., supported by representatives from Sandia National Laboratory, the National Institute for Standards and Testing, and the University of Georgia.

Although the SAIC TNA system is the only FM-''accepted' explosives detector currently at the prototype stage, there is considerable commercial interest in the development of more advanced versions of TNA. The FAA rule, requiring installation of an explosives detection system (EDS) at 40 U.S. airports over a 3-year period following the issuance of a final ruling, creates considerable incentive to industry to compete with SAIC. At approximately $1.0 million per unit, this would represent a $200 to $300 million market over the next several years. Several domestic and foreign firms (e.g., Gamma-metrics of San Diego), experienced in building similar inspection equipment, are seriously eyeing this market and are engaged in active development work to define their concepts, and SAIC is working to improve the performance of their system. It is possible that within a year or two, several such systems may be available for certification, possibly with some advanced features or options.

Another aspect to consider is the potential for TNA as a detector for explosives in carry-on baggage. Checked bags contain nitrogen in widely ranging amounts. The task of finding a small bomb against this varying background is very challenging. It is necessary to use information on the spatial distribution of nitrogen density to reduce the false-alarm rate even to its current high level. Since carry-on bags tend to have less mass than checked bags, the background would usually be less and the detection task easier. It would be useful to pursue this option, especially because now, only x rays are used to screen carry-on baggage, and it is extremely difficult, even for highly trained experts, to find a bomb using only standard x-ray images.[6] Some preliminary studies have been carried out on this problem by SAIC.

Fast Neutron Analysis (FNA)

Sponsor; FAA Technical Center is supporting some work at SAIC; there is some commercial development.

Status: Pre-prototype development.

Funding: $600,000 from FAA to SAIC for basic feasibility demonstration and preliminary conceptual design.

Basic Operating Principles of the Concept

As an improvement on TNA, more energetic neutrons can be utilized to give more information. When the slow neutron source of the TNA is replaced by a more energetic one, the interaction of the energetic neutrons with the nuclei of the elements in the object to be examined will produce gamma rays at different energies, characteristic of the elements, which can be detected and distinguished. These are often more copiously produced and thus easier to see above background than the gamma rays produced by thermal neutron irradiation. For instance, 14-MeV neutrons interacting with oxygen, carbon, and nitrogen will produce 6.1, 4.4, and 5.1 MeV gamma rays respectively. Measurement of each of these separately (see figure A-2) may yield a rough spatial distribution of the three elements in a manner similar to the TNA system.

Technical Description

An FNA system is physically similar to the TNA system, but there are significant differences in the source, the shielding requirements, and the gamma-ray detection arrays. A fast neutron source requires an accelerator, not a radioactive source, and is thus significantly more expensive from the beginning (at least by $250,000 and probably considerably more). An FNA system will almost certainly require more shielding than the TNA, representing another potential increase in cost, size, and weight. Several different concepts of fast-neutron sources are under development both in the United States and abroad (notably France). Many more elements, most importantly oxygen, can be measured by this technique.

Potential and Shortcomings

The obvious potential of the FNA is that it makes an essentially unambiguous determination of the presence of common explosives. It was shown in figure 4-4 that common explosives display a nearly unique range of nitrogen density to oxygen density. By being able to measure both these quantities as well as carbon and hydrogen density, FNA should greatly improve accurate identification of a hidden threat.

On the other hand, an obvious shortcoming of the FNA system is the use of fast neutrons. These neutrons create a significant background in the gamma-ray detectors, making it difficult to extract the information. The feasibility of commercial use of such a source, its shielding, and consequently, its operational restrictions in an airport environment have yet to be established, though a significant body of data from laboratories and from bore-hole oil-well logging does exist.

Pulsed Fast Neutron Analysis (PFNA)

Sponsor: FAA Technical Center.

Status: Basic R&D and feasibility experiments in progress under FAA sponsorship.

