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Law Enforcement and Corrections Standards and Testing Program

Guide for the Selection of Commercial Explosives Detection Systems for Law Enforcement Applications

NIJ Guide 100-99

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FOREWORD

The Office of Law Enforcement Standards (OLES) 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. OLES's function is to conduct research that will assist law enforcement and criminal justice agencies in the selection and procurement of quality equipment.

OLES is: (1) Subjecting existing equipment to laboratory testing and evaluation, and (2) conducting research leading to the development of several series of documents, including national standards, user guides, and technical reports.

This document covers research conducted by OLES under the sponsorship of the National Institute of Justice. Additional reports as well as other documents are being issued under the OLES program in the areas of protective clothing and equipment, communications systems, emergency equipment, investigative aids, security systems, vehicles, weapons, and analytical techniques and standard reference materials used by the forensic community.

Technical comments and suggestions concerning this report are invited from all interested parties. They may be addressed to the Office of Law Enforcement Standards, National Institute of Standards and Technology, 100 Bureau Drive, Stop 8102, Gaithersburg, MD 20899-8102.

David G. Boyd, Director
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COMMONLY USED SYMBOLS AND ABBREVIATIONS

A	ampere	H	henry	nm	nanometer
ac	alternating current	h	hour	No.	number
AM	amplitude modulation	hf	high frequency	o.d.	outside diameter
cd	candela	Hz	hertz	Ω	ohm
cm	centimeter	i.d.	inside diameter	p.	page
CP	chemically pure	in	inch	Pa	pascal
c/s	cycle per second	IR	infrared	pe	probable error
d	day	J	joule	pp.	pages
dB	decibel	L	lambert	ppm	parts per million
dc	direct current	L	liter	qt	quart
C	degree Celsius	lb	pound	rad	radian
F	degree Fahrenheit	lbf	pound-force	rf	radio frequency
dia	diameter	lbf·in	pound-force inch	rh	relative humidity
emf	electromotive force	lm	lumen	s	second
eq	equation	ln	logarithm (base e)	SD	standard deviation
F	farad	log	logarithm (base 10)	sec.	section
fc	footcandle	M	molar	SWR	standing wave ratio
fig.	figure	m	meter	uhf	ultrahigh frequency
FM	frequency modulation	min	minute	UV	ultraviolet
ft	foot	mm	millimeter	V	volt
ft/s	foot per second	mph	miles per hour	vhf	very high frequency
g	acceleration	m/s	meter per second	W	watt
g	gram	N	newton	λ	wavelength
gr	grain	N·m	newton meter	wt	weight

area=unit^2 (e.g., ft^2, in^2, etc.); volume=unit^3 (e.g., ft^3, m^3, etc.)

PREFIXES

d	deci (10^{-1})	da	deka (10)
c	centi (10^{-2})	h	hecto (10^{2})
m	milli (10^{-3})	k	kilo (10^{3})
µ	micro (10^{-6})	M	mega (10^{6})
n	nano (10^{-9})	G	giga (10^{9})
p	pico (10^{-12})	T	tera (10^{12})

COMMON CONVERSIONS (See ASTM E380)

0.30480 m =1ft
2.54 cm = 1 in
0.4535924 kg = 1 lb
0.06479891g = 1gr
0.9463529 L = 1 qt
3600000 J = 1 kW·hr

4.448222 N = lbf
1.355818 J =1 ft·lbf
0.1129848 N m = lbf·in
14.59390 N/m =1 lbf/ft
6894.757 Pa = 1 lbf/in^2
1.609344 km/h = mph

Temperature: T● $_C$ = (T● $_F$ 32)×5/9
Temperature: T● $_F$ = (T● $_C$ ×9/5)+32

GUIDE FOR THE SELECTION OF COMMERCIAL EXPLOSIVES DETECTION SYSTEMS FOR LAW ENFORCEMENT APPLICATIONS[*]

This document includes a variety of information that is intended to be useful to the law enforcement community in the selection of explosives detection techniques and equipment for different applications. It includes a thorough market survey of all trace and x-ray based commercial detection systems known to the authors as of October 1998, including company contact information along with data on each system's cost, size, and uses. Information is also included on some additional novel detection technologies, and on such standard techniques as canine and physical search. Brief technical discussions are presented that consider the principles of operation of the various technologies. These may be ignored by readers who find them too technical, while those wanting additional technical information can obtain it from the extensive list of references that is included as an appendix. Other sections of the document present matrices listing the most highly recommended detection techniques for a variety of scenarios, a list of desirable characteristics for explosives detection equipment for law enforcement work with charts rating commercial systems against these criteria, and a standard test protocol for the evaluation of trace detection equipment. In addition to a reference list, the appendices include a section providing basic information about different types of explosives and explosions. Any law enforcement personnel having comments or questions are encouraged to contact the authors at Sandia National Laboratories.

1. INTRODUCTION

The primary purpose of this document is to provide law enforcement agencies with information that should aid them in the selection and utilization of explosives detection equipment. The document is thus more practical than technical, emphasizing advice about the capabilities of different technologies, and what technologies are likely to work best in various applications. A wide variety of factors are considered that may be important to purchasers of detection equipment, including cost, sensitivity, portability, ease of use, etc. Some technical information is included in sections describing how the various detection technologies work, but the level of detail is not great. Readers finding this material too technical can skip it while still making use of the rest of the document, and readers desiring more technical detail can obtain it from the suggested readings in Appendix A-1.

The remainder of this document is divided into several sections as follows:

Section 2 presents a market survey of currently available explosives detection equipment. In tables 4 and 6, specific information is listed on 26 trace detection systems and 90 x-ray based detection systems. To the knowledge of the authors, this information is complete as of October 1998. The information in these tables includes the type of detector or detection technology used in each system, cost, recommended uses, system size and weight, and vendor contact information. In the case of x-ray based systems, the cost information can only be approximate, because most vendors are hesitant to quote a specific price for these (usually expensive) systems. The table on trace detection systems also includes sensitivity information as provided by the manufacturer, *but it must be remembered that this information comes from the manufacturer and*

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[*] Inclusion of specific technologies in this document is not an endorsement by the authors or by Sandia National Laboratories. This document includes detectors known to the authors as of October 1998. Some technologies may not be included in the text due to oversight by the authors. Some detector characteristics described are not fully quantifiable, and in such cases, comparisons between detectors are necessarily subjective.

is not based on independent tests by a third party. Some independent test data exist for a few systems, and in the experience of the authors, the claims made by the manufacturers are usually not out of line with the system's true performance. However, all independent test results known to the authors are either classified or unclassified controlled nuclear information, so these results are not included in this document, which is intended for public release. Parties interested in what independent test data exist should contact the authors. Also included in section 2 are definitions of commonly used terms such as throughput rate and portability, a discussion of explosive vapor pressures and the issue of vapor sampling versus swipe (particulate) sampling in trace detection, and information on how the different trace and x-ray systems operate and what their general capabilities are. Finally, other techniques are discussed, including canine detection (already familiar to most law enforcement agencies, for drugs if not for explosives) and a few novel (though usually expensive and not always fully developed) detection technologies that have appeared in recent years.

