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OVERVIEW OF EXPLOSIVES CONTROL MEASURES

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OVERVIEW OF EXPLOSIVES CONTROL MEASURES

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Abstract. The illegal use of explosives is an area of increasing concern among all law enforcement groups in the United States and around the world. Technical development of instruments and techniques to assist in the control of the illegal use of explosives are being actively pursued under the sponsorship of many government agencies. These control activities fall into three broad categories: (1) detection through the physical or chemical properties of the explosives, its package, or ancillary parts; (2) detection of a tag added to the explosive or necessary component; and (3) identification of explosives after detonation via the addition of a coded tag or characterization of natural residue.

The Aerospace Corporation, under contract to the Law Enforcement Assistance Administration of the U.S. Department of Justice; the Bureau of Alcohol, Tobacco and Firearms of the U.S. Department of the Treasury; and the Bureau of Mines of the U.S. Department of the Interior, has been heavily involved in each of these areas. A recent effort has been made to carry out a critical survey of applicable technology, from which this overview is derived.

Major efforts to date have been expended to solve the problem of untagged detection of explosives in controlled-access scenarios where speed of detection is a major factor. Vapor-characterization studies provide essential information on the practical limitations of vapor detection. Vapor detection techniques being pursued include electron capture methods, enzymatic reaction, and optical methods such as laser photoacoustics. Physical methods include thermal neutron capture, X-ray imaging, and nuclear magnetic resonance.

Detection tagging methods include vapor tagging which has been shown to be feasible and other methods such as heavy metal taggants that are still in the exploratory development phase.

Development of identification techniques using both rare-earth and color-coded taggants has reached the advanced development phase and is undergoing nationwide testing in the United States. Evaluation of new residue characterization techniques for nontagged cases has also been completed including chemical ionization, field ionization, high performance liquid chromatography, and enzymatic concepts.

Introduction

The illegal use of explosives is a widespread problem that is growing in severity. Used as weapons, explosives have become an easy and available tool for those with unstable minds, as well as for calculating criminals. Perhaps the most psychologically effective and physically dangerous use of explosives is accomplished by terrorists; innocent citizens are potential victims for no apparent reason. The terrorist bombings are the greatest threat to society; the societal effect can be greatly out of proportion to the actual danger presented—commerce can be slowed; human values are degraded; and the confidence of a society in itself eroded.

The concerns for the impact of terrorism and the illegal use of explosives are both national and international; the consequences of this threat can be direct, as in airport bombings such as at La Guardia, or indirect, as in the crash of the two 747s, diverted to Tenerife due to a bomb blast at their primary refueling destination.

What can be done? A realistic appraisal of the nature of the threat indicates that most bombings cannot be prevented. The number of actual and potential targets and types of bombs used is a problem with a solution which is prohibitively costly, even to eliminate that small fraction of bombings that might be prevented. Nevertheless, the application of available technology may provide law enforcement officials with some effective tools in their efforts to control the illegal use of explosives. These evolving control methods will allow protection of high-value and publicly accessed buildings, will provide information that will greatly aid in the investigation of those bombings that do occur, and will provide a quick answer to the question of type and source of the explosives used.

For the past 10 to 15 years, Federal agencies in the United States have been engaged in research and development of methods for detecting explosives, even though the total research and development funds have been relatively meager. In the past, these agencies have proceeded individually and have most often expended their limited funds for their own unique operational requirements, and, as a consequence, a broad technical baseline has never been fully established. The result is that there are no explosives-detection systems or identification techniques currently available that are both technically effective and operationally acceptable.

Within the past 4 years, an element of coordination and cooperation has developed among Federal agencies concerned with explosives control in the United States. The key agencies involved in cooperative development activities to date have been the Department of Defense (military explosives), the Department of Justice (significant funding for directed research and development activities in commercial explosives detection and identification), the Department of Transportation (airport security), and the Department of Treasury (explosives tagging and Interagency Advisory Committee coordination activities).

