HAND-HELD EXPLOSIVES SENSOR SYSTEM

by

Charles D. Bosco
Senior Research Engineer
Systems Management and Production Center
University of Alabama
Huntsville, Alabama

Prepared by

UTCA

University Transportation Center for Alabama
The University of Alabama, The University of Alabama in Birmingham,
and the University of Alabama at Huntsville

UTCA Report Number 03306
August 1, 2003

Technical Report Documentation Page

1. Report No **FHWA/CA/OR-**	**2. Government Accession No.**	**3. Recipient Catalog No.**

4. Title and Subtitle Hand-Held Explosives Sensor System	**5. Report Date** August 1, 2002 **6. Performing Organization Code**
7. Author Charles D. Bosco	**8. Performing Organization Report No.** UTCA Final Report
9. Performing Organization Name and Address Systems Management and Production Center University of Alabama Huntsville, AL 35899	**10. Work Unit No.** **11. Contract or Grant No.** UTCA Identification Number - 03306
12. Sponsoring Agency Name and Address University Transportation Center for Alabama P O Box 870205 University of Alabama Tuscaloosa, AL 35487-0205	**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code**

16. Abstract

One of the most important problems facing the U.S. Department of Transportation is the detection of illegal chemicals and explosives entering this country. There are various government agencies performing detection by means of physical inspections, sophisticated detection instrumentation and trained "sniffing" dogs. All of these methods have their limitations, especially costs.

The purpose of this investigation was to study the feasibility of integrating a variety of microcantilever sensors into a hand-held sensor system capable of sensing and identifying illegal explosives. Researchers at the University of Alabama at Huntsville have developed the capability to design, fabricate and test microcantilever devices that can detect trace amounts of most organic and inorganic chemicals. These sensors are so sensitive that, in some cases, they can exceed the sensitivity of trained dogs. The sensors are small enough that many sensors can be placed on a single silicon chip.

An extensive literature search was performed to determine the U.S. Department of Transportation's challenges in detecting contraband explosives. This included a technical evaluation of present-day detection instrumentation and the capabilities of sniffing dogs. It was followed by a detailed study of microcantilever technology and its application to explosives detection. To determine the latest state-of-the-art, interviews were conducted with a customs inspector, a sniffing dog handler, and the head of a microcantilever laboratory. Other sensor technology was investigated to ensure that microcantilevers are indeed the most appropriate for explosives detection.

The investigation concluded with a prototype design of a multi-sensor system, and a cost analysis of fabricating such a system.

17. Key Words Chemical sensors, microcantilever, explosives, homeland security	**18. Distribution Statement**

19. Security Class (report) Unclassified	**20. Security Class. (Of this page)** Unclassified	**21. No of Pages**	**22. Price**

Contents

List of Tables

List of Figures

Executive Summary

One of the most important problems facing the U.S. Department of Transportation is the detection of illegal chemicals and explosives entering this country. There are various government agencies performing detection by means of physical inspections, sophisticated detection instrumentation and trained “sniffing” dogs. The use of inspectors is expensive due to the limited number and the cost of personnel. Instrumentation is very useful, but the more sensitive instruments are very expensive, and therefore, are purchased in limited numbers. Sniffing dogs provide a very good compromise. The handlers provide the human evaluation and decision making while the dogs are very good at detecting trace odors of explosives, drugs, and currency. The problems associated with dogs are that a trained dog is expensive and requires a skilled handler and upkeep. Also, dogs cannot work long hours.

The purpose of this investigation was to study the feasibility of integrating a variety of microcantilever sensors into a hand-held sensor system capable of sensing and identifying illegal explosives. Researchers at the University of Alabama at Huntsville have developed the capability to design, fabricate and test microcantilever devices that can detect trace amounts of most organic and inorganic chemicals. These sensors are so sensitive that, in some cases, they can exceed the sensitivity of trained dogs. Also, hundreds of these sensors can be placed on a chip the size of a computer chip.

An extensive literature search was performed to determine the U.S. Department of Transportation’s challenges in detecting contraband explosives. This included a technical evaluation of present-day detection instrumentation and the capabilities of sniffing dogs. It was followed by a detailed study of microcantilever technology and its application to explosives detection. To determine the latest state-of-the-art, interviews were conducted with a customs inspector, a sniffing dog handler, and the head of a microcantilever laboratory. Other sensor technology was investigated to ensure that microcantilevers are indeed the most appropriate for explosives detection.

The investigation concluded with a prototype design of a multi-sensor system, and a cost analysis of fabricating such a system.

Section 1.0
Project Objective

One of the most important new scientific accomplishments to emerge recently from sensor research has been the development of microcantilever sensors. This sensor has been demonstrated to have such extreme sensitivity that specialized sensor systems using this technology have the potential to equal or exceed the detection capabilities of sniffing dogs and some of the more sensitive laboratory measuring equipment. The object of this investigation was to determine the feasibility of integrating a variety of microcantilever sensor devices in a hand-held sensor system capable of sensing and identifying trace amounts of explosives. Trained dogs and some specialized portable instrumentation traditionally do this work very well, however, the new microcantilever technology has the potential of replacing sniffing dogs and reducing the size and cost of portable instrumentation. A sensor system based on this technology could enjoy widespread use for U.S. Department of Transportation (USDOT) inspectors.

As part of this investigation, an analysis was made of the projected cost of a hand-held sensor, assuming that one could be built to match or exceed the effectiveness of dogs.

The approach to this investigation was to accomplish the following tasks:

1. Study the USDOT's challenges in identifying contraband containing explosives.
2. Study the present technology used to detect explosives and determine its effectiveness, ease of use, cost, and upkeep.
3. Evaluate the capability of sniffing dogs to detect explosives.
4. Evaluate microcantilever technology.
5. Determine whether a cost-affordable multi-sensor system can be designed and fabricated.

Section 2.0
Background

Introduction

The focus of this investigation is to support the U.S. Department of Transportation in its quest for new technology to improve the detection of contraband explosives. Consequently, it will be useful to briefly describe the problems encountered by USDOT inspectors.

The Department of Transportation is faced with the overwhelming task of preventing the transportation of illegal explosives into and throughout the United States. Since the tragic twin towers attack, the threat level has increased significantly. Recently, the government has formed the Homeland Defense Department to consolidate the many agencies that are responsible for protecting this country. At this writing, it is unclear as to how the new organization will operate.

Contraband consists of many things, including drugs and currency, however this investigation will only be concerned with the detection of explosives or chemicals used in explosives.

Currently, inspections are done using inspectors, detection instrumentation, and sniffing dogs. Each has its strong and weak points, but whenever additional personnel are hired, the expenses increase significantly. Sniffing dogs have been found to be very useful, but they can only detect explosives that are not well sealed. They have other limitations that will be discussed later. Large sophisticated x-ray and other inspection machines are very important in identifying well-sealed explosives embedded in cargo or luggage. These instruments are usually very expensive and even the portable versions are too expensive for wide distribution. These instruments also have their limitations, and which will be discussed later.

Transportation Inspection Problems

Because of the vast size of the United States, i.e., borders with two large countries, and two major seacoasts (not including the Gulf of Mexico and the Great Lakes), the job of government inspectors is daunting. This task became significantly more important after the attack on the New York twin towers in 2001. While the USDOT is increasing the number of inspectors and improving techniques, the cost and size of such an operation is overwhelming. Also, there is the problem of coordination with other agencies such as the Department of Commerce, Customs, etc. The new Homeland Defense Department will attempt to provide a uniform approach to inspections and to the identification of contraband.

One of the more recent attempts to address the problem was to increase the number of inspectors. At the time of this investigation the airports were hiring 50,000 new federal screeners to check passengers. However, only the tiniest percentage of containers, ships, trucks, and trains that enter the United States each day are subject to examination. Therefore, a weapon of mass destruction could be hidden among this cargo. Should the maritime or surface elements of America's global transportation system be used as a weapon-delivery device, the response would almost certainly be to shut the system down at an enormous cost to the economies of the United States and its trade partners. (Gary Hart and Warren B. Rudman, 2002)

Because of the costs and the number of inspectors needed, it is impossible to inspect all cargo before it enters the country, when it enters the country, and as it travels throughout the country. Even if it were possible, the delays in delivery would be intolerable. Therefore, an efficient process must be established whereby the USDOT can have a reasonable level of confidence that contraband has not passed through the inspection system. There are major obstacles to this process:

a. High cost of employing a large number of inspectors.
b. High cost of purchasing and maintaining sophisticated inspection equipment.
c. Long delays in delivery due to involved inspection techniques
d. Delays due to false positive signals from measuring equipment

Added to the above problems are the costs associated with training inspectors in the use of the new measuring equipment, and in the case of sniffing dogs, the cost of purchasing and maintaining them. The benefits and disadvantages of using sniffing dogs will be discussed in a later section.

As can be seen from the above, the major obstacle is cost. As in all finances, costs are managed in two ways, i.e., the elimination of waste or the increase in revenue. Elimination of waste is always desired, but because of the seriousness and scope of the problem, we can expect revenues to increase. The American public realizes that there are going to be significant costs associated with the protection of this country. However, even with large increases in funding, the problems will not be solved. While every single piece of cargo entering the country could theoretically be inspected, all trade would essentially stop. Given all this, then what is the answer?

The answer is to increase funding significantly for new technology to develop small, portable, non-intrusive, sensitive, low-cost inspection instrumentation. This would be a major undertaking, but the benefits would be worth it. It would allow effective inspections without significantly affecting the free flow of commerce.

There are over 40 departments of the United States government responsible for border inspections. However, no one agency searches specifically for explosives. (Conversation with a representative of Customs Service, 2003) The creation of the new Homeland Defense Department will attempt to bring these agencies together. In a memorandum concerning domestic preparedness, prior to the formation of the Department of Homeland Defense, Director Tom Ridge said the following. "It [the Department of Homeland Security] would assume responsibility for operational assets of the Coast Guard, Customs Service, Immigration and Naturalization Service and Border Patrol, the Animal and Plant Health Inspection Service of the Department of Agriculture, and the recently created Transportation Security Administration -

allowing a single government entity to manage entry into the United States." (Memorandum, Homeland Security 2001)

Methods of Detection

Aside from physical inspection by government agents, inspections are done using fixed instrumentation, portable instrumentation, and sniffing dogs. Depending on the particular situation, one or more of these techniques are used. When possible, a pre-screening analysis is used to determine cargo more likely to contain contraband.

Detection Instrumentation

There are many instruments available to detect explosives. Some are very large, sophisticated, and expensive, while others are smaller, but less sensitive. The big problem with instrumentation to detect explosives is that the preferred external sensitivity is usually achieved only in measurement laboratories. There are efforts underway to reduce the size of laboratory instrumentation to facilitate its use in the field. Also, new instrumentation is entering the market that is essentially laboratory technology reduced in size and made more rugged for field use. However, there is often a reduction in sensitivity and these instruments are usually too expensive to enjoy wide use.

There are many ways that inspections are conducted to detect explosives. Some of the more common techniques are:

- Detection of particulates on explosives
- Detection of particulates on concealment surfaces
- Vapor detection on dust
- Testing of samples wiped from packages
- Vapor detection of taggants placed in explosives
- Vapor detection of volatile explosive vapors
- Vapor detection of chemicals used for explosives

Except for the last three techniques, it is necessary to take samples from the suspected area and place these samples in a measuring instrument. For example, most explosives and narcotic substances do not have strong vapor presence and in the real world are very difficult to detect by vapor. Therefore, the most reliable collection and analysis method for those substances is particle collection. (USA Today 2001) This investigation will not deal with these techniques but will rather concentrate on examining the detection of chemical vapors. If vapor detection instrumentation can become much more sensitive, it may be able detect all but the most carefully packaged explosives.

Sniffing Dogs

The most effective and efficient method of detecting explosives in current use is a sniffing dog. Although new sensitive instrumentation is being developed, the government has no plans to replace sniffing dogs for detecting explosives. There are many advantages and disadvantages to using dogs and these will be discussed later. One of the more important advantages is explained by Mike Herstik, who trains dogs for military and law-enforcement clients. "A dog can go into an area and lead you to where the odor is coming from. Two canine teams could search a 20,000-seat arena in an hour and a half, while it might take a full day for 30 people with trace detectors to examine the same area." (USA Today 2001)

Recent studies have shown that sniffing dogs do not just react to a particular chemical smell, but to a combination of many smells that make up an explosive or narcotic. They are even able to ignore smells that are not related to the targeted chemical. Dogs that are trained to detect explosives will recognize a chemical signature. However, depending on their training (in a laboratory or in the field) the results will vary greatly. (Kenneth G. Furton and Lawrence J. Meyers 2001) For instrumentation to compete with dogs, it must be able to identify a particular pattern of chemicals (spectrum) mixed with background chemicals.

New Technology

Although new technology to detect explosives and other contraband is continuously being developed, it has been focused mainly on downsizing laboratory measurement instrumentation for use in the field. The most exciting new technologies are being developed in the fields of microelectronics and micromachining.

One example of new technology is a low-cost, portable device that can detect chemical and biological agents. It is being developed by the Georgia Tech Research Institute (GTRI), Atlanta, GA. GTRI researchers are developing an integrated-optic sensor housed on a 1 x 2 centimeter chip that could be produced for $200 to $300 per unit. The basis of this detection and identification is changes in the speed of light (referred to as phase shifts) which are analyzed with signal processing software incorporated into the sensor system. (Georgia Tech Research Institute Web Page 2003)

Another solid-state technology for detecting chemicals is the development of chemiresistors. Using dispersions of conductive materials, such as carbon and non-conductive chemoselective polymers, gas sensors based on conductimetric techniques (Gardner *et al.* 1998, Hatfield *et al.* 1994) are fabricated. In the correct ratio, the polymer/carbon composite becomes conductive and its resistance changes when exposed to different vapors. These types of chemical sensors are simple in concept and operation. (Pique *et al.* 2003)

It is the author's opinion that the most important technology under investigation today is in the area of micromachined cantilevers. Tiny microcantilevers are coated with polymers that can adsorb various chemicals. As the chemicals are collected the microcantilever's mass properties change and these changes are detected with optical and electrical measurements. The importance of this technology is that it provides sensitivity much greater than that of sniffing dogs and can detect a wide range of organic and inorganic chemicals. This technology will be discussed in detail later in this report.

Local Need for Explosives Detectors

While the detection of explosives is an important function of the USDOT and other government inspectors, there is also a need for this capability to be available at a local level. There are thousands of First Responders and local police that need explosive detection equipment but do not have it. According to David G. Boyd, Director of the Office of Science & Technology of the National Institute of Justice, Washington, DC, "In case of a bomb threat, the first response usually has to come from local authorities, such as the local police department. However, these local units are the least trained, least funded, and least equipped of all law enforcement forces when it comes to dealing with bombs.

The ideal equipment for local bomb squads and first responders should cost no more than $10 and be so small that it can be worn like a badge, on a belt, or stuffed in a pocket. It should be so reliable that it never misses the real thing and only false alarms once or twice a year" (Roth 1997)

This ideal technology is a long way from being realized, but as larger government organizations invest in new detection technology, the cost of a unit will decrease thus allowing more capability to come to local organizations.

Inspection at Different Locations

Inspection of cargo arriving in the United States and traveling within the country is a staggering effort. The areas of inspection can be listed as follows:

a. Ships arriving from other countries
b. Ships and boats traveling to different ports within the country
c. Airplanes, both in the country and inter-country
d. Rail, both in the country and inter-country
e. Trucking, both in the country and inter-country

Packages shipped by mail are inspected by the US Postal Service.

