CHAPTER 11

MASS SPECTROMETRY FOR SECURITY SCREENING OF EXPLOSIVES

JACK A. SYAGE AND KARL A. HANOLD

11.1 INTRODUCTION

Security and protection against rogue activities is one of the greatest mainstream public concerns. A broad range of countermeasures are needed, one of which is detection technology to warn against an imminent attack. In this chapter we review the issue of explosives trace detection (ETD) and describe the method of mass spectrometry (MS) as an alternative to existing technologies.

The performance criteria on which security screening technologies are judged are accuracy (high detection and low false positive rate), speed and cost. As terrorists become more sophisticated, there is a need to detect an increasing variety of threats (new explosives, chemical weapons, etc.). Systems must also be sufficiently automated for non-technical security personnel to operate. Acceptable defenses are now being deployed for baggage scanning, including differential X-ray and X-ray tomography. Swipe methods of sampling using ion mobility spectrometry (IMS) are also being used for high-touch areas of baggage and other items. Other ETD analyzers that have been deployed include gas chromatography (GC) with a variety of detectors such as chemiluminescence and electron capture detectors.

IMS is the most commonly deployed method for ETD devices. Its advantages are compact size and relatively low price. For applications requiring a handheld detector, IMS is an excellent choice. For applications that are more stationary, other alternatives to IMS are often used. Mass spectrometry is recognized for its superior performance with regard to sensitivity and specificity, which translate to lower false negative and false positive rates. Active programs are now in place to develop routine MS technology for security applications in airports and other venues.

Trace Chemical Sensing of Explosives, Edited by Ronald L. Woodfin

In this chapter we describe the application of MS to detection of trace explosives on people and baggage. We begin by summarizing a variety of candidate ETD detectors; however, we refrain from an in-depth discussion deferring instead to the many excellent review articles and proceedings that are available.[1,2,3,4] However, because of their similarities, we do compare the methods of MS and IMS and identify the strengths and weaknesses of each method.

11.2. DETECTION METHODS

The Transportation Security Administration (TSA) and the Federal Aviation Administration (FAA) have been responsible for ensuring safety of air travel and have invested significantly in developing technologies to combat the potential for terrorist attack by explosive devices. This has led to deployment of two types of detectors for screening baggage and people. Explosive detection systems (EDSs) detect bulk explosives hidden in checked baggage and operate using dual x-ray tomography. Explosives trace detectors (ETDs) detect vapor or particles of explosives that are contaminated on people and the surface of baggage. ETDs are also used to resolve alarms from EDSs. Currently ETDs are used on a selective basis to screen for personal items and carry-on bags, but not for directly screening individuals.

The explosives that are of greatest concern for screening purposes are the high explosives [e.g., trinitrotoluene (TNT), cyclotrimethylene trinitramine (RDX), pentaerythritol tetranitrate (PETN) and their composition forms (e.g., C-4, Semtex H, Detasheet], dynamites [e.g., nitroglycerin (NG) and ethylene glycal dinitrate (EGDN)] improvised explosives [e.g., ammonium nitrate (AN), ammonium nitrate fuel oil (ANFO), urea nitrate, triacetone triperoxide (TATP), black and smokeless powder] and ICAO taggant compounds [e.g., 2,3-dimethyl 2,3-dinitrobutane (DMNB) and EGDN] However there are a host of other explosives threats that are in the hands of terrorists (e.g., cyclotetramethylene tetranitramine (HMX), hexamethylene triperoxidediame (HMTD), black powder derivatives, etc.). In fact the U.S. Bureau of Alcohol, Tobacco, and Firearms lists over 200 explosives materials.[5]

11.2.1. Explosives Trace Detection

There is a good reason why there are many different analytical techniques for the detection of explosives. No single detector is suitable for all applications. The level of accuracy is somewhat a function of size, weight, and power requirements. Fixed location applications can use more sophisticated technology, whereas manportability imposes compromises in performance. The following summarizes explosives detection technology that is being pursued for threat detection applications (e.g., early warning systems and emergency first responders):

- *Mass spectrometry (MS):* MS offers high levels of sensitivity and specificity compared to other technologies for chemical detection. Its traditional disadvantages have been high cost and complexity. Over the last few years,

however, the economics have greatly improved and MS is now capable of routine and automated operation. MS has been used extensively for forensics applications,[6] but only recently has been developed for early warning security screening of explosives. Companies developing deployable MS-based screening include Hitachi, Syagen, Mass Spec Analytical, and Griffin Analytical.

- *Ion mobility spectrometry (IMS):*[7] IMS is similar in concept to MS except that the ions are dispersed by gas-phase viscosity and not by molecular weight. The main advantage of IMS is that it does not use a vacuum system, which greatly reduces the size, cost, and complexity relative to MS. However, the trade-off is that the measurement accuracy is considerably less than MS. This is especially true for complex samples or when screening for a large number of target compounds simultaneously. Companies deploying IMS in security applications include GE/Ion Track and Smiths Detection. New developments, such as field asymmetric ion mobility spectrometry (FAIMS) and commercialized by Sionex, are improving on detection accuracy of IMS.[8]
- *Gas chromatography (GC):* This method provides high-resolution separation of compounds that are then detected by a variety of means. The highest accuracy is obtained using an MS detector. However, for ETD applications, lower-cost detectors that are specific to explosives are often used such as electron capture detection (ECD), chemiluminescence detection (for the NO_2 group), or IMS. For other non-specific detectors, identification is dependent on accurate and reproducible retention times, which can introduce uncertainty in making definitive identifications. Companies that have commercialized GC for explosives screening include Thermedics, Scintrex, and Electronic Sensor Technology.
- *Optical spectroscopy:* Infrared (IR) and Raman spectroscopy can be used to make positive identifications; however, it is not well suited to complex mixtures or detecting compounds at very low concentrations. Long wavelength absorption spectroscopy such as millimeter wave are becoming attractive options as they provide the potential for very high specificity for volatilized explosives; however, the sensitivity is not very high due to the low absorption cross sections at these wavelengths.
- *Chemical sensors:* This approach is attractive for applications requiring a hand-held device and generally relies on an array of detectors, each of which responds differently to different compounds. The principal is for each target compound to give a different pattern of responses on the detector array. The detectors can respond to conductivity, wave propagation, fluorescence, or other indications. Chemical sensors are not very specific or sensitive for complex mixtures and the devices can be prone to high false positive rates.
- *New technologies:* The quest for broad-based explosives detectors that are fast, sensitive, specific, small, and inexpensive continues. Promising tech-

nologies include molecularly-imprinted polymer (MIP) sensors. It will take considerable time and work to develop MIPs for a wide range of compounds; however, results on selected test compounds showed mid ppb detection limits with a response time of 10-15 min.[9] Another interesting approach of a similar nature involves semiconductor organic polymers that can be made to undergo lasing action at very low thresholds. When specific compounds, such as TNT, bind to the polymer surface, the lasing action is quenched, giving a sensitive means for detection.[10] Though this method can be very sensitive its specificity against false positives from other non-explosives compounds is not yet documented.

11.2.2. Sampling Methods

Fast and accurate screening for trace levels of explosives and other targeted requires a sophisticated combination of components that work together as a system. The three basic functions of an ETD screening system are:

- Sample collection and compound enrichment
- Selective detection of targeted compounds
- Accurate measurement of targeted compounds

Sampling is difficult because the vapor pressures for most explosives are very low. For example the room temperature equilibrium headspace concentration of RDX in air is about 10 parts-per-trillion by volume (pptv). Collection of vapor is further compounded for explosives that are bound in matrices and wrappers and/or are concealed in wrappings or baggage. The prospects for trace detection of explosives are considered to be better when sampling objects for explosives contamination in the form of particles and residue.

Sample collection in airports and other venues is typically done with cloth swipes that the operator rubs across high-touch areas of baggage and other properties. The swipe is used to collect particulate residue. It is then inserted into the detector where it is heated to thermally desorb the residue into the analyzer. Another approach is to collect an air volume that is suspected to contain explosives particles. This method is more practical than using swipes for applications such as screening people for contamination indicative of concealed explosives or inside of containers where physical access is limited. Air sampling is often preceded by a method for dislodging particles from suspected objects, such as the use of air jets to ruffle and loosen particles. The surrounding volume of air is then collected and sifted to remove the vast majority of air, while retaining particles, residue, and condensable vapors. One way to concentrate the sample is to use a high-throughput, high-surface-area metal mesh. The mesh is then heated to thermally desorb the collected particles and vapor into the analyzer. This method of collection/concentration/desorption is used in one form or another for screening people for explosives (see Section 11.5.1).

