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## INNOVATIVE MINE DETECTION SYSTEMS

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Researchers in physical, chemical, and biological sciences are studying and developing methods that could reduce the false alarm rate and maintain or increase the probability of detection for mine clearance. New detection concepts involve searching for characteristics other than mine metal content. A variety of techniques that exploit properties of the electromagnetic spectrum are being explored. In addition, research is under way to develop methods based on acoustics of the mine casing. Biological and chemical methods for detecting explosive vapors also are being explored, as are methods for detecting bulk explosives based on chemical properties. Work also is under way to develop advanced prodders that provide information about the physical characteristics of the object being investigated.

This chapter describes the difficulties of predicting the performance of innovative mine detection methods and our method for assessing the potential of innovative systems. It then describes each type of innovative technology and evaluates its potential to improve on existing EMI detection systems. Table S.1 in the Summary provides an overview of the technology evaluations.

### **METHOD FOR EVALUATING INNOVATIVE MINE DETECTION SYSTEMS**

Predicting the potential for an innovative mine detection system to reduce the false alarm rate and increase the probability of detection is an inherently difficult task. Research is being conducted by a myriad of universities, government institutions, and private companies,

with different projects in various stages of development. However, most of the technologies have not yet been field tested. This makes it virtually impossible to assess operating characteristics (for example, ROC curves) with any specificity, thus precluding defensible quantitative performance comparisons.

Compounding the general lack of data to support quantitative evaluations is a lack of comparability of the data that are available. The performance of a landmine detection system depends on the types and depths of mines present, the environment in which the system is operated, and the human operator. For detectors that locate buried objects, such mine properties as size, shape, and metallic content substantially affect detector performance, as do the placements (depth and orientation) of the mines. Detectors that search for explosives can be sensitive to the type of explosive contained within the mine. Detector performance is also tied to persistent environmental attributes (such as soil type, terrain, vegetation, and clutter density) and transient atmospheric conditions (wind, humidity, soil moisture, and radio frequency or acoustic interference). Finally, such human factors as individual operator tuning of the detector and interpretation of the signals introduce additional sources of variability. Thus, results of reported field tests cannot be generalized, with operating characteristics being conditional on the set of experimental and field test conditions. As explained in Chapter One, such variability is clearly illustrated in the results of the International Pilot Project for Technology Cooperation field tests, shown in Figures 1.6 and 1.7. The primary implication is that even if published field results were available for all current technologies, comparing performance on these results alone would not be valid because of disparities in the testing conditions and because of variability of detector performance in different environments.

Because of the barriers to credible quantitative comparisons of innovative mine detection technologies, objective expert judgment is required to interpret the available data on detector performance. Without such judgment, it is easy to be misled. For example, many of the existing field tests have been conducted in environments in which confounding factors were minimized, yielding high probabilities of detection and low false alarm rates. Nonpartisan judgment thus was critical to the evaluations presented and to the stated tasks of the study.

To make the judgments about detector performance, we identified two sets of prominent academic, government, and private-sector scientists with expertise in landmine detection: (1) generalists, with broad and long-standing experience in the landmine detection community, and (2) specialists, currently at the forefront of developing specific cutting-edge detection technologies. Working with OSTP, we appointed eight generalists to form the RAND S&TPI/OSTP Landmine Detection Technology Task Force. Based on input from the task force members and our own independent literature review, we identified 23 leading specialists in current detection R&D efforts. Each specialist then wrote a technical paper addressing the mode of action, current capabilities and limitations, and potential future performance of his or her specific technology. We requested that each paper provide the following information:

- brief description of the basic physical principles and mine features (e.g., shape, explosives composition, metal content) exploited by the technology;
- state of development of the technology (laboratory, bench, field);
- current capabilities and operating characteristics (e.g., investigation times and examples of ROC curves from laboratory or field tests);
- known or suspected limitations or restrictions on applicability (background clutter, mine type, environmental conditions, etc.);
- estimated potential for improvement in the next two to seven years;
- outline of a sensible R&D program that could realize this potential, with rough projected costs to the extent possible; and
- references to key technical papers describing any testing (especially field testing) of the technology.

The papers are published as technical appendixes (A–W) to this report.

The appendixes provided a structure for the task force to evaluate the potential of each detection method. To conduct the evaluations, the task force held several conference calls and met for two days at RAND's Arlington, Va., office in May 2002. The "summary evalua-

tion” section included with each technology description below indicates the results of the task force evaluations.

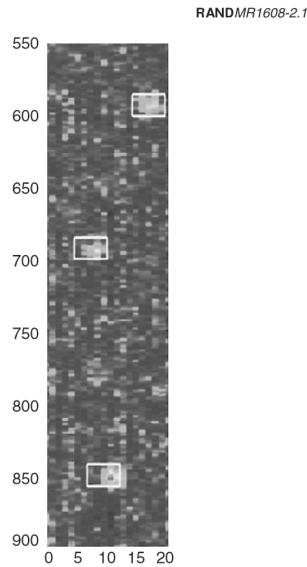
## INNOVATIVE ELECTROMAGNETIC DETECTION SYSTEMS

A number of innovative methods are being explored that search for buried mines based on changes in the electromagnetic properties of the surface soil and shallow subsurface. These methods include ground-penetrating radar (GPR), electrical impedance tomography (EIT), x-ray backscatter, and infrared/hyperspectral systems.

### Ground-Penetrating Radar

**Description.** GPR detects buried objects by emitting radio waves into the ground and then analyzing the return signals generated by reflections of the waves at the boundaries of materials with different indexes of refraction caused by differences in electrical properties. Generally, reflections occur at discontinuities in the dielectric constant, such as at the boundary between soil and a landmine or between soil and a large rock. A GPR system consists of an antenna or series of antennas that emit the waves and then pick up the return signal. A small computerized signal-processing system interprets the return signal to determine the object’s shape and position. The result is a visual image of the object (see, for example, Figure 2.1) or an audio signal indicating that its shape resembles a landmine, based on comparison with a mine reference library.

The major design control in a GPR system is the frequency of the radio wave. The scale at which GPR can detect objects is proportional to the wavelength of the input signal, so the quality of the image improves as the wavelength decreases and the frequency increases. However, at high frequencies, penetration of the incident wave into the soil can be poor. As a result, the designer must make a tradeoff between quality of the image and required penetration depth. The optimal design for maximizing image quality while ensuring sufficient penetration depth changes with environmental conditions, soil type, mine size, and mine position. Various alternative GPR designs are being explored to optimize the tradeoff between penetration depth and image quality under a wide range of conditions. Also criti-



SOURCE: Ackenhusen et al. (2001).  
 NOTE: The bottom target is a metallic mine;  
 the top two targets are low-metal mines.

