Existing and Potential Standoff Explosives Detection Techniques

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Committee on the Review of Existing and Potential Standoff Explosives Detection Techniques

Board on Chemical Sciences and Technology

Division on Earth and Life Studies

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This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

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Executive Summary

Recent terrorist attacks have led to an elevated concern with regard to national and international security and have prompted security measures to be increased. Following the 1988 bombing of Pan Am Flight 103 over Lockerbie, Scotland, airline security procedures, such as luggage and passenger screening, were assessed by a number of organizations, including the Federal Aviation Administration, the Office of Technology Assessment, and the National Research Council (NRC). These groups also looked into new bomb detection methodologies. The terrorist attacks of September 11, 2001, and the attempted shoe bombing of American Airlines Flight 63 in December 2001, led to reexamination of the issues related to airline security, but once more the increased scrutiny focused on the screening of luggage and passengers utilizing close-proximity explosives detection.

These security measures, however, were not designed for scenarios in which individuals appear in an open environment and a security decision must be made at a distance from the suspected explosive. For scenarios such as these, *standoff* explosives detection is required, where physical separation puts individuals and vital assets outside the zone of severe damage should an explosive device detonate. The difficulty of the standoff explosive detection task is exacerbated by several factors, including dynamic backgrounds that can interfere with the signal from the explosive, the potential for high false alarms, and the need to ascertain a threat quickly so that action can be taken.

To assist the Defense Advanced Research Projects Agency (DARPA) in its efforts to develop more effective, flexible explosive and bomb detection systems, the NRC has agreed to examine the scientific techniques currently used as the basis for explosives detection and to determine whether other techniques might provide promising research avenues with possible pathways to new detection protocols. This report addresses the following tasks:

- Describe the characteristics of explosives, bombs, and their components that are or might be used to provide a signature for exploitation in detection technology.
- Consider scientific techniques for exploiting these characteristics to detect explosives and explosive devices. Particular consideration must be given to discriminating possible signals from the background and interferents that can be anticipated in real applications.
- Discuss the potential for integrating such techniques into detection systems that would have sufficient sensitivity without an unacceptable false-positive rate. In proposing possible detection protocols, give consideration to trade-offs between desirable system characteristics, including relative ease of implementation.
- Propose areas for research that might be expected to yield significant advances in practical explosives and bomb detection technology in the near, mid, and long term.

CHALLENGES IN STANDOFF DETECTION

Successful standoff explosives technology involves detection of a weak signal in a noisy environment. This background is also often dynamic, so that exemplary performance in controlled laboratory settings may be quite poor performance in the field. The speed with which the detection is performed is a crucial factor when a potential threat is rapidly approaching. Finally, all explosives detection methods both generate alarms in the absence of threat, and do not alarm in the presence of a true threat.

ELEMENTS OF DETECTION: CONCEPTS AND THREATS

Detection of explosives involves receiving a signal, processing the signal, assessing the results, and ultimately deciding whether explosives are present or not. To assess the performance of a given detection methodology, concepts such as sensitivity (a measure of when a detector alarms if the substance of interest is present) and the receiver operating characteristic (ROC) curves are considered. ROC curves, which plot the probability of detection against the probability of false alarm (and thus combine sensitivity and specificity performance), are of particular interest because they provide a means of comparing two competing detection techniques.

Although these performance measurements are important, it is equally important to note that for a very low probability of explosives presences in the field, even tests with very high sensitivity and specificity can have unacceptably low proportions of observed alarms yielding true threats. It is important to note here the subtle but important difference between the rate of laboratory “false alarms” (the probability of an alarm given that no explosives are present) and the rate at which observed alarms in the field turns out to be false (the probability that no explosives are present given than an alarm has sounded). The latter is of particular concern for implementation because users may cease to react to alarms if this rate is exceedingly high. The proportion of alarms that turn out to be false associated with a particular detector is a function of the detector’s sensitivity, specificity, and the underlying probability of the true presence of explosives.

When assessing a detection system built on multiple detection technologies, a measure called system effectiveness (SE) is used to characterize the overall system performance in the presence of environmental, threat, and other potential detection confusers. SE is a measure of the degree to which a detection system can be expected to achieve a set of specific mission requirements; it can be expressed as a function of availability, dependability, and capability.

In considering any situation involving standoff detection of explosives, one must have some general understanding of the scenarios of concern (e.g., suicide bombing, concealed bombs in roadways, bombings in a stadium) and the parameters that describe the explosive device and the surrounding environment. Two scenarios were given primary consideration by the committee. The first—suicide bombings—is of concern because there is little time or opportunity to detect the bomb before detonation. The second—wide-area surveillance, or monitoring a large area for the presence of explosives—is of interest in order to prevent the illicit introduction of high explosives into an area being monitored.

These scenarios can be further refined by defining and identifying threat parameters involved in any particular scenario, including the following:

- *Threat parameters related to the local environment.* Particularly important is the identification of the intended target. Other parameters include meteorological conditions, as well as the possible presence of trace explosives and any other chemicals in the area where the detection will take place.
- *Threat parameters that describe the device.* These include the type of explosive, its mass, and the device’s construction.

- *Threat parameters that characterize the bomber.* These can include both psychological and physiological aspects of the bomber or bomb maker.

In describing explosives detection systems, two or more explosives technologies are considered completely orthogonal if the detection methods detect independent characteristics of the explosives device. Three potential significant advantages of a system of orthogonal detection technologies are:

1. a higher probability of detecting explosives over a range of potential threats,
2. increased difficulty in defeating the detection system, and
3. greater effectiveness in detecting explosives than any single technology.

SYSTEMS OF DETECTION

A positive indication of an explosives threat from a sensor does not mean that an explosive is present. Standoff explosives detection must take into account more than the single sensor indication, because a system that depends on a single signal yields excessive false alarms. The intent of a system of orthogonal detectors is detection of an explosive when one is present and extremely few indications of an explosive when one is not present. In order to achieve this goal, careful system design is needed to resolve ambiguous sensor information. In addition, a system allows one to consider additional aspects such as mass of explosive, available sampling time, available response actions and times, and the role of human judgement in assessing effectiveness.

To design an effective standoff explosives detection system—explosives detection where physical separation puts individuals and valuable assets outside the zone of severe damage from the potential detonation of an explosive device—the following issues must be considered:

- Multiple sensors of different types increase the number of possible indications that can be searched for in the environment.
- Both specificity and sensitivity can continue to increase with additional sensor types, as long as there are indications that each sensor type can find an explosive if an explosive is present during its interaction with the environment.
- The result coming from a standoff explosives detection system is not static, nor is it desirable that it be static.
- Novel threats will be recognized only incidentally via intersection with threat parameters currently considered by the system.

- Choice of sensor types and system design must be integral with the nature of the threats.

Recommendation: Research into *both* new sensor types *and* new systems of real-time integration and decision making is needed. The sensor system research agenda should emphasize the principle of *orthogonality* in mathematical consideration, sensor system design, and design of information leading to true detection

Threat Identification

Threat parameters can be used to identify the performance challenges that must be addressed when developing standoff explosives detection. These threat parameters include, but are not limited to, the following:

- Means of delivering the device to the point of detonation
- Location and timing of detonation
- Composition of the explosive
- Mass of the explosive
- Other components of the explosive device
- Dispersed materials

Additional considerations that may impact standoff explosives detection include ambient environmental conditions and the influence of humans present in the event.

Recommendation: Research is needed into the development of scenario-based threat parameters-decision trees for real-time decision making.

Recommendation: Because discrimination of a useful signal in a noisy environment is always a problem, a research effort should be aimed at determining baseline ambient conditions and detecting changes in ambient conditions in real time.

System Effectiveness

In order to properly evaluate a system comprised of multiple technologies, system effectiveness must be utilized. Within these orthogonal detection systems, both false positives (false alarms) and false negatives (misses) will occur. While system effectiveness will be a function of the sensitivity and specificity of the system, the system in turn will comprise the sensitivity and specificity of each component, as well as how the system is put together.

Recommendation: Research is recommended into methodologies to quantify system effectiveness (SE) for systems of sensors (a detection system) and for systems of detection systems allowing for noisy input from many sensors. Of particular importance is the definition and evaluation of a full spectrum of "false-positive" signals ranging from detector reliability, legitimate signals that do not represent true threats, or operator interpretation of detector signals. Appropriate ROCs and other measures of performance for such systems should be developed.

Distributed System, Distributed Sensors

The architecture of a system of explosive devices could consist of multiple arrays of different types of technologies. Distributed arrays can be fixed in one location with multiple sensors over a geographical area. While there are advantages in wide area coverage and standoff potential, there are significant technical challenges, including

- Communication between sensors
- Sensor sampling
- Data transfer
- Fusion of information
- Sensor fault detection
- Time to sample
- Detection decision making
- Deployment issues.

Recommendation: Research is recommended into rapid, remote collection and concentration of explosives samples and into distributed, low-cost sensors. Included here are small (nano) and perhaps mobile sensors, distributed arrays of sensors, and the use of convective streams with or without airborne adsorbing particles to gather chemical samples.

Recommendation: Research is needed on the integration of information from distributed orthogonal sensors to achieve real-time conflict resolution and decision making with high system effectiveness, and on integration tools based on data fusion and decision fusion. In addition, research coupling parallel sensors via decision fusion with sequential sensor systems may provide valuable insights.

A system for standoff detection cannot be static. Intended capability and ongoing performance must change to respond—at least—to new threats, new background conditions, changes in existing threats, and threats actively attempting to defeat the system.

Recommendation: Research is recommended to envision and devise real-time sensor system threat detection that adapts to new threats, new backgrounds, and new threats that behave like background. A system that autonomously evolves should be a focus of research, including methods to evolve the system design to increase system effectiveness and orthogonality, given detection anomalies.

CHEMICAL CHARACTERISTICS OF BOMBS

The diversity of potential explosive formulations makes detection of explosives based on their chemical characteristics a challenge. However, this diversity suggests that a consideration of the elemental composition of explosives might lead to new or improved detection approaches. If elemental formulations are considered, then few common chemicals would be mistaken for explosives.

All self-contained explosives must contain both oxidizing and reducing agents. This leads to a high preponderance of the more electronegative elements nitrogen and oxygen, and helps make explosives readily detectable by ion mobility spectrometry. As new explosives containing other electronegative elements are utilized, detection based on these atoms may be possible.

Recommendation: Improved detection systems will lead to development of new explosives. Research is needed on the identification and characterization of new chemical explosives that do not utilize nitrogen and have very low vapor pressures, for example, ionic liquids.

Several different atomic and molecular properties might be exploited in explosives detection. Nuclear properties identified from gamma-ray emissions provide a unique signature for some elements. Core electron ionization and subsequent characteristic X-ray emission gives rise to another broad class of methods that might be used for atom identification. Molecular spectroscopic techniques can be used to uniquely identify explosive molecules in the vapor phase, but the low vapor pressure of many explosives limits their use. LIDAR (light detection and ranging) techniques show promise for standoff applications; however, selectivity is problematic when detecting complex explosives mixtures with broad spectroscopic properties. Sensor array detectors (e.g., resistive, fluorescent) or "electronic noses" offer the possibility of specificity with relatively inexpensive instrumentation. Key issues that have to be addressed for these arrays are sample collection and concentration.

Recommendation: Research into the vapor space surrounding the bomber may lead to improved means of explosives detection. An increased quantitative understanding of vapor plume dynamics is required for application to explosives with high-volatility components such as triacetone triperoxide (TATP).

EXISTING DETECTION TECHNIQUES AND POTENTIAL APPLICATIONS TO STANDOFF DETECTION

Explosives detection techniques usually focus on either bulk explosives or traces of explosives. Detection of bulk explosives is carried out either by imaging characteristics of the explosive device or by detection of the explosive itself. Trace detection utilizes either emitted vapors from the explosive or explosive particles deposited on surfaces. Many explosives detection techniques are limited either by fundamental physical limits or by the circumstances of a particular scenario, for example, background interference.

Bulk Detection

- *X-rays.* This technology has good potential for imaging at standoff distances of 10 to 15 m. X-ray backscattering images reveal outlines of explosive devices. The imaging distance can be extended by developing new X-ray sources; X-ray optics (lenses and mirrors); and compact, inexpensive remote detection apparatus. An alternative approach may be coded aperture imagers since they are able to achieve high sensitivities with practical devices.
- *Infrared.* Preliminary experiments show that concealed explosives can be detected beneath clothing in an indoor setting using infrared techniques; these are less viable outdoors. To improve these techniques, research is needed on spectroscopic properties of human skin, clothing, and other relevant materials.
- *Terahertz.* Imaging in the terahertz region of the electromagnetic spectrum allows for detection of explosives hidden beneath clothing without exposing people to the danger of ionizing radiation. However, a fundamental limit on image resolution is encountered for wavelengths longer than 300 microns. Therefore, the shortest wavelength possible should be chosen to resolve items in the terahertz region. Absorption of terahertz radiation by atmospheric water absorption is also a limitation.
- *Microwaves (mm waves).* Even though the resolution of images using microwaves is fundamentally limited at standoff distances, explosive devices that use large amounts of metal will give anomalously large reflection that can be detected.

• *Neutrons, gamma rays, magnetic resonance and magnetic fields.* Although the use of neutron and gamma-ray explosives detection suffers from a combination of potential health hazards and limitations in sensitivity for standoff detection, explosives detection based on these technologies can potentially be used to screen large cargo containers at points of entry. Magnetic resonance techniques require close proximity and/or a large amount of bulk explosives, making them ill suited to standoff detection. Extremely sensitive magnetometers have been developed to detect metal objects; however, clutter from other metal objects is a significant limitation to their use for standoff explosive device detection.

Trace Detection

• *Optical absorption.* Explosive molecules may be identified by using their ultraviolet (UV), electronic, and vibrational resonances (absorptions). The need for large samples and the use of relatively fragile laboratory instrumentation remove these techniques from the standoff category unless lasers are used (see below).

• *Optical fluorescence.* This technique, for use in detecting granular materials, has standoff potential. Lack of very high sensitivity and problems of environmental quenching must be overcome.

• *LIDAR, DIAL, and DIRL.* LIDAR, differential absorption LIDAR (DIAL), and differential reflectance LIDAR (DIRL) may suffer from sensitivity limits in the 10- to 30-m range due to the very low molecular concentrations of explosive. However, nonlinear optical techniques can be used to increase signal-to-noise ratios since these techniques have the potential for increased signal-to-noise relative to linear techniques.

• *Array biosensors using captured antibodies.* These are not likely to be useful for remote explosives applications unless the size and cost of these sensors are dramatically reduced. Enzymes can detect explosives at the parts-per-trillion level but require concentrators and long analysis times.

• *Biomimetic sensors.* An important avenue for future research is the development of robotic "insects" with onboard sensors or samplers. One would hope to develop low-cost, nonintrusive devices that could be controlled remotely in any weather.

Recommendation: The committee recommends continued research into biomimetic sensing based on animals, but research should focus on distributed, low-cost sensors.

Orthogonal Detector Schemes

Hyperspectral imaging from widely disparate regions of the electromagnetic spectrum and the combination of explosive device imaging with identification of the material composition of the explosive in the device are two general approaches that should be applied in the development of orthogonal explosives detection systems.

Recommendation: Research is needed on new spectroscopic and imaging methods employable at a distance (passive and active). Examples include terahertz and microwave imaging and spectroscopy and X-ray backscattering.

BIOLOGICAL MARKERS

Biologically based systems for explosives detection are quite numerous, but their sensitivity, robustness, and efficacy for standoff monitoring remain undefined. Biological or biosensor approaches for explosives detection combine the specificity of molecular recognition of biomolecules with electronics for signal transduction. In many cases, modern molecular biology has provided the tools to isolate and modify the genes for receptor proteins to make biosensors. Efforts have been made to identify genes that are induced or activated by explosives. The utilization of such information could permit the engineering of plants and animals with luminescence or fluorescence reporter genes for passive monitoring of explosives.

Based on existing data, it appears that a variety of standoff spectroscopic or acoustic surveillance techniques could be used to detect physiological changes in bombers or bomb makers. These changes include body heat signatures, color changes of skin and tissues, and irregularities in heart beat and rate. Approaches such as these could overcome one of the main limitations to the use of biosensors for standoff detection, providing real-time feedback to the detector operator.

Recommendation: Research is needed on biological markers related to physiological changes in persons associated with bomb making and bomb delivery and based on the chemical composition of the explosive.

UNEXPLOITED POTENTIAL BASES OF DETECTION

As part of its charge, the committee considered a number of novel concepts for explosives detection. These concepts are described in detail in Chapter 7. A brief overview is presented here:

- *Dynamic behavior of an explosive vapor plume.* An understanding of this dynamic behavior will assist in the development of standoff explosives detection based on the explosive's spectroscopic properties.
- *Detection of a suicide bomber's local atmosphere.* Electronegative at-

oms present in high explosives may cause electron attachment and a subsequent depletion in negative ions around a person carrying concealed explosives as he or she walks through a background ion field. This depletion may be detectable.

- *Detection by detonation.* Remote detonation could be accomplished by mechanical or acoustic shock, high-intensity electromagnetic pulse, microwave radiation, or radio-frequency (RF) induction heating. This technique could be used only in situations where it was possible to disarm the bomber and explosive device without harming innocent bystanders.
- *Detection by self-reporting sensors.* The presence of explosives would be accomplished using standoff mine technologies, such as neutron activation analysis. Small sensors would be silent until a critical threshold of detection is reached.
- *Standoff Compton backscatter X-ray imaging.* Using low-energy X-rays, a target is illuminated and backscatter photons that have been emitted from the target are collected. Photomultipliers could be used to detect light flashes in plastic that result from these photons.
- *Distributed biological sensors.* Bees, moths, butterflies or other insects would be trained on biomarkers in the bomber such as those described in Chapter 6. Other options include fitting rats trained to detect explosives with a wireless global positioning system (GPS), a bioluminescent reporter gene, and a microphotocell. The goal would be for the rat to find clandestine bomb production facilities in crowded urban areas.

Recommendation: Feasibility studies should be developed on the ideas suggested in Chapter 7 to assess their potential in sensors suitable for standoff detection.

1

Introduction

MOTIVATION

The terrorist bombing of Pan Am Flight 103 over Lockerbie, Scotland, in December 1988, led to an extensive reexamination of procedures in place for airline security.[1] A number of government and nongovernmental organizations, including the Federal Aviation Administration, the Office of Technology Assessment, and the National Research Council, assessed procedures in place for airline security, including luggage and passenger screening, and looked at new bomb detection methodologies.[2] Following the attacks of September 11, 2001, and the attempted shoe bombing of American Airline Flight 63 in December 2001, the issue of airline security was again examined and additional detection and screening procedures were implemented at airport checkpoints.[3]

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[1]For initial responses, see Federal Aviation Administration Research, Engineering and Development Authorization Act of 1990, Public Law 101-508; Aviation Security Improvement Act of 1990, Public Law 101-604; and Federal Aviation Administration Authorization Act, Public Law 103-305.

[2]For example, see National Research Council, Committee on Commercial Aviation Security, *Reducing the Risk of Explosives on Commercial Aircraft*; National Academy Press: Washington, DC, 1990. U.S. Congress, Office of Technology Assessment, *Technology Against Terrorism: Securing Security*; U.S. Government Printing Office: Washington, DC, 1992. U.S. Congress, Office of Technology Assessment, U.S. Government Printing Office: Washington, DC, 1991.

[3]Although terrorist attacks in airlines naturally lead to greater examination of airline security and more awareness of the issue on the part of the general public, examination of airline security is an ongoing process. For example, see White House Committee on Aviation Safety and Security, Final Report to President Clinton, issued in 1997.

Although these terrorist acts were different in nature and execution, the increased security response following each event was based on a common procedure, airport passenger and baggage screening through a portal. In a portal system, each passenger and all luggage receives screening with detectors that are in close contact, at most 1-2 feet away.

As important as airline security and portal screening are, many terrorist threats fall outside the realm of airport portal security. Table 1.1 lists examples of these types of terrorist bombings that have occurred over the last 20 years. For a number of reasons (practicality, lack of awareness of a threat, insufficient checkpoints), screening systems were not in place or were easily defeated in those instances. All of the events in Table 1.1 are different, and none fit into the airport security scenario described above. In each of these events—as opposed to an airport portal screening—individuals or vehicles appear from an open environment and a se-

TABLE 1.1 Selected Terrorism Attacks Outside the Realm of Portal Screening Security

Location	Year	Type of Bombing	Deaths
Israel	2000-present	Suicide (individual)	>200
Najaf, Iraq	2003	Car	~100
UN Headquarters Baghdad, Iraq	2003	Suicide (truck)	~20
U.S. Military Checkpoint Najaf, Iraq	2003	Suicide (car)	4
Mumbai, India	2003	Car (multiple bombings)	45
Jakarta, Indonesia	2003	Car	14
Bali, Indonesia Nightclubs	2002	Car (multiple bombings)	202
USS Cole	2000	Suicide (boat)	19
U.S. Embassies Kenya and Tanzania	1998	Truck	223
U.S. Military Housing Dhahran, Saudi Arabia	1996	Truck	19
Murrah Federal Office Building Oklahoma City	1995	Truck	168
World Trade Center New York City	1993	Car	6
U.S. Marine Barracks Beirut, Lebanon	1983	Suicide (truck)	242
U.S. Embassy Beirut, Lebanon	1983	Suicide (truck)	63

curity decision about the individual or vehicle must be made at a distance. Sampling and sensing in these situations are made difficult by dynamic backgrounds, standoff considerations, and in some instances, pace.

A key component of identifying and responding to an impending terrorist attack that utilizes chemical explosives is to have methods and systems in place to protect military and civilian personnel without the benefit of portal control. This is a daunting challenge. In addition to the challenges of detection in environments with dynamic backgrounds, the variety of different explosives with an array of different chemical structures further complicates this task.

For these reasons, a single type of detector is unlikely to be applicable to all situations in which detection at a distance may be required. Because the problem of explosives detection encompasses so many different potential environments and situations, an essential component of any effective strategy is consideration of different scenarios. These can be broadly divided into two general categories, suicide bombers and wide-area surveillance. Both of these are addressed in this report.

FOCUS OF THE STUDY

The purview of the committee was to consider detection of chemically based explosives in the two basic scenarios of a suicide bomber (e.g., at a military checkpoint) or wide-area surveillance.[4] These scenarios were outlined to the committee by the sponsor at their first committee meeting.[5] Nuclear explosives were not considered, nor were explosives designed to deliver biological agents. The committee received briefings from outside experts and developed a knowledge base on existing chemical explosives and existing detection methods, without constraining itself to standoff detection techniques. The committee then examined potential new methods for detecting existing threats as well as methods for detecting potential new threats related to the two basic scenarios. The goal was to develop recommendations for research to further the development of novel standoff explosives detection methods. The committee was not tasked with and did not attempt to recommend new detection techniques.

The statement of task for the committee emphasizes identification of research that could reasonably lead to new approaches to standoff detection with good sensitivity and few false interpretations. The committee

[4]The committee's Statement of Task is given in Appendix A.
[5]See "Standoff Explosives Detection Study," Appendix C.

quickly realized that no single detector for all scenarios and devices is likely to be found. Rather, a systems approach incorporating orthogonal detection methods is necessary. Research is needed not only in the science of sensors but also in the systematic incorporation of multiple, orthogonal sensors leading to a sound decision-making process. Therefore, future research programs should develop the science and systems engineering of detection in parallel.

Although the cost of a detection system is certainly a factor in the deployment decision, it was not considered by the committee. For one thing, the economics of system and product development change substantially with time. For another, deployment of a detection system to very few wide-area surveillances has different cost parameters than providing each soldier in the field with a detection system. Similarly, the impact of detection on civil liberties was outside the scope of the committee's study.

STANDOFF DETECTION

Standoff detection involves decision making at a distance within a certain time frame. To focus its task, the committee developed the following definition:

> *Standoff explosive detection involves passive and active methods for sensing the presence of explosive devices when vital assets and those individuals monitoring, operating, and responding to the means of detection are physically separated from the explosive device. The physical separation should put the individuals and vital assets outside the zone of severe damage from a potential detonation of the device.*

This definition is necessarily situational. The key words "zone of severe damage" and "vital assets" must be specified. Vital assets are defined by cost and replacement, and depend on scenario and deployment. For example, the sensing elements of the detection system could be within the zone of severe damage, while the human and physical assets related to interpretation and decision making might be outside the zone. Defining the zone of severe damage is more problematic because it depends on the nature of the explosive—its power and collateral debris including shrapnel. For a pedestrian suicide bomber, the zone is taken to be 10 m, while for a vehicle suicide bombing the zone could be 100 m.[6] For wide-area surveillance—monitoring a large area for the presence of explo-

[6]Lou Wasserzug, Technical Support Working Group, presentation to the committee.

sives—the zone of severe damage is defined by the location of civilians rather than by the individuals and vital assets associated with detection.

Challenges in Standoff Detection

All explosives detection methods generate alarms in the absence of a true threat ("false positives," "false alarms") and fail to generate alarms in the presence of a true threat ("false negatives," "misses"). The associated frequencies (probabilities) of false negatives and false positives offer a means for comparison of proposed detectors. Although these two probabilities are not entirely comparable (one assumes the presence of a true threat, while the other assumes the absence of a true threat), they are related since adjusting a detection method to limit false positives typically results in an increase in false negatives and vice versa. A graph comparing the false-negative and false-positive probabilities for a variety of settings for a particular detection methodology yields the "receiver operating characteristic (ROC) curve," providing an approach for comparing the relative performance of proposed detection approaches.

In the absence of a single satisfactory approach, a system composed of multiple detectors may provide better overall performance (lower false-positive and false-negative rates, better ROC curve) than any of its component detectors. The multiple detectors may be redundant (i.e., measuring the same signal to reduce measurement error) or orthogonal—measuring different aspects of the same potential threat (e.g., chemical composition of a concealed package, detection of the presence of shrapnel). An effective detection system will integrate raw data, data summaries, or decisions (threat yes-no) from the individual detectors to arrive at an overall assessment of the threat situation.

In addition to the performance of proposed detection methods (individual detectors or detection systems), certain implementation issues considerably complicate standoff detection. First, successful implementation involves detection of a weak signal in a noisy environment. Second, the noisy background is often dynamic (e.g., changing humidity and ambient light, presence of non-threat-associated compounds triggering false alarms). Single-detector systems with exemplary performance in controlled laboratory settings often exhibit considerably poorer performance when applied in the field.

Several practical constraints also hamper the development of effective standoff detection techniques. Cost and expendability of detectors can limit deployment. Ease of transport, setup, and operation impacts the feasibility of any proposed detection methodology (e.g., portability by foot soldiers may be required in a military setting).

Finally, many attack scenarios provide a limited time for detection and decision; hence, any feasible standoff detection methodology must collect and interpret data as well as provide recommendations to operators in time to allow an appropriate response to an impending threat.

This report emphasizes the need to integrate basic science (e.g., biology, chemistry, physics) with systems thinking and decision making. Chapter 2 lays out the basic principles for viable standoff detection. A framework for developing detection *systems*, which identifies a decision process based on disparate data inputs, is described in Chapter 3. Chapter 4 summarizes the chemical characteristics of known explosive devices that could be exploited in a detection scheme, while Chapter 5 describes detection methods currently used or under development. In Chapter 6, the potential of exploiting biological markers associated with bomb makers and bombers is discussed. Examples of ideas for detection that have not been fully exploited to date are presented in Chapter 7. Recommendations for further research in specific areas can be found in the various chapters. The purpose of this report is to identify potentially useful research areas deserving more attention to advance the state of the art, rather than proposing best methods or specific solutions. The appendixes include the committee's statement of task, a glossary of terms used in the report, and a brief summary of the open session presentations to the committee.

2

Elements of Detection: Concepts, Threats, and Devices

Detection of explosives involves collecting a sample, processing the sample, and ultimately deciding whether explosives are present or not. In order to provide a common vocabulary for subsequent discussion of the properties and potential of various detection methodologies, the committee first reviews basic concepts relating to performance assessment, sample collection, the elements of a potential threat, and the related composition of explosive devices that may be exploited for detection.

SENSITIVITY, SPECIFICITY, AND ROC CURVES

The basic statistical and probabilistic elements of assessing performance of any detection methodology include *sensitivity*, *specificity*, and *receiver operating characteristic (ROC) curves*. The following contains a brief review of basic definitions of these measures and links them to notions of "false positives," "false negatives," "false-alarm rates," and the expected field performance of any detection method.

To start, suppose we have a detector with binary output ("yes" or "no"), and we have a binary measure of "truth" reflecting the actual presence or absence of an explosive. Also suppose we run a number of tests, recording for each test the true status and the detector reading. Consider the following 2×2 table reflecting the performance of the detector:

		Truth	
		Yes	No
Detector reading	Yes	*a*	*b*
	No	*c*	*d*

where *a*, *b*, *c*, and *d* reflect the number of times (out of $a + b + c + d$ total tests) that a particular combination of detector reading and true presence or absence occurs.

The column totals are set by the experimental design (i.e., we know there are $a + c$ tests run with explosives present and $b + d$ tests run with explosives absent). We typically treat the detector response as a random variable and are interested in the following conditional probabilities (letting *D* denote the status of the detector and *T* denote the status of the true presence or absence):

$$\text{True positive rate } (\textit{sensitivity})\text{: } \Pr(D = \text{Yes} \mid T = \text{Yes}) = a/(a + c),$$
$$\text{False positive rate: } \Pr(D = \text{Yes} \mid T = \text{No}) = b/(b + d),$$
$$\textit{Specificity}\text{: } \Pr(D = \text{No} \mid T = \text{No}) = d/(b + d).$$

Note that specificity is defined as (1 minus the false-positive rate). Verbally, *sensitivity* reflects the ability of the detector to identify explosives *if* an explosive is present (i.e., the detector "alarms" when it should), and *specificity* reflects the ability of the detector to identify explosives *only if* an explosive is present (i.e., the detector does not alarm when it should not).

Many detection systems are based on measurements of some quantity that has one range of values expected in the absence of explosives and another range of values expected in the presence of explosives. Suppose the ranges of measurement values in the presence and absence of explosives can be expressed as probability densities as in Figure 2.1. In this example, higher measurement values are more likely in the presence of an explosive, so we typically choose a cutoff value *m* and the detector alarms (D = Yes) when the observed measurement exceeds this value. Analogous conclusions follow when lower values indicate the presence of an explosive. When the distributions of values in the presence and absence of explosives overlap (as in Figure 2.1), we can have false positives (measure-

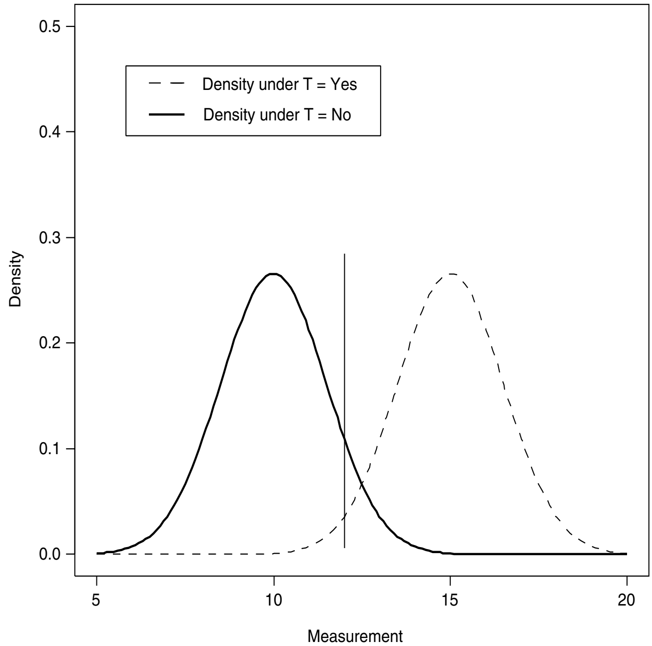

FIGURE 2.1 Probability density functions of test measurement in the absence (solid curve) and presence (dashed curve) of explosives. Setting the detection cut-off value at $m = 12$, sensitivity ($\Pr(M > m \mid T = \text{Yes})$) corresponds to the area under the dashed curve to the right of the vertical line, and specificity ($1 - \Pr(M > m \mid T = \text{No})$) corresponds to the area under the solid curve to the left of the vertical line.

ment greater than m in the absence of explosives [T = No]) and true positives (measurement greater than m in the presence of explosives [T = Yes]). If M denotes a random variable representing the measurement, then the event D = Yes is equivalent to the event $M > m$, so

$$\text{Sensitivity} = \Pr[M > m \mid T = \text{Yes}], \text{ and}$$
$$\text{Specificity} = 1 - \Pr[M > m \mid T = \text{No}].$$

The choice of the cutoff m influences both the sensitivity and the specificity of the detector as shown in Figure 2.2.