11.2.3. Quantitative vs. Screening Analysis

Quantitative analysis involves making measurements of samples of unknown concentrations and determining the concentration to some specified level of accuracy and precision. This is done by first generating a calibration curve that relates the instrument-measured intensity vs. concentration for a standard of the compound being measured. The unknown sample can then be measured and the intensity matched up against the calibration curve to determine the concentration. The accuracy of the instrument is based on how accurate and repeatable (precision) the concentration is measured. Because the unknown concentration can conceivably span a large concentration range, analyzers with large dynamic range are essential for quantitative analysis.

Screening analysis does not require determining precise concentrations, but instead must give a reliable indication of whether a target compound is present above some threshold concentration. The accuracy of a screening system is based on the probability of detection P_D of the target compound at the threshold concentration relative to the probability of false positive P_{FP} due to background compounds giving signal that appear indistinguishable to the target signal. Although, screening does not require as high a dynamic range as is needed for quantitative analysis, it is still an advantage because it can minimize the effect that a strong background signal can have on weak target signals and it can help resolve between strong background and strong target signal that might overlap. MS has a very large dynamic range (typically 10^4 to 10^6 range from weakest to strongest detectable signal strength) and records intensities that are essentially linear with compound concentration. This makes it a preferred tool for quantitative analysis, but as noted above is also beneficial for screening applications.

11.3. MASS SPECTROMETRY

11.3.1. Primer

We briefly summarize the variety of mass analyzers that are currently used for a wide range of chemical analysis applications and then discuss their specific attributes and how decisions are made as to what analyzer is best suited for a particular application.

11.2.1.1 Quadrupole The quadrupole mass analyzer consists of 4 cylindrical linear rods that act as a mass filter for the transmission of ions. Radiofrequency (RF) and direct current (DC) voltages are applied to the rods in such a way that the amplitude of the RF and DC controls the mass-to-charge ratio m/z of the ion that is stable in passing through the rods and the amplitude ratio of the RF to DC governs the resolution. The resolution is generally set at unit mass, which means that all ion masses, but one are rejected and not detected at any given time during an analysis. The characteristics of a quadrupole mass analyzer include:

- Sensitivity is high in single ion mass mode, but diminishes as the number of ions that are simultaneously monitored increases because the duty cycle for collecting any particular ion mass decreases.
- Resolution is moderate and not capable of accurate mass analysis sufficient to resolve different elemental compositions of the same nominal mass.
- Cost is low relative to other mass analyzers.

The quadrupole mass analyzer is a popular economical choice when known compounds are being analyzed and the filter can be set to a limited number of ions.

11.2.1.2 Quadrupole Ion Trap The quadruple ion trap operates under the same principal as the linear quadrupole filter except that geometrically it is wrapped around so that ions don't travel from one end to the other, but rather are trapped in an electrode structure consisting of a ring electrode and two endcap electrodes.[11] Similar to the linear quadruple, RF and DC voltages are applied to the device, but only to the ring electrode. The DC voltage determines the range of masses that are stable in both a linear quadrupole and a quadrupole ion trap analyzer. The latter device; however seeks to maximize the range of ions that are stabilized or trapped; this maximum range occurs for a zero DC voltage. Mass analysis of the trapped ions is then achieved by ramping the RF voltage amplitude, which acts to sequentially eject ions of increasing mass that are then measured by a detector. A valuable capability of ion traps is that voltage waveforms can be applied to the endcaps to isolate certain masses and to induce collisional dissociation to fragment the ions. This capability is important for identifying ions by deducing the structure from the ion fragmentation pattern. The characteristics of ion traps include:

- Sensitivity is medium to high for all ions within the mass stability region.
- Resolution is moderate and not capable of accurate mass analysis sufficient to resolve different elemental compositions of the same nominal mass.
- Scan rate is relatively slow.
- Cost is low to medium relative to other analyzers.
- It is capable of multiple MS analysis (MS/MS and MS^n) by selective ion fragmentation analysis for structure identification.

The commercial ion trap mass spectrometer (IT MS) can be an economical solution for detection of multiple targeted compounds; however repetition rate is relatively slow especially for MS/MS mode.

11.2.1.3 Time-of-Flight The principle of TOFMS is very simple and makes use of the energy equation $E=mv^2/2$ where m is mass and v is velocity. As illustrated in Figure 11.1, all ions are accelerated to constant energy E. The ions then enter a drift tube where they travel at velocity v. Because each ion mass m travels at a different velocity, the ions of different mass separate; the lighter ones

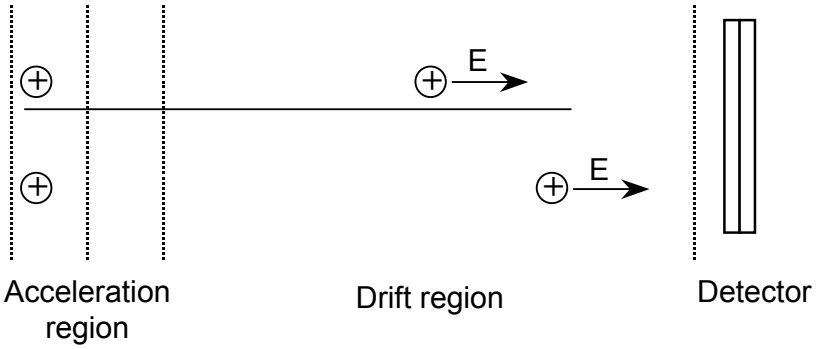

Figure 11.1 Separation of different ion masses by TOFMS.

run ahead of the heavier ones. This separation means that each ion mass hits the detector at a different time. Ions of the same mass arrive together and give a sharp peak in the TOF mass spectrum. Fast detection methods can measure the arrival times and the simple formula above can be used to transform the times to mass.

In practice TOFMS has additional complexities to improve resolution. For example a spatial spread in the initially formed ions can degrade resolution; however, this spread can be focused using a two-stage acceleration as shown in Figure 11.1. An initial energy spread can also degrade resolution, but can be focused using a reflectron at the end of the drift tube (not shown in Figure 11.1). A TOFMS instrument can achieve very high resolution and ion transmission efficiency making it very attractive for many applications. It can also detect all ion masses at once, which is an advantage for sensitive and high-speed detection of multiple compounds. However, there tends to be ion transmission losses in getting ions into the TOF acceleration region because of the need to restrict the initial energy and spatial distribution, despite the focusing methods described above. This makes TOFMS less sensitive than a quadrupole when monitoring only a very few compounds. However, the sensitivity of TOFMS is constant no matter how many ions masses are being probed. The characteristics of TOFMS include:

- Sensitivity is medium to high for all ion masses.
- Mass range can extend up to several thousand mass units.
- Resolution is very high and is capable of accurate mass analysis sufficient to resolve different elemental compositions of the same nominal mass.
- Scan rate is very high.
- Cost is medium to high relative to other analyzers.

TOFMS is a method of choice for a combination of high mass range, high resolution, and speed and for multiple compound analysis.

11.2.1.4 Fourier Transform MS Fourier transform mass spectrometry (FTMS), which is a modern manifestation of ion cyclotron resonance relies on the collection of ions in a high vacuum cell and containment with a magnetic field.

The ions orbit about the magnetic field axis. The ion masses and abundances are measured by applying a RF signal to excite them to a non-random spatial orientation, such that their motions induce an image current in a set of receiver plates. The image current consists of a superposition of oscillations corresponding to the orbit frequencies of the ions. The Fourier transform of the time-dependent signal gives the mass spectrum of the ions. The characteristics of FTMS are:

- Extremely high resolution (e.g., >100,000).
- Nearly unlimited mass range.
- Scan rate is slow.
- Cost is very high.

FTMS is an indispensable analyzer for large molecules such as proteins, but is not well suited for fast and sensitive screening of target compounds for the purposes of threat analysis.

11.2.1.5 Hybrid MS It is often desirable to combine mass analyzers into hybrid instruments that can perform additional levels of mass analysis. There are two major reasons for doing this: (1) to obtain structure analysis by isolating specific ion masses and then causing them to break into identifiable fragment ions and (2) additional sensitivity can be gained by removing all ions except the target ions, thus creating a clean background on which a known fragment ion can be sensitively observed. The major tandem or hybrid MS instruments include:

- Triple quadrupole: In the standard configuration, the first quadrupole is used to select a specific ion mass, the second quadrupole is a collision cell that induces the selected ion mass to fragment, and the third quadrupole is used to analyze the fragments. The triple quadrupole is a very popular choice for very sensitive and quantitative analysis of complex mixtures (e.g., drug analysis).
- Quadrupole/TOF: A version of the triple quadrupole is to replace the third quadrupole with a TOFMS. This provides potentially faster analysis and higher mass resolution.
- Ion trap/TOF: This combination is advantageous because it enables the MS^n capabilities of an ion trap with the high mass accuracy and speed of a TOF analyzer. The ion trap can either be a conventional hyperbolic Penning type device or a linear trap device. Below we describe the deployment of the former type ion trap/TOF for explosives detection.