**Figure 2.1—Images of Landmines Produced by GPR System**

cal in the design of a GPR system are signal-processing algorithms, which filter out clutter signals and select objects to be declared as mines.

GPR is a mature technology, but it has not yet been widely deployed for mine detection. GPR was first used in 1929 to measure the depth of an Austrian glacier (Olhoeft, 2002). The Army tested rudimentary GPR techniques for mine detection in the 1940s. The first commercial GPR systems were developed in 1972. Since then, use of GPR for locating buried objects ranging from utility pipelines to archaeological artifacts has proliferated. Although GPR is well established for these other uses, understanding how different environmental factors and mine characteristics affect its performance is far from complete. Until very recently, GPR was unable to meet performance targets for landmine detection established for military countermine operations (see Appendix E).

The Army is currently completing development of a landmine detection system that combines GPR and EMI. This system is called the Handheld Standoff Mine Detection System (HSTAMIDS) (see Figure 2.2). Field tested at Fort Leonard Wood, Mo., HSTAMIDS has achieved probabilities of detection of 1.00 (with a 90-percent confidence interval of 1.00–0.97) for metal antitank mines and 0.95 (with a 90-percent confidence interval of 0.97–0.93) for low-metal anti-personnel mines, with an average false alarm rate of 0.23 per square meter (see Appendix F). These test results cannot be extrapolated to predict performance in other mined environments or even under weather conditions different from those present on the day the test was performed because of the significant effects of soil type and moisture on GPR performance, as well as the variations in natural clutter objects. Nonetheless, they do illustrate the potential for a combined GPR/EMI system to achieve very high levels of performance if the integrated sensor system can be optimized to account for the effects of the local soil environment.



SOURCE: Minelab Countermine Division, [www.countermine.minelab.com/countermine.asp](http://www.countermine.minelab.com/countermine.asp).

**Figure 2.2—Prototype HSTAMIDS System**

**Strengths.** GPR has a number of advantages. First, it is complementary to conventional metal detectors. Rather than cueing exclusively off the presence of metal, it senses changes in the dielectric constant and therefore can find mines with a wide variety of types of casing (not just those with metal). Generating an image of the mine or another buried object based on dielectric constant variations is often possible because the required radar wavelength is generally smaller than most mines at frequencies that still have reasonable penetration depth. Second, GPR is a mature technology, with a long performance history from other applications. A fielded Army system (HSTAMIDS) combining GPR with EMI for mine detection already exists and is scheduled for production in 2003. Finally, GPR can be made lightweight and easy to operate, and it scans at a rate comparable to that of an EMI system.

**Limitations.** Natural subsurface inhomogeneities (such as roots, rocks, and water pockets) can cause the GPR to register return signals that resemble those of landmines and thus are a source of false alarms. In addition, GPR performance can be highly sensitive to complex interactions among mine metal content, interrogation frequency, soil moisture profiles, and the smoothness of the ground surface boundary. For example, Koh (1998) reports that because excessive water causes rapid attenuation of radio waves, GPR will perform poorly in wet soils for landmines buried below a depth of about 4 cm. However, theoretical investigations by Rappaport et al. (1999) indicate that increased soil moisture and interrogation frequency may actually strengthen the return signal for nonmetallic mines, but nonuniform soil moisture profiles (e.g., a wet surface and dry subsurface) and rough ground surfaces present difficulties. For the same mine, a given GPR can be very effective or ineffective, depending on soil moisture and mine location; such complex interplays make performance highly variable and difficult to predict. An additional limitation is that unless the GPR system is tuned to a sufficiently high frequency, it will miss very small plastic mines buried at shallow depths because the signal “bounce” at the ground surface (caused by the electrical property differences between air and soil) will mask the return signal from the mine. Finally, the GPR system designer must make a tradeoff between resolution of the return signal and depth, because high-frequency signals yield the best resolution but do not penetrate to depth.

**Summary Evaluation.** Current-generation GPR technology, such as that embodied in HSTAMIDS, has the potential for high performance. In addition, alternative approaches to GPR design (such as the Wichmann system referred to in Appendix E) have the potential to yield significant advancements over the available systems. However, the ability to model the radar response from different kinds of landmines and natural clutter is essential for yielding the expected performance gains. So far, such modeling is in its infancy. Ideally, GPR systems would be able to provide high-resolution images to a signal-processing system that could decide whether a buried object is a root, rock, clutter object, or landmine. Ralston et al. (in Appendix F) suggest development of a “library” of clutter signatures to aid in this task.

### Electrical Impedance Tomography

**Description.** EIT uses electrical currents to image the conductivity distribution of the medium under investigation. Current implementations use a two-dimensional array of electrodes placed on the ground, collecting conductivity data from stimulation of pairwise combinations of electrodes. The data are then post-processed with an algorithm that renders an image of the conductivity profile of the subsurface volume. Both metal and nonmetal mines create anomalies in the conductivity distribution that produce images, providing information about the presence and location of mines.

**Strengths.** Because both metallic and nonmetallic mines create conductivity anomalies, the technology is appropriate for detecting all types of mines. Moreover, it is especially well suited for mine detection in wet environments, such as beaches or marshes, because of the enhanced conductivity of the moist substrate. The equipment is relatively simple and inexpensive.

**Limitations.** The primary limitations are that the technology requires physical contact with the ground, which might detonate a mine, and that it cannot be used in such excessively dry, nonconductive environments as desert or rocky surfaces. The technology is also sensitive to electrical noise. Performance deteriorates substantially with the depth of the object being detected for fixed electrode array size, generally making it appropriate only for shallowly buried objects.

The resolution is not as fine as that provided by other imaging techniques, such as GPR.

**Summary Evaluation.** Because of its phenomenological limitations, EIT is probably not well suited for broad humanitarian demining needs. It has a potential niche for detecting nonmetallic mines in wet environments, a task that confounds other technologies. Even for this use, however, EIT is limited because it cannot detect at depth, and often mines in moist environments, such as rice paddies, are much deeper than those in shallow environments. A unique role for EIT in humanitarian demining is not apparent from the available information.

### **X-Ray Backscatter**

**Description.** Traditional x-ray radiography produces an image of an object by passing photons through the object. X rays have a very small wavelength with respect to mine sizes, so in principle they could produce high-quality images of mines. Although pass-through x-ray imaging of the subsurface is physically impossible, the backscatter of x rays may still be used to provide information about buried, irradiated objects. X-ray backscatter exploits the fact that mines and soils have slightly different mass densities and effective atomic numbers that differ by a factor of about two.