Section 3 presents three matrices that give recommendations about what technologies and systems to use for a variety of applications. These matrices provide a quick reference point for anyone having a specific application in mind, and wanting to know what sort of detection system he or she should consider purchasing. Five factors are included in defining the applications in these matrices: system portability, presence or absence of an explosives background in the area where screening will be performed, throughput rate, the type of item to be screened (people, packages, vehicles, etc.), and system cost. As a general rule, these matrices do not point to a single system or technique that is considered "best" in each circumstance, but rather point to several options that may meet the user's needs. Needless to say, in some cases there may be several detection systems that can do the desired job, while under other circumstances there may be no system that does everything the potential purchaser would like it to do. The latter is unfortunately most often true when severe cost restraints are placed on the system to be purchased, as is usually the case in this era of rapidly advancing technology but extremely limited budgets for technology in law enforcement. It must be stressed that the matrices in section 3 are intended to point the reader in the right direction, and they are a starting point rather than a solution in choosing a detection system. They are not a substitute for detailed discussions with both the vendor(s) and a knowledgeable third party.

Section 4 discusses various characteristics and performance parameters that could be used to judge both trace and x-ray based detection systems, and defines ideal and nominal capabilities or characteristics for these systems. Defining these parameters is to some degree arbitrary since the "ideal" will of course depend upon the specific application. The definitions used are based on the best judgment of the authors and some feedback received from several law enforcement agencies, *but it is really up to each potential purchaser to determine what the requirements are for his or her application.* Tables 10 and 11 rate various commercial detection systems as ideal, nominal, or subnominal for the different parameters considered, and this allows the reader to focus on those parameters that are most important to him/her and to make rapid comparisons. Once again, these tables serve as a starting point for obtaining information and should supplement but not replace detailed discussions with the vendor(s) and outside experts.

Section 5 briefly discusses the issue of system calibration. Since calibration is very system specific, little can be said in general about this topic. The best advice is to discuss the calibration procedure thoroughly with the vendor of the equipment, and if possible learn it hands-on from the vendor at an onsite installation and training visit.

Section 6 provides a protocol for the testing and evaluation of trace detection systems. Such testing is also rather system specific, but this protocol has been made as generic as possible. The protocol should be of interest to users wanting to determine performance parameters for the specific unit they have purchased, and to those wanting to monitor the performance of the system over an extended period of time. The protocol also includes some basic information about sampling, ensuring a detector is free of contamination, etc. For some users in the law enforcement community, the protocol may be of little interest, and these users can skip section 6 without losing any content that is crucial to understanding the rest of the document.

Section 7 contains a brief warning about buying equipment that may not be based on sound scientific principles. Briefly stated, detectors that appear to make unprecedented claims about detection capabilities *may* be based on faulty science, and in extreme cases could prove to be fraudulent. When dealing with technologies that appear to be new and report exciting new capabilities, it is especially important to discuss the purchase with an outside expert before making a final decision.

Section 8 provides a brief summary and conclusions section.

Appendix A-1 provides a list of suggested readings relating to the topic of explosives detection.

Appendix A-2 provides a glossary of terms used in explosives detection, many of which may not be familiar to the average reader.

Finally, Appendix A-3 contains an introduction to different types of explosives, their uses, and their properties.

Any law enforcement agencies desiring more information about this document or explosives detection in general are invited to contact the authors[1] of this document. The contact points are as follows:

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2. MARKET SURVEY OF COMMERCIALLY AVAILABLE EXPLOSIVES DETECTION EQUIPMENT

In this section four different divisions of explosive detection technology are discussed. Covered in the greatest detail are (1) trace detection technologies and (2) x-ray based detection systems, since these are by far the most widely developed technologies. Canine detection, which is really a form of trace detection already very familiar to most law enforcement agencies, is discussed more briefly. Finally, some novel detection technologies are briefly discussed. Most of these novel technologies are not fully commercially developed, but they are mentioned here for the sake of completeness. Readers should note that they might become more readily available and also cheaper in the near future.

Before the specific technologies are discussed, four key characteristics that help describe explosive detection systems and applications are defined and addressed. These characteristics are portability, the type of item being screened, system cost, and throughput rate. Some of this material is covered further in section 4, but a brief introduction is necessary at this point.

2.1 Portability

Portability simply refers to the ease with which a detection system can be moved from one location to another. Depending on the application, portability may or may not be important. If a system needs to be carried by a detective who is screening a room for explosives, portability is clearly important. On the other hand, if it is only to be used as a dedicated system for screening people at a single entrance to a courthouse, portability is not important. In general, systems are divided into three categories: portable, semiportable, and fixed site. A system is considered portable if it weighs less than 9.1 kg (20 lb) and can be easily carried by one person (or, in the case of a canine, led by one person). It is considered semiportable if it does not meet these definitions, but can be moved easily by two people, fit in no more than two boxes, and be easily stored in the trunk of a police car. Systems that are too large or too heavy to meet the definition of semiportable are considered fixed-site systems. These can be very large and heavy, and include personnel portals and many baggage screening systems.

2.2 Type of Item Being Screened

Explosives detection can be used in a variety of applications. Two major categories are search applications and screening of individual items. Search applications involve situations where a bomb is suspected of being in a general area, but the exact location is unknown. This would include, for example, searching a building or property grounds for a bomb, once a bomb threat has been communicated. In most search applications, canine detection will be the detection method of choice because of the dog’s rapid mobility and its ability to follow the scent to its source.

For screening of individual items, a wide variety of technologies can be useful in different situations. In general, the type of item screened will fall into one of four categories: people, hand-carried items, mailed or shipped items, and vehicles. Personnel screening involves detecting bombs or explosive material that is usually hidden under clothing. It can occur in many circumstances, ranging from suspect apprehension to screening large numbers of people entering a courthouse or some other facility. Screening of hand-carried items will usually occur alongside personnel screening. Specific items in this category include briefcases, backpacks, purses, hand-carried bags and packages, etc. Mailed and shipped items are used increasingly to transport bombs; these items can include letters, small packages, and large shipping crates. Vehicle screening can involve both single vehicles (e.g., suspect apprehension) and large numbers of vehicles at checkpoints. The vehicles involved can range from the smallest cars to fully loaded tractor-trailers.

2.3 Cost Range

Cost is one of the few characteristics associated with a detection system that can be fully quantified, and hence it is one of the easiest to get a handle on when comparing different systems. Obviously, a purchaser will want to know the exact cost of any system he or she is thinking about buying. Nevertheless, it is convenient when starting to look at different systems to divide them into low-, medium-, and high-cost ranges. The definitions of these ranges are given in table 1; note that they differ for trace systems and x-ray systems. Cost ranges are used when discussing x-ray systems. Often x-ray manufacturers are reluctant to quote an exact price until they have talked to the potential buyer.