11.3.2. QitTOF MS

The quadrupole ion trap, time-of-flight (QitTOF) MS analyzer was first developed by Lubman[12,13] and coworkers. QitTOF MS components were first sold commercially by R. M Jordan Company and a full commercial instrument first introduced by Syagen[14,15] and then by Shimadzu.[16] A schematic of the QitTOF configuration is shown in Figure 11.2. The principal role of the ion trap is to accumu-

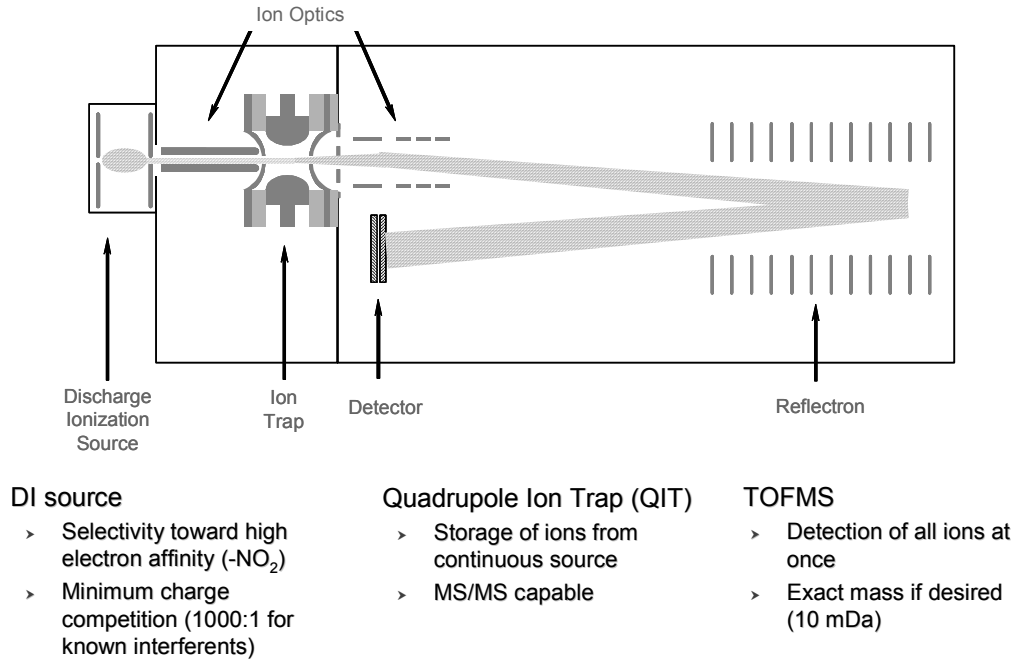

Figure 11.2 Schematic of the QitTOF MS detection system showing the individual components and their respective advantages. DI = discharge ionization.

late ions that are continuously generated by the ionizer. These accumulated ions are then pulsed into the TOFMS analyzer at relatively high repetition rates (e.g., 10-100 Hz). Because the TOFMS analysis is performed independently of the ion accumulation into the trap other than the short RF shutoff and pulse out time (about 50-100 μs), the duty cycle for collecting ions in the total analysis cycle is >99%. This is to be compared to an IT MS analyzer where duty cycle is typically <50% because the accumulated ions must be scanned out of the ion trap, which typically takes on the order of 100 ms.

The main benefits of QitTOF relative to other MS systems are:

- TOFMS analyzes all ions at once vs. quadrupole mass spectrometry, which can detect only one ion mass at a time
- QitTOF enables fast TOF detection compared to IT MS only
- QitTOF enables mass-selective analysis by MS^n analysis compared to TOFMS only

These features translate into high levels of performance in terms of speed, sensitivity, and specificity.

The ionizer is a key component of any MS detection system. The QitTOF MS detector that we employ for explosives detection uses a discharge electron attachment source to form negative ions for explosives. This source is a variation of the glow discharge ionization source developed by McLuckey and coworkers.[17,18,19]

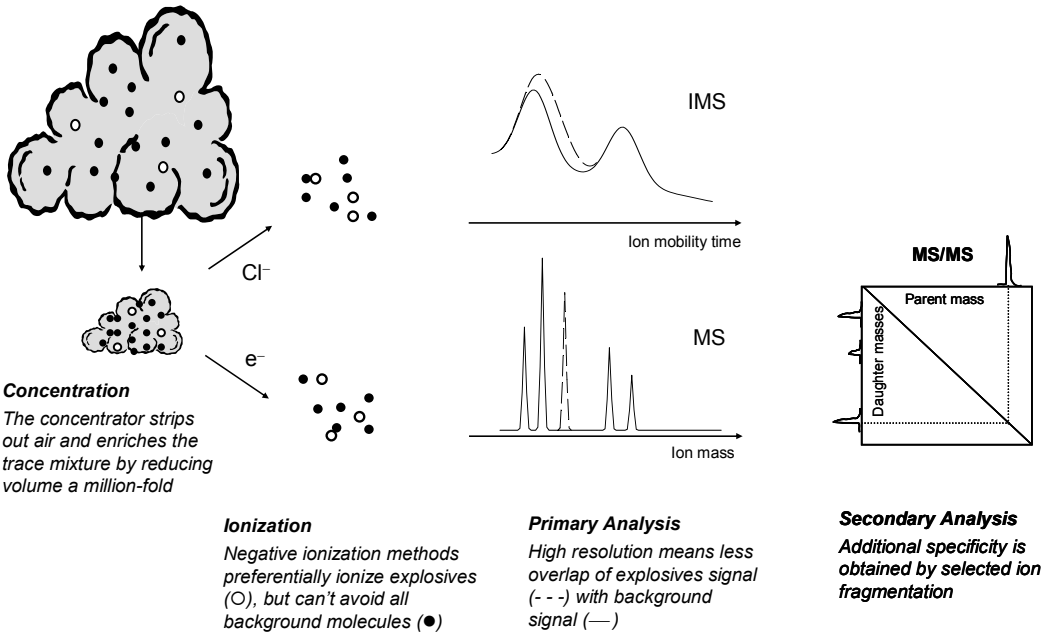

Figure 11.3 Comparison of ion mobility spectrometry (IMS) and mass spectrometry (MS) methods of detection in an overall high-speed screening system.

Explosives are very electronegative compounds that readily attach electrons. Most other common compounds that are likely to be sampled in a portal system are less electronegative, hence the ionization process provides a stage of selectivity in differentiating explosives compounds from common background. However, as portrayed in Figure 11.3, other compounds besides explosives can be ionized and therefore it is important to have the capability to further differentiate explosives signals. For our detector, MS^n provides this capability.

The QitTOF MS detection system has the following capabilities:

- High resolution
- High sensitivity
- Molecular weight identification
- Secondary confirmation by ion fragment analysis

The detector was designed for automated and unattended operation and for use by non-technical personnel. We present performance results for the QitTOF MS explosives detection system in Section 11.4.

11.3.3. Mass Spectrometry vs. Ion Mobility Spectrometry

Figure 11.3 is a starting point for comparing MS and IMS detectors in an overall screening system. Following the enrichment process described in 11.2.2, the collected sample is introduced into the detection system. For MS and IMS the

compounds are further selected for the explosives compounds using an ionization method that preferentially ionizes the compounds of interest. For example, explosives have properties that make them very reactive to negative ions and electrons. IMS generally uses a radioactive ^{63}Ni source to create a plasma of ions and charges to ionize neutral molecules. For negative ionization it is typical to add a reagent gas, such as methylene chloride, to enhance the ionization of explosives compounds. Because IMS generally operates at atmospheric pressure, these ionization sources also operate at this pressure and are susceptible to unwarranted ion-molecule reactions due to the many molecular collisions. The same ionization methods used for IMS may be used for MS, however, other options are available because MS operates at vacuum conditions and ionization may be chosen to occur anywhere from atmosphere to the vacuum pressure of the MS analyzer. This choice involves a tradeoff. Ionization at high pressure affords higher molecular densities and greater yield of ions, however, the ion distribution is prone to thermodynamic effects that can suppress ions of interest. Ionization at low pressure minimizes unwanted ion-molecule reactions, but the molecular densities are lower yielding fewer ions. The glow discharge ionizer described above operates at an intermediate pressure that gives adequate performance with regard to ion yield and minimum ion suppression.

