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Explosives Detection for Aviation Security

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The threat of terrorism against commercial aviation has received much attention in the past few years. In response, new ways to detect explosives and to combine techniques based on different phenomena into integrated security systems are being developed to improve aviation security. Several leading methods for explosives and weapons detection are presented.

IN THE PAST 20 YEARS, TERRORIST ATTACKS HAVE TAKEN ON AN increasingly international flavor, becoming acknowledged weapons in political and military disputes. As Clausewitz referred to war as being an extension of politics, so might terrorism be considered an extension of war, to be used when politics or war may not be as likely to accomplish the political goals of the practitioners. The advent of mass attacks on innocent individuals by means of car bombs, airline sabotage, and random mass attacks on passersby in public places has alarmed much of the world. Because of the shock at the spectacle of such events and because of the fear that all are vulnerable to this predation, there have been increasing calls on governments to do more to protect the public.

One way to counter terrorism is to satisfy the demands of the terrorists, especially when they advocate politically defensible or popular causes. However, capitulation or concessions are usually difficult to sustain politically and do not always resolve the problem. Another strategy for defense is to threaten and carry out military action against states that sponsor terrorism. The drawbacks of this strategy are that many acts of terrorism have no state sponsors and that many innocent people, residents of the targeted state, may be killed or wounded by such actions, even if the actions are carefully directed at military targets. Yet another way of defending the public is for authorities to infiltrate terrorist groups to gain advance notice of attacks, enabling them to forestall planned operations. This technique is frequently utilized by intelligence services around the world. It is often successful, although successes do not always come to the attention of the public. Infiltration and intelligence gathering do not, however, always work; there will always be some attacks that cannot be prevented by such means.

This article discusses some options for combating a major type of terrorism, airline bombings, in a fourth way: through the use of technology. This is a field in which the targets, often advanced Western states, may have a decided advantage over the terrorists. There is clearly no technical "fix" for such attacks. However, technology is a tool that can be used in conjunction with others to help reduce the frequency of terrorist acts, to mitigate such acts when they occur, and thereby to help save the lives of countless innocent victims. It is a tool that has been underrated in the past: research and development in relevant areas has not been funded particularly well—about \$70 million in federal appropriations have been identified for fiscal year 1990, less than 1% of total Department of Defense appropriations for similar levels of research and development.

Although domestic terrorism in the United States has been minimal in the last few years, American targets have been the objects of a large fraction of international terrorist incidents. Following the Gulf War, fears grew that Iraqi agents or their sympathizers would unleash terror against U.S. citizens around the world. Fortunately, these fears were not realized, but there still is concern that such attacks could occur in the near future. To understand how technol-

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ogy may help, the types of terrorist acts must first be listed. Acts of particular interest include bombings, armed attacks against facilities, kidnappings, assassinations, maimings, and vehicle hijackings. Figure 1 shows trends in such events for the past 20 years.

The most costly terrorist events in terms of loss of innocent lives have been bombings of commercial aircraft in flight. Much of the renewed demand for public action against terrorism in the United States was the result of the bombing of Pan American flight 103 over Lockerbie, Scotland, in December 1988 and of the pressure from two support groups formed by families of the victims. Within a year, two similar disasters occurred, causing hundreds of deaths: one a Union des Transports Aériens (UTA) flight over Niger, Africa, the other an Avianca flight out of Bogotá, Colombia.

As a result of these deaths and of the public outrage and concern generated, a major goal of counterterrorist research in the United States now lies in the prevention of such bombings. The research and development budget of the Federal Aviation Administration (FAA) for aviation security has more than tripled between 1989 and 1991, from $9.9 million to $30.3 million. The major portion of this work is associated with explosives detection, which will be the focus of this article.

Explosives Detection

Work has been proceeding in the area of weapons and explosives detection for aviation security for well over a decade. Instrumentation developed includes the familiar x-ray equipment visible at airports, more advanced x-ray techniques, explosive vapor detectors, and newer nuclear methods for detecting explosives, such as the thermal neutron analysis system, developed by Science Applications International Corporation (SAIC) under contract with the FAA. Possibilities for hardening aircraft and mitigating blast effects are also being studied. If successful, efforts in these areas would force the use of larger amounts of explosives, which would then be easier to detect.

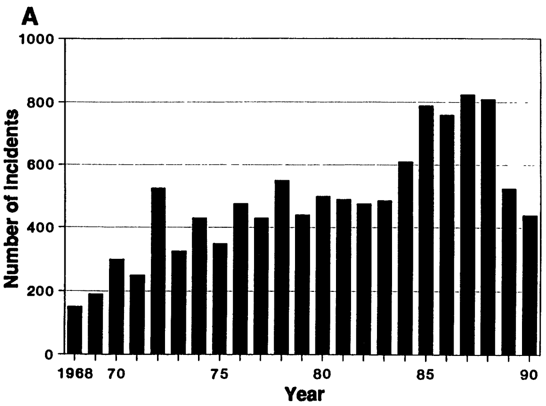
Another emerging field is systems integration, that is, the combining of individual security devices, such as sensors and detectors, with the human element, always needed to make a final decision on how to deal with and respond to an alarm. The field of human factors will have a major role in the design of security systems.

