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GAO

Report to Congressional Committees

June 2005

GROUNDWATER CONTAMINATION

DOD Uses and Develops a Range of Remediation Technologies to Clean Up Military Sites

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Highlights

Highlights of GAO-05-666, a report to congressional committees

June 2005

GROUNDWATER CONTAMINATION

DOD Uses and Develops a Range of Remediation Technologies to Clean Up Military Sites

Why GAO Did This Study

To date, the Department of Defense (DOD) has identified nearly 6,000 sites at its facilities that require groundwater remediation and has invested $20 billion over the past 10 years to clean up these sites. In the past, DOD primarily used “pump-and-treat” technologies to contain or eliminate hazardous contaminants in groundwater. However, the long cleanup times and high costs of using pump-and-treat technologies often make them expensive and ineffective for groundwater remediation.

As directed by Public Law 108-375 and as agreed, GAO (1) described current DOD groundwater remediation technologies and (2) examined whether any new technologies are being used or developed outside the department that may have potential for DOD’s use and the extent to which DOD is researching and developing new approaches to groundwater remediation.

GAO provided the Department of Defense with a draft copy of the report for its review and comment. DOD generally agreed with the contents stating that the report is an accurate summary of DOD’s use and field tests of remedial technologies. DOD also provided technical clarifications that have been incorporated, as appropriate.

www.gao.gov/cgi-bin/getrpt?GAO-05-666.

To view the full product, including the scope and methodology, click on the link above. For more information, contact Anu K. Mittal at (202) 512-3841 or mittala@gao.gov.

What GAO Found

DOD has implemented or field-tested all of the 15 types of generally accepted technologies currently available to remediate contaminated groundwater, including several alternatives to pump-and-treat technologies. Some of these technologies, such as bioremediation, introduce nutrients or other materials into the subsurface to stimulate microorganisms in the soil; these microorganisms consume the contaminant or produce byproducts that help break down contaminants into nontoxic or less-hazardous materials. DOD selects the most suitable technology for a given site on the basis of several factors, such as the type of contaminant and location in the subsurface, and the relative cost-effectiveness of a technology for a given site. DOD has identified a number of contaminants of concern at its facilities, each of which varies in its susceptibility to treatment. The table below shows the technologies DOD used to remediate contaminated groundwater.

GAO did not identify any alternative groundwater remediation technologies being used or developed outside DOD that the department has not considered or used. Most of the new approaches developed by commercial vendors and available to DOD generally use novel materials applied to contaminated sites with existing technologies. DOD actively researches and tests new approaches to groundwater remediation largely by developing and promoting the acceptance of innovative remediation technologies. For example, DOD’s Strategic Environmental Research and Development Program supports public and private research on contaminants of concern to DOD and innovative methods for their treatment.

Technologies DOD Components Used for Groundwater Remediation

Technology	Air Force	Army	Army Corps of Engineers	Defense Logistics Agency	Navy
In-situ					
Air sparging	X	X	X	X	X
Bioremediation	X	X	X	X	X
Enhanced recovery	X			X	X
Chemical treatments	X	X	X	X	X
Monitored natural attenuation	X	X	X	X	X
Multiphase extraction	X	X	X	X	X
Permeable reactive barriers	X	X	X	X	X
Phytoremediation	X	X	X		X
Thermal treatments	X	X	X		X
Ex-situ					
Advanced oxidation processes	X	X	X		X
Air stripping	X	X	X	X	X
Bioreactors		X	X		X
Constructed wetlands	X	X	X		X
Ion exchange	X	X	X		X
Adsorption (mass transfer)	X	X	X	X	X

Source: Department of Defense.

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Abbreviations

CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
DNAPL	dense nonaqueous phase liquids
DOD	Department of Defense
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
ITRC	Interstate Technology and Regulatory Council
LNAPL	light nonaqueous phase liquids
RCRA	Resource Conservation and Recovery Act
SERDP	Strategic Environmental Research and Development Program

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United States Government Accountability Office
Washington, D.C. 20548

June 30, 2005

The Honorable John Warner
Chairman
The Honorable Carl Levin
Ranking Minority Member
Committee on Armed Services
United States Senate

The Honorable Duncan L. Hunter
Chairman
The Honorable Ike Skelton
Ranking Minority Member
Committee on Armed Services
House of Representatives

The Department of Defense (DOD) has identified close to 6,000 sites at its active, closing, and formerly used defense facilities where the groundwater has been so contaminated by past defense activities and the improper disposal of hazardous wastes that cleanup (remediation) of the site is required.[1] Groundwater—the water found beneath the earth's surface that fills pores between soil particles, such as sand, clay, and gravel, or that fills cracks in bedrock—accounts for about 50 percent of the nation's municipal, domestic, and agricultural water supply. When groundwater becomes polluted, it can endanger public health or threaten the environment. DOD estimates that cleanup of its contaminated sites will cost billions of dollars and may take decades to complete because of the extent of the contamination and the complexity of groundwater systems.