As noted above MS analysis is based on attaching a charge to individual molecules to form ions and measuring their molecular weights. The molecular ions often fragment to give fragment ions of varying masses. Extensive fragmentation can be a hindrance to trace detection, especially if the background compounds likewise extensively fragment and interfere with explosives fragment signals. However, if the fragmentation can be limited and even controlled, then it can be used as a powerful confirmatory tool. The detection of a single ion signal may give excellent detection probability, however, it is susceptible to false positives depending on the masses of the background compounds. Parent and fragment ions of explosives compounds span a range of about 300 atomic mass units (e.g., PETN MW=316, NH_3 MW=17). MS provides unit mass resolution, so the overall resolution R for detection is about 300.

IMS is a method that also separates ions in time. Separation is based on the different speeds that ions drift through a viscous gas under the force of an electric field. The drift time depends on both molecular weight and size; they do not give a simple measure of molecular weight. The principal advantages of MS over IMS are higher resolution and molecular identification. As shown in Figure 11.3, higher resolution minimizes the problem of interference due to overlapping signals from different compounds. Practically speaking, IMS resolution, defined as the ratio of the total span of drift times for target ion signal and the ion signal width rarely exceeds 30. The measure of molecular weight by MS is a very strong indicator of what the compound is, unlike the measure of mobility times by IMS. For example, TNT has a molecular weight of 227. The probability of another compound having that molecular weight is very small. However, to positively confirm that a detected signal at molecular weight 227 is actually TNT, Syagen's QitTOF MS technology

can selectively fragment the molecular ion to determine its structure and definitively identify the detected compound. This secondary analysis portrayed in Figure 11.3 provides an unprecedented level of specificity for positively detecting targeted compounds. Another means to improve MS resolving power is to achieve resolution sufficient to resolve different elemental compositions of the same nominal unit mass, which effectively can raise the resolving power to several thousand.

A recent report from the National Academy of Sciences assessed the relative performance of IMS and MS and concluded that the latter provided from 10-10000 better resolution, which translates into improved accuracy in terms of probability of detection and false positive rates.[20] The higher end of this resolution range represents high-resolution instruments and MS/MS instruments.

A model for assessing detection accuracy in terms of the probability of detection P_D and the probability of false positive P_{FP} is given in Section 11.5. We summarize some of those conclusions here: (i) resolving power is very important for minimizing P_{PF}, (ii) for threat scenarios requiring screening of an increasing number of compounds, P_{PF} will rise, and (iii) to offset an unacceptable false positive rate, one must increase threshold levels, which degrades detection probability.

11.3.4 Other MS Analyzers Used for Explosives Detection

Detecting explosives in complex environments requires very sensitive and specific analyzers. Though MS offers excellent detection limits and resolutions (e.g., sensitivity and specificity), general-purpose laboratory instrumentation is not ideally suited for detecting trace levels of explosives in the presence of large abundances of potential interferent compounds. Furthermore MS has traditionally required a skilled operator not only to acquire data, but to interpret it. MS developments have tended to focus on the performance issues and less so on the operational issues.

We review MS developments centering on achieving a trace detector for early warning and first response as opposed to an analytical instrument for post-analysis of a suspected event. A key strategy has been to focus on ionization methods that preferentially ionize explosives relative to typical background compounds. McLuckey and co-workers developed an atmospheric sampling glow discharge ionization (ASGDI) source that could be operated in negative ion mode to achieve high sensitivity and specificity for detection of explosives (as also mentioned above).[17-19,21] They demonstrated coupling it to quadrupole and ion trap MS systems and achieved sensitivities of <10 ppt_v (and <10 pg) for volatized TNT and RDX (without preconcentration), as well as demonstrated sensitive detection for a wide variety of other explosives compounds. The ASGDI source operates at about 1 torr, which is sufficiently high pressure to obtain reasonable densities of explosives, yet low enough to minimize deleterious effects due to ion-molecule reactions. Atmospheric pressure ionization (API) sources, particularly chemical ionization using discharge methods, have been adapted to explosives detection and have achieved exceptional sensitivity. Lee et al. reported a detectable signal for TNT of

10 fg using an API/TOFMS instrument.[22] Work by a SCIEX/British Aerospace team demonstrated detection limits on the order of 1 pg for TNT, RDX, and PETN for an API/triple quad MS system in a program called CONDOR.[23,24] However, API sources, which are also used in IMS, are prone to ion-molecule reactions that can deplete the signal for explosives ions depending on the abundance of certain background compounds.

More sophisticated MS configurations have been demonstrated for selective explosives ionization and detection taking advantage of the high electron attachment cross section for explosives. Chutjian and coworkers developed the reversal electron attachment detection (READ) method, which relies on slowing and reversing an electron beam in a reflectron device.[25,26] The electron energy at the turning point is close to zero where the electron capture ratio is greatest. Laramie and coworkers developed the electron-capture negative ion MS (ECNIMS) system.[27] This system varies the electron energy, which enables differentiation of different types of explosives by monitoring the electron energies at which the dissociated NO_2^- ion appears. Because the READ and ECNIMS systems employ ionization in the high vacuum region of the MS, sensitivity is compromised by the low molecular densities in the ionization region.

11.4. RESULTS

In this section we present results to illustrate the capabilities of the QitTOF MS analyzer coupled to an electron attachment source that have been developed in our laboratories for commercial deployment of an explosives detector.[28,29]

11.4.1. Mass Spectral Signatures

The key to an effective trace explosives detection system is the simultaneous detectability of a broad range of compounds at trace levels in the presence of background compounds at much higher abundance. Achieving this capability is aided by a selective ionization process that maximizes the ion signal of compounds of interest while minimizing the ion signal from the more abundant background compounds. Furthermore it is essential that each compound have distinct and highly resolved molecular signatures to enable positive identification and differentiation from potential interferents. Figure 11.4 shows electron attachment QitTOF mass spectra of common explosives. These compounds are observed to have distinct mass spectral signatures. Because the spectral signals are very sharp, the probability of overlap with other compounds, such as background compounds, is very low relative to lower resolution detectors such as IMS. Nitroaromatic explosives (e.g., TNT, DNT, etc.) generally give molecular ion signal. Nitramines (e.g., RDX and HMX) give distinct peaks at m/z of 176, 129, and 102, but not at the molecular ion. Nitrate esters give the least distinct spectral signatures due to extensive dissociative electron attachment to give a predominant NO_3^- ion at m/z 62. PETN leads

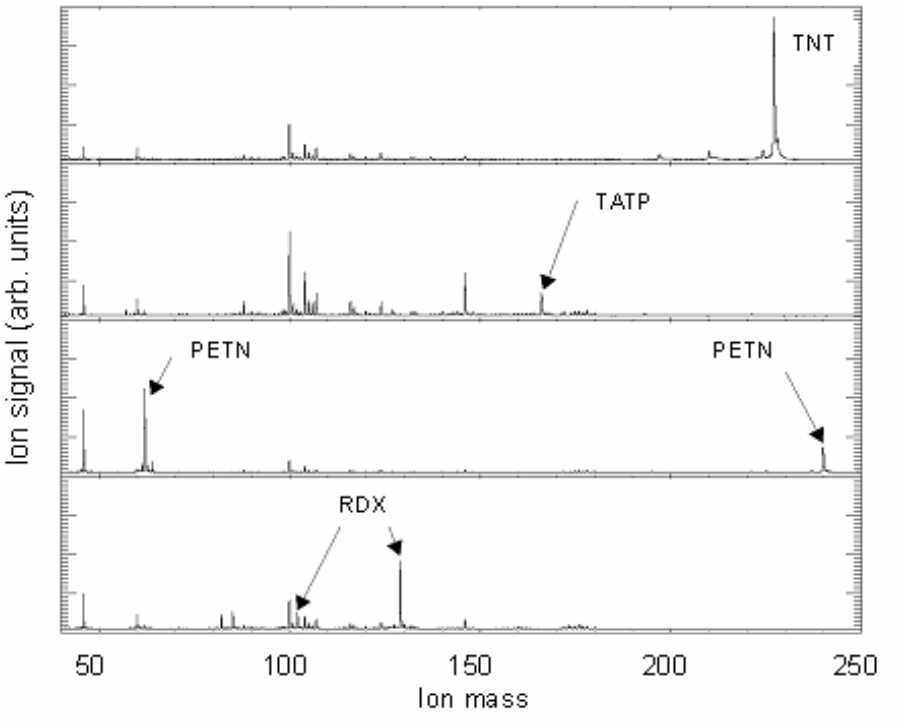

Figure 11.4 MS spectral signatures for selected explosives. Each compound gives a unique spectrum. Nitrate esters all have a common peak at m/z 62.

to significant signal at m/z 242 under optimized conditions to give the potential to distinguish some nitrate esters.