Table 1. Cost ranges for trace and x-ray explosive detection systems

Category	**Price Range $K**	**Price Range $K**
	Trace	**X-ray**
Low	< 30	< 70
Medium	30 to 100	70 to 300
High	> 100	> 300

Note that most trace systems cost less than $75K (several less than $30K), while most x-ray systems cost more than $100K. The authors realize that all of these numbers may seem staggeringly high to most police departments, and that cost will usually be one of the most limiting factors in making a procurement decision. Nevertheless, the ranges listed are convenient reflections of current costs in state-of-the-art explosives detection equipment.

2.4 Throughput Rate

When screening individual items, throughput rate refers to the number of items that can be screened per unit time. It can also be expressed in terms of the time required to screen a single item. For example, if personnel are being screened at a checkpoint using a personnel portal that processes five people every minute, the throughput rate can be expressed as 5 persons/min, 300 persons/h, etc. Alternatively, the screening time can be expressed as 12 s per person. Throughput rate is typically an issue only when large numbers of items need to be screened rapidly. Table 2 quantifies high, medium, and low throughput rates for the items discussed in section 2.2.

Table 2. Throughput rates

Screening time	Category
> 60 s	Low
10 s to 60 s	Medium
< 10 s	High

2.5 Trace Explosives Detection

Explosive detection techniques can be divided generally into two categories: bulk detection and trace detection. In bulk detection, a macroscopic mass of explosive material is detected directly, usually by viewing images made by x-ray scanners or similar equipment. In trace detection, the explosive is detected by chemical identification of microscopic residues of the explosive compound. These residues can be in either or both of two forms: vapor and particulate. Vapor refers to the gas-phase molecules that are emitted from a solid or liquid explosive because of its finite vapor pressure. Particulate contamination refers to microscopic particles of solid material that adhere to surfaces that have, directly or indirectly, come into contact with an explosive material. Explosive vapor pressures and their implications for detection are discussed in the next subsection, while the following subsection considers particulate contamination. Thereafter, several additional subsections are included on the different trace detection technologies that are currently available for explosive detection. Note that one consequence of using trace detection is that a valid alarm may be recorded for the object (person, package, vehicle, etc.) being screened, even if the object does not contain a concealed bomb. This can happen if the object has been contaminated with trace explosive material for any number of reasons, legitimate or otherwise. For example, when screening people it is possible to record a positive alarm for nitroglycerin from a heart patient using nitroglycerin tablets for medication purposes. For this reason, alarm resolution is always a key issue when utilizing trace detection technologies.

2.5.1 Vapor Pressures of Explosives

To have a good understanding of the trace detection of explosives, it is important to understand the concept of vapor pressure. The vapor pressure of a solid or liquid substance at a given temperature is the gas phase pressure of the substance that exists at equilibrium above the surface of the solid or liquid. All solids and liquids emit a certain amount of vapor at all temperatures above absolute zero (-273 °C), and at a given temperature the amount of vapor emitted is characteristic of the particular substance. As an illustrative example, consider a piece of solid (2,4,6-trinitrotoluene (TNT)) placed in a jar with the lid closed. Before the TNT is placed in the jar, there is no TNT vapor present in the jar, but once the TNT is inside with the lid shut, the pressure of gas-phase TNT in the jar will increase as vapor molecules are emitted by the solid. Eventually, a state of dynamic equilibrium will be reached, where the number of vapor molecules emitted by the solid per unit time is the same as the number per unit time readsorbed by the solid and the walls of the jar. There will then be a constant pressure of TNT gas in the jar, and the quantitative value of this pressure is the vapor pressure of TNT at the prevailing temperature. Note that the vapor pressure of a chemical at a specific temperature is the maximum pressure of the gas that may exist above a solid or liquid. If the system has not yet reached equilibrium, the actual pressure of the vapor may be less than the vapor pressure, but never more.

For convenience, vapor pressures are often expressed not in true pressure units but as relative concentrations in saturated air. Such concentrations are proportional to the true vapor pressure, and they often provide a clearer picture of the amounts of vapor that are involved. Figure 1 shows the vapor concentrations in saturated air of several high explosives at room temperature (25 °C or 77 °F).

