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A Technical Assessment of Portable Explosives Vapor Detection Devices

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FOREWORD

The Law Enforcement Standards Laboratory (LESL) of the National Institute of Standards and Technology (NIST) furnishes technical support to the National Institute of Justice (NIJ) program to strengthen law enforcement and criminal justice in the United States. LESL's function is to conduct research that will assist law enforcement and criminal justice agencies in the selection and procurement of quality equipment.

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This document covers research on law enforcement equipment conducted by LESL under the sponsorship of NIJ. Additional reports as well as other documents are being issued under the LESL program in the areas of protective equipment, communications equipment, security systems, weapons, emergency equipment, investigative aids, vehicles, and clothing.

Technical comments and suggestions concerning this report are invited from all interested parties. They may be addressed to the Law Enforcement Standards Laboratory, National Institute of Standards and Technology, Gaithersburg, MD 20899.

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A TECHNICAL ASSESSMENT OF PORTABLE EXPLOSIVES VAPOR DETECTION DEVICES

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The purpose of the present report is to provide objective information about the capabilities of electronic explosives detectors to local law enforcement agents. In this pursuit, we have been guided by consideration of the following frequently posed questions: 1) Do electronic explosives detectors work at all? 2) If so, what are the capabilities and limitations of commercially available explosives detectors? 3) In general terms, what is the present status of the field of explosives detection? and 4) What capabilities are likely to be available in the near future?

Key words: assessments; detectors; evaluation; explosives.

1. INTRODUCTION

Interest in the problem of explosives detection has closely paralleled the increase in public awareness of politically motivated terrorism which began in the 1960's and continues through the present day. Airplanes are particularly vulnerable to explosives, and the safety of airline passengers has always been a focal point of the multi-million dollar research effort in the field of explosives detection. The Federal Aviation Administration, in particular, has been very active in its support of explosives detection research. It is not surprising, therefore, that many of the recent breakthroughs in the design of explosive detection devices have become manifest in the form of large, complicated, and expensive instruments which are most suitable for use as dedicated detectors at major installations such as military bases and international airports.

Unfortunately, criminals do not limit their activities to facilities that can be protected by dedicated explosives detectors. Indeed, airports and military bases were cited in the Explosives Incidents Report published by the Bureau of Alcohol, Tobacco and Firearms, as primary targets in only about 100 of the nearly 12,000 bombings which were reported in the years between 1977 and 1986 [1][1]. The great majority of these bombings were directed at residential and commercial targets which come under the jurisdiction of local law enforcement agencies. For example, in Montgomery County, Maryland the police department responded to approximately one hundred calls relating to explosives in 1987 [2]. In New York City, there were nearly one thousand responses to bomb threats [3]. These investigators reported finding bombs in diverse places, ranging from schools to retail establishments. Some of the perpetrators were indeed political terrorists, but the majority were not. People suffering from severe emotional stress due to the loss of a job or a bitter divorce as well as professional criminals were also responsible for bombings. In fact, according to the statistics compiled in the Explosives Incidents Report covering the period between 1977 and 1986, vandalism and revenge rather than protest and extortion, were the primary motives in the majority of bombings for which a motive could be determined [1]. The illegal use of explosives is a widespread problem affecting every level of the law enforcement system. There is a definite need for reliable and inexpensive instruments which can be used in the field for the detection of explosives on a daily basis.

Objective information about the performance capabilities of commercial explosives detectors is difficult to find. The sources used in this report include studies conducted by the Federal Bureau of Investigation [4], the National Research Council Canada [5,6,7], and the Royal Canadian Mounted Police [8]. The results obtained in earlier investigations performed by Linenberg [9] and Williams [10] have been invalidated by the discovery that the explosives used in these tests were contaminated [6,11]. A more thorough evaluation study which is being sponsored by the Naval Explosives Ordnance Disposal Technology Center is currently underway at Virginia Polytechnic Institute and State University (VPISU) [12]. The objective of the VPISU study is to determine the sensitivities of some of the portable explosives detectors and to compare these values to the laboratory detection limits of the same explosives.

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[1] Numbers in brackets refer to the references in section 7.

The purpose of the present report is to disseminate information about the capabilities of portable explosives detectors to local law enforcement agencies and to provide a technical basis for the interpretation of this information. In this pursuit, we have been guided by consideration of the following frequently posed questions: 1) Do electronic explosives detectors work at all? 2) If so, what are the capabilities and limitations of commercially available explosives detectors? 3) In general terms, what is the present status of the field of explosives detection? and 4) What capabilities are likely to be available in the near future?

2. PROBLEM DEFINITION

2.1 Condensed Phase Versus Explosives Vapor Detection

Explosives can be detected in the condensed phase or indirectly by sensing explosives vapor. In the former case, radiation from a source in the explosives detector must actually make contact with the bulk explosive. As a consequence, condensed phase detection is a viable option only when searching small spaces where there is a reasonable likelihood of focusing a beam of radiation on the bulk explosive during the scan. Furthermore, these methods require a source of penetrating radiation such as X rays or neutrons, which constitute a health hazard so that they cannot be used for searching people entering restricted areas. On the other hand, the vapor which emanates from the bulk explosive will eventually fill even a large enclosure. In principle, this vapor should be detectable from any point inside of the enclosure. Unfortunately, most explosives only emit trace quantities of vapor so that this approach requires extremely sensitive detectors.

An example of a condensed phase detection method is thermal neutron analysis (TNA). The basis of TNA is the reaction between ^{14}N, the most abundant isotope of nitrogen, and thermal neutrons to produce ^{15}N. The energy which is generated by this reaction is dissipated in the form of γ radiation which is detected by a scintillation counter in the TNA explosives detector. Organonitrate explosives are distinguished from nonexplosive nitrogenous materials, such as leather and nylon, on the basis of density differences. In 1988 the Federal Aviation Administration awarded an $8.4 million contract to Science Applications International Corporation[2] for the development of five operational TNA explosives detectors to be installed at selected airports [13].

An example of an explosives vapor detector, is the chemiluminescent detector (CD) which has been developed by Thermedics Inc., of Woburn, Massachusetts using funds awarded by both the Federal Aviation Administration and the Department of State. The operational basis of a chemiluminescent explosives detector is the chemical reaction between nitric oxide (NO) and ozone (O_3) to form nitrogen dioxide (NO_2). The energy which is liberated in this reaction is given-off as light.

There are two operational steps in the chemiluminescent detection (CD) of explosives vapor. In the first step, organonitrate vapors are converted to nitric oxide. The process is similar to the one which takes place in the catalytic converter of an automobile exhaust system, except that in a CD it is the formation of NO, rather than the formation of CO_2 which is catalyzed. Once it has been formed, the NO is allowed to react with ozone and the intensity of resulting chemiluminescence light is measured with a photomultiplier.

2.2 Applications of Explosives Detectors

Explosives detectors are conventionally used in two distinct security operations. They are used to screen people and packages before entering restricted areas and they are used to verify the presence and determine the location of concealed explosives in buildings and vehicles. Both condensed phase and explosives vapor detectors are used in checkpoint screenings. However, because explosives vapor detectors are the method of choice for the search and clear operations which are conducted by local law enforcement agents, they will be the primary focus of this report.