To summarize a detector's performance across all possible choices for m, we may use the *ROC curve*. The ROC curve sees application in a wide variety of fields including (but not limited to) medical diagnosis and signal processing. The ROC curve is defined to be a plot of sensitivity versus

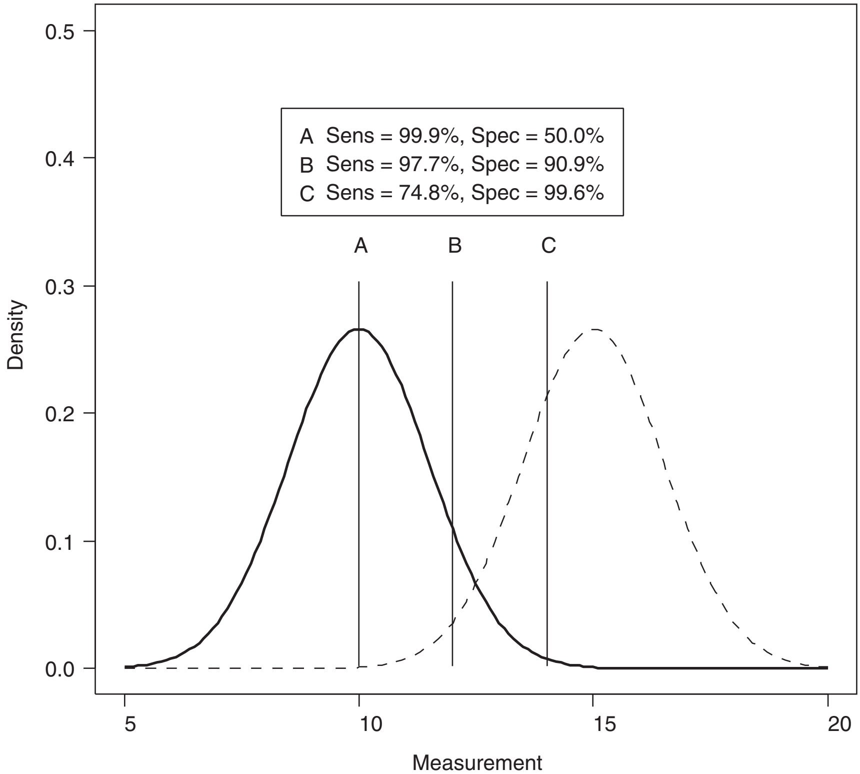

FIGURE 2.2 Impact of choice of cutoff value (m = 10, 12, and 14 for points labeled A, B, and C, respectively) on sensitivity and specificity, assuming normal distributions with means 10 and 15 and standard deviation of 1.5 for measurements in the absence and presence of explosives, respectively.

(1 – specificity) over a range of choices for m. Figure 2.3 illustrates the ROC curve associated with the simple example from Figures 2.1 and 2.2.

ROC curves by definition begin at the point (0,0) for cutoff values far to the left of the densities in Figures 2.1 and 2.2, and end at the point (1,1) for cutoff values far to the right. These points correspond to the extremes of 100% sensitivity and 0% specificity (every observation sets off the alarm) and 0% sensitivity and 100% specificity (no observation sets off the alarm), respectively. The ideal test corresponds to an ROC curve beginning at point (0,0) then immediately jumping to 100% sensitivity and 100% specificity, corresponding to no overlap in the probability densities of the measurement in the presence and absence of explosives. The "worst-case scenario" results when the density of the measurement remains identical

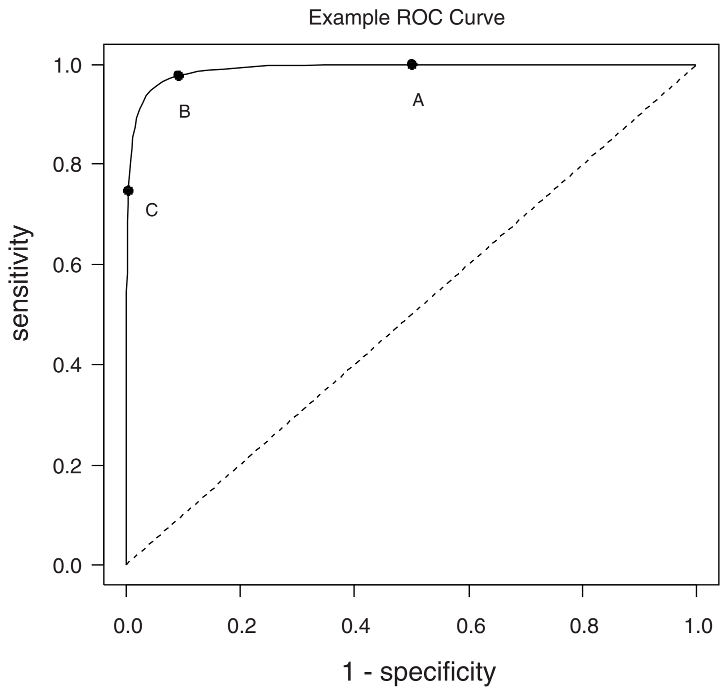

FIGURE 2.3 Example of an ROC curve based on densities shown in Figures 2.1 and 2.2. Points labeled A, B, and C correspond to the cutoffs m = 10, 12, and 14, respectively. The dashed line corresponds to the ROC curve when the detector has no ability to detect explosives (see text).

regardless of the presence of explosives (i.e., the test has no diagnostic value), yielding sensitivity identical to (1 – specificity) and an ROC curve falling along the line joining points (0,0) and (1,1).

ROC curves provide a means to compare two competing detection techniques. The technique with an ROC curve closer to the ideal (i.e., closer to the upper left-hand corner of the plot) will have better performance in terms of both sensitivity and specificity. Examination of Figure 2.2 suggests that densities with less overlap result in better detectors. Therefore, two ways to improve a detector are either to use measurements where the mean observation is very different depending on the presence or absence of explosives or to reduce measurement error (e.g., perhaps through increased sample size or longer observation time) so that the densities are more tightly defined around the mean measurement. While Figures 2.1 through 2.3 use normal densities to define ideas, any probability density for measurements provides the necessary information for ROC curves.

Estimation and inference for comparing ROC curves remain active topics in the statistical, medical imaging, and signal processing literature, although developments usually occur separately within disciplines with little cross-fertilization.

FIELD PERFORMANCE OF DETECTORS

Sensitivity, specificity (equivalently true or false positive rates), and ROC curves reflect commonly reported performance measures for any proposed detector, but one should keep in mind that even a detector with strong sensitivity and specificity can have unacceptable performance in the field, where a performance probability of interest is

$$\Pr(T = \text{Yes} \mid D = \text{Yes})$$

(i.e., the probability of the true presence of explosives), given an alarm occurs. Note that this probability (which corresponds to the notion of "positive predictive value" in the medical diagnostic testing literature) reverses the conditioning from the false positive/false negative rates defined above. The probability that no explosives are present given an alarm occurs, i.e.,

$$\Pr(T = \text{No} \mid D = \text{Yes}) = 1 - \Pr(T = \text{Yes} \mid D = \text{Yes}),$$

differs from the "false positive rate" $\Pr(D = \text{Yes} \mid T = \text{No})$, again through a reversal of conditioning. This probability (the proportion of observed alarms that are false) differs from the standard use of the phrase "false alarm rate" (the number of tests with no explosives that result in an alarm, synonymous with "false positive rate" defined above) in the literature. The primary difference is in the denominator, the false positive rate is the proportion of "alarms" among tests with no explosives, while the probability that no explosives are present given an alarm occurs is the proportion of "false alarms" among all alarms in the field.

The conditional probability $\Pr(T = \text{Yes} \mid D = \text{Yes})$ (the probability that an observe alarm is "true") depends on the sensitivity and specificity of the test and on the background frequency of both explosives (expected to be very low), via Bayes' Theorem

$$\Pr(T = \text{Yes} \mid D = \text{Yes}) = [\Pr(D = \text{Yes} \mid T = \text{Yes}) \Pr(T = \text{Yes})]/\Pr(D = \text{Yes}).$$

Typically, we do not have an estimate of $\Pr(D = \text{Yes})$ (the probability that the detector sets the alarm during use, averaged over settings with and without explosives) from the test results in the 2×2 table above, but we may express this probability in terms of known values through the law of total probability, that is,

$$\begin{aligned} \Pr(D = \text{Yes}) &= \Pr(D = \text{Yes} \mid T = \text{Yes})\Pr(T = \text{Yes}) + \\ &\quad \Pr(D = \text{Yes} \mid T = \text{No})\Pr(T = \text{No}), \\ &= (\text{Sensitivity}) \Pr(T = \text{Yes}) + \\ &\quad (1 - \text{Specificity})[1 - \Pr(T = \text{Yes})]. \end{aligned}$$

We will require an outside estimate of $\Pr(T = \text{“Yes”})$, the unconditional probability of the presence of explosives, since the quantity $(a + c)/(a + b + c + d)$ from the assessments of the test reflects the experimental design and not the true marginal probability of explosive presence among screened objects or locations in the field. We may obtain estimates of $\Pr(T = \text{Yes})$ under certain scenarios from Federal Bureau of Investigation or Bureau of Alcohol, Tobacco, Firearms and Explosives statistics.

The equations above indicate that the probability of no explosives given an alarm for a particular detector is a function of the detectors' sensitivity, specificity, and the underlying probability of the true presence of explosives (regardless of detection). For a very low probability of explosives presence in the field, even tests with very high sensitivity and specificity can have unacceptably high probabilities that any observed alarm is false. That is, even a test with a low "false alarm rate" (high specificity) can have a high probability of no explosives for any given alarm if the presence of explosives is rare enough. To illustrate, suppose we have a detector with 99% sensitivity and 99% specificity. Figure 2.4 plots the probability of no explosives given an observed alarm as a function of $\Pr(T = \text{Yes})$, and illustrates how this probability increases nonlinearly as the probability of the true presence of explosives decreases. Conceptually, the proportion of alarms that are false nears 100% as the presence of true explosives nears 0% since all alarms will be false if there is no chance of explosives in the system under surveillance. Figure 2.4 also illustrates $\Pr(D = \text{Yes})$, the marginal probability of an alarm, decreases linearly with $\Pr(T = \text{Yes})$ as suggested in the equations above. While this probability decreases, it does not go to zero (except in a "perfect" detector), and if the detector is applied to a very large number of individuals the number of false alarms can still be large (e.g., 1% of 500,000 people attending a sporting event).

Figure 2.4 illustrates the impact of wide application of a detection system in a situation where the event to be detected is extremely rare. While sobering, the public may be willing to accept a fairly high proportion of alarms that prove to be false if the general perception is that detec-

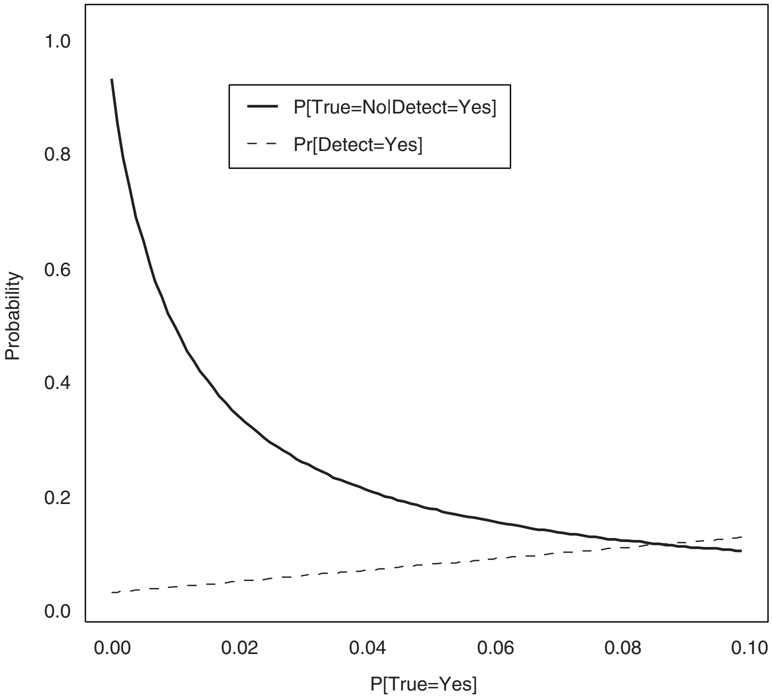

FIGURE 2.4 Probability of no explosives given an observed alarm as a function of the probability of the presence of explosives for fixed specificity and sensitivity (both 99%).

tion reduces the probability of an explosive-based event. For example, consider the performance of airport metal detectors as "weapons detectors." Most alarms occurring during screening are false with respect to weapons (i.e., the detectors detect metal, but not weapons), but most passengers accept such false alarms since there are many non-weapon reasons for an alarm to go off. This said, such a perception may not exist for explosives detectors.

SYSTEM EFFECTIVENESS

In the literature, the phrase "receiver operating characteristic" is commonly used in conjunction with individual device performance to identify the effectiveness of the device. To avoid ambiguity and to accommodate the assessment of a system built on multiple technologies, a measure called *system effectiveness* (SE) is used to characterize the overall system performance in the presence of environmental, threat, and other potential confusions. This SE is a function of threat characterization, technology, environment, and other factors. SE is quantified by combining quantitative measures of system, threat, and environmental attributes.

In addition, the concept of SE also allows us to broaden the scope of detection beyond the performance of particular sensors (via sensitivity and specificity) and incorporate additional concerns, e.g., the mass of the explosive, and the available sampling time. Also, SE allows us to move from assessments of detection to assessments of system performance, including additional factors such as human intervention (how do security forces effectively respond to an alarm from the detector, and how much time do they have to do it?). Finally, SE allows us to consider "false alarms" based on sensor unreliability (as considered via sensitivity and specificity above) as well as situations involving the legitimate presence of explosives that present no actual "threat" (e.g., a munitions delivery through a military checkpoint).

There are many definitions of system effectiveness, depending on the application. In this application, system effectiveness is defined as "a measure of the degree to which an item can be expected to achieve a set of specific mission requirements and which may be expressed as a function of availability, dependability and capability."[1] For standoff explosives detection, system effectiveness could include detection system availability, maintainability, system ROC, and the probability of avoiding defeat.

THREAT SCENARIOS

In considering any situation involving standoff detection of explosives, one must have some general understanding both of the overall scenario and of the parameters that describe the explosive device and the surrounding environment. This section discusses these topics, with particular attention to specific scenarios that the committee has been asked to consider. Since there is no single explosives detection technology that is applicable under all circumstances, it is important to understand the situation in as much detail as possible. Details that are not relevant to a specific detection technology may be important for other technologies, and an understanding of all potentially important parameters is thus a first

[1]U.S. Department of Defense. *Definitions of Effectiveness Terms for Reliability, Maintainability, Human Factors, and Safety*, MIL-STD-721B, August 1966.

critical step in the development of a system solution that may involve two or more orthogonal detection technologies (see Chapter 3).

In principle, there are an infinite number of situations in which standoff explosives detection might be utilized. Two scenarios (see Appendix B for a definition of scenario) that are of primary concern to the committee are the suicide bomber and wide-area surveillance.

Suicide bombings have occurred with increasing frequency in recent years, particularly in the Middle East. These bombings normally involve an individual who carries a concealed high explosive (HE) charge hidden either on his person or in a vehicle. This individual (the bomber) transports the explosive to his intended target—often a crowded public area where a large number of deaths will result, or perhaps a military checkpoint manned by forces he wishes to attack—and detonates the charge, killing himself along with his intended victims. Since the bomber does not have to plant the device and make his escape prior to its detonation, there is less time and opportunity to find the bomb prior to detonation than in scenarios involving a nonsuicidal bomber. Clearly, the ability to detect such an individual by any means *before* he reaches the intended target is an important goal that could be realized by the development of appropriate standoff explosives detection techniques.

Wide-area surveillance refers to monitoring a large area for the presence of explosives. The area under surveillance can be of almost any type: a military base, a secure government facility, a public building or event, and so forth. The goal in this situation is to prevent the illicit introduction of HE into the area being monitored and/or to pinpoint the location of any HE that has been brought into the area. The bomber in such a scenario may be either suicidal or nonsuicidal, and depending upon access to the area, the HE may be conveyed either on a person, in a vehicle, in a hand-carried item such as a brief case, or via mailing or shipping. Within the category of wide-area surveillance, two subcategories can be identified, which may be referred to as open and closed situations. A closed situation is one in which public access to the location or event is limited, and all persons present must pass through certain checkpoints before being admitted.[2] An example would be a Super Bowl, where all attending persons enter via stadium gates, or a military base, with a limited number of entrances manned by military security personnel. In such situations, the entry of HE into the area can be controlled in principle through applying appropriate detection technologies at the controlled checkpoints. An open

[2]Of course it is theoretically possible that some individuals may bypass the checkpoints and enter a facility or area illegally, but with proper security this can be made extremely difficult.

situation is one such as a large public event—for example, Mardi Gras or the Rose Parade—where public access is essentially unlimited, and there are thus no fixed checkpoints at which all incoming persons or vehicles can be screened. In this type of scenario, standoff detection of explosives within the wider area can be of vital importance.

Threat Parameters

Having outlined the above scenarios in broad terms, it is necessary to next consider those parameters that define the situation, collectively referred to here as threat parameters. These parameters can be broken down into three categories: (1) those relating to the local environment, (2) those describing the explosive device, and (3) those that characterize the bomber.

Threat Parameters Related to the Local Environment

Among threat parameters relating to the local environment, perhaps the most important is the intended target of the HE detonation. The target represents the motivation for the attack; thus, by understanding what the target is (or might be), one can begin to develop ideas about the likelihood of attacks involving HE detonation in different areas. In other words, an understanding of potential targets helps prioritize the areas that have to be monitored and protected. Broadly speaking, the target is usually either people or infrastructure. Within the former category, the goal can be either to kill and injure a large number of people or to kill a single important person such as a political leader. In the second category, the target could be a building or landmark that is of great symbolic import (i.e., the White House, Statue of Liberty, etc.) or one that might cause great economic or environmental damage if destroyed (dam, nuclear power plant). The timing of the detonation is clearly much more critical if people are the intended target. A bombing in a crowded sports stadium will have a much greater impact than a bombing in an empty sports stadium, whereas blowing up a dam will likely have the same impact regardless of when the explosion occurs. Some agencies and organizations interested in standoff explosives detection have specific areas, facilities, or people that they are tasked with protecting, while others (e.g., police) have responsibilities that span very large areas without specific, well-defined targets.

Another important threat parameter relating to the environment is the presence or absence of a background of trace explosives materials or potential interferents. Many explosive detection technologies rely on collection and identification of minute amounts of explosive vapor or particulate material to make detections (Chapter 4). Such technologies will tend to give frequent alarms when a background of trace explosive material is present; if these alarms are too frequent, they can render the technique unusable. An explosives background could be present in a number of situations—for example, in a battlefield setting or on a military base where large amounts of explosives are routinely stored or handled. Interferents are nonexplosive chemicals that lead to false alarms for explosives with certain types of chemical sensors,[3] and a background containing one or more of these chemicals thus can also inhibit the use of these detection technologies. Knowledge of the chemical background, which may change significantly over time, can therefore be essential in determining how best to perform explosives detection within a given area.

Other important environmental threat parameters are those relating to the ambient meteorology. Temperature is clearly important since it affects the amount of vapor that will be emitted by an HE charge (Chapter 3); this in turn may determine what vapor-based detection techniques are applicable. Atmospheric pressure can affect the calibration of some vapor sensors such as ion mobility spectrometers and must therefore also be taken into account. Humidity can be a factor, both because some explosive vapors may form clusters with water molecules and because interactions of the probing radiation with water vapor in air can limit the application of techniques such as terahertz spectroscopy. Dust particles in air can adsorb explosive vapors, interfering with some types of vapor detection but possibly also leading to improved sampling strategies based on collection of the particles. Wind conditions are obviously significant if one is attempting any type of vapor detection, since whatever plume of explosive vapor is present will be entrained in the prevailing air currents. All of the prevailing weather conditions will influence the *concentration* of explosive vapor that is available for sampling, and this concentration—which often will be extremely small—places constraints on the detection strategies that can be employed.

A final factor relating to the environment is the nature of the society in which the detection scheme is to be applied. This will often place constraints on the types of technology that can be utilized. For example, screening people by using low-dose backscatter X-ray systems to image beneath clothing has generally been judged too great an invasion of privacy for widespread use in the United States. The same technology would probably be considered acceptable in Israel, where a higher incidence of bombings has led to greater public tolerance for more invasive detection technologies. Technologies that are not widely accepted by the general

[3]For example, Matz, L. M.; Tornatore P.S.; Hill, H.H., Evaluation of suspected interferents for TNT detection by ion mobility spectrometry, *Talanta* **2001**, *54*, 171-179.

public, or that may violate constitutional or other legal rights when applied too broadly, are severely limited in their applicability to standoff explosives detection. However, consideration of this issue is beyond the scope of this study.

Threat Parameters That Describe the Device

Several key threat parameters characterize any explosive device. These include the type of explosive used, the mass of explosive, and several other factors relating to the device construction. Different detection strategies may or may not be appropriate, depending on the nature of the device.

Many types of explosives can be used as the main charge in a device, as will be revealed by perusal of any survey book on explosives and their properties.[4] Traditionally, some of the most widely used and studied explosives have been nitro-based compounds such as 2,4,6-trinitrotoluene (TNT), cyclotrimethylenetrinitramine (RDX), pentaerythritol tetranitrate (PETN), and nitroglycerin (NG). TNT is widely used in land mines, NG in the manufacture of dynamites, and RDX and PETN in the manufacture of plastic explosives such as C-4, detasheet, and semtex. Black powder is widely used in the construction of pipe bombs, while the favorite explosive for large vehicle bombs has been ammonium nitrate fuel oil (ANFO). Some more novel explosives that are being used increasingly, such as TATP, are fundamentally different because they lack nitrogen altogether. The choice of explosive in a device is of importance for two reasons. First, different explosives have different explosive energies per unit mass (kilojoules per gram). Since TNT is widely available and most explosives fall within a factor of two of TNT in energy per unit mass, it is common to express explosive masses in terms of a TNT equivalent mass (the mass of TNT that would produce an explosion of the same energy if detonated). Second, as discussed in Chapter 3, different explosives have different properties that make them more or less susceptible to various detection technologies. Perhaps the most obvious of these properties is vapor pressure, which varies over more than eight orders of magnitude for common high explosives. Other important properties that can influence detection schemes include density and atomic composition.

Given that explosives are characterized by specific energy content per unit mass, the mass of explosive in a device is of paramount importance. The greater the mass of explosive, the greater is the potential damage that

[4]Meyer, R.; Koehler, J.; Homburg, A. *Explosives*, Fifth edition; Wiley-VCH: Weinheim, Germany, 2002.

can be done. At the same time, a larger explosive mass in a device tends to make detection easier, so an adversary is usually faced with a trade-off between the amount of damage that a bomb can inflict and the probability that the device will be detected prior to detonation. Expressing the mass as a TNT equivalent mass provides a convenient basis for comparing the destructive power of different bombs. Note that the maximum possible explosive mass of a bomb will depend to a large degree on the means of conveyance. If there is no vehicular access to the target location and the bomb must be concealed on a person, no more than a few tens of pounds can be involved. On the other hand, if a vehicle can be used, the detonation may involve thousands of pounds of explosive. In addition to the explosive mass, the destructiveness of a bomb is also greatly influenced by the distance from the device to its intended target. A rule of thumb is that the mass of explosive required to inflict equivalent damage increases as the cube of the bomb-to-target distance.[5] This means that increasing the distance to the target by a factor of two increases the required explosive mass by a factor of eight. It can thus be seen that forcing the bomb to be detonated further from the target is one of the most effective forms of protecting a target. Standoff detection can, of course, be an important first step in preventing a bomb from being detonated in close proximity to its intended target, especially if the sensor and target are not collocated.

Besides the explosive material, other important device components include the casing or shielding around the main charge, the detonator, and any associated wiring. Very often, some or all of these components will be made of metal, and metal detection thus becomes one possible means of detecting the explosive device in some circumstances. Metal detection is probably most useful in scenarios involving checkpoint screening of personnel, where all persons can be passed through a standard metal detection portal such as those currently used in airports. This assumes that detonation at the screening point, although undesirable, would be less destructive than detonation at some points within the area being protected. Metal detection is not useful when vehicles are being screened for explosives, since the vehicles are themselves made of metal and the metal in an explosive device would not be distinguishable. There may be other methods that can be applied to the detection of detonators besides metal detection (Chapter 7), and such methods might also be used for detection of the explosive device, which in some cases may even involve remote detonation.

The casing or shielding around the explosive charge is important be-

[5] Kinney, G.F.; Graham, K.J. *Explosive Shocks in Air*, Second Edition; Springer Verlag: New York, 1985.

cause it may tend to mask the explosive from certain types of detection. An example would be a main charge inside a hermetically sealed container. In such a case, there would be no explosive vapor on the outside of the container, so any attempts to use a vapor detection technology to sense the chemical plume would be in vain. There are other examples involving non-vapor detection technologies. For example, nuclear quadrupole resonance (NQR) is susceptible to metal shielding. These examples emphasize the point that no single detection technology is adequate under all circumstances; hence an effective detection *system* may well involve two or more largely orthogonal detection technologies (Chapter 3).

An explosive device may cause damage not only due to the power released by the detonation, but also due to small flying objects that are propelled through the air. This is especially true when many people are present: such flying objects—whether metal, plastic, or shards of glass—can actually kill and injure more people that the explosion itself. Many devices intentionally have objects such as nails, thumb tacks, or sharp pieces of metal attached to their surfaces; when the device is detonated these objects—collectively referred to as "shrapnel"—become "bullets," any one of which might kill a person. In buildings with large windows, the glass fragments produced in the blast can serve the same purpose. The presence or absence of shrapnel on the device, along with the size and number of windows near the detonation, is thus of great importance in evaluating the possible injury the detonation may cause to humans.

An explosive detonation can cause additional harm to both humans and the environment if the detonation is used to disperse radioactive materials or biological or chemical agents. Scenarios involving such dispersal are outside the scope of the present study. Clearly, detecting a device prior to detonation is the best and most cost-effective means of dealing with such a threat.

Threat Parameters That Characterize the Bomber

A psychological profiling of individuals who carry out bombings is beyond the scope of the present study. Nevertheless, bombers may display certain characteristics that aid in their detection in some cases. A device concealed under clothing may weigh tens of pounds and thus add significantly to a person's weight. This increase would likely be useful for detection only in specialized cases where the perpetrator must pass through a man-trap portal, the weight may cause the individual to walk in an odd manner or have some other effect that might arouse suspicion. Nervous behavior might also be an indicator that could lead to detection. Exposure to large amounts of explosive material could even lead to physiological changes such as alterations in the chemical composition of a person's sweat. Some of these possibilities are explored further in Chapters 6 and 7.

ORTHOGONALITY

Two or more explosive detection technologies are completely orthogonal if the detection methods are mutually independent. That is, they detect independent characteristics of the explosive device. This definition allows for the possibility of partially independent (partially orthogonal) methods as well. For example, detecting the exact chemical compound by sniffing and spectroscopy of the vapor plume would be partially independent.

To employ two or more orthogonal detection technologies implies "system" of detectors. Successful standoff detection of an explosive when an explosive is present—and very few indications of an explosive when there is no explosive—is the intent of a system of orthogonal detectors.

Detection technologies may be orthogonal in method, but not in characteristic. For example, two hypothetical standoff detection technologies, one based on schlieren photography and the other on olfactory analysis of vapors, are orthogonal in method. Schlieren photography techniques would detect an image of the vapor plume from the explosive formed by refraction and scattering from areas of varying refractive index. Olfactory analysis of the vapors from the explosive would detect the aroma signature of the molecules in the vapor plume to determine the potential chemical composition of the explosive. Both methods depend, to some extent, on the existence and behavior of the vapor plume. So although the two hypothetical detection technologies would be orthogonal in method, they would be only partially orthogonal in practice. However, if the olfactory analysis also included a remote vapor sampling capability to concentrate the vapor, the independence between the two would be stronger.

A more orthogonal (i.e., independent) combination of detection technologies would be olfactory analysis and an imaging technology. The imaging technology would detect the shape, mass, or density of the explosive device and any potential detonators and shrapnel. These characteristics are strongly independent of the chemical composition of the device. However, the density of the explosive material would be related to its chemical composition.

The three potential significant advantages of a system of orthogonal detection technologies over a system dependent on one technology are the following:

1. It has a higher probability of detecting the presence of an explosive device over a range of potential threats.

2. It is more difficult for a potential bomber to avoid, confuse, or defeat the system.
3. It can be more effective in detecting explosive devices than any single technology.

However, the use of orthogonal detection technologies presents a significant challenge to implementation. That challenge is how to process the information from two orthogonal technologies when one is indicating positive for the presence of an explosive device and the other negative. This challenge is compounded when additional orthogonal or partially orthogonal technologies are employed.

3

Systems of Detection

INTRODUCTION

A positive indication of an explosive threat from a perfect sensor does not mean that an explosive is present. In reality, neither a perfect sensor nor a signal that is completely noise-free exists. Standoff explosives detection must take into account more than the single sensor indication, because a system that relies on only a single source of information is too likely to make decisions with excessive false positives (false alarms).

A signal from a perfect sensor, or from a network of perfect sensors, is not a decision. The essential function of the system is to decide what such detection means or implies. For example, if a sensor is designed to detect nitroglycerin, the detection of nitroglycerin does not necessarily imply that a bomber is present. The molecule could have come from an individual taking nitroglycerin for a heart condition. Other corroboration is required, and this need motivates other—generally orthogonal—information. In the example above, a terahertz image of the person may indicate an explosive vest loaded with dynamite, or a pill box.

More accurate decisions can be extracted from a set of diverse sources of noisy data than from any individual source alone. The intent of a system of orthogonal (i.e., diverse) detectors is successful standoff detection of an explosive when an explosive is present and very, very few indications of an explosive when there is none.

This is not a trivial task, nor is a system of orthogonal sensors a trivial artifact. The systematic resolution of conflicting or ambiguous sensor information requires careful system design. Consider an example of an analyte-specific chemical sensor, an active sniffing detector, combined with a limited-resolution imaging device. If one returns a positive indication and the other a negative indication, what is the decision of the system: yes or no? Methods providing for resolution of the conflict must take into account sensor performance, its past credibility or reliability, context, ambient conditions, or other environmental factors. Figure 3.1 shows an architecture for segregating detection, multisensor conflict resolution, and decision.

Little work in the systems context is aimed at finding extremely rare events. Field tests and operational environments usually have some data to work with. Extending the systems approach expressed in Figure 3.1 to very rare true occurrences is a topic of research interest.