There are two basic approaches to using backscattered x rays to create images of buried mines. Methods that collimate (i.e., align) the x rays employ focused beams and collimated detectors to form an image. The collimation process increases size and weight and dramatically reduces the number of photons available for imaging. Thus, high-power x-ray generators must be used as sources. The large size, weight, and power requirements of such systems are not amenable to person-portable detectors. Alternatively, uncollimated methods illuminate a broad area with x rays and then use a spatial filter to deconvolve the system response. They may be suitable for person-portable detection.

**Strengths.** To readily distinguish mines from soils, it is necessary to use low-energy incident photons (60–200 keV). In this energy range, cross sections are roughly 10 or more times larger than is possible with most other nuclear reactions that would be applicable to mine

detection. In addition, because of the reduced shielding thickness needed to stop low-energy photons, uncollimated systems can be made small and relatively lightweight. Largely because of the medical imaging industry, compact x-ray generators are now obtainable. Low-energy isotopic sources have been readily available for a long time. Practical imaging detectors are becoming more widespread, although it may be necessary to custom build for mine detection purposes. The medical imaging industry is likely to drive further advances in x-ray imaging hardware.

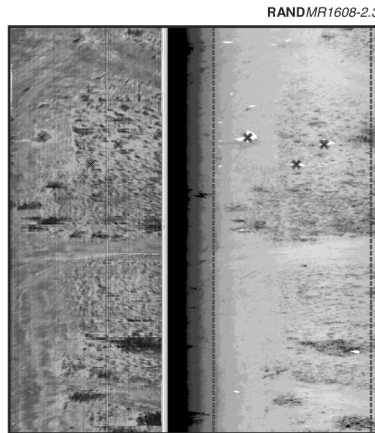
**Limitations.** In the required energy range, soil penetration of x-ray backscatter devices is poor. This limits detection to shallow mines (less than 10 cm deep). If source strengths are kept low enough to be safe for a person-portable system, the time required to obtain an image may be impractically long. In addition, the technology is sensitive to source/detector standoff variations and ground-surface fluctuations. Further, to image antipersonnel mines, high spatial resolution (on the order of 1 cm) is required. This may be difficult to achieve in the field. Finally, the technology emits radiation and thus will meet resistance to use because of actual or perceived risks.

**Summary Evaluation.** X-ray detection using the uncollimated imaging approach may be useful for handheld confirmatory detection of antipersonnel landmines. In fielded systems, images of mines are likely to be fuzzy but should still allow mines to be distinguished from most diffuse or elongated false alarms. On the whole, however, x-ray backscatter does not offer particular innovations or likely avenues of improvement relative to other technologies and is unlikely to yield substantial improvement in detection capabilities.

### **Infrared/Hyperspectral Systems**

**Description.** Infrared/hyperspectral methods detect anomalous variations in electromagnetic radiation reflected or emitted by either surface mines or the soil and vegetation immediately above buried mines (see Figure 2.3). The category encompasses technologies of diverse modes of action, including active and passive irradiation using a broad range of electromagnetic wavelengths.

Thermal detection methods exploit diurnal variations in temperatures of areas near mines relative to surrounding areas. For example,



SOURCE: Space Computer Corp., [www.spacecomputer.com](http://www.spacecomputer.com).

NOTE: The left pane shows the infrared image, while the right pane shows the visible image. Mine locations are denoted with “x.”

**Figure 2.3—Infrared Image of Mines**

mines or the soil above them tend to be warmer than surrounding areas during the day but lose heat more quickly at night. Laser illumination or high-powered microwave radiation can be used to induce these differential temperature profiles.

Nonthermal detection methods rely on the fact that areas near mines reflect light (either natural or artificial) differently than surrounding areas. Anthropogenic materials tend to preserve polarization because of their characteristically smooth surfaces, allowing discernment of surface mines. Moreover, the physical activity of emplacing mines changes the natural soil particle distribution by bringing small particles to the surface, which in turn affects the way in which the soil scatters light. Systematic changes in vegetation moisture levels immediately above buried mines also may be leveraged.

**Strengths.** These methods are attractive because they do not involve physical contact and can be used from a safe standoff distance. They are lightweight and are effective at scanning wide areas relatively quickly. When deployed from airborne platforms, they are particu-

larly effective for detecting surface mines. Collecting and processing the signals temporally (as opposed to in “snapshots”) tends to improve performance by tracking diurnal cycles.

**Limitations.** The methods, particularly thermal imaging, have been used in several prototype multisensor systems, but extreme variability in performance as a function of dynamic environmental characteristics has precluded their use for close-in detection and accurate identification of mine locations. Despite maturity of the sensor, the algorithms to process the signals in an informative way are relatively undeveloped and are not linked to physical phenomena. Thermal signatures currently are not well understood, and a comprehensive predictive model does not exist. Moreover, waves at the frequencies used by the methods cannot penetrate soil surfaces, and the localized hyperspectral anomalies produced by mine emplacement are ephemeral and are quickly eliminated by weathering. Thus, the technologies are able to detect buried mines under only limited transient conditions.

**Summary Evaluation.** With the possible exception of methods that would simulate solar heating as a means to enhance the thermal signatures of buried targets, infrared/hyperspectral methods are not particularly suitable for close-in buried mine detection. The underlying phenomena are not sufficiently characterized, and natural processes quickly erase the detectable surface anomalies. The technology has demonstrated ability and expected future promise for airborne minefield detection, especially for surface mines, but it is not expected to be useful for close-in detection of buried mines.

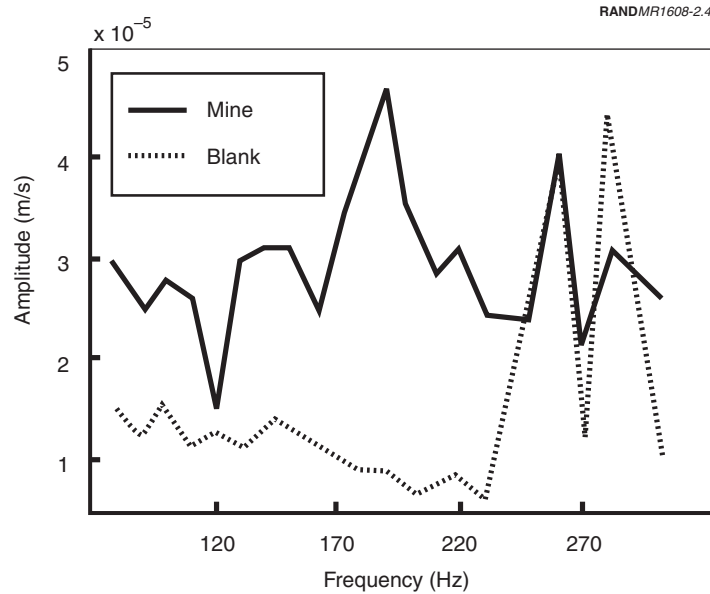
## ACOUSTIC/SEISMIC SYSTEMS

Acoustic/seismic methods look for mines by “vibrating” them with sound or seismic waves that are introduced into the ground. This process is analogous to tapping on a wall to search for wooden studs: materials with different properties vibrate differently when exposed to sound waves. These methods are unique among detection methods that identify the mine casing and components in that they are not based on electromagnetic properties.