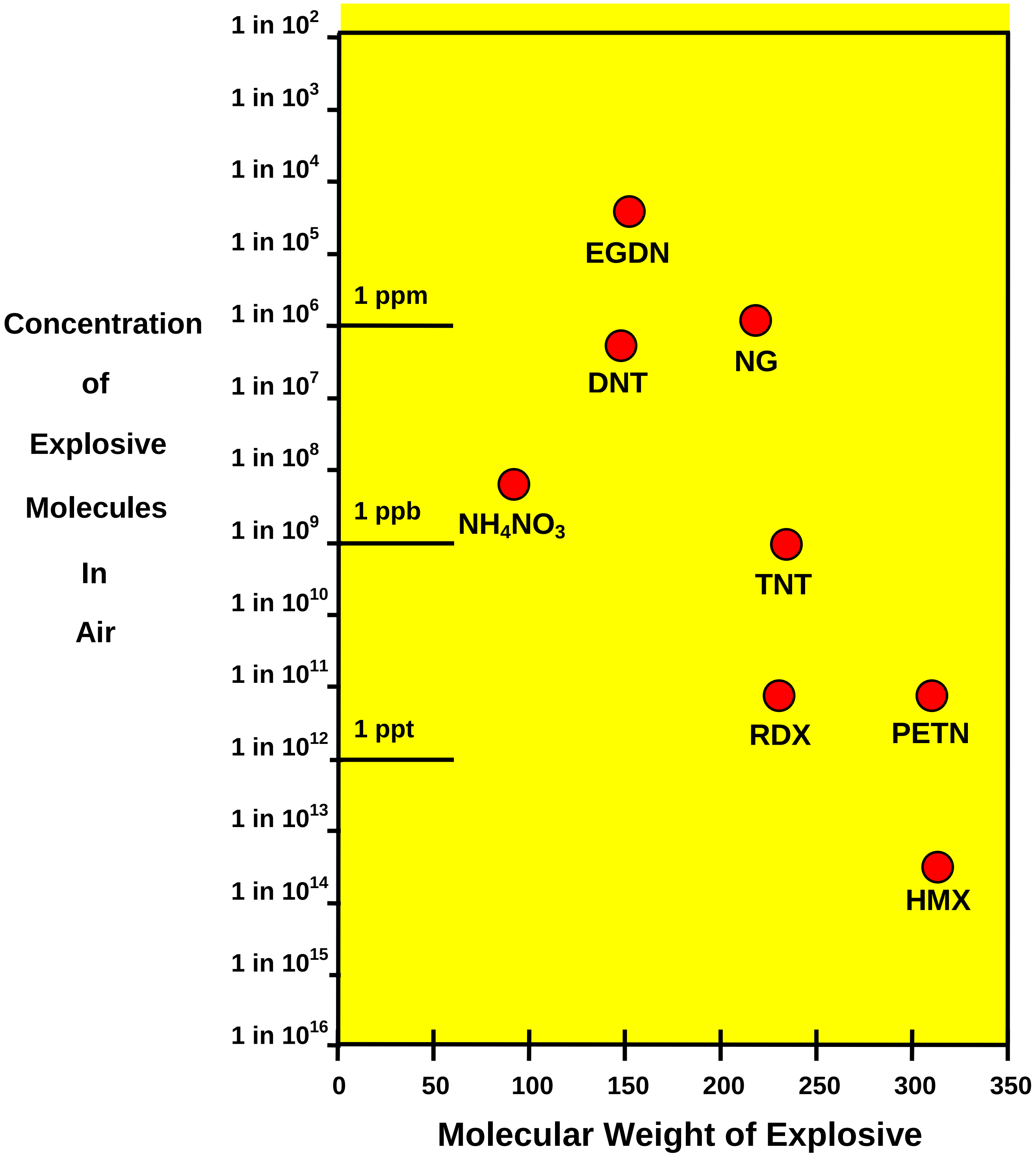

Figure 1. Vapor concentrations of neat high explosives in saturated air at 25 °C

Note that the vertical axis of figure 1 has an increasing logarithmic scale, so that each higher mark corresponds to a factor-of-ten increase in vapor pressure. The horizontal axis displays the molecular weights of the various compounds, and is not important in the following discussion. It can be seen that the vapor pressures of the explosives shown vary widely. For example, the vapor pressure of ethylene glycol dinitrate (EGDN) is about 10^9 times (or one billion times) higher than the vapor pressure of HMX (homocyclonite, or octogen). In general, the explosives can be broken into three groups based on their vapor pressures. The high vapor pressure explosives include EGDN, nitroglycerin (NG), and 2,4-dinitrotoluene (DNT). These explosives have saturated vapor concentrations in air close to or greater than one part per million (1 ppm), which means that at equilibrium there will be roughly one molecule of explosive vapor per every million air molecules. The medium vapor pressure explosives have saturated vapor concentrations in air near one part per billion (1 ppb), a factor of about 1,000 lower than the high-vapor-pressure explosives. The medium-vapor-pressure group includes TNT and NH_4NO_3 (ammonium nitrate). Finally, the low-vapor-pressure explosives have saturated vapor concentrations in air near or below the one part per trillion (1 ppt) level, approximately an additional factor of 1,000 lower than the medium-vapor-pressure explosives. The low-vapor-pressure group includes HMX, RDX (cyclotrimethylenetrinitramine or cyclonite), and pentaerythritol tetranitrate (PETN). These vapor pressures are for pure materials. Vapor pressures for mixtures containing these explosives may be even lower.

The relative values of the vapor pressures mentioned above have important implications for the trace detection of explosives. The high-vapor-pressure explosives are relatively easy to detect from their vapor using detectors such as ion mobility spectrometers or electron capture detectors. Thus dynamites, which usually contain EGDN and/or NG as an explosive ingredient, can usually be detected from their vapor. Detecting these compounds by swiping surfaces for particle contamination (see next section) is also possible in some cases, but it may be less effective than with lower-vapor-pressure explosives, because the high-vapor pressures cause small particles to evaporate rapidly. In other words, in the case of particle sampling, the evidence may not be present long enough to make a detection. The medium-vapor-pressure explosives can sometimes be detected from their vapor, but in many cases this will test the limits of sensitivity for gas-phase detection, and particle detection based on surface swiping is usually preferred. Ammonium nitrate is a somewhat special case because it is almost always used in quantities of hundreds or even thousands of pounds in devices such as car bombs, and not in small bombs that could be carried on a person or shipped through the mail. Thus when ammonium nitrate is used, there is likely to be lots of contamination present to make a swipe-based detection, and various bulk detection techniques (e.g., x-ray) should also be effective. The low-vapor-pressure explosives do not produce enough vapor to be detected from their vapor in any but the most exceptional circumstances, and efforts to detect these compounds using trace technology must focus on swipe collection of particulate material. This makes swiping the preferred collection technique when dealing with plastic explosives such as C-4, semtex, and detasheet, which contain RDX and/or PETN as the explosive ingredient.

The vapor pressure of a substance can be expressed as:

$$P_v = P_0 \exp^{(-\Delta G/RT)}$$

where P_v is the vapor pressure, P_0 is a constant with the same units as P_v, ΔG is the free energy of sublimation (for a solid) or vaporization (for a liquid) in units of J/mole, R is the gas constant in units of J/K● mole and T is the temperature in °K. An important point that can be gleaned from this equation is that P_v depends upon the temperature as discussed above, and in fact the value of P_v will increase exponentially with increasing temperature. Because of this exponential dependence, the effect of temperature on vapor pressure is quite dramatic. For example, for solid TNT near room temperature, the vapor pressure approximately doubles with every 5 °C (9 °F) increase in the temperature of the solid. Thus one cubic centimeter of air that is saturated with TNT vapor will contain about 0.096 ng of TNT at 25 °C, 0.19 ng of TNT at 30 °C, and 0.38 ng of TNT at 35 °C (1 ng = 10^{-9} g = one billionth of 1 g). This means that one possible way to increase the chances of a successful vapor detection if a package or suitcase is suspected of containing a bomb is to heat the object. However, this is not always possible, and it can lead to interference problems if the object also contains another material that is more vaporous than the explosive. It should be pointed out that the numbers given for TNT vapor are very small compared to the amount of TNT contained in a typical particle in a fingerprint, which might contain several micrograms of TNT (1 µg = 1,000 ng). For a high-vapor-pressure explosive such as NG, the vapor concentration in air will be about 1,000 times higher than in the case of TNT. Therefore, the amount of NG vapor in a cubic centimeter (ccm) of saturated air will start to approach the amount present in a typical piece of particle contamination.

A detailed report on the vapor pressures of several common high explosives has been published by Dionne et al. (Ref. 57 in App. 1). This study investigated the vapor pressures of TNT, RDX, PETN, NG, and NH_4NO_3 over a wide range of temperatures. In each case, an empirical formula was derived for the vapor pressure over a certain temperature range. For example, in the case of TNT, it was found that the vapor pressure could be calculated from:

$$\text{Log } P_v(\text{ppt}) = (-7243/T) + 25.56,$$

where Log P_v(ppt) is the base ten logarithm of the vapor pressure in units of parts per trillion (ppt), and T is the temperature in °K. This equation is valid for temperatures between approximately 21 °C and 144 °C. Similar equations for the other explosives, referred to collectively as the Dionne equations, provide a convenient means for estimating the vapor pressures of these explosives at different temperatures.

A final important point about vapor pressures and vapor detection of explosives involves the low-vapor-pressure plastic explosives based on RDX and PETN. It has already been pointed out that RDX and PETN have extremely low vapor pressures, and the vapor pressures of the plastic explosives containing these compounds are even lower, due to the presence of oils and plasticizing agents that give the plastic explosive its form and consistency. When these explosives are manufactured, they are often spiked with a high-vapor-pressure nitro-compound called a taggant. Common taggants include ortho-mononitrotoluene (o-MNT), para-mononitrotoluene (p-MNT), and dimethyldinitrobutane (DMDNB). These taggants have vapor pressures similar to NG or EGDN, and their presence makes vapor detection of plastic explosives possible. However, relying on vapor detection with plastic explosives is still very risky, because old or homemade samples of plastic explosives will not contain the taggant. Nevertheless, detection of one of the taggants using gas-phase sampling with a trace detection system should be interpreted as possibly indicating the presence of a plastic explosive.