The technical breakthroughs which are now being made in the field of explosives detection will eventually benefit every level of the law enforcement system. It must be recognized, however, that the problems involved in conducting security screenings for explosives at airports are entirely different, albeit no less formidable [11] from those encountered by investigators trying to locate concealed explosives in less controlled environments. Baggage, for example, can be subjected to penetrative radiation or even opened in the search for explosives or detonation devices. Furthermore, passengers can be required to enter booths designed to facilitate the sampling of explosives prior to boarding aircraft. In these cases, the searches are

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[2] Certain commercial equipment, instruments, materials, or companies are identified in this report. In no case does such identification imply recommendation or condemnation by the National Institute of Standards and Technology or the National Institute of Justice, nor does it imply that the equipment identified is necessarily the best available for the purpose.

confined to small spaces where the temperature and airflow can be adjusted to increase the likelihood of detecting concealed explosives. The use of sampling booths also increases the possibility that micro-particulates from the explosive will make contact with the detector probe. Even the most insensitive of detectors will respond to the presence of these micro-particulates. In the event that an airplane must be searched, it is still a relatively small enclosure with a controlled airflow. Indeed, it is possible to analyze large volumes of the cabin air for explosives vapor in a single pass by sampling at the outflow and dump valves of the airplane [5,14].

The instruments which are designed to facilitate security checks for explosives at airports and other large facilities are large, expensive, and complicated to use. Portable units, which are the primary focus of this report, are much better suited to the search and clear operations which are routinely performed by local bomb squads.

Apart from purely technical problems, there are wide-ranging political, social, and economic ramifications of explosives detection which must be taken into account. In conducting searches for explosives, law enforcement agents must maintain a delicate balance between the safety and civil rights of the public. Many of these considerations are unique to the field of explosives detection, and they place severe demands on the performance capabilities of explosives detectors.

A common situation encountered by local bomb investigation units is a bomb threat affecting a public building. It is a fact that most bomb threats turn out to be hoaxes. In New York City for example, all calls relating to explosives are screened. A response by the bomb squad was deemed to be warranted in only about 20 percent of the approximately 5000 calls that they received in 1987 [3].

Despite the enormous financial, organizational, and emotional stresses involved in responding to a bomb threat, there are few who would argue the wisdom of taking precautionary measures whenever the presence of an explosive is suspected. The consequences of inactivity are simply too great. If, however, the detection method is not reliable, in the sense that it gives an inordinate number of false alarms, there are adverse consequences. Depending on the situation, these will include infringement of civil liberties, financial losses, and undesirable responses on the part of both the victims and the perpetrators of the crime. For example, many people will be reluctant to leave an area if they have reason to suspect a false alarm. On the other hand, depending on their motivations, the perpetrators may very well be encouraged by over-reactions. The consequences of the opposite scenario, that is the possibility that the detector fails to alarm on an explosive, are disastrous and the safety of bomb investigators and the public should never be placed in jeopardy because of an unjustified reliance on any particular method of explosives detection.

2.3 Canine Detection of Explosives

An opinion expressed by many bomb investigators and technicians is that the most effective way to detect explosives is to use dogs which are specifically trained to respond to the presence of explosives. The mechanism by which dogs detect explosives has not been definitively established, but it is presumed that their acute sense of smell plays a major role. Some leading researchers in the field of explosives detection have argued that in some cases the dogs must be responding to the scent left by the person who planted the explosive rather than to the explosive itself [6]. This would explain why these dogs can detect the presence of a pipe bomb even when there are effectively no explosive vapors.

Whatever the mechanism is, dogs are sensitive explosives detectors. Dogs are more versatile than electronic detectors in that they are apparently able to detect a wider range of explosives. Claims about the success of canine explosives detectors range from about 70 percent [5] to 90 percent [1] depending on the source of the information. Perhaps the best testimonial to the ability of dogs to detect explosives is that the United States Secret Service routinely uses dogs to clear an area prior to a visit by the President and other dignitaries [15].

Despite the confidence that many bomb investigators place in their dogs, they do not provide a perfect solution to the problem of explosives detection. One of the most frequently cited problems with canine detectors is that training standards are not uniform, and as a result, there is a wide disparity in the abilities of these dogs to detect explosives [16]. The dogs used by the Secret Service are highly regarded, but they are constantly tested and reinforced by dedicated and experienced handlers. This is an extremely expensive proposition and most municipalities simply do not have the resources to maintain this level of training. As a consequence, the quality of many of the local canine explosives detection teams is compromised.

In addition to the expense involved in the maintenance of an effective team, dogs are also susceptible to fatigue, health related problems, and limitations imposed by physical characteristics. The fact that electronic devices are not affected by these conditions provides the basis for the belief that electronic detectors might be useful to complement dogs in the investigation of explosives.

3. EXPLOSIVES VAPOR DETECTION TECHNOLOGY

3.1 Principles of Detection

The detection of explosives is accomplished on the basis of concentration measurements involving a small number of characteristic compounds. Some of these characteristic compounds are ethylene glycol dinitrate (EGDN), pentaerythritol tetranitrate (PETN), and cyclotrimethylene trinitroamine (RDX). In fact, common explosives are actually complex mixtures consisting of an active explosive and a large number of structural materials and impurities. Analyses using gas chromatography have revealed the presence of about a hundred different compounds in samples of common explosive materials [17]. Some explosive fillers which are frequently encountered by law enforcement agents are listed along with their major components in table 1.

TABLE 1. *Compositions of some common explosive fillers*[a]

Explosive filler	*Major components*
Amatol	trinitrotoluene and ammonium nitrate
ANFO	ammonium nitrate and liquid hydrocarbons
C-4	cyclotrimethylene trinitroamine, polyisobutylene, motor oil, and di-(2-ethylhexyl) sebacate
dynamite[b]	nitroglycerine, sodium nitrate, carbonaceous material, nitrocellulose, and EGDN
black powder[b]	potassium nitrate, charcoal, and sulphur
smokeless powder[b]	nitrocellulose, nitroglycerine, and stabilizers

[a] Information taken from reference 29.

[b] There are many formulations in use.

3.1.1 Organonitrate Explosives

Many common explosives, including dynamite and plastic explosives, contain chemical compounds called organonitrates. This means that these compounds contain the chemical grouping, NO_2, covalently bonded to a carbon based molecule. Some additional examples of organonitrates present in explosives are nitroglycerine (NG), trinitrotoluene (TNT), and nitrocellulose (NC). The great majority of commercial explosives detectors are designed to respond to the presence of organonitrates.

Problems can arise when the quantity of explosives vapor is insufficient to elicit a measurable response, and because organonitrates, and related compounds, are also present in many nonexplosive substances. For this reason, no explosives detection device is perfect. There is always the possibility that it will fail to detect a specific type of explosive or that it will respond to a nonexplosive. The former occurrence is called a false negative and the latter is called a false positive.