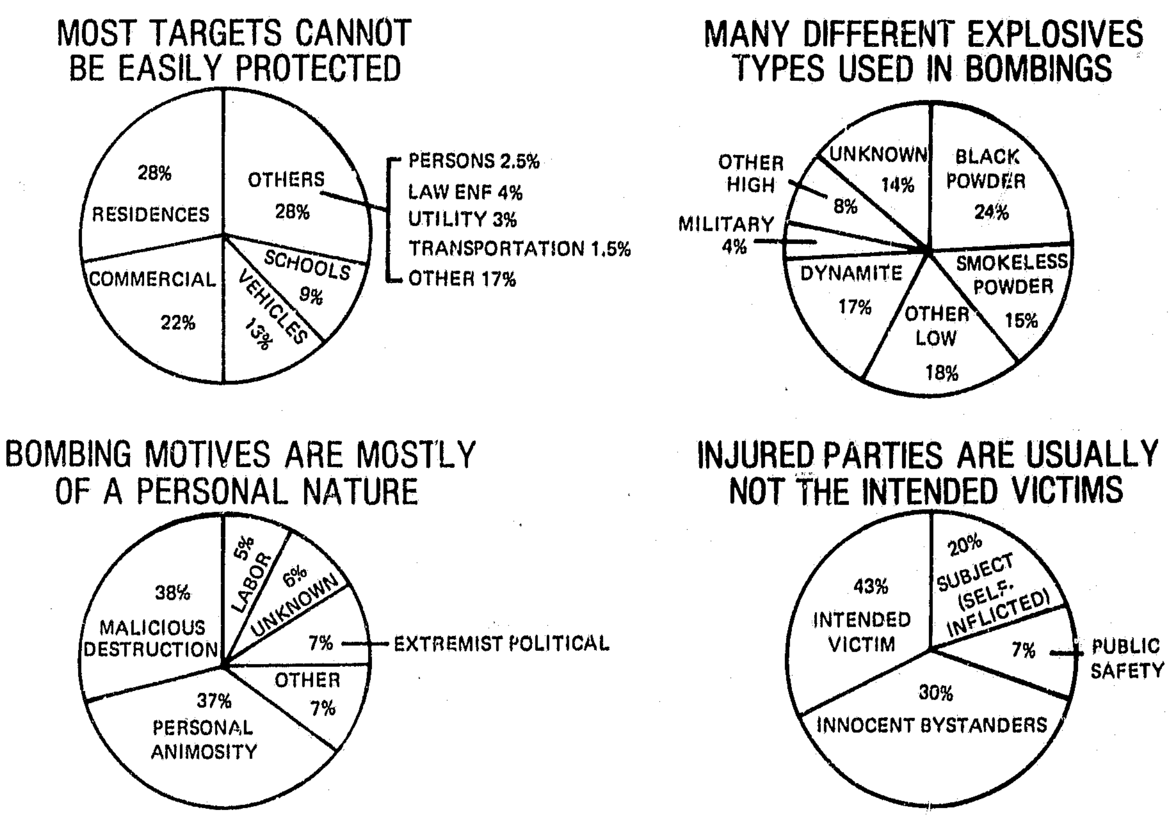
Several of these agencies have contracted The Aerospace Corporation to provide technical management for a diverse range of research and development efforts, as well as for operational demonstrations and tests. Under contract to the Law Enforcement Assistance Administration of the Department of Justice, a wide range of advanced developments in tagged and untagged explosives detection and identification have been carried out through these studies and subcontracted research, as well as through overview of research carried out by other Government-sponsored research laboratories. This paper is largely based on a state-of-art survey conducted for this organization. Also included in this paper are descriptions of the following efforts. For the Bureau of Mines of the Department of the Interior, analytical studies and advanced planning have been carried out for identification tagging. For the Bureau of Alcohol, Tobacco and Firearms of the Department of the Treasury, a major effort in the development and testing of identification and detection techniques is in progress with initial emphasis on tagging methods.

Threat and Operational Summary

Threat Data

The explosives threat within the United States has been inferred from statistics kept by the Bomb Data Center of the Federal Bureau of Investigation (FBI) and from case lists maintained by the Bureau of Alcohol, Tobacco and Firearms. Since the FBI's Bomb Summary Data publication began in 1972, there has been a significant increase in the number of deaths and personal injuries and in the amount of property damage occurring because of illegal bombings, while the number of actual and attempted bombings has remained at approximately 2000 per year. The severity of bombings has grown because of an increasing percentage of explosives bombings and a decreasing percentage of incendiary bombings. The nature of the explosives threat is summarized in the data in Figure 1. These data were derived from January to December 1976 FBI bomb summary data for 1326 incidents, but are typical of other years.

Historically, over 60 percent of bomb targets are residences, commercial establishments, and vehicles. There are over 100 million of these potential targets, and it is virtually impossible to



Reference: Federal Bureau of Investigation, Department of Justice, "Bomb Data Program Incident Summary for December 1976."

Figure 1. Explosives Threat and Target Summary

provide specific protection for each. The conclusion must be that most potential targets cannot be protected; some bombings will always be successful. It should also be noted that high visibility targets, such as transportation facilities, make up less than 2 percent of all targets, but have the greatest percentage of injuries and deaths (e.g., the La Guardia Airport bombing in December 1975).

There are many different types of explosives used in bombings, and many more types are available to the bomber. However, in approximately half the explosive bombings, dynamites and commercial powders were used. For these type explosives, some known explosives detection techniques might be effective. Table 1 provides a simplified breakdown of the more common explosives types that are threat candidates, along with their legitimate and illegal uses. Commercial explosives are also readily available for bombings through direct consumer purchase or through theft—more than 25,000 pounds of explosives are stolen or unaccounted for each year. Effective licensing and control methods could reduce this figure considerably and make the purchase of explosives more difficult for the illegal user. However, this could not be substantially effective without imposing an unacceptably large burden on the legitimate user; hence, the need for other control methods.

Bombing motives appear to be mostly personal in nature, with malicious destruction and personal animosity accounting for 75 percent of the assigned motives. Less than 10 percent of the assigned motives are attributed to terrorist and political bombings; however, a greater fear factor results because of the larger number of innocent people injured and greater property damage that occurs.

Bombing is also a dangerous business; 20 percent of the injuries happen to the bomber himself. More than half of all bombing injuries are suffered by persons other than the apparently intended victim.

Operational Considerations

Three general operational scenarios are defined that can be considered for the detection and identification of explosives. These are controlled-access protection, large-area searches to detect and disarm a bomb before an explosion, and investigation to lead to the conviction of the criminal. These general operational scenarios are listed in Table 2 with examples of typical use.

Controlled-access scenarios include those in which a cognizant agency controls the points by which explosives could enter a protected area. The scenario includes searches of individuals, property carried by individuals, and cargo. Detection techniques acceptable for property, such as ionizing radiation, are probably not acceptable for searches of persons.

Large-area-search scenarios include those in which the area may already have explosives present which must be found. This scenario includes determining that explosives are present and finding the specific location of the explosives within the protected area (e.g., by monitoring airplanes, building air conditioner).

The investigation scenario may involve the identification of the coded wrapper of an unexploded bomb found at the scene of a bombing attempt or the identification of characteristic residue for an exploded bomb. The unexploded bomb identification can lead to the last legal owners of the explosive. The identification and analysis of residue can provide the same information if taggants have been added or the explosive type if no taggants are present. In either case this scenario includes gathering all available evidence to help find and convict the guilty party.