Several physical and chemical characteristics are useful for distinguishing explosives from innocent articles. Figure 2 shows the characteristics of the more common explosives that have been used in terrorist bombings. Of these, high explosives such as RDX and PETN, frequently used with plastic filler, are the most serious threats in aircraft sabotage because they can be easily molded for concealment, are very stable in the absence of a detonator, and are able in small amounts to destroy a large airplane in flight. They are, in fact, the explosives most commonly used for this purpose.

Most explosives contain rather large amounts of nitrogen and are relatively dense (1.3 to 1.6 g/cm^3). Some not listed, such as perchlorates, do not contain nitrogen, but most of those are unstable and difficult to work with.

X-rays. Standard x-ray scanners transmit a beam through an object, producing an image reduced in intensity by absorption and scattering processes, primarily by electrons in the intervening material—lower intensity means more material, in a broad sense. The transmitted beam is attenuated exponentially by a factor e^{-ax}, where a is an absorption parameter dependent on the beam energy and the effective atomic number Z_{eff} (equivalent to the average number of electrons per atom) in the intervening material and x is the thickness of the object. The parameter a increases rapidly with Z_{eff} and increases with decreasing photon energy. One view and one beam energy will not suffice to resolve objects hidden behind others. The value of simple scanners lies primarily in detecting weapons made of dense metal that are difficult to conceal in an x-ray image without arousing suspicions. Explosives can be placed behind or within items of higher atomic number and remain undetected.

One way of countering this strategy is to use a dual-energy x-ray system. Because each energy generates a different absorption constant, comparing the transmission from two images produced by different beam energies can provide a clue to the effective atomic number along the beam in the examined object. In practice, the determination of Z_{eff} by this method is only approximate, allowing the device to distinguish higher from lower atomic number along the line of the beam but providing little resolution in atomic number (Z). One limitation arises from the fact that the energy spectra are often broad, not yielding sufficiently distinct image information. Another limitation comes from the single view. However, systems currently in use that are produced by EG&G Astrophysics and by Heimann GmbH, a subsidiary of Siemens AG, can distinguish dense



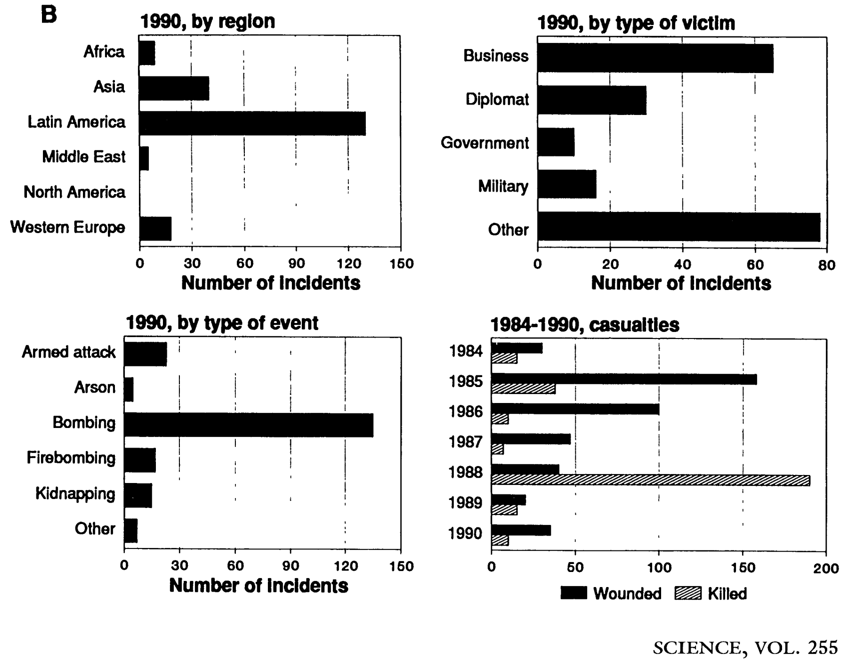


Fig. 1. Distribution of international terrorist attacks 1968 through 1990 (*4, 5*). (**A**) All international terrorist incidents; (**B**) anti–United States attacks.

organic objects from metals and from less dense organic objects, such as food, clothes, and other items usually found in suitcases.

Another technique, developed by American Science and Engineering, uses Compton backscattering to distinguish high Z from low Z items. X-rays show absorption characteristics that rise rapidly with Z, owing to the strong dependence of a on Z. Dark areas in the image correspond to higher density materials, with higher Z materials more effective at absorption for the same density.