The definition and implementation of an effective standoff detection *system* involves a myriad of (sometimes overlapping) issues at varying levels of abstraction. Many such issues are discussed in the sections below, followed by a summary of related promising future research areas.

Background Noise Leading to Confusion

Background noise obscures positive indication of the explosive when an explosive is actually present. An effective system must discern the true signal in a cluttered background. Three levels of system effectiveness in the presence of noise can be distinguished:

1. Technology development is the exploration of the sensor itself. Generally, background noise is hardly present in this bench-top like development.
2. Laboratory development moves the sensor, and possibly the sensor system, to a less constrained environment, but one still largely free of background noise.
3. Field trial is the best test of the system in an uncontrolled environment. Technology and laboratory development are validated in the field trial only in the presence of full environmental and background noise.

Note that an active threat, intending to be surreptitious, may well be designed to look exactly like background noise. Also note that flooding the background with contamination or with mimics of the signal will effectively negate the operation of specific sensors using that detection means.

Orthogonal Improvement over Any Individual Detection Technology

A system that incorporates different, largely independent, modes for standoff explosive detection, while challenging, is better than a single sen-

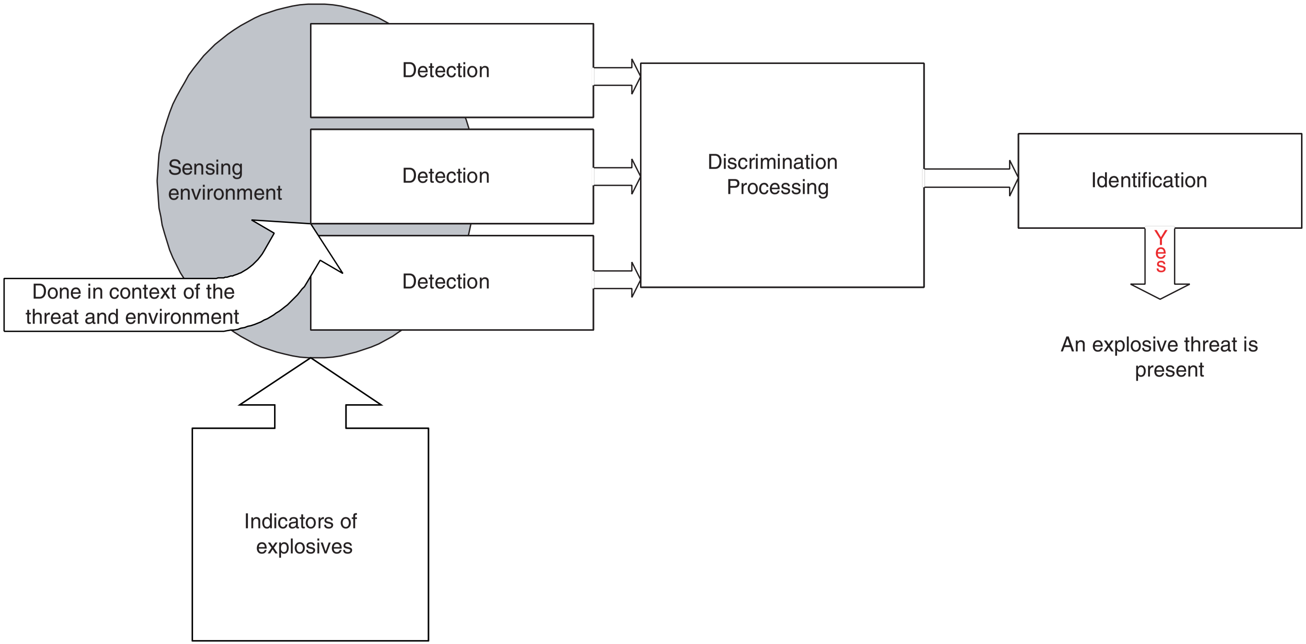

FIGURE 3.1 System concept showing segregation of detection—done in an environment—from the discrimination processing of the sensor signals and the identification of a threat. The subsequent step—to positively report the threat—is a considered decision.

sor in several dimensions. Consider an environment that contains a population of detectable *indications* of an explosive, as shown in Figure 3.1. The detection and decision goal is to search the environment, actively or passively, and detect as many of those indications as possible. (And at some point, as indications are detected, it will be possible to properly conclude that an explosive is present.)

A sensor searches the environment, but a particular sensor *type* can find indicators only of a particular *type* (e.g., an imaging sensor may find *shape* indicators of an explosive, but *cannot* detect *molecular* indicators.) Therefore, only a limited set of all possible indications can be found by a particular type of sensor. Multiple sensors of different types increase the number of possible indications that can be searched for in the environment. Eventually the increased number of indications permits the positive decision: yes there is an explosive present.

In the system using multiple types of sensors, sensitivity (the ability of the system to identify explosives if an explosive is present) is increased because the system will find more of the possible indications of an explosive. Specificity (the ability of the system to identify explosives *only if* an explosive is present) is increased because there are more sensor types, and they will jointly report finding indications only when an explosive is actually present. The probability of a false alarm is reduced because the several different sensor types are less likely to all report a false positive at one time. Both specificity and sensitivity can continue to increase with additional sensor types, as long as there are indications that each sensor type can find an explosive if an explosive is present during its interaction with the environment. The committee's hypothesis is that very high specificity can be achieved with a detector-decision system.

An array, or multiplicity of identical sensors can provide temporal (movement) and spatial (location) information about an explosive device. However, an array of identical sensors does not necessarily increase the specificity of the system over that of one sensor, especially if a false alarm from a single sensor in the array results in a system-wide false alarm. A solution to increase the explosive detection system specificity would be to utilize multiple arrays of different sensor types and/or a single array of different sensor types along with an appropriate detector-decision scheme.

Robustness with the orthogonal system is also increased. The system can show robust, if somewhat degraded, response when subjected to various indignities. In the simplest case, some sensor types will continue to function if the system is presented with a single insult. For example, in an active war environment, molecular detection of military explosives will be problematic because the background amount of RDX from munitions will flood the environment. Backscatter soft X-ray imaging, however, will be unaffected by that background. The potential partial degradation of the system must be countered by system design.

Similarly, during actual attack on the detection system, some sensor types are likely to be disabled or rendered otherwise ineffective. The orthogonal sensor-type system will still detect, but at reduced performance, until all orthogonal detection means are effectively disabled.

The result coming from a standoff explosives detection system is not static, nor is it desirable that it be static. Indeed, the likelihood of accurate threat assessment arising from the orthogonal multisensor-type system should vary with time, (i.e., as more multidimensional information is gathered, the detection estimate accuracy could increase or decrease). From the system point of view, time is inherent in the detector's operation, in all processing and consideration steps, and in communication. In addition, time to react to the threat is increased by system and human response time.

Recommendation: Research into *both* new sensor types *and* new systems of real-time integration and decision making is needed. The sensor system research agenda should emphasize the principle of *orthogonality* in mathematical consideration, sensor system design, and design of information leading to true detection

Threat Analysis Qualifies System Capability

The effectiveness of the system is inherently dependent upon threats considered in the context of the environment. Novel threats or insults will be recognized only accidentally through overlap with threats currently considered by the system. Figure 3.2 shows this graphically. In the figure, sensor type A is capable of detecting explosive indicators T_1, T_2, and T_3, while sensor type B is capable of detecting explosive indicators T_1, T_3, and T_4. $T_{unknown}$ is not detected by sensor types A and B but is serendipitously found by type C.

The environment is segregated into domains that: (1) we can control (e.g., control by design features) and (2) we cannot control: natural and background, some of which is predictable (e.g., sunset).

The threat context is itself corporate. It includes, at least, the following:

- the chemistry or physics of the threat (e.g., material characteristics of the explosive or propellant);
- the behavior (mode of operating) of the threat vector (a generalized notion of how the threat reaches its target); and

- the threat embodiment, expressed in terms of differing technologies and the flexibility and capability of human actor(s).

Note: We must assume the threat is constantly changing. The system's response—evolution—must be instilled as a requirement in the fundamental system design.

The choice of sensor types and system design must be integral with the nature of the threats. Threat analysis is used in the safeguards and security industries to identify the capabilities and motivation of adversaries to support assessment of the vulnerabilities of assets. Analysis of the vulnerability of assets includes assessment of the performance of security devices, structures, personnel, and processes. Thus, it is necessary in the case of standoff explosives detection to characterize the threats and assets (and the context in which detection must take place) to be able to develop effective technologies.

Threat Parameters

Figure 3.3 is an illustration of a partially completed threat analysis for a potential suicide bomber attack, using an event tree approach. While other approaches, such as probabilistic risk analysis, are also used for this type of analysis, this illustration shows a set of paths. Each path is made

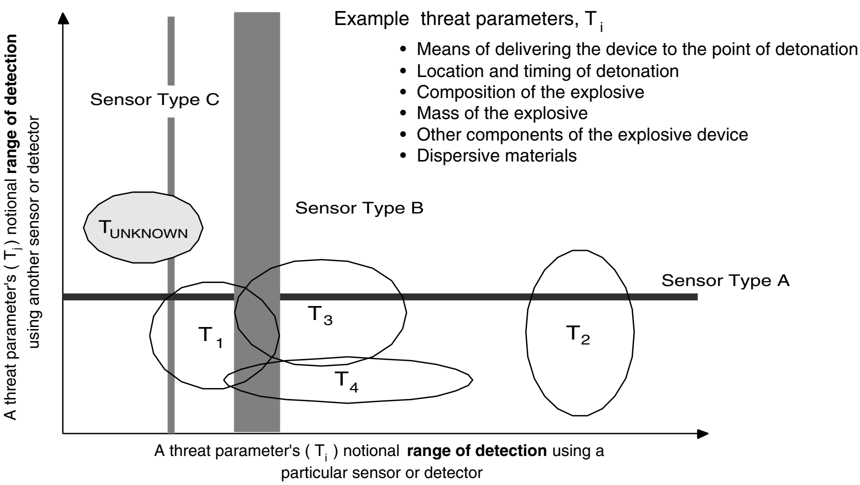

FIGURE 3.2 Notional threat space characterization showing dependence of the overall system shows effectiveness on the characterized and mapped threat. The effect of $T_{unknown}$ on system effectiveness cannot be assessed.

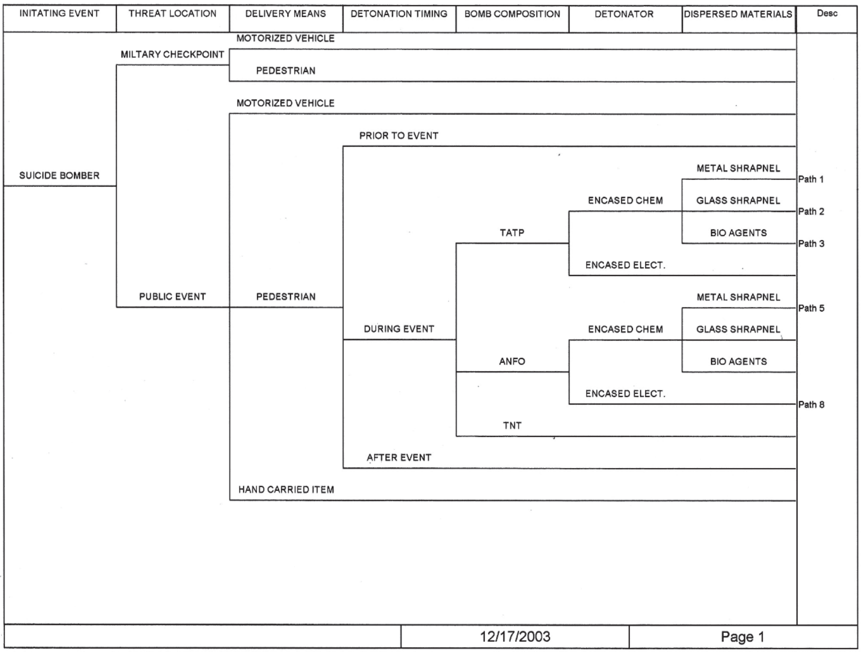

FIGURE 3.3 Threat evaluation via event tree analysis. Each path consists of a series of characteristics defining the specifics of a particular threat

up of a series of characteristics that define the specifics of a particular threat. These characteristics can be used to advantage when developing detection technologies and systems, and they also present challenges to detection success. For example, path 1 and path 5 (threats 1 and 5) are essentially identical except for the "bomb composition." This means that detection based solely on a single type of bomb chemical composition will be effective only in the case of one threat or the other. On the other hand, detection technology that is based on the presence of potential metal shrapnel would potentially be effective in both cases.

These characteristics of the threats—*threat parameters*—can be used to identify the performance challenges and necessary capabilities when developing standoff explosives detection. The threat parameters include, at a minimum, the following.

- *Means of delivering the device to the point of detonation.* Four distinct methods of bringing an explosive device into an area are (1) concealed on a person (e.g., under clothing); (2) in a hand-carried item such as a brief-case, backpack, or purse; (3) in a vehicle (this could include airplanes and boats in some circumstances); and (4) via mailing or shipping. In some cases, the explosive material may be transported separately from other bomb components and the device assembled after passing through checkpoints or portals. For many scenarios all of the above four means will not be possible—for example, there are many places that a person can go but a vehicle cannot.

- *Location and timing of detonation.* Location is critical because the effects of a detonation are dependent on the distance from the intended target. A rule of thumb is that the mass of explosive material required to cause equivalent damage increases as the cube of the distance (e.g., if the detonation-to-target distance is doubled, the required explosive mass increases by a factor of eight).[1] Thus a good way to protect a specific potential target is to limit how closely a bomb (especially a large bomb such as a vehicle bomb) can approach the target. Oklahoma City and the Baghdad UN bombing are excellent examples: the effects of the blast would have been less devastating if it had not been possible to approach the buildings so closely. Timing is also critical in many scenarios, especially those in which harming people is the primary intent. A bombing in a sports stadium will have less impact if it occurs when the stadium is empty.
- *Composition of the explosive.* The type of explosive (TNT, RDX, triacetonetriperoxide [TATP], ammonium nitrate-fuel oil [ANFO], etc.) is important both from the point of view of detection and because the explosive power differs for different compounds. The presence of other materials within the explosive, such as plasticizers, impurities, and taggants, can also be important. Plasticizers and other compounds that are added to an explosive formulation may reduce the vapor pressure of the explosive, thus making trace detection more difficult. However, these compounds may be detectable themselves, and may thus offer additional possibilities for detection. Impurities may also aid in detection, especially if they have high vapor pressures. An example involving drugs rather than an explosive is the detection of cocaine using canines: there is evidence that at least in some cases the dogs detect methyl benzoate, a volatile impurity in the cocaine, rather than the cocaine itself. Taggants can be of two types: (1) volatile compounds that are added to a formulation to aid in vapor detection (e.g., mononitrotoluenes in plastic explosives) or (2) chemicals that are added as a signature to trace the explosive to a particular manufacturer when doing forensic analysis after a blast. Both types are useful, but of course homemade explosives will not be tagged.

[1] Kinney, G.F.; Graham, K.J. *Explosive Shocks in Air,* Second Edition; Springer Verlag: New York, 1985.

- *Mass of explosive.* The mass of explosive in a device is critical in assessing how much damage it can do. Traditionally, explosive mass is converted to a TNT equivalent mass, TNT being a common, representative nitro-based explosive. Most common high explosives have from 0.6 to 1.7 times the explosive power (or heat of explosion) of TNT (4.2 kJ/g).
- *Other components of the explosive device.* This can include the casing, detonator, shrapnel, and so forth. The detonator and casing may aid in detection using standard metal detection portals if they contain metal. The casing of a bomb can also influence the magnitude of the blast produced and the amount of trace material that is available externally for detection. Shrapnel, usually involving nails or other small pieces of sharp metal but possibly also glass or plastic, can greatly increase harm to humans under some circumstances. When a bomb is detonated in or near a building occupied by large numbers of people, the shards of flying glass that can be produced from shattered windows have the same effect as shrapnel, sometimes harming more people than the blast itself or the structural damage to the building.
- *Dispersed materials.* In addition to shrapnel, the effects of an explosion can become much more serious if the bomb is used to disperse harmful materials such as radioactive materials, biological agents, or chemical agents. The dispersal of radioactive material using a so-called dirty bomb is outside the scope of this study.

The ambient environment is a factor in detection performance. Ambient conditions are normally of secondary importance, but they can influence detection, background, and the effects of an explosion. Ambient temperature affects the vapor pressure of the explosive and can thus influence detection, and some detectors may cease to function at extreme temperatures. Atmospheric pressure and humidity can influence some detection technologies such as ion mobility spectrometry (IMS), requiring at the least that detectors be recalibrated if these conditions change significantly. Detection of nitrogen-based explosives will be affected by the presence of other nonexplosive nitrogen-based substances in the environment.

Finally, additional considerations and risks are introduced with each human in the loop (entering data, operating detection equipment, and/or reading results).

Recommendation: Because discrimination of a useful signal in a noisy environment is always a problem, a research effort should be aimed at determining baseline ambient conditions and detecting changes in ambient conditions in real time.

Even in the presence of careful analysis and corresponding system design, there is a possibility that we cannot detect what we have not imagined. Indeed, we may be able to detect only those things that we have postulated.

Anomaly Detection and Response

For standoff explosives detection in the scenarios under consideration here, there is a complication: explosives are not present very often, and false alarms are bad because they induce personnel to either disregard the alarm or disable it. Within the environment context of the operational system, conditions are either normal or abnormal. If abnormal, then they are abnormal for a reason. The system response to this condition is to investigate the abnormality in order to properly alarm and properly respond to changes in the threat environment.

When the architectural framework of Figure 3.1 is applied to the threat environment, some confounding considerations result, as shown in Figure 3.4. The dynamic variability of the threat and environment will produce a kind of dynamic barrier between detection and discrimination: this will be a probabilistic discrimination, whether explicitly so or not. Our natural inability to postulate all threat vectors will similarly produce a barrier between discrimination and the identification and decision element. In short, all systems will contain the possibility of both false negatives (reporting "no" in the presence of a true threat) and false positives (reporting "yes" in the absence of a true threat); therefore accurate assess-

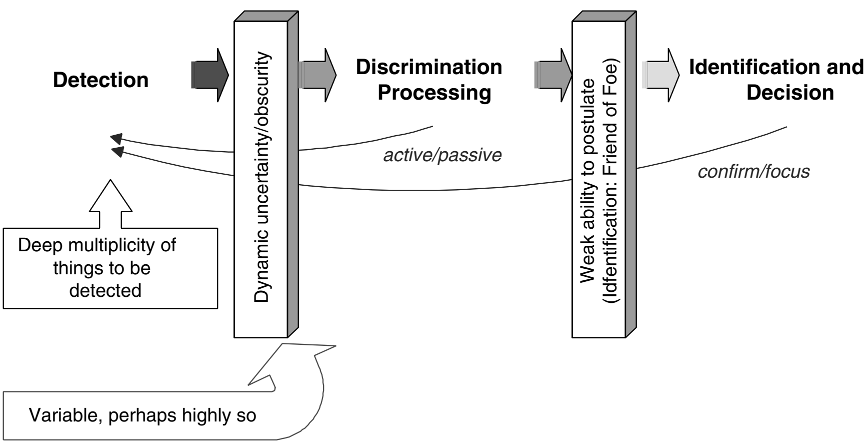

FIGURE 3.4 Information obscuration and the effect of weak threat parameter postulates.

ment of the sensitivity and specificity of system components and the system as a whole under a variety of threat scenarios is critical for accurate evaluation of the detection system.

Key feedback control signals are required in the system to increase its ability to properly determine the likelihood of an accurate threat assessment. Simply moving from a passive detection system to one that includes active elements, asking the processing steps to confirm or focus their attention, can profoundly the affect assessment of system performance.

Field validation is an explicit need and goal for system realization.

Design and Operational Requirements of a Threat Identification System

To meet the challenges of threat characteristics, dynamic ambient conditions, human in-the-loop variability, and information obscuration, operational requirements can be developed to achieve a threat identification system with maximum effectiveness:

1. *Quick identification.* The detection system should be able to respond quickly by detecting and identifying the threat with dispatch. However, this must be traded with system sensitivity to noise, which can lead to frequent false alarms that are disruptive. This is analogous to the trade-off between robustness and performance in the design of control systems.

2. *Isolability of threat type.* Isolability is the ability of the system to distinguish between different threat types. Under ideal conditions, free of noise and modeling uncertainties, this amounts to saying that the threat classifier should be able to generate output that is orthogonal to threats that have not occurred. Of course, the ability to design isolable classifiers depends to a great extent on the threat characteristics. There is also a trade-off between isolability and the rejection of modeling uncertainties. Most of the classifiers work with various forms of redundant information and hence there is only a limited degree of freedom for classifier design. For this reason, a classifier with a high degree of isolability would usually do a poor job in rejecting modeling uncertainties and vice versa.

3. *Robustness.* One would want the threat identification system to be robust to various noise and uncertainties in the threat environment. One would like its performance to degrade gracefully instead of failing totally and abruptly. In the presence of noise, thresholds may have to be chosen conservatively. Thus, as noted earlier, robustness needs are to be balanced with those of performance.

4. Identification novelty. One other requirement for the identification system is to be able to decide, given current threat conditions, whether the threat is a previously known type or a new, unknown kind.

5. Confidence measures. An important practical requirement for the identification system is in building the user's confidence in its reliability. This could be greatly facilitated if the system could provide an *a priori* estimate of detection or classification errors that can occur. Such error measures would be useful to project confidence levels on the decisions by the system, giving the user a better feel for the reliability of the recommendations made by the system.

6. Adaptability. Threats and threat environments can, in general, change and evolve. Thus, the identification system should be adaptable to such changes. It should be possible to expand the scope of the system gradually as new cases and problems emerge and more information becomes available.

7. Explanation facility. Besides the ability to identify the threat, the threat ID system should also be capable of providing some explanations of why a particular decision or decisions were arrived at. This requires the ability to reason about cause-and-effect relationships in the threat environment to justify its recommendations. This could enable the threat monitoring personnel to interpret and evaluate the system's decisions and take appropriate actions by utilizing their experience as well. One would like the threat identification system to not only justify why certain hypotheses were proposed but also explain why certain other hypotheses were not proposed.

8. Modeling requirements. The amount of modeling required for the development of the threat ID system is an important issue. For fast and easy deployment, the modeling effort should be as minimal as possible without sacrificing performance too much.

9. Computational requirements. Usually, quick real-time solutions would require algorithms and implementations that are computationally less complex but might entail high storage requirements. One would prefer a threat ID system that is able to achieve a reasonable balance between these two competing requirements.

Recommendation: Research is needed into the development of scenario-based threat parameters-decision trees for real-time decision making.

ROC of Systems—System Quantification; System Effectiveness

In the literature, the phrase "receiver operating characteristic" (ROC) is commonly used in conjunction with individual device performance to identify the effectiveness of the device. To avoid ambiguity and accommodate the assessment of a system built on multiple technologies, a measure called system effectiveness (SE) is used to characterize overall system performance in the presence of environmental, threat, and other potential confusions. This SE is a function of threat characterization, technology, environment, and other factors.

System effectiveness will be algorithmically determinable. System and component requirements can then be stated without bias. The proposed system conceptual architecture provides a foundation for calculating system effectiveness.

Within the system context of orthogonal methods of detection, we still have false positives (false alarms) and false negatives (misses), and these are subject to a spectrum of influences, including the sensitivity and specificity of each component and the manner in which components are connected. Therefore, while the SE is a function of the sensitivity and specificity of the system, that system SE comprises the sensitivity and specificity of each piece of the system and the allied structure of the system itself.

A topic for research would be the mathematical formalism for system effectiveness evaluation and the related system decision making methods in the context of uncertainty.

Opposite to determining SE is the need to design a system so that it delivers a particular SE. This is a complicated task because information to support the decision is most likely expressed in a probability model, rather than a binary indication.

Recommendation: Research is recommended into methodologies to quantify system effectiveness (SE) for systems of sensors (a detection system) and for systems of detection systems allowing for noisy input from many sensors. Of particular importance is the definition and evaluation of a full spectrum of "false positive" signals ranging from detector reliability, legitimate signals that do not represent true threats, or operator interpretation of detector signals. Appropriate ROCs and other measures of performance for such systems should be developed.

Distributed System, Distributed Sensors

The architecture of a system of explosive detection devices and technologies for check-point and wide-area surveillance could consist of multiple arrays of different types of devices and technologies. The advantages of this type of system are

- detection of potential explosive devices over a substantially larger area than with a single fixed detector;

- ability to obtain spatial and temporal information about the explosive device in relation to the potential target;
- provision of substantial standoff detection capability; and
- decreased likelihood of successful defeat or avoidance of detection in relation to single-location detectors.

Arrays of detectors or sensors are currently being used and developed for many different scientific, public safety and security, and military applications including radio astronomy, fixed platform radar, optical sensing, and acoustic battlefield monitoring.

One example is the Department of Defense development of rapidly deployable marine and land-based acoustic-seismic sensor arrays. "Depending on the applications, these arrays may contain optical geophones, fiber optic hydrophones, and/or fiber optic microphones. On land, these sensor arrays may be deployed in all types of terrain for such applications as perimeter security and ground surveillance to name a few. Marine applications include harbor monitoring and fiber optic acoustic arrays for critical passive sonar platforms involved with anti submarine warfare."[2]

Distributed arrays can be fixed in one location with multiple sensors or distributed over a geographical area. The most likely design for an explosive detection application, especially for wide-area surveillance, would be a set of spatially and geographically distributed arrays of orthogonal and/or partially orthogonal sensors. Although distributed arrays provide the advantage of broad coverage and increased standoff capability, they present some substantial technical challenges. The following are among the most significant:

- Communications between sensors, arrays, and decision makers
- Sensor sampling and refresh approaches and rates
- Effective data transfer, integration, and assessment within an array
- Fusion of information from different sensor or detection technology types
- Sensor fault detection and isolation to maintain array data integrity
- Operationally acceptable times to sense, analyze, and identify the explosive device
- Intelligent aggregation of information for detection decision making
- Ease of deployment, maintenance, and operation

[2]Northrop Grumman Electronic Systems, Navigation Systems Division, Product Details, Marine and Land-based Sensor Arrays.

Recommendation: Research is recommended into rapid, remote collection and concentration of explosives samples and into distributed, low-cost sensors. Included here are small (nano) and perhaps mobile sensors, distributed arrays of sensors, and the use of convective streams with or without airborne adsorbing particles to gather chemical samples.

Decision Fusion

Figure 3.5 shows a sensor data fusion approach in which unprocessed sensor data are provided en masse to a data fusion center. Decisions are rendered on the basis of processing the amalgamated raw data.

Alternatively, Figure 3.1 shows multiple detectors providing disparate signals—considered input—to discrimination processing. This information is fused, resulting in qualified information leading to a decision. The detectors can, in this case, serve as relatively autonomous agent devices providing processed information for the explosives identification decision.

The goal of decision fusion is the combination of input from multiple sensors or detectors. There are several approaches, assuming conditional independence of the individual sensor indications (sensor alarms) permits an optimization of system performance using either Bayesian decision theory or Nehman-Pearson results.

Under the Bayesian alternative, for a set of conditionally independent sensors or detectors, the optimal fused decision is the weighted sum of the individual results. The weights depend on the sensitivity and specificity of individual tests or sensor system behaviors. Current areas of interest involve algorithms and approximations when sensitivity and specificity are unknown or are time-varying.

System dependency will require a substantially more complex structure for fusion. Winnowing processes and voting processes represent areas of current interest for decision making.

Recommendation: Research is needed on the integration of information from distributed orthogonal sensors to achieve real-time conflict resolution and decision making with high system effectiveness, and on integration tools based on data fusion and decision fusion. In addition, research coupling parallel sensors via decision fusion with sequential sensor systems may provide valuable insights.

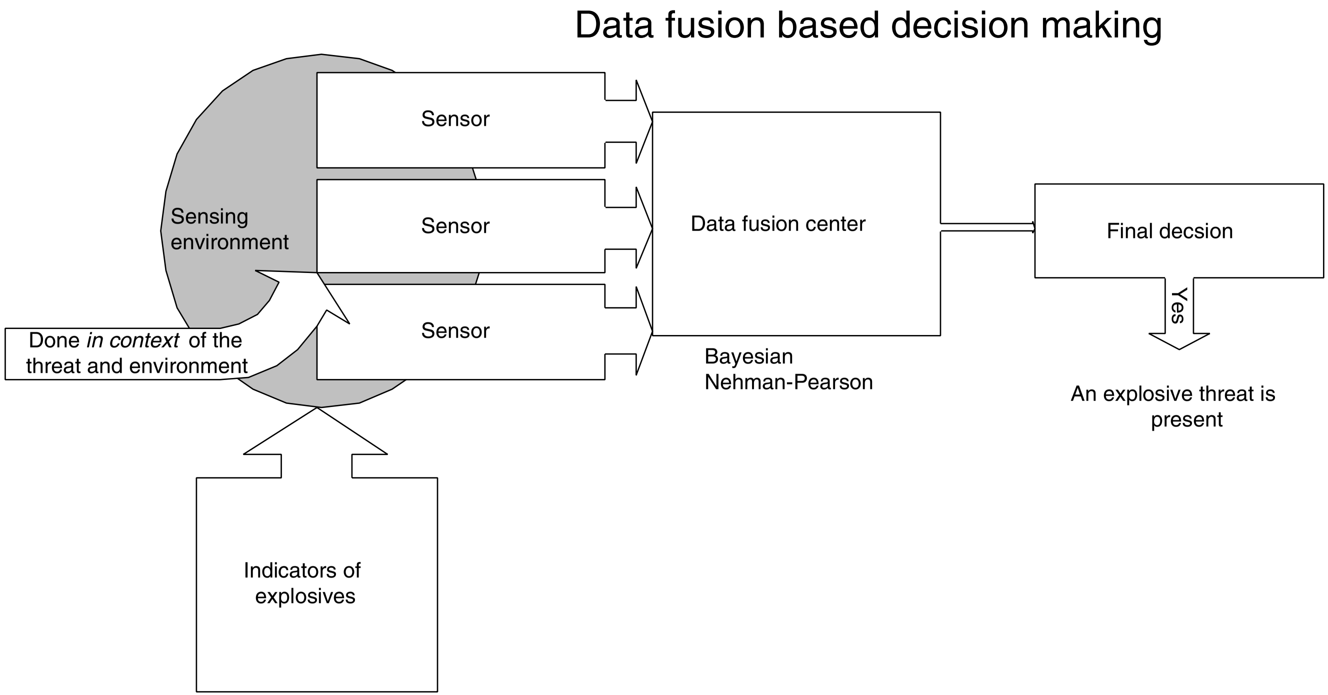

FIGURE 3.5 Data fusion-based decision making. Data fusion is performed to unite sensor data and lead to a decision on the presence of an explosive.

Noise In-Truth Out

One of the underlying concepts for a system of orthogonal and/or partially orthogonal detection technologies is, as previously stated, that near-perfect decisions can be extracted from an accumulation of less than perfect information. This is especially applicable to current explosives detection technologies. Existing technologies all have limitations that can significantly impact either their sensitivity, their specificity, or both.

However, by combining diverse technologies in a system, it is possible to provide an aggregate detection result that is adequate for standoff applications. For example, consider a system consisting of a trace detection technology for nitrogen-based explosives and infrared imaging. When the trace detection is positive, it could indicate the presence of TNT, nitrogen-based fertilizer, or nitroglycerin tablets for a heart condition. When a suspicious image is obtained, it could indicate an explosive vest worn by a bomber or a back brace. Taken together, the two detector indications provide a more positive indication of the presence of an explosive device than each indication by itself.