Table 3 depicts the three scenarios that are currently being used or have been operationally attempted over the past several years. Although each technique described has had some limited application, none of the techniques has proved feasible for widespread use in controlling the illegal use of explosives.

Table 1. Candidate Threat Explosives Categories

Explosive Type	Major Ingredients	Detonation Configuration	Use	
			Legitimate	Illegal
Dynamites	NG/EGDN Ammonium nitrate	Cap initiation Unconfined	Mining Demolition	"Suitcase" bombs
Slurries/Water Gels	Ammonium nitrate	Cap initiation Unconfined	Mining Demolition	Current low usage
Military	Compositions of TNT, RDX, PETN, etc.	Cap initiation Possible booster Unconfined	Military	Letter bombs Sophisticated "plastique"
Powders	Black: S, C, KNO_3 Smokeless: nitrocellulose	Flame, primer initiation Confined detonation	Firearms	Pipe bombs
Blasting agents	ANFO (Ammonium Nitrate Fuel Oil)	Cap and booster Unconfined Sophistication required	Mining	Current low usage Large bombs (U of Wisconsin)
Homemade	Various combinations: e.g., ammonium perchlorate sugar	Combinations of above Dangerous to handle	None	Current low usage

Table 2. Operational Scenarios

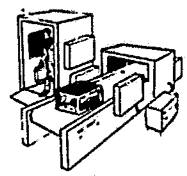
Scenario	Application	Use				
		Transportation	Public Buildings	Postal	Residential Commercial	Mine Safety
Controlled-Access Search 	Personnel	X	X			
	Property and baggage	X	X	X		
	Cargo	X		X		
Large-Area Search 	Threat Call	X	X		X	
	Continuous monitoring	X	X	X		
	Periodic search	X	X			
Investigation 	Residue identification	X	X	X	X	X

Table 3. Present Techniques for Preventing Terrorist Bombings

Scenario	Measure	Advantage	Disadvantage
Controlled-Access Search	X-rays of hand-carried baggage	Good deterrence	Operator sensitive
	Hand search of persons	Effective Good deterrence	Time consuming Requires cooperation
	Walk-through metal detector	Good deterrence	Large false-alarm rate Detects metal only
	Letter-bomb (metal) detector (RF field)	Good screening technique	Low piece rate
	Vapor detectors (electron capture)	Reasonable detection in close proximity	Many interfering species
Large-Area Search	Trained dogs	Positive detection	15-minute attention span
	Hand search	Positive detection	Time consuming
Investigation	Coded wrappers (date/plant/shift)	Positive identification prior to explosion	No postexplosion identification
	Analysis of debris	Determination of explosive type, size, location	Insufficient for investigative leads

Operational Requirements

For a given operational scenario, technical requirements must be defined with consideration for the performance requirements of a detection system. There are a number of categories of operational requirements for an explosives detector (e.g., cost, size, equipment reliability, operator proficiency), which are obviously scenario-dependent. An instrument carried by an agent in a total building search for explosives, for example, would most likely have to be smaller than a detection unit for screening checked luggage at an airport.

The important operational requirements of false positives (false alarms that can disrupt normal operations when an explosive is suspected) and false negatives (failing to detect an actual explosive) necessitate the specification of technical requirements for detection devices. These technical requirements govern whether a given detection concept can, in practice, reliably detect the presence of explosives in typical situations (e.g., airports). In addition, these requirements are closely related to the requirements for interference-free detection threshold of a given technique for natural or tagged components of explosives; the detection specificity of the technique for the desired component in the presence of other interfering components; and the selectivity of the technique for multiple explosive component types given that there are many different explosives for which protection is necessary.

A specific example for the determination of a detection threshold technical requirement for natural explosives vapors is summarized in Figure 2 and is the result of a vapor characterization study completed during 1976. Starting with a systematic determination of the type and amount of vapors present in typical explosives, it provided one of the operational requirements for trace-vapor detection in realistic environments.

The specific objectives of the vapor characterization study were to determine: (1) the identity and rate of emission of vapor species given off by different explosives materials; (2) the equilibrium pressures of these vapors; (3) the rate at which these vapors escape through various typical barriers such as suitcases or plastic wrappings; and (4) the incidence of vapors present in the air environments where search requirements may exist or the presence of other interfering vapors which might mask the explosive vapors. The measurements for this study were performed by the Analytical Research Laboratories, Inc., an Aerospace subcontractor, and resulted in vapor-detector technical-performance requirements for several types of bombs and search situations.

The measurement method involved explosive samples placed in a chamber and flushed with nitrogen gas for up to three days. Vapor released by the explosives were trapped with the nitrogen gas for later analysis. This analysis yielded the type of vapor outgassed by the explosive material, its emission rate, and its rate of escape through various types of barriers. Air collected at

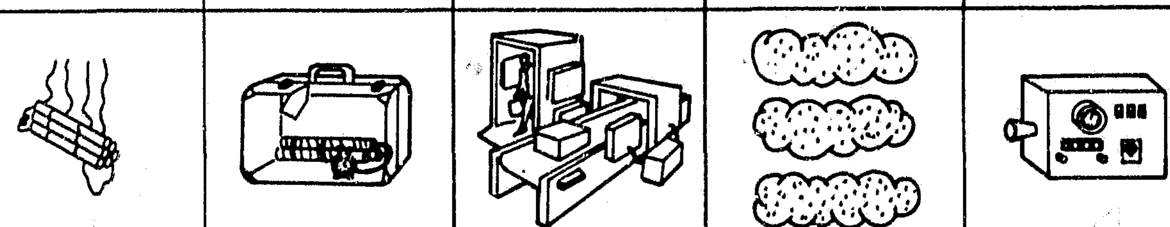
VAPOR CONSTITUENTS AND RATES	BARRIERS	VOLUMETRIC DILUTION	INTERFERENCES	DETECTION REQUIREMENTS
				