At x-ray energies of interest, around 80 to 150 keV, absorption occurs because of the photoelectric effect, and scattering arises mainly from the Compton effect. In this energy region, Compton scattering provides the main signal at large scattering angles. In Compton scattering—a collision between an x-ray and an electron—the scattered x-ray photon has a unique wavelength, dependent on the incident photon energy and scattering angle. A simple formula, derived from conservation of energy and momentum, relates these parameters:

$$\lambda = \lambda_0 + h/mc(1 - \cos x) \qquad (1)$$

Here λ is the wavelength of the scattered photon, λ_0 is the wavelength of the incident photon, h is Planck's constant, m is the electron mass, c is the speed of light, and x is the scattering angle of the photon. From energy conservation, the energy of the scattered photon is reduced by the recoil kinetic energy of the struck electron. For 100-keV x-rays, the backscattered photon is reduced in energy by nearly 40%, increasing significantly the characteristic absorption parameter a. Photons scattered at large angles are thus even more strongly absorbed by the photoelectric effect on the way out of the target than are unscattered photons that make up the transmitted beam.

The result is that a dual-energy system has effectively been created; the transmitted beam is one energy and the beam of scattered Compton photons is the other. Together, information is provided that can separate the effects of density and Z dependence, allowing the system to indicate high-density, low Z material, the signature of explosives. A limitation is that the scattered photons, being so reduced in energy, have a lower range and thus cannot probe material as deeply as the more energetic incident beam. Because of increased absorption at lower energy, low Z material provides much larger Compton signals than high Z materials do. Comparison of the transmitted image with the backscattered one shows differences arising from the fact that the backscattered photons are absorbed to a higher degree—with a Z dependence different from the transmitted beam—on the way to the detector. X-ray units based on this

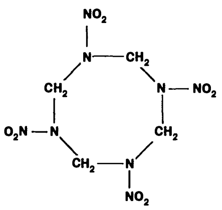
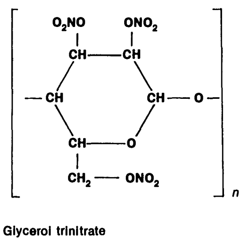
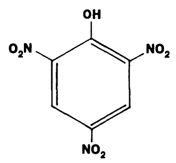
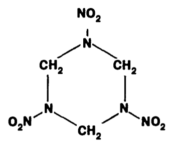
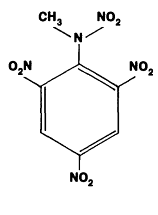
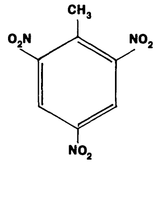
Trade or Popular name(s)	Chemical name, formula, and structure	Comments
AN, Ammo-Nite	Ammonium nitrate $(NH_4)^+ (NO_3)^-$	Also commonly used as a fertilizer. Frequently mixed with fuel oil to make explosive called ANFO.
Black powder		Mixture of potassium or sodium nitrate, sulfur, and charcoal. Explosive most commonly used in terrorist bombs in the United States.
Composition B		60:40:1 mixture of RDX:TNT:wax
Dynamite		Compositions have varied over the years. The explosive components of modern dynamites are principally EGDN and NG absorbed onto combustible pulp (for example, wood meal, starch, rye flour).
EGDN	Ethylene glycol dinitrate H_2C-ONO_2 H_2C-ONO_2	One of the main components of dynamite. Quite volatile, making detection by "sniffers" relatively easy.
HMX, Octogen	Cyclotetra-methylene tetranitramine; 1,3,5,7-Tetranitro-1,3,5,7-tetrazacyclooctane 	A military plastic explosive.
Nitrocellulose, gun cotton*		Main component of smokeless powder.
NG Nitroglycerine	Glycerol trinitrate H_2C-ONO_2 $H-CONO_2$ H_2C-ONO_2	
PETN	Pentaerythritol tetranitrate $O_2NOCH_2-C(CH_2ONO_2)_3$	A plastic explosive available in bulk form, or with modifications, in sheet form under trade name "Detasheet." Unusually low nitrogen density for a plastic explosive:18% by weight (compare with RDX).
Picric Acid	Trinitrophenol 	
RDX, Research Division X, Formula X, Cyclonite Hexogen	Cyclotrimethylenetrinitramine; 1,3,5-Trinitro-1,3,5-triazacyclohexane 	Primary ingredient of military plastic explosives known as C-3 and C-4; 38% nitrogen by weight.
SEMTEX		A Czechoslovakian-made explosive composed of a mixture of varying proportions of RDX and PETN along with binder and plasticizer.
Tetryl, Tetralite	2,4,6,N-Tetranitro-N-methylanaline; 2,4,6-Trinitrophenyl-methyl nitramine 	Most common military booster.
TNT	Trinitrotoluene 	A castable explosive.

Fig. 2. Common explosives and some of their characteristics (*4, 6*). *In practice, the nitration of cellulose is not complete.

principle are used in some airports but have been used more by government agencies for protecting sensitive facilities.

Elaborations of these techniques are being developed. EG&G Astrophysics is working on a dual-view, dual-energy system. The second view will help resolve ambiguities that arise from objects hidden behind others in the first view. Another company, Vivid Technologies, is developing very sensitive pattern-recognition algorithms with high resolution in conjunction with a dual-energy system that may also help resolve ambiguities. Furthermore, extending to a large number of views, Imatron Industrial Products is applying computerized tomography (CT) techniques developed for medical diagnosis to detection of explosives. The multiplicity of views yields three-dimensional images with high spatial resolution that make concealment far more difficult. The drawback of CT is the time needed to image each 1-cm-thick slice, although as computer algorithms become more efficient and faster electronics become available, the time needed for an image will decrease.