The spectra in Figure 11.4 were recorded from headspace vapor either at room temperature (TNT, PETN) or elevated temperature (about 50°C for RDX). For TNT this corresponds to a saturated headspace vapor pressure of less than 10 ppb. At these levels strong signal is observed with relatively weak signal from room air. Explosives compounds that have been detected by the MS detector with high sensitivity include TNT, ADNT, DNT, MNT, TNB, DNB, DMNB, RDX, HMX, EGDN, NG, PETN, and TATP.

11.4.2. MS/MS Analysis

For molecular screening purposes a single stage of MS is usually sufficient to alert to the presence of explosives compounds while maintaining a sufficiently low false positive rate. However, if a more definitive identification is needed the Qit-TOF mass analyzer allows additional stages of ion mass identification through the process of ion mass-selected collision-induced dissociation (CID). In this method the presence of a target ion signal can be used to trigger an excitation waveform in the QIT that excites the target ion to high kinetic energy. When these energetic ions collide with the buffer gas in the trap (typically ambient air), they dissociate to fragment ions. The fragment ion signals are typically very specific to given

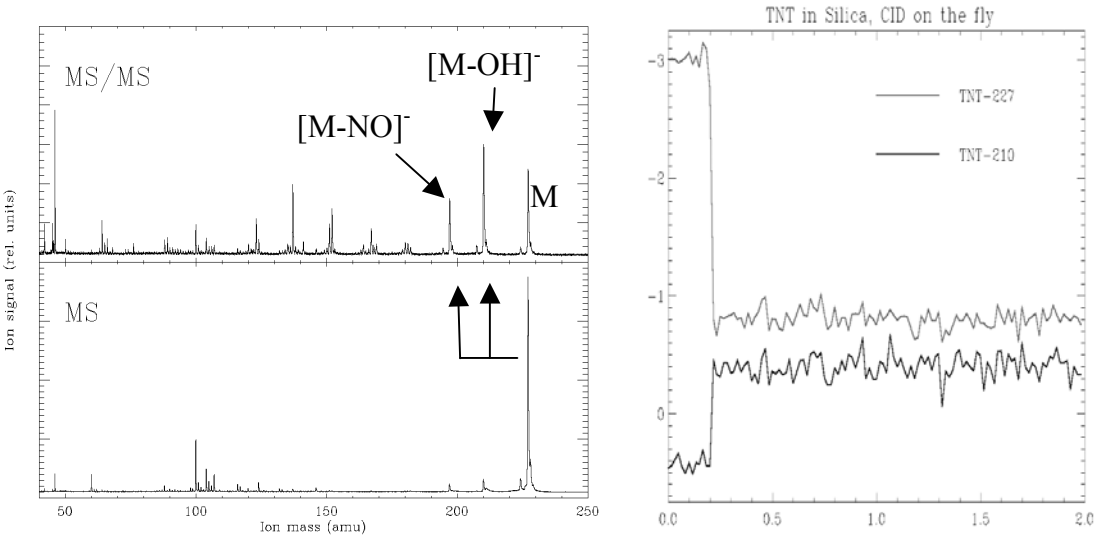

Figure 11.5 TNT detection using MS/MS. (Left) MS and MS/MS spectra. (Right) molecular and fragment ion signal vs. time showing speed and stability of MS/MS analysis (time in s).

compounds and greatly increase the confidence in the identification of target compounds.

Figure 11.5 shows an example of detection of TNT headspace vapor at room temperature in MS mode and in MS/MS mode. In the latter example, the detector is programmed to trigger an excitation waveform when an ion signal at m/z 227 (TNT) is observed. The observation of fragment ions at m/z 210 and 197 is positive identification of TNT.

11.4.3. Limits of Detection

The electron attachment source coupled to the QitTOF MS analyzer achieves excellent sensitivity. A limit of detection (LOD) was measured for a wide variety of explosives compounds by depositing known quantities of compound onto a heated tube connected to the inlet of the MS detector. The tube was then rapidly heated to desorb the compound, which flowed into the ionizer using room air as a carrier gas. Figure 11.6 shows a linearity plot for TNT. The LOD is defined as the quantity of compound that gives a signal intensity that is a factor of three greater than the standard deviation of the background signal (i.e., 3σ). The LOD for TNT is about 1 pg. Similar measurements give LODs for RDX and PETN of about 5 pg and 20 pg, respectively. All other compounds tested fall in the LOD range of 2-20 pg, except DMNB and ANFO, which are less sensitive.

The ion source was described above as operating well below atmospheric pressure, which greatly reduces the incidence of undesirable ion-molecule chemistry. In other words, the ion source is kinetically controlled which means that the ionization process is preserved by the short time the molecules are in the source

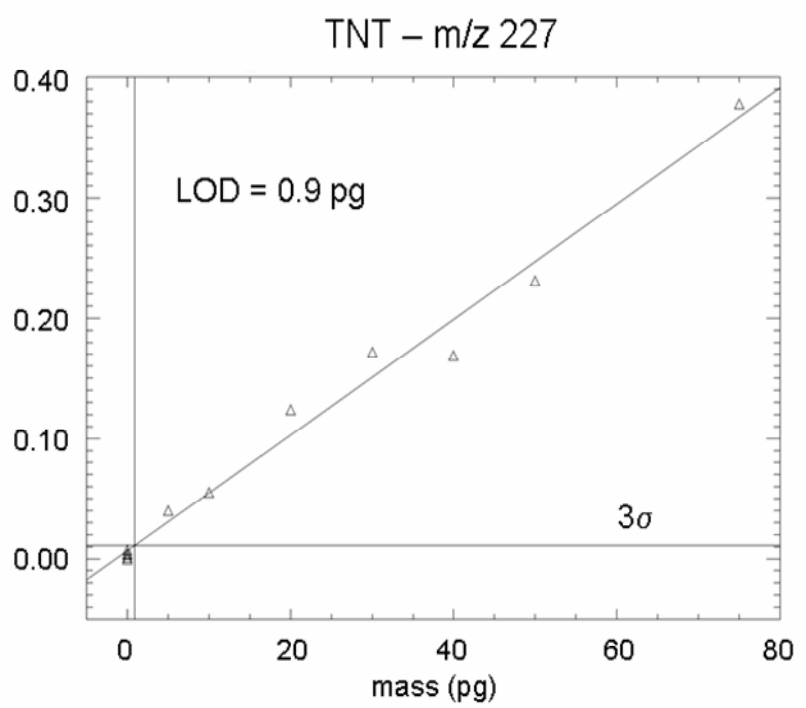

Figure 11.6 Detector sensitivity. 3σ limits of detection are 1 pg for TNT, 5 pg for RDX, and 20 pg for PETN.

and that the ions typically do not have time to exchange charge or reach thermodynamic equilibrium. Because of this property, the detector is much less susceptible to masking agents than are detectors that use atmospheric pressure ionizers. To illustrate this advantage, Figure 11.7 shows the detection of TNT by itself and in the presence of a masking agent at 5000× the mass of the TNT. This shows that a large abundance of masking agent has minimal effect on the detectability of TNT.

11.5. DETECTION ACCURACY – A MODEL

11.5.1. False-Positive Analysis

Resolving power R is a measure of specificity and is a primary factor contributing to the probability of false positives. The salient issue is the probability that a background signal will overlap with a target explosives signal. We can qualitatively express this probability using a Poisson distribution function of the form

$$P(a) = e^{-m}\left[\frac{m^a}{a!}\right] \tag{11.1}$$

where m in this case is the fraction of all detection channels that are target channels and $P(a)$ is the probability that the presence of background signals will fall on