MEASURED • DYNAMITES • ETHYLENE GLYCOL DINITRATE (EGDN) 10-90 NANOLITERS/MIN FOR ONE STICK • NITROGLYCERINE 10-90 NANOLITERS/MIN FOR ONE STICK • OTHERS MUCH LOWER • GELS • METHYL AMINE • C-4 (Fresh) • CYCLOHEXANONE • SMOKELESS POWDERS (Single Base) • DIPHENYL AMINE (DPA)	MEASURED • DYNAMITES (EGDN) • CONCENTRATION INSIDE BARRIERS DOWN FACTOR OF 5-10 • UNAIDED ESCAPE REDUCED A FACTOR OF 1-50 THOUSAND	CALCULATED • LUGGAGE AND PACKAGES • 5 PERCENT RECOVERY FROM 15 LITERS BRIEFCASE IN A 250 LITER CHAMBER • DILUTION FACTOR 200 TO 300 NORMAL • PEOPLE • DILUTION FACTOR OF 1000 MINIMUM	MEASURED • LUGGAGE • ACETONE • FREON 11, 12 • PENTANE • HEXANE • CYCLOHEXANONE • BENZENE • KETONES • XYLENES • TRANSPORTATION TERMINALS • OZONE-HYDROCARBONS • WATER • CARBON DIOXIDE • NITROGEN DIOXIDE	CALCULATED • DYNAMITES (EGDN) • EXPECTED CONCENTRATION ~100 PARTS IN 10^9 • REQUIRED 1 PART IN 10^9 • SMOKELESS (DPA) • EXPECTED CONCENTRATION LESS THAN 1 PART IN 10^{12} • NOT DETECTABLE • C-4 (CYCLOHEXANONE) • EXPECTED CONCENTRATION 3 PARTS IN 10^{11} • REQUIRED 1 PART IN 10^{11} • GELS (METHYLAMINE) • CONCENTRATION EXPECTED 1 PART IN 10^{13} • NOT DETECTABLE

Figure 2. Summary of the Results of the Vapor Characterization Study

airports and bus terminals was subjected to a similar analysis to determine the composition of typical operational environments.

The primary conclusion of this study was that only nitroglycerin-based dynamites and perhaps trinitrotoluene emit sufficient natural vapors to be detectable by existing technology and that detection thresholds on the order of 1 part in 10^{10} for such vapors is required.

State-of-the-Art Overview

Introduction: Explosives Characteristics

If a given explosives type is to be detected prior to detonation, or the residue uniquely identified after an explosion, there are a number of physical parameters which can be considered. These are summarized in Figure 3 for typical bomb components.

For explosives detection, there are two general approaches. First, those properties that occur naturally might be sensed. These properties include the natural vapors (such as ethylene glycol dinitrate or nitroglycerin); the bulk properties of the explosive itself (such as the high nitrogen content of explosives); or the detonation chain (blasting cap, wires, battery, or timer). Second, a physical tag or unnatural ingredient could be added to the explosive at the time of manufacture. For instance, a highly detectable vapor of unusual metal might be added to blasting caps or the bulk explosives in order to aid detection.

Two similar approaches hold true for the identification of explosives. First, the manufacturer's marks of identification on the wrappers of unexploded devices can be analyzed, or the natural residue in the case of exploded devices. Second, identification taggants can be added at manufacture which survive the detonation and which yield plant, type, and time of manufacture. This would allow bomb investigators to trace the explosive to the last legal owners.

Natural-Vapor Detection

Commercial explosives manufactured in the United States are predominantly either nitroglycerin- (NG) and ethylene glycol dinitrate- (EGDN) based or ammonium nitrate-based (slurries). A small quantity of nitrostarch-based dynamite is also produced. Studies of the rates of emission of characteristic vapors from dynamite and slurries, smokeless and black powders, and military explosives have been carried out. These studies indicated that only NG-/EGDN-based dynamites are good candidates for vapor detection among commercial dynamites. Smokeless powders emit characteristic molecules at very low rates. Many military dynamites are based on trinitrotoluene (TNT) which contains an appreciable quantity of dinitrotoluene (DNT) as an impurity, and this material can be detected. Other military explosives do not emit a characteristic molecule; however, fresh C-4 (a plastique explosive) emits cyclohexanone which is relatively distinctive.

The emphasis in this section on natural-vapor detection techniques is on the three molecules NG, EGDN, and DNT. These three vapors share two important characteristics: (1) they are highly electronegative, and (2) they have strong absorption bands in the infrared at 9 to 12 μm. In addition, both NG and EGDN are temperature-sensitive, especially in the presence of metal surfaces, and tend to decompose at slightly above ambient temperatures.