Inspecting Ships Before Entering a Port

The first line of defense is to detect contraband explosives before they enter a port. However, due to the large number of ships arriving every day and the limited resources of the Coast Guard, this has to be done selectively.

The key to successful searches is screening. While every ship is screened, based on profiling criteria, very few ships are actually searched. This again is due to limited resources. To screen these shipments the Commerce Department has established a Three-Tier Program that attempts to collect information about shipments prior to their arrival in the United States. But even this approach has its limitations. A review of the program was done at three foreign ports that have implemented the program. The officials found that, "….the Three Tier Targeting Program had two operational problems that contributed to their loss of confidence in the program's ability to distinguish high- from low-risk shipments: (1) there was little information available in any database for researching foreign manufacturers; and (2) local officials doubted the reliability of the designations, citing some examples of narcotics seizures from shipments designated as “low-risk”, and the lack of a significant number of seizures from shipments designated as “high-risk”.(GAO/GGD-98-175 1998)

Another problem with attempting to stop smuggling at sea is that the smugglers constantly revise their methods to avoid detection. According to the Customs’ Strategic Plan: Fiscal Years 1997-2002, drug smugglers have moved from (1) using small planes and fast boats to smuggle drugs into the Southeastern United States in the early 1980’s, to (2) using commercial cargo and international carriers in the mid- to late-1980’s, and (3) exploiting the Southwest border in the 1990’s. Customs performs its mission with a workforce of about 19,000 personnel. (GAO/GGD-98-175 1998)

To make the search of ships more effective, U.S. Customs has instituted a program to pre-screen cargo at foreign ports. Recently, the governments of Canada, the Netherlands, Belgium, France, and Singapore have agreed to participate in the CSI [Container Security Initiative] and allow U.S. Customs inspectors to be placed at seaports in their nations to pre-screen U.S.-bound sea cargo. U.S. Customs inspectors are already in place at the Canadian seaports of Montreal, Halifax, and Vancouver. (Boyd 2002)

The heavy emphasis on pre-screening is due to the limited resources available to inspect all cargo. If instrumentation could be developed that would allow all cargo to be non-intrusively inspected with a high degree of accuracy, smuggling of explosives would come to a virtual halt.

Inspecting at Ports

A major concern for the country’s security is centered around the vast number of cargo ships that bring containers to this country. Because of the large size of these containers, it is possible to conceal a substantial amount of explosives for future use, or worse, to damage a port. Robert Bonner, Commissioner, U.S. Customs Service, in August 26, 2002, has said, “There is virtually no security for what is the primary system to transport global trade. The consequence of a terrorist incident using a container would be profound. … If terrorists used a sea container to conceal a weapon of mass destruction and detonated it on arrival at a port, the impact on global trade and the global economy could be immediate and devastating—all nations would be affected. No container ships would be allowed to unload at U.S. ports after such an event.(Gary Hart and Warren B. Rudman, 2002).

It is obvious from the above statement that the United States faces a daunting problem. There is a vast amount of cargo entering the country from all over the world and, because of limited inspection capability, only a small portion of the cargo can be inspected. It is currently believed that only two percent of the sea containers entering the country are inspected. This is totally unacceptable. However, the U.S. Customs Service disputes this assertion. Their answer is, “Some reports have stated that the U.S. Customs Service inspects only 2 percent of the 5.7 million sea containers entering the country each year. The two-percent figure erroneously implies that 98 percent of sea containers receive no attention or security at all from Customs.

U.S. Customs thoroughly screens and examines 100% of the shipments that pose a risk to our country and we are doing that today. Our goal is to screen these shipments before they depart for the United States whenever possible." (Customs.gov 2003) This statement refers to screening. This is different from inspection. By carefully choosing which containers to inspect, the effectiveness of the inspection is improved, but the fact remains that most cargo is not inspected.

The first choice of inspection is the use of non-intrusive technology. This is because physical inspections are time consuming and require the use of many inspectors. U.S. Customs inspectors use full-truck gamma ray and x-ray machines to scan the contents of containers. These units can scan the interior of a full-size 40-foot container in under a minute. Specially trained dogs check for traces of narcotics, currency, and explosives. Inspectors use personal radiation detectors to scan for signs of radioactive materials. Inspectors also use such special high-tech tools as densitometers and fiber-optic scopes to peer inside suspicious containers. The arsenal of inspection tools is expanding daily. In 2003, for example, Customs hopes to have a total of 8,500 radiation pagers and 150 large-scale X-ray and gamma ray systems in place. Other systems are being bolstered as well. Finally, if necessary, containers are opened and unloaded for a lengthy, more thorough carton-by-carton inspection. (Boyd 2002, Customs.gov 2003)

Inspecting Borders

Border inspections are probably the most challenging of all. Thousands of cars, trucks, and people cross into the United States every day, making it virtually impossible to inspect all vehicles and people. Inspections are done using visual means, instrumentation, and sniffing dogs. However, even with these tools, inspections are performed on only a very small number of people and vehicles.

Inspections are done by random searches and by identifying suspicious vehicles and people. Even when sniffing dogs are used, it is not always possible to have the right dog at the right place. Dogs are trained to either detect drugs, explosives, or currency. Because of their specialization, a dog trained to detect drugs will not detect explosives. If highly sensitive instrumentation is used it may be possible to detect all three, by either non-intrusive means ("seeing" into the vehicle) or analyzing swabs that have been swiped on luggage or other areas.

There is also another problem with searching for explosives. That is, explosives are rarely found. Smuggling of drugs and currency is much more prevalent. Therefore, it is difficult to justify the development of instrumentation that will only detect explosives. What is needed is instrumentation that can analyze all odors and identify drugs, currency, and explosives.

In general, if one wants to take the risk, it is not very difficult to transport explosives across the U.S. border.

Inspecting at Airports

Because of the World Trade Center attack, airport inspections have been significantly increased. New inspectors have been hired and new inspection technology is being put into place. Inspection takes place both at the gates, where passengers are screened and searched, and in the baggage areas where the luggage and packages are inspected. Inspection of baggage requires sophisticated measuring equipment and, in some cases, sniffing dogs.

It was the author's intention to publish current information concerning the effectiveness of airlines in identifying contraband in luggage or carried by passengers. This was not possible because the detection rates are sensitive information protected under DOT regulation 14 CFR Part 191. These figures are only available to appropriate personnel and they cannot be published.

Inspecting Railroads and Trucking

There is concern that explosives will be moved throughout the country by trucks and by rail, but the treatment of this subject is very complex and considered beyond the scope of this study.

Section 3
Explosives

Introduction

The detection of explosives is a very complicated task. Explosives are composed of many chemicals with different volatilities. Therefore, only a part of the explosive might be detected. This becomes an additional problem when some chemicals that are major components in explosives also have legitimate commercial use. Therefore, the detection of a particular chemical does not necessarily indicate the presence of explosives.

Furton and Myers (2001) have compiled a list of typical mixtures of organic high-explosive chemicals, shown in Table 3-1. These are found in both the military and commercial sectors.

Table 3-1 Chemical composition of commonly used explosives (Kenneth G. Furton and Lawrence J. Meyers 2001)

Commonly Used Explosives	Main Compositions
C-2 (Aitkin 1995)	RDX+TNT+DNT+NC+MNT
C-3 (Aitkin 1995)	RDX+TNT+DNT+Tetryl+NC
C-4 (Aitkin 1995)	RDX+Polyisobutylene+Fuel oil
Cyclotol (Aitkin 1995)	RDX+TNT
DBX (Aitkin 1995)	TNT+RDX+AN+AL
HTA-3 (Aitkin 1995)	HMX+TNT+AL
Pentolite (Aitkin 1995)	PETN+TNT
PTX-1 (Aitkin 1995)	RDX+TNT+Tetryl
PTX-2 (Aitkin 1995)	RDX+TNT+PETN
Tetryol (Aitkin 1995)	TNT+Tetryl
Dynamite (Fytche *et al.* 1992)	NG+NC+SN
Red Diamond (Kenneth G. Furton and Lawrence J. Meyers 2001)	NG+EGDN+SN+AN+Chalk+NaCl

Furton and Myers (2001) have also compiled a table of major chemicals found in explosives. Their results are given in Table 3-2.

Table 3-2 Common major chemicals found in explosives and explosive mixtures (Kenneth G. Furton and Lawrence J. Meyers 2001)

Compound Class	Example	Symbol	Commonly found in the following
Aliphatic Nitro	Nitromethane		
	Hydrazine		Rocket fuel and liquid component of two-part explosive
Aromatic nitro (C-NO$_2$)	Nitrobenzene	NB	
	Nitrotoluene	NT	
	Dinitrobenzene	DNB	
	Dinitrotoluene	DNT	
	Amino-dinitrotoluene	A-DNT	
	Trinitrobenzene	TNB	
	2,4,6-trinitrotoluene	TNT	Composition B with equal part RDX, Pentolite with equal part PETN
	2,4-dinitrotoluene	DNT	
	picric acid		
Nitrate ester (C-O-NO$_2$)	Methyl nitrate		
	Nitroglycerin	NG	Certain dynamites, pharmaceutical
	Ethyl glycol dinitrate	EGDN	Some dynamites
	Diethylene glycol dinitrate	DEGDN	
		MTN	
	Pentaerythitol tetranitrate	PETN	Detonating cord, Detasheet (Flex-X military name), Semtex with RDX
	Nitrocellulose		“guncotton”’main component of single-based smokeless powder
	Nitrocellulose and NG		Double-based smokeless powder
	Nitrocellulose, NG and nitroguanidine		triple-based smokeless powder
Nitramines (C-N-NO$_2$)	Methylamine nitrate		
	Tetranitro-N-methyaniline	Tetrl	
	Trinitro-triazacylohexane (cyclonite)	RDX	C-4, tetrytol-military dynamite w/TNT
	Tetranitro-tetrazacylooctane (octogen)	HMX	Her Majesty’s Explosive
Acid salts (NH$_4^+$)	Ammonium nitrate		ANFO with fuel oil, nitro-carbo-nitrates (NCN) w/oil
	Ammonium perchlorate		
	Potassium nitrate		Black powder with charcoal and sulfur
Primary Explosives	Lead azide		
	Lead styphnate		Blasting caps
	Mercury fulminate		
	Tetramino nitrate		
	Hexamethylene triperoxide diamine	HMTD	
	Triacetone triperoxide	TATP	

The tables show that there are many chemicals that go into the manufacturing of explosives. This has implications for the detection of explosives. For measuring instruments or sniffing dogs to positively identify explosives, they must be able to identify a suite of chemicals in prescribed concentrations. Even when this can be done, the situation is further complicated by the fact that contraband is usually sealed in some fashion to avoid detection. This produces a major change in the normal chemical signature, assuming there is anything detected at all.

TATP (Triacetonetriperoxide) is a sensitive and relatively easily produced high explosive used primarily by terrorist organizations. Israel has seen an increase in its use in terrorist bombings, and due to its lack of solid by-products upon detonation, TATP has been difficult to identify in post-explosion analysis. (Tamiri 1998, Byall 2001)

HMTD (Hexamethylenetriperoxidediamine) is another sensitive high explosive that has occasionally been used by terrorist groups. The Algerian terrorist arrested upon entry to the US from Canada prior to the millennium celebration was found to possess a quantity of HMTD, in addition to RDX (trinitrotrianacyclohexane), EGDN (ethyl glycol dinitrate) and over 100 pounds of urea. (Byall 2001)

Urea nitrate, the suspected explosive in the 1993 World Trade Center bombing, is another explosive made from easily obtained starting materials.

Although a number of common chemicals could be used in illegal bombings, the common explosive chemical likely to be of greatest threat is ammonium nitrate. This is based on availability and accessibility, ease of bomb making, cost, and history of prior use, indicating that AN (ammonium nitrate) is by far the most obvious material for making large bombs. (National Academy Press 1998)

Because ammonium nitrate is the material most likely to be used in highly destructive bombings, it has the highest priority for control despite the extreme complexity of its distribution system in the United States and its singular importance for the mining, commercial explosives, and agricultural industries. Other chemicals of concern are sodium nitrate, potassium nitrate, nitromethane, concentrated nitric acid, concentrated hydrogen peroxide, sodium chlorate, potassium chlorate, and potassium perchlorate.

Many high explosives used in bombings are stolen. Common targets of theft are believed to be small end users, many of whom may not have the legally required magazines for storing high explosives securely. Explosives stolen from these users are available for use as detonators, boosters, or as the main charge in improvised bombs.

It is not feasible to control all possible chemical precursors to explosives. There has been a call to control ammonium nitrate, sodium nitrate, potassium nitrate, nitromethane, concentrated nitric acid, concentrated hydrogen peroxide, sodium chlorate, potassium chlorate, and potassium perchlorate. Urea and acetone also meet the criteria for control but are adequately controlled if access to nitric acid and hydrogen peroxide is limited. This list of chemicals may change over time if the materials preferred for bomb making change.

Taggants

With advanced analytical instrumentation, detection of trace amount of explosives is fairly easy under laboratory conditions; however, this kind of sensitivity is difficult to achieve in the field. Just a small amount (a few pounds) of concealed plastic or sheet explosives is all that is required to destroy an airliner. (National Academy Press 1998) The problem in the field is that illegal explosives are sealed and wrapped to avoid detection. Also, some of these chemicals have low volatility which makes them even more difficult to detect.

To address the volatility issue, taggants are added to explosives. Taggants are very volatile chemicals that are added to explosives to aid in detection. Taggants can also by used to identify the origin of the explosives. However, terrorists know about the existence of tangents and have illegal access to unmarked explosives. In fact, inspectors know that terrorists will avoid explosives with taggants.

Because of the difficulty in detecting explosives that do not contain taggants, in 1998 the Committee on Marking, Rendering Inert, and Licensing of Explosive Materials Board on Chemical Sciences and Technology, Commission on Physical Sciences, Mathematics, and Applications, National Research Council, recommended that there be a strategic national investment focused on the detection of unmarked explosives. They also recommended deploying detection equipment based on existing technology to other critical sectors beyond airports.

The use of taggants is not without problems. Many of the explosives used by terrorists have been stolen from legitimate companies. It would seem that when these explosives are used in terrorist acts, the source of the explosives would be determined and vital information will be obtained. However, governmental record keeping is very poor. For example, the annual bombing statistics reported by the Federal Bureau of Investigation and by the Bureau of Alcohol, Tobacco, and Firearms differ somewhat. In addition, neither agency maintains complete records on the frequency of illegal use of common explosive chemicals, and neither has definitive, statistically sound information on sources of stolen commercial explosives used in bombings. (National Academy Press 1998)

Following the Pan Am 103 bombing, the International Civil Aviation Organization (ICAO) worked to have plastic, sheet and flexible explosives marked with a detectable taggant. An ad-hoc study group evaluated many marking agents, and in 1998 the ICAO Convention went into effect. (Stancl and Mostak 1998) Of the several marking agents approved by the ICAO Convention, DMNB (2,3-dimethyl 2,3-dinitrobutane) is the most favored and has been the subject of several published reports. (Byall 2001)

Ion mobility spectrometry (IMS) has become the most widely used detection system for aviation. The primary method involves the collection of explosives particles on a swab by vacuuming or swiping people or hand-carried items. The IMS system will create a chemical spectrum that can be analyzed. This method has civil rights implications because people must be physically contacted. Also, collection can be complicated by contaminants and the process slows down the movement of people. Vapor detection of the taggant DMNB in C4 explosives was investigated using a hand-held IMS. The results concluded that detection of DMNB vapor is a practical method for detecting tagged explosives. (Ewing and Miller 2001)

While taggants are an important part of detecting explosives and for identifying their source before and after their use, they are only a small solution to a major problem. Of course, it is preferable to have explosives entering the country contain taggants because they are easier to detect. For example, explosives such as RDX and PETN have low vapor pressures. However, terrorists will avoid explosives that contain taggents for obvious reasons.