3.1.2 The Mechanism of Explosives Vapor Detection

In principle, all substances, including organonitrate explosives, emit molecules in the form of a vapor at any temperature above absolute zero (−273 °C). These molecules move in all directions and eventually equilibrate throughout the enclosure to a vapor pressure which is characteristic of the substance. The value of this vapor pressure depends on the substance, and to a lesser extent, on the exact ambient temperature. As these molecules move about they can collide with anything in their path including other molecules and, what is more relevant to the present discussion, with the probe of an explosives detector. An explosive can only be detected if there are sufficient collisions to trigger a response. The number of collisions is proportional to the amount of explosive vapor in the atmosphere, which, in turn, is related to the vapor pressure of the explosive. The limit of detection of an explosives detector, which is usually expressed in concentration units (e.g., parts per billion),[3] is the minimum amount of an explosive which will elicit a measurable response. In principle, it is possible to improve the limit of detection by scanning over longer time periods. However, effective trade-offs between sensitivity and response time are often difficult, and sometimes impossible, to achieve in practical instrumentation.

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[3] Conventional U.S. terminology used throughout this report.

Unfortunately, explosives tend to have extremely low vapor pressures, corresponding to equilibrium concentrations ranging from about six parts per trillion (ppt) in RDX to 37 parts per million (ppm) in EGDN (table 2). This means that there will never be more than six RDX molecules in an average sample of a trillion molecules. EGDN is abundant by comparison but there are still only 37 EGDN molecules for every million molecules in the atmosphere. Furthermore, the actual concentrations of explosives vapor in the atmosphere of an enclosure depend strongly on external factors such as airflow and the material used to confine the explosive. These concentrations are usually only a small fraction of the corresponding vapor pressures. Pipe bombs, for example, which are constructed by encasing black or smokeless powder in a metal pipe, are difficult to detect because the metallic casing obstructs the outward flow of vapors. Air-conditioning and ventilation systems exacerbate this problem.

TABLE 2. *Equilibrium vapor phase concentrations of some compounds which characterize explosives*[a]

Compound	*Concentration (ppb)*
Ethylene Glycol Dinitrate (EGDN)	37,000[b]
Nitroglycerine (NG)	580[c]
Mono-nitrotoluene (MNT)	224[b]
Di-nitrotoluene (DNT)	184[b]
Ammonium Nitrite (AN)	12[c]
Trinitrotoluene (TNT)	9.4[c]
Pentaerythritol Tetranitrate (PETN)	0.018[c]
Cyclonite (RDX)	0.006[c]

[a] Concentrations obtained from the formula, 760=X(VP), where VP is the vapor pressure measured in millimeters of mercury and X is the mole fraction of the characteristic compound. The concentration in parts per billion is obtained by multiplying the mole fraction by 10^9 (one billion).

[b] Values obtained from reference 28.

[c] Reference 30.

3.2 Classifications of Detectors

There are four broad categories of explosives detectors. They are: biosensors, such as dogs and other trained animals; spectroscopic techniques, like infrared spectroscopy, laser photo acoustic measurements, and nuclear magnetic resonance; ionization devices which include nitrogen-phosphorous detectors, electron capture detectors, thermal neutron, ion mobility and mass spectrometers; and chemical methods including enzymatic reactions, immuno-responses, and chemiluminescence.

Prototype detection devices which fall into each of these classifications have been built and tested. The most significant progress in explosives vapor detection has been achieved with ionization based detection devices. For this reason, this report focuses on this methodology in general, and on electron capture detection and ion mobility spectrometry in particular, since these are the most affordable and available options at the present time.

3.2.1 Electron Capture and Nitrogen-Phosphorous Detectors

The common theme of ionization based detection is the presence of a source of ionizing radiation. In an electron capture detector (ECD) a radioactive foil is used to generate beta particles (fast moving electrons) which are slowed down in collisions with an inert carrier gas. These thermalized electrons are eventually captured by the analyte (explosive), which must have a high affinity for electrons, resulting in a measurable loss of current. The mechanism is slightly different in a nitrogen-phosphorous detector (NPD) where a source of thermal energy, commonly a flame or an electric arc, is used to remove electrons from (ionize) the nitrogen or phosphorous atoms present in the analyte (explosive). The current produced in this way is proportional to the concentration of the analyte.

Stand-alone ionization detectors do not usually exhibit a high degree of selectivity. As a result, electron capture and nitrogen-phosphorous detection devices are routinely coupled with gas chromatographs (GC) which are designed to filter out the interferents. A GC consists of a heated injection port emptying into a column which is coated with an adsorbent material (stationary phase). The analyte is transported through the column by an inert carrier gas. The operant principle is that compounds transported through a column by a carrier gas have different affinities for the stationary phase. The result is that components in a mixture can be separated on the basis of the amount of time required to traverse the length of the column (retention time).

Explosives detectors are calibrated electronically so that the operator is alerted when components elute from the chromatographic column with retention times which are characteristic of certain explosives. It is impossible to design a column with the ability to separate all of the components in any mixture. There is always the possibility that an innocuous compound will elute with the same retention time as an explosive, giving rise to a false positive. However, extremely effective columns can be designed when the identity of the target compounds and the nature of the mixtures are known in advance. For example, the composition, length, and temperature of the columns used in the Scintrex EVD-1 explosives detector have been chosen to achieve optimal selectivity and instrument response time for the detection of EGDN.

3.2.2 Detectors Based on Mass and Ion-Mobility Spectrometry

A variety of ionizing sources have been used in mass spectrometers (MS). Conventionally, these sources require a vacuum which makes sampling the ambient atmosphere for explosives or any other analyte impossible. Recent advances, however, have resulted in the development of atmospheric pressure ionization sources (APIS) [18].

An APIS is well-suited for use in both MS and ion mobility spectrometers (IMS). The usual source of ionization energy in an APIS is a beta emitter just as it is in an ECD. The beta particles, which are simply fast moving electrons, generate ions in collisions with an inert carrier gas, such as N_2. Once these ions are generated they become involved in a series of ion reactions resulting in the formation of the so-called reactive ions. These reactive ions, which typically involve protonated water and negatively charged oxygen, eventually impart a charge to the molecules present in the sample. In an MS these charged molecules or ions are separated by mass using a magnetic field, whereas in an IMS the ions are separated by their mobility in an electric field. A spectrum, which is a plot of the number of ions as a function of mass (MS) or mobility (IMS) can be measured and used to identify the sample components in much the same way as a fingerprint can be used to identify a person. The presence of an explosive is presumed when a mass or mobility spectrum which is characteristic of this explosive is observed. Component identifications obtained from MS and IMS detectors are usually more reliable than concentration measurements made with these instruments, whereas the reverse holds true for ECD and NPD detectors.

IMS detectors are highly selective and they are often used without chromatography. This is an important advantage because the chromatography is the time consuming step. IMS explosives detectors give an almost instantaneous response. It is also possible to circumvent the need for a GC in MS detectors by interfacing magnetic sectors. In a tandem MS (MS/MS) the first magnetic sector can be thought of as a filter which separates the sample components by mass in much the same way as a chromatographic column separates components by their affinities to the stationary phase. The difference is that this process is almost instantaneous. A definitive identification of the explosive is made from the spectrum which results from the interaction of the analyte with the second magnetic sector.