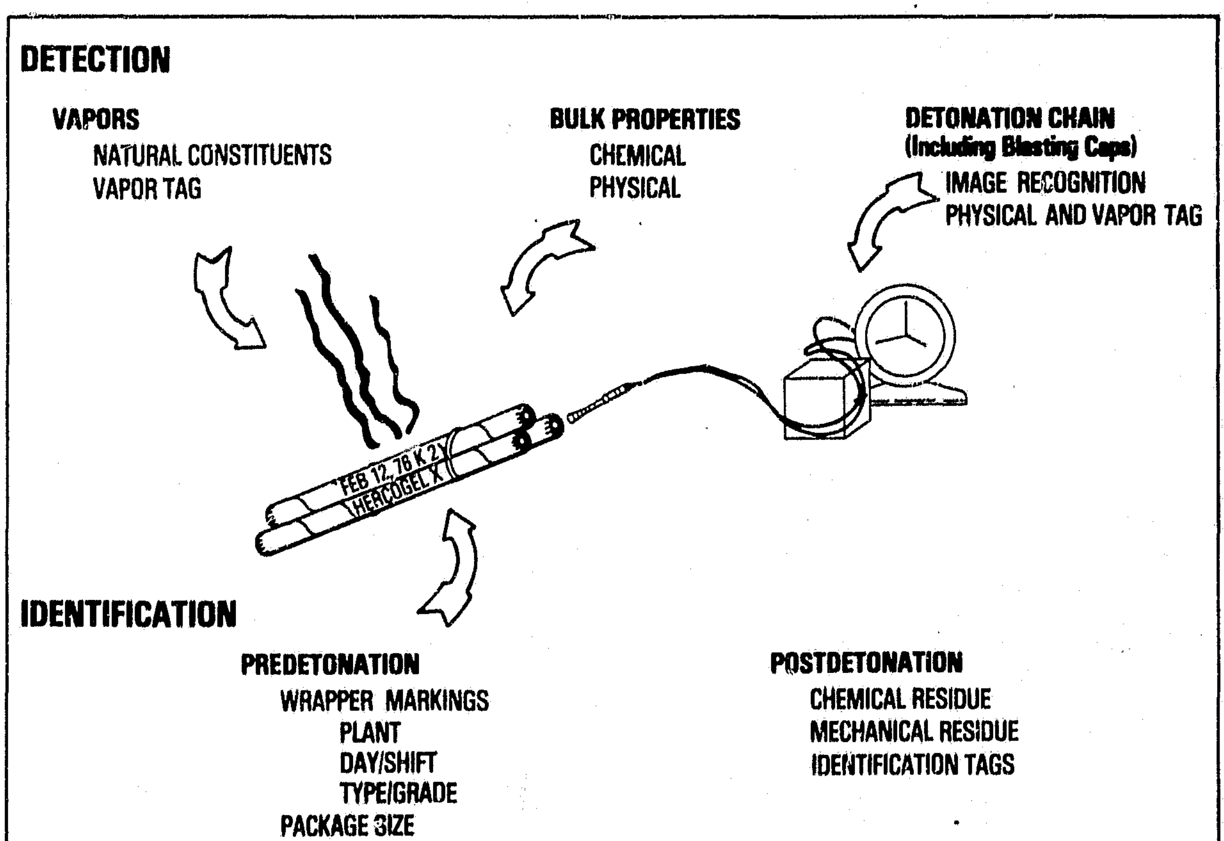


Figure 3. Explosives Detection and Identification Parameters

The infrared absorption bands are broad and do not exhibit fine structure; hence, optical methods are inherently of low resolution.

Electron-capture techniques are widely regarded as having reached the most advanced stage of development. Nevertheless, none have resulted in widespread application. While they have a detection threshold which is outstanding, often on the order of 1 part in 10^{12} or better, their specificity is usually inadequate, giving rise to high false-alarm rates. When coupled with a gas chromatograph for specificity, the slow response time is unacceptable except in limited circumstances. Only by coupling the electron-capture detector with an as yet unknown explosive-vapor selective device can it be made a widely applicable technique.

Laser-photoacoustic detection relies on the existance of the previously mentioned IR absorption bands. Feasibility studies indicate that a detection threshold of 0.1 part per billion (ppb) is achievable, and that a value of 2 to 5 ppb is attainable even with the interferences that can occur in polluted atmospheres. A breadboard system is presently under development.

Ion-mobility spectrometry (plasma chromatography) relies on the electronegative character of the molecules and distinguishes them on the basis of their drift velocity in an electric field. The technique has been applied to TNT where a detection threshold of 0.01 ppb has been demonstrated. Virtually no quantitative work has been carried out to assess the effect of interferences. Because the normal mode of operation is to heat the system to about 100°C, EGDN and NG have never been observed in the system; only a decomposition product identified as NO_3^- has been recorded. Selectively is a function of the resolution, which is about 4 milliseconds at a drift time of 50 milliseconds. This qualifies the device as having a resolution about equivalent to that of laser photoacoustics.

Mass spectrometry has been demonstrated to have a detection threshold of about 0.1 ppb for DNT; however, the demonstration instrument was crude, and an order of magnitude improvement can be projected with confidence. The mass spectrometer technique has good resolution (1 u); hence, its specificity is outstanding. The potential of the mass-spectrometry technique will be realized only if the ionization technique demonstrated for sulfur hexafluoride and DNT (pulsed corona discharge) is equally applicable to EGDN and NG. Based on this presumption, mass spectrometry has the highest potential of all known detection means for explosive vapors.

The detection of explosives vapors by a specific enzymatic reaction has been demonstrated for TNT vapors with a detection threshold of 10^{-12} g. In general, an enzymatic technique should have the highest specificity of any presently known technique, as well as the lowest threshold of detection. Its major drawback is the speed of response (about 2 minutes) which does not appear to be reducible to less than about 0.5 minute.

After additional development, several other techniques are likely to be able to fulfill the reasonable requirements of vapor detection of explosives; however, the limited nature of these systems precludes their universal application and the rapid change in explosives manufacturers' product lines from NG-based dynamites to sensitized ammonium nitrate-based explosives poses a severe limitation of any vapor-detection method.

Despite these many limitations in vapor-detection technology, the continued development of appropriate vapor-detection techniques is justified on two primary grounds: (1) the development of vapor taggants can significantly increase the effectiveness of vapor detectors, and (2) only vapor detectors are known to be applicable to the detection of explosives carried by people. Table 4 summarizes the key characteristics for current vapor-detection techniques.