There is a natural analogue for an effective system made up of imperfect (less than precise) individual detectors. Research on artificial olfactory systems at Tufts University discovered that the natural olfactory "system" appears to consist of many low-performance detectors (cells). Each of these detectors responds to a broad range of input providing amplitude, frequency, and temporal indications. Figure 3.6 is a notional illustration of the range of input that can be detected by two sensors. The area of overlap of the two provides more precise information than any one does. Research indicates that the natural olfactory system works in this fashion. It is a system made up of many imprecise detectors (cells) and processors for receiving and analyzing the information from each cell to resolve the odorant into a specific aroma.

Evolving Standoff Detection

A system for standoff detection cannot be static. Intended capability and ongoing performance must change to respond—at least—to new threats, new background conditions, changes in existing threats, and threats actively attempting to defeat the system.

Mechanisms for modifying system behavior and capability are an area of considerable research interest spanning a spectrum from identification of a new threat's characteristics to structural change in the system design. Adaptation may be done in an evolutionary way or via manual alteration of the system. The system may successfully respond to parameter changes developed during adaptive parameter tuning or to more structural

FIGURE 3.6 Illustration of precise detection with two imprecise sensors.

changes incorporating new algorithms devised during supervised learning, unsupervised learning, or combined hybrid techniques.

Given the proposed orthogonal nature of the system, the addition of new sensors that exploit novel orthogonal means of detection may be a highly appropriate response to compromised system capabilities.

Adaptation requires mechanisms for learning, and especially for learning from system detection failures expressed either as false alarms or as analogues of false negatives.

Recommendation: Research is recommended to envision and devise real-time sensor system threat detection that adapts to new threats, new backgrounds, and new threats that behave like background. A system that autonomously evolves should be a focus of research, including methods to evolve the system design to increase system effectiveness and orthogonality, given detection anomalies.

System Architecture

The system architecture of Figure 3.7 is divided into elements:

- *Detection*: physical and/or informational methods to gain a signal in the presence of the background noise, whatever it may be, of that particular device or method.
- *Discrimination processing*: the focus of algorithmic methodology to discriminate likely true threats from a multiplicity of signals arising above background. These methods may be objective, heuristic, physics-based, artificial intelligence (AI), or other. These discrimination algorithms operate in the presence of the several detection methods.
- *Identification*: given processed information, is this a threat: decision yes or no. The identification approach, in general, would use several different signal inputs to arrive at the decision. The signals could be from different sources at the same time, or from the same source observed at different times or from a combination of both. If yes, some appropriate attribute information must be provided. Note that it should be possible to show a probability of this assessment being accurate, perhaps with a formal probability, and perhaps with an ordered listing of the sources of uncertainty.

While care must be taken in designing self-learning systems in a threat- poor environment (they may learn that nothing is a threat), there

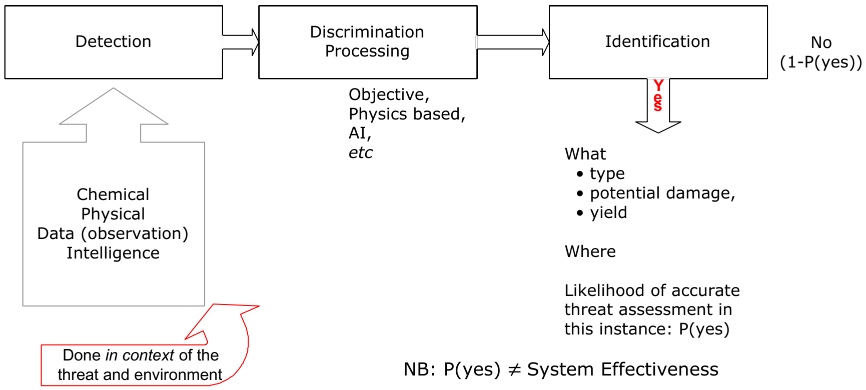

FIGURE 3.7 System concept showing segregation of detection—done in an environment—from the discrimination processing of the sensor signals and the identification of a threat, and from subsequent decision to report the threat.

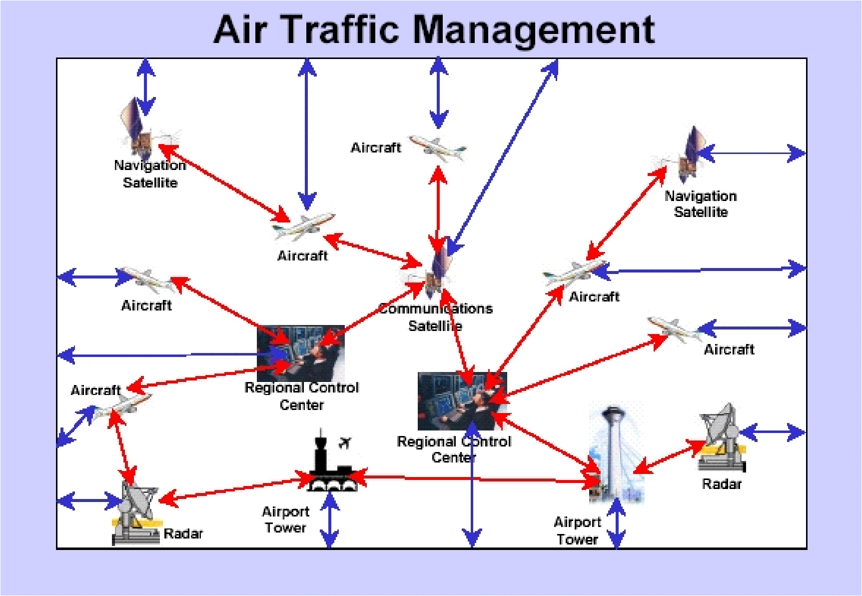

FIGURE 3.8 System-of-systems notional example showing independent, autonomous system elements carrying out their tasks and providing central authority (authorities) with discriminated information for final decision making.

should also be a feedback mechanism in the figure used to tune the system to improve its performance. Tuning would arise from whether the identification was correct or false. Thus, there should be a "model refinement" or "learning" capability in the system that is active during the detection experience, thereby mitigating the difficulty of tuning the system on simulated or artificial threats and yet requiring the system to identify very low rate real threats.

It is generally assumed that the detection methods involve several different technologies, operating in semi- or completely orthogonal modes. The degree to which they are orthogonal will impact system effectiveness. Detection is done in the context of potential environments amd the threats.

System-of-Systems Perspective

The detection system, especially for cases of a wide-area surveillance, could be designed as a system of systems. Implicit in this definition is the autonomous behavior of many parts of the system, especially remote sensor-detector systems. Elements of the system execute tasks including detection and discrimination, all supporting the central authority of identification and final decision. The system effectiveness measure can serve as a metric for a dynamic allocation of resource optimization processes. A notional, compatible, example is show in Figure 3.8.

A system-of-systems approach provides a more complex solution, perhaps suitable to very complex, highly time-varying environments. It also increases autonomy at the sensor-detector and perhaps discriminator levels. Several principal issues are also exposed: detectors could demonstrate competitive behaviors, and interoperability requirements and implications will arise.

4

Chemical Characteristics of Bombs

COMPOSITION OF BOMBS

While few chemicals find use as military explosives (Table 4.1), these can be combined with platiscizers and other materials to create a plethora of formulations.[1,2] The problem of terrorism and suicide bombers, however, narrows the focus to high explosives. Several such explosives, as well as some plasticizers and taggants found in plastique explosives, are listed in Table 4.1 along with their abbreviations. The devastating shock wave that accompanies detonation of a high explosive (HE), results in widespread damage and loss of life. High explosives consist of an intimate mixture of oxidant and reductant, either within a single molecule, such as nitroglycerin, pentaerythritol tetranitrate (PETN), trinitrotoline (TNT), or triacetone triperoxide (TATP), or within an ionic solid, such as ammonium nitrate, when mixed with fuel oil. Mixtures of high explosives are frequently used. For example, Semtex is a blend of cyclomethylenetrinitramine (RDX) and PETN. Reductants (e.g., aluminum powder, fuel oil)

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[1]Köhler, J.; Meyer, R.; Homburg, A. *Explosives*, Fifth Revised Edition; Wiley-VCH: Weinheim, Germany, **2001**. Urbanski, T. *Chemistry and Technology of Explosives*, Vol. 3; Pergamon Press: Oxford, **1965**. Urbanski, T. *Chemistry and Technology of Explosives*, Vol. 4; Pergamon Press: Oxford, **1984**. Manelis, G. B.; Nazin, G. M.; Rubtsov, Yu. I.; Strunin, V. A. *Thermal Decomposition and Combustion of Explosives and Propellants*; Taylor & Francis: London, **2003**.

[2]Yinon, J. *Forensic and Environmental Detection of Explosives*; John Wiley & Sons: Chichester, UK, 1999, pp 88-93.

may be added to solids such as ammonium nitrate, which have excess oxidizing power, in order to increase the explosive yield.

The diversity of molecular features found in explosives suggests that a consideration of the elemental compositions might lead to new or improved detection approaches. Table 4.1 provides a summary of high explosives that would be relatively simple to prepare or that could reasonably be obtained by a determined individual. It also contains some other explosive types for comparison. If elemental formulations are considered, few common chemicals would be mistaken for explosives. The empirical formulas of all of the high explosives in Table 4.1 were entered in the online Aldrich catalog of common laboratory and industrial chemicals and polymers. Only two explosive elemental compositions had other isomers among the 90,000 chemicals in the catalog. One was TNT, which has the same composition as dinitroanthranilic acid. The latter compound is carcinogenic and was a former dye intermediate that is being phased out. The diacetone and triacetone peroxides (e.g., TATP) pose the greatest problem for a detection scheme based solely on elemental constituents. These explosives have the same elemental composition as several organic compounds, including the specialty polymer poly(propylene adiponate). However, the high volatilities of these compounds might make it feasible to detect the vapor plume by molecular spectroscopic techniques, such as microwave or infrared (IR) spectroscopy. For example, the carbonyl stretching absorption in the infrared spectrum at 1740 cm^{-1} is intense and diagnostic of acetone.

All explosives must contain both oxidizing and reducing agents. Strong oxidizing agents require the use of the most electronegative elements nitrogen, oxygen, fluorine, and chlorine. Therefore, one common aspect of HE compositions is a large percentage of the more electronegative elements nitrogen and oxygen. Chlorine and fluorine are used less often in explosives because of its difficult chemistry and greater expense. Also, fluorine's extreme oxidizing power may lead to unstable explosive formulations. The preponderance of highly electronegative elements in explosives is one reason why their detection by IMS (ion mobility spectrometry), which employs electron attachment to neutral explosive molecules, succeeds.

The light elements carbon and hydrogen usually serve as the reducing components of HE formulations. Occasionally, metal powders of the lighter elements (aluminum or magnesium) are added as supplemental reducing agents in explosive mixtures. Black powder, which is a less energetic material, uses both charcoal and elemental sulfur as reductants.[3]

[3]National Research Council, Committee on Smokeless and Black Powder. *Black and Smokeless Powders. Technologies for Finding Bombs and the Bomb Maker;* National Academy Press: Washington, DC, **1998**.

TABLE 4.1 Some Representative Common High Explosives and Their Compositions[a]

Explosives Based on Nitrogen	Formula	wt % C	wt % H	wt % N	wt % O	Sum N + O
Ammonium nitrate (AN)	$H_4N_2O_3$	0	5.04	35.01	59.97	94.98
Ammonium picrate (Expl D)	$C_6H_6N_4O_7$	29.28	2.46	22.76	45.5	68.26
Cyclonite (RDX)	$C_3H_6N_6O_6$	16.22	2.72	37.84	43.22	81.06
Ethylenediamine dinitrate	$C_2H_{10}N_4O_6$	12.91	5.42	30.1	51.58	81.68
Guanidine nitrate	$CH_6N_4O_3$	9.84	4.95	45.89	39.32	85.21
Hexamethylenetriperoxide diamine (HMTD)	$C_6H_{12}N_2O_6$	34.62	5.81	13.46	46.11	59.57
Hexanitrohexaazaisowurtzitane (HNIW or CL20)	$C_6H_6N_{12}O_{12}$	16.45	1.38	38.36	43.82	82.18
Hydrazine nitrate	$H_5N_3O_3$		5.3	44.2	50.09	94.29
Mannitol hexanitrate	$C_6H_8N_6O_{18}$	15.94	1.78	18.59	63.69	82.28
Monomethylamine nitrate	$CH_4N_2O_3$	13.05	4.38	30.43	52.14	82.57
Nitrocellulose	$C_6H_7N_3O_{11}$	24.24	2.37	14.14	59.23	73.37
Nitroglycerin (NG)	$C_3H_5N_3O_9$	15.87	2.22	18.5	63.41	81.91
Nitrotriazolone (NTO)	$C_2H_2N_4O_3$	18.47	1.55	43.08	36.9	79.98
Octogen (HMX)	$C_4H_8N_8O_8$	16.22	2.72	37.84	43.22	81.06
Pentaerythritol tetranitrate (PETN)	$C_5H_8N_4O_{12}$	19	2.55	17.72	60.73	78.45
Picric acid	$C_6H_3N_3O_7$	31.46	1.32	18.34	48.88	67.22
Tetrazene	$C_2H_8N_{10}O$	12.77	4.29	74.44	8.5	82.94
Tetryl	$C_7H_5N_5O_8$	29.28	1.76	24.39	44.58	68.97

Trinitrobenzene (TNB)	$C_6H_3N_3O_6$	33.82	1.42	19.72	45.05	64.77
Trinitrotoluene (TNT)	$C_7H_5N_3O_6$	37.02	2.22	18.5	42.26	60.76
Triaminoguanidine nitrate (TAGN)	$CH_9N_7O_3$	7.19	5.43	58.67	28.72	87.39
Triaminotrinitrobenzene (TATB)	$C_6H_6N_6O_6$	27.92	2.34	32.55	37.19	69.74
1,3,3-Trinitroazetidine (TNAZ)	$C_3H_4N_4O_6$	18.76	2.1	29.17	49.98	79.15
Trinitrochlorobenzene	$C_6H_2ClN_3O_6$	29.11	0.81	16.97	38.78	55.75
Trinitropyridine	$C_5H_2N_4O_6$	28.05	0.94	26.17	44.84	71.01
Urea nitrate	$CH_5N_3O_4$	9.76	4.09	34.14	52	86.14
Average (%)		20.29	2.98	30.81	46.14	76.95
Standard deviation		±8.15	±1.38	±11.01	±8.01	±8.47
Maximum/minimum (%)		37/0	5/0.8	58/13	63/9	95/56
Other Explosive Types						
Ammonium perchlorate	H_4NO_4Cl	0	3.43	11.92	54.47	66.39
Lead styphnate	$C_6H_3N_3O_9Pb$	15.39	0.65	8.97	30.75	39.72
Triacetone triperoxide (TATP)	$C_9H_{18}O_6$	48.64	8.16	0	43.2	43.2
Black powder		10	0	10.4	35.6	46
Tetraamminecopper perchlorate	$H_{24}Cl_2CuN_4O_8$		7.06	16.35	37.35	53.7
Average				11.91	40.27	49.80
Standard deviation				±2.23	±6.85	±8.19

[a]For additional listings of explosives considered important in forensic investigations, see TWGFEX: The Technical Working Group for Fire and Explosions, http://www.twgfex.org.

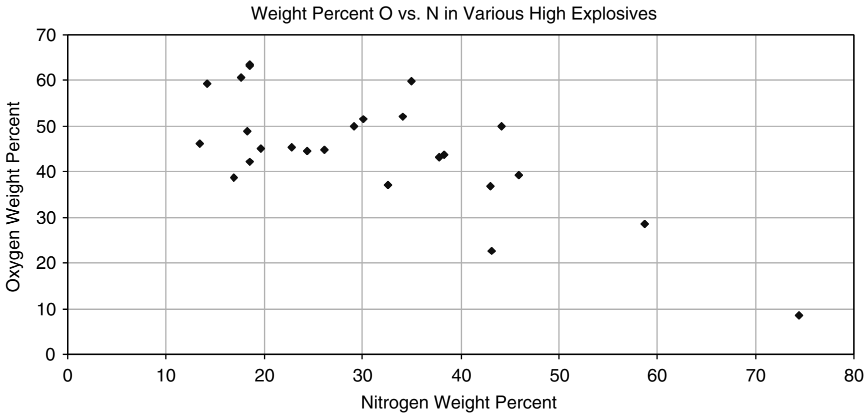

FIGURE 4.1 Plot of the weight percent of oxygen versus nitrogen for the high explosives based on nitrogen listed in Table 4.1.

These general observations suggest that a focus on the percentage composition of the most electronegative elements might be a useful identifier of explosive formulations.

The majority of high-explosive formulations use inorganic or organic nitrate or nitro functional groups as the oxidant. The correlation between nitrogen and oxygen content is roughly linear, as shown in the scatter plot in Figure 4.1. The nitrogen content of a wide variety of nitrogen-containing explosives is 31 ± 12%. Oxygen composition is even more constant at 45 ± 8%. This suggests that dual analysis of nitrogen and oxygen content might provide a more reliable indication of high explosives than techniques based on nitrogen content alone. Indeed, it has been stated, "A measurement of the oxygen and nitrogen densities, to an uncertainty of ±20%, gives a unique separation of explosives from other compounds."[4] Note, however, that this analysis will fail for certain explosives that do not contain nitrogen, for example TATP.

While analysis such as this is not useful for energetic materials such as TATP, it may be quite useful for more "common" explosive materials such as ammonium nitrate/fuel oil, or black and smokeless powders. Ammonium nitrate (AN) in particular is readily available and when mixed with fuel oil is capable of producing widespread explosive dam-

[4]Yinon, J. *Forensic and Environmental Detection of Explosives*; John Wiley & Sons: Chichester, UK, 1999.

age. Therefore, the ability to exploit the nitrogen and oxygen content in AN may provide a useful means of detection of this material in explosive devices.

From a chemical point of view, the other possible elements of high electronegativity that might be employed in explosives are chlorine and fluorine. For example, perchlorate and chlorate salts are used in certain energetic materials formulations. Ammonium perchlorate, which is mixed with a powdered aluminum-polymer binder, finds use as a solid rocket fuel. Metal powder-potassium chlorate mixtures are used in fireworks. Chlorine-based explosives could be detected by an elemental analysis approach, since a high chlorine-oxygen-nitrogen content is indicative of such species. The explosives employed by terrorists and suicide bombers will continue to evolve as military establishments worldwide strive to build more efficient and/or more energetic materials. As terrorists and other potential bombers become more sophisticated, both in their choice of explosive materials and in the way these materials are procured, transported, and concealed, detection methods must be changed concomitantly.

For example, in the near term, a new class of energetic materials, ionic liquids (e.g., 4-diamino-1,2,4-triazolium dinitroamide [$(NH_2TazN(NO_2)_2$], is just appearing in the open literature.[5] The syntheses of these liquids or low-melting salts from readily available compounds are very straightforward. Most of them could be identified with a technique that relies on N + O content for identification.

Other new explosive materials are fluorine-containing derivatives of the familiar RDX and octogen (HMX).[6] These tend to be more dense and thus have greater impact per unit mass. Although many of these compounds could probably be detected with the same techniques used for RDX and HMX (e.g., negative polarity IMS) or those that use bulk properties, as the percentage of fluorine vis-à-vis oxygen increases, an analysis based on nitrogen and oxygen content becomes problematic. This could be corrected with the addition of fluorine to the list of electronegative elements scanned.

Recommendation: Improved detection systems will lead to development of new explosives. Research is needed on the identifica-

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[5]Drake, G.; Hawkins, T.; Brand, A.; Hall, L.; Mckay, M.; Vij, A.; Ismail, *I. Propellants, Explosives, Pyrotechnics* **2003**, *28*, 174-180.

[6]Chapman, R. D.; Welker, M. R.; Kreutzberger, C. D. *J. Org. Chem*. **1998**, *63*, 1566–1570. Chapman, R. D.; Gilardi, R. D.; Welker, M. F.; Kreutzberger, C. B. *J. Org. Chem*. **1999**, *64*, 960-965. Axenrod, T.; Guan, X.-P.; Sun, J.; Qi, L.; Chapman, R. D.; Gilardi, R. D. *Tetrahedron Letters* **2001**, *42*, 2621-2623.

tion and characterization of new chemical explosives that do not utilize nitrogen and have very low vapor pressures, for example, ionic liquids.

PLUMES AND VAPOR PRESSURES

Existing explosive detection approaches for luggage rely on estimating physical characteristics, such as the density and approximate elemental nitrogen content, by using X-ray scattering (e.g., X-ray computer tomographic [CT] analysis).[7] The reason for the existing focus on analysis of solid materials is that the low volatility of many explosives precludes detection of emanating molecular vapors (see Figure 4.2). Vapors that are emitted from a bomb may be present at concentrations two to four orders of magnitude less than the equilibrium vapor pressures shown in the figure, both because of enclosure in a bomb package and because explosive compositions containing other compounds may have lower vapor pressures than those shown for the pure explosive compounds.

In some cases, more volatile impurities (e.g., dinitrotoluene [DNT] in TNT) can be employed in specific explosive detection applications, such as landmine detection. Some energetic plasticizers[8] or taggants[9] used in plastique explosives, such as mononitrotoluene (MNT), diglycol dinitrate (DEGN), dimethyldinitrobutane (DMNB), ethylene glycol dinitrate (EGDN), or butanetriol trinitrate (BTTN), are volatile enough for vapor detection of these species to be used as an indicator of the presence of explosive compounds. Nitroglycerin, a high explosive and constituent of dynamite, is another volatile species that might be detected directly in the vapor phase. The vapor pressures of less volatile explosives are very temperature dependent. For example, the vapor pressure of TNT increases by approximately a factor of four between 20 and 30ºC.[10] This means that the probability of detecting explosives will depend strongly on the ambient

[7]Yinon, J. *Forensic and Environmental Detection of Explosives*; John Wiley & Sons: Chichester, UK, **1999**.

[8]Köhler, J.; Meyer, R.; Homburg, A. *Explosives*, Fifth Revised Edition., Wiley-VCH: Weinheim, Germany, **2001**. Urbanski, T. *Chemistry and Technology of Explosives*, Vol. 3; Pergamon Press: Oxford, UK, **1965**. Urbanski, T. *Chemistry and Technology of Explosives*, Vol. 4; Pergamon Press: Oxford, UK, **1984**. Manelis, G. B.; Nazin, G. M.; Rubtsov, Yu. I.; Strunin, V. A. *Thermal Decomposition and Combustion of Explosives and Propellants*; Taylor & Francis: London, **2003**.

[9]National Research Council, Committee on Marking, Rendering Inert, and Licensing of Explosive Materials. *An Integrated National Strategy for Marking, Tagging, Rendering Inert, and Licensing Explosives and Their Precursors*; National Academy Press: Washington, DC**, 1998**.

[10]Dionne, B. C.; Rounbehler, D. P.; Achter, E. K.; Hobbs, J. R.; Fine, D. H. *J. Energetic Mater.* **1986**, *4*, 447-472.

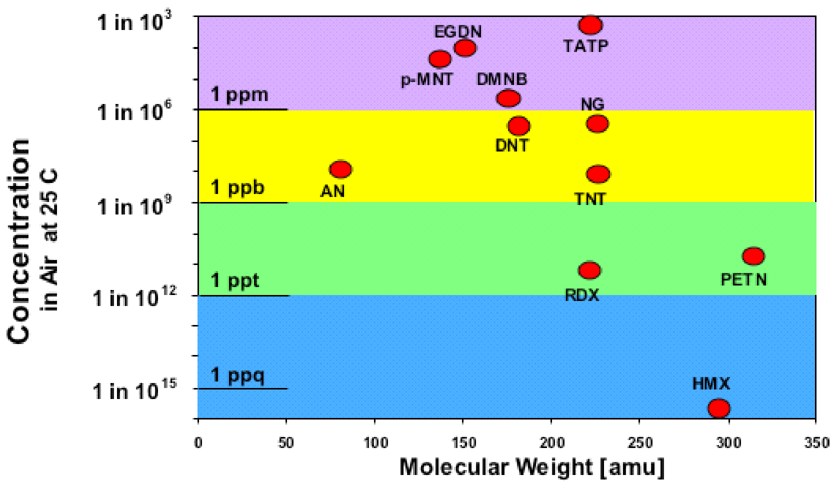

FIGURE 4.2 Vapor pressures of high explosives and additives. (Courtesy of J. Parmeter et al., Sandia National Laboratory)

temperature. Another variable to consider is the tendency of high explosives to adsorb strongly on surfaces. It is well known in land mine detection studies that both dogs and chemical sensors show improved performance when soil moisture content is high.[11] Water competes with TNT and DNT for binding on soil particles, thereby releasing more TNT and DNT into the soil airspace where these molecules can diffuse out for improved detection.

ATOMIC AND MOLECULAR PROPERTIES

Several different atomic and molecular properties might be exploited in explosives detection. Two excellent detailed descriptions exist,[12] so the following discussion focuses on general categories.

[11]Phelan, J. M.; Webb, S. W.; Gozdor, M.; Cal, M.; Barnett, J. L. *Proceedings of SPIE-The International Society for Optical Engineering, Pt. 2, Detection and Remediation Technologies for Mines and Minelike Targets VI* **2001**, 868-878. Phelan, J. M.; Webb, S. W.; Rodacy, P. J.; Barnett, J. L. *Environmental Impact to the Chemical Signature Emanating from Buried Ordance*, SAND2001-2902; Sandia National Laboratory, **2001**, 55 pp.

[12]References 1 and 2.

Atomic Properties

Although atomic absorption spectroscopy and atomic fluorescence can be used to determine elemental composition (after atomization of a sample in a flame or plasma), these methods require direct sampling and work best for heavier elements. They have not been considered for standoff detection of explosives. Several neutron techniques have been explored[13,14,15] and some are being considered commercially for land mine detection and cargo screening. Gamma rays, which are emitted from radioactive nuclei that form after neutron bombardment, can provide a unique signature for each element. Techniques that measure transmitted, attenuated, or scattered neutrons can provide imaging, as well as information about elemental composition. Being electrically neutral, neutrons do not interact strongly with matter. Their penetrating nature is an asset for screening cargo and luggage; however, the inconvenience, expense, and hazards of radioactive, accelerator, and reactor neutron sources limit their application to settings in which human exposure can be prevented with certainty. The photonuclear reaction employs resonant gamma-ray absorption to produce an unstable nucleus that is subject to radioactive decay. This is another method that has been applied to determining elemental nitrogen content.[16]

Core electron ionization and subsequent characteristic X-ray emission gives rise to another broad class of methods, which might potentially be used for atom identification. X-ray absorption edge behavior can also provide element-specific detection. The above techniques mainly diagnose the type of elements present, rather than being strongly influenced by molecular properties. Techniques that involve X-ray emission are advantageous, since computer tomography can be used to create a three-dimensional image of the target.

Besides the characteristic emissions, X-ray scattering has been employed to broadly distinguish light elements from heavier elements in imaging applications; however, the light elements carbon, nitrogen, and

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[13]Yinon, J. *Forensic and Environmental Detection of Explosives*; John Wiley & Sons: Chichester, UK, **1999**.

[14]Bruschini, C. *Commercial Systems for the Direct Detection of Explosives for Explosive Ordnance Disposal Tasks*; EPFL-DI-LAP Internal Note, February 2001, 68 pp.; http://diwww.epfl.ch/lami/detec/detec.html#Detec_doc.

[15]Singh, S.; Singh, M. *Explosives detection systems (EDS) for aviation security*; *Signal Processing* **2003**, *83*, 31-55.

[16]Habiger, K.W.; Clifford, J.R.; Miller, R.B.; McCullough, W.F. EXDEP/CTX: *A*n explosive detection system for screening luggage with high energy X-rays; *Proc. IEEE Particle Accelerator Conf*. **1994**, *4*, 2622-2624.

oxygen are not easily differentiated from each other. Cargo screening equipment using both transmitted and backscattered X-rays for imaging has been developed by several vendors.

Molecular Properties

Spectroscopic methods, which reflect structure and type, provide means that are capable of identifying specific explosives being used. These span the range of methods from those that are relatively unspecific for large molecules, such as ultraviolet-visible (UV-Vis) spectroscopy, to highly specific identifiers, such as mass spectrometry. It is useful to examine the various techniques in the context of whether they are applied to detect small amounts of vapors emanating from bulk solid explosives or trace particulates.

Molecular Vapors Emitted by Explosives

As noted above, the vapor plume from an explosive may contain from as much as 1000 parts per million (ppm) to fractions of a part per trillion (ppt) of the molecular constituents, impurities, or decomposition products. This provides an opportunity for identification by gas-phase molecular spectroscopies. Molecular spectroscopic techniques can be used to uniquely identify explosive molecules in the vapor phase, but the low vapor pressure of many explosives means that this will often not be feasible. Most packaged explosives (nitroglycerin, EGDN-based dynamites, and TATP being notable exceptions) emit so little material into the gas phase that detection is feasible only near the surface of these materials. Chemically specific spectroscopic probes therefore require direct sampling, near-proximity instrumentation measurements, and perhaps preconcentration. There is an inherent problem with increasingly more sensitive means of molecular detection. Ultrasensitive detection methods could give rise to high nuisance alarms due to the trace residues from the use of recreational firearms or medical use of nitroglycerin as a heart medication. Ultrasensitive detection approaches would be problematic in explosive-rich military environments and could also lead to false alarms due to the presence of chemical interferents.

Some techniques applied for the identification of explosive molecules in the vapor phase include UV-Vis, infrared, and microwave absorption. Fluorescence in the UV-Vis has also been employed. For large molecules, the UV-Vis and fluorescence characteristics of electronic spectra are broad, so specificity is low. The presence of other compounds that absorb or emit in similar spectral regions limits the usefulness of these methods. Infrared spectra probe characteristic vibrations of a molecule, and the presence of the $–NO_2$ group in many high explosives offers a characteristic spectral feature that can indicate the presence of an explosive. Alternative spectroscopic (e.g., photoacoustic) probes, as well as laser techniques, such as cavity ring-down spectroscopy and LIDAR(light detection and ranging) for UV absorption or fluorescence have been explored.[17] The LIDAR techniques offer the possibility of standoff detection; however, they suffer from the breadth of electronic spectral features for large molecules. For that reason, selective luminescent granular sensors (e.g., "smart dust") have been developed, whose luminescence is affected by adsorption of explosive molecules and can be probed remotely by LIDAR.[18] The application of nanosensors to explosives detection is an area yet to be explored.

Direct sampling ionization methods[19] include gas chromatography (GC) interfaced with electron capture detectors (ECD). Mass spectrometry can provide unique identification, and when interfaced with GC even complex mixtures can be analyzed. Gas chromatography-mass spectrometry (GC-MS) is the gold standard for chemical analysis; however, it requires bulky, expensive, and delicate equipment as well as direct sampling. The development of MEMS (microelectromechancial systems) approaches to GC separations and interest in developing fieldable mass spectrometers may lead to advances that make these approaches better adapted for field deployment. The chief ion method currently used is IMS, which employs an electron source at ambient pressures to create negative ions of explosive vapors and characterize them by their drift times in a fixed electric field. It is not as selective as GC-MS, but it has been widely deployed for several reasons, including relatively low cost and simplicity of instrumentation.

Recommendation: Research into the vapor space surrounding the bomber may lead to improved means of explosives detection. An increased quantitative understanding of vapor plume dynamics is required for application to explosives with high-volatility components such as TATP.

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[17]Steinfeld, J. I.; Wormhoudt, J. *Ann. Rev. Phys. Chem.* **1998**, *49*, 203-232. Fidric, B. G.; Provencal, R. A.; Tan, S. M.; Crosson, E. R.; Kachanov, A. A.; Paldus, B. A. Bananas, explosives and the future of cavity ring-down spectroscopy *Optics & Photonics News* **2003**, *14(7)*, 24-29.