Section 4
Detection Instrumentation

While detection of explosives or chemical components of explosives is important, it is sometimes crucial to identify the nature of the explosive. This provides guidance to the organization that has responsibility for disposing of the explosives. The first order of business is to detect traces of hidden explosives. This is done using vapor detection, chemical testing, or sniffing dogs. However, these tests are considered as "presumptive" and not as absolute identification. Detection consists of an alert that indicates a "target-type material" such as an explosive or a "group-type" has been found. Identification is the incorporation of the results of additional confirmatory testing beyond the initial tests. Identification is thus the independent confirmation of the preliminary results. (Byall 2001)

As previously stated, there are major problems with detecting and identifying explosives that are hidden in cargo. Here is a list of just a few of them:

- If the explosives are wrapped well enough, the only way they can be detected is by means of x-ray and other non-intrusive equipment.
- If trace amounts of explosive chemicals are present, they may be present on dust or packaging surfaces.
- To examine dust or surfaces requires taking swab samples and sophisticated measurement equipment.
- If vapor is detectable, it only provides information about one or more components of possible explosives.
- If all the components of the explosive can be sensed, it will require equipment that can perform spectral analysis. Dogs can provide a general identification along with detection. That is, an explosives trained dog can detect explosives, even if the exact kind is unknown.

Therefore, depending on the situation, there are many methods for detecting and identifying explosives. However, there is a problem that the most accurate methods of detecting and identifying explosives require either laboratory analysis or portable versions of laboratory equipment. In most cases, the analysis is not quick enough to examine a steady stream of cargo or luggage. There are some portable systems in use, but they usually lack the sensitivity of laboratory equipment. Their benefit is to rapidly isolate potential contraband.

Some of the more sophisticated instrumentation is mainly used to determine the nature of an explosive after the fact. Residue from the site of the explosion is examined to determine the type of explosive used.

The following is a list of instrumentation used in the laboratory and sometimes in the field to detect and analyze explosives:

- Thin Layer Chromatography: For a variety of reasons, this technology remains attractive both in the laboratory and in the field. One reason is that, it can be used inexpensively and readily to perform analysis at a scene. For example, it can demonstrate explosive product contamination of soil at a site with greater validity than that offered by other simple presumptive tests. (Nam *et al.* 2000, Mares *et al.* 1998)

- Raman Spectroscopy: Raman spectroscopy has always had potential for explosives analysis, but its application was severely limited by the instrumentation available. The Raman effect is inherently weak, but by using UV-excited resonance Raman band intensities are increased and allow identification of explosive species in complex mixtures. (Sands et al. 1998) It would be a very valuable instrument for field use if it could be made portable. (Byall 2001)

- Ion Mobility Spectrometry: With clean samples, rapid and sensitive examinations can be done, but sensitivity declines with dirty or complex samples. (Phillips 1999) The Royal Canadian Mounted Police uses this instrument at bombing scenes to rapidly screen those exhibits that will be further examined in the laboratory, and also to screen work areas, tools and equipment that are involved with explosive processing. (Byall 2001, Norman *et al.* 1998)

- Gas Chromatograpy (GC): This technique is widely used to detect trace amounts of organic explosives. It has the ability to examine thermally labile explosives such as nitrate esters (e.g. nitroglycerine) and nitramines (e.g. RDX). (Byall 2001) There is considerable variation in detectors used with the gas chromatograph, but the major ones used for explosive analysis are:

  - The electron capture detector (ECD)
  - The thermal energy analyzer (TEA)
  - The mass spectrometer (MS)

Electron capture detectors have good sensitivity and have been used for three decades. Walsh describes the examination of soil, contaminated with TNT, DNT (dinitrotoluene), RDX and HMX ("octogen", tetranitrotetrazacylooctane, sometimes called "Her Majesty's Explosive"), using GC/ECD with a deactivated port liner and wide bore capillary column, which detected these explosives at levels of less than one microgram/kilogram of soil. (Byall 2001, Walsh 2001)

The TEA detector, which may be used with both gas and liquid chromatography systems, is based on infrared chemiluminescence and has excellent sensitivity for nitro and nitroso compounds that pyrolyze to produce NO or NOx. It has good selectivity and has become a standard method in a number of large laboratories. The Northern Ireland laboratory found GC/TEA to be more sensitive and selective than GC/ECD. (Irwin 1999) Using packed capillary columns and carbon dioxide as the mobile phase, GC/TEA was used to detect nitroglycerine in sub-microgram/mL concentrations. (Bowerbank *et al.* 2000)

The EGIS 3000 portable explosives detector, incorporating a vacuum sampler, high speed GC and chemiluminescence (TEA) detector is a fast, sensitive and selective instrument used in both laboratory and field situations. (Elias *et al.* 1998, Bromberg *et al.* 1998, Ornath *et al.* 1998) It is comparable to a conventional laboratory GC/TEA system. (Byall 2001)

Mass Spectrometry: This technique has been used for identification of low levels of explosives for many years, but its applications continue to increase with new spectrometer designs and improved interfaces with either gas or liquid chromatographs. The Israel National Police Laboratory reports detection levels of 1-50 ng for nitroaromatics, NG (nitroglycerin) and EGDN, and higher detection levels for PETN (pentaerythitol tetranitrate), RDX and tetryl using GC/MS. (Tamiri 1999) High

- Performance Liquid Chromatography (HPLC): This instrument coupled with mass spectrometry continues to be a useful technique, especially for thermally sensitive explosives. HPLC/MS is used as a screening technique prior to GC/TEA, or a confirmation for GC/TEA results.

Inorganic explosives are widely encountered in many countries, usually as the filler in a pipe, tube, bottle or other container. For example, during the five year period 1993 to 1997 ATF reported over 10,000 bombings or attempted bombings, with over one-third of these being pipe bombs. (Bureau of Alcohol, Tobacco and Firearms 1998) In spite of the number of these devices, new methodologies for the examination of low explosives have received relatively little attention. Common inorganic explosives include propellants such as conventional or modified black powder, pyrotechnic mixtures and a variety of improvised compositions. Water gel, slurry and ANFO (ammonium nitrate plus fuel oil) explosives may also be considered in the inorganic category because they are primarily based on ammonium or other inorganic nitrates. (Byall 2001)

For inorganic explosives, ion chromatography (IC) and more recently capillary electrophoresis (CE) are used to provide sensitive and specific information on the by-products that remain from the rapid intense-heat burning of these materials. (McCord 2000) Aqueous extracts of debris are analyzed by capillary electrophoresis, allowing separation of chloride, chlorate, nitrate, nitrite and perchlorate anions. The advantages of CE are ease of sample preparation, micro-sampling capabilities and rapid analysis of both anions and cations. (Miller et al. 2001, Rey 1999)

Pyrotechnic residues may be examined by a scanning electron microscope coupled with an energy dispersive x-ray analyzer (SEM/EDX). This is a rapid screening technique for unknown bulk residues from improvised compositions, and provides an elemental profile of the residue, with further analysis being done by more sophisticated instrumentation, e.g. FTIR (Fast Fourier Transform Infrared Spectroscopy). (Byall 2001, Phillips 2000)

A novel method for identifying inorganic components in post-blast debris involves placing the particles on filter paper and placing one end of the paper in a color test solution. As the solution rises it reacts with certain particles to produce a stain under the particle. The particle is then removed and examined further by GC/MS, FTIR, or SEM/EDX. (Byall 2001, Glattstein et al. 1998)

At the present time, the CTX 5000, made by InVision Technologies, Foster City, CA, is the inspection system of choice at airports. It is based on computer tomography and costs about

$900K per unit. The FAA says it is doing an adequate job in screening checked-in luggage for explosives. (Roth 1997)

Trace detectors in current use are conventional mass spectrometry, ion mobility spectrometry, and sniffing dogs.

Section 5
Sniffing Dogs

Introduction

At this time, the most important and versatile chemical detector is a sniffing dog. While a dog has many limitations, its combination of sensitivity and flexibility is not easily matched. There is an ongoing effort, both in government and in industry, to develop portable sensor systems that will emulate and exceed the capabilities of sniffing dogs. The following is an analysis of sniffing dogs.

Capability of Sniffing Dogs

The ability of dogs to detect and identify odors is truly amazing. They are able to perform these tasks due to the specialized construction of their noses. Scientists have estimated that a dog's nose has about 220 million mucus-coated olfactory receptors, roughly 40 times as many as humans. (Derr 2002) Nerve cells in the epithelium, sensitive tissue lining the nasal cavity, are capable of recognizing and responding to an extraordinarily large repertoire of stimuli - some 10,000 chemical odors. They accomplish this feat, at least in part, with numerous mucus-coated fibers, which contain the receptor proteins. Those receptors recognize different chemicals and transmit that information to the brain, which perceives the chemicals as an odor. The brain is essentially saying something like, “I'm seeing activity in positions 1, 15, and 54 of the olfactory bulb, which correspond to odorant receptors 1, 15, and 54, so that must be jasmine.” Most odors consist of mixtures of odorant molecules. Therefore, other odors would be identified by different combinations.

Accuracy

Dogs have been used as chemical detectors throughout the history of man. Starting with tracking game, dogs have been used in a variety of tasks, including tracking people and detecting buried people and bodies. In World War II dogs were used to detect explosives. Recently, the civilian use of dogs for the detection of drugs and explosives has become more widespread. There has been much written about the benefits and capabilities of sniffing dogs, but much of the information is not based on scientific studies. Most of the work is reported in trade publications, books, manuals, and government reports.

Although there have not been many detailed scientific studies, there is enough information available to document that sniffing dogs have a very well developed sensitivity and a high degree of accuracy. This has been an important capability in the search for hidden explosives.

Furton and Myers (2001) have done a review of all the available literature and have scientifically evaluated the state-of-the-art of explosive detection. In the area of mine detection, Nolan and

Gravitte (1977) performed experiments using dogs to sniff for land mines and found their accuracy to be from 80 to 90 percent. Secret Service bomb dogs, considered among the best in the world, are retested weekly and must have an accuracy percentage in the upper 90's. (Derr 2002)

Another specific example of the reliability of explosive detection canines being repeatedly substantiated is at the Department of Defense program. This program has about 500 explosives detection canines worldwide and has a proficiency requirement of at least 95% detection rate for the targets (known explosive odor standards) and 5% or less nonproductive rate (alerts to distracter odors). (Furton and Meyers 2001, Hannum and Parameter 1998) Also, the North American Police Work Dog Association requires a minimum of 91.6% pass rate on target odors, including six different explosive odor classes and four or five different search areas. (Furton and Meyers 2001, N.A.P.W.D.A. 1998) So it can be seen that the accuracy of dogs in detecting explosives is very good.

The accuracy of sniffing dogs is so good that they generally meet or exceed the expected 90-95% confidence intervals used in forensic science for instrumental methods and legal conclusions requiring “beyond a reasonable doubt”. (Kenneth G. Furton and Lawrence J. Meyers 2001, Aitkin 1995) Although there is limited data available, the published proficiency and certification standards of government agencies and national certification organizations indicates that canines are tested to a level equivalent, if not superior, to instruments.

Sensitivity

There has been much written concerning the sensitivity of dogs to minute traces of chemicals. Auburn University, Alabama (website 2003), has been performing studies of the mechanisms used by sniffing dogs to detect odors. A sample of some of their results is given in Figure 5-1 that shows the sensitivity of sniffing dogs for various chemicals.

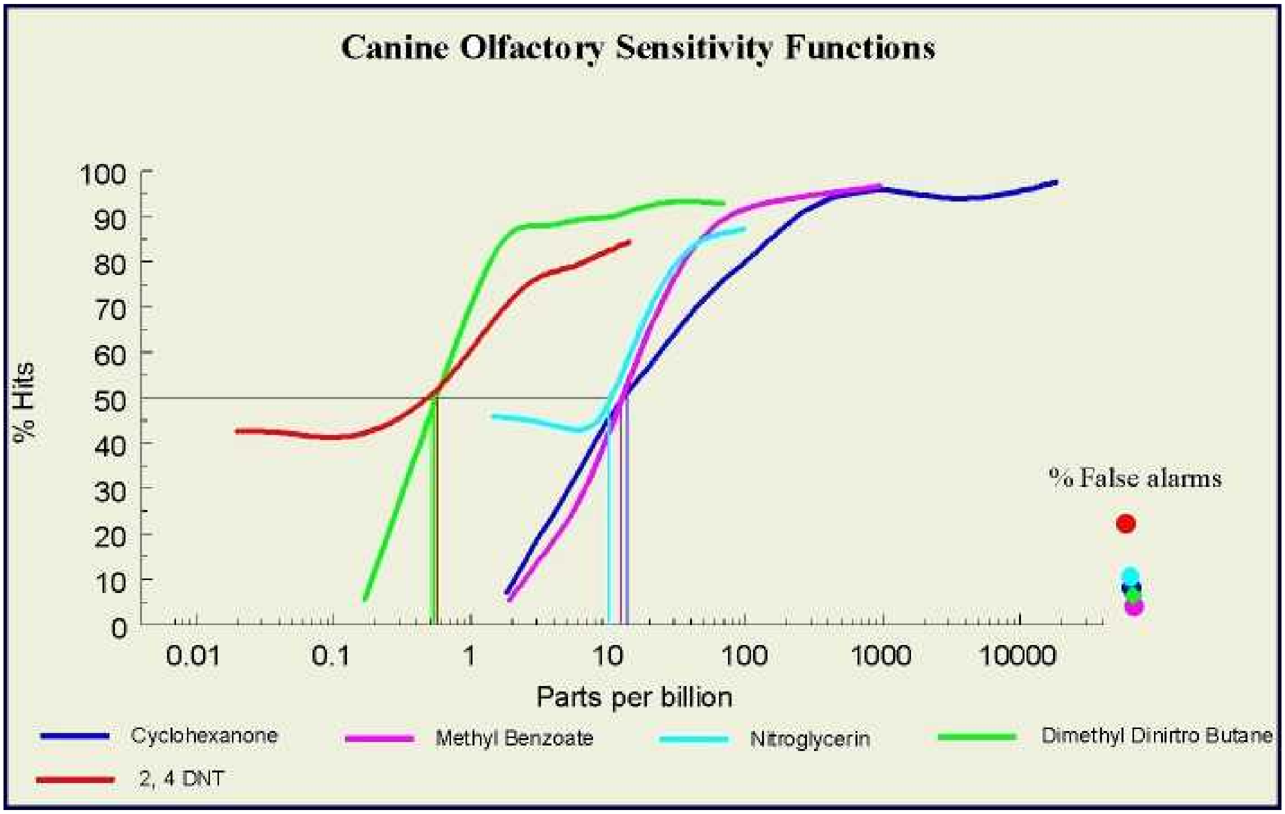

Figure 5-1. Canine olfactory sensitivity functions [Auburn University website 2003)]

This graph shows the average olfactory functions for dogs to a number of substances:

- Cyclohexanone is a vapor constituent of C-4 explosive
- Methyl benzoate is a degradation product and vapor constituent of cocaine hydrochloride
- Nitroglycerin is found in many explosive and propellant compounds
- Dimethyldinitrobutane butane is a detection taggant
- 2, 4 DNT is a vapor constituent of TNT explosive

Sensitivity is described in the graph by plotting the dog's detection (% hits) across a range of concentration (parts per billion) for each substance. The percent false alarms, which is the percentage of responses to a target lever when clean air was presented, is also displayed to further describe the accuracy of the dogs in detecting each substance.