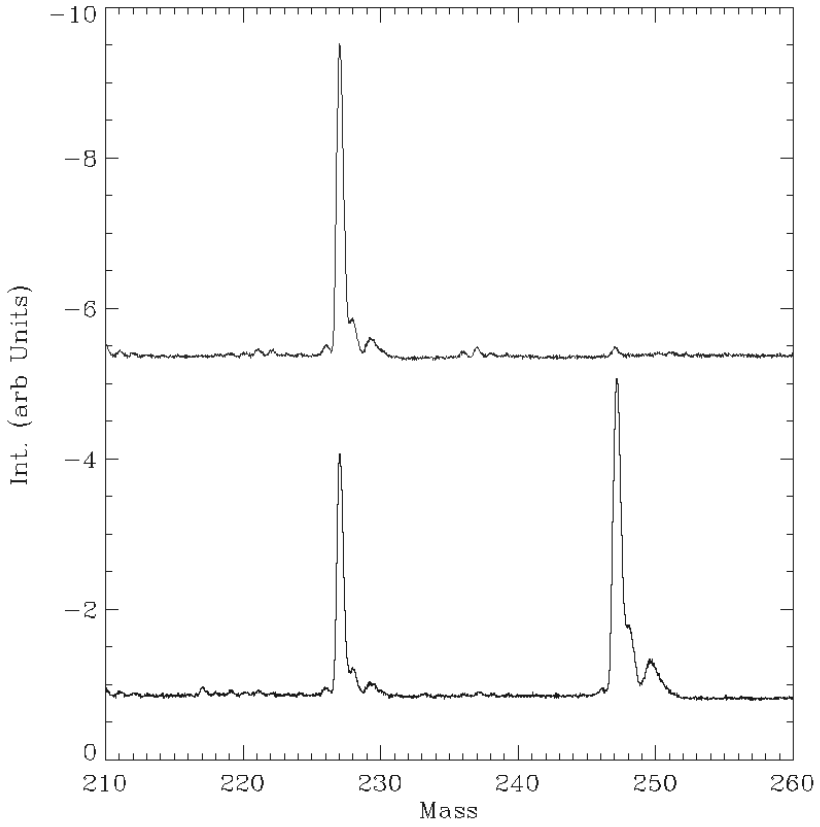

Figure 11.7 Spectrum showing injection of 2 ng of TNT (upper) and injection of 2 ng and 10 micrograms of 1-nitropyrene.

target channels by *a* times. A value of *a*>1 is only relevant if there is more than one background signal. The value of *m* is given by

$$m = N_b \frac{N_e}{R} \tag{11.2}$$

where N_e is the number of ion masses being detected for the target explosives compounds, N_b is the number of all background ion masses whose intensity exceeds the threshold intensities for the target explosives signals, and *R* is the detector resolution. P_{FP} is related to *P(a)* by summing over the probability of background signals overlapping with target signals one, two, three … (a=1,2,3 …) times by the expression

$$P_{FP} = \sum_a P(a) \tag{11.3}$$

The probability of a background signal overlapping with a target signal once [e.g., *P(a=1)*] will normally be the dominant term in Eq. (3), but the higher *a* terms can

become significant if the number of background signals N_b becomes large. The analysis of P_{FP} using the above Poisson analysis is approximate because it does not assume different threshold levels for different explosives signals nor strategies based on detection of multiple ion signals for a single explosive compound. However, the Poisson distribution is very useful for making qualitative assessments of how P_{FP} depends on resolving power R and on the number of explosives compounds that can be screened simultaneously.

11.5.2. Receiver Operator Characteristics (ROC)

Sensitivity and specificity are the figures of merit for screening detectors. Sensitivity is related to the limit of detection and is important for maximizing P_D for some required detection concentration. Specificity is related to how well the instrument can discriminate between different compounds and is important for minimizing P_{FP}. The P_d and P_{FP} response is strongly dependent on the target threshold concentration required. By setting the threshold level low (to very sensitive levels), the P_d will increase, however, P_{FP} will also increase because the probability of signal noise or background exceeding the threshold increases with decreasing threshold level. Raising the threshold level to reduce P_{FP}, however, increases the risk of missing a target compound (decreased P_D). A convenient way to represent the dependence of P_D and P_{FP} on threshold level is by making a series of measurements and plotting P_D vs. P_{FP} at the required threshold concentration. This type of signal detection analysis was advanced during World War II for the monitoring of radar images where it was necessary for radar receiver operators to make judgments on whether a blip was due to enemy or friendly objects, or just noise. Consequently the analysis is known as "Receiver Operator Characteristics" or ROC. Figure 11.8 illustrates the relationship between linearity plots of intensity (and intensity variation) vs. concentration to ROC plots or what are more often called ROC curves. Basically, what is desired is for the distribution of signal level at a required concentration to be completely separated from the distribution of signal level for the background. ROC curves can be generated from a series of measurements at one concentration or a series of concentrations as shown in Figure 11.8.

The ability to discriminate target signal from background constitutes specificity. Figure 11.9 illustrates by way of ROC curves the characteristics of P_D vs. P_{FP} for prototypical high and low specificity detectors.

11.5.3. MS vs. IMS Accuracy

It is possible to assess the relative susceptibility of MS and IMS to false positives using the qualitative Poisson analysis in Section 11.5.1. We begin by assuming typical resolutions for MS and IMS of R = 300 and 30, respectively. First we evaluate the detection accuracy of MS and IMS for detection of varying numbers of target explosives ion signals N_e. For simplicity we assume that there is only one background ion signal that exceeds the threshold intensity for the target ion sig-

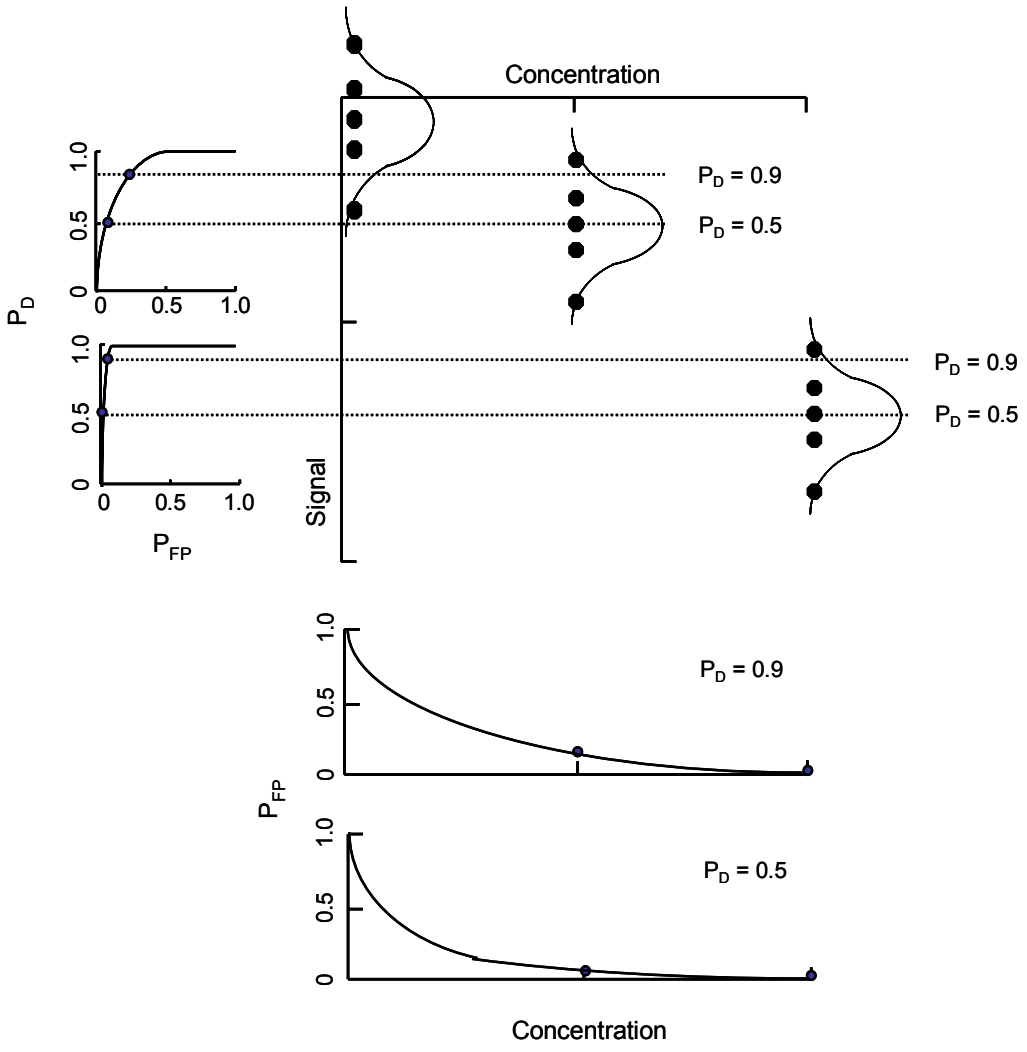

Figure 11.8 Basis for taking signal data at different concentrations to generate ROC curves for showing the P_D and P_{FP} dependence.

nals. We will then be assessing the probability that this background ion signal overlaps with a target ion signal to give a false positive. Keep in mind that the number of background ion signals that can potentially trigger a false positive is generally greater than one and is a function of the level of the threshold intensity used for detecting target compounds, as will be consider below. Figure 11.10 summarizes the value of P_{FP} (*~P(a)*, Eq. 3) for a small and large number of targeted ion masses (N_e = 3 and 10, respectively). These results show that with regard to false positives an analyzer with low resolving power may be fine for a limited number of targeted compounds (e.g., N_e =3) , however, P_{FP} becomes excessive for increasing number of target signals. Higher resolution is clearly very important for enabling a greater number of ion signals that can be simultaneously monitored while still maintaining acceptable P_{FP} values.