Nuclear techniques. 1) Thermal neutron analysis (TNA). This is the best known nuclear technique and was funded for several years by the FAA. Six machines for detecting explosives in checked baggage have been purchased; some have been tested at John F. Kennedy International Airport, New York (JFK); Miami International Airport; Dulles International Airport in the Washington, D.C., area; and Gatwick Airport, near London.

The principle behind TNA is the detection of anomalously high concentrations of nitrogen contained in most explosives by means of activation by thermal neutrons. Generated by a californium-252 source, and then moderated, a "bath" of thermal neutrons penetrates the examined object. The capture reaction

$$^{14}\mathrm{N} + \text{thermal neutron} \rightarrow {}^{15}\mathrm{N} + \tau \text{ (10.8 MeV)} \quad (2)$$

produces gamma rays τ that are characteristic of nitrogen and, fortunately, high enough in energy that they may be separated from the general background caused by the concomitant neutron activation of nonexplosive materials. The density of nitrogen in an object may then be deduced by the gamma ray intensity (see Fig. 3 for an indication of the effectiveness of such information). Some information on location of nitrogen concentrations within the object is available, but the spatial resolution is not good. Although not perfect, the determination of nitrogen content is a useful tool for distinguishing explosives from many common items. Nevertheless, experience has shown that, in order to be sensitive to the small quantities of explosives that must be found, one must reduce TNA device detection thresholds to the point that they suffer from a high false alarm rate. The experimental values for detection probabilities (as a function of the mass of the hidden explosive) and the corresponding false alarm rates for this and other potential detection methods are classified by the Department of Transportation.

In order to counter this false alarm problem, TNA devices have been married to high-resolution x-ray machines that have improved performance. However, indications are that TNA devices by themselves would have a hard time detecting small, lethal bombs with a high probability while maintaining a false alarm rate low enough not to disrupt normal airline operations. Nevertheless, no other bulk detection method seems as yet to be as advanced as TNA.

2) Nuclear resonance absorption. This nuclear technique is being explored by scientists from the Soreq Nuclear Center in Israel and the Los Alamos National Laboratory and is funded by the FAA. There is a sharp peak in the absorption cross section for the reaction $^{14}\mathrm{N}(\tau,p)^{13}\mathrm{C}$ around 9.17 MeV. The loss of intensity of a transmitted gamma ray beam of the correct energy can provide an unambiguous signal for nitrogen. The inverse process may be used to generate the gamma rays by means of a low-energy proton beam (1.7 MeV) against a carbon-13 target. An important advantage of the method is that it can have a spatial resolution (in one view) comparable to the width of the gamma ray beam, a few millimeters, which provides the location of nitrogen concentrations and can be used to help reduce false alarms. A prototype may be available for testing within 2 or 3 years.

This technique does require design and construction of a high-current accelerator to achieve the desired rate of flow. Application for airport use strongly relies on production of a very low maintenance, high-availability accelerator. Additional problems will arise from the cost and, possibly, the size and weight of such a component.

3) Fast neutrons. Another way to reduce false alarms would be to detect elements other than nitrogen. Detection of oxygen in addition, for example, would further eliminate many confounding materials (Fig. 4). A number of techniques have been proposed for

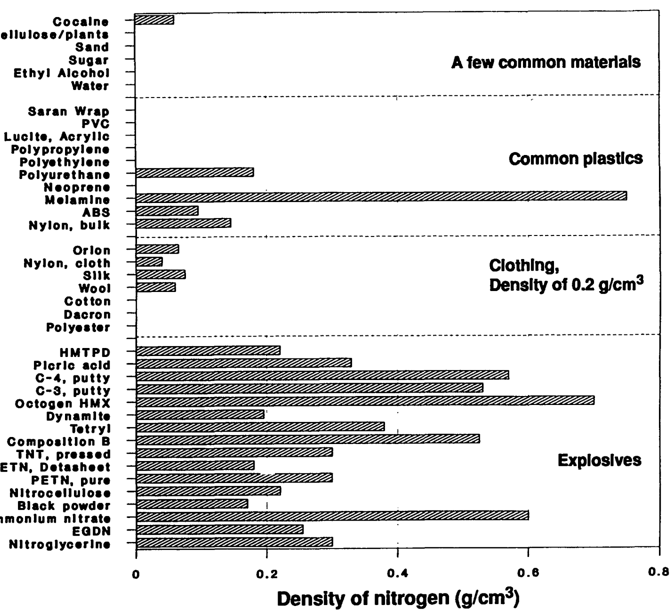


Fig. 3. Nitrogen density of common materials and explosives (*4, 7*).