Comparison With Instrumentation

Although it has been shown that dogs are highly reliable in detecting explosives, it is instructive to compare their accuracy to that of instrumentation. One scientific study on the reliability of one of the most commonly used portable ion mobility spectrometry instruments, the Ionscan (Barringer Instruments, Warren, NJ), showed 14 of 139 (10%) innocuous substances tested caused false positives when detecting controlled substances. (Kenneth G. Furton and Lawrence J. Meyers 2001, Fytche *et al.* 1992) In another study evaluating the utility of the Ionscan for the detection of trace explosive, evidence demonstrated the instrument registered a positive response on 12 of 17 (71%) post-blast fragments from improvised explosive devices. (Furton and Meyers 2001, Fetterolf and Clark 1993) Therefore, much work must be done before field instrumentation can reliably match that of sniffing dogs.

In conclusion, while the recorded accomplishments of sniffing dogs are impressive, they are basically the result of empirical studies and are not technically scientific. This is difficult due to the many behavioral factors that must be evaluated. These are, type and duration of search, alertness of the team, responsiveness of the dog to the handler, and the handler's skill in observing the behavior of the dog and interpreting those observations. However, because sniffing dogs can sustain an accuracy of 90 percent, they can compete favorably with modern measuring instruments.

Volatility Problems

For sniffing dogs to be trained, they must be exposed to explosives or the components that make up explosives. Table 5-2 of Section 3.0 shows a list of example chemicals that are potential training aids (also known as positive controls) used to train dogs to detect odors during operating conditions. However, in many cases, the major chemical component in explosive mixtures have very low vapor pressures or limited olfactory receptor response making them unlikely odor signature chemicals. (Kenneth G. Furton and Lawrence J. Meyers 2001)

The chemicals composing the scent of an explosive arise from the source by evaporation, sublimation, and mechanical disturbances causing particles of the source to be released into the atmosphere, often in an unpredictable fashion. Other problems arise from the fact that hidden explosives are frequently wrapped in plastic food wraps and metal foil to conceal the scent.

In theory, all explosives emit molecules in the form of a vapor at any temperature above absolute zero (-273.15 degrees C). These molecules move in all directions and eventually equilibrate throughout the enclosure to a vapor pressure which is characteristic of the substance. The value of this vapor pressure depends on the type of explosive and on the temperature. Therefore, in principle, if they are sensitive enough, detector dogs and explosive vapor detectors should be able to detect these explosives. In fact, there are generally other constituent chemicals present in explosive mixtures with substantially higher vapor pressures which dogs (and instruments) can use as odorant signatures. The equivalent vapor pressures of common explosives, particularly at low temperatures, can be extremely low.

There is a wide range of vapor pressures between various explosives. (Kenneth G. Furton and Lawrence J. Meyers 2001) For example, it is notable that there are seven orders of magnitude difference in the vapor pressure of EGDN and RDX. The very low vapor pressures of many explosives, including PETN, RDX, and HMX, make the detection of the parent molecule unlikely, particularly at room temperature.

Since explosive odors (as well as drugs, accelerants, and other items of interest) are generally not single chemicals, it is first necessary to determine what chemicals constitute the odorant signature. (Kenneth G. Furton and Lawrence J. Meyers 2001) This does not solve a problem but introduces a new one. For the sake of argument, let us assume that there is an explosive composed of five constituent chemicals. These chemicals will be present in different concentrations and each chemical will have a particular volatility. Barring any attempt to hide or mask the odors from this explosive, one can recognize the particular explosive by its chemical signature. This is determined by identifying the separate chemicals and their concentration in air. However, what happens when two of the constituent chemicals are not very volatile (also, the temperature may be very low)? In this case one might only detect three of the five constituents and have to surmise that explosives exist at all. This will be further complicated by smugglers taking great care in packaging.

Sometimes explosives are packaged in the presence of materials that have strong odors in order to mask the smell of the explosives. Dogs are very useful in this case because they have the advantage over current instrumental methods in their ability to detect contraband odors in the presence of significant extraneous odors. (Kenneth G. Furton and Lawrence J. Meyers 2001)

Limitations of Sniffing Dogs

Even though sniffing dogs are extremely useful for detecting explosives, they do have their limitations. A sniffing dog can cost thousands of dollars, requires a skilled handler, and requires continuous training and upkeep. Also, dogs get bored and cannot work long hours. Because of this, it is important that dogs be given a diversity of jobs. If bag after bag is continuously passing an inspection point, humans lose interest and so do dogs. (Roth 1997)

Recently, when bomb-sniffing dogs indicated the presence of explosives in the cars of three medical students bound for Miami, the authorities detained the men and closed a major thoroughfare across South Florida. No trace of explosives was found in their cars. (Derr 2002) Although this does not happen often, there are various reasons why this happens.

1. ***The dogs' handlers are excited.*** Experts on explosives detection say that when dogs' handlers are excited and stressed, the dogs may overreact and falsely suggest that explosives are present when they are not. False alerts are better than missing a live bomb, they say, but it is better for the dogs to be accurate. (Derr 2002)

2. ***The dog is looking for a reward.*** Dr. Meyers of Auburn University says, "Dogs want rewards, and so they will give false alerts to get them. Dogs lie. We know they do." (Derr 2002)

3. ***Explosive odors were present.*** While concerned about missed targets, many trainers and handlers deny that their dogs sound false alarms, and so they do not record them, especially if they occur in the field. They argue instead that the dog is picking up a faint trace of a substance that was once present, or that a handler caused the dog to err. (Derr 2002)

There are other limits on dogs' performance that are frequently overlooked. Dr. Meyers says that poor handlers alone, can cause dogs' vaunted accuracy rate of 85 percent to 95 percent to plummet to 60 percent. (Derr 2002) Handlers can create errors by pulling their dogs away from things they are investigating, by letting them search too long in a single place or by inciting the dog through some gesture, glance or emotion, even unconscious. Trainers say the message “travels right down the leash”. Another error that handlers can make is not checking whether the dog is sniffing. If the dog is panting, but not sniffing, the scent is not being registered. (Derr 2002)

Mainly for that reason, the few studies of dog performance that have been done suggest that dogs perform best off their leashes. Off-leash work is common in Europe, but for a variety of social and legal reasons, dogs are worked almost exclusively on-leash in the United States, says Dr. Paul Waggoner, interim director of the Canine and Detection Research Institute at Auburn. (Derr 2002)

Another factor that can affect the accuracy of detection is weather. Dry, hot weather can cause the mucus in the dog’s nose to dry out. Hot, humid weather brings early fatigue. Extreme cold kills scents, and the wind scatters them. (Derr 2002)

As can be seen from the above, dogs have a remarkable ability to detect minute odors and are important in performing inspections. However, they are only as good as their handlers and their training. But, even with these limitations, dogs appear to be the best combination of sensitivity, accuracy and flexibility.

Comparison of Sniffing Dogs to Sensing Instrumentation

Dogs and instrumentation both have their strengths and limitations. To consider the limitations of using sniffing dogs in the proper context, their capabilities and usefulness must be compared to current measuring equipment. A good comparison is given in Table 5-1. (Kenneth G. Furton and Lawrence J. Meyers 2001).

Table 5-1 General comparison between instrumental explosive detection devices and trained detector dogs. (Kenneth G. Furton and Lawrence J. Meyers 2001)

Aspect	Instrument	Canine
Duty cycle	24 hr/day theoretical)	~8 hr/day (20 min on/40 min break dependent on conditions
Calibration standards	Can be run simultaneously(i.e. chromatography based)	Run individually
I.D. of explosive	Presumptive I.D. possible (limited by selectivity factors)	Not trained to I.D. with different alerts
Operator/handler influence	Less of a factor	A potential factor
Environmental conditions	Less affected	May adversely affect (i.e. high temperature)
Instrument lifetime	Generally ~10 yrs	Generally 6-8 years
State of scientific knowledge	Relatively mature	Late emerging
Courtroom acceptance	Generally unchallenged	Sometimes challenged
Selectivity (vs. interferents)	Sometimes problematic	Very good
Overall speed of detection	Generally slower	Generally faster
Mobility	Limited at present	Very versatile
Integrated sampling system	Problematic/inefficient	Highly efficient
Scent to source	Difficult with present technology	Natural and quick
Intrusiveness	Variable (apprehensiveness not uncommon)	Often innocuous (breed dependent)
Initial cost	~$45,000	~$6000
Annual cost (exclude personnel)	~$4,000 (service contract)	~$2000 (vet and food bill)
Sensitivity	Very good/well known	Very good/few studies
Target chemical(s)	Parent explosive(s)/well studied	Odorant signatures/mostly unknown
Toxicological considerations	Minimal (operator may be affected at excessive levels)	Minimal (team may be affected at excessive levels)
Downtime	Varies with instrument, operator, and manufacturer	Varies with breed, handler, and medical condition
Instrument components	Varies with manufacturer (variable sampling, separation, detection, I.D. technology)	Varies with agency (variable breed, training, alert and reward systems)
Initial calibration	Generally performed by manufacturer (specifications vary by manufacturers)	Generally performed by supplier (specifications vary by supplier with minimum 6 weeks training)
Operator training	Typically a 40 hr course	Typically a 40 hr course minimum
Certifications	Varies, annually to biannually	Annually to biannually
Re-calibration	Daily to weekly	Daily to weekly
Scientific foundation	Electronics, computer science, analytical chemistry	Neurophysiology, behavioral psychology, analytical chemistry
Potential affects on performance	Electronics/mechanical	Disease conditions

A review of the above table indicates that there are no overwhelming differences between the use of dogs as detectors and the use of instruments. Each system has its advantages and disadvantages. However, the table compares the ability of dogs to the present technology. Because of this, the results can be misleading. While the present technology is being advanced in laboratories all over the world, only a slight improvement can be expected from dogs in the future.

Even though it looks like dogs will not be replaced in the near future, it is probable that dog will never be replaced. A previous law required that bomb-detection machines to be installed at all large U.S. airports by the end of 2002. Even if this has taken place, the FAA has no plans to retire its dogs. Prior to 2002, the FAA had 188 canine teams working full-time at 39 major airports across the country. The agency planned to add teams to 25 more airports in 2002 and 16 more in 2003 (Kenneth G Furton and Lawrence J. Meyers 2001).

Because of their versatility, sniffing dogs will always be valuable in searching for explosives. Dogs have the advantage of detecting explosive odors, and also to lead a handler to the source of the odor. This is very useful when a very large area is to be searched.

Army Working Dogs

To present a users perspective of the use of sniffing dogs, an interview was conducted with Captain Jack Rush, Kennelmaster of the Military Working Dog Branch, U.S. Army Redstone Arsenal, Alabama. This organization has several dogs that are trained to detect explosives and narcotics. Though these dogs are maintained by the Army at Redstone Arsenal, they are frequently employed by other agencies.

The following is a list of questions that were posed to Captain Rush, followed by his answers paraphrased. Although no direct quotes are included, every effort was made to be as accurate as possible.

1. ***What explosives can dogs detect?*** All sniffing dogs can pretty much detect the presence of all explosives. However, the response to a detected explosive will vary depending on how certain the dog is. The response must be interpreted by the handler who is intimately attuned to the dog's personality. The handler must also be able to recognize if the response is due to some sort of distraction, e.g., food.

2. ***Is it possible to place a decoy explosive so that when the dog detects it the search will end and the real explosives will not be detected?*** This will not happen because if anything is detected, the search will not end until the entire cargo is searched. This is a law enforcement decision rather than a dog-handler decision.

3. ***How do you treat false positive detections?*** Captain Rush believes that there is rarely a false positive detection. The dog is not looking for explosives, but a particular odor. If the dog detects the odor it means that a combination of smells is present. There could have been explosives in the container at one time or there might have been (or still be) chemicals that would be found in explosives. Fertilizers that contain nitrates can cause a dog to give a false positive. However, the dog is not wrong, it just was not explosives.

4. ***How good are sniffing dogs at detecting odors that have been masked?*** Criminals have attempted to mask explosives and narcotics smells with everything from coffee to baby's diapers. It is very difficult to do this since the dog is able to discriminate between what he is looking for and everything else. If what he is looking for is there, he will smell it while ignoring all the other odors. Captain Rush told of a case where a sniffing dog detected narcotics that were sealed in a drum of tar.

5. ***Can one dog be worked by more than one handler?*** This is an important question because detection instrumentation could be handled by more than one technician, assuming proper training. Military dogs are only assigned to one handler. In some cases, two dogs may be assigned to the same handler, but each dog has only one handler. This is because of the unique bond between the handler and the dog.

6. ***How easy is it for a dog to get distracted?*** New working dogs will tend to get distracted, however, fully trained dogs are rarely distracted. This is because their training consists of exposing them to strange environments, e.g., wooden floors, tile floors, rugs, elevators, escalators, groups of people, loud noises, etc. Eventually the dogs will ignore the surroundings and concentrate on the job.

7. ***How long can a dog work before he gets tired?*** Dogs can work for one or two hours before they need a break. However, as long as they get periodic breaks, they can work for long hours. When a dog looks for explosives it is not working, it is playing. The dog and the handler play a game. The handler “hides” the explosives and, if the dog can find where, he gets a reward. The dog is given “hints” by having the handler take him to various places where the explosives may be hidden. In this way, a game that keeps a dog happy results in stopping crime. Sometimes if the dog has been working for a long time without finding anything, the handler will “plant” something for the dog to find so that he does not get discouraged.

8. ***How often does the dog need to be retrained?*** Retraining take place once a week using real explosives.

9. ***At what age do you start a dog’s training?*** Dogs are started at 1 to 2 years old. It takes approximately 6 months to train a sniffing dog, but it will take years of experience before the dog and handler reach their peak.

10. ***Do dogs get too old to work?*** Dogs can work for many years, but if they develop physical problems, such as bad hips in German Shepherds, they can no longer go into confined or high areas.

11. ***What is the cost of a sniffing dog?*** The prices vary from \$6000-\$15,000. However, this is just the initial cost. There is upkeep of both the dog and the expense of the handler. Also, there is always the burden of continuous training.

12. ***How often do dogs miss detecting explosives?*** When this happens, it is almost always the fault of the handler. It may be that the handler did not place the dog in the proper position to sniff the suspected area. Also, sometimes the handler will not notice that the dog had his nose in position but had not yet sniffed. There are techniques that handlers must learn to be sure that the dog is in the right position to do the job. This is truly a team effort.

Section 6
Current Instrumentation

At this time there are many commercially available instruments for the detection of explosives and other contraband. The most popular instrument is the CTX 5000. Because of its high price, it is difficult to have this instrument widely distributed.

Although not as good as the more sophisticated laboratory equipment, there are some portable explosive detectors commercially available. A few are discussed below:

- Thermo-Redox Detector – manufactured by the P.W. Allen company of Tewdesbury, UK. It can detect both RDX and PETN. It is very light weight, weighing only 3 kilograms, and detects and locates a wide variety of explosive devices including organonitrate and plastic based explosives.

- M600P Contraband Detector – manufactured by The Mistral Group, Bethesda, MD. This instrument can detect contraband such as drugs, explosives, weapons, currency, etc. It uses sensitive microwave energy to detect differences in density. The depth of penetration is about 4 ft in air and is correspondingly less depending on the dielectric properties of the materials being tested. For example, for a bale of wool the depth is about 30 inches and for a water slurry, 6 inches.