[18]Simonson, R. J.; Hance, B. G.; Schmitt, R. L.; Johnson, M. S.; Hargis, P. J., Jr. *Proceedings of SPIE-The International Society for Optical Engineering, Pt. 2, Detection and Remediation Technologies for Mines and Minelike Targets VI* **2001**, 879-889.

[19]Yinon, J. *Forensic and Environmental Detection of Explosives*; John Wiley & Sons: Chichester, UK, **1999**.

Vapor plume research is particularly required for high-volatility components such as TATP both because this high volatility could be exploited with detection techniques that are not applicable to low-volatility components, and, especially in the case of TATP, its lack of nitrogen may make it undetectable by some traditional detection techniques.

Bulk Explosives

Typical high explosives used by terrorists, such as PETN and RDX, have total densities between 1.2 and 1.8 g/cm^3.[20] X-ray imaging approaches combined with computer tomography allow estimation of densities of objects and form the basis for the airport CTX luggage scanners. The rate of false positives from a simple density determination could be improved by additional elemental or molecular information. Nuclear quadrupole resonance (NQR) is being explored as an adjunct method for nitrogen detection. Since nuclear quadrupole energy levels are perturbed by the chemical environment, the technique can offer explosive-specific information. However, the sensitivity toward different nitrogen-based explosives is variable.[21,22] Nuclear magnetic resonance (NMR) is a technique that has not yet been widely utilized in the detection of explosives. Pulsed NMR to examine H-N coupling via T_1/T_2 measurements has been tried. This approach is complicated by the requirement of a strong homogeneous auxiliary magnetic field.[23] Even though the resonance frequencies in NQR are low and hence the technique is a less sensitive technique, nonetheless NQR has been demonstrated to be useful in practice for explosives detection.

Diffracted X-rays may provide information that can be used to detect crystalline explosive compounds such as RDX and some other high explosives. Measurement of low-angle X-ray scattering has the potential to detect such materials with high specificity, since the diffraction peaks arise from the regular order of atoms within molecules arranged in a periodic lattice.[24]

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[20]Habiger, K.W.; Clifford, J.R.; Miller, R.B.; McCullough, W.F. EXDEP/CTX: An explosive detection system for screening luggage with high energy X-rays; *Proc. IEEE Particle Accelerator Conf*. **1994**, *4*, 2622-2624.

[21]Yinon, J. *Forensic and Environmental Detection of Explosives;* John Wiley & Sons: Chichester, UK, **1999**.

[22]Ostafin, M.; Nogaj, B. Detection of Plastic Explosives in Luggage with 14N Nuclear Quadrupole Resonance Spectroscopy, *Appl. Mag. Res.* **2000**, *19*, 571-578.

[23]Yinon, J. *Forensic and Environmental Detection of Explosives;* John Wiley & Sons: Chichester, UK, **1999**.

[24]Green, M. C.; Partain, L. D. *Proceedings of SPIE-The International Society for Optical Engineering. Nondestructive Detection and Measurement for Homeland Security* **2003**, 63-72.

Microwave and terahertz imaging are being explored as standoff methods for detecting concealed solid explosives,[25] but these techniques lack chemical specificity. Some resonant absorption occurs in the low-frequency microwave region, which may be exploited to give useful specificity.

Trace Particulate or Adsorbed Explosives

The propensity of explosive vapors and explosive particles of low volatility to adsorb strongly to bulk surfaces[26] or dust particles is the basis for several explosive detection schemes. Fine particulates of explosives may also be dislodged during the bomb making process and adhere to packing material, as well as the clothing and skin of a bomb maker. Raman microspectroscopy using fiber-optic techniques has been employed to determine characteristic vibrational spectral features, which can be used to identify explosives particles or surfaces contaminated with explosives.[27] In one common application of IMS, a probe with an affinity for explosive particulates is rubbed on potentially contaminated luggage or shoe surfaces. Heating the probe to about 200°C in the IMS inlet vaporizes low-volatility solid explosives, such as RDX, for detection.

Catalytic or oxidative decomposition of many explosives yields NO_2 that can be detected by highly sensitive chemiluminescence schemes. Immunoassay has been shown to be a viable detection method for several nitrogen-based explosives.[28] The ability of explosive molecules to quench the luminescence of conjugated polymers has been explored as a sensitive method for trace detection.[29] Specificity can be improved by adopting an

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[25]Falconer, D. G.; Watters, D. G. *Proceedings of SPIE-The International Society for Optical Engineering. Substance Identification Analytics* **1994**, 301-309. Federici, J. F.; Gary, D.; Schulkin, B.; Huang, F.; Altan, H.; Barat, R.; Zimdars, D., *Appl. Phys. Lett.* **2003**, *83*, 2477-2479.

[26]Bender, E.; Hogan, A.; Leggett, D.; Miskolczy, G.; MacDonald, S. Surface contamination by TNT, *J. Forensic Sci.* **1992**, *37*, 1673-8.

[27]Yinon, J. *Forensic and Environmental Detection of Explosives;* John Wiley & Sons: Chichester, UK, **1999**.

[28]Yinon, J. *Forensic and Environmental Detection of Explosives*; John Wiley & Sons: Chichester, UK, **1999**.

[29]Yang, J.-S.; Swager, T. M. Fluorescent porous polymer films as TNT chemosensors: Electronic and structural effects, *J. Am. Chem. Soc.* **1998**, *120*, 5321-5322. Goodspar, J. V. *Anal. Chem.* **2001**, *73*, 2004-2011. Liu, Y.; Mills, R. C.; Boncella, J. M.; Schanze, K. S., *Langmuir*, **2001**, *17*, 7452-7455; Albert, K. J.; Walt, D. R. *Anal. Chem.* **2000**, *72*, 1947-1955. McQuade, D. T.; Pullen, A. E.; Swager, T. M. Conjugated polymer-based chemical sensors, *Chem. Rev.* **2000**, *100*, 2537-2574. Sohn, H.; Sailor, M. J.; Magde, D.; Trogler, W. C. Detection of nitroaromatic explosives based on photoluminescent polymers containing metalloles, *J. Am. Chem. Soc.* **2003**, *125*, 3821-3830.

"electronic nose" approach with an array of sensors with differing responses to analyte.[30]

FUTURE POSSIBILITIES

For standoff detection one has either to examine a characteristic physical emission, to probe with a beam of particles or radiation and observe a characteristic emission, or else to collect a sample remotely. Various bulk material properties can be used to indicate the probable presence of explosives. Properties, such as density and effective atomic number, are presently used to indicate the presence of an explosive, but are not unique identifiers. False-alarm rates occur because such diagnostics lack true chemical specificity. A detailed analysis of the weight percent of all elements present in a solid would offer greater specificity if it could be engineered in a practical system. In the absence of an analysis of all elements present, a determination of nitrogen and oxygen content would identify a wide variety of nitrogen-based explosive materials with a high degree of certainty. An analysis of just the nitrogen content is useful but less specific. At present, neutron techniques seem to be the techniques most likely to provide such information for concealed explosives.

Trace detection methods must surmount the issue of sample collection to be useful in a standoff mode. Vapor and particle collection booths, which preconcentrate samples for analysis, have been prototyped for walk-in passenger screening. LIDAR techniques show promise for standoff applications; however, the issue of selectivity becomes problematic when detecting complex explosive molecules with broad spectroscopic features. Sensor array detectors (e.g., resistive, fluorescent) or "electronic noses" present the possibility of specificity with relatively inexpensive instrumentation. Key issues that have to be faced include sample collection and concentration. The application of MEMS technology to explosive sensing shows promise, as does the application of nanotechnology (e.g., smart dust). Explosives are also molecules with high exotherms for anaerobic thermal decomposition, which might be exploited in microcalorimetry using MEMS technology.[31] The development of inexpensive se-

[30] Albert, K. J.; Dickinson, T. A.; Walt, D. R.; White, J.; Kauer, J. S. *Proceedings of SPIE-The International Society for Optical Engineering, Pt. 1, Detection and Remediation Technologies for Mines and Minelike Targets III* **1998**, 426-431. Yinon, J. Detection of explosives by electronic noses, *Anal. Chem.* **2003**, *75*, 99A-105A; Hopkins, A. R.; Lewis, N. S. Detection and classification characteristics of arrays of carbon black/organic polymer composite chemiresistive vapor detectors for the nerve agent simulants dimethylmethylphosphonate and diisopropylmethylphosphonate, *Anal. Chem.* **2001**, *73*, 884-892.

[31] Fair, R. B.; Pamula, V.; Pollack, M. *Proceedings of SPIE-The International Society for Optical Engineering. Detection and Remediation Technologies for Mines and Minelike Targets II* **1997**, 671-679.

lective miniature sensors offers the possibility of deploying sensor networks that could monitor large areas and perhaps react to a mobile source of trace explosives.

Biology is also expected to contribute to new sensing approaches. Chemically specific higher biological systems, such as dogs, require close proximity to the explosive material being sensed, but the sensor is mobile. Similarly, bees have been trained to locate specific explosives.[32] For example, spiking sugar water with TNT trains them to associate food with the odor of TNT. Robotics or unmanned air vehicles provide an engineered analogue to these approaches. Many nitro-based explosives are also potent vasodilators (e.g., nitroglycerin for angina), which suggests biological detection schemes. Other novel approaches to explosive detection are considered in Chapter 7.

[32]Rodacy, P. J.; Bender, S.; Bromenshenk, J.; Henderson, C.; Bender, G. *Proceedings of SPIE-The International Society for Optical Engineering. Pt. 1 Detection and Remediation Technologies for Mines and Minelike Targets VII* **2002**, 474-481.

5
Existing Detection Techniques and Potential Applications to Standoff Detection

INTRODUCTION

Detection of explosives is based on a wide variety of technologies that focus on either bulk explosives or traces of explosives. Bulk explosives can be detected indirectly by imaging characteristic shapes of the explosive charge, detonators, and wires or directly by detecting the chemical composition or dielectric properties of the explosive material. Trace detection relies on vapors emitted from the explosive or on explosive particles that are deposited on nearby surfaces. Explosive detection is a very challenging task, and combinations of the various techniques offer increased sensitivities and selectivities. There are numerous technologies for detecting explosives that have been proposed, are in the research stage, or are currently in use. A recent review of technologies and products being used today is available on the web.[1] A more general review of explosives detection can be found in a government reports[2] and in books cover-

[1]Burschini, C. Commercial Systems for the Direct Detection of Explosives (for Explosive Ordnance Disposal Tasks), *ExploStudy*, Final Report, 2001. Ecole Polytechnique Federale de Lausanne, Switzerland. http://diwww.epfl.ch/lami/detec/ExploStudyv1.0.pdf (pdf file) or http://diwww.epfl.ch/lami/detec/explostudy.html (html file).

[2]U.S. Congress, Office of Technology Assessment, *Technology Against Terrorism, The Federal Effort*; U.S. Government Printing Office: Washington, DC, 1991. http://www.wws.princeton.edu/~ota/disk1/1991/9139.html (html file) or http://www.wws.princeton.edu/cgi-bin/byteserv.prl/~ota/disk1/1991/9139/9139.PDF (pdf file). The National Institute of Justice, *Survey of Commercially Available Explosives Detection Technologies and Equipment*, NIJ Office of Science and Technology: Washington, DC, 1998. For an extensive bibliography of

ing explosives detection.[3] The existing technologies for explosives detection can be separated into two categories, bulk detection shown in Figure 5.1(a) and trace detection shown in Figure 5.1(b).

This report is concerned particularly with standoff detection, where the vital data collection apparatus for explosive detection is located far enough away from the explosive devices that it will not be damaged and personnel operating the apparatus will not be harmed. The amount of standoff distance that is required will depend on the size of the explosive device, but standoff distances are usually defined as 10 m or more. In Figure 5.1, technologies that have the potential to achieve standoff detection are distinguished by cross-hatching. In addition to the ideal standoff configuration, where the entire detection system is at a safe distance from the explosive, systems having remote components that are not "vital" to the detection device were also included. These nonvital components could include low-cost detectors or a distributed detector network that reports back to a central detection apparatus located at a standoff distance using either optical or wireless signaling. These nonvital components could easily be replaced if destroyed. These partially remote detection schemes are marked by cross-hatching in Figure 5.1(a) and (b).

Pointing toward research and development directions that can significantly advance the standoff detection of explosives is a major goal of this report. These R&D directions are highlighted in Figure 5.1 with a dotted pattern. The research directions described in this section are often extensions of existing technologies or combinations of existing research directions with the development of explosive detection devices. Novel detection techniques and their associated research directions are described in Chapter 7 of this report. Explosives detection is not easy or simple. Detection technologies vary with the scenario of the explosive situation. Each method and accompanying scenario has fundamental, practical, and even cultural limitations. Many explosive detection techniques are limited either by fundamental physical constraints (e.g., resolution limits for microwave imaging) or by the circumstances of a particular scenario (e.g., background explosive residue in embattled locations such as Iraq). The committee concentrates on standoff scenarios for both civilian and mili-

papers, reports, and presentations on the analysis and detection of explosives, see http://www.ncfs.ucf.edu/twgfex/Analysis%20and%20Detection%20of%20Explosives.pdf.

[3] *Advances in Analysis and Detection of Explosives*, Proceedings of the 4th International Symposium on Analysis and Detection of Explosives, September 7-10, 1992, Jerusalem, Israel; J. Yinon, Ed., Kluwer Academic Publishers: Dordrecht, Netherlands. *Modern Methods and Applications in the Analysis of Explosives*. J. Yinon and S. Zitrin, Eds., John Wiley & Sons: 1993.

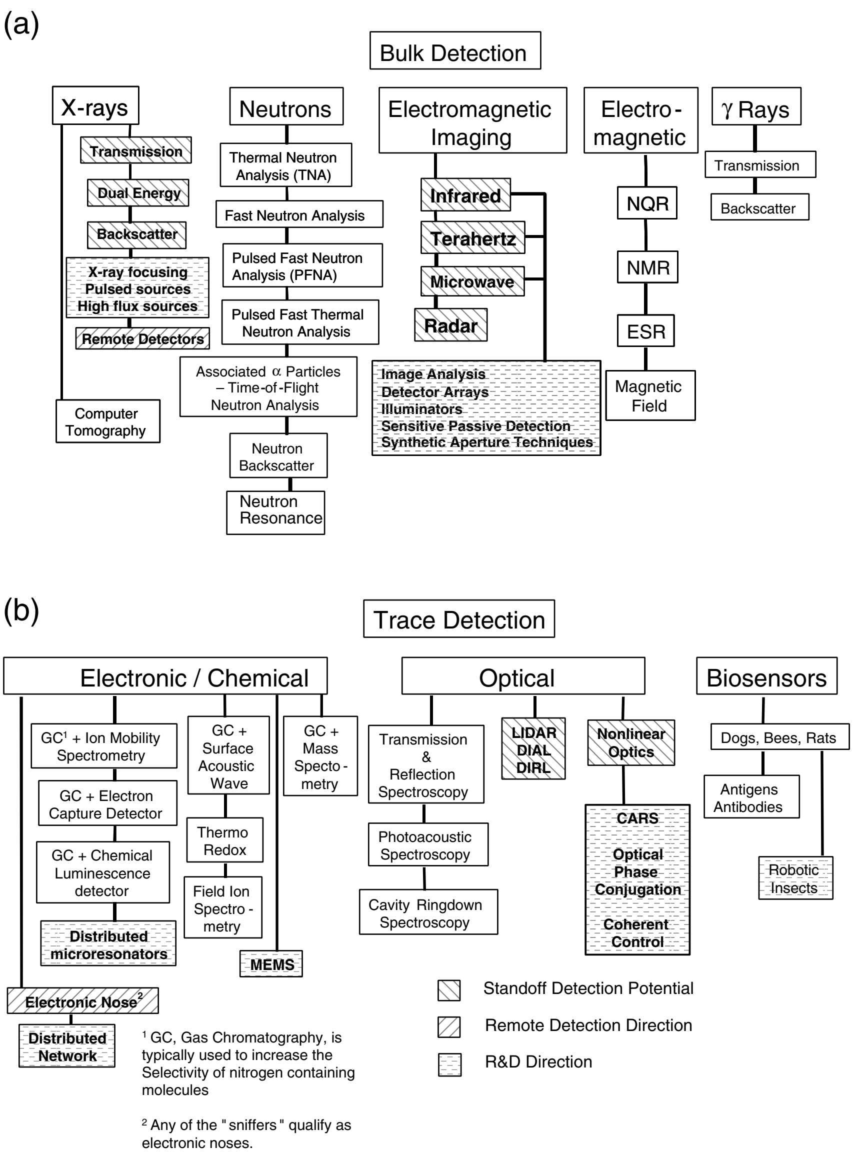

FIGURE 5.1 Chart showing many of the existing technologies for (a) bulk and (b) trace explosive detection, including those with potential for standoff detection, cross-hatched from left downwards to right. Research and development directions that would advance the sensitivity, selectivity, and standoff distance are marked with a dotted background. Specifically remote detection schemes are crosshatched from left upwards to right.

tary situations. Many of the existing techniques have been well described in the literature. This report describes in more detail the techniques that have potential for standoff and remote detection. Each topic includes (1) a technology overview, (2) scenarios of interest, (3) advantages of the technique, (4) limits and disadvantages of the technique, and (5) research directions that may be fruitful in advancing or expanding the applicability of the technique.

BULK DETECTION

Imaging is a primary technique for standoff detection scenarios. Most bombs have distinguishing spatial features and uniquely shaped metal components such as wires, detonators, and batteries. Explosive dielectric constants allow at least a limited discrimination from the background for X-ray and microwave imaging techniques. The reflection, absorption, and scattering for various explosives in a set of spectral bands can be categorized, and this information can be used as a data base for image analysis. This section describes several imaging techniques using radiation with wavelengths spanning the range from radio waves to gamma rays. Most of the bulk detection techniques that have potential for standoff detection involve imaging.

X-Rays

X-rays have been used for many years to search for explosives and other contraband in luggage and cargo containers.[4] Since X-ray radiation is ionizing, there are health concerns when people are exposed to it. However, for imaging out to standoff distances of 10 to 20 meters, these health issues may not be prohibitive. Transmission X-ray imaging requires a detector on the opposite side of the target from the transmitter. The detector could be a low-cost plastic sheet monitored by an inexpensive camera with a wireless link to a data analysis base. Inexpensive detectors and cameras could be concealed and replaced if they are damaged. Transmission images give good resolution and detect shapes of objects shadowed as a result of their high X-ray absorption. More recent X-ray imaging uses backscattering where both detector and transmitter are colocated. Examples of backscatter X-ray images from a suitcase, several persons, and a vehicle are shown in Figures 5.2-5.4. The backscattered image is bright for organic materials since the incident and backscattered X-rays penetrate

[4]See, for example, "Review of DARPA's Counter-Narcotics Program."

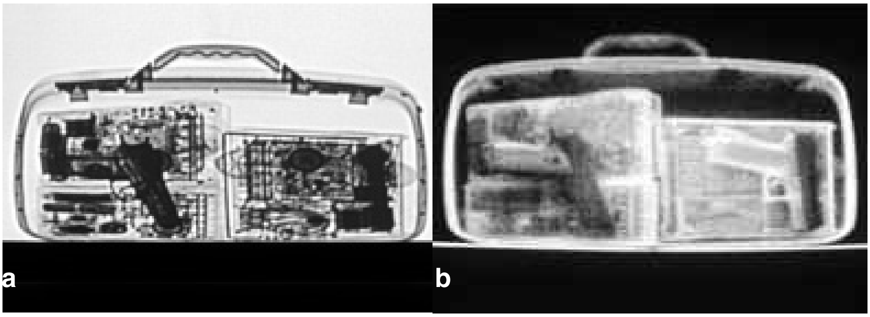

FIGURE 5.2 (a) Transmission and (b) backscatter X-ray images of a suitcase containing two guns, one plastic and one metal. The transmission image (a) shows a radio on the right in which a plastic Glock 17 automatic pistol is concealed. A metal gun is visible in image (a). The backscatter image of the same suitcase in (b) clearly shows the plastic gun on the right. (AS&E)

FIGURE 5.3 Standoff X-ray detection showing hidden explosives and other items on personnel. Images were taken from a van moving at 0.3 to 6 miles per hour using X-ray backscattering in "drive-by" mode. The mock suicide vest contained simulated C4 explosives and pipe bombs. Both the explosives and the pipe bombs are easy to see and are distinguishable from normal objects under clothing. (AS&E)

deep into the organic materials, where atoms contain fewer electrons than the atoms in materials (e.g., metals) made of heavier elements. As in the case of transmission imaging, the detectors for backscattering could be located closer to the target than the transmitter to enhance image resolution and decrease losses caused by absorption in air and the angular

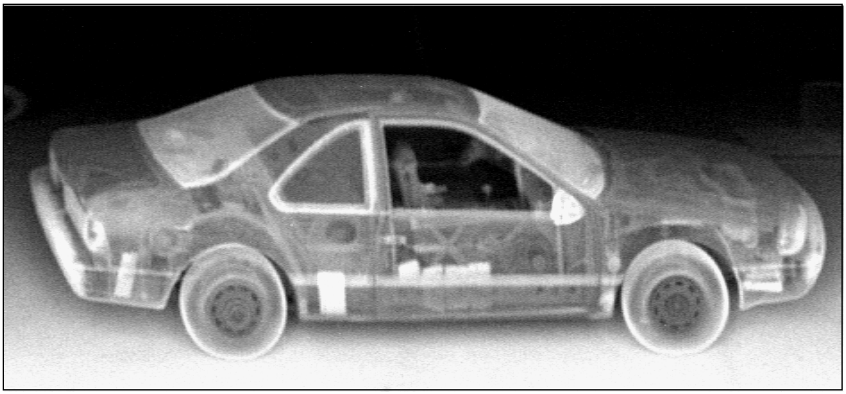

FIGURE 5.4 X-ray image of a car containing C4 explosive packages (just in front of the front wheel, to the rear of the door, in the roof just above the door, and in the back fender), drugs (in the door), and a 150 pound ANFO (ammonium nitrate-fuel oil) bomb with a grenade detonator (in the trunk). (AS&E)

spread of the beam. AS&E[5] is building a backscatter X-ray imaging system with the potential to image objects 22 feet away. It also has systems in which the detector and video readout camera are located remotely.

A combination of both transmission and backscatter aids in detection since the transmission images have better resolution and the backscatter images have better discrimination between organic and nonorganic materials. Dual-energy X-ray sources further enhance the discrimination between organic and nonorganic compounds, specifically between explosives and background objects. Computer tomographic X-ray images give great detail but require appreciably longer times for scanning and data analysis. For scenarios calling for searches of cargo, trucks, and so forth, there are systems available[6] that can image out to 20 feet through large trucks and cargo containers.

There is good potential for X-ray imaging at standoff distance of approximately 15 m. Research in the areas of high photon flux X-ray sources, pulsed X-ray sources, smaller focal spots for scanned beams, and focused X-ray beams[7] can contribute to the successful development of standoff X-

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[5]American Science and Engineering (AS&E), Inc., Billerica, MA, personal communication.
[6]AS&E, personal communication.
[7]Windt, D. W/SiC X-Ray multilayers optimized for use above 100 keV, *Applied Optics* **2003 42**, 2415; also see http://www.srl.caltech.edu/HEFT/.

ray imagers. An alternative approach may be coded aperture imagers since they are able to achieve high sensitivities with practical devices. Lower-energy X-rays (<100 keV) may have potential for better discrimination between organic and inorganic materials. However, the lower-energy region has the disadvantage of higher absorption in air as well as in the explosive apparatus. Another important area for future research and development is computer image analysis of images such as those shown in Figure 5.2. This could allow better image interpretation and partially solve the privacy issues that arise with images of people in which private body parts appear. People may be less likely to object to image analysis if no one actually sees the images and if the images can be "deleted" immediately after analysis.

In summary, X-ray imaging has good potential for standoff detection for distances up to approximately 15 m. Its advantages are excellent image resolution along with limited discrimination between explosives and background items. The disadvantages of X-ray imaging are the perceived health concerns that arise with ionizing radiation as well as the cultural and legal issues that arise when imaging people through their clothing. The standoff distance for X-rays is a challenge; however, there is hope that it can be extended to at least 15 m. The cost and size of X-ray detection systems are also a concern. Size is especially a concern in military scenarios where portability is at a premium.

Infrared

In the infrared (IR) spectral range (wavelengths between 1 and 10 microns), clothing, explosive packages, and most other items are opaque to radiation. However the body or other objects near room temperature passively emit thermal IR radiation. This thermal radiation can be detected easily with simple, relatively inexpensive IR imaging cameras. Objects differing slightly in their surface temperature are easily distinguished, even for temperature differences beneath a surface. An example of detecting subsurface temperature abnormalities beneath the skin is shown in Figure 5.5.

Infrared imaging is of considerable interest for scenarios involving suicide bombers since the clothing covering the explosive pack should be at a slightly different temperature than clothing nearer the skin. However, outdoor settings present a challenge to infrared imaging because thermal differences are more difficult to detect due to air currents and other radiation sources (e.g. the sun).

The response time for detecting a suicide bomber must be less than 10 seconds since one must typically stop the bomber as he walks toward a

FIGURE 5.5 Infrared image of a person's back reveals a healing spinal operation beneath the skin. Small temperature differences of less than a few tenths of a degree are detectable and can reveal anomalous temperature distributions on the surface of clothing caused by metal or plastic objects hidden beneath the clothing.

target area.[8] The IR detection scheme can easily detect image patterns in this time frame. Real-time motion videos using multiple views (possibly filtered into various spectral windows) of the evolving scene could give this detection technique a major advantage in rapidly interpreting complex scenes.

Another important advantage of the thermal imaging technique is its simplicity and the well-developed imaging technology in the infrared. The disadvantage is the lack of selectivity for explosives. One must rely on identifying a unique shape from a thermal pattern of the outer surface of the target. The resulting image is blurred by the effects of thermal conduction and air convection in and around clothing. Items other than explosives (e.g., cell phones) might result in anomalous images similar to those produced by explosives. Simple countermeasures (e.g., uniform insulation under the clothing) might be used against this detection scheme.

Research in the IR spectral range is needed to study the spectroscopic properties (e.g., thermal emissivity versus wavelength) of human skin,

[8]David Huestis, SRI International, presentation to the committee.

clothing, and other relevant materials. This information might lead to differential spectroscopic techniques that could improve IR imaging for explosive detection. To optimize standoff detection, other important areas for development include cooled detector arrays and advanced image processing techniques.

In summary, IR imaging is a very important technique for standoff detection. Its advantages are the readily accessible technology, real-time response, and sensitivity to the image patterns typical of suicide bomber scenarios. Its disadvantage is the lack of specificity for explosives or explosive type. One could use it as a preliminary screening process for sorting out potential explosive carriers.

Terahertz

Clothing and many other materials become nearly transparent as the radiation wavelength increases to the terahertz range, wavelengths longer than 300 microns corresponding to 1-THz frequencies. Imaging in this region allows detection of explosives hidden beneath clothing without the danger of ionizing radiation. There is hope that explosives will be found to have distinguishing spectral features in this spectral range so that one will have something more than simple shapes with small dielectric index contrasts to use as explosive identifiers. Explosives certainly have unique spectral features due to the bending and twisting modes of the explosive molecules. However, the sharp spectral lines associated with these modes in the gas phase will probably be broadened so much in the solid and liquid phases that they cannot be used for unique identification. There is also the possibility that the radiation scattering caused by the granularity or crystal structures of explosives could enhance image contrast.

Health hazards for terahertz and microwave radiation do not appear to be a major concern. The present limits[9] are set at radiation levels less than 100 mW/cm^2. This should allow for more than adequate active illumination of portal areas and even wide areas at sports events or travel terminals. Passive thermal radiation is another possibility for imaging; however detecting small differences in thermal radiation in this spectral region is very challenging and would probably require detectors cooled to very low temperatures.

[9]Occupational Health and Safety Administration standards 1910.97, Non-ionizing radiation; see http://www.osha-slc.gov/SLTC/radiofrequencyradiation/.

Technology is just beginning to be developed for the terahertz spectral region. Sources in use at present include gas lasers[10] that are bulky and lack stability for field environments. Pulsed sources[11] based on photocurrents induced by ultra-short laser pulses are inefficient sources that require large optical input powers and only achieve tens of microwatts average output power at present. High-power free electron laser sources[12] are being developed, but they are far too large and expensive for applications to explosive detection. A very interesting potential, compact, low-cost source is the quantum cascade laser. These tiny semiconductor lasers have now been operated down to frequencies as low as 1.5 THz.[13] Another interesting compact source[14] is based on nonlinear mixing between closely spaced diode laser sources and Raman shifted laser lines in the infrared to form coherent beams in the terahertz range. Compact sources with output powers between 10 mW and 1 W would be very useful for illuminating potential explosive scenarios in the terahertz range.

At slightly lower frequencies in the range between 100 GHz and 1 THz, powerful gyrotron tube sources[15] are being developed. These can generate up to megawatts of power in pulsed mode and kilowatts in continuous operating mode. These sources could be used to actively illuminate wide areas for explosive surveillance.

Enhanced image resolution is the advantage of the shorter-wavelength terahertz regime. For wavelengths longer than 100 microns, including the terahertz, microwave, and radio wave spectral bands, one encounters a fundamental limit to the image resolution, ΔL, at a distance L. This resolution limit is expressed as

$$\Delta L/L > \lambda/D, \tag{1}$$

[10]Terahertz gas lasers generate radiation directly using molecular transitions in gases (see Chang, T. Y.; Bridges, T. J. Laser action and 452, 496, and 541 microns in optically pumped CH_3F, *Optical Communications* **1970, 1**, (423), e.g., The relatively powerful methonal laser with a wavelength of 119 microns, or indirectly using mixing of CO_2 or ammonia laser lines in metal-insulator-metal (MIM) diodes, see Evenson, K. M.; Jennins, D. A.; Peterson F. R. *Appl. Phys. Lett.* **1984**, **44**, 576.

[11]Fergeson, B.; Zhang, X.-C. *Nature Mater* **2002, 1**, 26.

[12]Neil, G. R.; et al.Production of high power femtosecond terahertz radiation, *Nuclear Inst. and Methods in Physics Research* **A 2003, 507**, 573.

[13]Williams, B. S.; Kumar, S.; Callebaut, H. ; Hu, Q.; Reno, J. L. *Electronics Lett.* **2003, 39**, 916. Scalari, G.; Ajili, L.; Faist, J.; Beere, H.; Linfield, E.; Ritchie, D.; Davies, G. Appl. Phys. Lett. **2003**, **82**, 3165. Kohler, R.; Tredicucci, A.; Beltram, F.; Beere, H.; Linfield, E.; Davies, A. G.; Ritchie, D. A.; Dhillon S. S.; Sitori, C. *Appl. Phys. Lett.* **2003, 82**, 1518.

[14]Alex Dudelzak, Canadian Space Agency, personal communication.

[15]Piosczyk, B.; Braz, O.; Dammertz, G.; Iatrou, C. T.; Kern, S.; Kuntze, M.; Mobius, A.; Thumm, M.; Flyagin, V. A.; Khishnyak, V. I.; Malygin, V. I.; Pavelyev, A. B.; Zapevalov, V. E. A 1.5MW, 140-GHz, TE28, 16-Coaxial Cavity Gyrotron, IEEE *Transactions on Plasma Science* **1997**, **25**, 460.

where λ is the radiation wavelength and *D* is the aperture of the antenna that collects the radiation used for forming the image. For example, to resolve a metal component in an explosive package with a resolution of 1 cm at a distance of 20 m using terahertz or microwave radiation with a wavelength of 1 mm, a collecting antenna nearly 2 m in diameter is required. These large dimensions place constraints on the concealment and portability of the detection apparatus useful for standoff detection at distances greater than 10 m. This fundamental resolution limit indicates that one should choose the shortest wavelength possible in order to resolve objects at standoff distances in the terahertz regime.