DOD identifies, investigates, and cleans up contaminated groundwater through its Defense Environmental Restoration Program. This program was established by section 211 of the Superfund Amendments and Reauthorization Act of 1986, which amended the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. In fiscal year 2004, DOD obligated approximately $1.7 billion for environmental restoration activities, including groundwater remediation, on active, closing, and formerly used defense facilities. Multiple DOD

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[1] Remediation of a contaminated site involves efforts to remove, destroy, or isolate contaminants found in the groundwater. In some cases, disposal practices at these sites predate the enactment of relevant environmental cleanup statutes.

entities—the Air Force, Army, Defense Logistics Agency, and Navy—are responsible for groundwater remediation on active DOD facilities.[2] In addition, the U.S. Army Corps of Engineers (Corps) is responsible for groundwater remediation on properties formerly owned, leased, or used by the military.[3] The Air Force has the greatest number of sites with contaminated groundwater needing remediation, followed by the Navy, Army, Corps, and Defense Logistics Agency.[4] DOD must carry out its groundwater remediation program in a manner consistent with section 120 of CERCLA. Section 120 addresses the cleanup of federal facilities and, among other things, provides for participation in cleanup decisions by the state in which a federal facility is located. Personnel from the installation where the contamination is located work with DOD-hired contractors; regulators (federal, state, local, or tribal); and other stakeholders to evaluate and select appropriate technologies to achieve cleanup goals (e.g., treatment or containment of contaminants). DOD may use a single technology or a combination of technologies to clean up the groundwater at a particular site.

In the past, DOD primarily used traditional “pump-and-treat” technologies to contain or eliminate hazardous contaminants in groundwater. Pump-and-treat technologies extract contaminated groundwater for treatment in above-ground (ex-situ) facilities and are often used to prevent the further spread of contamination in the groundwater. However, according to DOD, the Environmental Protection Agency (EPA), and groundwater remediation experts we consulted, pump-and-treat often is expensive because of long cleanup times, inefficiencies in removing contaminants from the subsurface, and the costs associated with disposing of the contaminant and treated water. Recently, DOD has begun to use alternatives to pump-and-treat technologies that rely on a variety of biological, chemical, or physical processes to treat the contaminated groundwater underground (in-situ).

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[2] The Navy oversees environmental restoration on Marine Corps facilities.

[3] The Corps may also participate in groundwater remediation activities on active Army installations, some Air Force installations, and properties that are scheduled for closure as part of the Base Realignment and Closure Act process.

[4] For the purposes of this report, we have defined a “site” as a specific area of contamination and a “facility” as a geographically contiguous area under DOD’s ownership or control within which a contaminated site or sites are located. A single DOD facility may contain multiple sites requiring cleanup.

As directed by Public Law 108-375,[5] and as agreed with your offices, this report (1) describes the groundwater remediation technologies that DOD is currently using or field-testing and (2) examines whether any new groundwater remediation technologies are being used outside the department or are being developed by commercial vendors that may have potential for DOD's use, and the extent to which DOD is researching and developing new approaches to groundwater remediation. In addition, this report provides limited information on the key characteristics, benefits, and limitations of selected groundwater remediation technologies in appendix II.

GAO Definition of Groundwater Remediation Technology

For this report, we define a technology as a distinct technical method or approach for containing, treating, or removing contaminants found in groundwater.

Any modifications or enhancements to a technology, such as variations in the material or equipment used during treatment, are not considered to be a separate technology.

To determine the range of groundwater remediation technologies DOD is currently using or field-testing, we developed a questionnaire that we sent to the DOD components responsible for DOD's groundwater cleanup efforts—the Air Force, Army, Corps, Defense Logistics Agency, and Navy. In the questionnaire, we listed 15 technologies that are currently available for the treatment of contaminated groundwater and asked the DOD components to indicate which of the technologies they have used and to provide examples of specific groundwater remediation projects.[6] We developed this list of technologies by reviewing existing lists developed by the National Research Council, EPA, and others, as well as by working with a groundwater remediation consulting firm and five nationally recognized groundwater remediation experts. To identify DOD components involved with groundwater remediation activities, we met with department officials responsible for developing policy on groundwater remediation and for researching and developing groundwater remediation technologies. We reviewed documents, reports, and guidance on groundwater remediation from DOD, EPA, and the National Academy of Sciences; and visited an Air Force groundwater remediation project and a facility DOD uses to test innovative groundwater remediation technologies. In addition, we attended a national groundwater remediation conference, and spoke with a number of commercial vendors of groundwater remediation technologies about their products and efforts to develop innovative approaches to groundwater remediation. Information presented in this report is based on publicly available documents and information provided by government officials, independent consultants, and experts. We did not review