- EVD-3000 Hand-Held Explosives Detector – manufactured by Intelligent Detection Systems (IDS), Ottawa, Canada. This hand-held explosives detector is designed for search applications that require portability and quick detection. It detects traces of both particulates and vapors (for commercial and military explosives, including plastics), allowing for non-invasive searches of luggage, mail, vehicles, documents, and containers.

  It is claimed to be the only hand-held device capable of detecting the presence of plastic and high-vapor-pressure explosives, including taggants. It can identify minute traces of C-4, TNT, Dynamite, PETN, Semtex, EGDN, DMNB, RDX, and nitroglycerine. The EVD-3000 does both vapor and particulate sampling and weighs 6.6 pounds. Its approximate cost is $20,000.

- Sabre 2000 – manufactured by Barringer Instruments, Warren, NJ. This system can detect and identify up to 30 substances in a few seconds, and can analyze both vapor and trace particulate samples. Vapor samples are collected from the target area or object by drawing ambient air into the detector. It detects the following substances: RDX, PETN, TNT, Semtex, NG, HMX, ammonium nitrate, and others. The analysis time is 10 to 15 seconds. The unit weighs under 5.8 pounds and it is claimed to be the lightest trace detector available for true field applications, weighing 5.8 pounds. The system costs approximately $25,000.

- zNose Model 200 – manufactured by Electronic Sensor Technology, Newbury Park, CA. This is a hand-held gas chromatograph (GC) that uses a SAW (standing acoustic wave) detector, fast GC column and internal sampling pump and preconcentrator. Within 10 seconds, the system captures a vapor sample, injects and passes it through a GC column, and determines the concentration of chemicals in the vapor. This instrument is designed for maximum flexibility and applications requiring quick and accurate vapor screening.

- Model 4100 Trace Vapor Analyzer – manufactured by Electronic Sensor Technology, Newbury Park, CA. The components of this system are mounted in a field portable fiberglass case that weighs approximately 35 pounds. The system captures a vapor or particle sample in a pre-concentration trap. The sample is then injected into a Surface Acoustic Wave (SAW) detector. The signature of the sample is compared to a library of chemical signatures. The cost of the system is approximately $23,700.

- Ion Track Vapor Tracer – manufactured by Ion Track Instruments, Wilmington, MA. The system was developed and tested with support from the U.S. Department of Defense. It detects all high explosives and plastic explosives including RDX, PETN, TNT, dynamite, and Semtex.

  The system works by drawing a sample vapor into the detector, where it is heated, ionized, and then identified by its unique plasmagram. It will also analyze trace particles swiped with a glove. The detector weighs seven pounds and costs approximately $30,000.

- Ion Track Itemizer – manufactured by Ion Track Instruments, Wilmington, MA. The system detects trace quantities of explosives by analyzing samples obtained by either wiping a surface with a filter paper or by use of a battery operated vacuum that uses a sample trap. The sample is analyzed within five seconds. The entire system weighs 43 pounds. It can detect all common narcotics and explosives including dynamite, Semtex, RDX, PETN, and TNT. The system costs approximately $44,000.

  Sensitivity data of the Ion Track Itemizer was provided by the FAA and the White House Office of National Drug Control Policy (Georgia Tech Institute 2001) and is reproduced I Table 6-1:

Table 6-1 Sensitivity of ion track itemizer

Material	Minimum Detectable Quantity (picograms)
RDX	20
TNT	6
PETN	27
Cocaine	2
Heroin	8

There are many other detection systems that are important, but they are very large and will not be considered in this investigation. A few as outlined in the following paragraphs for reference purposes:

- Sentinel II – manufactured by Smiths Detection, Warren, NJ. A person is directed to enter the portal where air is used to gently dislodge particles and vapors trapped on the body and clothing. These are drawn into the Sentinel II where they are analyzed.

- GC-Ionscan – manufactured by Smiths Detection, Warren, NJ. This is a very large system.

- Ionscan 400B – manufactured by Barringer Instruments, Warren, NJ. This is a very large system that detects both narcotics and explosives. These units are deployed in 58 countries worldwide. It detects the following explosive substances: RDX, PETN, TNT, Semtex, Nitrates, NG, HMX, and others. The system weighs 57 pounds and costs approximately $48,000.

- EGIS 3000 – manufactured by Thermo Detection, Woburn, MA. This is an explosive detection system consisting of a free-standing analytical unit and a lightweight hand-held sampling unit. The analytical unit weighs 300 pounds. The sampling unit is then plugged into the analytical unit. The analysis takes approximately 15 seconds. It can detect nine individual materials to include nitroglycerine, TNT, RDX, EGDN, DNT, PXTN, AND PETN. The approximate cost is $151,000.

Recently, with support from DOE's Office of Nonproliferation and National Security, ORNL researchers have also been developing a fully self-contained, battery-powered measuring instrument for use in detecting threat chemicals. The size will be reduced from that of a desk to a briefcase. (ORNL Review 1999) It is called a multithreat analyzer and is intended to be carried by a worker to any site that is difficult to reach with a vehicle or wherever portable monitoring is required. It would be used to search for drugs in cargo containers or hidden explosives in an airplane cabin or mine field.

It will work as follows. If vapor molecules of TNT are present, for example, they are sucked through a long tube into the ion trap analyzer cell. There they are converted to ions that are trapped in the cell's electric field when a radio frequency (rf) signal of 100 volts is applied. As the rf voltage is ramped up to as high as 7500 volts, ions of increasingly higher mass escape the trap. These ions are counted. By applying the rf voltage known to eject TNT and checking for a signal, it is possible to determine whether the explosive is present. (ORNL Review 1999)

Section 7
Microcantilever Technology

Introduction

There are many methods used to detect contraband explosives, each one having its limitations. If present electronics technology could reproduce a dog's sniffing capability at a reasonable cost, it would be a major aid in detecting chemicals. Such instrumentation could be used by almost anyone with minimal training, and while the operator might get tired, the instrument could be in service for long hours. In this investigation we will look into the possibility of employing microcantilever technology to approach or exceed the sniffing capability of dogs.

Microcantilever technology is one of the most promising new sensor technologies to emerge in the past decade. In 1991 Thomas Thundat of Oak Ridge National Laboratory was using an atomic-force microscope to examine the effect of humidity on DNA. However, Thundat noticed that the humidity degraded the performance of the microscope's cantilever, which is used to map the atomic mountains and valleys of surfaces, just as a phonograph stylus traces grooves in a vinyl record. It then occurred to him that this microscopic springboard had the potential to be a sensor. Because of the availability of new micromachining techniques, his group was able to fabricate silicon chips containing tiny microcantilevers that are barely visible to the naked eye. (ORNL Review 1999)

Since 1991 there has been much progress in the development of this technology. It is now generally believed that microcantilevers can be the basis of a universal platform for real-time, in-situ measurement of a wide range of physical, chemical, and biochemical properties. (Thundat *et al.* 1997)

Microcantilever technology is now being implemented to develop an extremely flexible family of sensors based on the response of the quartz crystal microbalance to changes in surface properties and mass. (Wachter and Thundat 1995, Kepley *et al.* 1992, Akamine *et al.* 1990, Rugar and Hansma, Sarid 1991, Cleveland *et al.* 1994, Thundat *et al.* 1994) These micromechanical sensors are devices that measure physical quantities by utilizing variation in the physical properties of specifically fabricated microstructures. They are fabricated using standard techniques for mass production of integrated circuits (IC's). In recent years, micromechanical sensors have attracted much attention due to advances in microfabrication technology, which have resulted in improved dynamic response, greatly reduced size, high precision, and increased reliability. Tools are currently being developed to integrate micromechanical components with on-chip electronic circuitry and even telemetry. Therefore, micromechanical systems offer a clear path to the development and mass production of extremely sensitive, low-cost sensors.

These sensors are so sensitive that, in some cases, they can exceed the capability of trained dogs to detect explosives and dangerous chemicals. For example, dogs can detect 10^{-12} grams/m^3 of mercury while a microcantilever sensor can detect 10^{-16} grams/m^3. Laboratory conditions have shown a detection sensitivity of 10^{-18} grams/m^3. (Thundat *et al.* 1997, Ward and Buttry 1990) This level of detection would be a valuable asset for a DOT inspector. Because these devices are very small, they require very little power to operate.

Micromechanical sensors also satisfy the ever-increasing drive toward miniaturization, which demands even smaller detection devices and sensors than are available today. Micromachined, mass-produced cantilevers, such as those used by atomic force microscopes, are excellent micromechanical sensors (Wachter and Thundat 1995, Gimzewshi et al. 1994, Thundat *et al.* 1994)

Background Technology

Microcantilever technology is based on a physical property called piezoelectricity. In 1880 Jacques and Pierre Curie discovered that a mechanical stress applied to the surfaces of various crystals, including quartz, rochelle salt, and tourmaline, afforded a corresponding electrical potential across the crystal whose magnitude was proportional to the applied stress (Curie and Curie 1880) This behavior is referred to as the piezoelectric effect, which is derived from the Greek word *piezein* meaning to press. The charges generated in the quartz crystal are due to the formation of dipoles that result from the displacement of atoms in an accentric crystalline material. Shortly after their initial discovery, the Curies experimentally verified the converse piezoelectric effect in which application of a voltage across these crystals afforded a corresponding mechanical strain. The “motor generator” properties associated with piezoelectricity were eventually exploited for the development of underwater sound transducers (sonar) and electromechanical devices such as speakers, microphones, and phonograph pickups. (Mason 1950, Ward and Buttry 1990)

In the 1920’s, Cady demonstrated that the converse piezoelectric effect could be exploited for the construction of very stable oscillator circuits, wherein application of an alternating electric field across a quartz crystal substrate resulted in an alternating strain field. This caused a vibrational, or oscillatory, motion in the quartz crystal, resulting in the generation of acoustic standing waves. Depending on various criteria, the quartz oscillator exhibited a strong preference to vibrate at a characteristic resonant frequency. Impedance analyses generally reveal sharp conductance peaks at this frequency, indicative of high quality factors Q, the ratio of energy stored to energy dissipated per cycle; values of Q can exceed 100,000. Because quartz crystals vibrate with minimal energy dissipation, they are nearly ideal oscillators; their low cost, ruggedness, low defect concentration, ready fabrication, and chemical inertness have resulted in their wide use in frequency control and filter circuits. (Ward and Buttry 1990)

In 1957 Sauerbrey provided a description and experimental proof (by way of evaporative metal deposition) of the mass-frequency relation for foreign layers deposited on thickness-shear mode crystals that are still widely used today for determination of mass changes at the surface of shear mode transducers (Sauerbrey 1959) This mass sensing format is commonly referred to as the quartz crystal microbalance (QCM). The derivation of the mass-frequency relation implicitly relies on the assumption that a deposited foreign material exists entirely at the antinode of the standing wave propagating across the thickness of the quartz crystal, so that the foreign deposit could be treated as an extension of the quartz crystal. Thus, the frequency change is calculated as though it were the result of an increase in the thickness of the quartz crystal

$$\frac{\Delta f}{f_0} = \frac{-\Delta t}{t_q} \qquad (7\text{-}1)$$

Where Δt is change in thickness, t_q is the quartz thickness, Δf is the measured frequency shift, and f_0 the fundamental frequency of the quartz crystal prior to a mass change. With appropriate substitution of the terms on the left side of Eq. (7-1), it can be shown that Eq. (7-2) can be developed.

$$\Delta f = \frac{-2f_0^2 \Delta m}{A\sqrt{\rho_q \mu_q}} = \frac{-2f^2 \Delta m}{nA\sqrt{\rho_q \mu_q}} \qquad (7\text{-}2)$$

Where Δm is the mass change, A the piezoelectric active area, ρ_q the density of quartz, and μ_q the shear modulus. Therefore, a change in the mass per unit area, or the areal density, results in a corresponding change in frequency. Although Eq. (7-2) is rigorously valid only for infinitesimally thin films that have acoustic impedances identical to that of quartz, in practice it is valid up to loadings approaching 10% of the crystal mass. (Ward and Buttry 1990)

Sensor Detection Methods

It has been shown (ORNL Review 1999) that a cantilever bends or changes its natural vibration in a measurable way if it is coated with a material that attracts another material from the air. For example, a cantilever coated with a gelatin absorbs water, causing it to bend and measure humidity. Cantilevers can also be used to measure changes in temperature, sound wave velocities, and fluid pressures and flow rates.

Cantilevers can store electrical charge or resist the flow of electricity. When a cantilever bends or changes in its vibration, this ability is altered in a way that can be measured electrically. Also, by steadily bouncing a laser diode light off the cantilever, bends or wiggles can be detected by measuring changes in the angle of light deflection in an optical position-sensitive detector. (ORNL Review 1999)

The deflections of these cantilevers can be detected with sub-angstrom precision using current techniques perfected for AFM [atomic force microscopes] technology such as optical, piezoresistive, piezoelectric, capacitive, and electron tunneling. (Sarid 1991, Britton *et al.* 1999)

Figure 7-1 (Britton et al. 1999) shows two examples of beam deflection detection. These are changes in stress and changes in frequency.

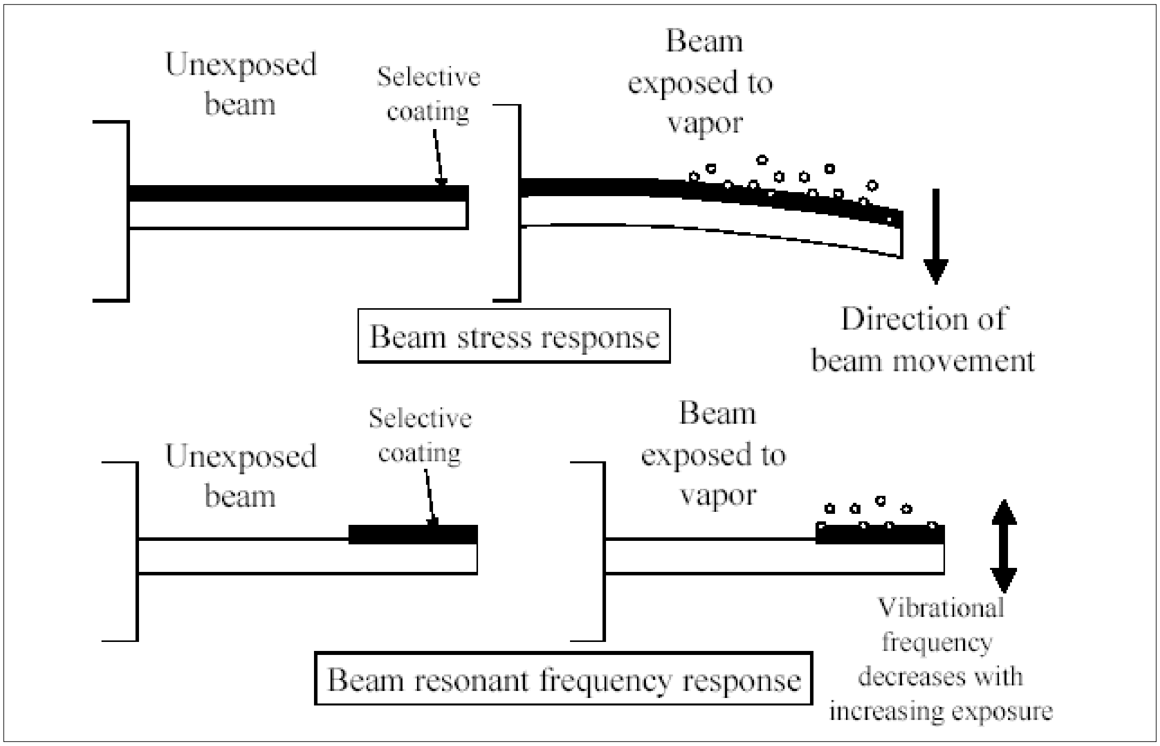

Figure 7-1 Different microcantilever responses (Britton et al. 1999)

Because of the versatility of microcantilevers, it should be possible to develop a large variety of physical, chemical, and biological sensors. These sensors could operate by detecting changes in resonance response or deflection caused by mass loading, surface stress variation, or changes in damping conditions. For resonance measurements, four resonance response parameters – resonance frequency, amplitude, Q-factor, and deflection – can be detected simultaneously. Surface stress produced as molecules adsorbed on a microcantilever can be observed as changes in deflections. Because of this, it can be shown that molecular adsorption of chemical vapors can be detected using microcantilevers with chemically specific coatings. (Thundat *et al.* 1997)

Previous work has shown that microcantilever bending can be readily determined by a number of means, including optical, capacitive, piezoresistive, and electron tunneling with extremely high sensitivity. (Datskos *et al.* 2001, Sarid 1991) While the optical readout method is useful with single element designs, practical implementation of microcantilever arrays may require the use of other readout methods, such as piezoresistance or capacitance. (Datskos *et al.* 2001)

Physical Properties

One of the more important features of microcantilever sensors is their small size. These sensors are about the size of a period on this page. This coupled with the new advances in the field of micromachining has made it possible to fabricate hundreds of cantilevers on a single chip. It fact, there is still plenty of room available for measurement electronics.