2.5.2 Particulate Contamination

Particulate contamination, which can also be referred to simply as particle contamination, consists of microscopic solid particles, often with masses on the order of a few micrograms. Explosives in general tend to be rather sticky, and a person handling a macroscopic piece of the solid material will quickly transfer large amounts of such contamination to his or her hands. This material will then be transferred to any additional surfaces that are touched by the hands, which will likely include parts of the person's clothing as well as doorknobs, tabletops, and other objects he/she contacts. While it is hard to make generalizations, a typical fingerprint will contain many particles, often with a total mass on the order of 100 μg. For low- and medium-vapor-pressure explosives at room temperature, this amounts to more material than would be present in a liter of air saturated with vapor by a factor of 1,000 to 1,000,000. Thus, for these explosives, the ability to make detections based on particulate contamination is crucial, as was alluded to in the preceding section.

Particulate contamination is usually sampled by wiping the surface to be screened with a swipe pad provided by the manufacturer of the trace detection system being used. Once this is done, the swipe pad can be inserted into a sampling port on the instrument, and in a matter of seconds it can be analyzed for the presence of explosives. This works best with briefcases and similar small packages. When screening people, this sort of surface swiping will necessitate physical contact with the test subject, and in some situations this may be considered excessively invasive. It should be noted that while careful handling of the explosive and the proper use of disposable gloves can greatly reduce the spread of particulate contamination, reducing it to zero is extremely difficult. Most bomb builders and carriers will not have the expertise required to do a clean job, so this method of sampling has very wide applications.

2.5.3 Trace Technologies

The following subsections discuss specific trace detection technologies. A listing of different trace technologies and their acronyms is given in table 3.

Table 3. Trace detector technologies and their acronyms

Acronym	Detector Type
Color	**Color** Change of Test Paper
ECD	**E**lectron **C**apture **D**etector
FIS	**F**ield **I**on **S**pectrometer
GC/CL	**G**as **C**hromatograph / **C**hemi**L**uminescence
GC/ECD	**G**as **C**hromatograph / **E**lectron **C**apture **D**etector
GC/IMS	**G**as **C**hromatograph / **I**on **M**obility **S**pectrometer
GC/MS	**G**as **C**hromatograph / **M**ass **S**pectrometer
GC/SAW	**G**as **C**hromatograph / **S**urface **A**coustic **W**ave
IMS	**I**on **M**obility **S**pectrometer
TR	**T**hermo-**R**edox

2.5.3.1 Ion Mobility Spectrometry

Ion mobility spectrometry (IMS) is one of the most widely used techniques for the trace detection of explosives and other contraband materials. The principle of operation of an IMS is shown in figure 2. The spectrometer consists of two main sections: the ionization region and the drift region. In a typical IMS, ambient air is drawn into an inlet port at the rate of a few hundred cubic centimeters per minute (ccm/min). The purpose of the instrument is to analyze this air for explosives or other compounds of interest, which may be present in the air in the form of vapor or airborne particulate matter. The air first enters the ionization region, where electrons interact with the incoming molecules to form positive or negative ions. In the case of explosives, it is negative ions that are formed. The source of the ionizing electrons is a small, sealed piece of metal that has been coated with a radioactive material, usually nickel-63 (63Ni[28]). Once ions are formed, they are periodically admitted into the drift region through an electronically shuttered gate. The ions are drawn through the gate by a static electric field, which pulls them towards a metal collection plate at the far end of the drift region. This "drift" of the ions from one end of the drift region to the other occurs at atmospheric pressure, with many collisions between the ions and the various molecules present. The time that it takes the ions to travel the length of the drift region is called the drift time, and is a complex function of the charge, mass, and size of the ion. Typical drift times are on the order of a few milliseconds (1 ms = 0.001 s). The current collected at the metal plate is measured as a function of time, and an IMS spectrum is a plot of ion current versus time, with different peaks representing different specific ions. An IMS spectrum of an air sample containing two types of explosives is shown in figure 3. Sometimes an additional gas called the dopant or carrier gas is admitted into the IMS to aid in the ionization process; very commonly methylene chloride or some other gas that easily forms chloride ions is used. Ions from this gas usually form the largest peak in the IMS spectrum, commonly known as the reactant ion peak or RIP, which serves as a reference peak.