### Description

Acoustic/seismic mine detection systems typically generate sound (above ground) from an off-the-shelf loudspeaker, although there are many possible configurations. Some of the acoustic energy reflects off the ground surface, but the rest penetrates the ground in the form of waves that propagate through the soil. When an object such as a mine is buried, some of the energy reflects upward toward the ground surface, causing vibration at the surface (see Figure 2.4). Specialized sensors can detect these vibrations without contacting the ground. A variety of different kinds of sensors (laser Doppler vibrometers, radars, ultrasonic devices, microphones) have been tried.

Researchers have field tested acoustic/seismic methods for landmine detection on approximately 300 buried antitank and antipersonnel



SOURCE: Rosen et al. (2000).

**Figure 2.4—Amplitude of Surface Vibration of Ground over a Mine (solid line) and a Blank (dashed line) in Response to Sound Waves**

mines and several hundred square meters of clutter locations at Army field sites in Virginia and Arizona (see Appendix G). Initial tests focused on antitank mines and yielded high probabilities of detection and low false alarm rates. For example, in one test, the acoustic system identified 18 of 19 mines buried in dirt and gravel, yielding a probability of detection of 95 percent. There was only one false alarm in the test, even though the test site was seeded with clutter items that had confounded a GPR system (Rosen et al., 2000). When the system was modified with advanced signal-processing algorithms, the false alarm rate dropped to zero.

### **Strengths**

Acoustic/seismic sensors are based on completely different physical effects than any other sensor. For example, they sense differences in mechanical properties of the mine and soil, while GPR and EMI sensors detect differences in electromagnetic properties. Thus, acoustic/seismic sensors would complement existing sensors well.

Acoustic/seismic systems also have the potential for very low false alarm rates. In experiments to date, false alarms from naturally occurring clutter, such as rocks and scrap metal, have been extremely low (although such hollow clutter items as soda bottles and cans would cause false alarms because the resonance patterns of these objects are similar to those of mines). An additional strength is that, unlike GPR systems, these sensors are unaffected by moisture and weather, although frozen ground may limit the sensor's capability.

### **Limitations**

The greatest limitation of acoustic/seismic systems is that they do not detect mines at depth because the resonant response attenuates significantly with depth. With current experimental systems, mines deeper than approximately one mine diameter are difficult to find.

Also problematic is the slow speed of existing systems. Speed currently is limited by the displacement sensor, which senses the vibrations at the surface caused by the sound waves. These displacements are very small (less than 1  $\mu\text{m}$ ) and are thus difficult to measure

quickly in the adverse conditions of a minefield. The required scan time for locating antipersonnel mines may range from 125 to 1,000 seconds per square meter (see Appendix H). However, a number of methods are being investigated to speed up the detection process. For example, an array of  $N$  sensors will speed the system by a factor of  $N$ . Small prototypes of such arrays have been developed and can be expanded and improved with further work.

An additional limitation of existing systems is that moderate to heavy vegetation can interfere with the laser Doppler vibrometers that are commonly used to sense the vibrations at the ground surface. A new type of sensor could be developed, however, to overcome this flaw.

### **Summary Evaluation**

Significant progress has been made in the past five to ten years in developing acoustic/seismic mine detection systems. Interactions between the seismic waves and buried mines and clutter are much better understood, as are the seismic sources and displacement sensors. The systems show great potential, but more research is needed to make them practical. The development of an array of displacement sensors that is fast, can penetrate vegetation, and can function in the adverse conditions of a real minefield would be especially useful.

### **EXPLOSIVE VAPOR DETECTION TECHNIQUES**

Each detection technology discussed above searches for the casing or mechanical components of a mine. Additional research is taking place to develop methods—both biological and chemical—that identify the presence of explosive vapors emanating from mines.

Ideally, such sensors would determine whether explosive vapors are present above an anomaly located by a metal detector or other device. Although each method has a different theoretical basis, all are designed to sense low concentrations of explosive compounds or their derivatives in soil or the boundary layer of air at the soil surface. Determining the performance potential of each chemical- or biological-sensing technology requires an understanding of how explosives migrate away from landmines as well as knowledge of the chemical and physical principles of the sensor.

When a mine is buried in the soil, it almost always will gradually release explosives or chemical derivatives to the surrounding soil through either leakage from cracks and seams or vapor transport through the mine casing (in the case of plastic mines). While typically about 95 percent of the explosive will adsorb to the surrounding soil, the remaining 5 percent will travel away from the mine, mostly through dissolution in water in the soil pores (see Appendix Q). Some of this explosive will migrate to the ground surface in vapor form.

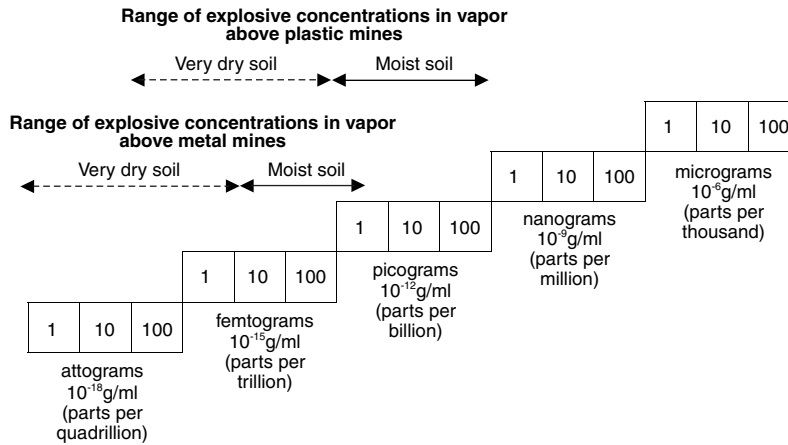
One of the key issues in detecting explosive vapors and residues is that the concentrations available for detection are extremely low (see Appendix Q). Thus the sensor must be able to operate at a very low detection threshold. The analyte that is the focus of most explosive detection research is 2,4-dinitrotoluene (2,4-DNT), which is a byproduct of trinitrotoluene (TNT) manufacturing that is present as an impurity in military-grade TNT. TNT has a very short half-life in soil (about a day at 22°C) because it is easily biodegraded and has very low vapor pressure; 2,4-DNT is much less easily biodegraded and has a higher vapor pressure, so it is the dominant chemical present in the explosive signature from most landmines. In experiments from a landmine test site reported in Appendix Q, the 2,4-DNT and 2,4,6-TNT concentrations in air above the soil were  $200 \times 10^{-15}$  g per milliliter and  $1 \times 10^{-15}$  g per milliliter, respectively.