4. PERFORMANCE EVALUATIONS

4.1 Requirements of Detection Devices

The detection of hidden explosives is a challenging problem which makes stringent demands on the capabilities of explosives detectors. To be effective these devices must possess the combined characteristics of sophisticated laboratory instrumentation and reliable field equipment. Some of the attributes that an effective explosive detector should have are listed below.

1) *Sensitivity.* Many common explosives have exceedingly low vapor pressures. Therefore, explosives detectors must be capable of detecting infinitesimal concentrations of explosives vapor.

2) Selectivity. Explosives detectors must be capable of discriminating between actual explosives and the hundreds of innocuous compounds which are present in the atmosphere. Failure to meet standards of selectivity means that the detector will produce an inordinate number of false positives.

3) *The ability to detect a wide range of compounds.* No known detector is equally responsive to all compounds. However, to be useful a detector must demonstrate an acceptable level of sensitivity and selectivity for the large variety of explosives which are encountered in bomb investigations.

4) *A short response time.* A slow response is detrimental to effective search strategies. The most reliable way to use an explosives vapor detector is to perform a detailed point-by-point search of the entire enclosure. This is a major concern of bomb investigators and technicians who must complete the task of clearing an enclosure as quickly as possible.

5) *Ease of operation.* Clearly, any instrument must be used correctly to be effective. Easy to use explosives detectors have an advantage over more complicated instruments with similar capabilities. Looking for a bomb is a difficult and stressful activity, and investigators should not be burdened with unnecessarily complicated and temperamental instrumentation. A laboratory instrument, such as the PCP Phemto-Chem 100, is extremely effective, but it is not designed for the detection of explosives in the field. The fact that bomb investigators and technicians are highly trained, however, should not be overlooked. The requirements for certification in the United States include the successful completion of a 4-week training course given under the auspices of the Federal Bureau of Investigation. Explosives detectors must be sensitive as well as fieldworthy and performance standards should not be sacrificed in the misguided notion that simplicity of operation must be achieved at any cost.

6) *Affordability.* The so-called state of the art detection devices are prohibitively expensive both to purchase and to maintain. The price tags on instruments such as the Thermedics chemiluminescent detector (approximately $100,000) and the Sciex mobile mass spectrometer (on the order of $1 million) are simply out of the range of most local law enforcement agencies. Portable explosives detectors, such as the Graseby Dynamics PD5 or the Scintrex EVD-1, range in price from about $15,000 to $30,000.

7) *An ability to process large sample volumes.* By no means is it inevitable that the concentrations of explosives vapor will equilibrate throughout the enclosure. Rather, it is much more likely that the vapor will be localized in small pockets, the locations of which are determined by the origin of the vapor and the air circulation in the enclosure. A reliable detection strategy therefore, requires sampling a large area. This can be achieved by a point-by-point search strategy where the investigator moves the detector throughout the enclosure or by diverting the airflow into the detector so that the entire atmosphere can be analyzed. In either case, a large volume of sample must be processed.

4.2 Capabilities of Commercially Available Explosives Vapor Detectors

4.2.1 Overview

At the present time, there are about a dozen commercially available portable explosives vapor detection devices. A list of some of the models and their manufacturers are presented in tables 3 and 4. A summary of the capabilities of modern explosives detection devices, which are listed by detector classification, is given in table 5. The market for explosives detectors is extremely competitive and the capabilities of these devices have been strongly promoted by representatives of the companies selling them. Unfortunately, it is not a trivial matter to refute or validate these claims because there are no standards for the performance of explosives detectors or for the compositions of the explosives that they are supposed to detect.

TABLE 3. *A list of commercially available explosives detectors*[a]

Model	*Detector classification*	*Manufacturer*
Phemto-Chem 100	IMS[b]	PCP
PD5	IMS	Graseby Dynamics
Ultrateck	IMS	ION Track
LM 201	ECD	Leigh Marslan
SA 19	ECD	T. J. Sas and Son
ITI 97	GC/ECD	ION Track
GC-710	GC/ECD	Xonics
EVD-1	GC/ECD	Scintrex
Scanex Jr.	GC/ECD	Sentex
T-54	GC/ECD	XID

[a] Information obtained from references 4, 6, 9, and 10.

[b] This is a laboratory instrument, rather than a portable explosives detector.

TABLE 4. *Addresses of selected manufacturers of explosives detectors*

Manufacturer	*Address*
PCP	2155 Indian Rd., West Palm Beach, FL 33409
Graseby Dynamics	Park Ave., Bushey, Watford, Herts, England WD2 2BW
Ion Track Instruments	109 Terrace Hall Ave., Burlington, MA 01803
Xonics	6862 Hayvenhurst Ave., Van Nuys, CA 91406
Scintrex	222 Snidercroft Rd., Concord, Ontario, Canada L4K 1B5
Sentex	553 Broad Ave., Ridgefield, NJ 07657
XID	338 Delawanna Ave., Clifton, NJ 07014-1015
Thermedics	470 Wildwood St., Woburn, MA 01888-1799

TABLE 5. *Capabilities of explosives detectors*[a]

Detector classification[b]	*Limits of detection*	*Selectivity*	*Range of detection*	*Response time*	*Ease of operation*	*Cost ($K)*
ECD[c] (P)	1 ppb	poor	organonitrates	2 s	simple	≈15
GC/ECD[d] (P)	1 ppt	excellent	organonitrates	3 min	simple	≈30
IMS (D)	1 ppt	good	organonitrates	+2 s	difficult	≈40
IMS (P)	1 ppb	good	organonitrates	2 s	simple	≈15
MS/MS (D)	1 ppt	excellent	organonitrates	+20 s	difficult	100+
CD (D)	5 ppb[e]	good	organonitrates	20 s	difficult	100+

[a] Information obtained from references 6, 7, 9, 11, 20, 22, and 29.

[b] The symbols P and D are used to denote portable and dedicated detectors, respectively.

[c] ECD equipped with a semi-permeable membrane but no preconcentrator.

[d] ECD equipped with both a GC and a preconcentrator.

[e] This value was taken from reference 29 (p. 254). It is probably not representative of the capabilities of the Thermedics Egis II CD.

For example, suppose that an explosive detector correctly indicates the presence of C-4, a military plastic explosive, in a demonstration. The crucial question is will this instrument detect C-4 in the field? A positive response may be due to a contaminant in the explosive used in the demonstration, which is not present in all, or even most, plastic explosives (see appendix).

Most of the portable explosives detectors are about the size of a briefcase and they can be transported to the site of a bomb investigation without difficulty (see figs. 1 and 2). The conventional design of an ECD explosives detector, such as the EVD-1, consists of an analyzer and a hand held probe. Once a point-by-point search has begun, only the probe is moved. After a sample is collected in the probe it is injected into the analyzer and the analysis proceeds while another sample is being collected. The portable explosives detectors are characteristically easy to use and maintain. The Royal Canadian Mounted Police, which use the EVD-1 on a routine basis, have found that a training program is essential, but that a 1-week course is sufficient to ensure competence with these instruments [8].