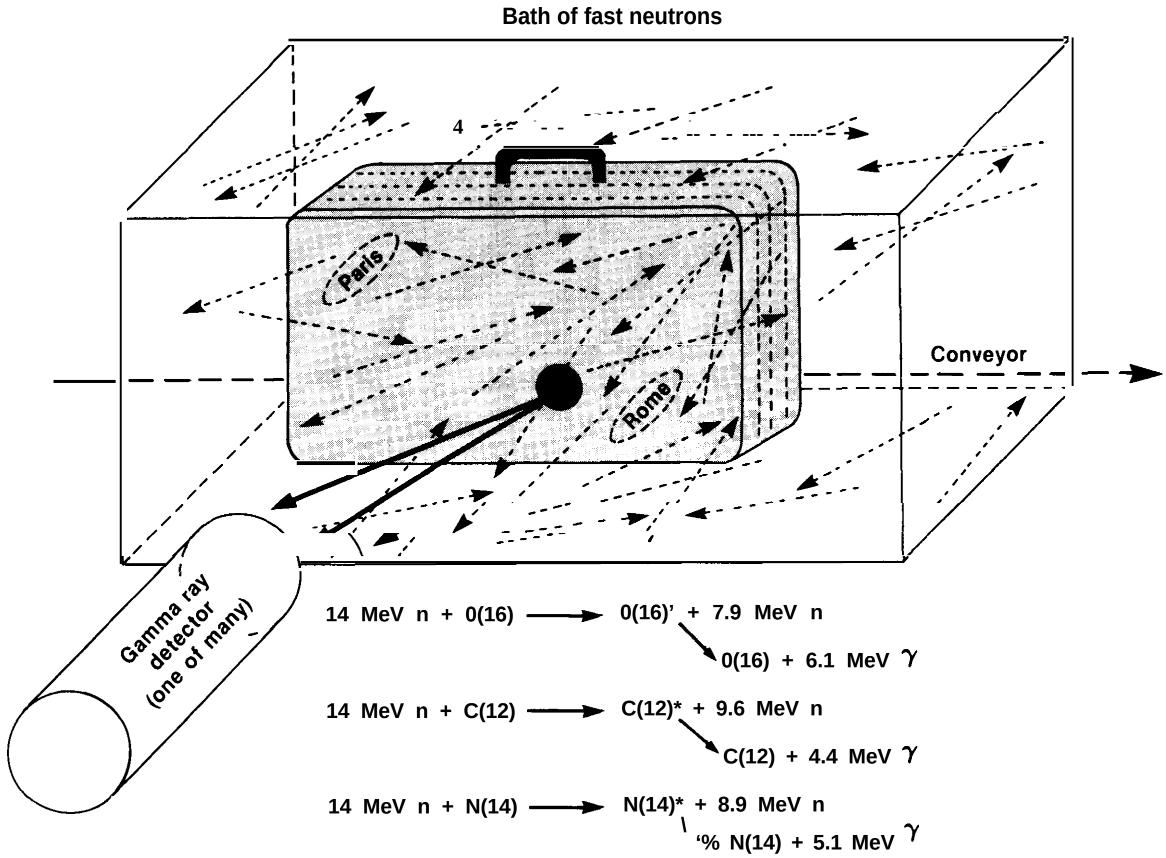
Funding: *$220,000* from FAA to SAIC

[6] The detailed results vary with many parameters, but several general characteristics are repeatedly seen. The following statements should be kept in mind when considering TNA/XENIS test results:

- Detection Probability, P_D, is generally given as a weighted average for a specified selection (usually 5) of different explosives.
- When thresholds are reduced, false alarm rates rise rapidly.

Another adjunct to x rays for screening carry-on baggage could be advanced vapor detection systems, now just coming on the market.

Figure A-2-Sketch of Apparatus for Fast Neutron Analysis of Nitrogen, Carbon, and Oxygen



SOURCE: Lee Grodzins, 1990.

Basic Principles of Operation of the Concept

The PFNA concept is similar to the FNA system, except that a pulsed beam of neutrons is utilized. A focused, collimated beam is passed through the object, resulting in the emission of gamma rays of specific energies, characteristic of elemental constituents of the sample. This method uses penetrating neutrons at lower energies than in FNA. At these energies, the probability for gamma-ray production by nuclear reactions with oxygen, carbon, chlorine and nitrogen is about the same as for 14 MeV neutrons; however, the gamma-ray spectrum is cleaner and shows a much better signal-to-noise ratio. The gamma-rays are detected, as before, by scintillators that provide gamma-ray energy information by which the element can be identified. The neutron beam profile provides the two-dimensional position information required to determine the spatial distribution. The third dimension, derived by timing and image reconstruction, constitutes a significant improvement over the basic FNA technique. A schematic view is shown in figure A-3.