Figure 2.5 summarizes the ranges of concentrations of 2,4-DNT and TNT vapors likely to be found in surface soils above landmines. To be effective, an explosive vapor detection system must be sensitive to concentrations as low as  $10^{-18}$  g per milliliter if the soil is very dry or as low as  $10^{-15}$  g per milliliter if the soil is moist.

## Biological Methods

Biological detection methods involve the use of mammals, insects, or microorganisms to detect explosives. Like chemical sensors, these methods rely on detection of explosive compounds rather than on detection of metal or changes in the physical properties of the sub-surface. Thus, they have the potential for reducing false alarm rates from metal clutter. Each of the different methods operates on a different set of principles and is at a different stage of development. The oldest involves using trained dogs, which were first shown to be

RANDMR1608-2.5



SOURCE: Adapted from a figure by R. Harmon, Army Research Office.

NOTE: To be effective in all environments, a vapor detector ideally would sense concentrations as low as 10<sup>-18</sup> g per milliliter in dry soil and 10<sup>-15</sup> g per milliliter in moist soil.

**Figure 2.5—Range of Concentrations of 2,4-DNT and TNT in Boundary Layer of Air Near Soil Above Landmines**

capable of smelling landmines in the late 1970s (Johnston et al., 1998). Methods employing insects and microorganisms are newer approaches that have not yet been fielded.

**Dogs and Rats.** *Description.* Mine dog detection teams have long assisted in humanitarian demining efforts. For example, more than 200 mine detection dogs currently are at work in Afghanistan. These dogs can detect mines about 95 percent of the time under favorable weather and soil moisture conditions (Horowitz et al., 1996).

Dogs have a keen sense of smell, originating from their ancestral survival needs to find food, determine territorial boundaries, and sense the presence of enemies (see Appendix T). By offering dogs a reward of food or play, they can be trained to signal when they smell mines. In the mine detection context, dogs walk ahead of their handlers, noses to the ground, and sit at the first scent of a mine (see Figure 2.6). A manual deminer then follows and investigates the area with a probe. In another application, known as Remote Explosive

Scent Tracing mode, dogs sniff at filters that have collected vapors near suspected mine locations. If a dog identifies a filter as containing explosives, then a deminer returns to the location from which the vapor was sampled to look for a mine.

Currently, dogs are capable of detecting explosive vapors at concentrations lower than those measurable by the best chemical sensors, so the lower limit at which they can detect explosives is uncertain (Phelan and Barnett, 2002). One recent study recognized that available laboratory chemical analytical methods are far from the sensitivity limits of the dog. Nevertheless, it attempted to determine the detection threshold for dogs by diluting soil contaminated with explosives to varying levels, two of which were 10 and 100 times lower (based on extrapolation, not detection) than the current chemical detection limit (Phelan and Barnett, 2002). The researchers tested the ability of three different teams of trained dogs (one from the United States, one from Angola, and another from Norway) to identify explosives in samples from the various dilutions. They found that a few of the dogs could correctly identify samples containing an estimated  $10^{-16}$  g per milliliter of TNT or DNT. However, performance varied by many orders of magnitude depending on the individual dog, how it was trained, and the manner in which the training



SOURCE: RONCO Consulting Corp.,  
[www.roncoconsulting.com](http://www.roncoconsulting.com).

**Figure 2.6—Mine-Detecting Dog in Bosnia**

was reinforced. Further, detection performance of the dogs used in this study also appears to have been influenced by environmental conditions associated with the testing location and procedures followed, including the inadvertent use of TNT-contaminated soil samples as “clean” controls in testing at least one group of dogs.

As an alternative to using dogs or in conjunction with using dogs, researchers at the University of Antwerp have trained African giant pouch rats to detect mines. The rats are trained using food rewards to signal the presence of explosives by scratching the ground surface with their feet. Field tests of the use of rats in mine detection have begun.

*Strengths.* Canines are proven to work exceptionally well in many scenarios and under many environmental conditions. The olfactory sensitivity of some, but not all, dogs is higher than the best currently available mechanical detection methods. Advantages of using rats include the possibility that they could be deployed in large numbers and that they do not weigh enough to trigger mines, which reduces the possibility of injury.

*Limitations.* Dog performance varies widely depending on the individual dog, how it was trained, and the capabilities of the handler. Further, dogs may need to be retrained periodically because they can become confused if they discover behaviors other than explosives detection that lead to a reward. An additional limitation is that when trained to detect high levels of explosives, dogs may not automatically detect much lower levels and may need to be specially trained for this purpose. Like other methods that rely on vapor detection, performance of mine detection dogs can be confounded by environmental or weather conditions that cause explosive vapors to migrate away from the mine or that result in concentrations of vapors that are too low even for dogs to detect. Rats likely would have similar limitations.

*Summary Evaluation.* Canines are proven performers and a valuable asset in demining. However, continued investigation of the sensitivity of canine olfaction and how this varies with the dog and with training is necessary to understand the factors that affect reliability. Additionally, the vapor and particle signature of the mine in the field must continue to be investigated to better understand performance

potential for canines. Additional research to explore the potential for deployment of African giant pouch rats in demining also is warranted.

**Bees.** *Description.* By lacing sugar with a target chemical and placing the sugar in the bees' natural foraging area, bees can be trained to associate the chemical odor with food and to swarm over any location containing the target odorant. Entomologists have trained bees to detect a variety of explosives and have been researching ways to use trained bees in humanitarian demining. There are two suggested strategies. The first involves monitoring the movement of bees trained to detect explosives and keeping track of the locations where they swarm. The second involves sampling the beehive for the presence of explosives, which can be transported to the hive on the bees' mop-like hairs.

Several field tests have been conducted to investigate the potential use of bees in mine detection (see Appendix S). The most recent and comprehensive test involved placing DNT in petri dishes, covering the DNT with sand, and placing the dishes in a flat, open space for subsequent detection by the bees. In these experiments, bees proved capable of detecting DNT concentrations that were estimated to be 0.7–13.0 ppb (approximately  $10^{-12}$  g per milliliter). Earlier lab testing had indicated that bees could detect concentrations down to 20 ppt.