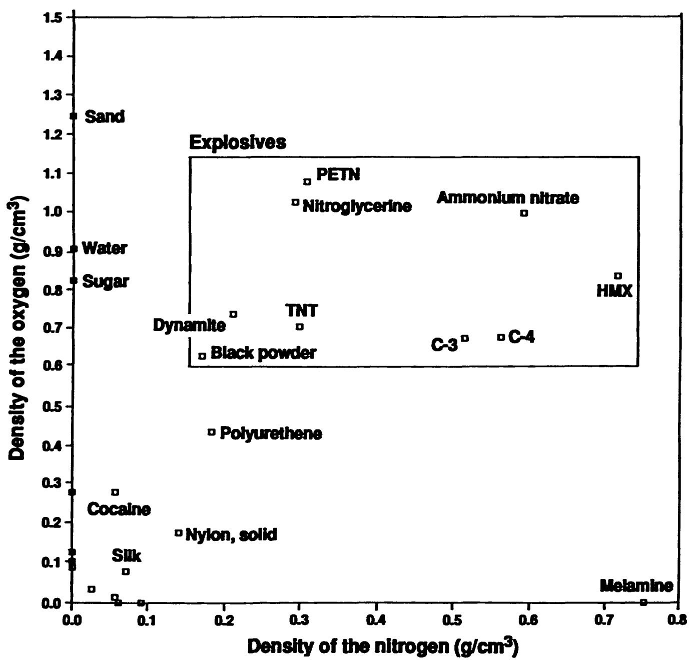


Fig. 4. Correlation between oxygen and nitrogen densities in explosives and other materials (*4, 7*).

using fast neutrons to accomplish this, again requiring the use of an accelerator. One method utilizes neutron activation of nitrogen, oxygen, and carbon by 14-MeV neutrons, producing excited states with relatively high cross sections in those nuclei. The neutrons are produced by the well-known D-T (deuterium-tritium) nuclear reaction, which produces an alpha particle (a helium-4 nucleus) and a 14-MeV neutron. The excited nuclear states decay, producing gamma rays of characteristic energies: 6.1 MeV for oxygen-16, 4.4 MeV for carbon-12, and 5.1 MeV for nitrogen-14.

The neutron beam may be scanned over the object as it moves past on a conveyor belt. This technique then yields a two-dimensional distribution of the C, N, and O content. The third dimension may be obtained with a pulsed beam—the velocity of the neutron is well determined and that of the gamma ray is, of course, even better determined. Then, the time from the beam pulse to the sensing of the emitted gamma ray determines the distance of the interaction point from the particle accelerator's exit. Researchers, among them some from SAIC, hope to achieve resolutions on the order of a centimeter in each dimension.

4) Associated production. This related technique is also able to determine C, N, and O content. This method also uses 14-MeV neutrons from the D-T reaction but detects, in addition, the recoil alpha particle. The direction of the outgoing alpha is measured, determining unambiguously the direction of the outgoing neutron. Thus, when a gamma ray from the decay of the excited state is detected, the location of the neutron's interaction with the nucleus is known to be along the neutron's trajectory. The third dimension (along the neutron's path) of the point of interaction is determined from the time elapsed between the detection of the alpha and that of the gamma. The distribution of many interaction points for each of the nuclear species allows the observer to determine the location of material within an inspected object that has C, N, and O proportions consistent with those of an explosive. With this technique, one can irradiate the whole object at once rather than use neutron beam scanning to find the locations of the interactions. Work on this technique has proceeded independently at Nuclear Diagnostic Systems, Incorporated, and at several Department of Energy laboratories.

Problems with this method include the lack of an appropriate, reliable accelerator. Compact commercial D-T accelerators have been used for years as well-loggers in petroleum exploration. However, some increase in intensity and lifetime are needed.

Vapor detection. Another way of attacking the problem of detection is to detect molecules of vapor given off by a mass of explosive. Unfortunately, most explosives of interest have very low vapor pressures, posing a severe challenge for any detection system (Fig. 5). Whereas EGDN, a major component of dynamite produced in the United States, has a relatively high pressure (about 1 part in 10^4), nitroglycerin has a vapor pressure that is a factor of 100 lower, and the plastic explosives are in the range of 1 part per 10^{12} or less. Moreover, in the real world, a terrorist is unlikely to present the detector with a volume of saturated air. At best, the fraction of molecules available to a "sniffer" will be reduced further by a few orders of magnitude. Current estimates are that useful detectors will need to be sensitive to 1 to 100 fg (1 fg = 10^{-15} g) of explosive material.

However, there are some positive features to the problem as well. Explosives molecules are very sticky; they easily adhere to most surfaces. Whereas one might, in principle, be able to wrap an explosive well enough to reduce the number of molecules of vapor surrounding the object to a very low level, it may be very difficult to clean all nearby surfaces contaminated with explosives molecules while the bomb was being wrapped.