Another important constraint is imposed by absorption of water vapor in the air. As shown in Figure 5.6, there is appreciable absorption from water vapor over path lengths greater than 10 m for radiation with wavelengths between 300 microns and 10 microns. The ideal frequency range for imaging is in the region from 100 GHz to 1 THz, where the atmosphere and clothing absorption limits are not limiting and moderately good resolution can be obtained at standoff distances.

Sensitive detectors[16] and detector arrays[17] are now being developed for the terahertz regime. For example, in the astrophysics community there are sensitive bolometer and superconductor-insulator-superconductor (SIS) mixer detectors. Detector arrays as large as 10,000 pixels are being planned; however at present the yield for fabricating detector arrays is quite low. The most sensitive detectors in the terahertz and subterahertz regime are cooled to low temperatures. Researchers at that National Institute of Standards and Technology[18] are developing room-temperature bolometer detectors that are of great interest for explosive detection since they could be widely deployed at much more reasonable costs than the low-temperature detectors.

Microwaves

There is a fuzzy boundary between terahertz and microwaves. Both technologies claim the region between 100 and 300 GHz. Electronic am-

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[16]See review article: Carlstrom, J. E.; Zmuidzinas, J. Millimeter and Submillimeter Techniques, *Reviews of Radio Science 1993-1995*, W. Stone, Ed. Oxford University Press: Oxford, UK, 1996.

[17]See http://fcrao.astro.umass.edu/instrumentation/sequoia/seq.html .

[18]MacDonald, M. E.; Grossman, E. N. Niobium microbolometers for far-infrared detection, *IEEE Transactions on Microwave Theory and Techniques* **1995**, **43**, 893. Grossman, E. N.; Miller, A. J. Active millimeter-wave imaging for concealed weapons detection, *SPIE* **2003**. Grossman E. N.; Bhupathiraju, A. K.; Miller, A. J.; Reintsema, C. D. Concealed weapons detection using an uncooled niobium microbolometer system, *SPIE* **2003**.

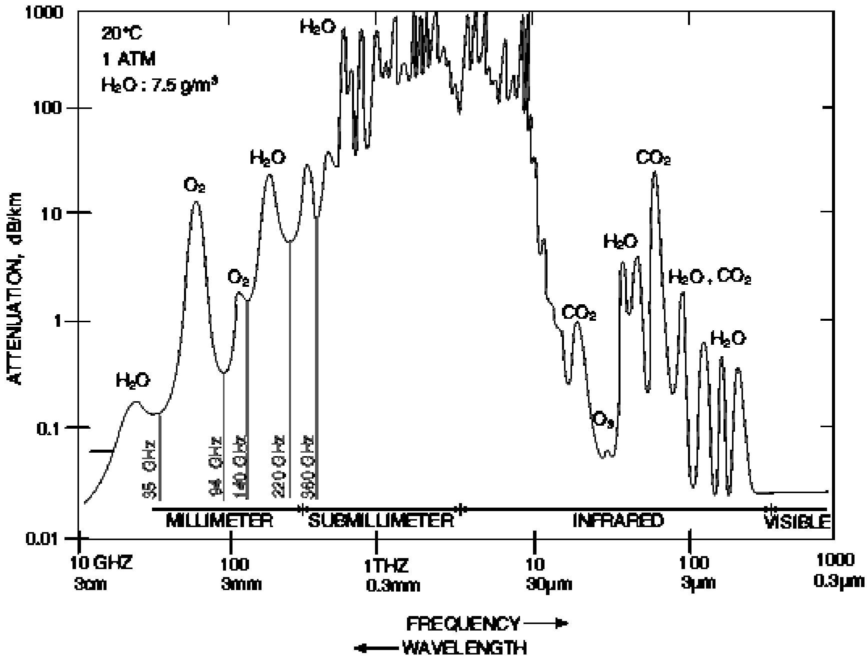

FIGURE 5.6 Absorption in air spanning the microwave to visible regions of the spectrum. Absorption greater than 500 dB/km or 0.5 dB/m causes problems for standoff detection. As shown in the graph, this limits the useful range for standoff imaging to the regions outside the range between 300 microns and 10 microns.

plifiers and sources are rapidly being developed[19] for this frequency range since there are applications in the telecommunications industry where data rates are approaching 100 gigabytes per second. Arrays of low-noise amplifiers suitable for imaging arrays and sources with watts of output power are possible. These areas merit future research and development for imaging applications in the frequency range between 100 and 300 GHz.

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[19]Y. K. Chen, Bell Laboratories, Lucent Technologies, Murray Hill, NJ, personal communication. Also see for low-noise amplifiers: Lai, R.; Gaier, T.; Nisimoto, M.; Lee, K.; Barsky, M.; Raja, R.; Sholley, M.; Barber, G.; Streit, D. MMIC low-noise amplifiers and applications above 100GHz, *IEEE GaAs Digest* **2000**, 139. Crowe, T. W.; Mettaush, R. J.; Roser, H. P.; Bishop, W. L.; Peatham, W. C. B.; Lui, X. GaAs Schottky diodes for THz mixing applications, *Proceeding of the IEEE* **1992**, **80**, 1827. Weinreb, S.; Gaier, T.; Lai, R.; Barsky, M.; Leong, Y. C.; Samoska, L. High gain 150-215GHz MMIC amplifier with intergral waveguide transitions, *IEEE Microwave and Guided Wave Letters* **1999**, **9**, 282.

At 300 GHz the water vapor absorption will allow imaging out to 50 m but the antenna required for 1-cm resolution at these distances is nearly 5 m according to Equation 1. This suggests that synthetic aperture techniques are another important research topic for terahertz imaging. Using both phase and amplitude information along with Doppler shifts of moving targets, there is hope that smaller antennas can be used and the required resolution still be achieved. Visible and terahertz images of a person carrying a gun and a knife are shown in Figure 5.7.

At frequencies below 50 GHz in the microwave regime, the resolution at standoff distances is fundamentally limited, according to Equation 1.

FIGURE 5.7 Visible and terahertz images of a man carrying a knife hidden in a newspaper and a gun in his pants. (QinetiQ.)

Good images[20] have been obtained in this region but only at distances of a few meters. Microwave and radio-frequency radars also can give information about the anomalously large fractions of metal content in targets. Even though there is no resolution of the image, anomalously large reflection from explosive packages containing large amounts of metal (e.g., pipe bombs) could be an asset for detecting some forms of suicide bombers.

Neutrons, Gamma Rays, Magnetic Resonance, and Magnetic Fields

Neutron and γ-ray explosive detection both suffer from a combination of health hazards and limitations in sensitivity for standoff detection. Neutrons penetrate typical bulk explosives. Both fast neutrons[21] and thermal neutrons have been proposed for detection. Thermal neutrons can be captured by ^{14}N nuclei and result in γ-rays of a specific energy (10.8 MeV). The distribution and level of γ-rays at this energy can in principle be used to detect nitrogen-rich explosives. There are background problems from other activated nuclei and cosmic rays. Expensive cooled detectors can in principle give sufficient energy discrimination to reduce these backgrounds. Long counting times are typically required to get sufficient signal-to-noise ratio for good identification. In summary, neutron detection techniques do not appear to have good potential for standoff detection, because of both health hazards and insufficient sensitivity. They can play an important role in specific scenarios such as detection of explosives in trucks, boats, and other cargo situations.[22]

Gamma rays can be used to locate or image nitrogen-rich explosives.[23] For example, resonance scattering techniques identify ^{14}N using resonance gamma-ray scattering at 9.17 MeV γ-ray energies. A number of background problems could be circumvented by using detectors with sufficient energy resolution. Even without specific resonance interaction processes, γ-rays can be used in transmission and backscattering geometries

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[20]McMakin, D. L.; Sheen, D. M.; Hall, T. E. Millimeter wave imaging for concealed weapons detection, *Proceeding SPIE* **2003**, **5048**, 52-62.

[21]Lefevre, H. W.; Chmelik, M. S.; Rasmussen, R. J.; Schofield, R. M. S.; Sieger, G. E.; Overley, J. C. Using fast-neutron transmission spectroscopy (FNTS) to handle luggage for hidden explosives. Can it be made practical for first-line airport use?, *Second FAA Explosives Conference*, Atlantic City, November 1996. Rasmussen, R. J.; Fanselow, W. S.; Lefevre, H. W.; Chmelik, M. S.; Overley, J. C.; Brown, A. P.; Sieger, G. E; Schofield; R. M. S. Average atomic number of heterogeneous mixtures from the ratio of gamma to fast-neutron attenuations, *Nucl. Instr. Meth. B* **1997**, *124*, 611.

[22]*Assessment of the Practicality of Pulsed Fast Neutron Analysis for Aviation Security*, National Academy Press, Washington, DC (2002).

[23]See, for example, http://www.sc.doe.gov/henp/np/homeland/Posters/BNLWielop Gamma.pdf.

in a manner very similar to that used for X-rays. As with neutrons, health issues may limit the scenarios of interest. However, the major disadvantage of γ-ray techniques is that the sources used to generate the gamma-ray flux required for standoff scenarios are likely to be very large and costly. Research in this area appears to be much less promising for standoff detection than for other techniques.

Ships at docks and trucks on bridges that could be carrying tons of explosives in cargo containers are important scenarios for explosives detection. Gamma-ray and neutron beam explosive detection instruments can potentially screen these large cargo containers at ports of entry, although throughput rates may prohibit the screening of all cargo in some cases. Cargo vessels and trucks could be cleared of personnel to avoid health problems. Large, expensive, spatially fixed equipment may be worth considering for fixed facilities. These techniques still have the disadvantage that, at best, they detect explosives only through the high content of specific nuclei, not the specific molecular structure of an explosive. This can lead to false alarms for nitrogen-rich nonexplosive materials and also means that explosives that lack nitrogen, such as TATP, will not be detected.

Magnetic resonance techniques[24] rely on exciting either the nuclear quadruple resonance (NQR) unique to the electric field gradients in explosive molecules or the nuclear magnetic resonance (NMR) of nuclei in explosive molecules (e.g., RDX or TNT) in a magnetic field. NQR identifies a specific explosive compound since the electric field gradients that produce the resonance are unique to a particular molecule. While NMR in the laboratory is an excellent analytical technique, in practice for finding explosives in the field it is the hydrogen NMR signal that is obtained. The hydrogen in most explosives exhibits very long T1 and very short T2 NMR relaxation times, and so the explosive can be distinguished from most other benign materials. These magnetic resonance techniques require close proximity (<1 m) to a large amount (>10 g) of bulk explosive. This limit makes magnetic resonance techniques ill suited to standoff detection.

Earth's magnetic field is perturbed when a metal object moves through it. Since bombs often have metal parts, they will cause magnetic perturbations as the carrier moves. Extremely sensitive magnetometers[25] have recently been developed, (e.g., those based on microelectromechanical [MEMS] technology). The sensitivity is impressive: a moving rifle can be detected at a distance of a kilometer. However, there will typically be

[24]see references 1 and 3; also see http://www.qm.com/.

[25]S. Arney, Bell Laboratoroies, Lucent Technologies, Murray Hill, NJ, personal communication.

many other moving metal components in explosive detection scenarios. This "clutter" of the area of interest for explosive detection probably eliminates metal detection at standoff distances from being a primary technique.

TRACE DETECTION

Trace detection at standoff distances is a particularly challenging task. Saturated vapor pressures for many of the common explosives are very low (approximately 10 parts per billion [ppb] for TNT and 10 parts per trillion [ppt] for cyclomethylenetrinitramine [RDX] and pentaerythritoltetranitrate [PETN], see Chapter 3). In many scenarios the air volume containing the explosive is large, at least the size of a large room. Diffusion of a gas in a large volume of air will eventually establish a saturation vapor pressure, but this will take many hours. In most explosives detection scenarios, air currents, charging of the explosive molecules, and adsorption onto nearby surfaces will determine the actual concentration of explosive molecules. Even though the probability of the molecules sticking to surfaces may be much less than 1, the surface area is huge. Many explosive molecules are strongly electronegative (i.e., they have a high probability of attaching an electron and becoming charged). Both air currents and large electric fields in the air will form plumes of explosive molecules in the localized airspace near the explosive, similar to smoke drifting from a cigarette or aroma from a rose. The actual concentration of molecules in these plumes can easily be 100 to 10,000 times lower than that predicted by the saturated vapor pressure. This makes detection of explosive vapors a monumental challenge. Griffy[26] developed a semi-empirical theoretical model for the evaporation (sublimation) of such explosives and showed basically that it is better to sample surfaces for explosive residue than to probe the air for explosive vapors. This conclusion is confirmed by the common practices used in trace detection, where swiping of surfaces is usually preferred to vacuum collection of vapor. Consequently, sampling methodology is vital to the performance of any trace detection techniques.[27]

Many trace detection schemes rely on stimulating an increased flux of molecules or particles for the explosive device. For example, turbulent airstreams, "minicyclones," and laser ablation or deflagration are used to

[26]Griffy, T. A. A Model of Explosive Vapor Concentration II, In *Advances in Analysis and Detection of Explosives*, Proceedings of the 4th International Symposium on Analysis and Detection of Explosives, September 7-10, 1992, Jerusalem, Israel; J. Yinon, Ed; Kluwer Academic Publishers: Dordrecht, Netherlands, pp 503-511.

[27]See references 1 and 3.

increase the trace material available for analysis. In the case of dogs, stirring the local environment with the dog's body, head, and foot motion may contribute to sensitivity.

Concentrators are another common sampling technique for trace explosive detection. For example, a vacuum system near a portal can be used to accumulate a large air sample from which explosive molecules can be concentrated by filters. A dog's nose works in part on this principle. The dog inhales and collects particles and molecules over a surprisingly large area in the nose, in the range of 10 m^2.[28] There is still hope that research will find a way to fabricate electronic, chemical, biological, or optical "noses" that will equal or exceed the dog's nose.

Molecules of the explosive provide a unique identifier for each explosive since there are relatively sharp spectral absorption lines due to electronic transitions in the ultraviolet (UV) and vibrational absorption lines in the IR and terahertz ranges. As described above there is the problem of the very low concentrations available in the gas phase. If the molecules are incorporated into small granular particles or are absorbed on surfaces, the molecular absorption lines are dramatically broadened and their utility for unique identification using optical spectroscopy is diminished. This is more of a problem for the IR and terahertz vibrational, bending, and torsional spectral lines.

One typically finds particulate explosive material around nonhermetically sealed explosives associated with contamination on the skin, explosive container, or nearby objects. The total amount of particulate material is often much larger than the amount of gaseous vapor. A number of trace techniques[29] (see Figure 5.1), including mass spectrometry, ion mobility spectrometry, electron capture, surface acoustic wave sensors, thermo-redox and field ion spectrometry, can identify explosive materials from small grains. Many of these techniques are often combined with front-end gas chromatography, which prefractionates the molecules in incoming samples and thus increases selectivity. Some of these techniques have been configured to act as "sniffers" and can serve as choke or checkpoint detectors at a remote location (thus, belonging to the remote detection category). However, as shown in Figure 5.8, they are bulky and need miniaturization for use as distributed sensors.

It seems reasonable that we can hope to construct a "sniffer" at least as good as a dog's nose. These artificial noses could be tailored to specific

[28]See reference 3.
[29]See references 1-3.

FIGURE 5.8 Military personnel using the IonTrack (now GE Interlogix) "sniffer," which is capable of detecting drugs and explosives. It is based on ion trap mobility spectrometer (ITMS) technology. See http://www.geindustrial.com/ge-interlogix/iontrack/app_military.html.

explosives and deployed as networks of detectors in sensitive areas. However, it will take a considerable amount of further research and new ideas to achieve this goal. It has been demonstrated[30] that one can chemically form sites that selectively attract explosive molecules. These selective chemical bonding sites can be detected by fluorescence quenching (sensitivities as low as femtograms of material) and other techniques (e.g., resistive changes in thin films). However, these bonding sites can be saturated in a field environment with interferents. For example, common fumes and odors in the environment might be troublesome interferents in many explosive detection scenarios.

In principle it is possible to form a remote explosive sensor using a large area coated with a luminescent material designed so that the luminescence is quenched by small quantities of explosive molecules. Patterns of explosive plumes could in principle be observed at a distance by imaging a quenched luminescent pattern caused by a nearby explosive on a surface coated with the luminescent material. Luminescent sensitivity can be enhanced by arrays of optical micro-resonator structures formed using

[30]Yang, J.S.; Swager, T.M. *J. Am. Chem. Soc.* **1998**, *120*, 5321. Levitsky, I.A.; Kim, J.; Swager, T.M. *J. Am. Chem. Soc.* **1999**, *121*, 1466. McQuade, D.T.; Hegedus, A.H.; Swager,T.M. *J. Am. Chem Soc.* **2000**, *122*, 12389.

photonic crystals,[31] microdisks,[32] and microcylinders. The sensitivity of these structures appears to be adequate for some scenarios, but the disadvantage at present is selectivity and saturation from interferents. Cycling of the luminescent detectors is also a challenge.

Electronic noses based on the change in resistance of inorganic or organic[33] semiconductors are another potential technique for making low-cost sensitive detectors that could be deployed in arrays or networks over a large area. There are presently[34] several hand-held instruments (weighing between 1.5 and 7 pounds) and portable instruments (weighing between 18 and 43 pounds) that can be used as remote point sensors. An important avenue for research and development is to explore the fabrication of compact, inexpensive electronic noses that can be used in arrays with a variety of resistive materials, each sensitive to a particular molecule. These multiple sensor arrays could effectively increase the selectivity of electronic noses and help solve the problem of interferent saturation. Plans exist for downsizing a commercial system based on chemical sensing arrays to "devices as small as 1-inch high and 1-inch wide that could be used to create a network of sensors that could be deployed around a stadium." [35]

Instead of a simple change in resistance one can hope that catalytic chemical processes can be developed that effectively amplify the response of electrochemical detectors. This may be part of the secret to the sensitivity of dog's noses.

Very recently another technique has been developed[36] using MEMS technology. The resonant frequency of micron-sized mechanical "tuning forks" is extremely sensitive to the mass of molecules absorbed on the resonant mechanism surfaces. Using a molecular film coating on the microresonator allows one to detect explosive molecule concentrations in

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[31] Joannopoulos, J. D.; Meade, R. D.; Winn, J. N. *Photonic Crystals*; Princeton University Press: Princeton, NJ, 1995.

[32] Kuwata-Gonokami, M.; Jordan, R. H.; Dodabalapur, A.; Katz, H. E.; Schilling, M. L.; Slusher, R. E. Polymer microdisk and microring lasers, *Optics Letters* **1995**, **20**, 2093-2095.

[33] Crone, B.; Dodabalapur, A.; Gelperin, A.; Torsi, L.; Katz, H.E.; Lovinger, R.; Bao, Z. Odor sensing and recognition with organic field-effect sensors and circuits, *Applied Physics Letters* **2001, 78**, 2229-2231.

[34] Burschini, C. Commercial Systems for the Direct Detection of Explosives (for Explosive Ordnance Disposal Tasks) *ExploStudy*, Final Report; Ecole Polytechnique Federale de Lausanne: Switzerland, **2001,** p. 67.

[35] Kanable, R. What's that smell? Electronic noses help first responders sniff out trouble, *Law Enforcement Technology* **2003**, 74-77.

[36] Pinnaduwage L. A.; Boiadjiev, V.; Hawk, J. E.; Thundat, T. Sensitive detection of plastic explosives with self-assembled monolayer-coated microcantilevers, *Appl. Phys. Lett.* **2003**, **83**, 1471.

the range of 10 ppt. However, this technique suffers from the same selectivity and saturation problems described above. These limits may be surmountable with continued research. The tiny MEMS devices have the advantage that they are potentially very low cost and could be deployed in arrays, possibly with low-cost wireless reporting to a central analysis hub.

Optical

Optical Absorption and Fluorescence

Optical absorption has the potential to uniquely identify explosive molecules by using their UV electronic and infrared vibrational resonances. However most of the techniques require collecting a sample and analyzing it over a time period sufficient to increase the signal-to-noise ratio to the desired level. For example, photoacoustic spectroscopy[37] using infrared active vibrational transitions has the sensitivity to detect 10 ppt with an averaging time of the order of 10 seconds. Similarly, surface enhanced Raman scattering[38] and cavity ring-down spectroscopy[39] (decreasing the Q of an optical cavity by the vibrational absorption of a molecule) can detect very low molecular concentrations in the parts per trillion range. The major disadvantage of these techniques is that large samples have to be acquired and analyzed with relatively expensive and fragile apparatus. This removes them from the standoff and remote category. They may be useful in fixed portal scenarios.

Optical fluorescence[40] from granular materials is an interesting technique with standoff potential. Trace amounts of explosive can be laser irradiated in the UV where they strongly absorb and decompose into fragments that can undergo laser-induced fluorescence. The resulting fluorescent patterns can then be imaged from a standoff distance. The disadvantages of this technique are lack of very high sensitivity and problems of quenching the fluorescence with environmental contaminants.

[37]C. K. N. Patel, personal communication. Also see Webber, M.E.; Pushkarsky, M.B.; Patel, C.K.N. Fiber-amplified enhanced photoacoustic spectroscopy using near-infrared tunable diode lasers, *Applied Optics* 2003, **42**, 12 and http://www.pranalytica.com/tech.htm.

[38]Shibamoto, K.; Katayama, K.; Fujinami, M.; Sawada, T. Fundamental processes of surface enhanced Raman scattering detected with transient reflecting grating spectroscopy, *Rev. Scien. Inst.* **2003**, **74***(1)*, 910-912 (2003) and references contained therein.

[39]He, Y.; Orr, B.J. Rapidly swept, continuous-wave cavity ringdown spectroscopy with optical heterodyne detection: single and multi-wavelength sensing of gases, *Appl. Phys.***2002, B 75**, 267-280 and references contained therein.

[40]Heflinger, D.; Arusi-Parpar, T.; Ron, Y. ; Lavi, R. *Opt. Commun*. **2002**, *204*, 327. See also Cabalo, J.; Sausa, R. *Applied Spectroscopy* **2003**, *57*, 1196.

LIDAR, DIAL, and *DIRL*

These techniques include laser, light detection and ranging (LIDAR), differential absorption LIDAR (DIAL), and differential reflectance LIDAR (DIRL). Some forms of LIDAR have been used in environmental pollution studies[41] and in chemical agent plume detection. LIDAR[42] operates on the principle that radiation from a pulsed illuminating source is backscattered to a detector. The explosive molecules in the pulsed laser illuminating beam will absorb when the source light is tuned to a molecular resonance (typically a vibrational resonance in the IR spectral range). This absorption attenuates the backscattered beam, thus allowing detection of the explosive. Backscatter can result from particulates in the air. At standoff distances in the 10- to 30-m range, the very low molecular concentrations characteristic of explosive molecules result in sensitivity limits for these laser ranging techniques. It is possible that nonlinear optical techniques (e.g., optical phase conjugation)[43] can be used to increase the signal-to-noise ratios. These techniques are generally used in a sensing rather than an imaging mode. In the sensing mode, they can locate the direction and distance of a target but cannot image it. Imaging is possible by scanning a scene and mapping the returned signal.

Research in this area is needed to obtain the detailed spectral absorption characteristics of explosive vapors and the spectral reflectance characteristics of explosive particles (of varying particle size). This should facilitate the choice of spectral bands for performing differential absorption or reflectance LIDAR. Instead of using particles in the air for the required backscattering, one can use retro-reflectors similar to those seen on highway signs. This is another example of using low-cost remote apparatus. The use of retro-reflectors would restrict this technique to portal scenarios.

Imaging using the DIAL or DIRL mode is a form of dual-spectral imaging. Although these techniques involve two laser wavelengths for illumination, one can use the *equivalent* technique of illuminating with a broadband source and viewing with two narrow-band filters. At present, there is one such "equivalent" explosive imaging system. It uses solar illumination and an imaging system with two rotating infrared filters and is designed to detect adhered particles of a nonnitrate explosive. Another

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[41]Sachse, G; LeBel, P.; Steele, T.; Rana, M. Application of a new gas correlation sensor to remote vehicular exhaust measurements, *Proc. Eighth On-Road Vehicle Emissions Workshop*, 1998.

[42]These are common terms in the optical remote sensing field.

[43]Alex Dudelzak, LDI[3] Inc., personal communication.

technique[44] uses a sample of the gas to be detected as a filter in one of the laser beam channels and electro-optic switching from the filtered channel to the unfiltered channel.

The dual-spectral system mentioned above is a special case of hyper- or multispectral imaging. These techniques should be explored for detecting airborne or surface-adhered explosive molecules. This requires obtaining a complete set of spectroscopic characteristics, from the UV to the millimeter wave region, of the explosive material in various forms (gaseous and particulate of diverse size). Banded spectroscopy combined with imaging should also be explored further. The challenge in these multi- or hyper-spectral techniques is to obtain "processed" images in real time.

Finally there are novel sensing schemes[45] based on LIDAR that use laser to sense the position and motion of the ground or objects near the explosive after the ground has been subjected to an acoustic shock. The seismic disturbances in the ground or containers can have unique motional responses detectable remotely by the LIDAR apparatus.

Nonlinear Optical

Nonlinear optical interactions of light with gaseous or solid materials typically vary as the square of the intensity of the optical field. For example, if two exciting laser beams are focused on a volume of gas containing explosive molecules, the light scattered from a third laser that is tuned to have a frequency shifted from the two exciting lasers by the vibrational frequency of the molecule, will produce a fourth beam whose intensity varies as the square of the exciting beams (see Figure 5.9).

This process is called coherent anti-Stokes Raman scattering (CARS).[46] CARS has the advantage that the detected signal can be increased dramatically with the square of the exciting intensity. This is an example of the opportunity for increased signal-to-noise ratios obtainable with nonlinear detection techniques relative to linear optical techniques. At present, CARS systems have not been developed that have enough stability for deployment in the field. This nonlinear technique requires stability of both the laser frequency and the pointing accuracy of better than tenths of a degree, which are difficult to achieve in the field with fluctuating air currents. These techniques require that the phases of the various fields be

[44] Sachse, G; LeBel, P.; Steele, T.; Rana, M. Application of a new gas correlation sensor to remote vehicular exhaust measurements, *Proc. Eighth On-Road Vehicle Emissions Workshop*, 1998.

[45] Xian, N.; Sabatier, J.M. An experimental study of antipersonnel landmine detection using acoustic-to-seismic coupling, *J. Acoust., Soc., Am.* **2003**, *113*, 1333-1341.

[46] Shen, Y.R. *The Principles of Nonlinear Optics*; John Wiley & Sons: 1991, pp 267-272.

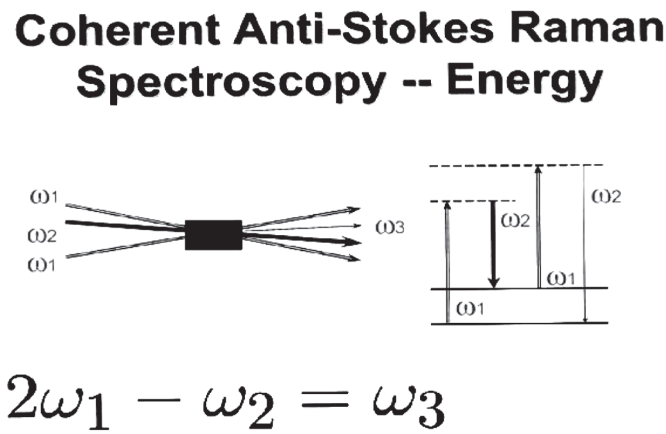

FIGURE 5.9 Two high-intensity exciting laser beams are incident on a sample of explosive molecules (black box). A third laser beam tuned to the difference vibrational frequency of the molecule to be detected results in coherent scattering of a fourth beam.

matched and coherent over relatively large distances of the order of a meter, again a difficult task in the field. One interesting possibility is to use CARS techniques for molecules collected at surfaces. A surface monolayer of molecules can be detected by CARS techniques in the laboratory; it remains to be seen if this can be done in the field.

Other nonlinear optical techniques that could be exploited include optical phase conjugation and excitation of index gratings using crossed laser beams. Optical phase conjugation has the potential to defeat optical distortions caused by a turbulent atmosphere. A nonlinear LIDAR system is certainly an interesting avenue for future research.

Exciting molecules to their excited states dramatically changes their effective index of refraction for reflecting and scattering light. Explosive molecules absorb light predominantly in the UV portion of the spectrum. Each explosive molecule has unique absorption spectra so that excitation techniques have the potential for high selectivity. Molecules that absorb illuminating radiation can be detected by monitoring the luminescence or their refractive properties. Using a new research technique called coherent control could further enhance molecular selectivity.[47] Ultra-short la-

[47]Li, B.; Turinici, G.; Ramakhrishna, V.; Rabitz, H. Optimal dynamic discrimination of similar molecules through quantum learning control, *J. Phys. CHem. B* **2002**, *106*, 8125. Levis, R.J.; Rabitz, H. Closing the loop on bond selective chemistry using tailored strong field pulses, *J. Phys. Chem.* **2002**, *106*, 6427.

ser pulses contain a broad spectrum of light. By manipulating the phase and amplitude of this light over a range of frequencies near an explosive molecule's absorption band, one can "coherently control" the final state of the molecule. For example, one could choose to selectively ionize or dissociate particular explosive molecules or excite them to specific states to optimize their luminescence. These new ideas from fundamental optics research have to be studied for their applicability to explosives detection.

In summary, nonlinear optical techniques have the potential for increased signal-to-noise ratios relative to linear techniques. Optical phase conjugation should be studied for optimizing the signal returned from LIDAR excitation. Nonlinear spectroscopy and coherent control of the excitation of explosive molecules should be studied for possible applications to explosive detection. The disadvantage of these techniques is that many of them may be limited by the very small concentrations of explosive molecules as well as adverse field environments. The low vapor concentrations associated with most common explosives near room temperature may mean that at least in some cases, LIDAR could best be applied to the detection of explosive particles adsorbed on surfaces, rather than to vapor detection.

Biological

Array biosensors have been developed for simultaneous analysis of multiple molecular samples. A patterned array of different capture antibodies, designed to be highly specific to explosive molecules, can be immobilized on the surface of a planar waveguide, with each different capture antibody at a different site. These capture antibodies remove explosive molecules from a sample. A second, fluorescent "tracer" antibody binds to the captured target, resulting in a fluorescent "sandwich" A diode laser excites the fluorescence, and a charge-coupled device (CCD) camera detects the pattern of fluorescent antigen-antibody complexes on the sensor surface. Flow cells and microfluidic technologies can make the apparatus compact. Computer analysis results in an analysis in several minutes. Since samples of the explosive molecules are required for these techniques, they are not considered to be standoff or remote unless the size and cost are dramatically reduced. They also have the disadvantage of the possibility of interferent signals in field environments.

Enzymes can be used to catalyze the reduction of explosive molecules. These techniques can be sensitive at the parts per trillion level but require concentrators and long analysis times. They can be made highly specific to particular explosive molecules. Research in this area could lead to the type of detection used by animal noses. At present, this is not classified as a standoff or remote technique.

Dogs, rats, and bees can be trained to detect explosive vapors. The committee does not classify these techniques as standoff or remote. An important avenue for future research is the development of robotic "insects" with onboard sensors or samplers. One would hope to develop low-cost, nonintrusive devices that could be controlled remotely in any weather. Surveillance teams circulating in crowded areas such as sporting events could wear similar compact detection devices. It should also be possible to relay the data in primitive form to fixed centers for data analysis using wireless local area networks (LANs).

Recommendation: The committee recommends continued research into biomimetic sensing based on animals, but research should focus on distributed, low-cost sensors.