The typical dimensions of commercially available micromachined, mass-produced microcantilevers are 50-200 µm long, 10-40 µm wide and 0.3-3 µm thick, with mass in the range of a few nanograms. The resonant frequency of these cantilevers is in the range of a few kHz to a few hundred kHz. (Britton *et al.* 1999)

Microcantilever Sensitivity

The most outstanding attribute of the microcantilever sensor is its sensitivity as a chemical detector. While it should be possible to develop small microcantilever explosive detectors having the same flexibility as sniffing dogs, this technology promises to greatly exceed the sensitivity of sniffing dogs.

Sensitivity Analysis

When discussing the benefits of microcantilever detectors, the issue of sensitivity is of paramount importance. The microcantilever sensor has great promise as a portable detection and identification system, but if it is to replace sniffing dogs in versatility, it must at least match their sensitivity.

The microcantilever is a member of the class of electromechanical sensors, which includes the quartz-crystal microbalance (QCM), the standing acoustic wave (SAW) device, the Lamb-wave resonator and other resonating sensor structures. These are used as gravimetric sensors in which sorption of analytes results in mass or modulus induced frequency changes. The fact that the cantilever can be readily produced with sub-micron thickness favors its high sensitivity. To compare the microcantilever to other gravimetric sensing devices, it is necessary to determine the sensitivity of the sensor. The mass sensitivity of a sensor is given by (Ward and Buttry 1990, Grate *et al.* 1993, Ballantine *et al.* 1997)

$$S_m = \lim_{\Delta m \to 0} \frac{1}{f}\frac{\Delta f}{\Delta m} = \frac{1}{f}\frac{df}{dm} \qquad (7\text{-}3)$$

where Δm and dm are normalized to the active sensor area of the device. As can be seen from this expression, the sensitivity is the fractional change of the resonant frequency of the structure with addition of mass to the sensor. When applying this definition to the case of the microcantilever, two coating configurations are considered, a distributed load (DL-MCS) where the entire cantilever surface is covered, and the end load (EL-MCS) where just the end of the cantilever is coated with the polymer.

$$S_m = \frac{1}{\rho\, t} \qquad \text{distributed load (DL-MCS)} \qquad (7\text{-}4)$$

$$S_m = \frac{-\xi}{2\rho(\xi\, t_d + 0.24t)} \qquad \text{end load (EL-MCS)} \qquad (7\text{-}5)$$

where ξ and t_d are the fractional area coverage and thickness of the deposited mass and ρ is the density of the cantilever material for the EL-MCS case. It has been found that adding mass to the end of a cantilever results in a decrease of the resonant frequency of the device and as mass is added in a distributed loading situation (corresponding to a cross-sectional thickness increase), the resonant frequency increases. (Thundat *et al.* 1997)

Another characterization of a sensor is its minimum detection limits. The minimum detectable mass density (MDMD) can be obtained by rearranging Eq. (7-1) as:

$$\Delta m_{\min} = \frac{1}{S_m}\frac{\Delta f_{\min}}{f} \qquad (7\text{-}6)$$

where Δm_{min}, Δf_{min} are the minimum detectable mass density and minimum detectable frequency change, respectively. Typically, minimum detectable mass density values are experimentally quoted results due to specifics of the sensor as well as the frequency detector limitations determining Δf_{min}.

Comparison to Existing State-of-the-Art Techniques

To better understand the sensitivity of microcantilever sensors, it is important to examine them in the context of present accepted methods as well as current state-of-the-art sensors. Table 7-1 compares the exceptional performance for the detection of mercury vapor of microcantilever sensors to other methods. All of these devices with the exception of the microcantilever sensor and the Surface Acoustic Wave (SAW) device are large stand alone or bench-top instruments not amenable to miniaturization. (Thundat unpublished)

Table 7-1 Comparison of techniques for mercury analysis (Thundat unpublished)

Technique	Hg Detection Limit (μg)
Microcantilever Sensor (MCS)	0.00000001
Differential pulse voltametry	0.00004
Zeeman spectroscopy-cold Vapor (AA)	0.00007
Spark source mass spectrometry	0.0001
Surface acoustic wave device (SAW)	0.0001
Cold vapor atomic absorption (AA)	0.0005
Neutron activation analysis	0.002
X-ray flourescence	0.01
Polarography	20

Table 7-2 presents a tabulation of operation frequencies along with mass sensitivities and MDMD levels for several gravimetric acoustic wave devices based upon the sensitivity and the minimum detectable mass given by the above equations. Despite their large size and power requirements, SAW devices and Quartz Crystal Microbalances (QCM) can often yield sensitivity in the sub-nanogram range. Microcantilevers offer much higher sensitivity - in the range of femtograms. It is doubtful that any chemical sensor based on mass detection will rival the chemical selectivity offered by conventional spectroscopic techniques. The main advantage of microcantilever sensors lies with chemical selectivity based on the array concept. Although arraying can be accomplished for SAW and QCM sensors, the number of elements in an array will be quite limited due to their size and power requirements. Microcantilevers, with their extremely small size, can be made into an array incorporating thousands of elements and all necessary electronics and readout mechanisms. This versatility is key to the development of orthogonal arrays. Regeneration based on heat will be difficult for SAW and QCM due to their large thermal masses. Microcantilevers, on the other hand, can be heated to several degrees centigrade in milliseconds by passing currents through the cantilever or by an adjacent heater. It is encouraging to note that while parts-per-billion sensitivity of analytes has become possible only relatively recently with conventional mass detection devices, it is already routine with low-cost microcantilevers, even at this early stage of development. (Thundat unpublished)

Table 7-2 Gravimetric sensitivity comparison of oscillating acoustic wave devices (Thundat *et al.* 1997)

Device type	f_o (MHz)	S_m (cm^2/g)	MDMD (ng/cm^2)
DL- MCS	5-0.02	10,000	0.02
EL—MCS	5-0.02	5,000	0.04
SAW	112	151	1.2
QCM	6	14	10
SH—APM	104	65	1.0
FPW (Lamb)	2.6	951	0.4

From these results, the average ratio of the minimum detectable frequency shift to operation frequency for these techniques is approximately 2 x 10^{-7}. If this general result is used in equation (7-2), a minimum detectable mass (MDM) of approximately 10^{-16} g can be obtained for microcantilever sensors. (Thundat *et al.* 1997)

The most important property of microcantilever sensors is their ability to detect very small trace amounts of chemicals. While initially it was thought that these sensors could detect with sensitivities on the order of picograms per cubic meter (Wachter and Thundat 1995, (Wachter and Thundat 1995, Cleveland *et al.* 1994, Thundat *et al.* 2003, Thundat et.al. 2003), later research has shown that this sensitivity can be extended to parts-per-trillion (Datskos *et al.* 2001, Britton et al. 2000) This sensitivity far exceeds the ability of sniffing dogs.

This increase in sensitivity has been accomplished by carefully optimizing the geometrical design of the cantilever and its coatings. For example, Binh *et. al.* have proposed a cantilever design having MHz resonance frequency and mass resolution of 10^{-18} g. (Wachter and Thundat 1995, Binh *et al.* 1994) This approach achieves an extremely high quality factor (Q>1000) under vacuum through the use of special end-loaded cantilevers that are extremely narrow and have a low inherent mass. (Wachter and Thundat 1995) T.D. Stowe (1997) demonstrated a device with a measured force resolution of 5.6 x 10^{-18} N/√Hz. The fundamental limitations on sensitivity are due to thermomechanical noise in the microcantilever. This mechanical noise is analogous to Johnson noise in a resistor and is governed by the dissipation of mechanical energy in the cantilever structure.

In general, the sensitivity and specificity of microcantilever sensors can be optimized by careful geometric design of the cantilever and its coatings. For example, the mass sensitivity of a cantilever is proportional to $1/\rho t$, where ρ is the density of the cantilever material and t is the thickness of the cantilever. Therefore, by reducing the thickness of the cantilever, the mass sensitivity can be improved by a few orders of magnitude. However, smaller thicknesses demand shorter cantilevers and increased resonance frequency.

Microcantilevers as small as 30 µm have been developed. (Walters *et al.* 1996) The sensitivity of detection can also be increased by judicious optimization of damping effects by choice of cantilever materials, operating media, and geometry of the cantilever. The chemical selectivity of cantilevers depends on the selection of surface coating for chemical interactions. (Thundat *et al.* 1997)

Detection of Explosives

Since the development of microcantilever sensors, it has been thought that these sensors could be used to detect explosives or the chemicals constituents of explosives. In general, even if microcantilever devices can become as sensitive as sniffing dogs, the devices will still be subject to some of the limitations experienced by dogs. Dogs can only detect vapors that exist. Therefore, explosives well packaged with clean packing material will not be detected by either dogs nor vapor sensors. However, if the full potential of microcantilevers can be developed, all but the most carefully packaged explosives will be detected.

For example, TNT is solid at room temperature, has very low vapor pressure (10^{-6} Torr), and its detection under ambient conditions presents a challenge. However, microcantilever sensors can detect TNT. (Datskos *et al.* 2001)

Under funding from the Federal Aviation Administration (FAA), Thundat and his colleagues at Oak Ridge National Laboratory are developing a matchbox-size device to detect explosives in airport luggage and land mines. The device will contain cantilevers coated with platinum or a transition metal. If TNT is present when a cantilever is heated to 570°C and held at that temperature for 0.1 sec, the TNT will react with the coating, causing a mini-explosion (autocombustion). The cantilever's resulting characteristic wiggle can be teased out of the background noise using a wavelet analysis algorithm. (ORNL Review 1999)

In the very latest work on microcantilever development for explosives detection, Pinnaduwage (2003), of the Oak Ridge National Laboratory, have conducted a series of measurements on adsorption/desorption of explosive vapors TNT (trinitrotoluene), PETN (pentaerythritol tetranitrate), and RDX (hexahydro-1,3,5-triazine) on piezoresistive silicon microcantilevers. The mass change of the microcantilever due to the adsorption or desorption of explosive molecules was deduced from the change in its resonance frequency. In the first series of measurements, they monitored the mass loading of a cantilever exposed to well-characterized explosive vapor streams. These measurements were used to estimate the ability of the explosive molecules to "stick" to the microcantilever. In another set of measurements, they monitored the mass unloading due to desorption of explosive molecules from the cantilever surfaces. Depending on the amount loaded on the cantilever, TNT desorption took a few minutes to tens of minutes (for nanogram quantities of TNT). On the other hand, desorption of PETN and RDX took many hours. There is a good correlation between the desorption time and the melting point of the particular substance. (Pinnaduwage *et al.* 2003)

It is obvious that one cannot wait hours for the desorption of explosive molecules from a microcantilever sensor. However, the technology is under continuous development and,there are many ways to get around the problems in a practical system. For example, it might be possible to develop a system using disposable sensors that could be replace for each new inspection is begun.

Advantages of Microcantilevers over Conventional Sensors

Microcantilever sensors have many advantages over conventional sensors, but their main advantages are their size, extreme sensitivity, and low power consumption. They even have advantages over solid state sensors, not only because of sensitivity, but also because of the more simple micromaching technology. For sensors that require the measurement of resonant frequency, microcantilevers have better sensitivity because of the low mass and thickness compared to quartz-crystal microbalances, and surface-acoustic wave sensors, for example. Additionally, arrays of cantilevers can readily be fabricated on single chips, allowing mass production. (Britton *et al.* 2000)

Because of the microcantilever sensor's low power consumption, an array of capacitively read cantilevers, each selectively coated, appears to be ideal for broad applications involving environmental and industrial monitoring. (Britton *et al.* 2000)

Another area where microcantilever sensors are superior is in their reaction time. Conventional methods can take minutes to hours to detect and measure a chemical. In some cases, the recovery time is very long or detector material has to be replaced.

In new work with standing acoustic wave (SAW) devices, a fast initial response of the order of milliseconds was observed for a 5 second DMMP (dimethylmethylphosphonate) exposure. When the DMMP vapor was turned off, the SAW frequencies returned to their original value, albeit more slowly, due to the time it took to remove all traces of DMMP vapor from the test chamber. Research on chemiresistor sensors (sensors whose resistance changes in the presence of a particular chemical) has shown them to have slower response times than SAW devices and lower sensitivity. (Pique *et al.* 2003) Chemiresistor sensors are not as sensitive as microcantilevers, but have value in their simplicity of operation. SAW can approach the sensitivity of microcantilever devices, but are more complex to fabricate.

Comparison of Microcantilever Sensors to Sniffing Dogs

Because dogs can easily detect vaporized organic chemicals such as acetone and toluene at part-per-billion levels, they are employed in searching airline passenger baggage for explosives and in detecting land mines. The Treasury Department's Alcoholism, Tobacco and Firearms agency has taken the concept one step further. It is looking for a device that emulates a dog's nose and that could be part of a walking cane to detect the presence of an explosive. One possible technology is Oak Ridge National Laboratory's (ORNL) calorimetric microspectrometer (CalSpec), which received an R&D 100 Award in 1998. Another candidate technology is ORNL's "nose on a chip" device, which contains a series of cantilevers individually coated to pick up a different specific organic compound. (ORNL Review 1999)

Dogs not only detect individual chemicals but also are able to recognize a combination of many chemicals. It is said that while a human may smell hamburgers at McDonalds, a dog will also smell bread, pickles, onions, cleaning fluids, the mixture of people, etc. Therefore, if the capability of sniffing dogs is to be emulated, the sensor system must contain a suite of individual sensors. The system must be coupled with sophisticated software that can identify combinations of component chemicals and determine the important result.

Microcantilever sensors are uniquely qualified to provide a suite of hundreds of individual sensors that can provide chemical specificity that is difficult, if not impossible, to achieve with individual sensors. (Britton et al. 2000) In fact, an array of cantilevers can be coated with a variety of low-specificity materials; such an array could be used in conjunction with pattern-recognition methods to achieve selective fingerprinting of a broad range of analytes. (Wachter and Thundat 1995)

Oak Ridge National Laboratory and the University of Tennessee have built a 10-element microcantilever array to sense mercury and hydrogen. They employed capacitance measurements as the sensing mode. Because the measured capacitance is small, $\sim 10^{-12}$ F, low-noise amplifiers were essential for precision measurements. (Britton *et al.* 2000) In general, the array response can also be used to recognize a mixture of chemical constituents.