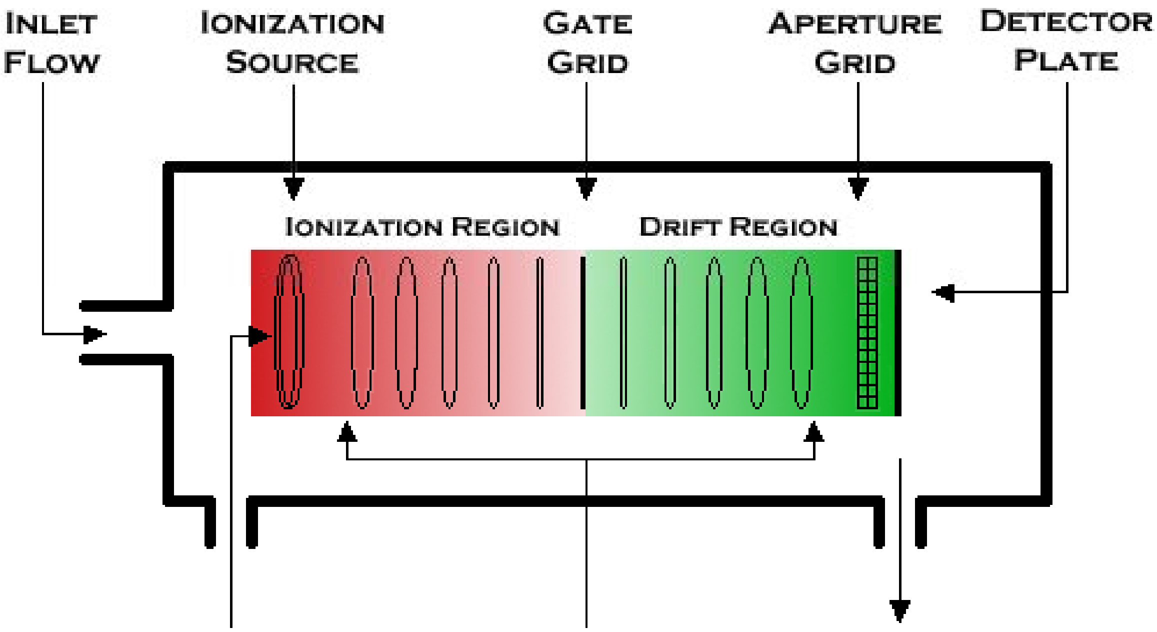

Figure 2. Schematic of ion mobility spectrometer (IMS) operation

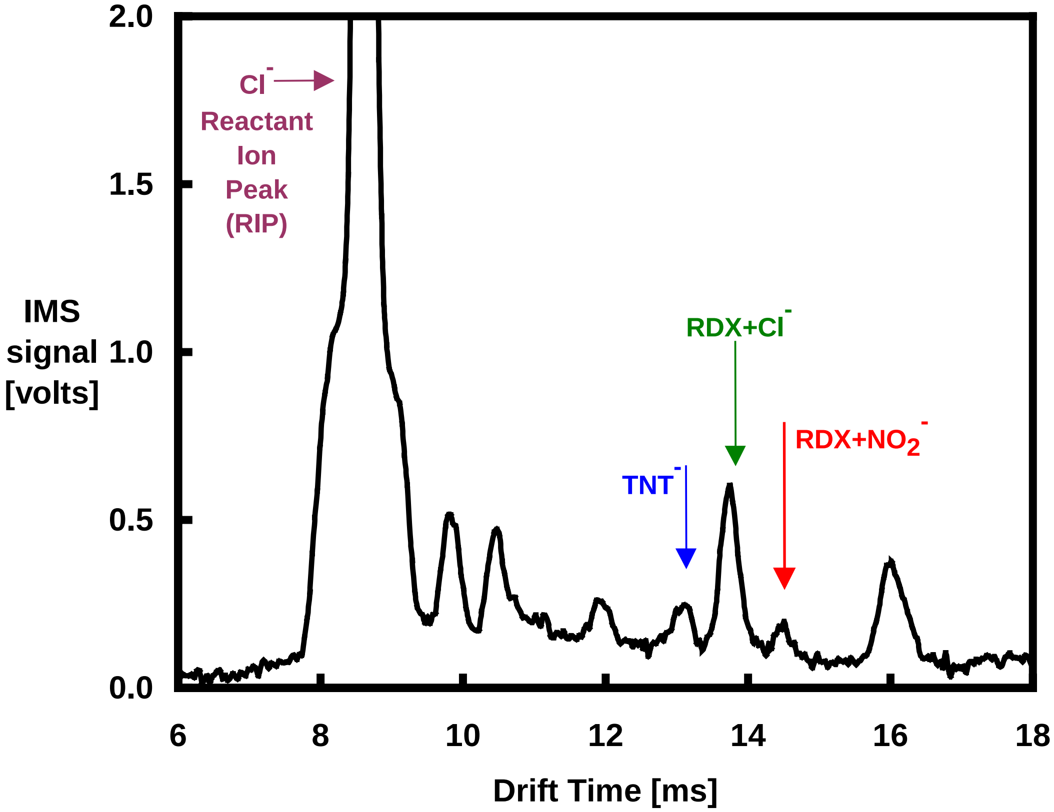

Figure 3. IMS spectrum, a plot of signal vs. drift time

There are a number of features of IMS that make it attractive for the trace detection of explosives. This technique has probably been more widely developed for commercial applications of trace explosives detection than any other. A number of companies market IMS systems, including Barringer, Graseby, and Ion Track Instruments (see table 4). By the standards of most technology-based explosives detectors, IMS systems are moderately priced, with several systems in the \$30K to \$50K range. Upkeep costs vary from system to system, but are moderate in most cases. Most IMS systems are small and portable enough to be moved around in the trunk of a police cruiser, and can be operated by a person with only a few hours of training. These instruments have response times of only a few seconds, the proven ability to detect a number of key explosives, subparts per billion sensitivity in some cases, and audio and visual alarms that tell the operator when an explosive has been detected, and what type. The most effective means for collecting a sample for presentation to one of these systems is surface swiping, but vacuum collection of samples is also possible with many systems. Figures 4-7 show photos of some commercial IMS systems.

Figure 4. Commercial IMS explosives detection system, Barringer Ionscan 400

Figure 5. ***Commercial IMS explosives detection system, Graseby Plastec***

Figure 6. Commercial IMS explosives detection system, Ion Track Instruments Vapor Trace

Figure 7. Commercial IMS explosives detection system, Intelligent Detection Systems ORION

Like all detection techniques, IMS also has certain weaknesses and drawbacks. As mentioned above, a radioactive material is used as the source of ionizing electrons in the ionization region. This source typically has a strength of about 10 mCi and does not pose any health risks if the system is operated properly, but simply having such a source may lead to some extra paperwork and regulatory oversight. Several attempts have been made to develop an IMS with a non-radioactive electron source such as a plasma discharge, but to date no such systems are commercially available. Most IMS systems do not run off batteries but rather require an electrical outlet, and this limits some field applications. There is a nontrivial warmup time, usually on the order of 10 min, associated with these systems. The drift time associated with a given ion is dependent on atmospheric pressure and can thus change during inclement weather or when the spectrometer is moved more than a few hundred feet in elevation. This requires little more than routine, periodic recalibration, but users need to be aware of this potential problem. Like other technology-based trace detection techniques, IMS systems cannot yet compete with canines in their ability to follow a scent to its source.

Another drawback of IMS in some applications is that the peak resolution is not outstanding, and two different ions of similar size and mass may appear to give only a single peak rather than two distinct peaks in an IMS spectrum. One method of attacking this problem is to prefraction the molecules entering the IMS by first passing the incoming gas through a gas chromatograph (GC). A GC column is essentially a hollow tube, usually packed with beads that are coated with a special chemical substance, referred to as the stationary phase. This coating interacts more strongly with some molecules than with others, so if a gas flow containing different types of molecules is admitted into the GC, molecules that interact more strongly with the stationary phase will take longer to pass through the column. This means that an originally random mixture of different molecules can be sorted by type, with each species exiting the GC at a different time. The time it takes a certain molecule to travel through the length of the GC column is referred to as the retention time. If two molecules have identical drift times in an IMS, they will almost certainly have different retention times in the GC, and their peaks can thus be temporally resolved because they will enter the IMS at different times. A combined system of this type is referred to as GC/IMS, and such instruments are marketed by Intelligent Detection Systems (see table 4) for approximately $75K.