The instruments which have been referred to in this report as dedicated explosives detectors are larger, to the extent that transporting them from headquarters to the scene of the investigation would be a difficult process. The Thermedics chemiluminescent detector, which weighs hundreds of pounds, is transported in a specially designed cart. The MS/MS unit developed at Oak Ridge National Laboratory and the Phemto-Chem 100 have similar transportation needs. Despite this problem, these devices can be equipped with hand held probes, and at least in principle, used in the same way as the portable explosives detectors once they are on site. Although dedicated explosives detectors generally have greater capabilities than portable units, the cost of these instruments is an overriding consideration. The dedicated explosives detectors are expensive to purchase. They are also complicated to use and must be serviced and maintained by trained technicians. These factors would appear to preclude a strong interest from local law enforcement agencies. Further references to these instruments are included for the purpose of defining the state of the art and to illustrate future directions in explosives detection technology.

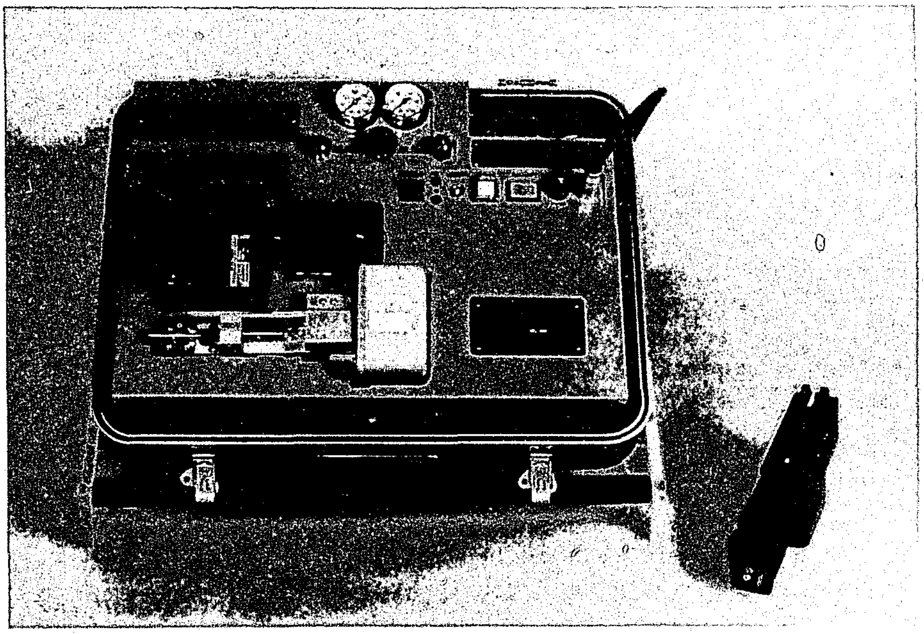

Figure 1. *Photograph of the Scintrex EVD-1 explosives detector. Note the detachable probe in the lower right hand corner.*

Figure 2. *Photograph of the Graseby PD5 explosives detector.*

All of the portable instruments are variations of either ECD or IMS detectors. These instruments are very effective in detecting nitro-based dynamite—an explosive which is frequently used in illegal incidents. A series of performance tests involving four commercially available explosives detectors were recently conducted by the Forensic Science Research and Training Center at the FBI Academy in Quantico, Virginia [4].

The Ion Track Model 97, Scintrex EVD-1, and Graseby PD5 completed the entire evaluation without instrumental failure. Each of these detectors correctly indicated the presence of dynamite which was concealed in briefcases, luggage, a hotel room, and the trunk of a car. In addition, both the Model 97 and the EVD-1 alarmed on a briefcase containing TNT. The Sentex Scanex Jr., which is also distributed by XID corporation as the Model T-54, was withdrawn by the manufacturer before the completion of the evaluations due to a malfunction.

The portable ECD explosives detectors have the potential to detect EGDN, NG, dinitrotoluene (DNT), and perhaps even TNT [4,6,11]. However, despite claims to the contrary, it is unlikely that any of the commercially available portable detectors is useful in detecting black powder, which was the second most frequently used filler in explosives incidents which occurred in the years between 1977 through 1986 [1]. Existing portable units are also ineffective in detecting flammable liquids (which were cited as the most frequently used explosive filler), ammonium nitrate (which is the active component in ANFO, ammonium nitrate and fuel oil), PETN, and RDX, the active compound in C-4 and other plastic explosives.

The reason that most commercial detectors do not respond to flammable liquids, such as kerosene and gasoline, is because these substances do not contain any organonitrates. Although both RDX and PETN are organonitrates, they have extremely low vapor pressures and the inexpensive portable units simply do not have the sensitivity to detect such minute concentrations of vapor. The active explosive in black powder is potassium nitrate, which like ammonium nitrate, is a nitrate salt. Nitrate salts contain nitrogen and oxygen just as the organonitrates do, but it is in the form of the inorganic nitrate ion NO_3^-, rather than as NO_2. This structural variation results in a completely different set of chemical properties so that the commercial explosives detectors, which are designed to give a specific response to organonitrates, are not effective in detecting nitrate salts.

4.2.2 Portable Electron Capture Explosives Detectors

ECD portable explosives detectors come in two variants. The so-called real-time analyzers which make use of a membrane which is permeable to the analyte but which excludes oxygen (which interferes with the operation of an ECD) and batch analyzers where the ECD is preceded by a GC (GC/ECD). The advantage of using a semi-permeable membrane rather than a GC is that this permits an instantaneous or a real-time response. The disadvantage is a drastic reduction in selectivity. An ECD is an extremely sensitive detector but it will respond to almost any compound that has an affinity for electrons. Without a GC, there is no way to distinguish organonitrate explosives from innocuous compounds which contain hydroxy or halogen functionalities that also have a propensity for electron capture. According to Elias of the National Research Council Canada, who along with others conducted extensive field trials at Montreal International Airport, the use of real-time ECD devices is of "little more than marginal value" in detecting hidden explosives [14].

GC/ECD explosives detectors are much more selective, and Elias found that they were useful in revealing bombs which were overlooked in visual/hand searches [14]. Indeed, it is quite possible that these devices are a little too selective. The EVD-1 explosives detector, which we believe to be representative of the entire class of GC/ECD explosives detectors, is only programmed to detect EGDN, DNT, and ethylene glycol mononitrate (EGMN). A block diagram depicting the functional regions of the EVD-1 explosives detector is presented in figure 3.

Despite the narrow range of compounds that it can detect, the EVD-1 is generally considered to be among the best of the commercially available explosives detectors. In fact, it is presently being used at all of the major international airports in Canada. The Royal Canadian Mounted Police have carried out extensive laboratory evaluations of the EVD-1 and it has met their performance requirements. Royal Canadian Mounted Police scientists did not encounter a single false positive even though they tested more than 70 substances for potential interference [8]. The EVD-1 is sensitive to EGDN at concentrations approaching 1 ppt [7,14]. This value is probably a little better than other GC/ECD explosives detectors, and is at least as good as some of the more expensive dedicated instruments. This exceptional sensitivity is due in part to the presence of continuous action preconcentrator (CAP) in the probe which selectively adsorbs EGDN vapor.