ORTHOGONAL DETECTOR SCHEMES

It is important to consider using multiple detection technologies in a coordinated detection effort. No one technique appears to solve the explosive detection problem. Two promising directions using "orthogonal" detection techniques are discussed here (i.e., techniques that measure properties of the explosive that are not closely related). Examples of orthogonal measurements include the geometric shape of the explosive device and the composition of the explosive, or an image of the wires and detonator along with a thermal image of the clothing of a suicide bomber.

Hyperspectral Detectors

Imaging is a powerful tool for standoff detection. However, the information presented in the image varies widely with the spectral region imaged. For example, a terahertz or millimeter wavelength microwave image does not clearly show the facial features of the person imaged. Hyperspectral imaging refers to combining the information from widely disparate regions of the spectrum. A thermal IR image could be combined with a terahertz image to yield a much more specific indicator of a potential suicide bomber than either individual image.

Computer analysis of multiple images could yield orders-of-magnitude improvement in imaging detection systems. Computer analysis might alleviate some of the concern for privacy since no one need actually look at the images. Computer analysis also reduces the possibility of human error.

Combining Imaging and Material Composition

Imaging alone does not give a complete identification of explosives. It is clearly a major advantage to combine an image with a measurement of the specific explosive composition. Many composition detection techniques only identify an anomalous nitrogen content, and do not provide conclusive evidence of the presence of an explosive device. A combined image, showing wires or a dielectric shape in the form of an explosive device and an anomalously large nitrogen concentration, would enhance the decision-making task. An example of a portal scenario with combined imaging and nitrogen concentration is a backscatter X-ray image of a truck along with a neutron scattering signal showing anomalously high nitrogen concentrations. Another example is a suicide bomber imaged by a terahertz scan paired with an indication of explosive molecules by a LIDAR signal from the plume of vapors arising from the bomber.

Recommendation: Research is needed on new spectroscopic and imaging methods employable at a distance (passive and active). Examples include terahertz and microwave imaging and spectroscopy and X-ray backscattering.

6

Biological Markers

Biologically based systems for explosives detection are quite numerous. However, their efficacy for standoff monitoring, sensitivity, and robustness remains undefined. It is likely that many of these systems suffer similar fundamental limitations (comparative to instrumental analytical methods) in contacting a target analyte at a sufficiently high, localized concentration to produce a detection signal in a relative time frame suitable for standoff detection. Consequently, remote standoff detection of explosives using biological sensor technology or electronic noses to replace or improve upon the trained canine olfactory sense has been difficult to achieve.

Biological or biosensor approaches for explosives detection combine the specificity of molecular recognition of biomolecules with electronics for signal transduction and measurement. These biomolecules may be directly coupled to the analytical device or they may be part of a living cell or organism, which in turn is a component of the analytical system.

Antibodies have been applied in many difficult immunosensor formats, including fiber-optic evanescent and surface acoustic waves, flow injection,[1] and surface plasmon resonance immunosensors, to provide direct recognition of an analyte. Textbook examples[2] of this technology are

[1]Kusterbeck, A. W.; Charles, P.T. Field demonstration of a portable flow immunosensor. *Field Anal. Chem. & Technol.* **1998**, *2(6)*, 341-350.

[2]Kress-Rogers, E. *Handbook of Biosensors and Electronic Noses. Medicine, Food, and the Environment.* CRC Press: Boca Raton, FL, 1997.

replete with design, application, and sensitivity considerations. In addition to antibodies, a variety of other proteins, ranging from receptors in olfactory neurons to G proteins and bacteriorhodopsin have been explored as potential bioaffinity biosensor elements. In general, these biosensor systems have implementation requirements (size, power, ruggedness) that are not dissimilar to a spectrophotometer, laser, gas chromatography (GC), or mass spectroscopy (MS) based systems. In other words, biosensor systems have instrumentation requirements that may limit their use for standoff detection in the field.

In many cases, modern molecular biology has provided the tools to isolate and modify the genes for individual receptors or signaling proteins to make new biosensor capability. A recent example used computational biology to analyze a binding protein and predict changes to an amino acid sequence that would create new proteins capable of specifically binding to an analyte such as trinitrotoluene (TNT).[3] By directed mutagenesis, the DNA encoding the binding protein was synthesized and cloned into bacteria. The fluorescent properties of the protein changed on binding to TNT, providing a direct real-time measure of TNT binding. Furthermore, the binding protein could be linked to a second signal via a signal transduction mechanism to activate a transcriptional fusion in living cells to produce a whole-cell TNT biosensor system. Engineered bacterial strains have previously been developed that couple bioluminescent (*lux*) or fluorescent (green fluorescent protein [GFP]) reporter proteins to transcriptional activation by chemicals such as TNT, to create biosensor organisms that have been explored for use in explosives detection[4] or coupled directly to microluminometer chip technology for whole-cell biosensing.[5] Efforts have been made to identify genes that are induced or activated by explosives such as TNT for both mammalian[6] and plant systems.[7] This raises the potential of engineering animals or plants with lu-

[3]Looger, L. L.; Dwyer, M. A.; Smith, J. J.; Hellinga, H. W. *Nature* **2003**, *423*, 185-190.

[4]Burlage, R. S.; Patek, D.R.; Everman, K. R. Method for Detection of Buried Explosives Using a Biosensor. U.S. Patent 5, 972,638, 1999.

[5]Simpson, M. L.; Sayler, G. S.; Applegate, B. M.; Ripp, S. A.; Nivens, D. E.; Paulus, M.J.; Jellison, G. E., Jr. Bioluminescent-bioreporter integrated circuits form novel whole-cell biosensors. *Trends Biotech.* **1998**, *16*, 332-338.

[6]Tchounwou, P.B.; Wilson, B. A.; Ishaque, A. B.; Schneider, J. Transcriptional activation of stress genes and cytotoxicity in human liver carcinoma cells (HepG2) exposed to 2,4,6-trinitrotoluene, 2,4-dinitrotoluene, and 2,6-dinitrotoluene. *Environmental Toxicology* **2001,** *16*, 209-216.

[7]Jackson, P. Development of Methods That Detect and Monitor Environment Munitions Contaminants Using Plant Sentinels and Molecular Probes. U.S. Department of Energy, 1996, NTIS, AD-A309 583.

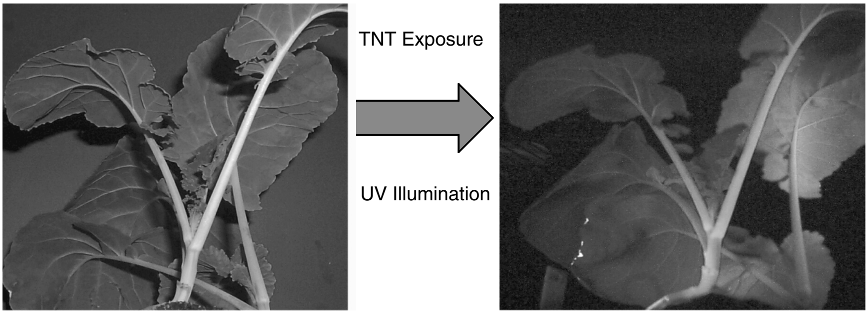

FIGURE 6.1 Canola plant engineered with a GFP reporter fusion responsive to TNT exposure. Right panel indicative of positive plant response in passive sentinel monitoring. (N. Stewart, University of Tennessee)

minescence or fluorescence reporter genes for passive monitoring for explosives as conceptually suggested by Figure 6.1.

Although there is potential for biological sensor technology, the ability to implement this technology, particularly from a standoff perspective, has not yet been shown to be practical.

HUMAN EXPOSURE BIOMARKERS FOR ORTHOGONAL DETECTION OF EXPLOSIVES

Sources and Exposure

Exposure to explosives produces wide-ranging biological effects from the organ system to the subcelluar. The ability to produce such signatures is highly variable according to the classes of explosives and exposure history. The published literature to support these analyses is highly variable in source, availability, and information content. However, the National Library of Medicine TOXNET Hazardous Substances Database does an excellent job of summarizing this material.

Literature studies, exposure analysis, and toxicological properties have been conducted by the military (Wright Patterson Air Force Base, Soldiers Biological and Chemical Command, for example) and its government contactors (GeoCenters, for example), the Environmental Protection Agency, the National Institute for Occupational Safety and Health, and the Agency for Toxic Substances and Disease Registry (ATSDR) among others. These studies provide a source of information on exposure to explosives such as cyclotrimethylenetrinitramine (RDX) in cooking fuel, TNT, dinitrotoluene (DNT), and picric acid as environmental contaminants and RDX in fireworks, as well as explosives themselves and explosion residuals. The ATSDR ToxFAQ database is a relatively comprehensive source for summary information on occurrence, exposure, and effects.

In general, explosives are readily bioavailable to human populations through the usual contact, inhalation, and ingestion sources from which they may be bioaccumulated, although not necessarily biomagnified. A recent report clearly demonstrates that many nitrated aromatic explosives are readily partitioned (1-2 hours) from contaminated soil to skin through dermal percutaneous absorption.[8] Such uptake is correlated with solubility and vapor pressure and thus is similarly driven during direct topical exposure. Ultimately, the body burden of the parent explosive or metabolites, cellular and subcellular effects, and resulting analytical detection sensitivity are determined by the chronic or acute nature of the exposure history. Consequently, there would likely be significant biosignature differences between bomb makers and bomb carriers who should exhibit differing exposure histories.

Effects

Most explosives demonstrate multiple effects. For example, propylene glycol dinitrate (PGDN) reportedly produces effects as ambiguous as headaches and as specific as methemoglobinemia, with other effects ranging from transient central nervous system (CNS) effects to vascular collapse.[9] Other explosives such as TNT have been identified as carcinogens. Many of the nitrated explosives are associated with headaches on exposure, which is due to the vascular dilating effect of nitrate, characteristic of therapeutic agents such as nitroglycerin. Metabolites, conjugates, and DNA adducts are frequently encountered for broad groups of explosives, and these may in themselves represent suitable signatures for detection and exposure analysis because they may pigment the skin or be excreted in urine.

Biological Signatures

Potential biological signatures exist across all levels but with indeterminate value for standoff detection purposes. Those explosives producing vascular effects typically associated with headaches are candidates for

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[8]Refenrath, W. G. et. al. *Toxicol. Appl. Pharmacol.* **2002**, *182*, 160-168.
[9]Forman, S. A. *Toxicol. Letters* **1988**, *43*, 51-65.

biosignatures due to altered blood flow, localized temperature differentials and perhaps concomitant skin discoloration. ATSDR database information supports a conclusion that TNT and picric acid in addition to producing headaches, are also skin irritants and systemic colorants, producing yellow pigmentation (including hair) on prolonged exposure. TNT metabolites excreted in urine typically impart amber to red color to the urine. These pathologies along with the previously mentioned skin partitioning of explosives suggest the prospects for Fourier transform infrared (FTIR) skin spectrometric sensing.[10]

Nitrates, particularly dinitrobenzene (DNB), trinitrobenzene (TNB), and PGDN, typically produce methemoglobinemia at higher exposure concentrations. A common symptom of this potentially fatal syndrome is a blue cast to the skin due to NO_3 competitive binding to hemoglobin.

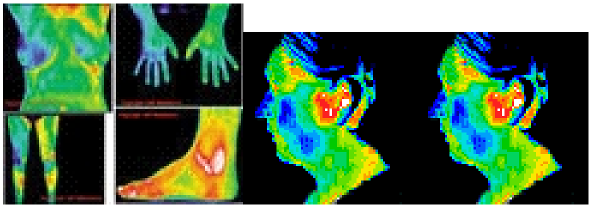
Analogous to genotoxic environmental pollutants, explosives with mutagenic and/or DNA adducting properties can produce biomarkers of subcellular damage. Characteristically, these biomarkers are difficult to assess and analytical improvements are necessary. Furthermore discriminating other environmental insults, such as smoke, may make unambiguous results difficult to achieve.

A comprehensive analytical solution could include infrared (IR) imaging of the skin, particularly face and hands, for increased blood flow. IR thermographic technology is already used extensively in medicine and sports therapy. Such screening was utilized in the outbreak of severe acute respiratory syndrome (SARS). Figure 6.2 shows the general capabilities of thermographic imaging and a specific example of SARS thermal imaging. It should be noted that the use of thermographic technology in relatively open environments (as opposed to controlled situations such as customs at an airport) has not yet been extensively investigated, and technological and privacy issues will probably have to be addressed.[11]

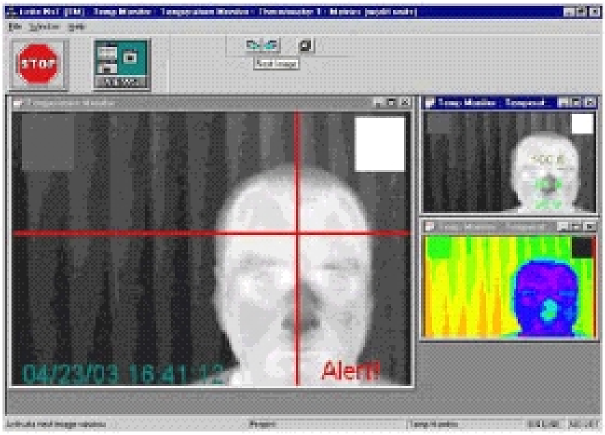
Many hazardous chemical exposures result in contact dermatitis and rashes. These conditions, in addition to increased blood flow, would offer IR and other spectral patterns that could be analyzed in a standoff capability. The same holds true for situations in which methemoglobinemia alters apparent skin color or situations in which skin is dyed or pickled (picric acid). Hyperspectral image analysis such as that available to the Littoral Airborne Sensor-Hyperspectral (LASH, U.S. Navy) or passive so-

[10]See, for example, work in this area by Professor Reinhardt Brunch, Department of Physics, University of Nevada, Reno; http://www.physics.unr.edu/faculty/bruch/Opticmain.htm.

[11]Pang, C.; Gu, D. L. Some problems about detecting the suspected cases of SARS according to the local skin temperatures on face. *Space Med. Med. Eng. (Beijing)* **2003**, *16*(3), 231-234.



(a)



(b)

FIGURE 6.2 A generalized example of (a) the routine capability available for thermographic imaging, and (b) its use in screening for potential SARS cases.

nar in the case of heartbeat or pulse analysis may provide an existing path to an analytical solution for multispectrum analysis.

Although they would not constitute a standalone, independent measure of explosives, biological signatures could be relatively inexpensive (when implemented with other hyperspectral methods) to use as part of an integrated system of explosives detection. The analytical (spectroscopic) methods needed to implement this technology either presently exist or are in development for other applications. In addition, a large data base could be developed rapidly and could have broader applications such as drug transport screening.

The use of biological signatures could be expanded to direct detection of skin or surface absorbed explosives using laser-induced fluorescence. This could be applicable to both portal scenarios and large unsupervised crowds.

Potential Challenges

There are potential barriers to the use of biological signatures in standoff explosives detection that must be addressed. Hyperspectral imaging has inherent limitations. Confounding factors such as other pathological conditions and natural variations in temperature and skin color must be filtered out if this technology is to be effective. The volume of people and characteristics to be screened may lead to very large data processing and management requirements. Finally, this approach may be relatively insensitive to conditions of minimal or short-term exposure to explosives and thus miss individuals who are exposed to explosives only immediately prior to a bombing.

While thermographic imaging is well established, hyperspectral imaging is less developed for whole body analysis. Research would be required to determine if this approach can be implemented for real-time standoff analysis. A key question is whether hyperspectral images can be obtained that can discriminate between natural population variance, other pathological disease state conditions, and actual explosive exposure. If the use of hyperspectral imaging is determined to be useful for standoff explosives detection, it must be determined whether analytical tools such as LASH could be directly applicable for its implementation or whether new hyperspectral tools would be required.

Research would also be needed to evaluate the explosive's exposure path and history with respect to sensitivity of detection. For example, does casual exposure of a bomber create a signature that can be discriminated, or does it take the chronic exposure of a bomb maker to create a sufficient signature? Can superficial skin-absorbed explosives, or explosives in hair, be excited (illuminated) to produce an explosive biosignature spectrum directly?

As noted earlier, biosignatures would best be utilized as an orthogonal technology in a systems approach to standoff explosives detection. To effectively integrate the use of biosignatures, research would be needed into how well imaging data bases correlate for behavioral imaging versus biosignature imaging, and whether meaningful orthogonal relationships exist. In like manner, a systems approach would require that an orthogonal relationship be established between biosignatures and other methods of direct explosives detection or imaging.

Recommendation: Research is needed on biological markers related to physiological changes in persons associated with bomb making and bomb delivery and based on the chemical composition of the explosive.

7

Unexploited Potential Bases of Detection

As part of the charge of this committee, committee members undertook the development of novel concepts for explosives detection. "Novel" here refers to the fact that the idea appears not to have been exploited for explosives detection, rather than implying that the idea is new. Each of these ideas is presented in a separate section below, with the purpose of identifying future research directions.

DYNAMICAL BEHAVIOR OF AN EXPLOSIVE VAPOR PLUME

Hypothesis and Concept

An understanding of the dynamical behavior of the vapor plume emanating from an explosive will assist the development of devices for detecting explosives at a distance via their molecular properties, namely, their spectroscopic properties.[1] This understanding should answer questions such as: What is the shape of the plume? What is its behavior over time? How is it affected when one introduces airborne dust particles, surfaces of different composition, and air currents?

A way to study the plume behavior is to image it. Two possible "imaging" approaches to this problem are the ultraviolet (UV) imaging of the explosive and schlieren photography. For the former, nitrogen-based explosives have a very strong absorption band in the short-wave UV due to

[1] Additional detail on the explosive vapor plume is given in Chapter 4.

the presence of aromatic rings.[2] Therefore, explosive vapors, *if they are dense enough*, should look dark when viewed with a UV image intensifier. A UV reflective background would be necessary to enhance the contrast. Schlieren photography, on the other hand, is based on vapor density differences, the image being formed by refraction and scattering from areas of varying refractive index. The evaporation of acetone from a container or the heat waves emanating from a human body are clearly "seen." The question is whether or not the current schlieren technology is *sensitive enough* to detect the vapors coming off an explosive.

Novelty

The imaging of an explosive vapor plume has not been done. The closest we have is the theoretical and semitheoretical work of Dr. Thomas A. Griffy of the University of Texas at Austin.[3] Although this work considered the diffusion of explosive vapors emanating from a block of explosive, the more useful results are what happen at the end. Griffy showed that most of the vapor being emitted by a nitrogen-based explosive ends up adhering to surfaces; there is hardly any that is airborne. His results help explain why swabbing surfaces is much more effective in gathering explosive residue (most of which is from contamination) than sampling the air.

Relevance to the Committee's Mission

The mission of the committee is to generate ideas for the standoff detection of explosives. If standoff detection technology is used that probes the spectroscopic properties of the explosive, it would be helpful to know how much explosive vapor is airborne around an explosive mass and how much is adhered to nearby surfaces. Furthermore, if most of it is adhered, it would be useful to know how readily it can be dislodged from a distance. Clearly, understanding the "physics of the plume" is critical for designing and using spectroscopy-based detection technology.

Spectroscopy-based standoff detection techniques that would rely on the plume behavior include remote sensing and remote imaging optical techniques. Among these are those that use LIDAR ([laser] light detection

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[2]Yinon, J.; Zitrin, S. *The Analysis of Explosives*, In *Ultraviolet and Visible Spectroscopy.* Pergamon Press: 1981, Chapter 10, pp 141-153.

[3]Griffy, T.A. A model of explosive vapor concentration II. In *Advances in Analysis and Detection of Explosives*, Proceedings of the Fourth International Symposium on Analysis and Detection of Explosives, September 7-10, 1992, Jerusalem, Israel, J. Yinon, Ed.; Kluwer Academic Publishers: Dordrecht, Netherlands, 1992, pp 503-511.

and ranging], DIAL (differential absorption LIDAR), and DIRL (differential reflectance LIDAR). These involve laser illumination usually in the infrared (IR) region, but there are also multi- and hyperspectral imaging and sensing techniques that operate in this and other spectral regions. All of these optical techniques operate on the principle of radiation (from an illuminating source) being absorbed by the target material and detecting the attenuated backscattered radiation. At present, there exists a dual spectral explosive imaging system designed to detect adhered particles of a particular nitrogen-containing explosive. This system uses solar illumination for viewing.

Existing Technology Related to This Idea

At present, the only two technologies known to us that address imaging the dynamic behavior of the plume are the two mentioned above, namely, UV imaging and schlieren photography.[4]

Advantages

For imaging the explosive vapor plume, we would ideally like to see a technique that reveals the presence of any explosive material within its view. One common way to emphasize a target within the viewing field of an imager is to colorize it, giving it strong visual contrast. A major advantage of exploring the imaging idea is the ability to view in real time the dynamics (time behavior) of the sublimation-diffusion process.

Disadvantages

Based on the work of Griffy, we expect to see less airborne explosive-laden particles and more adhered explosive material on surfaces. By adhered explosive materials is meant adsorbed vapors, adsorbed explosive-laden particles, and adhered explosive particles or residue. Therefore, there may be no advantage to studying the dynamics of the vapor plume if the explosive is in a closed environment where almost all of the emitted explosive vapor is adhered to surfaces.

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[4]Settles, G.S. *Schlieren and Shadowgraphs Techniques: Visualization Phenomena in Transparent Media,* Springer-Verlag: 2001, 390 pp.

Research Needed to Demonstrate Feasibility

To gain an understanding of the vapor plume, research that focuses on imaging these plumes is necessary. Experiments would be needed that reveal the dynamic behavior of a vapor plume, from its origin at the surface of the explosive to its final destination on surfaces, under idealized laboratory conditions. Additional research should be extended to outdoor conditions, including the behavior of the plume from a moving target such as a person on foot or a moving vehicle. Furthermore, most "real-world" cases are not at the elevated temperatures that might be necessary in these experiments for imaging the plume. Thus, attempts should be made to extrapolate the findings to anticipated environmental conditions.

Additional research on the vapor plume would model vapor generation, transport, adsorption to airborne particles, natural convection, and a moving versus stationary source; experimental testing of the model through measurements of vapor concentration versus time and spatial position would also be needed.

In order to perform standoff measurement of plume characteristics, schlieren photography and other techniques to detect chemical information about a plume should be utilized to detect chemical signatures of explosives.

DETECTION OF A SUICIDE BOMBER'S LOCAL ATMOSPHERE—ANOMALIES IN THE ATMOSPHERIC ION BACKGROUND

Hypothesis and Concept

Would the tendency for high explosives containing electronegative nitro or peroxide groups to undergo electron attachment cause depletion in negative ions around a person carrying concealed explosives as he or she walks through the background ion field? It is well known that the atmosphere contains background positive and negative ions.[5] The ambient atmospheric ion concentration is 250 positive ions and 200 negative ions per cubic centimeter. A net current of 2000 A flows from the atmosphere to the Earth's surface. One highly speculative approach would be to image the ion charge aura in a surveillance area and see whether anomalies could be correlated with the presence of explosives. Although the approach is unlikely to be highly specific, it may be useful as part of a systems design using orthogonal sensors. Several issues would have to be explored.

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[5]Wahlin, L. *Atmospheric Electrostatics;* John Wiley & Sons: New York, 1989, 130 pp.

Novelty

To the committee's knowledge, such a detection approach has not yet been explored. There are several possibilities for measurement. The ion density of air can be measured and tracked with inexpensive ($60) electronics based on the Gerdien Cylinder.[6] However, this would require sampling at many points over an area under surveillance. Another possibility would be to measure the variation in the 4×10^{-12} A/m^2 current that flows between the atmosphere and Earth's surface because of the excess positive ions in the atmosphere and compensating negative charge at the Earth's surface. This would be a very challenging measurement, where new research ideas could be useful. Ideally, one would prefer to image the electric field distribution in a surveillance area. The average "fair-weather field" strength at the Earth's surface is 100 V/m.

Relevance to the Committee's Mission

This approach might provide a method of broad-area surveillance for concealed explosives, which would be nonhazardous to subjects being examined.

Existing Technology Related to This Idea

Measurable perturbation of the background ion concentration has been claimed in human breath.[7] It may be possible to amplify the atmospheric ion background for improved detection sensitivity at an entry portal through the use of van de Graff generators or some other method. This would provide a higher density of ions, if the rate of charge attachment is a limiting factor.

Advantages

This technology represents a nondestructive and noninvasive method for broad-area surveillance to detect concealed explosives.

Challenges

Background variations with altitude, solar wind strength, and electrical storms will be significant; however, these effects would be expected to

[6]Carlson, S. *Counting atmospheric ions*, *Scientific American*, September 1999, 96-97.

[7]Suchanowski, A.; Wiszniewski, A. *Changes in ion concentration in the air during the breathing process of a human being*. *Polish Journal of Environmental Studies* 1999, *8*(4), 259-263.

be homogeneous over a given area being monitored. Metal objects may also provide an impediment.

Research Needed to Demonstrate Feasibility

Measurement sensitivity and detection specificity are expected to be the most serious issues in testing this new approach. Detailed knowledge of the chemical distribution of component ions present in the atmosphere, and their role in any variations detected, should be defined. Although these experiments would be more technically challenging, they would provide understanding of the origin of any observed effects that might aid in rational design of the method.

DETECTION BY DETONATION

Hypothesis and Concept

The goal of this approach is to detect the presence of an explosive by remotely detonating it at a safe standoff distance. Detonation takes place by adding sufficient energy to the explosive that the exothermic reaction initiates. Alternatively, energy is added to the explosive or allied circuitry by one of several possible means: radio frequency (RF) excitation, acoustic shock, focused millimeter wavelength radiation, and perhaps others. For example, RF radiation will excite a resonance in some metallic structure in a bomb (wires, detonator, etc.). One can find dimensional resonances by sweeping the RF frequency at each point of focus during some (relatively short) dwell time.

Novelty

Coupling chemistry and remote energy is common (consider microwave ovens), but applying this general idea to the initiation of an explosive is novel.[8] Detonation by coupling the electronics or wires of a detonator in a bomb using remote energy is directly novel.

Relevance to the Committee's Mission

Detection is accomplished using relatively simple physical devices. Issues of background noise and other interferent confusions are entirely

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[8]Won, I. J.; Keiswetter, D. Electromagnetic Induction Spectroscopy. In *Detection and Remediation Technologies for Mines and Minelike Targets III*, A. C. Dubey, J. F. Harvey, and T. Broach, Eds. *Proceedings of SPIE* **1998**, *3392*, 14-21.

finessed. Sensitivity of the system is high for those explosives that couple to the delivered energy. Sensitivity barriers can be overcome in other explosives (those that do not couple) with greater power.

Existing Technology Related to This Idea

Some consideration has been given to this technology during research for advanced general luggage scanning (now being performed by X-ray and computer tomography [CT]). Stealth technology modeling (absorption of RF) could provide design guidance for these systems. Microwave oven technology and microwave curing of composites may provide insights. RF induction is a common process.

Advantages

The approach has a dual effect: the explosive is detected and destroyed, and the human bombers are deterred, because they do not reach their intended target. From an information point of view, other schemes work to return substantial information to the detector and identifier. This approach returns only one bit: explosion yes or no. This system has merit for military checkpoint scenarios.

Standoff detonation is quite possible with both millimeter wavelength radiation and RF radiation. Both millimeter wavelength and RF radiation (typically at frequencies of 1 GHZ or less) can be transported with transmission lines and focused with phased array antennas.

Challenges

Any of the methods in this approach transfer energy to the explosive or possibly to the detonation hardware. A reasonable impedance match between explosive, or detonation hardware, and incoming energy is necessary to minimize the extent of the energy source.

Various explosives admit to different means of energetic excitation, so this system may be somewhat selective both in terms of explosives detonated and in terms of energy source specifics. For example, shock-resistant explosives would essentially not be detonated by acoustic energy.

Several of the methods are not appropriate for human exposure. For example, relatively high-energy RF exposure is excessively painful.

Essentially any method of energy delivery would require focusing to accomplish standoff detection.

Research Needed to Demonstrate Feasibility

Coupling of energy source and classes of explosives of interest is one research focus. Energy source wavelength and physics, focusing, directing, intensity, and cost of generation will all be of interest. Focused millimeter wavelength electromagnetic radiation and focused radio-frequency energy are of particular interest.

Low observable research in the millimeter wave regime could serve as a basis for this work. Similarly, radiation effects laboratories have considerable experience in remotely energizing structures and circuits.

Scenarios for using this technology are limited to certain kinds of military checkpoint situations. Understanding interaction between energy sources and intensities, and the human body, will be important to expanding the use of this technology.

Remotely causing current flow, or sparking, in wires associated with electrical explosive detonators may require a measure of research study as well as engineering.

Hyperspectral radiation may be used for greater sensitivity in initiating detonation if the explosive is simultaneously responsive to several frequencies. Hyperspectral radiation may also expand the range of explosives affected by exposure, because different explosive classes are sensitive to different energy wavelengths.

DETECTION BY SELF-REPORTING SENSORS

Hypothesis and Concept

The goal of this approach is to detect the presence of explosives using remote standoff mine technologies such as neutron activation analysis. The idea is to distribute small sensors that are silent until they reach a critical threshold of detection. Each device can have multiple sensors. Once a threshold is crossed, the device activates and sends a signal that locates it in a physical space. If the sensors are spread out, the path to the explosive can be tracked at a rate dependent on the rate at which the detectors can determine the presence of explosive material. The key element of this idea is to use vast numbers of detectors that need not be probed but report back only when a certain threshold is reached.

Novelty

This approach couples detection technologies with the need for area surveillance. The standoff mine technology requires energy sources that last for long periods of time and are activated by motion. This concept would couple microfluidic detection technologies with reporting systems that are location sensitive. It does not require continuous interrogation of sensors but provides opportunities for large numbers of sensors to be distributed overa large area.

Relevance to the Committee's Mission

Detection is accomplished using proximal probes (i.e., probes that must be close to explosive), but this provides opportunity for wide-area detection.

Existing Technology Related to This Idea

Microfludic technologies are being developed based on chemically specific methods. The limitation of these technologies lies in the need to get close to explosive. The concept being suggested here is to marry this with communication systems where small probes can be distributed widely, have a long working life, and report in when threshold levels are crossed.

Advantages

This approach has the advantage of allowing detection systems to be distributed easily (dropping or gluing down at random or strategic locations for a big event, e.g., a Super Bowl Game). The device will be needed only for a short period of time, and when not needed the listening device is simply turned off. This system has applications is wide-area surveillance.

Challenges

This method relies on the sensitivity and speed of measurements of microdetectors. If the microdetectors cannot measure the trace of the explosive, the distribution of sensors will not be useful. Making the detectors and responding units requires miniaturization of sensors.

Research Needed to Demonstrate Feasibility

Research and demonstration of reliable detection sensors with the required sensitivity and accuracy for use in these devices is required. Research is also needed to couple microfluidic detectors with radio-frequency transmission systems that have location sensitivity.

STANDOFF COMPTON BACKSCATTER X-RAY IMAGING

Hypothesis and Concept

Using low-energy x-rays, the target is illuminated and Compton backscatter photons are collected that are subsequently emitted from the target.[9] Photomultipliers detect light flashes in plastic that result from the backscatter photons. Standoff capability results from locating the detector near the target (e.g., in the ground) or from using a relatively large detector near the source X-ray emitter. The image is assembled by scanning the X-rays over the target and detecting in synchronization the backscattered photons. Backscattered photons are produced relatively efficiently by substances of low atomic number.

Novelty

The novelty of this approach is in using a large detector or standoff placement of the detector very near a checkpoint while keeping emitter and electronics at a distance. Furthermore, low-energy X-rays are quite effective for this application. In fact, higher-energy X-rays will produce increasingly less response.