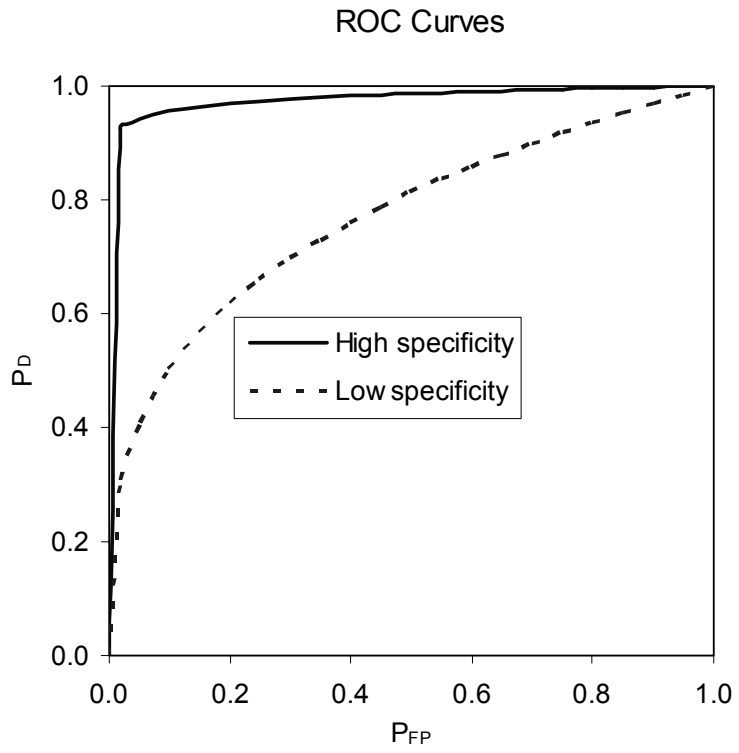

Figure 11.9 Illustrative example of ROC curves for a screening system with high and low specificity.

We now consider how P_{FP} depends on the number of background signals N_b. This number will depend on the complexity of the sample, but also as noted above is directly related to the threshold intensity of the target ion signals chosen for analysis. Figure 11.11 shows the dependence of P_{FP} on N_b for the cases of $R = 30$ and 300 and $N_e = 3$ and 10. Not surprisingly, high R is directly correlated with low P_{FP}. By increasing the threshold levels, the value of N_b will decrease as will P_{FP}. However as illustrated in Figure 11.9, the detection probability P_D will also decrease. This trade-off leads to an important judgment call when setting screening instruments. *In situations where the frequency of positive events is very low, it is tempting to increase the threshold intensities in order to minimize the inconvenience of false positives. However, if a threat scenario demands a high P_D, the importance of high resolving power becomes very clear.*

The above analysis may be summarized as follows:

- The false positive rate is a function of the number of background signals.
- The probability of a background signal triggering a false positive becomes less likely for analyzers with higher resolution.
- The greater the number of explosives that are targeted for detection, the greater the probability that background signal will trigger false positives.

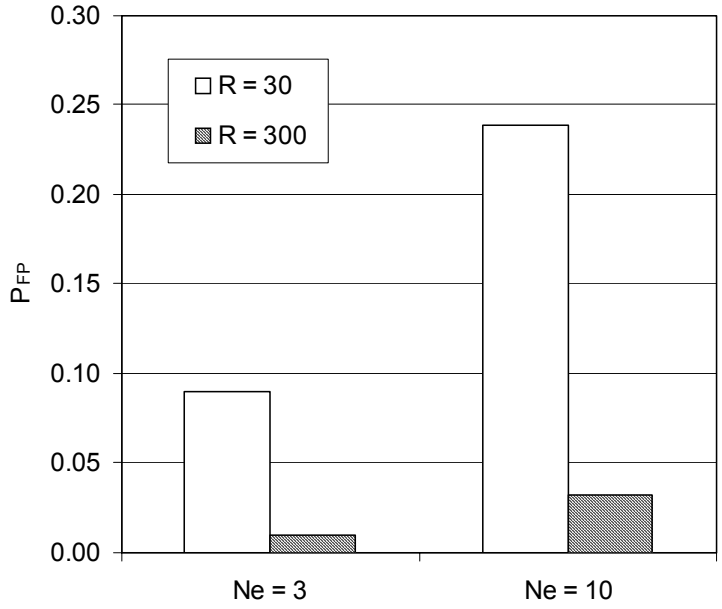

Figure 11.10 Dependence of P_{FP} on number of targeted explosives ion signals N_e and resolution R.

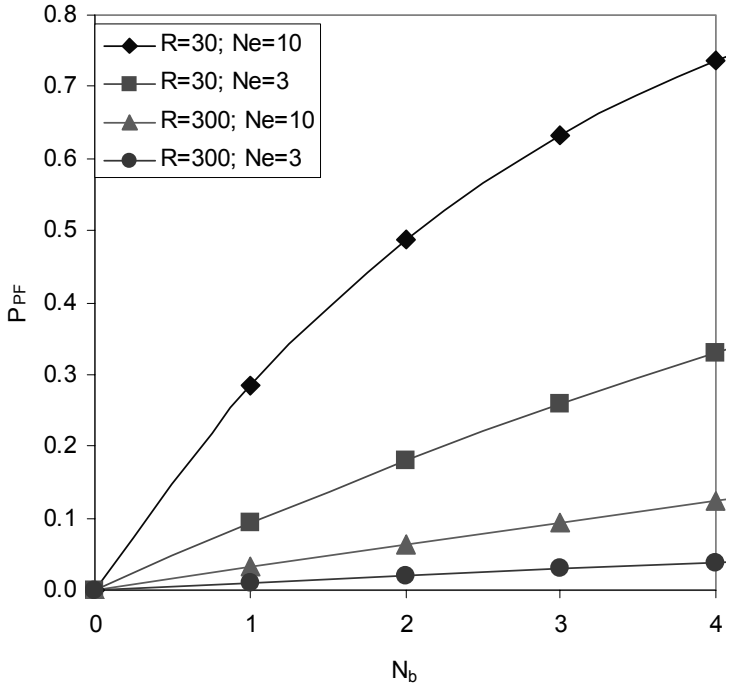

Figure 11.11 Dependence of P_{FP} on number of background ion signals N_b and resolution R.

- False positives may be reduced by raising the threshold intensity for alarming on a target explosive; however, this comes at the expense of a lower detection probability.

11.6. APPLICATIONS

11.6.1. Personnel Screening

The lack of a capability to screen for explosives hidden on an individual is a major vulnerability in aviation and general security. Personal privacy issues and perceived health risks have deterred the use of bulk detectors, such as x-ray, x-ray backscatter and millimeter wave, for screening of individuals for concealed explosives. Consequently, the TSA is focused on trace detection as the best solution for passenger screening in airports. The TSA has determined that individuals carrying as little as 1 lb of concealed explosives get sufficiently contaminated to be detectable by portal devices that use trace detectors. The level of contamination on an individual's exterior clothing that can be routinely detected by the best portal devices is about 1 μg or about 1 part in 10^9 of the explosive mass.

The method of sampling individuals is essentially "sniffing" their exterior (e.g., clothing and skin) for contamination from handling explosives. Because the vapor pressures of explosives are very low, the sample that is collected consists of particles and residue. Though it is desirable that the sampling of people not make contact with the subject, a contact portal is a viable option and has been demonstrated. Contact is usually done by using paddles that act by vacuuming particles from clothing and flowing the sample to a concentrator.[30,31] Non-contact collection is usually done by impinging the individual with air jets to shake loose the particles and then flowing the large air volume in the portal through a concentrator to remove the collect the particles.[28,29,32] Non-contact is obviously the preferred method provided it achieves sufficient collection efficiency from people. Different methods of sample collection of the dislodged particles have been developed in current portals. One method developed by Sandia National Laboratories involves pulling the air volume through a metal mesh concentrator. The sample is then thermally desorbed by passing a current through the metal mesh.[32] The vaporized sample is then analyzed by a detector such as IMS or MS. Another method relies on the natural convective boundary layer surrounding individuals. This air volume rises and is collected and detected at the top of the portal opening.[33]

Portals have been developed with and without doors. Open portals without doors permit easy passage for passengers and a less claustrophobic environment. Closed portals with doors offer access control and more efficient sample collection. Figure 11.12 shows a portal with doors and Figure 11.13 shows the internal components for collecting and analyzing sample. For this particular portal the airflow is done in a closed loop using a blower and concentrator without interaction with external air that can dilute the sample concentration.