The limited range of detection exhibited by the EVD-1 and related instruments, means that they are prone to false negatives. This deficiency is to some extent mitigated by the fact that many explosives manufactured in the United States and Canada contain EGDN as an impurity [6,8]. The ubiquity of this substance is probably the source of the positive responses to RDX and PETN that Linenberg [9] and others have observed with ECD explosives detectors.

Another drawback of the GC/ECD class of explosives detectors is their relatively long response time. It requires about 3 min to collect and analyze a sample with the EVD-1. This is a major concern for bomb investigators who claim that a thorough point-by-point search of a hotel suite could take hours to complete using a GC/ECD detector, whereas a search team with two dogs can clear the same suite in less than 30 min [3].

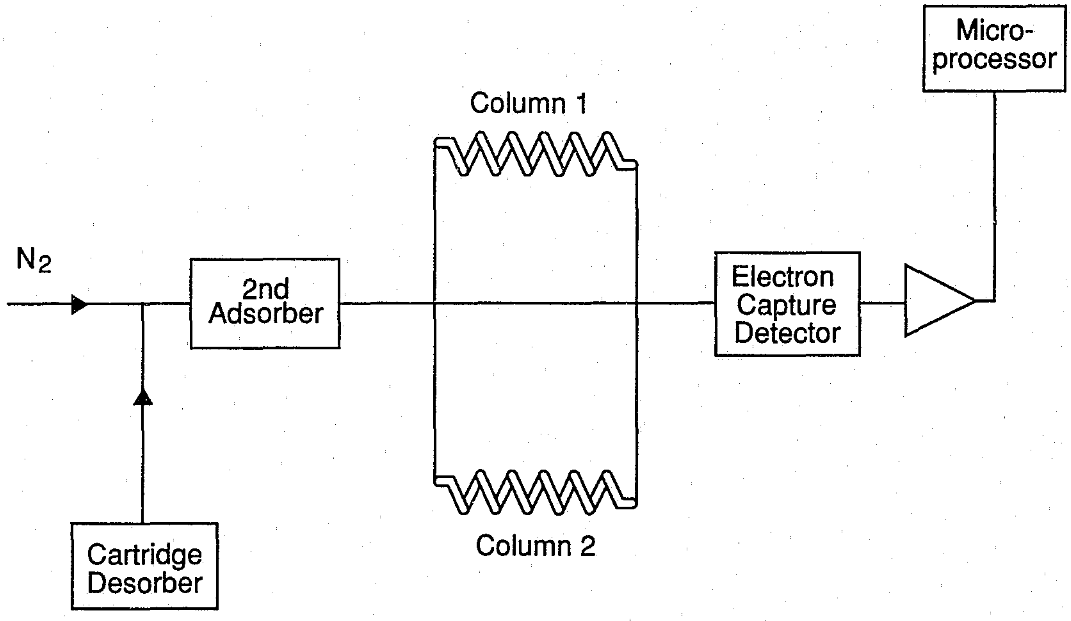

FIGURE 3. *A diagram of the functional regions of the EVD-1 (taken from reference 4). The dual-column design facilitates the reproducible retention time measurements by referencing all sample retention times to the amount of time that it requires the carrier gas to traverse the reference column.*

Elias has pointed out that there are some situations when the long response time of GC/ECD detectors is not a serious deficiency because the time required to perform an analysis does not increase in proportion to the volume of the sample. Elias and his coworkers have conducted field tests which involved analyzing the large volumes of cabin air which were exhausted from the air conditioning systems of passenger jets [5,14]. Based on these tests, they estimated that there is a 20–40 percent probability of detecting concealed explosives in an airplane by sampling the cabin air exhaust at the dump valve with currently available GC/ECD detectors. This is a much poorer success rate than the 50–70 percent which they estimated for point-by-point searches with the same detectors, but it takes significantly less time. The entire atmosphere of the cabin is analyzed by processing a small number of representative samples. There will always be some trade-off between reliability and response time; however, this compromise will become more attractive as more sensitive detectors are made available.

4.2.3 Portable Ion-Mobility Explosives Detectors

Portable IMS detectors are a fairly recent invention and they have not yet permeated the market to the extent that ECD detectors have. Only Graseby Dynamics and Ion Track Instruments are presently producing portable IMS detectors. However, this situation is likely to change in the immediate future. Science Applications International Corporation, which already is under contract with the Federal Aviation Administration to develop five fixed installation TNA explosives detectors, has expressed a strong interest in developing a portable IMS explosives detector.

Although they are less sensitive than ECD detectors, IMS detectors can be used without a GC and have an almost instantaneous response (2–3 s). A block diagram of the Graseby PD5 is given in figure 4. The PD5, which has a minimum detectable concentration of EGDN of about one part per billion (ppb) [6,7], is an example of a commercially available portable IMS unit. The experimentally determined detection limit of this instrument with respect to EGDN, suggests a range of detectability which is limited to those organonitrate explosives having vapor pressures which exceed 1 ppb. Although a stand-alone IMS detector is more selective than the comparable ECD, the stand-alone IMS is probably less selective than is a typical GC/ECD detector. Thus, portable IMS units such as the PD5 may sacrifice a degree of selectivity for an instantaneous response.

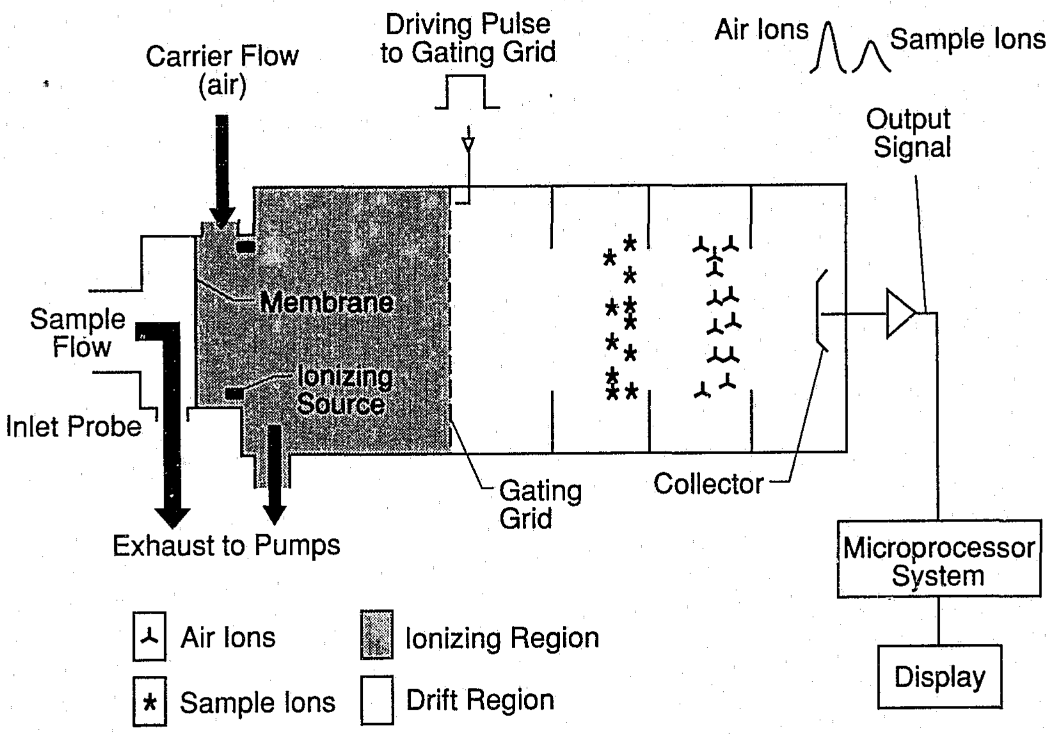

FIGURE 4. *A diagram of the PD5 (taken from reference 4) depicting the reaction zone where the sample acquires a negative charge and the drift region where the mobilities of the resulting ions are measured by time of flight.*