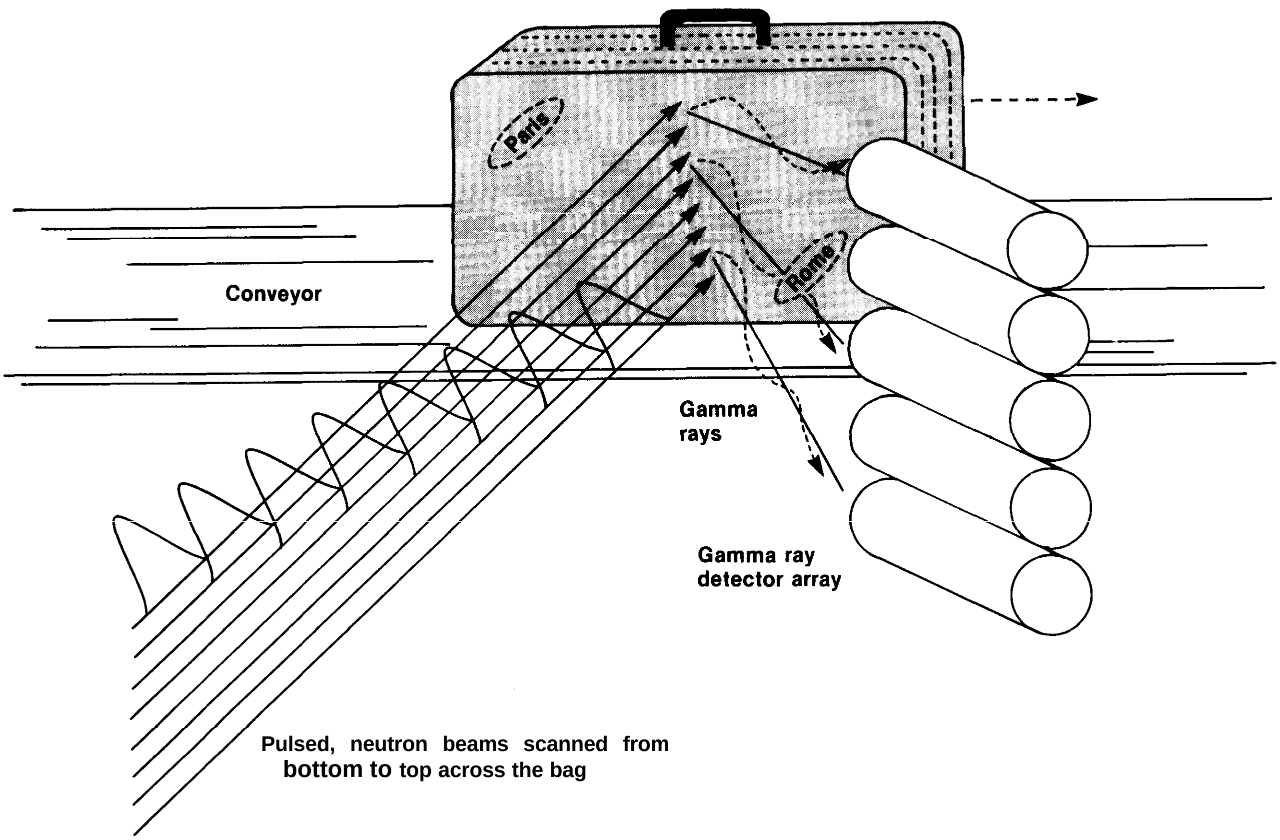
Technical Description

Neutrons are generated by a pulsed accelerator in precisely timed bursts. The arrival of the gamma-rays is also accurately timed. The position of "interaction along the neutron beam is determined using the time interval between these pulses and the neutron speed, giving a third dimension to the element density distribution.