Physical-Property Detection

The range and variety of materials that have explosive properties are very great. Properties common to all explosives are not particularly evident. For commercial explosives, the single common denominator is the presence of a large percentage of nitrogen. Attempts to exploit the presence of nitrogen using thermal neutron-capture/gamma-ray analysis have not been notable for their success. The difficulty arises because of the overwhelming number of low-energy gamma rays that must be processed for each 10.8-MeV nitrogen-capture gamma ray recorded.

Most commercial explosives manufactured within the United States contain ammonium nitrate. This includes the dynamites, although a limited group of high-strength dynamites contains only NG or EGDN, nitrocotton, and possibly some carbonaceous filler. In all cases, ammonium nitrate exists in solid form, although in the case of the slurries/water gels there is also ammonium nitrate in solution. Ammonium nitrate has a relatively unique nuclear magnetic resonance (NMR) signature with a long (seconds) decay time which can be distinguished from most hydrogeneous materials (e.g., plastics). It appears that the NMR concept may be capable of relatively specific detection of commercial explosives containing ammonium nitrate. By adding a nuclear quadrupole resonance (NQR) signal to this concept, certain military explosives are detectable as well. While far from commercial instrument application, this development (currently sponsored by the Federal Aviation Administration) is the most promising technique demonstrated to date.

Other physical properties of explosives which can be exploited are density and average atomic number. For most commercial explosives, the density (ρ) falls within the range of $1.05 < \rho < 1.5$. Explosives contain predominantly nitrogenous material, and the average atomic number is relatively low ($5<Z<7$). The two characteristics when combined are relatively unique and, when further combined with shape information, appear to define explosives with a high degree of certainty (98+ percent).

The variation of X-ray transmission resulting from the density of explosives has been used to detect explosives in a system which also generates a crude image and applies a shape criterion. This system (developed under the sponsorship of the Federal Aviation Administration) appears to have a limited capability because a variety of suitcase contents appear to simulate explosives. Further improvements are possible, and a system meeting appropriate criteria may be achievable.

There are several means of taking advantage of the combined atomic number and density characteristics, the simplest being to carry out a two-energy transmission measurement. This has been implemented in a device designed to detect bicycle bombs. In

Table 4. Summary of Key Characteristics of Explosives-Vapor-Detection Techniques

Method	Sampling	Threshold of Detection (ppb)	Specificity	Response Time (sec)	Recycle Time (sec)	Types of Vapor Species	Number of Vapor Species
Electron Capture (gas chromatographic)	Discrete	0.01	Low	15-120	60-90	Electronegative	Up to 4
Electron Capture (dual channel)	Continuous	1	Low	~10	40-60	Electronegative	No limit
Laser Photoacoustic	Continuous	0.1	Moderate	5-10	None	All	No limit
Plasma Chromatography (ion mobility spectroscopy)	Continuous	0.01	Moderate	5-10	None	Electropositive and electronegative	No limit
Mass Spectroscopy	Continuous	0.01	High	5-10	None	All	No limit
Enzymatic Reaction	Discrete	10^{-14} mole	Very high	60-90	None	All	Separate subsystem for each species
Thermal Decomposition	Discrete	High but unknown	Low	~15	60-90	Electronegative	No limit
Laser Raman Spectroscopy	Continuous	10	Moderate	5-10	None	All	No limit
U.S. Customs Thermionic Unit.	Continuous	Unknown	Low	~10	None	Oxygenated/ chlorinated	No limit

principle, the two-energy method looks feasible for such items as pipe bombs, but it requires multiple measurements.

A more powerful tool for taking advantage of the atomic number and density characteristics of explosives is to employ a modification of tomography techniques. In this case, a dual-energy scan is capable of generating the linear attenuation coefficient for each discrete volume element in the scanned object. Because two μ values, one for each energy, are available, one can compute the average atomic number Z and density ρ for each element. Contiguous elements having ρ and Z values consistent with an explosive could be evaluated using a simple shape algorithm. No such explosives-detection system has been constructed or tested; however, theoretical calculations indicate that the system would be capable of detecting explosives with high probability (>95 percent) and low false-alarm rate (<5 percent). The major disadvantages would be cost and complexity.

The NMR and tomographic detection techniques offer the greatest promise of a near-universal explosives-detection capability, but both have inherent limitations. The limitations are more obvious in the case of NMR, which will not detect smokeless or black powders or homemade pyrotechnic mixtures and is easily defeated by shielding. For tomography, the limitations which are most serious relate to speed/resolution product and the feasibility of shielding. False alarms based on a combination of a low atomic number material in a metallic container may be a problem also, e.g., aerosol shaving creams have characteristics at the borderline of the atomic number and density of explosives. Table 5 summarizes the key characteristics for current nontagged, nonvapor detection techniques.

Tagging for Predetonation Detection

Many of the detection techniques developed for explosives vapors are equally valid for vapor taggants. The major area of study for vapor taggants is in the method of incorporation of the taggants in the explosives or the detonation chain. The area of most intense study deals with the addition of a vapor taggant to the seal plug of the blasting cap. A variety of potential materials are under study. The most promising of these are a number of perfluorocy[illegible]o-alkanes, as well as a range of perfluoroethers. The emphasis in these studies is to determine taggant materials which are safe, can be incorporated into existing plug material, do not exist in the environment, and are tropospherically degradable. A secondary characteristic is ease of detection.

Because many of the more desirable vapor taggants will not dissolve in the presently used blasting cap elastomeric seals, alternative seals as well as alternative methods of incorporation are being sought. Because many of these desirable vapors are highly fluorinated compounds, they are soluble in fluorinated elastomers such as the Viton series or fluorosilicone rubbers. Some of these have physical properties similar to the presently used Buna-N and Kraton elastomers. They might be used with relatively little modification of the manufacturing process.