Portable explosives detectors, as exemplified by the PD5 and EVD-1, are effective in the detection of a limited range of organonitrate explosives. On the basis of the results obtained from field tests conducted at the Montreal and Ottawa airports, Seman and coworkers concluded that the find-rate for explosives hidden in airplanes could be significantly improved by using portable explosives detectors to backup visual/hand and canine searches [5]. These results, however, do not warrant the exclusive use of portable explosives detectors. These devices are efficacious only when they are used to complement visual/hand and canine searches.

5. NEW DIRECTIONS IN EXPLOSIVES DETECTION

5.1 The Near Future

There are considerable research efforts in explosives detection in many countries including the United States, Canada, Israel, and the United Kingdom. Noteworthy accomplishments in North America have been made at Sandia and Oak Ridge National Laboratories in the United States and at the National Research Council Canada.

At Sandia, researchers have developed a great deal of expertise with IMS detectors in general and the Phemto-Chem 100 IMS in particular. The difference between this instrument and portable IMS explosives detectors is the flexibility that the analyst has in adjusting the conditions which are relevant to the analysis. In the laboratory instrument, inlet and reaction cell temperatures as well as the magnitude and polarity of the electric field can be optimized for the detection of specific explosives [19]. The operator of a portable IMS explosives detector, such as the PD5, has no control over these variables. Frank Conrad and his coworkers at Sandia, have already demonstrated that in addition to EGDN, NG, and TNT, the Phemto-Chem 100 can also detect RDX and PETN vapors [20]. This suggests that portable IMS explosives detectors with parts per trillion sensitivity may be available in the near future. Conrad's group is now actively involved in the development of a compact IMS detector which can be used to screen humans for explosives upon boarding aircraft or upon entering other secured facilities.

At Oak Ridge National Laboratory another research group has designed and built a tandem mass spectrometer for explosives detection [21]. In principle, multisector mass spectrometry is the preferred technique for achieving a broad range of detectability and a maximum degree of selectivity.

The Oak Ridge MS/MS explosives detector was recently subjected to rigorous performance testing at Sandia National Laboratories. The limit of detection of this instrument was determined to be in the range of

1 ppt of organonitrate vapor [22]. In this regard, however, it should be noted that this instrument must be serviced and maintained by trained personnel in order to ensure optimal performance. A simple disruption such as a power failure can adversely affect the sensitivity of this instrument to the point where it can no longer detect RDX [23]. At the present time, optimal performance of this instrument requires a degree of vigilance beyond what is considered reasonable for a field instrument.

The Oak Ridge group is presently building a prototype explosives detector based on an ion-trap MS, which in principle, should be even more selective than the tandem MS. In this technique, a gaseous sample is ionized in a cavity where it is exposed to a magnetic field. The geometry of the cavity is such that for a fixed magnetic field strength, only ions having a specific ratio of mass to charge can escape to the detector. The magnetic field strength is varied by design to permit the sequential passage of ions, creating in effect, a series of mass filters. In principle, each of these filters enhances the selectivity of the analysis in the same way that the presence of additional magnetic sectors improves the selectivity of tandem MS. The Oak Ridge group expects to have an operational instrument in the next couple of years.

The research group headed by Lorne Elias at the National Research Council Canada has made many contributions to the field of explosives detection, including the development of the EVD-1 explosives detector. One of their priorities is to find methods to reduce the response time of GC/ECD explosives detectors. Elias thinks that progress in the design of more efficient columns for the chromatographic analysis of explosives will result in the development of a GC/ECD detector with a response time of less than a minute.

A related achievement has already been claimed by scientists working on the Thermedics Egis II chemiluminescent explosives detector. This explosives detector, which is assumed to use some type of separation technique, is claimed to have a response time of less than 20 s for organonitrate explosives [24,25]. At the present time, however, performance claims made by representatives of the manufacturer (Thermedics) have not been demonstrated to the satisfaction of many workers in the field of explosives detection.

Elias' group at the National Research Council Canada is also investigating the performance characteristics of the continuous action preconcentrator (CAP). There are indications that the full potential of the CAP device has not yet been realized. Based on these considerations, Elias thinks that there is the potential for at least an order of magnitude improvement in the sensitivity of GC/ECD detectors. The record of past accomplishments by this research group provides a strong basis for the belief that a GC/ECD which can respond to sub-ppt concentrations of explosives vapor in less than a minute will be available in the near future.

5.2 Long-Range Perspectives

The Thermedics, Phemto-Chem 100, and Oak Ridge explosives detectors represent the present state of the art in explosives detection. For the time being, however, the expense involved in purchasing, maintaining, and operating this equipment makes these instruments viable only for use as dedicated detectors at airports and other large facilities.

There is reason to question whether these instruments would be capable of meeting the needs of local law enforcement operations even if they were both easy to use and affordable. Computer models developed by Thomas Griffey, have indicated that actual concentrations of explosives vapor in an enclosure may be significantly lower than previously expected. Predictions from Griffey's models indicate that, despite the presence of few regions of relatively high concentrations, the average level of explosives vapor in a typical enclosure is on the order of 10^{-3} times the equilibrium vapor pressure of the explosive [26]. The same calculations suggest that even these minute pressures are not attained until after the substance has coated the walls of the enclosure—a process which takes many hours to complete. With this in mind, it is not difficult to think of scenarios that would overwhelm the capabilities of any existing explosives detection device. Suppose for example, that the airflow is away from the detector, and that the explosive is encased in metal, and that there has not been sufficient time for the explosive vapor to equilibrate; in this situation a bomb would probably not be detected even by the most sensitive detector. It may become necessary to examine entirely new lines of research before there is significant progress in solving the more intractable problems of explosives detection.

5.2.1 The Use of Artificial Intelligence in Explosives Detection

The studies conducted by Elias and his coworkers have indicated that explosives detectors are not effective unless they are used in conjunction with a visual/hand search conducted by trained personnel [5,14]. This observation suggests that the search strategy is an important facet of explosives detection. Past research efforts have concentrated on improving sensitivity and decreasing response time. The possibility of developing computerized search strategies has been overlooked, although there have been some developments in related areas. The bomb squad in New York City, for example, already uses programmed robots to assist in the disarming of explosives [27], and the Thermedics chemiluminescent explosive detector uses a computer program to determine optimal sampling conditions [25].