The neutrons are generated by the deuterium-deuterium (d-d) reaction and produced mainly in the direction of the deuteron beam. The accelerator is larger and more expensive than the deuterium-tritium (d-t) neutron generators used in FNA, due to their higher voltage.

preliminary studies have demonstrated the feasibility of determiningg the position of the elemental constituents of different samples. Better accuracy is expected with the use of shorter duration deuteron beams and gamma-ray detectors with better temporal resolution. Pulsed d-t generators could also be used instead of continuously operating ones with the main advantage of lower acceler-

Figure A-3-Sketch of Apparatus for Pulsed Neutron Beam Analysis



SOURCE: Lee Grodzins, 1990.

ator cost, size, and weight. However, they present a poorer signal-to-noise ratio and require heavier shielding.[7]

Potential and Shortcomings

The attraction of the PFNA system is its unambiguous determination of the elemental composition characteristic of explosives and the spatial information on the location of these elemental concentrations. These features make the PFNA a potentially powerful technique for explosives detection.

To date, only the basic feasibility of PFNA has been established. The R&D required for the construction of a practical, collimated, pulsed energetic neutron beam, however, is a technological problem, and the requirement for making it safe and operationally acceptable, as well as cost-effective, complicates the matter. The PFNA system represents a considerable research and development problem, likely requiring 3 to 5 years before its commercial utilization can be assessed. A thorough evaluation of the operational issues of such a system should precede the large expenditures-for cost, space, performance and accelerator safety-that would be required to develop such a system.

Nuclear Resonance Absorption (NRA) of Gamma-Rays

Sponsor; FAA Technical Center is supporting research at LANL and the Israel Atomic Energy Commission Nuclear Research Center at Soreq.

Status: Feasibility experiments completed in Fall 1989, more research funding is likely.

Funding: About $l million in fiscal years 1988 and 1989; requests for a program of $1 to $3 million per year for the next 2 to 3 years are under discussion.

Basic Operating Principles and Goals of Concept

Physicists at the Soreq Nuclear Research Center of the Israel Atomic Energy Commission proposed a scheme to the FAA in 1986 in which the presence of nitrogen would

[7]This description owes much to the comments of T. Gozani of SAIC.

be detected by measuring the absorption of gamma rays traversing a piece of baggage. The probability of absorption of the gamma rays of a particular energy by nitrogen nuclei is very high. Scintillators would detect the transmitted gamma rays. A dip in the detected gamma rays would indicate presence of nitrogen in the baggage.

The technique is derived from the existence of a narrow state of excitation energy in ^{14}N, resulting in a sharp resonance of the cross section for the reaction $^{14}N(\gamma,p)^{13}C$ producing a proton and a ^{13}C nucleus. The gamma-ray transition rate from the ground state of ^{14}N to the excited state is extraordinarily large. This means that gamma rays of exactly the resonant energy are very strongly absorbed by ordinary nitrogen nuclei, thus providing a unique and clear signature of the presence of nitrogen, as opposed to other elements.

The inverse reaction (protons on a target of ^{13}C nuclei) can be used to generate the probing beam of gamma rays, resulting in gamma rays of just the right energy for the subsequent resonance absorption. The effective size of the source of these gamma rays can be made very small, allowing an imaging capability. This technique has been demonstrated to be capable of detecting nitrogen at levels similar to FAA's current requirements. Since the signature is unique and the gamma rays very penetrating, the technique is impervious to attempts to avoid detection by shielding the explosives.

Technical Description

The geometry of the NRA technique is very similar to the familiar x-ray systems used at airports. However, instead of a fan shaped beam of x rays, one uses a fan shaped beam of gamma rays at precisely the right energy to pass through the luggage (see figures A-4 and A-5).

A small electrostatic accelerator produces a proton beam. When a beam of low energy protons, produced by a small electrostatic accelerator, hits a ^{13}C target, the residual ^{14}N is produced in the desired excited state. From this state, high-energy gamma rays are produced the great majority of the time (the balance being low-energy gamma rays). At one particular angle with respect to the proton beam, the energy of the gamma rays is exactly what is required by the resonant absorption in nitrogen. The beam spread depends primarily on the spread of energy in the proton beam, the quality of its focusing, and the thickness of the carbon target. The beam spread and various other parameters of the apparatus have been measured in the completed feasibility program to determine the practical performance limits of the concept.