It is currently believed that available fabrication techniques are not generic enough to be capable of simultaneous deposition of polymer thin films without affecting their chemical integrity and physicochemical properties, while producing thin, uniform and solvent-free coatings, in discrete or continuous fashion. Also, most of these techniques are not appropriate for the fabrication of multilayers, since they rely on the application of a solvent solution containing the material of interest, which may dissolve any previously deposited layers. (Pique *et al.* 2003) This is no longer true due to the latest coating techniques and methods of performing measurements. According to investigators at the University of Alabama at Huntsville, new techniques similar to ink jet printing are being used to coat microcantilevers.

Researchers at the Oak Ridge National Laboratory are developing techniques to fabricate multi-element sensor chips. Once these methods are perfected, work must be done to integrate the different sensor measurements in order to detect complex chemicals.

Based on microelectromechanical fabrication of silicon combined with the sensitivity utilized in atomic force microscopy, the techniques promise to revolutionize applications where multiple properties need to be monitored economically. Micromachining technologies currently available could be used to make multielement or multitarget sensor arrays involving hundreds of cantilevers for physical measurements as well as the specification of organic and inorganic constituents in environments without significantly increasing the size, complexity, or cost of an overall sensor package. The primary advantages of the microcantilever method are its sensitivity based on the ability to detect cantilever motion with subnanometer precision; its ability to be fabricated into a multielement sensor array; and its ability to work in air, vacuum, or liquid. No other sensing technology offers such versatility. (Thundat *et al.* 1997) Because of the work being done by the Oak Ridge National Laboratory and others, it seems highly probable that the new microcantiler technology will be able to replace sniffing dogs.

Accuracy and Stability

Questions must be answered concerning the stability, ruggedness, and accuracy of the microcantilever devices. Before we can consider utilizing the sensitivity of microcantilevers for portable, mobile detection of explosives, we must be satisfied that the intrinsic accuracy can be maintained under field conditions. Most extremely accurate measurement instruments require laboratory conditions, i.e., controlled temperature, pressure, humidity, vibration, etc. Therefore, it is reasonable to ask what can be expected from microcantilever sensors under non-laboratory conditions.

Current research by Thundat and others (Britton et al. 2000) has demonstrated that multiple sensors can be fabricated on a chip. It appears possible to fabricate hundreds of microcantilever sensors on a chip. When this is accomplished, some of the sensors can be used to compensate for changes in environmental conditions. For example, the frequency response of uncoated microcantilevers will vary with temperature. This variation can be used to correct measurements obtained from coated microcantilevers. Similar measurements can be performed for other environmental changes.

Assuming reasonable stability can be achieved by compensating measurements, the question of accuracy remains. Again, the advantage of having hundreds of sensors solves the problem. Groups of sensors can be assigned the task of detecting a particular chemical. The measurement electronics will then poll the reading of each sensor. If only one sensor detects the chemical, it is probably a false positive reading. If the overwhelming majority of the sensors detect a chemical, it is probably a good reading. There will also be some microcantilevers that will be dedicated to providing calibration.

Therefore, a well-constructed microcantilever sensing system will provide both accurate and stable measurements.

University of Alabama Nanometer/Micrometer Fabrication Facility

The University of Alabama at Huntsville (UAH) has established a Nanometer/Micrometer Fabrication Facility which has a world-class capability to design, fabricate and test microcantilever devices. They are currently testing a six-sensor device (coated with polymers) as a precursor to placing hundreds of sensors on a chip. This will allow the detection of a suite of chemicals, including those that comprise explosives. Such a device will aid not only in the detection, but also in the identification of the particular explosives.

The UAH Smart Microsensor Array Facility is currently researching and testing microcantilever sensor devices. The devices are being fabricated at UAH’s Nanometer/Micrometer Fabrication Facility. These sensors can be tailored to detect a wide range of airborne threats. They have the capability to detect trace amounts of most chemicals, including chlorine gas, mustard gas, and seran nerve agent. UAH has in-house technology to design and fabricate a hand-held device capable of detecting a large selection of chemicals at one time. With this special technology located at one facility, it should be possible for this university laboratory to build a sensor system that can detect very small concentrations of explosive chemicals.

As part of this investigation, the author interviewed Dr. Michael George who is the Director of the UAH Smart Microsensor Array Facility. This laboratory is located in a dedicated facility of the Materials Science Building. Dr. George was asked the following questions. His answers follow the questions and have been paraphrased, but every effort was made to ensure accuracy.

1. ***How is your laboratory staffed and who are your customers?*** The laboratory is headed by Dr. Michael George who also performs hands-on work. He is supported by two post–doctoral investigators and a number of graduate students. His primary customer at this time is the National Aeronautical and Space Administration (NASA).

2. ***What is significant about your research?*** Currently, it is only one of a few laboratories in the world that has developed a multi-array sensor. Dr. George's group is in the process of optimizing a six-element sensor chip and its associated solid-state electronics. They are also performing investigations on the detection of biomolecules and have a program to develop alternate detection methodologies.

3. ***Are you performing any research directed toward explosives detection?*** No. However, we have the technology in place to direct our research in that area.

4. ***What methods do you use to detect microcantilever changes?*** The laboratory has concentrated mainly on optical and piezoelectric detection methods. Lately there has been more effort placed on the piezoelectric detection because it is less complex than optical measurements. Although piezoelectric methods easily allow scanning of many microcantilevers, there have been techniques used by other laboratories whereby many microcantilevers have been scanned using one optical source.

5. ***If you could place hundreds of sensors on a chip, what problems would you have with fabrication and/or measurements?*** There will be no problems placing coatings on the many different microcantilever sensors because of the latest techniques used. The industry is going toward an "ink jet" method, similar to the technique used in computer printers. This method will allow different polymers to be sprayed on under computer control.

   There should be no problems with sensors interfering with each other if the chip is designed properly. These problems are well understood by the industry.

   Finally, while measuring hundreds of sensors on a chip simultaneously will be a challenge, it is one that can be solved. If optical measurements are used, it is probably possible to have one laser continue to scan approximately 25 sensors. If a hundred sensors were placed on a chip, then only four lasers would be necessary. The electronics for measurement can also be placed on the same chip. If piezoelectric measurement is employed, the complexity of the design will be greatly reduced. However, there are other measurement techniques that are being developed.

6. ***What do you think the future direction of this technology will be?*** Microcantilever technology has been shown to provide very sensitive sensing of many different physical and

chemical properties. Microcantilevers can sense temperature, pressure, vibration, chemical odors, etc., which will allow humans to greatly extend their natural senses. The technology not only has great promise for expanding our sensing of the world, but also could assist those who have lost sensing. These devices might allow someone with an artificial hand to "feel" what is being touched. We have only just begun to exploit this exciting new technology.

Section 8
Prototype of Explosive Sensor Design

Introduction

After considering the current state-of-the-art of microcantilever sensors, and considering their potential advantages over sniffing dogs and other electronic instrumentation, a conclusion was reached that it should be possible to design and build a hand-held, low-cost sensor system based on microcantilever technology. The following is an attempt to describe a prototype system and determine the costs involved in developing such a system.

Developing the Sensors

Micromaching technology is mature enough so that fabricate microcantilever devices can be consistently fabricated. The detection of a few chemicals has been demonstrated. However, much more work is needed to develop specific polymers to address chemical threats to this country. A simple sensor will consist of a microcantilever coated with a special polymer that selectively adsorbs the desired chemical while being inert to other chemicals. This type of simple sensor is very valuable when the user knows exactly what chemical is to be detected and that chemical is one for which polymer coatings have already been developed, e.g., chlorine. For the case where one wants to detect explosives, the design and fabrication becomes more complicated.

The following are typical scenarios for detecting explosives:

Case 1. The explosives are well packaged and no vapor escapes.

Case 2. The explosives are not well packaged, but only traces of the most volatile chemicals escape.

Case 3. The explosives are not well packaged and a strong decoy chemical is used to confuse sniffing dogs.

Case 4. The explosives are not well packaged and trace amounts of the explosives are emitted.

For Case 1, microcantilever sensors have no value. The only way the explosives could be detected would be by using x-ray or other instrumentation, or by a physical search based on profile information. However, in some cases the explosives could be detected if the wrapping material contained traces of the explosives.

For Case 2, it is not possible to positively detect explosives; however, if the chemical or chemicals detected are constituents of explosives and the cargo should not contain these chemicals, it can lead inspectors to do a physical search. In some cases the chemicals will be detected due to out-gassing from legitimate sources, but this can be determined with a physical search.

For Case 3, a very selective sensor is necessary. Sniffing dogs have been trained to disregard smells that would distract them. Although dogs have a good record of being able to detect explosives and drugs wrapped in coffee and even baby diapers, they can be deceived. A very sensitive, selective sensor is needed to perform this task and microcantilever sensors hold promise in meeting this need.

For Case 4, the easiest case, sniffing dogs and instrumentation do a good job. The limitations have been described previously. Sniffing dogs are very versatile and have good sensitivity. Instrumentation is very accurate, but the more accurate instruments require time to make an analysis. Microcantilever sensors have the potential to surpass the sensitivity of sniffing dogs by an order of magnitude and at the same time provide a rapid identification of the detected explosive.

An important first step in the design and fabrication of a microcantilever-based explosives detector is the development of a suite of individual sensors. A list must be made of the constituent chemicals of the most common explosives. Work must then be done to develop polymers that will detect these chemicals. Finally, all these sensors must be placed on one chip so that a spectrum of chemicals can be detected.

The concept of a multi-chemical sensor is appealing, but it is not as simple to implement as it may seem. Assuming one can develop all the necessary polymers, there is the question of placing them all on the same chip. This should be a solvable problem due to the latest ink-jet type technology to coat microcantilevers. Also, to achieve fault tolerance, more than one sensor should be placed on the chip so that redundancy will eliminate false positive indications. Other microcantilevers must be added for calibration and temperature compensation.

The technology is in place to fabricate an explosives sensor system. Present work being done to develop polymers is very promising and more and more universities and laboratories around the world are investigating microcantilever technology.

Designing the Electronics

A chip containing multiple sensors can be fabricated, but an assumption must be made that all, or most, of the required polymers necessary to detect explosive chemicals can be developed. This being possible, the author envisions the following design. The chip will require sophisticated electronics to process the complex multiple sensor information. For the first stage, each sensor must be monitored and its output continuously evaluated. There will also be calibration and temperature compensation functions taking place periodically.

When one or more sensors detects a chemical, the electronics instrumentation will perform the following:

1. Alert the system that a particular chemical has been detected.

2. Measure and record the intensity.
3. Poll all the sensors of like composition to eliminate a false signal.

Since present day electronics can be made very small, it should be possible to have the measurement electronics placed on the same chip as the sensors. Also, because of the simplicity of microcantilever sensors, no complex signal processing is required.

Designing the Software

The sensor system electronics will be performing a host of processes, especially when it is detecting many chemicals simultaneously. Therefore, specialized software must be written so that this raw data can be transformed to a type of information that is valuable to the user. The software will take all the data and compare it to information stored in a database. This information will contain the composition of various explosives and the relative volatilities of the chemicals. Based on the received information, the software program will either positively identify an explosive or provide a probability of detection.

In the case of a badly packaged explosive, it is possible that a sensor system could be designed to positively identify a particular explosive by detecting its constituent chemicals. Because the measurement would contain the relative intensity of each constituent, software, internal to the system should be able to perform an identification. This multi-sensor system should be able to provide a real-time spectral analysis for identifying explosives. However, this is the ideal case. More than likely, the explosives will be hidden and an attempt will be made to carefully package them. In this case, the sensor system will have incomplete information, if any.

For the case where the sensor system can only detect the most volatile chemicals, the software will provide the user a list of possible explosives and the probability for each one being detected. In this case the inspectors must make a decision as to whether they should perform a physical search. They can be aided in their decision by using other information such as country of origin or any suspicious information.

Designing the Display

The most important component of the sensor system is the display. It must be very easy to use and to understand. Use of the system should require little or no training. The display will probably consist of a back-lighted liquid crystal display (LCD) that will show some neutral pattern when the system is not detecting any explosives. When explosives are detected, the system should sound an alarm and display a list of possible explosives detected. The list will be displayed in the order of probability with positive identification at the top. A percent probability value will be assigned to each explosive listed. Since this list may change as the sensor is moved around, the user will have the ability to freeze any particular reading so the results can be evaluated before they change.

Designing the Power Supply

There is nothing particularly difficult to providing an adequate power supply to the system. The batteries should last at least 8 hours and replacing batteries should be simple to do. There should be no need to design special batteries for this operation.

Designing the Package

There are many important considerations that must be taken into account when designing the package of a sensor system. For one thing, it must be rugged. Since inspectors will use the units in various environments, they must be able to tolerate rough handling. Also, if the system is to be used on a ship, for example by the Coast Guard, it must be able to tolerate salt spray.

It is also possible that this system will be used in cold temperature. Extremely cold temperatures affect electronics so that circuits become unstable. To eliminate this problem, the units should be fitted with internal heating strips that will automatically heat the electronics when the temperature drops below a pre-set point. These heating strips are commercially available, but they place a drain on the battery when used. When using the sensor system in a very cold environment, the inspectors must plan on replacing batteries more often.

Estimated Research and Development Effort

The previously described sensor system would be a valuable tool in the detection of illegal explosives, however much development work and funding will be required to make such a system a reality. The cost of such a system has been estimated using information gathered from microcantilever and micromachining researchers at the University of Alabama. Software estimates have been developed from information received from software experts also at the University. The packaging and manufacturing information has been estimated based on pricing of a similar package developed at UAH.

Sensor Development

A large expenditure of funds will be required to properly design the required sensor system. The researchers at the University of Alabama laboratories have estimated that it could completely design and test a 6-sensor system in 18 months for approximately $2.5 million. A system that can completely, or almost completely, detect all the chemicals in explosives will take longer to develop and cost more. This figure could double and so could the time to complete.

Electronics Development

The electronics circuitry should not be unusually complicated and can probably be designed and fabricated for $100-$200K.

Software Development

The software development should be fairly straightforward and can should cost no more than $100K.

Development of Package

To design and fabricate a small, rugged package for the system it will not be necessary to completely design the system. There are companies available that can build compact, hand-held systems in a standard computer package. Estimates for developing a packaged system are approximately $500K.

The above estimate is based on proposal UAH has received for the packaging of the UAH developed Automatic Large Area Radiation Mapping (ALARM) system. This was the cost of a package design for a rugged, hand-held system and four prototypes.

Estimate of Final Cost of Sensor System

When all the above costs are added together, an estimate is made of sensor polymer development carts, and a little extra funding added to included unforeseen events, the total cost of the research and development of a hand-held, rugged, explosives sensor system is estimated to cost approximately $3.5 to $5.0 million. Although this is an initial estimate, it is not an unreasonably high price when one considers the benefits of such a system.

To determine the price of a system that is mass-produced, a similar system designed by UAH was studied. The university has developed a hand-held radiation mapping system and has estimated that the wholesale price will be approximately $1700 a unit for limited production. The explosives detection and identification system described in this study is much more complex. However, the major expenses occur during research and development. Based on the author’s experience, it would not be unreasonable to expect the explosives unit to be mass-produced for under $3,000 each. Of course, this would be the wholesale price, but the price should come down as production techniques improve and production levels increase. There is a very large potential market for this product.