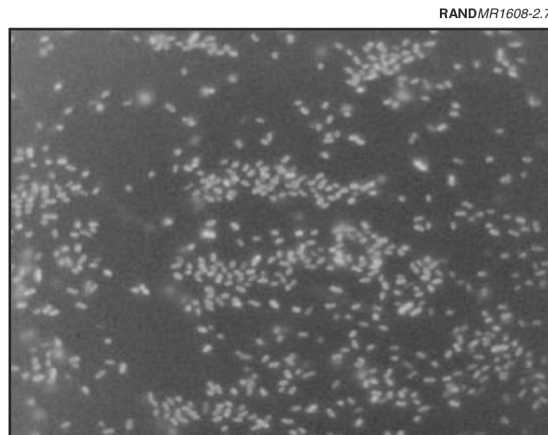
*Strengths.* Trained bees detect explosives and therefore are not limited by the same types of false alarms that plague metal detectors. They also potentially could search a relatively large area in a short time.

*Limitations.* As for chemical and bacterial detection systems, more needs to be understood about the fate and transport of explosives in the subsurface before the full potential of trained bees to detect landmines can be understood. To date, no field trials using actual mines have been conducted. Further, bees can only work under limited environmental and weather conditions. They do not work at all at temperatures below 40°F. In addition, all tests to date have been in clear, open fields; whether bees would perform in forested or other heavily vegetated environments is unknown. The inability to track bee movements also currently poses difficulties.

*Summary Evaluation.* Continued investigation of the use of bees in mine detection is warranted. Experiments under more realistic conditions could give a better indication of the potential of this method. However, clear decision points should be established for determining whether to continue with research funding, if the method continues to look promising, or to terminate it, if there are insurmountable obstacles.

**Bacteria.** *Description.* During the 1990s, researchers engineered a strain of bacteria that fluoresce in the presence of TNT (see Appendix R and Kercel et al., 1997). A regulatory protein in the bacteria recognizes the shape of the TNT molecule and fluoresces whenever the molecule is present (see Figure 2.7). In principle, a bacterial mine detection process would involve spraying bacteria on the mine-affected area, possibly using an airborne system. The bacteria would be allowed to grow for several hours. Then, a survey team would return to search for fluorescent signals. The search could be conducted either from an airborne system or using a handheld fluorescence detector.

One field trial using bacteria has been conducted. Five targets containing from 4 oz to 10 lb (100 g to 5 kg) of TNT were placed in a



SOURCE: [http://attic.jcte.jcs.mil/documents/forerunner\\_07\\_01.pdf](http://attic.jcte.jcs.mil/documents/forerunner_07_01.pdf).

**Figure 2.7—Bacteria Fluorescing in the Presence of TNT**

quarter-acre field site. The bacteria detected all five targets, but there were also two false alarms. Based on this single field trial, it is not possible to determine the lowest concentration of explosive that bacteria are capable of detecting.

*Strengths.* Like chemical sensors, bacteria can be engineered to be highly specific to the explosive of concern. The regulatory protein that causes the bacteria to fluoresce recognizes only TNT and structurally similar molecules. Thus, this method has the potential to reduce false alarms from clutter objects. An additional advantage is that it may allow coverage of a large area in a relatively short time. In theory, the unit cost of this method should decrease as the size of the search area increases.

*Limitations.* The limited research to date has revealed possible environmental limitations of this method. Bacteria are highly sensitive to environmental conditions. The existing strain used to locate TNT cannot survive at extreme temperatures. In addition, the method functions only in moist soil because dry soil quickly absorbs the bacteria. Another limitation is that the potential for false alarms is unknown. For example, the two false alarms in the single field test could have resulted from the migration of explosives away from the targets or from some other chemical in the environment that triggered the fluorescent response. An additional problem in experimental trials was that the fluorescence detector missed some of the signals from the bacteria. Finally, the performance potential of this method will be limited by the fate and transport of explosives in the subsurface. If the explosives migrate away from the mine, then the bacterial signal may occur at a distance from the mine. In addition to these operational limitations, public concerns about introducing genetically engineered organisms into the environment may limit the application of bacteria in mine detection.

*Summary Evaluation.* The potential for using bacteria in mine detection remains largely untested, except for the single field trial referenced in Appendix R. Nonetheless, continued investigation is warranted as long as clear decision points for terminating or continuing funding are established. For example, if research shows that environmental confounding factors (such as moisture conditions and temperature) preclude the use of bacteria in all but an ideal

environment, then research may need to be halted unless bacterial strains can be bred to overcome these limitations.

## Chemical Methods

**Description.** A variety of possible nonbiological mechanisms for detecting low concentrations of explosives in air or in soil samples have been investigated in recent years (see Table 2.1). Most of these investigations resulted from DARPA's "Dog's Nose" program, which sponsored R&D leading to the development of highly sensitive odor detection devices. Some of the techniques were patterned after the mammalian nose. For example, one approach uses arrays of polymer-based sensors that detect explosive vapors (and other volatile chemicals) based on the amount of swelling in the polymers

**Table 2.1**  
**Chemical and Physical Methods for Sensing Explosive Vapors**

Sensor Category	Description	Approximate Detection Limit (g explosive per ml air)
Fluorescent	Measure a change in fluorescence wavelength on the tip of a polymer-coated glass fiber or on an antibody biosensor that occurs in response to the presence of explosives	$10^{-15}$
Electrochemical	Measure changes in electrical resistance of arrays of polymers upon contact with explosive vapors; alternatively, measure changes in electrical properties in coupled electrode pair during reduction or oxidation of explosives	$10^{-12}$
Piezoelectric	Measure shift in resonant frequency of various materials (thin polymer, quartz microcrystal, or other) due to mass change upon exposure to explosive vapor	$10^{-11}$
Spectroscopic	Compare the spectral response of a sample with that of a reference material	$10^{-9}$

caused by exposure to the analyte of concern (Freund and Lewis, 1995; Doleman and Lewis, 2001; Hopkins and Lewis, 2001). These swelling differences, in turn, lead to easily detected changes in electrical resistance of the polymers. Like mammalian noses, these sensors rely on low-level responses of multiple different types of receptors (many polymer types in the case of the mechanical sensors, and many types of receptor proteins in the case of the mammalian nose).

Of the various vapor sensors, a system using novel fluorescent polymers is closest to being deployable and currently has the lowest detection limit, as shown in Table 2.1 (Yang and Swager, 1998; Cumming et al., 2001). The sensor consists of two glass slides, each covered by a thin film of the fluorescent polymer. When a sample of air containing explosives passes between the slides, some of the explosive binds to the polymer and in the process temporarily reduces the amount of fluorescent light that the slides emit. A small photomultiplier device detects the reduced light emission, and electronics signal the operator that explosives are present. Nomadics Inc. has developed a man-portable prototype of this system and has conducted limited field tests (see Figure 2.8). The current system can



SOURCE: Nomadics Inc., [www.nomadics.com](http://www.nomadics.com).

**Figure 2.8—Nomadics' Sensor for Detecting Explosive Vapors**

detect explosive vapor concentrations as low as  $10^{-15}$  g per milliliter, and additional development work is expected to lower this threshold (Cumming et al., 2001).