No attempt, however, has been made to design a computerized detector which uses artificial intelligence to direct the search for explosives. A computer program of this type, which is often referred to as an expert system, might utilize a site-specific database containing a list of probable hiding places determined from past experiences and information about the airflow and the building ventilation system. As the computer directed search proceeds, a concentration versus location map could be updated and a mathematical algorithm used to determine the exact position of the maximum in the explosives concentration.

Introducing this type of capability into existing explosives detection devices is not necessarily a difficult task. The required hardware which includes serial ports, an analog to digital converter (ADC), and a microcomputer are commonplace. Of course, different classes of detectors are not equally well suited to this type modification. Two essential characteristics are a short response time and the ability to analyze large volumes of sample.

5.2.2 Computer Directed Fourier Transform Infrared Explosives Detection

Artificial intelligence can be further exploited by utilizing the appropriate analytical instrumentation. Thus for example, a more sophisticated expert system could be integrated with a Fourier transform infrared spectrometer (FTIR) so that the infrared radiation is focused on the probable hiding places of explosives. Any explosives material which is in the line-of-site of the infrared beam will selectively absorb the incident infrared radiation over a wide range of frequencies, thus giving rise to a characteristic spectrum.

In addition to a line-of-site detector, an FTIR would make it possible to sample an entire room for explosives in a single pass by filling the enclosure with infrared radiation. In this way, the enclosure itself becomes the sample cell. This idea is similar in spirit to that whole-cabin sampling strategy pioneered by Elias, but it is not limited to enclosures with controlled airflows. Indeed, there is no way to implement this strategy with instrumentation based on electron capture detection, mass spectrometry, or ion mobility spectrometry. There is a significant sacrifice in sensitivity which would result from using an FTIR rather than an MS or IMS detector, but it is possible that this deficiency may be more than compensated for by the increase in search effectiveness which results from directing the detector to the analyte rather than the more conventional strategy of bringing the sample to the detector.

6. CONCLUSIONS

The illegal use of explosives is a widespread problem. There is a definite need for reliable and inexpensive instruments which can be used by local law enforcement agents to detect explosives in the field. The present generation of portable electronic explosives detectors, however, can only detect a limited range of organonitrate explosives which include ethylene glycol dinitrate, nitroglycerin, and in some cases, trinitrotoluene. These instruments are not sensitive or versatile enough to detect inorganic nitrate explosives or the lower vapor pressure organonitrate explosives consistently. In practice this means that the portable detectors are useful for indicating the presence of dynamite but they will most likely fail to alarm on pipe bombs and plastic explosives. On this basis, we conclude that at the present time, commercially available portable explosives detectors do not have the capabilities to supplant canine and visual/hand searches as the primary methods of explosives detection.

On the other hand, studies have indicated that portable electronic explosives vapor detectors do improve the efficiency of canine and visual/hand searches for concealed explosives. This equipment can be effectively used for the corroboration and identification of suspected explosives and to search areas which are inaccessible to canines. Local law enforcement agencies which have professionally-staffed bomb investigation units should consider the possibility of employing explosives vapor detectors in their investigations.

Confusion regarding the performance capabilities of portable explosives detectors has served to undermine the widespread acceptance of these devices. Bomb investigators and technicians are understandably reluctant to use equipment which has not been subjected to uniform evaluations conducted by an impartial organization. The development of performance standards for explosives detectors and standard reference materials for explosives would do much to improve this situation. The instruments which have been referred to in this report as dedicated explosives detectors have greater capabilities than their portable counterparts. However, they are expensive to purchase and difficult to transport to the site of an investigation. In addition, these instruments tend to be very complicated, and consequently, they are both difficult to operate and to maintain.

Technological advances leading to improvements in the sensitivity and response time of explosives detectors are occurring at a rapid rate. This bodes well for the future and it would be prudent of bomb investigators and technicians to begin the process of familiarizing themselves with this equipment. Much of the current research effort, however, is directed to the development of dedicated explosives detectors which are not designed to solve the problems encountered by local law enforcement units. This emphasis is likely to change as bomb investigators and technicians begin to take a more active interest in the electronic detection of explosives.

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APPENDIX—HOW TO EVALUATE A PORTABLE EXPLOSIVES DETECTOR

The effective evaluation of an explosive detector requires a strategy which is based on an understanding of the properties of explosives and the general capabilities of explosives detection devices. The limitations of portable explosives detectors, which have been recounted in the body of this report, should not be overlooked when evaluating specific models. Claims of positive responses to RDX, PETN, and black powder should be regarded with skepticism and should not be accepted in lieu of a more thorough investigation. It is quite likely that an apparent positive response to these compounds is due to contamination of the test explosives or of the explosive detector itself.

Organonitrate explosives are polar molecules. This means that there are regions of positive and negative charges in the molecule. In effect, the polarity of these molecules makes them stick to each other and to other polar materials. It is not surprising therefore, that cross-contamination is a problem whenever explosives are stored in close proximity. This is particularly true if dynamite containing EGDN is present. The high volatility of EGDN relative to other explosives, makes it mobile in air currents which exacerbates the problem. The use of cross-contaminated explosives introduces an unacceptable level of ambiguity into performance evaluations of explosives detectors and should be avoided whenever possible.

Contamination can also affect the detector itself. Residual organonitrates from previous use can trigger inappropriate detector responses. These can include false positives, as well as false negatives resulting from detector saturation and a concomitant loss of sensitivity.

On this basis, we offer the following specific recommendations:

1) Performance tests should be conducted by the people who are expected to use them. Portable explosives detectors are easy to use so that law enforcement personnel should be able to master operating procedures after a brief demonstration by the manufacturer's representative. Law enforcement agents should not be satisfied with orchestrated demonstrations of the capabilities of explosives detectors.
2) Use test explosives with a known storage history. Do not cross-contaminate explosives even to the extent of placing supposedly sealed explosives in the same bunker. In this regard it should be noted that in the recent evaluations conducted at the Forensic Science Research and Training Center, investigators found that a single stick of dynamite produced enough vapor in an hour to be detectable by an EVD-1 explosives detector anywhere within a three-story 42,000 square foot laboratory facility [4].
3) Tests should be made under controlled laboratory conditions and, if possible, in simulated field trials involving concealed explosives.
4) Do not allow the probe of the detector to come into physical contact with bulk explosives. Rather, point the probe in a direction where it is likely to get a "sniff" of the vapor. If contact with the bulk sample is made micro-particulates or drops may enter and saturate the detector rendering it ineffective until it is cleaned. A thorough evaluation, however, might include a deliberate attempt to saturate the detector in an effort to determine the propensity of the particular model to this type of contamination. This experiment should be deferred until the end of the evaluation for obvious reasons.
5) The detector should be cleared after a positive response by taking a sample of uncontaminated air and verifying that the measured response returns to the baseline value.
6) Test for false positives by sampling a wide range of commonplace interferents. These might include perfumes, alcohol, chlorinated solvents, and gasoline.