# SUMMARY

Antipersonnel mines remain a significant international threat to civilians despite recent intense efforts by the United States, other developed countries, and humanitarian aid organizations to clear them from postconflict regions. Mines claim an estimated 15,000–20,000 victims per year in some 90 countries. They jeopardize the resumption of normal activities—from subsistence farming to commercial enterprise—long after periods of conflict have ceased. For example, in Afghanistan during 2000, mines claimed 150–300 victims per month, half of them children. Although most of these mines were emplaced during the Soviet occupation of Afghanistan (from 1979 to 1988), they continue to pose a serious risk to returning refugees and have placed vast tracts of farmland off limits. The United States currently invests about $100 million annually in humanitarian mine clearance—the largest commitment of any country. Despite this investment and the funding from many other developed nations and nongovernmental organizations, at the current rate clearing all existing mines could take 450–500 years.

This report addresses the following questions:

- What innovative research and development (R&D) is being conducted to improve antipersonnel mine detection capabilities?
- What is the potential for each innovative technology to improve the speed and safety of humanitarian demining?
- What are the barriers to completing development of innovative technologies?

- What funding would be required, and what are the options for federal investments to foster development of promising mine detection technologies?

We focus on close-in detection of antipersonnel mines rather than on airborne or other remote systems for identifying minefields.

The report was written by RAND S&TPI staff and a task force of eight experts in mine detection from universities and U.S. and Canadian government agencies. In addition, 23 scientists provided background papers with details on specific mine detection technologies; these papers are published in this report as separate appendixes.

## LIMITATIONS OF CONVENTIONAL MINE DETECTION TECHNOLOGIES

The tools available to mine detection teams today largely resemble those used during World War II. A deminer is equipped with a hand-held metal detector and a prodding device, such as a pointed stick or screwdriver. The demining crew first clears a mined area of vegetation and then divides it into lanes of about a meter wide. A deminer then slowly advances down each lane while swinging the metal detector low to the ground. When the detector signals the presence of an anomaly, a second deminer probes the suspected area to determine whether it contains a buried mine.

The overwhelming limitation of the conventional process is that the metal detector finds every piece of metal scrap, without providing information about whether the item is indeed a mine. For example, of approximately 200 million items excavated during humanitarian demining in Cambodia between 1992 and 1998, only about 500,000 items (less than 0.3 percent) were antipersonnel mines or other explosive devices. The large number of false alarms makes humanitarian mine detection a slow, dangerous, and expensive process. Every buried item signaled by the detector must be investigated manually. Prodding with too much force, or failure to confirm the presence of a mine during probing, can lead to serious injury or death. Adjusting a conventional detector to reduce the false alarm rate results in a simultaneous decrease in the probability of finding a mine, meaning more mines will be left behind when the demining operation is completed. For humanitarian demining, trading off reductions in false alarms for reductions in the likelihood of finding buried mines is unacceptable.

## CAPABILITIES OF INNOVATIVE MINE DETECTION TECHNOLOGIES

Research is under way to develop new detection methods that search for characteristics other than metal content. The aim of these methods is to substantially reduce the false alarm rate while maintaining a high probability of detection, thereby saving time and reducing the chance of injury to the deminer. Table S.1 summarizes these methods. The second column indicates the detection principle on which each is based. The remaining columns summarize the strengths, limitations, and performance potential of each. Chapter Two and the appendixes provide detailed reviews of each technology.

As shown in Table S.1, no single mine detection technology can operate effectively against all mine types in all settings. For example, nuclear quadrupole resonance can find mines containing the explosive cyclotrimethylenenitramine (known as royal demolition explosive [RDX]) relatively quickly, but it is slow in confirming the presence of trinitrotoluene (TNT). Acoustic mine detection systems have demonstrated very low false alarm rates, but they cannot find mines buried at depths greater than about one mine diameter. Chemical vapor sensors can find plastic mines in moist soils, but they have difficulty locating metal mines in dry environments.