**Advantages.** Vapor and residue sensors detect explosives and therefore could serve as complements to detection devices that rely on physical features of the mine. In addition, most of the methods have the potential to be engineered as small, lightweight, easily transportable, and simple-to-operate systems with relatively low power requirements. The Nomadics prototype already available is comparable in size to a typical metal detector and, like a metal detector, can operate at a walking pace. It has an extremely low detection threshold ( $10^{-15}$  g per milliliter).

**Limitations.** Perhaps the greatest obstacle that these systems must overcome is the need for a probability of detection of one if they are to replace manual prodders for confirming the presence of mines. No deminer will exchange a conventional prodder for a device that has less than near-perfect probability of detection because of the obvious safety concerns involved. The detection sensitivity of current technologies, with the exception of the fluorescent polymer approach, is not low enough to provide for reliable detection of metal-encased mines in dry soil, and even this method may not perform well in the driest of environments. Another problem is that the presence of explosive residues in soil from sources other than landmines will trigger false alarms. This limitation would apply primarily to battlefield environments because dispersed explosives remaining after weapons are fired will biodegrade over time. Naturally occurring chemicals that react with the polymers also may cause false alarms. For all of these systems, the effects of variations in environmental conditions, especially soil moisture, on performance is not well understood. Further, the location at which explosive vapors are present at the highest concentration is often displaced from the mine location. Current understanding of explosives fate and transport from buried mines is insufficient to allow for the reliable location of a mine based on measurement of the extended explosive vapor signal.

**Summary Evaluation.** Explosive vapor and residue detectors have the potential to be used as confirmatory sensors for landmines if the probability of detection can be increased to near one. Whether this is possible cannot be determined without additional basic research.

Research is necessary to establish the lower limits of detection for the different types of vapor sensors. Also needed are further investigations to allow quantitative modeling of the amounts and locations of explosives available for detection at the surface under different environmental conditions.

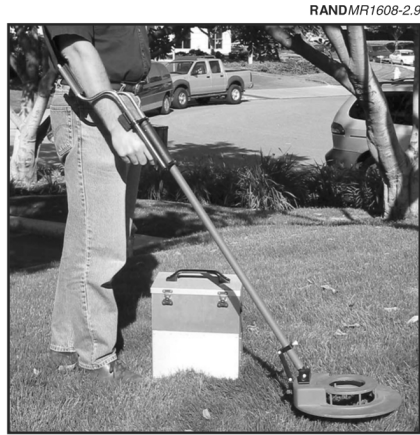
## **BULK EXPLOSIVE DETECTION TECHNIQUES**

Biological and chemical methods for detecting explosive vapors currently are limited by incomplete knowledge of how explosive vapors migrate in the shallow subsurface. An additional category of explosive detection technologies overcomes this limitation by searching for the bulk explosive inside the mine. Methods being explored for this purpose include nuclear quadrupole resonance (NQR) and a variety of methods that use the interaction of neutrons with components of the explosive. These technologies emerged from interest in detecting bulk explosives in passenger baggage for the airline industry and in investigating the potential presence of explosive devices in other settings.

### **Nuclear Quadrupole Resonance**

**Description.** NQR is a radio frequency (RF) technique that can be used to interrogate and detect specific chemical compounds, including explosives. An NQR device induces an RF pulse of an appropriate frequency in the subsurface via a coil suspended above ground (see the prototype in Figure 2.9). This RF pulse causes the explosives' nuclei to resonate and induce an electric potential in a receiver coil. This phenomenon is similar to that exploited by magnetic resonance imaging (MRI) used in medical testing, but NQR uses the internal electric field gradient of the crystalline material rather than an external static magnetic field to initially align the nuclei.

**Strengths.** NQR has a number of features that make it particularly well suited for landmine detection. The primary attraction of NQR is its specificity to landmines: In principle, it signals only in the presence of bulk quantities of specific explosives. Unlike many other technologies, its false alarm rate is not driven by ground clutter but rather by its signal-to-noise ratio (SNR). The SNR increases with the



SOURCE: A. Hibbs, Quantum Applied Science and Research Inc.

**Figure 2.9—Prototype Handheld NQR Mine Detector**

square root of the interrogation time and also increases linearly with the mass of the explosive. Thus, with sufficient interrogation time, NQR can achieve nearly perfect operating characteristics (probability of detection near one with probability of false alarm near zero). This makes NQR more attractive as a confirmation sensor used to interrogate only those locations identified by other detectors (e.g., GPR, EMI) as likely mine locations. Interrogation times of 0.5–3.0 minutes may be sufficient for performance that leads to high probability of detection (more than 0.99) and low probability of false alarm (less than 0.05). The NQR signal from cyclotrimethylenenitramine (RDX) is particularly large, implying high performance and small interrogation times (less than three seconds) for detection of mines containing RDX. Another positive feature of NQR is that it is relatively robust to diverse soil conditions; for example, because it requires bulk concentration of explosives to declare, it is not misled by trace explosive residues as can be the case with vapor-sensing techniques.

**Limitations.** The major weakness of NQR is the fact that, because of its nuclear properties, TNT, which comprises the explosive fill of most landmines, provides a substantially weaker signal than either RDX or tetryl, posing a formidable SNR problem. Moreover, TNT

inherently requires longer interrogation times because its nuclear properties preclude interrogation more frequently than once per five to ten seconds. Another significant limitation is the susceptibility of NQR to RF interference from the environment. This is especially problematic for TNT detection because the frequencies required to induce a response from TNT (790–900 kHz) are in the AM radio band. When present, radio signals overwhelm the response from TNT.

An additional weakness is that NQR cannot locate explosives that are encased in metal because the RF waves will not penetrate the case. This is not a major weakness because a large majority of antipersonnel mines have plastic cases, and EMI detection can successfully detect those with metal cases. NQR also cannot detect liquid explosives, but very few antipersonnel mines use liquid explosives.

NQR is very sensitive to the distance between the detection coil and the explosive. Therefore, the detection coil must be operated very close to the ground, which can be problematic in rough or highly vegetated terrain. Moreover, current implementations require stationary detection for optimal results; detection in motion substantially degrades the SNR.

**Summary Evaluation.** NQR is an explosive-specific detection technology that offers considerable promise as a technique for reducing false alarms as compared with such conventional detection approaches as EMI. It offers opportunities for improvement not addressed by competing technologies—most notably that its potency derives from unique explosive signatures of mines. In principle, this specificity affords it the possibility of a zero false alarm rate against nonmetal mines. Currently, the most promising role of NQR is that of a confirmation sensor used in conjunction with a conventional scanning sensor or as part of an integrated multisensor detection system.