The dog is the original vapor detector. Although controlled experiments have not been done to quantify sensitivity and selectivity, most experts feel that dogs are still more sensitive than the best electromechanical sniffers. For many purposes, the dog is still the vapor detector of choice. Authorities often turn to canines to sweep buildings to assure the absence of explosives, to respond to specific tips or threats, and to examine suspicious parcels or vehicles. However, for some applications, dogs are not appropriate. The volume of flow at airports makes the use of dogs prohibitively expensive; each dog requires an assigned handler to work best—the canine detector is really a specific dog-handler team. Further, dogs get bored in 20 to 30 min and need a play period before returning to work. These factors result in high operational costs for the job of checking tens of millions of bags per year for international flights to or from the United States. Further, "canine factors" complicate effectiveness. Like humans, dogs have good days and bad days, variable moods, and show behavioral variations difficult to monitor in a quantifiable way. Thus, there has been a strong effort by the FAA and others to develop technological methods for detecting vapors.

The earliest vapor detectors in commercial production were electron-capture devices. These detectors subjected air samples, together with an argon carrier, to a radioactive source of electrons. The plasma generated produced a constant current. Explosives molecules are usually highly electronegative, and the presence of even a small number of molecules will remove some electrons from the flow, resulting in a measurable reduction in the steady current, and thus providing a usable signal. The first detectors were, however, only sensitive to the higher vapor pressure explosives. Efforts continue to improve sensitivity to the degree that plastic explosives are also detectable.

More recent developments in rapid gas chromatography and in ion mobility spectrometry have resulted in detectors that can detect

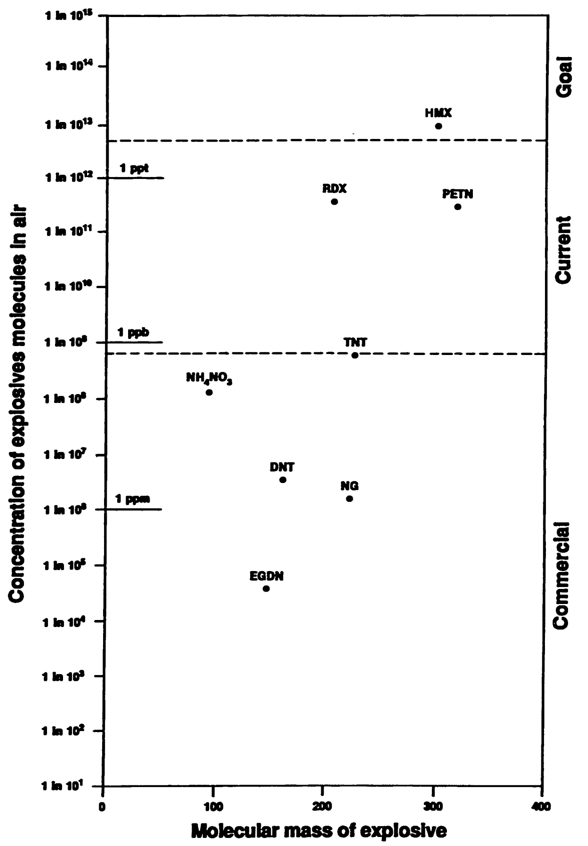


Fig. 5. Vapor pressures of several explosives in air at room temperature and atmospheric pressure (*4, 8*).

plastic explosives, at least under some scenarios. One U.S. corporation has combined gas chromatography with detection by chemiluminescent reaction of ozone with the NO produced by pyrolyzation of the explosives molecule. The coincidence of detection of a photon produced by the reaction, together with an appropriate time window from the chromatographic column, gives specificity to the measurement. Several airports in Europe use this equipment as an adjunct to security, and one airline is testing it in the United States.

Ion mobility spectrometry, also in a commercial stage, uses the drift speed of ionized molecules between two electrodes to identify explosives. The speed is a relatively specific characteristic that is successful in the identification of particular molecular species. Other techniques beginning to become commercially available include two-stage mass spectroscopy and fluoroimmunoassay. The former identifies molecular species in an air sample by standard mass spectroscopy techniques; to reduce ambiguities, collisions are induced between molecules in the sample and neutral atoms, such as helium, before a second stage is used to detect characteristic breakdown products of the explosives molecules. The latter method, deriving from biotechnology, produces antibodies to the specific explosives molecule, for example, TNT or RDX. Each species of explosives requires its own antibody, produced by stimulating the immune system of an animal with the explosive molecule as antigen. The separated antibody is tagged with a fluorescently labeled radical. In the presence of the explosive, the antibody reacts with it, freeing the radical, which is then detected through its fluorescence.

Some of these systems are already in commercial production, and others may be available shortly. As with nuclear and x-ray detectors, their sensitivity can only be determined in realistic operational tests. The FAA is moving to establish protocols and tests for all these approaches in collaboration with the National Research Council and the Idaho National Engineering Laboratory.

Major Issues

The three fundamental issues for all detection techniques are detection probability, the false alarm rate (how often will innocent objects appear suspicious?), and the rate of throughput. Both the detection probability and the false alarm rate of explosives detectors can only be realistically determined in an operational setting—at an airport, in the case of aviation security. It is vital for this purpose that a "background" of real luggage be used to test a device for false alarm rates and that double-blind use of explosives or carefully calibrated simulants be applied to measure probability of detection as a function of quantity of explosive.