Given the limitations of individual sensor technologies, major breakthroughs in mine detection capability are likely to occur only with the development of a multisensor system. The multisensor system we envision would combine two or more of the technologies listed as "promising" in Table S.1 and would leverage advanced algorithms that would process the raw signals in concert to determine whether they are consistent with known mine characteristics. Rather than bringing together two commercially available technologies to form the combined sensor platform, the technology optimization and integration would occur at the design stage, and the development of

**Table S.1**

**Summary of the Detection Technologies Reviewed**

| Technology | Operating Principle | Strengths | Limitations | Potential for Humanitarian Mine Detection |
|---|---|---|---|---|
| **Electromagnetic** | | | | |
| Electromagnetic induction | Induces electric currents in metal components of mine | Performs in a range of environments | Metal clutter; low-metal mines | Established technology |
| Ground-penetrating radar | Reflects radio waves off mine/soil interface | Detects all anomalies, even if nonmetal | Roots, rocks, water pockets, other natural clutter; extremely moist or dry environments | Established technology |
| Electrical impedance tomography | Determines electrical conductivity distribution | Detects all anomalies, even if nonmetal | Dry environments; can detonate mine | Unlikely to yield major gains |
| X-ray backscatter | Images buried objects with x rays | Advanced imaging ability | Slow; emits radiation | Unlikely to yield major gains |
| Infrared/hyperspectral | Assesses temperature, light reflectance differences | Operates from safe standoff distances and scans wide areas quickly | Cannot locate individual mines | Not suitable for close-in detection |
| **Acoustic/Seismic** | Reflects sound or seismic waves off mines | Low false alarm rate; not reliant on electromagnetic properties | Deep mines; vegetation cover; frozen ground | Promising |

**Table S.1—continued**

| Technology | Operating Principle | Strengths | Limitations | Potential for Humanitarian Mine Detection |
|---|---|---|---|---|
| **Explosive Vapor** | | | | |
| Biological (dogs, bees, bacteria) | Living organisms detect explosive vapors | Confirms presence of explosives | Dry environments | Basic research needed to determine potential (though dogs are widely used) |
| Fluorescent | Measures changes in polymer fluorescence in presence of explosive vapors | Confirms presence of explosives | Dry environments | Basic research needed to determine operational potential |
| Electrochemical | Measures changes in polymer electrical resistance upon exposure to explosive vapors | Confirms presence of explosives | Dry environments | Basic research needed to determine whether detection limit can be reduced |
| Piezoelectric | Measures shift in resonant frequency of various materials upon exposure to explosive vapors | Confirms presence of explosives | Dry environments | Basic research needed to determine whether detection limit can be reduced |
| Spectroscopic | Analyzes spectral response of sample | Confirms presence of explosives | Dry environments | Basic research needed to determine whether detection limit can be reduced |

**Table S.1—continued**

| Technology | Operating Principle | Strengths | Limitations | Potential for Humanitarian Mine Detection |
|---|---|---|---|---|
| **Bulk Explosives** | | | | |
| Nuclear quadrupole resonance | Induces radio frequency pulse that causes the chemical bonds in explosives to resonate | Identifies bulk explosives | TNT; liquid explosives; radio frequency interference; quartz-bearing and magnetic soils | Promising |
| Neutron | Induces radiation emissions from the atomic nuclei in explosives | Identifies the elemental content of bulk explosives | Not specific to explosives molecule; moist soil; ground-surface fluctuations | Unlikely to yield major gains |
| **Advanced Prodders/ Probes** | Provide feedback about nature of probed object and amount of force applied by probe | Could deploy almost any type of detection method | Hard ground, roots, rocks; requires physical contact with mine | Promising |

algorithms for advanced signal processing would be an integral part of the process. The result would be a single, highly sensitive, and performance-optimized detection system that provides one specific signal to the operator. The Army countermine program currently is developing a dual-sensor system that combines separate electromagnetic induction (EMI) and ground-penetrating radar (GPR) technologies as part of a single operational platform known as the Handheld Standoff Mine Detection System (HSTAMIDS). However, HSTAMIDS does not use advanced signal processing. Rather, the operator receives two separate outputs: one from the EMI device and one from the GPR. This dual-sensor system does not make optimal use of the totality of information available from the combined sensors.