Table 5. Summary of Key Characteristics for Nontagged, Nonvapor Detection Techniques

Method	Scenario	Type of Bomb	Detection Criteria	Specificity	Response Time (sec)	Complexity
Conventional X-Ray	Controlled access	All	Density: operator interpretation	Low	2-5	Moderate
Gamma-Ray Transmission	Controlled access	All	Density: automatic shape discrimination	Low	2-5	Moderate
Dual-Energy Gamma/X-Ray Transmission	Controlled access	Pipe	Density: atomic number	High	2-5	Moderate
Gamma/Neutron Transmission	Letters/flats	Plastic	Density: atomic number; hydrogen content	High	0.01	Moderate
Gamma-Ray Scattering	Controlled access	All	Density	High	10-30	High
Dual-Energy Tomography	Controlled access	All	Density: atomic number	High	10-30	High
Thermal-Neutron Capture	Controlled access	All	Nitrogen content	Moderate	10-30	High
X-Ray Fluorescence	Controlled access: letters/flats	All	Lead content (detonator)	Low	10-30	Moderate
Dielectric Discontinuity	Letters/flats	Plastic	Inhomogeneous mixtures	High	0.01	Moderate
Capacitance	Letters/flats	Plastic	Capacitance	Low	0.01	Low
Nuclear-Magnetic Resonance	Controlled access	All	Hydrogen resonance decay times	Moderate	10-30	High
Nuclear Quadrupole Resonance	Controlled access: personnel search	RDX; possibly TNT	Nitrogen resonance absorption	Very high	5-10	Low

Of quite a different character are various ammonium salts that sublime at room temperature. Such materials as deuteroammonium formate and deuteromethylamine fluoroborate have relatively high vapor pressures and do not exist naturally. Because they degrade readily, they will not exhibit an increasing background. Incorporation of these salts into the plugs is expected to be relatively simple.

A third technique involves the microencapsulation of vapor taggant material and the incorporation of the microcapsules into blasting caps. This technique, in common with the use of ammonium salts, provides a relatively constant emission rate. In addition, microencapsulation allows a high loading factor in the seal plug, compared to dissolving a fluoro compound in the plug material.

Other potential techniques that are in the exploratory feasibility phase include the use of coded harmonic radar tagging, X-ray fluorescence detection of heavy metal alloyed blasting caps, and an electromagnetic technique which would result in the detonator becoming inoperable on application of a particular signal.

The tagging for detection of other materials is under active study. Both smokeless and black powders are expected to be amenable to tagging with a microencapsulated material. Detonating cord and fuse cord tagging are being studied and, again, the use of microencapsulated material is a promising candidate taggant.

One or more of the above methods should reach the point of demonstrable feasibility within a year and will be tested on a pilot scale in order to insure that no unforeseen problems in manufacturability, compatibility, or detectability emerge. Table 6 summarizes the key characteristics for predetonation detection tagging techniques.

Explosives Identification From Residue Analysis

A serious deficiency exists in the ability to identify the type of explosive involved in an illegal blast, based on an analysis of the residue collected at the bomb scene. Most of the techniques now

Table 6. Summary of Key Characteristics for Predetonation-Detection Tagging Techniques

Tagging Technique	Principle	Explosive Component	Threshold of Detection	Specificity	Cost
SF_6 Vapors	Impregnated SF_6 in Teflon plugs, electron capture detection	Blasting cap plug insert	1 part in 10^{12}	Background 5 parts in 10^{12} now, 10% per year increase	5-10 cents per cap
Other Highly Fluorinated Vapors (ketones, ethers, and alkanes)	Impregnated vapor detection by electron capture, optics, or mass spectrometry	Blasting cap plug or dip coating	TBD, probably 1 part in 10^{12}	No detectable background at present (< 1 part in 10^{14})	5-10 cents per cap
Deuterated Ammonium Salts	Deuterium replacement of hydrogen yields unique detection by optical means (UV or IR)	Blasting cap plug or dip coating	TBD, probably 1 part in 10^{12}	No detectable background (< 1 part in 10^{16} calculated)	5 cents per cap
Heavy Metal Taggants (uranium, bismuth, thorium)	Characteristic X-ray fluorescence detected after excitation	Blasting cap casing alloy	Milligram quantities with distributed geometry	Few background interferences	5-10 cents per cap
Neutron Capture Taggants (dysprosium, gadolinium	Characteristic decay gammas detected after thermal neutron excitation	Dip-coated blasting cap or distributed in bulk explosive	Milligram quantities with distributed geometry	Few background interferences	1 cent per pound explosives, 1 cent per cap
Radar Harmonic Taggants	Radar reradiation from passive electronic component	Blasting cap plug insert with cap and lead wires serving as dipole elements	Unshielded detection at greater than 1 meter	TBD, coded response possible	5-50 cents per cap depending upon coding

in use require the collection of micrograms to milligrams of the explosive used. Even when such quantities are collected, the overwhelming quantity of extraneous material may preclude successful identification. In approximately 40 percent of cases where debris is submitted for analysis, identification is unsuccessful.

It is not immediately apparent that identification will be successful even using advanced techniques because, for many explosives, the reactions should be complete, and the failure to identify the explosive involved may result from the fact that none remains. This is a pessimistic view and, in reality, characteristic residue probably does exist, albeit in very small amounts.

A variety of techniques for explosives residue identification is in relatively common use. These range from simple spot test procedures requiring a milligram of material to infrared (IR) methods capable of detecting a microgram of explosives. These methods are relatively specific but are not capable of detecting and identifying residue at the nanogram or less level (the quantities that are most likely to be present if the explosive detonates efficiently).