Relevance to the Committee's Mission

This is an imaging technology that favors explosive-like low effective atomic number materials. The result is an image of the interior of the target with reasonable resolution and highlighted explosives. This would be particularly significant for the military checkpoint challenge.

Existing Technology Related to This Idea

A number of companies make one-side Compton backscatter scanning systems (the emitter and detector can be placed near one another, in contrast to transmission X-ray approaches).

Modeling of the Compton backscatter effect, leading to design of an effective system, can be undertaken using standard codes such as MCDP. Lawrence Livermore National Laboratory has a group advertising this capability, for example.

[9] Additional information on X-ray backscatter is presented in Chapter 5.

Advantages

Backscatter systems produce an image from X-rays that are scattered back from the screened object toward the source (and not only transmitted as in the standard machines described above). Because low-Z (low Z_{eff}, the effective atomic number) materials are more efficient at scattering X-rays, explosive-like materials are contrasted more—they stand out clearly in the backscatter image, while they are often barely visible in a transmitted image (low contrast). Metals, of course, are highly visible in the transmitted image.

The low-energy X-rays mean that target exposure to higher-energy photons is minimized. As to shielding, this class of backscatter interaction is possible to about $^1/_2$ inch of aluminum and about 6 to 14 inches of carbon epoxy composite material.

In dual systems (transmission and backscatter), a quantitative measure of the backscattered X-rays, together with absorption measurement, provides information that can help separate the effects of density and Z_{eff}, in order to identify high-density, low-Z_{eff} materials (the signature of explosives).

Challenges

This approach is fundamentally limited by the number of backscatter photons detected. Backscatter photons emit essentially in all directions from the target. Detecting enough of the photons to assess the target's structure requires a relatively large sheet of plastic in terms of solid angle or a modest one close to the target.

The system will not produce a particularly high-resolution image of the target. Resolution would be increased by more photons, but not in a linear manner. Also, X-rays penetrate deeply into the target, so backscatter emission can happen anywhere in depth. The image is just a kind of integration in depth.

Research Needed to Demonstrate Feasibility

If modeling of Compton backscatter shows promise for standoff, such a device should be built and assessed. Modeling of the system to guide its design should accompany the implementation planning stages. Both small portable systems and standoff systems, especially those that are checkpoint based or portal or tunnel based, should show promise.

DISTRIBUTED BIOLOGICAL SENSORS

Hypothesis and Concept

Could bees, moths, or butterflies be trained on bombers' biomarkers such as those outlined in Chapter 6? Could rat packs trained on explosives or drugs be fitted with a wireless global positioning system (GPS), a bioluminescent reporter gene, and a microphotocell and released in sewers to locate outflow from bomb factories or drug labs?

Novelty

The novelty of this approach is the use of bees and rats for preemptive explosives detection. Bioluminescent genes have been demonstrated with microluminometers.

Relevance to the Committee's Mission

Preemptive location of bombers and bomb makers for arrest or surveillance would be possible with this technology. Drug labs might also be located with this approach.

Existing Technology Related to This Idea

Bees and rats have been prepared for explosives detection.

Advantages

This approach offers a broad sampling method for wide-area screening. There is the potential to find the problem at its source.

Challenges

The return of butterflies, moths, and rats and the relatively short lifetime of butterflies and moths are challenges given the investment in training. Also, rats are disease vectors.

Research Needed to Demonstrate Feasibility

Field trials would be needed to test this approach. In principle, the technology exists, so a rat could be modified with a bioluminescent reporter and sensor (photocell).

RECOMMENDATION

Recommendation: Feasibility studies should be developed on the ideas suggested in Chapter 7 to assess their potential in sensors suitable for standoff detection.

8

Summary of Committee Recommendations

In its deliberations, the committee focused its recommendations to meet its charge as expressed in its statement of task (Appendix A). Therefore, the committee's recommendations fall into four main areas outlined in its task: characteristics of explosives, signal discrimination, detection systems, and areas of research.

CHARACTERISTICS OF EXPLOSIVES, BOMBS, AND THEIR COMPONENTS

In its statement of task, the committee was asked to describe the characteristics of explosives, bombs, and their components that are or might be used to provide a signature for exploitation in detection technology. The committee makes the following series of recommendations based on this aspect of the committee's charge.

As noted in Chapter 4, the ability to detect explosive vapors is hampered by the lack of volatility of many energetic materials and bomb casings that help to confine vapors emitted by explosives. That being said, many explosive compounds do contain volatile impurities that can serve as markers indicating the presence of explosives. An understanding of the vapor plume dynamics may provide new insights into detection methodologies for these materials.

> **Recommendation: Research into the vapor space about the bomber may lead to improved means of explosives detection. An increased quantitative understanding of vapor plume dynamics is required**

for application to explosives with high-volatility components such as TATP.

Also noted in Chapter 4 was the fact that strong oxidizing agents present in all explosives must make use of one or more of the most electronegative elements. Currently, IMS technology utilizes the presence of these electronegative elements to detect explosives. Research into analysis by nitrogen and oxygen composition may yield additional means of explosives detection. As noted in the FBI presentation to the committee by Dr. Bermeister, terrorists will adapt when barriers prevent them from undertaking their attacks utilizing traditional explosives and methods. It is therefore prudent to be aware of breakthroughs and advances in the development of new explosives, particularly those that utilize novel chemical functionality.

Recommendation: Improved detection systems will lead to development of new explosives. Research is needed on the identification and characterization of new chemical explosives that do not utilize nitrogen and have very low vapor pressures, for example, ionic liquids.

While most of the focus in explosives detection has been on physical properties of chemical explosives and how those properties can be exploited, it is essential to take into account not just the explosive but all other components of the bomb, including those who assemble the device and those who deliver it. As opposed to other methodologies that analyze potential bombers, for example, gait analysis, physiological changes resulting from exposure to explosive materials may be quantifiable. Human exposure biomarkers are addressed in detail in Chapter 5.

Recommendation: Research is needed on biological markers related to physiological changes of persons associated with bomb making and bomb delivery and based on the chemical composition of the explosive.

SIGNAL DISCRIMINATION FROM BACKGROUND

In its statement of task, the committee was asked to pay particular consideration to discriminating possible signals from explosives from background and interferents that can be anticipated in real applications. Development of a database of likely background conditions for use in system testing and implementation, and exploration methods for monitoring changes in background in real time would permit detection of weaker signals, and thus expand the possibilities of standoff detection. Research in detection of real-time changes in ambient conditions is essential for explosives detection because of the variety of scenarios where explosives detection must be made. Only by overcoming the challenge of detecting a signal in a dynamic, noisy background environment will effective standoff detection be achieved.

Recommendation: Because discrimination of a useful signal in a noisy environment is always a problem, a research effort should be aimed at determining baseline ambient conditions and detecting changes in ambient conditions in real time.

DETECTION SYSTEMS INTEGRATION

The following findings and recommendations are made by the committee in response to its charge to discuss the potential for integrating detection techniques into detection systems that would have sufficient sensitivity without an unacceptable false positive rate. A number of presenters to the committee remarked that there is no "silver bullet" explosives detection. It is highly unlikely that a single means of detection will be effective in all the environments (e.g., indoor/outdoor, military/civilian) and for all potential explosives (e.g., military ordnance, improvised explosives, ammonium nitrate-based explosives) where standoff explosives detection is required. As a result, multiple detectors embedded in a decision-making system are required. The committee focused much of its attention on this issue.

The effectiveness of detection systems depends in great part on the scenario and threat parameters assumed in building the system. This must be appreciated in any research and development effort.

Recommendation: Research into *both* new sensors *and* new systems of real-time integration and decision making is needed. The sensor research agenda should emphasize the principle of *orthogonality* in mathematical consideration, sensor system design, and design of information leading to true detection.

The ability to deploy multiple, orthogonal detectors, each measuring different aspects of the same potential threat is needed to provide better overall detector performance. In order to successfully combine multiple detectors into an integrated, decision-making detection system, the committee recommends the following areas for research:

Recommendation: Research is recommended into methodologies to quantify system effectiveness (SE) for systems of sensors (a detection system) and for systems of detection systems allowing for noisy input from many sensors. Of particular importance is the definition and evaluation of a full spectrum of "false positive" signals rang-

ing from detector reliability, legitimate signals that do not represent true threats, or operator interpretation of detector signals. Appropriate ROCs and other measures of performance for such systems should be developed.

Recommendation: Research is needed into the development of scenario-threat parameters-decision trees for real-time decision making.

Recommendation: Research is needed on the integration of information from distributed orthogonal sensors to achieve real-time conflict resolution and decision making with high system effectiveness, and on integration tools based on data fusion and decision fusion. In addition, research coupling parallel sensors via decision fusion with sequential sensor systems may provide valuable insights.

Recommendation: Research is recommended to envision and devise real-time sensor system threat detection that adapts to new threats, new backgrounds, and new threats that behave like background. A system that autonomously evolves should be a focus of research, including methods to evolve the system design to increase system effectiveness and orthogonality, given detection anomalies.

AREAS OF RESEARCH

The committee was asked to propose areas of research that might be expected to yield significant advances in practical explosives and bomb detection technology in the near, mid, and long term. Some of the recommendations for research were presented earlier in this chapter. The recommendations below are for additional areas of research that were identified by the committee as it analyzed the challenges involved in effective standoff detection. In keeping with the committee's statement of task, these recommendations are divided into research expected to yield significant advances in the near, mid, and long term:

Research Recommendations for Near-Term Technology Advances

Wide-area surveillance depends heavily on the distribution of multiple low-cost sensors, and effective integration of the data received by these sensors. The development of inexpensive sensors is presently a field of active research for a multitude of applications. A thorough overview of the current state of sensor research would provide a useful baseline for determining advances needed in sensors for standoff explosives detection applications.

Recommendation: Research is recommended into rapid, remote collection and concentration of explosives samples and into distributed, low-cost sensors. Included here are small (nano) and perhaps mobile sensors, distributed arrays of sensors, and the use of convective streams with or without airborne adsorbing particles to gather chemical samples.

As discussed in Chapter 5, a number of imaging methods are currently under active and extensive development for use in explosives detection. While some of these methods are either in use now or are close to deployment, significant limitations still remain for their use as effective standoff explosives detection. For imaging, atmospheric water and the need for significant object of interest/background temperature differentials pose limitations on where and how these detectors can be used. In addition, in most cases detection using spectroscopy is relatively immature compared to imaging.

Recommendation: Research is needed on new spectroscopic and imaging methods employable at a distance (passive and active). Examples include terahertz and microwave imaging and spectroscopy and X-ray backscattering.

Research Recommendations for Mid-Term Technology Advances

Research into the pathways and processes involved in sensing by animals has made great strides in recent years. Additional effort is now needed into how best to integrate this understanding in the development of low-cost biomimetic devices.

Recommendation: The committee recommends continued research into biomimetic sensing based on animals, but research should focus on distributed, low-cost sensors.

Effective standoff detection requires not only identification of the threat, but action to intercept the threat before major damage can be inflicted by the perpetrator. Preemptive detonation has been a focus of research, but its impact on innocent bystanders and equipment still makes it impractical for deployment. Research into preemptive disabling of explosive devices should build on the knowledge gained from the development of active sensing technologies.

Research Recommendations for Long-Term Technology Advances

As the committee heard many times over the course of this study, the challenges posed in the development of effective standoff explosives detection technologies are extensive and dynamic. Signal discrimination, mitigation of false alarms, the emergence of new explosive compounds that can potentially thwart an explosives detector are just a few of the difficulties that must be addressed. In light of these issues, it is essential that researchers and program managers be willing to engage in high-risk/high-payoff research. Fresh, bold approaches using innovative thinking should be encouraged from the outset, even when the barriers to implementation initially may appear to be formidable.

Recommendation: Research is needed on biological markers related to physiological changes in persons associated with bomb making and bomb delivery and based on the chemical composition of the explosive.

Recommendation: Feasibility studies should be developed on the ideas suggested in Chapter 7 to assess their potential in sensors suitable for standoff detection.

Appendixes

Appendix A
Statement of Task
Review of Existing and Potential Standoff Explosives Detection Techniques

To assist DARPA in its efforts to develop more effective, flexible explosive and bomb detection systems, the NRC will examine the scientific techniques currently used as the basis for explosives detection, and consider whether other fundamentally different chemical, physical, radiological, systems analysis, or other techniques might provide promising research avenues with possible pathways to new detection protocols. This review will:

- Describe the characteristics of explosives, bombs, and their components that are or might be used to provide a signature for exploitation in detection technology.
- Consider scientific techniques for exploiting these characteristics to detect explosives and explosive devices. Particular consideration must be given to discriminating possible signals from the background and interferents that can be anticipated in real applications.
- Discuss the potential for integrating such techniques into detection systems that would have sufficient sensitivity without an unacceptable false positive rate. In proposing possible detection protocols, give consideration to trade-offs between desirable system characteristics, including relative ease of implementation.
- Propose areas for research that might be expected to yield significant advances in practical explosives and bomb detection technology in the near, mid, and long term.

Appendix B

Glossary

Active. Those measurements that require external stimulation (e.g., incident electromagnetic radiation) or direct sample collection to obtain data.

Data Fusion. Combination of unprocessed data from multiple sensors to create unified input for a detection method or system.

Decision Fusion. Combination of results from multiple detectors to create a decision.

Detector. A data collection and processing technology. In this report, a "detector" both collects and evaluates data in order to provide assessment regarding the presence of characteristics or indications of explosives or explosive devices. The "detectors" are contrasted with "sensors," which collect data but do not evaluate the data with respect to the presence of explosives.

False Negative. A detector reading suggesting the absence of an explosive or explosive devices when explosives are, in fact, present. The probability of observing a false negative is referred to as the "false-negative probability" or "false-negative rate."

False Positive. A detector reading suggesting the presence of an explosive or explosive device when explosives are not present. The probability of observing a false positive is referred to as the "false positive probability" or "false positive rate" and is equivalent to the specificity of the detector.

Orthogonal Detection Methods. Two or more explosive detection technologies that are mutually independent. That is, they detect independent characteristics of the explosive device.

Passive. Those measurements that develop the data for a threat analysis from inputs that are freely arriving at a sensor or detector. The item being analyzed is neither disturbed nor subjected to external manipulation to collect data. Examples include collecting images (e.g., thermal infrared or terahertz) or spectroscopic data without external illumination (though it does include those based on emission profiles) or chemical sampling without directly probing of the source or target.

Positive Predictive Value. The probability that a detector reading suggesting the presence of explosives or explosive devices corresponds to the true presence of an explosive or explosive device.

Remote. For explosives detection, a far-enough distance that the detector operator or vital assets are not severely damaged if the explosive device detonates.

ROC (Receiver Operating Characteristic) Curve. A plot of the sensitivity (probability of observing a true positive) versus the converse of specificity (probability of observing a false positive) for the full range of possible decision criteria.

Sampling. In this report, the collection of a physical sample for analysis (e.g., physical contact, wiping, active or passive collection of vapors, and active or passive collection of particles).

Scenario. A posited future state with an allied set of possible future events—a story line—that is used to explore concepts. Scenarios are thought experiments; they are basic tools for being anticipatory. A scenario serves as a working prototype of an idea in a context; developing that scenario objectively exposes hidden assumptions and contingencies about the environment, actors, or context.

*Sensitivit*y. A detection approach is *sensitive* when it alarms *if* the substance of interest is present.

Sensors. A data collection technology. Sensors pass along data without determination of the presence or absence of explosives, explosive devices, or their accompanying characteristics, whereas detectors measure data and evaluate of the data with respect to the presence of explosives.

Specificity. A detection approach is *specific* when it alarms *only if* the substance of interest is present.

Standoff Explosive Detection. Passive and active methods for sensing the presence of explosive devices when vital assets and those individuals monitoring, operating, and responding to the means of detection are separated physically from the explosive device. The physical separation should put the individuals and vital assets outside the zone of severe damage from a potential detonation of the device.

Systems Effectiveness. "A measure of the degree to which an item can be expected to achieve a set of specific mission requirements and which may be expressed as a function of availability, dependability and capability" (*Definitions of Effectiveness Terms for Reliability, Maintainability, Human Factors, and Safety*, MIL-STD-721B, U.S. Department of Defense, Aug. 1966). For standoff explosives detection, system effectiveness could include detection system availability, maintainability, system ROC, and the probability of avoiding defeat.

Threat Parameters. Characteristics of threats used in developing a threat analysis. These include, for example, delivery methods for a device, location and timing of a detonation, explosive composition, mass of explosive, other device components, and dispersed materials.

True Negative. A detector reading suggesting the absence of explosives or explosive devices when no explosives are present. The probability of observing a true negative is referred to as the true negative rate or true negative fraction.

True Positive. A detector reading suggesting the presence of explosives or explosive devices when explosives are present. The probability of observing a true positive is referred to as the true positive rate or true positive fraction and is equivalent to the sensitivity of a detector.

Appendix C

Presentations to the Committee

The Committee on the Review of Existing and Potential Standoff Explosives Detection Techniques met four times over the course of its study. At these meetings, the committee was briefed by experts on various aspects of standoff explosives detection. Included in this appendix are brief summaries of each of the presentations. These summaries are the work of the committee and NRC staff.

STANDOFF EXPLOSIVES DETECTION STUDY

Lisa Porter, Defense Advanced Research Projects Agency (DARPA)

DARPA has requested that the National Research Council (NRC) undertake the present study in order to address the issues and problems related to standoff explosives detection. Standoff explosives detection is the ability to detect explosives at a distance. Two main scenarios can be envisioned for the application of standoff explosives detection. The first is broad-area surveillance, particularly at events with large crowds such as the Super Bowl. A second scenario is the ability to detect a suicide bomber before the bomber is able to reach his or her target and detonate the explosive. Low-probability, high-consequence situations such as these are the main priority for DARPA in its request for this study. Detection of land mines is not a primary consideration for the NRC study.

DARPA requests that the committee identify new approaches and new ways of thinking about the problem of standoff explosives detection. When considering standoff explosives detection, sensitivity *and* specificity must be taken together. Requirements for standoff explosives detection are a high probability of detection combined with a low probability of false alarms. In order to meet this goal, it is necessary to consider the background in the field when explosives detection is being performed and both its impact on the explosives signal and its potential to contribute to false alarms.

Linking together different detectors for a systems approach to standoff explosives detection is desirable, but doing so must invoke a good systems approach. Effective sensor fusion will depend upon the orthogonality of the sensors. True orthogonality is defined in terms of the false alarms that trigger the sensors, and not necessarily the signal that is being detected.

The committee is tasked with both reviewing what detection systems now exist and trying to determine what could exist. In undertaking this task, the committee may want to consider physical or chemical aspects of explosives that have not yet been exploited. The committee should consider techniques for exploiting these characteristics. The committee should also consider whether there are systems-level approaches that should be exploited.

In addition to these considerations, the committee should take into account the speed and applicability of any novel standoff detection system. The committee should be willing to suggest "out of-the-box" approaches to this problem—including ones that combine chemical, physical, and visual means of detection.

STANDOFF EXPLOSIVES DETECTION

Lyle Malotky, Science Advisor
Transportation Security Administration (TSA),
U.S. Department of Homeland Security

The mission of the TSA is focused more on civilian protection than on protection of military personnel or assets. With this mission, the TSA seeks modes of detection that ensure the safety of the population being screened and can perform the detection task in a timely manner, so that neither commerce nor traffic is significantly impacted.

When looking at the issue of standoff explosives detection, a number of factors must be taken into account. A variety of bombing scenarios can be envisioned, and detection must be geared toward one or more of these. Scenarios include suicide bombers, car or truck bombs, boat bombs, abandoned packages, and booby traps, to name a few. In addition to bombing scenarios, the variety of explosives to be used and to be detected must also be examined. Ammonium nitrate, dynamite, military explosives, black and smokeless powder, acetone and hydrogen peroxide, and acid, to name a few, might all potentially be used in an explosive device.

In addition to the explosives and the scenarios in which they might be used, other challenges confront those who work to detect explosives. In addition to the aforementioned variety of explosives, the quantity of explosives used plays a large factor in determining whether a particular mode of explosives detection will be adequate. Another significant challenge is presented by materials that can produce false alarms, such as nitroglycerin used for medical purposes.

When considering novel approaches to explosives detection, all chemical and physical aspects of the explosive device should be examined for possible exploitation. Full use of the electromagnetic spectrum may provide novel means by which explosives can be detected. For example, use of radio-frequency, neutron analysis, or X-ray backscatter may offer opportunities for finding concealed explosives. Electro-optical properties, including millimeter wave imaging, radar, terahertz imaging or spectroscopy, the dielectric constant of explosives, or Raman spectroscopy are just some of the other options available for this task.

The elemental composition of commonly used explosives may be a means by which explosives can be detected in a package or in luggage. The high nitrogen and oxygen content in many explosives can provide a characteristic signal for these compounds. Characteristics such as the low vapor pressure of many explosives result in vapor clouds that can be detected using infrared (IR), ultraviolet (UV), or double photon techniques. In addition, vapor sensors can also be sent to the bomb—for example, through the use of nanoparticles, indigenous or dispersed plants or bacteria, trained insects or animals, or potentially nano-robots.

Thermal and mechanical properties of bombs may also be used for detection. IR imaging of a suicide bomber, sonic imaging, anomalous movement of cars or people, or detection of the components of a bomb such as the battery, switch, detonator, or container also may be utilized for standoff explosives detection.

EXPLOSIVES DETECTION

Steven Burmeister
Federal Bureau of Investigation Explosives Unit

Any standoff explosives detection system must be adaptable and flexible. Terrorists and their methods will change and adapt when confronted with new barriers to execution of their attacks. From the standpoint of detection, the use of homemade mixtures to produce explosives and the development of compounds such as acetone peroxides that are easy to produce and difficult to detect—although they are also extremely difficult to handle safely—present challenges to those seeking to stop terrorist attacks.

A number of detection technologies presently exist or are close to implementation, but many of these pose difficulties for use in standoff detection. Ion mobility spectroscopy (IMS) provides detection in the nano- to picogram range, and recycling of the detector for multiple scans can be achieved in minutes. However, the IMS detector must be quite close to the explosive for effective detection. Likewise, Raman spectroscopy must be close to the source. Gas chromatography-mass spectroscopy (GC-MS) and portable Fourier transform infrared (FTIR) can achieve standoff detection using a laser beam and a telescope, but issues of background interference and the form of the explosive (e.g., FTIR requires a solid sample) must be considered when using these technologies. Dogs present the most versatile means for explosives detection, but they cannot provide truly standoff detection and they require frequent breaks when performing their task. Trained insects may potentially be used for explosives detection, but there are problems to be overcome in training and specificity of detection.

EXPLOSIVES DETECTION

Richard Strobel
Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Forensics Lab

ATF has seen a steady decline in the use of commercial high explosives in bombings since the 1970s. Currently, the most prevalent explosives used in criminal bombings in the United States are commercially manufactured low explosives such as black and smokeless powders. Many of the more recent high-profile bombings seen both in the United States and abroad utilize improvised explosives. Homemade explosives such as black powder, triacetonetriperoxide (TATP), hexamethylenetriperoxidediamine (HMTD), chlorates, and perchlorates mixed with sugar or other fuels have come to be used instead of commercial explosives.

While many bombings are acts of vandalism with very few fatalities, the growing utilization of suicide bombings overseas demonstrates the damage that can be inflicted by a single person. In Israel, suicide bombers mostly used TATP as the main charge, and in many cases the bomb is fronted with shrapnel on a belt, copper foil for extra shrapnel, a battery switch, and anticoagulants.

ATF has developed a program to use dogs for explosives detection. This program has trained more than 400 dogs for use in explosives detection, both domestically and in other countries.

MILLIMETER WAVE TECHNOLOGY

Trent DePersia
National Institute of Justice, Office of Science and Technology (OST)

Passive millimeter wave technology has been developed for use in standoff detection. This technology is based on measurement of emissivity and is used mainly to detect metals, thus providing a means of detecting at least some explosive devices. Presently, this technology has effective standoff capability at approximately 10 m.

Millimeter wave machines are presently large (approximately 650 pounds) and expensive (on the order of $100,000). For this technology to be used regularly on the state and local level, portable devices must be developed with cost on the order of $10,000 to $30,000. Resolution of objects using this technology must be in the millimeter to centimeter range, and standoff capability must be at least 10 m.

Millimeter wave technology is based not on a chemical signature, but rather on millimeter wave thermal emission by all objects. The differences in emission between objects make imaging possible. The difference in temperature between an object and the environment also impacts the ability to resolve objects using this technology. Since millimeter wave technology is used to measure changes, it provides a complement to other technologies in its ability to image an area to see if a change has occurred, for example, to determine if a package has been left.

REPRESENTATION OF ODOR INFORMATION IN THE OLFACTORY SYSTEM: FROM BIOLOGY TO AN ARTIFICIAL NOSE

John Kauer
Tufts University

Through the use of olfactory coding and the development of an "artificial nose," real-world problems can be solved using neurobiological principles. Biomimetic approaches to sensing allow researchers to learn from nature. For example, in biological organisms, any one sensor in a group of a thousand may not be particularly effective, but the cooperative nature of this mass of sensors provides the organism with the ability to detect with great sensitivity and selectivity.

Analysis of specifically how sensing is performed in living systems provides still further insights. Detection of a specific odor does not involve detection of a specific compound, but rather groups of as many as 500 different molecules. For an organism to effectively sense and identify an odor, a number of capabilities must work in concert. Sensors must be regenerative so that bound molecules can be dislodged. Multiple sensing as opposed to single specific binding must occur. With multiple sensing, only 32 receptors are required to discriminate among 1000 agents. Using only single specific binding, 1000 receptors would be required to detect 1000 agents. For multiple sensing to be effective, the brain must undertake the sorting of the multitude of information coming from the receptors.

Insights such as these have led to the development of an artificial sensing device. A 16-channel fluorimeter, consisting of a 16-sensor array composed of polymeric sensors, has been developed.

EXPLOSIVES DETECTION

Laura Goldstein
Bureau of Customs and Border Protection

There are approximately 300 ports of entry for cargo into the United States. Seventeen million cargo containers cross U.S. borders every year. The Bureau of Customs and Border Protection has responsibility for screening and examining these cargo containers and is able to screen approximately 5 to 10% of all containers. For detection of illegitimate explosives, a variety of detection methods are used. IMS technology in the form of hand-held ion track vapor tracers is used to screen packages. For examination of trucks and rail cars, gamma-ray imaging and X-ray systems are used, the goal being to search for changes in density that might indicate illicit cargo. Present detection technologies pose problems—particularly in the form of false positives when using vapor tracers even with legitimate cargo such as fertilizer and new leather, for example.

LAND MINE DETECTION AND IDENTIFICATION USING TERAHERTZ SPECTROSCOPY AND IMAGING

Robert Osiander
Johns Hopkins University Advanced Physics Laboratory

Terahertz (THz) spectroscopy and imaging presents several advantages. High-resolution imaging can be attained, and terahertz radiation can penetrate dielectric materials. When THz imaging is used in the scattering mode, excellent resolution can be attained when imaging. For example, 1-mm resolution at a 10-m distance from an object has been achieved. Work on in this field has also pointed to the use of THz radiation for spectroscopy.

Although THz technology presents many advantages, there are still obstacles to be overcome. Water absorption presently limits the effective range of THz instruments for use in standoff imaging to approximately 10 m on a rainy day and 100 m on a clear day. In attempting to develop portable THz systems, issues of power sources, signal discrimination and background interference, scattering by particles (both in the soil and as aerosols), and the aforementioned problem with atmospheric water must all be addressed and overcome.

A number of labs are working to use THz radiation in real-time explosives-specific chemical sensors. So-called passive THz spectroscopy for imaging is potentially feasible, but the technology for such a device is not yet available.

NOVEL METHODS FOR EXPLOSIVES DETECTION— SUICIDE BOMBER DETECTION

David Huestis
SRI International

Because it is difficult to detect explosives long range, research has focused on the detection of the hardware of a bomb, not the explosive itself. With this approach, an assumption is made that at least part of an explosive device contains metal.

When developing standoff detection devices, scenarios must be taken into account. For example, it is assumed that a potential bomber approaching a checkpoint advances at 1 m/s. Therefore, if a standoff detector has an effective range of 30 m and an individual is identified approaching a checkpoint from 30 m away, there is a 10-second window during which identification of any bomb and appropriate action must be made before the bomber is close enough to inflict major damage and/or casualties.

To perform detection under these tight time constraints, a number of approaches have been developed. For a potential suicide bomber, nonlinear radar, which detects metal-metal friction through harmonic returns, is a possible means of detection. Terahertz imaging at 0.1- to 1.0-mm wavelengths can provide both visual identification of an explosive device and chemical imaging through the use of THz spectroscopy.

Distributed sensors to detect metals and/or chemicals can also be used for standoff detection. Tracking can be done through optical means, and feedback provided through wireless communications. Once an effective sensor has been developed, miniaturization should be undertaken to increase its applicability.

An orthogonal systems approach to standoff detection provides advantages such as increases in standoff range and increased spatial resolution.

A MILLIMETER WAVE IMAGING ARRAY FOR CONCEALED WEAPONS DETECTION

Erich Grossman
National Institute of Standards and Technology (NIST)

The THz program at NIST is focused on concealed weapons detection. The goal is to develop a low-cost, widely deployed system with standoff capability of at least 8 m. THz radiation is particularly well suited for such detection because clothing is transparent at less than 500 GHz, while metals are perfect reflectors.

Terahertz detection is possible using both active and passive methods. While passive detection outdoors is effective because the difference in temperature between the human body and the sky (background) is approximately 100 degrees, providing sufficient contrast, indoor contrast is much lower so that coherent detectors are needed to boost low-power contrast indoors.

For active THz detection, high-powered sources are required. Active sources are relatively inexpensive, on the order of $5000, but the lack of these sources is a primary reason why THz spectroscopy has not been explored in more depth.

Lithographic antennas are being developed, the goal of which is to adapt the pixel idea to THz imaging by having several antennas in an array tuned to a specific wavelength. When combined with multiple sources, imaging of metals is possible.

In order for THz imaging and spectroscopy to be widely used for detection, a combination of high-powered sources and low-cost detectors must be developed.

STANDOFF EXPLOSIVES DETECTION

Lou Wasserzug
Technical Support Working Group (TSWG)

For standoff detection to be effective at protecting personnel and valuable assets, standoff must be defined as a minimum of 30 to 50 feet from an individual suicide bomber, and 500 to 1000 feet for a vehicle bomb. TSWG approaches this task (and others) by conducting interagency research with oversight provided by the U.S. State Department.

To this end, TSWG has undertaken a number of research programs to address the challenge of standoff detection. For example, detection of ammonium nitrate powder on a vehicle was successful at close range but could not be made to work at standoff distances. This and other projects point out the difficulties involved in standoff detection because of issues such as background interference and interference occurring as a result of temperature variations over the course of a day, for example.

Other practical concerns impact the ability to perform effective standoff detection. Nuisance alarms, caused by actual detection of explosives that are not of interest, such as spent munitions, must be taken into account when determining whether an actual threat exists. While the technology for explosives imaging may be more feasible than that for explosives spectroscopy, the fact that imaging requires human interpretation whereas spectroscopy can be automated must be considered.

In any explosives detection scenario, choice of the proper tool for the job is essential. To that end, a variety of technologies are in place for explosive detection in a number of widely different locations and facilities. Imaging by low-dose X-ray backscatter is now used at entry points within the United States and is under consideration for additional uses as well. Infrared imagers are being assessed, and thermal emission technology is being revisited. Tests using this technology indicate that it may be useful in identifying suicide bombers. Passive millimeter wave imaging is a project in development, the goal of which is to provide a man-portable imaging system. In addition, nonimaging millimeter wave technology is being developed, whose goal is to look at anomalies in reflectance.