Advances in signal processing and understanding of single-sensor systems make the development of a multisensor system with a single signal possible in principle. Preliminary research has shown the potential for multisensor systems to reduce the number of false alarms by as much as a factor of 12. However, additional research is needed to establish a comprehensive technical basis for the design of such a system. Based on the time and costs required to create HSTAMIDS ($73 million over 15 years), we estimate that the new multisensor system would require a total investment of $135 million. Currently, the United States is not funding the necessary research. In 2002, the United States invested $2.7 million for close-in mine detection R&D for humanitarian demining. Of this amount, nearly $2.0 million went to making incremental improvements to existing EMI and GPR systems, and the rest funded research on explosive chemical vapor detection systems. No funding was allocated toward research that would lead to the development of an integrated multisensor system for humanitarian demining.

At the outset of this project, the Office of Science and Technology Policy asked RAND S&TPI whether development of an innovative mine detection system could enable mine clearance to advance 10 times faster than is currently possible. A multisensor system could reduce the false alarm rate by a factor of 10 or more. However, gains in mine clearance speed are not directly proportional to reductions in the false alarm rate because a substantial portion of the total clearance time is spent on site preparation activities, such as vegetation clearance. Very limited research has been conducted to date to analyze actual mine clearance data for determining what gains are theoretically possible with improved detection systems. The existing, limited research predicts that a system that eliminated 99 percent of false alarms would improve overall clearance rates by 60–300 percent of current rates, depending on the amount of vegetation present. Such gains would save billions to tens of billions of dollars in the total cost expected to clear all mines and would spare a large number of deminer and civilian lives. Pursuing development of an advanced multisensor system is worthwhile, even if order-of-magnitude decreases in clearance time are not possible with improved detection technology alone.

## RECOMMENDATION: INITIATE AN R&D PROGRAM TO DEVELOP A MULTISENSOR SYSTEM

We recommend that the federal government undertake an R&D effort to develop a multisensor mine detection system. The first step in developing the program should be a short, preliminary study (costing less than $1 million) to consolidate existing theoretical and empirical research related to multisensor systems and signal processing. This preliminary study would be used to develop a blueprint for the R&D needed to produce a prototype system. We estimate that initial prototype development would cost approximately $60 million. The program should address the following four broad areas:

- algorithmic fusion of data from individual sensors (to develop the theory necessary to support an advanced multisensor system), funded at approximately $2.0–3.2 million per year;
- integration of component technologies (to address system engineering issues associated with combining multiple sensors as part of a single-sensor platform), funded at approximately $1.25–2.00 million per year;
- methods for detecting the chemical components of explosives (to further develop components of the multisensor system that would search for explosives rather than for the mine casing and mechanical components), supported at approximately $2.5–4.0 million per year; and

- techniques for modeling how soil conditions in the shallow subsurface environment affect various mine sensors (to allow predictions of integrated sensor system performance across the broad range of natural environments in which mines occur), funded at $500,000–800,000 per year.

Depending on the amount of resources invested in this research, a prototype multisensor system could be available within seven years. Once the prototype is developed, additional allocations totaling approximately $135 million will be needed to fund the engineering and development of an optimal, deployable system.

The benefits of a program to develop an advanced, multisensor system would include more rapid capability to help restore stability to postconflict regions, such as Afghanistan; more mines cleared per U.S. dollar spent on humanitarian demining; fewer deminer and civilian casualties; and utility to military countermine operations. In addition, the results of R&D on advanced signal processing and sensor fusion would be transferable to other applications in environmental, geophysical, medical, and other sciences.