The rate of throughput for high flow rate applications must be such that the impact on operations will be negligible. A study for the Air Transport Association (a trade group of air carriers) by the Institute of Transportation Studies at the University of California, Berkeley, analyzed impacts of an explosives screening device with a postulated 5% false alarm rate (*1*). This study found significant delay problems at high-flow airports even at this relatively low false alarm rate; it also looked specifically at the TNA device matched with its x-ray adjunct. One conclusion was that if the x-ray information were correlated automatically with the TNA information on nitrogen content, the flow rate of TNA would be degraded by about one-quarter from the rate of 600 bags per hour specified in the FAA rule governing explosives detection systems (*2*). Further, if the false alarm rate of TNA (or any other detection system) were substantially higher than 5%, delays would be long. High traffic sites, such as at JFK where, for international flights, 3000 to 4000 bags per hour need to be examined at peak times, are illustrative. For example, a 20% false alarm rate would require a careful searching of 600 to 800 bags per hour, a daunting task requiring large numbers of trained personnel.

Weapons Detection

This is a relatively mature field, having been developed since the early 1970s in response to a large number of hijackings in the United States, mostly to Cuba. The earlier machines for detecting weapons carried on persons were magnetometers, sensitive to magnetic anomalies from the presence of the relatively large amounts of ferromagnetic material in even small handguns. More recent eddy-current equipment is more sensitive and less susceptible to false alarms. Improvements were necessary because manufacturers began producing weapons with little or no ferromagnetic material and with little metal in general. An electromagnetic pulse is passed through a walk-through portal, and the eddy currents generated in solid metal within or near the portal are detected. Changes from an established baseline indicate the presence of metal. Sensitivity and specificity may be enhanced by the appropriate relative timing of the pulse and the windows of detection. As noted above, standard x-ray equipment is used to detect weapons in carry-on baggage.

Future developments may include the use of millimeter wave imaging to inspect persons. Anomalies in the reflectance of the electromagnetic waves permit imaging of items carried under or within garments. These objects might be weapons, even if void of metal content, or explosives. There has also been an effort to develop microdose x-rays for the same purpose. Such techniques, using Compton backscattered radiation (see above), have been demonstrated for doses as low as 10^{-6} roentgen-equivalent-man (μrem), less than the dose of radiation received in 5 min from natural background sources and substantially less than the increased dosage received on most flights from cosmic radiation. Whether it will be acceptable to the public to expose all passengers (or a subset, perhaps selected by other screening techniques) to electromagnetic or ionizing radiation for detection of contraband remains to be seen.

Integrating Security

Unfortunately, at present it appears that no single technology will suffice to detect explosives at the level desired (threshold quantities on the order of less than a kilogram have been cited in the popular press as necessary for detection in the aviation security context) while maintaining false alarm rates low enough that air travel will not be clogged unacceptably. Some half a billion air passengers with a billion pieces of luggage travel each year in the United States. Travelers on international flights on U.S. carriers are fewer, but still number about 40 million per year. High false alarm rates would require closer inspection, probably by hand, of a very large number of items.

A suggested approach is to combine technologies in such a way that the strengths of one may compensate for the weaknesses of others. In addition, clever combining of independent (or relatively independent) techniques may achieve probabilities of detection and false alarm rates that are more acceptable than those of systems based on one method alone. Further, such a system may even be less costly than the single method alternative and could have an acceptable throughput.

One possibility would be to use a series of three detectors, each using a measurement based on a different technology. An item that caused an alarm on the first detector would be passed to the second for further examination; one that passed would be released. A similar procedure would be used for the second stage. This amounts

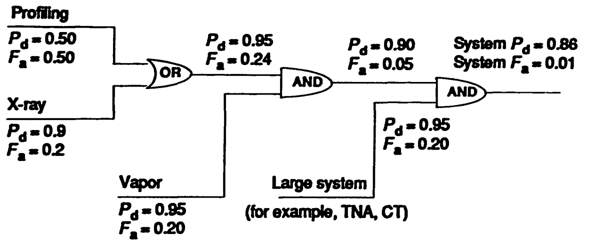


Fig. 6. Logic schematic of a combined system for detecting explosives in baggage (*4*). F_a, false alarm probability.

to an "AND" gate with the three devices as inputs. Only if an item caused an alarm on all three would it be necessary to inspect the object by hand, probably in the presence of the passenger. There would be several advantages to the system. First, the false alarm rate would be reduced. If the three devices were based on independent phenomenologies (say, vapor detection, x-rays, and TNA), the false alarm rate would be the product of the individual ones (*3*). If each device had a false alarm rate of 20% the false alarm rate of the system would be less than 1%. On a jumbo jet, instead of having to inspect 600 to 700 bags, only 6 to 7 bags might need intensive handling.