Figure 11.12 Picture of a MS-based portal for screening people. This device uses doors to control access.

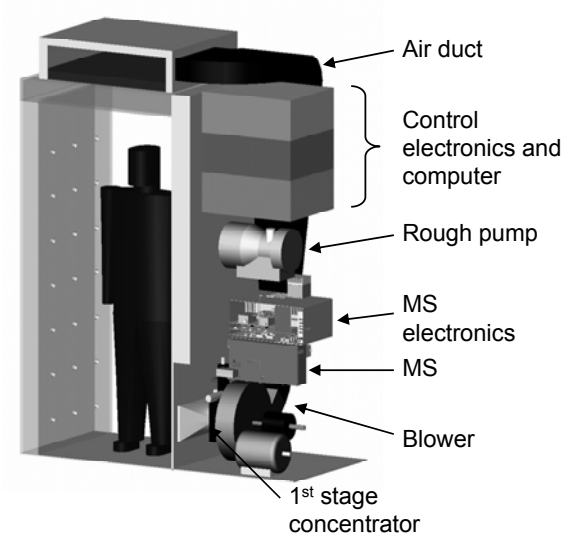

Figure 11.13 Internal components of the MS-based portal. 1st stage refers to the concentrator.

Unfortunately there are not many publicly released test results for portals (test results are generally classified). Testing is typically done by two methods. TSA testing is conducted using patches of cloth upon which calibrated quantities of explosives are deposited. These patches are adhered to various locations on people to test for collection and detection efficiency. The quantities of explosives placed on these patches represent levels of contamination the TSA has determined are typically for bomb carriers. Another method primarily used by overseas users is to place bulk explosives on individuals and test for the detection of actual contamination. In order for the test to be realistic, the concealed explosives must be on individual sufficiently long for contamination to occur, though generally the "soak time" is only several minutes, rather than the more extended periods expected of an actual bomber.

11.6.2. Other Applications

ETD detectors using IMS are ubiquitous in airports with over 6000 units purchased for U.S. airports alone since 9/11. These detectors use cloth swipes to collect sample as described earlier. Recently Hitachi introduced a MS version of the ETD detector using the swipe method. Little data is available at this time.

Another novel application of MS is the screening of boarding passes for explosives (and narcotics).[34] The MS detector in that case uses APCI and a triple quadrupole MS analyzer operating in MS/MS mode. Detection is made by monitoring parent and characteristic fragment ions (e.g., those that differ in mass by the NO_2 or NO fragment). The boarding pass screener was shown to operate at a throughput rate of up to 1000 boarding passes per hour and was able to detect between 10 and 50 pg of explosives residue from the surface of the card depending on the compound monitored.

11.7. SUMMARY AND CONCLUSION

Mass spectrometry is often referred to as the gold standard for molecular detection and identification. Traditionally a lab-based research tool, MS is now being developed for automated operation in rugged environments by technically unskilled operators. It is therefore inevitable that MS will find a major role in security applications, particularly where detection accuracy outweighs the requirements for size and cost. In this chapter we compared IMS to MS, but in fact the determining factor regarding which detector to deploy depends on application. When inexpensive, handheld analyzers are required, IMS is the best choice. For stationary applications where compactness is less important then the superior performance of MS offers compelling benefits.

ACKNOWLEDGMENTS

We are grateful to Dr. Tom Chamberlain and Dr. Richard Lareau of the TSA/FAA for their support of the Syagen/Sandia collaboration. Finally this work was made possible by the exceptional contributions of the Sandia team consisting of Kevin Linker, Chuck Rhykerd, and Frank Bouchier.

REFERENCES

[1] Moore DS. Instrumentation for Trace Detection of High Explosives, Rev. Sci. Instrum. 2004, 75:2499-2512.

[2] Steinfeld JI, Wormhoudt J. Explosives Detection: A Challenge for Physical Chemistry, Annu. Rev. Phys. Chem. 1998. 49:203-32.

[3] Kahn SM, ed. Proc. 1st Proc. Int. Symp. Explosives Detection Technology, 1992, FAA, Atlantic City.

[4] Makky WH, ed. Proc. 2nd Explosive Detection Technology Symp. & Aviation Security Technology Conf. 1996, FAA, Atlantic City.

[5] Buckles BA. Federal Register, 2002, 67: 20864.

[6] Yinon, J. Mass Spectrom. Rev. 1991, 10: 179.

[7] Eiceman, GA.; Karpas, Z. "Ion Mobility Spectrometry," 1994, CRC Press, Boca Raton, FL.

[8] Spangler GE, Miller RA. Int. J. Mass Spectrometry 2002, 214: 95-104.

[9] Jenkins AL, Bae SY, Lochner JM, Jensen JL. in Proc. 2nd Joint Conf. on Point Detection for Chem. Bio. Def., 2004, Williamsburg, VA.

[10] Rose A, Zhu ZG, Madigan CF, Swager TM, Bulovic V. Nature 2005, 434:876.

[11] March RE, Todd JFJ. "Practical Aspects of Ion Trap Mass Spectrometry," Vol 1, 1995, CRC Press, New York.

[12] Michael SM, Chien BM, Lubman DM. *Anal. Chem*. **1993**, *65:* 2614.

[13] Michael SM, Chien BM, Lubman DM. *Rev. Sci. Instrum*. **1992**, *63:* 4277.

[14] Syage JA, Evans MA. *Spectroscopy, 2001,* **16:**14.

[15] Syage JA, Nies BJ, Evans MD, Hanold KA, *J. Am. Soc. Mass Spectrom*. 2001, **12:**648.

[16] Ding, L, Kawatoh E, Tanaka K, Smith AJ, Kumashiro S. Proc. SPIE, 1999, 3777: 144.

[17] Asano KG, Goeringer DE, McLuckey SA. *Anal Chem*. 1995, **67:**2739.

[18] Chambers DM, McLuckey SA, Glish GL, *Anal Chem*.1993, **65:**778.

[19] McLuckey SA, Glish GL, Asano KG, Grant BC. *Anal Chem*. 1988, **60:**2220.

[20] National Research Council, "Opportunities to Improve Airport Passenger Screening with Mass Spectrometry," 2003, National Academies Press, Washington DC.

[21] McLuckey SA, Van Berkel GJ, Goeringer DE, Glish GL, *Anal. Chem*. 1994, **66:**689A, 737A.

[22] Lee HG, Lee ED, Lee ML. Proc. Int. Symp. Explosives Detection Technol., 1st , edited by Khan SM, Atlantic City, FAA, 1992, 619.

[23] Stott WR, Davidson WR, Sleeman R, Proc. SPIE, 1994, 2092: 53.

[24] Bennett G, Sleeman R, Davidson WR, Stott, WR, Proc. SPIE, 1994, 2276: 363.

[25] Boumsellek S, Alajajian SH, Chutjian A, J. Am. Soc. Mass Spectrom. 1992, 3: 243.

[26] Boumsellek S, Chutjian A, Anal. Chem. 1992, 64: 2096.

[27] Laramee JA, Kocher CA, Deinzer ML, Anal. Chem. 1992, 64: 2316.

[28] Syage JA, Hanold KA, Hanning-Lee MA, "Mass Spectrometry Based Personnel Screening System," Proc. INMM – 42nd Annual Meeting, (2001).

[29] Chamberlain T, Hanold K, Hanning-Lee M, Liu Y, Syage J, Linker K, Rhykerd C, Bouchier R, "Multi-Threat Mass Spectrometer Detector," *Proc. of the ICAO Workshop,* (DERA, UK, 2000).

[30] Wendel GJ, Bromberg EEA, Durfee MK, Curby W. See Ref. 4, p. 181.

[31] McGann W, Jenkins A, Ribeiro K. See Ref. 3, p. 518.

[32] Parmeter JE, Linker KL, Rhykerd CL, Hannum DW. See Ref. 4, p. 187.

[33] Settles GS, Ferree HC, Tronosky MD, Moyer ZM, McGann WJ, 3rd International Symposium on Explosive Detection and Aviation Security, 2001, FAA, Atlantic City.

[34] Sleeman R, Richards SL, Stott WR, Davidson WR, Luke JG, Keely BJ, Fletcher I, Burton A. Proc. of the 50th ASMS Conf. on Mass Spectrom. and Allied Topics, 2002, Orlando, FL.