In addition to the proton-beam/accelerator, the apparatus consists of a thin, cooled target and a detector array aligned precisely to intercept the cone of gamma rays which are emitted at the optimum angle. There are two choices of detectors under consideration, resonant detectors favored by Soreq investigators and nonresonant detectors proposed by a group from LANL that has cooperated with the Soreq group in the program. Each of the schemes has its advantages and disadvantages and a clear choice is not obvious at this time. The nonresonant detector is much more efficient and is commercially available, but must sort out resonant absorption (specific to nitrogen) from a nonspecific background. The resonant detector needs developmental work, has lower inherent efficiency, but produces a more unambiguous signal.

Measurements have been made, both with a nonresonant detector (a commercial BGO scintillator) and with a resonant detector array. In both cases, luggage with simulated explosives was passed through the beam of gamma rays in front of the detectors. Images were formed by computer reconstruction of the data from the detectors, creating an array of pixels. The total nitrogen was obtained by summing over all the pixels. When the total nitrogen content was above some critical quantity, an image was constructed to give the distribution and location of the nitrogen. Explosive samples were detected with very small amounts of nitrogen, either in blocks or sheets and hidden within a radio. Impressive images of simulated explosives have been obtained, using computer image-enhancement techniques. The experiments that were performed have been used to design potential prototype systems that would be able to handle the FAA requirements for an airport luggage inspection system.