Section 9
Conclusions and Recommendations

The purpose of this investigation was to determine the feasibility of applying the new microcantilever technology to the detection of explosives. An important part of the investigation was to determine whether a hand-held sensor system, based on microcantilever technology, could be developed to provide a simple and accurate explosives detection system for USDOT inspectors.

The first part of this investigation dealt with defining the present-day problems faced by USDOT inspectors in their search for contraband explosives. Although the inspection process has improved since the 9/11 attack on the New York twin towers, there are national and local plans to continue to improve inspections. The future looks promising for limiting the movement of explosives into the country or moved throughout the country; however, it will be many years before a high-confidence level will be achieved that most explosives will be detected. The main barriers are related to cost. There is the cost of additional personnel, expensive sophisticated measuring equipment, and sniffing dogs with their handlers. The other related barrier is the huge influx of commerce into the United States daily.

Because sniffing dogs are an important component of inspecting for explosives, their capabilities were investigated. While there are not many scientific studies of sniffing dogs (Auburn University had done one study) there is a massive amount of empirical data to define what these dogs can do. Sniffing dogs are very valuable for detecting explosives. If trace odors of explosive chemicals are present, these dogs will detect them, even in minute quantities. They can not only detect individual chemicals, but can identify groups of chemicals that make up particular explosives. Because they are so specialized, however, explosive detecting dogs cannot detect narcotics or currency. Other dogs are trained to detect these.

When sniffing dogs were compared to current instrumentation, they compared favorably. The dogs had their advantages and the instruments had theirs. It was not possible to do a one-to-one comparison to show that one had an overwhelming advantage over another because they have different strengths. Dogs are more versatile, mobile, and have excellent sensitivity. Also, compared to instruments, their costs are reasonable. When looking to the future, however, it is clear that instrumentation will win out. Sniffing dogs are about as optimized as they can get. Further improvement in the use of sniffing dogs will be minimal. However, because of the worldwide interest in developing detection instrumentation, we can expect technology to far exceed the capability of sniffing dogs. With all this said though, sniffing dogs will be with us for some time.

Because of the current interest in microcantilever technology, the investigation was focused on determining the capabilities of sensors developed with this technology. There are many researchers in the world performing research on microcantilevers, but the more significant work is being performed by the Oak Ridge National Laboratory, TN; IBM Zurich; and the University of Alabama at Huntsville, AL. This versatile technology has unlimited potential. Sensors are extremely small, reasonably simple to fabricate and can detect multiple physical properties. The full potential of these sensors is just beginning to be exploited.

Microcantilever sensors can not only detect individual chemicals associated with explosives, but, if multiple sensors are fabricated on a chip, they have the ability to detect a chemical spectrum. This, of course, requires signal processing. Laboratory measurements have shown that these sensors have a sensitivity that far exceeds that of dogs and field instruments.

After carefully considering all the evidence, it became obvious that a multi-sensor, explosives detection system, based on microcantilever sensor technology, is feasible to design and fabricate. It not only can be developed, but should be. It has the potential to combine the accuracy of laboratory bench equipment with the versatility of sniffing dogs.

In order to get some idea of what kind of detection system could be developed and what it would cost, a draft design was considered. Because the design has few details, the estimated cost figures are only approximate. However, the results show that the costs will be in line with other projects of like complexity and well worth the cost because of the potential for saving lives.

Section 10
References

Gary Hart and Warren B. Rudman, Co-Chairs, Stephen E. Flynn, Project Director, America–Still Unprepared, Still in Danger, Report of an Independent Task Force Sponsored by the Council on Foreign Relations, December 4, 2002

Conversation with a representative of Customs Service, 2003, Tel: (202)354-1000

Memorandum, Homeland Security: Domestic Preparedness After Sep. 11, 2001", pg. 2 (http://www.homelandsecurity.org/bulletin/ESDPMemoRidge.pdf)

USA Today, Bomb-sniffing technology takes on dogs, Nov. 27, 2001

Kenneth G. Furton and Lawrence J. Meyers,The scientific foundation and efficacy of the use of canines as chemical detectors for explosives, Talanta **54** (2001) 487-500

http://gtresearchnews.gatech.edu/reshor/rh-win02/r-first.html

J.W. Gardner, M. Craven, C. Dow, E.L. Hines, Meas. Sci. Technol. 9 (1998) 120.

J.V. Hatfield, P. Neaves, P.J. Hicks, K. Persaud, P. Travers, Sensors and Actuators B: Chem. 18 (1994) 221.

A. Pique, R.C.Y. Auyeung, J.L. Stepnowski, D.W. Weir, C.B. Arnold, R.A. McGill, and D.B. Chrisey, Laser processing of polymer thin films for chemical sensor applications, Surface and Coatings Technology, vol 163-4 (2003), pgs. 293-294.

A. Maureen Roth, Detecting Illegal Substances, Chemical and Engineering News, September 29, 1997)

GAO/GGD-98-175, Customs Service Drug Interdiction - Internal Control Weaknesses and Other Concerns with Low-Risk Cargo Entry Programs, letter to Sen. Diane Feinstein, July 31, 1998

Dean Boyd, Protecting America from weapons of mass destruction, Customs multi-layered approach, U.S. Customs Today, July 2002

Customs.gov, The 2% Myth, February 2003 http://www.customs/xp/cgov/newsroom/breakingnew/safeamerica/2myth.eml

C.G.G. Aitkin, “Statistics and the Evaluation of Evidence for Forensic Scientists”, John Wiley & Sons, New York, 1995

L.M. Fytche, M. Hupe, J. Kovar, P. Pilon, J. Forensic Sci. 37 (1992) 1550

Tamiri T, Abramovich-Bar S, Zitrin S and Levy J. Clandestine laboratories for manufacturing explosives. Proceedings from 6th International Symposium on Analysis and Detection of Explosives 1998; July 6-10: Prague, Czech Republic

Elliott B. Byall, Explosives Report, 13th INTERPOL Forensic Science Symposium, Lyon, France, October 16-19 2001

Committee on Marking, Rendering Inert, and Licensing of Explosive Materials Board on Chemical Sciences and Technology, Commission on Physical Sciences, Mathematics, and Applications, National Research Council, National Academy Press, Washington, D.C. 1998

Stancl M and Mostak P. Marking of explosives. Proceedings from 6th International Symposium on Analysis and Detection of Explosives 1998; July 6-10: Prague, Czech Republic

R.G. Ewing and C.J. Miller, Detection of Volatile Vapors Emitted from Explosives with a Handheld Ion Mobility Spectrometer, Field Analytical Chemistry and Technology, 5(5):215-221, 2001

Nam SI, Leggett DC, Jenkins TF and Stutz MH. On-site analysis of explosives in soil: Evaluation of thin layer chromatography for confirmation of analyte identity. American Environmental Laboratory 2000; 2: 4-7.

Mares B, Pokorny J and Dvorak P. Analysis of post-blast traces of explosives by TLC in model conditions. Proceedings from 6th International Symposium on Analysis and Detection of Explosives 1998; July 6-10: Prague, Czech Republic

Sands HS, Hayward IP, Kirkbride TE, Bennett R, Lacey RJ and Batchelder DN. UV-excited resonance Raman spectroscopy of narcotics and explosives. Journal of Forensic Sciences 1998; 43: 509-513.

Phillips SA. Ion mobility spectrometry (IMS). Proceedings from Workshop on Explosives Trace Analysis Methods 1999; April 28-29: Forensic Explosives Laboratory, DERA, United Kingdom.

Norman EWW, Bouchard F and Baril E. A survey of explosives contamination of police personnel, equipment and work spaces in the Ottawa area. Proceedings from 6th International Symposium on Analysis and Detection of Explosives 1998; July 6-10: Prague, Czech Republic.

Walsh ME. Determination of nitroaromatic, nitromine, and nitrate ester explosives in soil by gas chromatography and an electron capture detector. Talanta 2001; 54: 427-438.

Irwin A. Gas chromatography with chemiluminescence detection (GC/TEA). Proceedings from Workshop on Explosives Trace Analysis Methods 1999; April 28-29: Forensic Explosives Laboratory, DERA, United Kingdom.

Bowerbank CR, Smith PA, Fetterolf DD and Lee ML. Solvating gas chromatography with chemiluminescence detection of nitroglycerine and other explosives. Journal of Chromatography A 2000; 902: 413-419

Elias L, Wilson DE and Castonguay JP. Laboratory and airport testing of trace explosive detectors. Proceedings from 6th International Symposium on Analysis and Detection of Explosives 1998; July 6-10: Prague, Czech Republic.

Bromberg EE, Durfee M, Fine D, Miskolczy G and Hallowell S. Design of a trace based automatic explosives luggage detection system. Proceedings from 6th International Symposium on Analysis and Detection of Explosives 1998; July 6-10: Prague, Czech Republic.

Ornath F, Buechler S, Lancet D, Barel S, Nivon U, Matsliah L, et al.Trace automated explosives detection for cargo, mail and luggage security screening. Proceedings from 6th International Symposium on Analysis and Detection of Explosives 1998; July 6-10: Prague, Czech Republic.

Tamiri T. Gas chromatography with mass spectrometric detection. Proceedings from Workshop on Explosives Trace Analysis Methods 1999; April 28-29: Forensic Explosives Laboratory, DERA, United Kingdom

Bureau of Alcohol, Tobacco and Firearms. 1997 Arson and Explosives Incident Report, Washington, DC: Department of Treasury; 1998.

McCord BR. Analysis of low explosives by capillary electrophoresis and ion chromatography. 220th American Chemical Society, Washington, DC, August 20-24, 2000, Abstract #147.

Miller ML, Doyle JM, Lee RA and Gillette R. Analysis of anions by capillary electrophoresis and ion chromatography for forensic applications. Forensic Science Communications 2001; 3.

Rey V. Capillary electrophoresis (CE). Proceedings from Workshop on Explosives Trace Analysis Methods 1999; April 28-29: Forensic Explosives Laboratory, DERA, United Kingdom

Phillips SA. The analysis of pyrotechnic residues by scanning electron microscopy and energy dispersive x-ray analysis (SEM/EDS). Proceedings from International Workshop on Forensic Aspects of Low Explosive Devices 2000; February 9-11: Forensic Explosives Laboratory, DERA, United Kingdom.

Glattstein B, Levin N and Abramovich-Bar S. Detection and identification of low explosive residues by a non-destructive staining method combined with FTIR, SEM/EDX and GC-MS.

Proceedings from 6th International Symposium on Analysis and Detection of Explosives, 1998, July 6-10, Prague, Czech Republic

Mark Derr, With Dog Detectives, Mistakes Can Happen, New York Times, Dec 23, 2002.

R. V. Nolan and D.L. Gravitte, Mine detecting K-9's: Summary Report 1975-1976, U.S. Army Technical Report, 1977

D.W. Hannum and J.E. Parameter, Survey of Commercially Available Explosives Detection Technologies and Equipment, Sandia National Laboratories, September 1998, National Institute of Justice, NCJ 171133

North American Police Work Dog Association Certification Rules (N.A.P.W.D.A.), N.A.P.W.D.A., Perry, OH, 1998, pp. 1-23

D.D. Fetterolf, T.D. Clark, J. Forensic Sci. 38 (1993) 28

Georgia Tech Institute, Evaluation of Ion Mobility Spectrometry Technology for Narcotics Identification, GSA/FEDSIM Contract No. GS00T99AJD0015, 12 Apr 2001

ORNL Review, Reducing the Threat of War and Terrorism, June 1999

T. Thundat, P.I. Oden, and R.J. Warmack,Microcantilever Sensors, Microscale Thermophysical Engineering, 1:185-199, 1997

E.A. Wachter and T. Thundat, Micromechanical Sensors for Chemical and Physical Measurements, Rev. Sci. Instrum., vol 66, pp. 3662-3667, 1995

L.J. Kepley, R.M. Crooks, and A.J. Ricco, Anal. Chem. 64, 3191 (1992)

S. Akamine, R.C. Barrett, and C.F. Quate, Appl. Phys. Lett. 57, 316 (1990)

D. Rugar and P.K. Hansma, Phys. Today, October 1990, p. 23.

D. Sarid, Scanning Force Microscopy, (Oxford University Press, New York, 1991)

J.P. Cleveland, S. Manne, D. Bocek, and P.D. Hansma, Rev. Sci.Instrum. 64, 403 (1994)

T. Thundat, R.J. Warmack, G.Y. Chen, and D. P. Allison, Appl. Phys. Lett., 64, 2894 (1994)

M.D. Ward and D.A. Buttry, In-Situ Interfacial Mass Detection with Piezoelectric Transducers, Science, vol. 249, pp. 1000-1007, 1990

J.K. Gimzewshi, C.H. Gerber, E. Mayer, and R.R. Schlitter, Observations of a Chemical Reaction Using Micromechanical Sensor, Chem. Phys. Lett., vol 217, pp. 589-594, 1994

P. Curie and J. Curie, C. R. Acad. Sci. 91, 294 (1880)

W.P. Mason, Piezoelectric Crystals and Their Applications to Ultrasonics, Van Nostrand, New York, 1950

Michael D. Ward and Daniel A. Buttry, In Situ Interfacial Mass Detection with Piezoelectric Transducers, Science, Vol 249, 31 August 1990

G. Sauerbrey, Z. Phys. 155, 206, 1959

C.L. Britton, Jr. et al, Battery-powered, Wireless MEMS Sensors for High-Sensitivity Chemical and Biological Sensing, , Advanced Research in VLSI, 1999, Proceedings, 20 th Anniversity Conference on, 21-24 March 1999, Pgs. 359-368.

P.G. Datskos, M.J. Sepaniak, C.A. Tipple, and N. Lavrik,Photomechanical chemical microsensors, Sensors and Actuators B (76) 2001 393-402

J.W. Grate, S.J. Martin, and R.M. White, Acoustic Wave Microsensors, Anal. Chem., vol. 65, pp. 978A-996A, 1993

D.S. Ballantine, R.M. White, S.J. Martin, A.J. Ricco, G.C. Frye, E.T. Zellers, and H.Wohltjen, Acoustic Wave Sensors – Theory, Design, and Physiochemical Applications, Academic Press, San Diego, CA, 1997

T. Thundat, E.A. Wachter, S.L. Sharp, and R.J. Warmack, Appl. Phys. Lett. 2003

T. Thundat, G.Y. Chen, R.J. Warmack, D.P. Allison, and E.A. Wachter, Anal. Chem. 2003

T. Thundat (unpublished)

C.L. Britton, Jr., R.L. Jones, P.I. Oden, Z. Hu, R.J. Warmack, S.F. Smith, W.L. Bryan, and J. M. Rochelle, Multiple-input microcantilever sensors, Ultramicroscopy, Volume 82, Issues 1-4, Feb 2000 17-21

V.T. Binh, N. Garcia, and A.L. Levanuk, Surf. Sci. Lett. 301, L224 (1994)

T.D. Stowe, et al, Attonewton force detection using ultrathin silicon cantilevers, Appl. Phys. Lett. 71(2), 14 July 1997

D.A. Walters, J.P. Cleaveland, N.H. Thompson, P.K. Hansma, M.A. Wendman, G. Gurley, and V. Ellings, Short Cantilevers for Atomic Force Microscopy, Rev. Sci. Instrum., vol. 67, pp. 3583-3590, 1996

L.A. Pinnaduwage et al, Adsorption/Desorption Characteristics of Explosive Vapors on Uncoated Silicon Microcantilever Surfaces, Oxford 2003 Scanning Probe Microscopy, Sensors, and Nanostructures Conference, Bristol, UK, 2003

http://www.vetmed.auburn.edu/ibds/doglab.htm