2.5.3.2 Chemiluminescence

Most explosive compounds, including all of those shown in the preceding chart of gas phase concentrations in saturated air, contain either nitro (NO_2) or nitrate (NO_3) groups. The compounds commonly used as taggants in plastic explosives also contain NO_2 groups. Detectors based on chemiluminescence take advantage of this common property of most explosives by detecting infrared light that is emitted from electronically excited NO_2 molecules, denoted as NO_2^*. In a chemiluminescence system, explosive molecules are first pyrolyzed to produce nitric oxide (NO). The NO molecules are then reacted with ozone (O_3) in an evacuated reaction chamber maintained at a pressure of about 3 torr = 0.4 kPa. This reaction produces the excited state molecules, NO_2^*. A photomultiplier situated behind a red light filter is used to detect the infrared photons of a characteristic frequency that are emitted when the NO_2^* molecules decay to form unexcited NO_2. The signal output measured by the photomultiplier is directly proportional to the amount of NO present in the reaction chamber, and this signal is thus used to detect the presence of explosives in a chemiluminescence system. The overall sequence of reactions can be summarized as follows (where the chemical equations have not been balanced):

$$\text{Explosive molecules } \rightarrow \text{NO (pyrolysis)}$$

$$NO + O_3 \rightarrow NO_2^*$$

$$NO_2^* \rightarrow NO_2 + \text{infrared photons}$$

Used alone, chemiluminescence is not capable of identifying what type of explosive molecule is present. Indeed, all that can be said is that a molecule must initially have been present that decomposed to yield NO molecules, and such molecules include not only explosives and taggants but also species found in fertilizers, some perfumes, and other potential interferents. For this reason, chemiluminescence detectors are not used alone but are fitted with a front-end gas chromatograph (GC), as described in the section on ion mobility spectrometry. The GC allows different molecules that are detected with the chemiluminescence detector to be specifically identified based on their GC retention times, and the resulting system is referred to as a GC/chemiluminescence (GC/CL) detector. Systems of this type are marketed by Thermedics (see table 4).

The best-known GC/chemiluminescence system is the Thermedics Egis. It is capable of analyzing samples in 18 s, and because of its high sensitivity and excellent selectivity it is a popular system with laboratory researchers and forensic analysts. However, its cost of approximately $150K is 2 to 3 times the cost of a typical IMS system. One nice feature of chemiluminescence detectors is that they do not utilize a radioactive ionization source, and thus avoid some of the paperwork and regulatory oversight that may be associated with IMS detectors. A drawback of chemiluminescence systems is their inability to detect explosives that are not nitro-based.

2.5.3.3 Electron Capture Detectors

An electron capture detector or ECD detects explosives and other types of molecules having high electron affinities. A schematic diagram of a typical ECD detector is shown in figure 8. In an ECD, a vapor sample is drawn into an inlet port, and this vapor mixes with a stream of inert carrier gas (usually helium or argon). The gas flow then travels through an ionization region to an exhaust line. In transit, the gas flow passes through a chamber with a radioactive material that acts as an electron source, as in an IMS. The source material is usually either nickel-63 ($63Ni^{28}$) or tritium. The emitted electrons become thermalized through collisions with the gas in the chamber, and eventually are collected at an anode. Under equilibrium conditions, there is thus a constant standing current at the anode. The basic principle behind an ECD is that this standing current is characteristic of the gas mixture being drawn into the system. If the gas mixture originally consists, e.g., of helium and room air, the standing current will be reduced if the vapor of an explosive enters the chamber. This happens because the explosive molecules have a high electron affinity and thus a tendency to capture free electrons and form stable negative ions, leaving fewer electrons to reach the anode. Thus, a reduction of the measured standing current is evidence that an explosive or some similar species is present. As with a chemiluminescence detector, the ECD by itself cannot distinguish individual types of explosives from each other or certain interferents, so a gas chromatograph is placed on the front end to allow temporal identification of different explosives. Several companies market detectors of this type (see table 4), referred to as GC/ECD detectors. A photo of a commercially available GC/ECD device is displayed in figure 9.

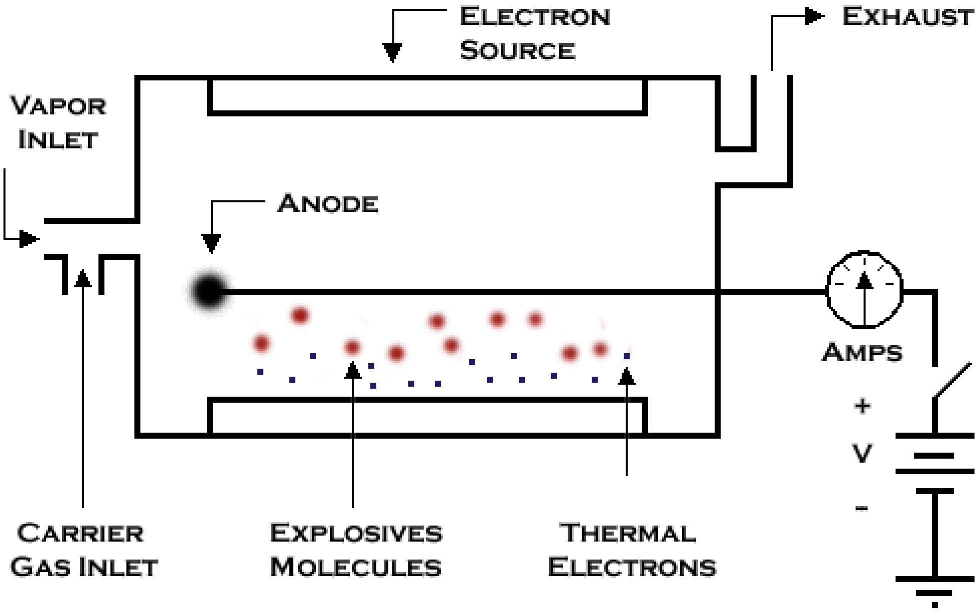

Figure 8. Schematic diagram of operation of an electron capture detector (ECD)

Figure 9. Commercial electron capture detector (ECD), Ion Track Instruments Model 97

This type of detector has a rapid response and typical sensitivities of about 1 ppb for most electron-capturing compounds. This sensitivity is somewhat less than the sensitivity of a typical IMS or chemiluminescence system, but it is still adequate for some applications. However, GC/ECD detectors usually cost less than IMS or chemiluminescence systems, with several systems available for $20K or less. These systems also tend to be smaller, lighter, and more easily portable. As with an IMS, the fact that the instrument has a radioactive ionization source can lead to some extra regulatory oversight. Another problem with ECD systems is that they require an ultrapure carrier gas, usually contained in a small cylinder, and the availability of this carrier gas can put limits on field applications.

2.5.3.4 Surface Acoustic Wave Sensors

Surface acoustic wave (SAW) sensors are usually coupled with a front end GC, as is the case with ECD and chemiluminescence detectors. The principal component of a SAW sensor is a piezoelectric crystal that resonates at a specific, measurable frequency. When molecules condense on the surface of this crystal, the resonant frequency shifts in proportion to the mass of material condensed. The frequency shift also depends upon the properties of the material being deposited, the surface temperature, and the chemical nature of the crystal surface.

In a typical system, the exit gas from the GC is focussed onto the SAW resonator crystal using a carefully positioned and temperature controlled nozzle. A thermoelectric cooler maintains the SAW surface at sufficiently low temperatures to ensure efficient trapping of the molecules of interest. The crystal surface can also be heated in order to desorb vapors and thus clean the surface. The temperature of the surface allows control of sensor specificity, by preventing adsorption of species with vapor pressures above a certain level. This feature is useful in distinguishing between high and low vapor pressure explosives. During sampling, vapors are concentrated in a cryo-trap before being desorbed into the GC for temporal separation.

SAW sensors are marketed by Electronic Sensor Technology, Inc. (see Table 4). Pictured in figure 10 is EST’s Model 4100. Total analysis time, including sample concentration in the cryo-trap, is typically 10 s to15 s. The system is advertised to have parts per billion sensitivity to certain types of explosives. It is about the size of a large briefcase, and is operational within 10 min of startup. The cost is about $25K, similar to some GC/ECD systems.