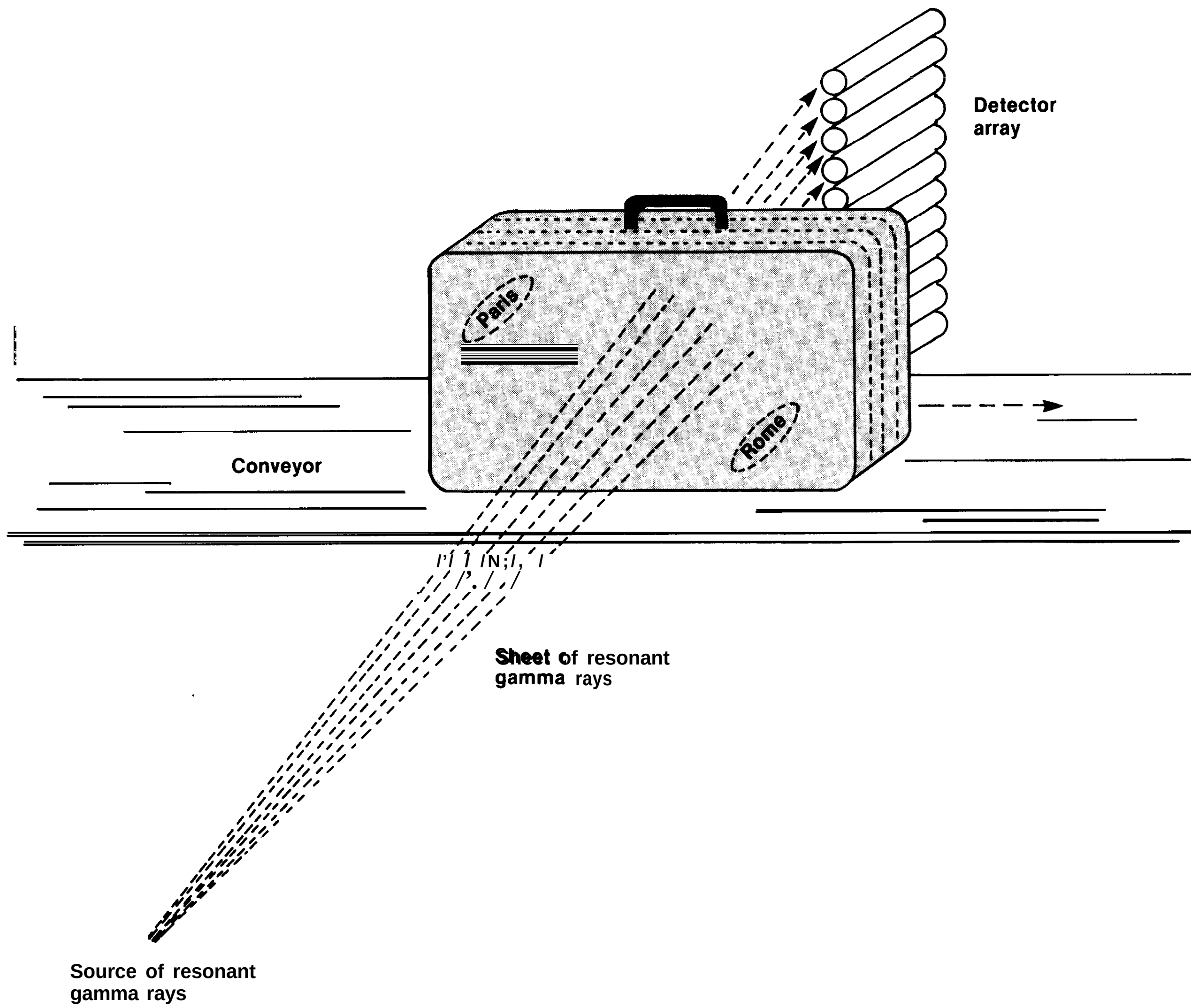
Potential and Shortcomings

The NRA system may have considerable potential for the FAA luggage explosive detection system (EDS) mission. It appears to have the needed sensitivity and spatial resolution and it measures nitrogen unambiguously. However, like the current version of TNA, it does not measure anything but nitrogen.

The major choice that needs to be made at this time is the level of investment in this technology and the program emphasis for the immediate future. The question is, should the program be aimed at demonstrating this technology in the near term with a pre-prototype device, based on currently available hardware, that can be operated in an airport environment, or should the program be aimed at assessing the ultimate potential of this system (higher sensitivity with low false-alarm rate) in the long term, or should money be made available for both?

Even if a major program based on this technology were to be initiated, it would take about 2 years to demonstrate the technology in the field and another 2 or 3 years before an optimized system could be made available to the airlines. At best, this could be cut to 3 years on a fast-track high-risk (probably greater than about $10 million) program, directed immediately at an advanced performance system.

Figure A-4-Resonant Absorption of Gamma Rays



SOURCE: Lee Grodzins, 1990.

There are no good estimates of the cost, size, weight, and operating parameters that could be expected from such a system and a paper study aimed at determining such parameters under various technology assumptions could be valuable. In making a cost comparison with the TNA system, the NRA's accelerator will most probably be significantly more expensive than the current isotopic source for TNA. Some of this increased cost maybe made up by less expensive shielding (since gamma rays are easier to shield than neutrons, and the 1.747 MeV protons have too low an energy to induce much radioactivity in the apparatus) and a cheaper detector system. The resonant absorption technique is one of the more promising advanced technologies and such a study could quantify its potential.

Associated Particle Production

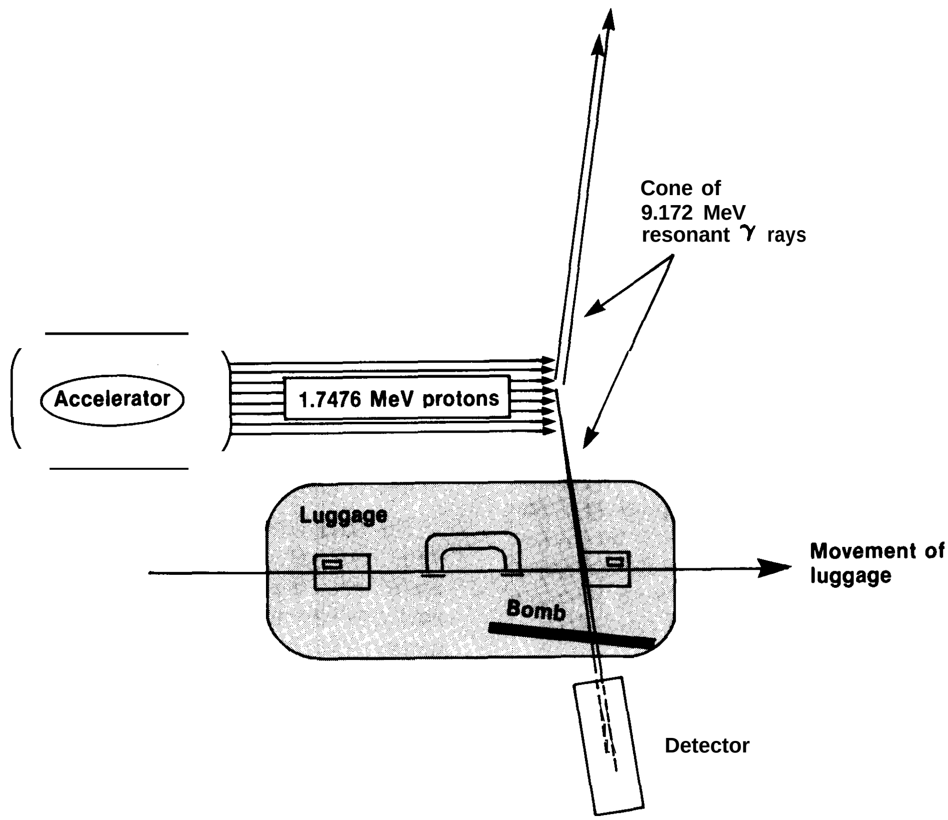
Sponsor: FAA Technical Center—DOE at Los Alamos National Laboratory, previously sponsored by TSWG.