Advanced laboratory techniques capable of separating and identifying picograms of material are available and can be applied, if the appropriate separation, preparation, and calibration methods are developed. The technique of greatest promise involves high-pressure liquid chromatography (HPLC), frequently called high-performance liquid chromatography. This technique, when coupled with appropriate extractive and preparative methods, has been used to isolate and identify femtogram quantities of materials. The use of HPLC is especially useful where the material involved is heat-sensitive, as are NG, EGDN, and PETN, or cannot be successfully chromatographed in the gas phase, as RDX and HMX. The use of HPLC to separate and isolate relatively pure samples of RDX, HMX, and TNT has been demonstrated with the sample identity positively established using chemical ionization mass spectrometry; however, the appropriate extractive and preparatory methods needed to apply these techniques to debris recovered at a bomb scene have not been developed.

Based on the known capabilities of the HPLC method and the probability that some unreacted explosive exists after detonation, the use of HPLC combined with extractive and/or preconcentration methods and followed by chemical ionization mass spectrometry, appears to offer a very high probability of explosives type identification. Table 7 summarizes the key characteristics for untagged residue identification techniques.

Tagging for Identification

As pointed out in the introduction, it is not possible to prevent the majority of bombings, even though this is the desired result. In order to meet part of the goal of eliminating the threat of bombings, The Bureau of Alcohol, Tobacco and Firearms instituted a record-keeping system which is capable of identifying and tracing the distribution and use of a relatively small quantity (~12,000 pounds) of high explosives, provided a cartridge or case is found. Because this is rarely the case after a bombing, tagging of the explosives to achieve a comparable result has been implemented on a pilot scale.

The taggants consist of microparticles added to explosives at the time of manufacture. These particles can be configured so as to generate up to 10^6 individual codes, a number which provides for individualization of each 10,000 pounds of explosives for a period of 5 years. These taggants have been tested in the highest strength dynamites and shown to survive. They are magnetic and fluorescent, properties which make recovery after a blast relatively simple, even in rather adverse circumstances. Two types appear capable of surviving the severe environment of detonation and of being recovered from the debris and decoded, and only these two

Table 7. Summary of Untagged Residue Identification Techniques

Method	Type of Analyte	Specificity	Routine Detection Threshold (grams)	Instrumentation Complexity	Present Usage
X-Ray Diffraction	Inorganic salts	High	10^{-3}	Very high	Low
Spark Emission	Metals	High	10^{-3}	High	Low
Atomic Absorption	Metals	High	10^{-9}	Moderate	Low
Dispersive Infrared 2.5 – 15μm KBr Pellet	Inorganic salts and organics	Moderate	10^{-3}	Moderate	Very high
Diamond Cell	Inorganic salts and organics	Moderate	10^{-4}	Moderate	Moderate
Fourier Transform Infrared 2.5 – 15μm	Inorganic salts and organics	Moderate	10^{-6}	Very high	Low, state of the art
Chemical Spot Tests	Inorganic salts and organic	Low	10^{-3}	Low	Very high
Thin-Layer Chromatography	Organics	Low	10^{-3}	Low	Very high
Gas-Liquid Chromatographic	Organics	Moderate	10^{-9}	Moderate	Low
High-Pressure Liquid Chromatography	Organics	Moderate	10^{-9}	Moderate	Low
Combined Gas Liquid Chromatography Chemical Ionization Mass Spectrometry	Organics	Very high	10^{-9}	Very high	Low, state of the art
Combined High-Pressure Liquid Chromatography with Chemical Ionization Mass Spectrometry	Organics	Very high	10^{-9}	Very high	Low, state of the art
Enzymatic Reaction	Organics	Very high (TNT)	10^{-12}	High	None operational

are being considered as candidates for national implementation and for use in the pilot test.

One is a color-coded taggant, the other an inorganic particle coded with rare-earth doped compounds.

Decoding of both taggants after recovery requires laboratory facilities. The color-coded taggant is decoded by visual observation of colors using a laboratory microscope, although a less sophisticated determination can be made with a field microscope. The rare-earth taggant is decoded with an instrument package consisting of a laser and a monochrometer.

The identification tagging and tracing program is expected to have a significant impact in increasing the conviction rate for bombings, improving the physical security of explosives, and in reducing the number of bombings and attempted bombings. There also is likely to be some displacement effect and serious efforts are underway to develop effective techniques for identification tagging of smokeless and black powders, boosters (primers), and blasting caps.

Conclusions

There is a wide range of exploratory development and test activities currently underway sponsored by a number of Federal agencies within the United States. A number of the techniques look promising for partial solutions to the explosives problem, but none appear to provide total solutions. In order to increase the probability of detection and to minimize the potential false alarms, a combination of techniques may be required for a controlled-access scenario, with a nonvapor-screening technique backed up by a confirmatory vapor technique. The detection may be based on the properties of either the characteristics of the natural explosives or added taggants.

The primary research over the past 10 years has been on natural-vapor detectors, but the vapor-characterization study clearly indicates the limitation inherent in this technique. Natural-vapor techniques alone cannot be depended upon, since a declining fraction of commercial high explosives emit vapors, emission rates are low for those explosives which do contain NG/EGDN, and there are significant difficulties in moving and extracting the appropriate vapors from the large quantities of air involved.

Significant new development is needed in the areas of physical property explosives detectors and detection-taggant techniques. New classes of laboratory analyses (e.g., high-efficiency ionization methods for mass spectrometry, enzymatic reactions, and liquid chromatography) should be applied to explosives-residue characterization for investigative purposes to complement the identification tagging program for cap-sensitive high explosives currently being implemented in the United States by the Bureau of Alcohol, Tobacco and Firearms.

In order to perform this additional work, the interagency cooperation within the United States over the past several years and the growing international cooperation on data exchange must be continued. As indicated in the introduction, the overall explosives control problem is technically and politically difficult. It will take considerable development and implementation funds (in the tens of millions of dollars) to allow any measurable impact on the explosives problem.