Figure 10. Photo of a surface acoustic wave detector, the EST Model 4100

2.5.3.5 Thermo-Redox Detectors

Thermo-redox technology is based on the thermal decomposition of explosive molecules and the subsequent reduction of NO_2 groups. Air containing the explosive sample is drawn into a system inlet at a rate of approximately 1.5 L/min. The air is next passed through a concentrator tube, which selectively adsorbs explosive vapor using a proprietary coating on the tube's coils. The sample is then pyrolyzed to liberate NO_2 molecules, and these molecules are detected using proprietary technology. Those interested in additional information on this technology should contact Intelligent Detection Systems (see table 4), which now markets the thermo-redox based equipment formerly marketed by Scintrex.

The thermo-redox system currently marketed, the EVD-3000, is a hand-held unit that costs approximately $23K, pictured in figure 11. It can analyze both vapor and particle samples, and contains no radioactive source. Since only the presence of NO_2 groups is detected, this technology cannot distinguish among different explosives and potential interferences that contain NO_2 groups. Thus, the system identifies the presence of an "explosive-like" material, without identifying a specific explosive. Furthermore, the technology cannot detect explosives that do not contain NO_2 groups.

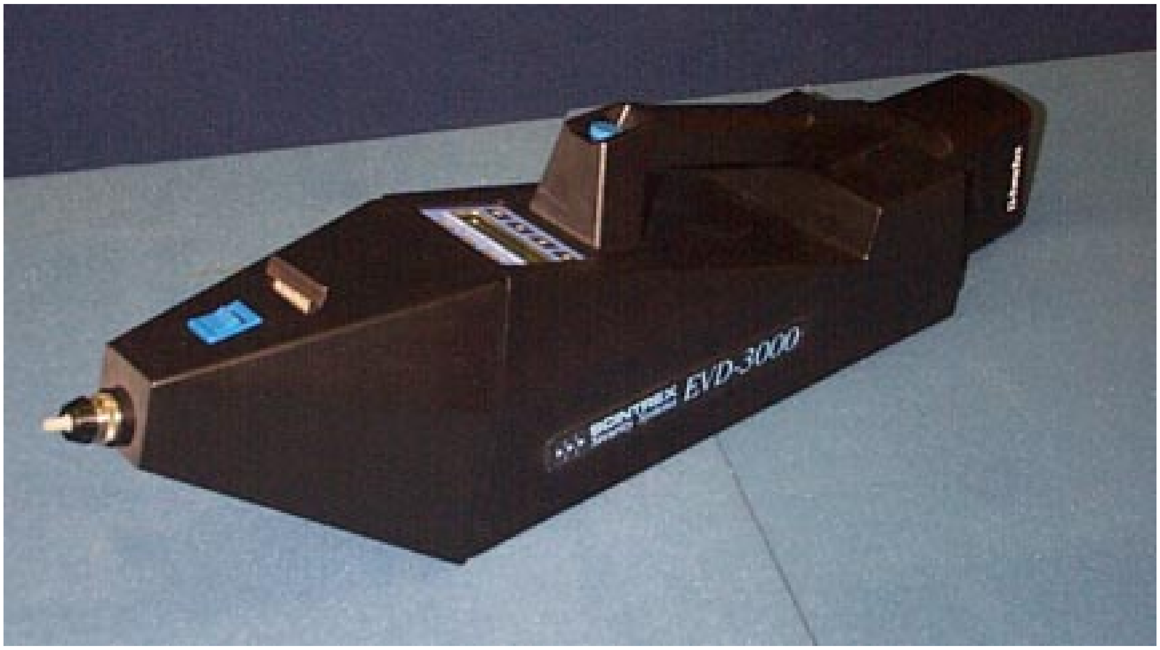

Figure 11. Photo of a Thermo-Redox detector, Sintrex/IDS EVD-3000

2.5.3.6 Field Ion Spectrometry

Field ion spectrometry (FIS) is a relatively new trace detection technology (1994) that is related to IMS. It incorporates a unique ion filter using dual transverse fields, which allows interferences to be eliminated electronically, without the use of GC columns, membranes, or other physical separation methods. FIS is similar to IMS in that it involves separating and quantifying ions while they are carried in a gas at atmospheric pressure. Furthermore, both systems utilize soft ionization methods that yield spectra where the species of interest produce the main features (i.e., under proper conditions there is little decomposition of the analyte).

In FIS, ions enter an analytical volume defined by a pair of parallel conducting plates where they execute two motions. The first is a longitudinal drift between the plates due to the bulk motion of a clean, dry carrier stream of air. The second is an oscillating motion transverse to the bulk flow velocity that occurs as the ions respond to an asymmetric, time-varying electric field imposed between the two plates. In response to the asymmetric field, the ions tend to migrate towards one of the plates where they will be neutralized. A second DC field is simultaneously established across the plates and can be used to balance or compensate for the drift introduced by the primary field. The DC field intensity needed to compensate for the AC field induced drift depends on the mobility of the particular ion under investigation, so that only specific ions can pass completely through the analytical volume and into the collection area for detection. Therefore, the device can be tuned to selectively pass only the ions of interest. Scanning the DC field intensity produces a spectrum of ion current versus field intensity that is known as an ionogram.

The sole manufacturer of FIS sensors is Mine Safety Applications (MSA) – see table 4. Their system, pictured in figure 12, can currently be purchased for about \$30K. The sensor has no moving parts except for a small recirculation fan and no consumables except a replaceable calibrator and gas purification filters. The size of the system is 0.022.66 m^3 (0.8 ft^3), excluding a computer for control and display. The manufacturer has reported detection limits for explosives such as TNT, RDX, and PETN in the low picogram range. To our knowledge, there have not yet been any independent tests to verify this. A response time of 2 s for a single target molecule plus another 5 s for each additional target molecule has been reported. Like an IMS, an FIS uses a small radioactive source for ionization. Because of the newness of this technique, the current systems may be better adapted to laboratory research than to routine field applications, but this could change in the future.

Figure 12. Photo of a field ion spectrometer (FIS) by MSA

2.5.3.7 Mass Spectrometry

Mass spectrometry (MS) has long been one of the most powerful techniques available for laboratory chemical analysis. Although it is rarely used in routine field applications and may thus be of little interest to law enforcement agencies doing explosive detection, it is discussed briefly here for completeness and because of this widespread laboratory use. While there are different types of mass spectrometers, this is basically a magnetic filtering technique. Molecules are first ionized and then passed through a magnetic filter, which allows ions to be identified based on their charge-to-mass ratio. In some systems, the MS is connected to a front-end GC. Mass spectrometers have excellent specificity for identifying different ions, and some systems have sub-picogram sensitivity. Mass spectrometers tend to be expensive. Table 4 lists one mass spectrometer system that costs $70K, with an advertised sensitivity in the low parts per billion range for some analytes.