Status: Early Research.

Basic Operating Principles

The technique uses high energy (14 MeV) neutrons and 3 MeV alpha particles from a deuterium-tritium reaction. The direction and timing of the alpha particles are

Figure A-5-Resonant Absorption of Gamma Rays



SOURCE: Lee Grodzins, 1990.

measured to determine uniquely the direction and timing of the neutrons. The timing and energy of the gamma rays that result from the interaction of these neutrons with the nuclei of the examined object are also measured. By combining the gamma-ray data with the alpha-particle and time-of-flight information, a three-dimensional mapping of the carbon, nitrogen, and oxygen in the baggage may be obtained. The spatial resolution of this system should be adequate to see small explosives.

This technique is another one that has the potential to provide an unambiguous and spatial determination and, consequently, should be highly effective for detection. Preliminary experiments have been performed at LANL with promising results, but fielding this technology would not be likely for many years.

Nitrogen-13 Production-Positron Emission Tomography

Sponsor: DARPA, in cooperation with Sandia National Laboratories, supporting Titan Corp. (Spectron Division).

Status: Funded demonstration program.

Funding; $2.83 million over three years, of which $1.78 million went to Titan from DARPA, and $1.05 million went to Titan from Sandia.

Basic Operating Principles:

In this technique, a gamma-ray beam activates the ^{14}N isotope[8] in explosives to an excited state of a radioactive isotope of nitrogen (^{13}N). A neutron is also emitted, which is not important for this application. The reaction is:

$$\text{gamma-ray} + {}^{14}N = {}^{13}N^* + n.$$

Following activation, the nitrogen-13 isotope decays with a ten-minute half-life, emitting positrons (the positively charged antiparticle of an electron). Each positron immediately annihilates with an electron in the region, producing two back-to-back 511-keV photons that are detected by scintillation counters.

The gamma-ray beam is produced by a specifically designed radio-frequency linear accelerator (RF-LINAC).

[8] In nature, over 99 percent of nitrogen exists as the isotope ^{14}N with the balance being ^{15}N.

The accelerator first produces an electron beam of about 14 MeV energy. The electrons then strike a tantalum or tungsten target and produce gamma radiation with a maximum energy equal to that of the electron beam. The gamma rays interact with explosives and activate the nitrogen via the above photonuclear reaction.

One advantage of this approach is that, by tracing back the paths of the two 511-keV photons, one can achieve excellent spatial resolution, perhaps on the order of a centimeter or so in each dimension.[9] The ability to image will be vital in order to eliminate background coming from those few isotopes that might confuse the picture.[10] A final assessment on how well this system can get rid of background awaits the testing of a prototype.

One of the features of this system is that, because of the 10-minute half-life of the radioactive nitrogen isotope, the irradiation and detection stations can be separated, reducing background problems and simplifying detection. Further, it is easy to have multiple detector stations for each radiation source (the accelerator). It is proposed to use this system in tandem with standard x-ray seaming or tomography equipment to achieve high resolution.