## Neutron Methods

**Description.** Neutron interrogation techniques involve distinguishing the explosives in landmines from surrounding soil materials by probing the soil with neutrons and/or detecting returning neutrons. Differences in the intensity, energy, and other characteristics of the

returning radiation can be used to indicate the presence of explosives.

Only three of the many possible reactions involving neutrons or gamma rays have reasonable potential for landmine detection. The first, *thermal neutron analysis*, is the only nuclear technique that is currently fielded by a military: The Canadian military uses it as a vehicle-mounted confirmatory detector for antitank mines (see Appendix N). Size and weight limits imposed by physics preclude it from being person-portable or being able to detect small antipersonnel mines in practical applications. The second method, known as *fast neutron analysis*, has similar limitations. The third method, *neutron moderation*, is the only one of the three with the potential to yield a person-portable detector for antipersonnel mines. Neutron moderation discerns buried materials with low atomic numbers (e.g., hydrogen).

**Strengths.** The physical properties of neutron moderation allow the technology to use low-strength source radiation, which reduces shielding required to protect workers from radiation exposure. Thus, designing a handheld system may be possible. Costs of a production imager are expected to be moderate.

**Limitations.** Neutron activation methods can, at best, measure relative numbers of specific atoms but cannot determine what molecular structure is present. Because neutron moderation is most sensitive to hydrogen, hydrogenous materials, particularly water, produce many false alarms. Thus, to detect landmines successfully, it is necessary to use the response from the neutrons to generate a visual image of the area under investigation. Simulations show that the method will work in soil with 10-percent moisture or less and may be usable when moisture content is as high as 20 percent. Ground-surface fluctuations and sensor height variation also contribute to false alarms in nonimaging systems. Imaging can reduce these effects, although some degradation of the image is expected.

With sources having sufficiently low strength to be practical for handheld use, a few seconds will be required to acquire an image. This makes neutron moderation imaging more suitable for confirmation than for primary detection. Also, there is a perceived (more than actual) radiation hazard associated with nuclear techniques

that must be overcome by the users. Broad-area, low-power electronic neutron sources, under development by Defence R&D Canada, could reduce this perceived risk.

**Summary Evaluation.** The majority of neutron technologies have physical limitations that preclude them from being portable. Only one technology—neutron moderation imaging—may be useful for handheld confirmation of antipersonnel landmines. In fielded systems, images of these mines are likely to appear as fuzzy blobs, but that will still allow mines to be distinguished from most diffuse or elongated false alarms generated by moisture. On balance, however, neutron moderation imaging is very unlikely to yield substantial improvements in detection speed beyond what is capable with other confirming detectors.

## INNOVATIVE PRODDERS AND PROBES

The last step in mine detection has long been probing manually to determine whether a signaled item is a mine or just harmless clutter. The probe operator learns through experience to feel or hear the difference between a mine casing and other buried objects. Probing is dangerous. Deminers often inadvertently apply sufficient force to the mine to detonate it. This excess force does not always cause the mine to explode, but when it does, the probe itself can become a deadly projectile. New concepts are being explored to improve the safety of probing and to help discriminate mines from clutter.

### Description

Research to improve prodders and probes has followed two lines of investigation: (1) development of probes that would signal to the deminer when too much force is being applied and (2) development of “smart” probes that provide information about the characteristics of the item being investigated. These latter probes are intended to provide information about some physical, electromagnetic, or chemical characteristic of the object being investigated in order to identify it. The only such probe engineered to date delivers an acoustic pulse to determine whether the object is plastic, metal, rock, or wood (see Appendix W). Performance of this smart probe was mixed in limited testing: In a Canadian test, it correctly identified 80

percent of the mines, but in a U.S. test it identified only 69 percent of the mines. An improved version identified 97 percent of the mines in a Canadian test. An alternative type of smart probe that is in the research stage sprays focused jets of cold or heated water at regular intervals to detect mines by sound or thermal signature.

### **Strengths**

Probing is an established step in manual demining. Improved probes could decrease the risks to deminers by providing feedback about the nature of the object being investigated. In addition, theoretically, a probe could deliver any of a number of different detection methods (acoustic, electromagnetic, thermal, chemical, etc.), and the proximity of the probe to the landmine could improve performance. For example, methods based on identifying explosive vapors likely would perform better in close proximity to the mine, where vapor concentrations are much greater than those on the surface. However, such advanced probes have yet to be developed.

### **Limitations**

Any improved probe must essentially identify mines 100 percent of the time to be accepted by the demining community. This is because deminers view their current conventional probes as 100-percent accurate. Some field testing has borne this out: A conventional military prodder in one field experiment correctly distinguished between 38 mines and 119 rocks (see Appendix W). In addition, instrumented probes may not be useful in dense ground or in ground with extensive root structures.

### **Summary Evaluation**

Because the probe is likely to remain part of the deminer's tool kit for the foreseeable future, limited efforts to develop more sophisticated probes should continue. To be useful in speeding up demining operations, probes must be able to identify rapidly and accurately whether the detected item is a mine or another object. Research should continue on instrumented probes with detection devices that analyze the material content of the item under investigation. To

increase probe safety, work should continue to develop probes that indicate the level of force being applied.

### **ADVANCED SIGNAL PROCESSING AND SIGNATURE MODELING**

This chapter described a diverse range of innovative sensors for obtaining signals that indicate the presence of landmines. Underlying nearly all of these technologies are algorithms that translate these signals into information that can be used (by either a human operator or an automated system) to make a declaration decision. Traditionally, these algorithms have been very simple and have focused on detecting anomalies in the subsurface, as opposed to providing information about the size, shape, or chemical content of the object. For example, conventional handheld EMI detectors provide information only about the strength of the return signal. Typically, the frequency of the audible tone increases as the received signal strength increases. The operator then decides what signal strength to use as an indicator of the possible presence of a mine. Without the additional step of discriminating background clutter from legitimate targets, the number of false alarms is large and hampers the detection and clearance process.

The primary goal of advanced signal-processing algorithms is to maximize the use of information generated by the sensor to help discriminate targets from background clutter. Recent efforts have combined information from physical models specific to the particular sensor technology, statistical analyses of the generated signals, and spatial information to achieve this goal (see Appendixes U and V). Advanced algorithms leveraging statistical models have been shown to reduce the false alarm rate for EMI, GPR, and combined sensors in certain settings (Collins et al., 2002; Lewis et al., 2002; Witten et al., 2002). Because of fundamental physical limitations of the technologies, no amount of signal processing will eliminate all false alarms from EMI and GPR systems. Nonetheless, such advanced algorithms are important to improving mine detection technologies. For nearly all types of sensors, advanced algorithms could be or are being developed that make efficient use of the generated signal to improve operating characteristics. More important, advanced signal-processing and signal fusion methods are crucial to

the development of next-generation mine detection systems discussed in the next chapter.