Another advantage is that the second and third stages, which look at only a fraction of the bags, may be useful even if their rates of throughput are low. Further, fewer units would be needed in later stages. Slower devices (such as CT or nuclear techniques that rely on acquiring large numbers of counts for statistically significant detection) may well be more sensitive, which is logically desirable for a later stage, because they are called upon to resolve suspicious items. Also, if the slower devices are more expensive, another advantage of this system is that fewer will be needed. A TNA device will cost at least $1 million per unit. On the other hand, an advanced x-ray system or a vapor detector may only cost $100,000 to $200,000. If only one type of detector, say a TNA device, were used, as the FAA initially envisioned, some 19 would probably be needed at JFK. However, if a successful three-stage system were feasible, perhaps only 1 would be needed, with 19 cheaper devices used for the first stage and 4 less-expensive devices for the second.

A disadvantage lies in the combined probability of detection, which, like the false alarm rate, propagates as the product of the individual probabilities if the phenomena used are independent. If each stage has a 90% probability of detecting the threshold amount of explosive, the three independent stages will only have a 73% probability of detection—better than nothing, but not comforting.

This disadvantage might be addressed by considering "OR" gates as well as "AND" gates. As an example, if the first stage were composed of two different types of detector, with the proviso that an alarm from even one would occasion further investigation by following stages, the first stage might have a very high detection probability—for independent systems, the detection probability P_d would be

$$P_d = P_{d1} + P_{d2} - P_{d1}P_{d2} \tag{3}$$

where P_{d1} and P_{d2} are the respective detection probabilities. For two systems of 80% probability, a combined probability of 96% might be achieved. False alarm rates combine in the same way.

A possible system could be designed in three stages (Fig. 6). The first would consist of an OR gate between profiling (that is, selecting passengers for closer scrutiny on the basis of certain behavioral and other criteria) and an advanced x-ray system. The second would be a vapor detector, and the third a sophisticated, expensive system such as TNA or CT.

Whether individual components with the assigned characteristics will be developed soon is not certain (although similar high detection probabilities and low false alarm rates were originally required by the FAA for acceptance of any device as an approved explosives detection system), but it is clear that by making appropriate choices of components, a system can be designed that should be operationally superior to a single element.

Explosives detection for passengers and baggage forms only a part of the aviation security problem. There are other pathways than passengers for explosives or weapons to make their way aboard commercial aircraft. Suborned airline or airport personnel, catering services, cargo, and air mail all provide possibilities for the malefactor. A complete security system must guard against all of these. The FAA is developing an overall security system for airports, based on a "test bed" at Baltimore-Washington International Airport. Supported by personnel from Sandia National Laboratories, which has been responsible for many aspects of physical protection for the nation's nuclear facilities and nuclear material, the project aims at understanding how all possible pathways for introduction of weapons or explosives onto aircraft might be blocked. The security system makes use of hardware (for example, access control systems, barriers, alarms, and detection devices), combined security systems, and prescribed procedures. The project utilizes both computer modeling and expert input. It is intended not only to prevent sabotage by outsiders, but to prevent circumvention by an insider, that is, by someone with approved access to sensitive areas. This multiyear project, in the design phase, is scheduled to enter the hardware and implementation stage shortly.

Summary

This review of some technologies for detecting explosives has not been exhaustive (in particular, the vital human element in any security system has not been touched upon—the discipline of human factors has much to contribute, for example, in the improvement of profiling) and provides only a brief outline of some promising lines of research and development. Much progress has recently been made in several areas, but further development of several explosives detection techniques is necessary, as is development of integrated detection systems that use several different types of devices. Technology will never provide a panacea for terrorism, but it does furnish many useful tools that will help reduce the threat and save innocent lives (*4*).

REFERENCES AND NOTES

1. G. D. Goslin and M. M. Hansen, *Research Report UCB-ITS-RR-90-14* (University of California, Berkeley, CA, July 1990).
2. *Fed. Regist.* **54** (no. 170), 36938 (5 September 1989).
3. Total independence will not be achieved in practice. However, near-independence still would permit a significant drop in false alarms that would need to be handled by time-consuming, human-intensive methods.
4. This article is based on information developed during the course of two studies by the Office of Technology Assessment: U.S. Congress, Office of Technology Assessment, *Technology Against Terrorism: The Federal Effort, OTA-ISC-481* (Government Printing Office, Washington, DC, July 1991); U.S. Congress, Office of Technology Assessment, *Technology Against Terrorism: Structuring Security, OTA-ISC-511* (Government Printing Office, Washington, DC, January 1992). Much of the information in this article may be found therein in more detail. Figures are taken from these reports.
5. Data from U.S. Department of State, *Patterns of Global Terrorism: 1990* (Office of the Secretary of State, Washington, DC, 1991).
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7. Data source: L. Grodzins, private communication.
8. Data source: F. Conrad, private communication.
9. The author acknowledges vital discussions with L. Grodzins and Y. Alexander and repeated, essential conversations with principal collaborators on the OTA project: D. Kyle, P. Rose, and A. Shaw. The opinions expressed are the author's own and do not necessarily reflect those of the sponsoring institutions, the Technology Assessment Board, or the Technology Assessment Advisory Council of the Office of Technology Assessment.