Status

This technique, designated by the vendor as Explosive Detection Using Energetic Photons (EXDEP), has been experimentally checked in the laboratory for detection of buried mines. A demonstration system is currently under construction at Titan for testing in realistic situations. An aggressive program aimed at the FAA mission would probably require about 3 to 4 years, and $5 to $10 million. As with other energetic particle beam concepts, the accelerator, its cost, size, and shielding requirements are major issues.

Pulsed Neutron Backscatter (PNB)

Sponsor; Commercial development to date by PENETRON, Inc.

Status: Some laboratory measurements made to verify concept

Funding: Proposal submitted to FAA under Broad Agency Announcement.

Basic Operating Principles

The PNB concept is based on the fact that fast neutrons will interact frequently with light nuclei by elastic collisions (roughly equivalent to billiard balls bouncing off each other). Since the collisions are elastic, there is no change in the structure of the nucleus; rather, the neutrons scatter in particular directions with unique reduced energy determined by the mass of the nucleus hit. Thus, by measuring the energy of the scattered neutrons, the nucleus that had been struck can be identified.

Two physical phenomena are used to detect and analyze remotely concealed substances, such as explosives and narcotics. One is Neutron Elastic Back Scatter (NEBS) and the other is Neutron Resonant Elastic Scatter NRES).

In NEBS, carbon, oxygen, and nitrogen all produce different back-scatter velocities. The intensity of the back-scattered signals contains information on the amounts of an element present, while the ratios between the signals from various elemental nuclei scatterers indicate the chemical composition of the substance. The system is optimized for explosives by its choice of energy.

The back-scattered neutron energy is measured by a large array of detectors using the neutrons' "time of flight" (i.e., the time of arrival of the neutron allows the device to infer the velocity, which is simply related to its energy). The measured energy spectrum then produces characteristic peaks for the specific elemental nuclei. From a knowledge of the elastic back-scatter cross sections at a given energy and the relative height of the peaks, the ratios of the elements are determined. Explosives have unique ratios among their carbon, nitrogen, and oxygen quantities. These are signatures" by which they can be distinguished from other materials. Access from only one side is needed to carry out the examination.

In NRES, the incident neutron energy is varied first to excite a resonance peak due to nitrogen, and then to a nonresonant energy. Both energies are in a region where there are no resonances for either carbon or oxygen. The use of a resonant technique to highlight the signals from nitrogen while retaining carbon and oxygen signals has been demonstrated. Two complementary and simultaneous techniques would then be used to identify target elements; in combination, high detection probabilities and low false-alarm rates may be feasible.

The system has some limited capability of separating signals from different locations along the path of the neutrons. Signals from different depths will produce smearing of the time-of-flight spectrum. Time-gating of the arriving neutrons should produce depth measurements as well as sharpen the spectrum. The ability to separate these signals has yet to be established experimentally, but PENETRON claims that analysis shows that separation should be achievable.

[9] In the related medical technique of positron emission tomography, resolutions on the order of millimeters are achieved. In the case of explosive detection in baggage using the proposed system, thick NaI crystal detectors, which limit spatial resolution, will be needed for high efficiency.

[10] The developers propose to couple this technique with an x-ray system that would give a second resolved image to aid in distinguishing between nitrogen and the sources of background.

Laboratory measurements have been made utilizing a Van de Graaff accelerator at the University of Kentucky, with typical materials characteristic of explosives, narcotics, and several common materials indicating promising results. A definitive proof-of-concept demonstration requires the use of a dedicated facility.

Status

Promising laboratory experiments have been performed to verify the proposed scheme. A proof-of-concept program is needed to determine the difficulty of making the required measurements in a realistic material, in which different substances are mixed. This concept uses relatively low-energy neutrons and, consequently, the shielding requirement would be moderate. The accelerator technology also appears to be within sight. It is claimed that this technology should be amenable to extrapolation to the large cargo container problem encountered in freight hauling.

This concept is covered by several patents issued to Dr. Henry Gomberg and Dr. Marcus McEllistrem. The patents are assigned to PENETRON, Inc., a joint venture of Ann Arbor Nuclear, Inc. and the Environmental Research Institute of Michigan.