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[5] Ronald W. Reagan National Defense Authorization Act for Fiscal Year 2000, Pub. L. No. 108-375, § 316, 118 Stat. 1811, 1843 (Oct. 28, 2004).

[6] See appendix II for more information on each of the 15 technologies.

nonpublic research and development activities that may be ongoing in private laboratories. A more detailed description of our scope and methodology is presented in appendix I. We performed our work from January 2005 through May 2005, in accordance with generally accepted government auditing standards.

Results in Brief

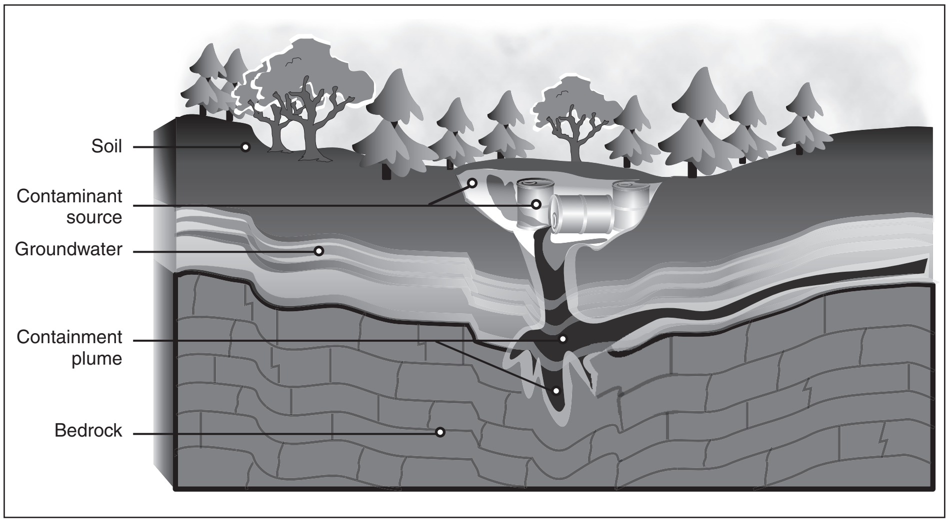
DOD has implemented or field-tested all of the 15 types of generally accepted technologies currently available to remediate groundwater. These various remediation technologies include both in-situ and ex-situ treatments, each of which relies on biological, chemical, or physical processes to clean up groundwater. Of these 15 types of technologies, the Navy reported that it has used all 15 and the Air Force, Army, and Corps have used 14 each. The Defense Logistics Agency, which has significantly fewer sites to clean up than the other DOD components, reported using 9 of the 15 technologies. According to department officials, DOD selects the most suitable technology for a given site on the basis of a number of factors, such as the type of contaminant and its location in the subsurface, and the relative cost-effectiveness of a technology for a given site. DOD has identified a number of contaminants of concern at its facilities, each of which varies in its behavior and susceptibility to treatment by the various technologies. Some of the contaminants, such as chlorinated solvents, can potentially be treated using 14 of the 15 technologies, while others, such as metals, can only be treated effectively with 7 of the 15 technologies. According to analyses conducted by groups such as EPA and the Federal Remediation Technologies Roundtable, the cost-effectiveness and performance of each technology can vary significantly depending, in part, on site-specific conditions. A more detailed description of each of the technologies we identified for cleaning up groundwater is presented in appendix II.

We did not identify any alternative technologies for groundwater remediation being used or developed outside of DOD that it has not considered or employed. However, we did identify a number of new approaches to groundwater remediation being developed by commercial vendors—most of which are also being explored or used by DOD—that are based on modifications of or enhancements to existing technologies. Most of the new approaches involve the use of novel materials applied to contaminated sites using existing technologies. For example, DOD has recently used molasses and vegetable oils at several bioremediation projects to stimulate microorganisms in the subsurface to biodegrade contaminants. Other alternative approaches being developed by commercial vendors usually involve modifying the design of existing technologies. For example, DOD is exploring the use of nanoscale rather than granular sized metals to clean up sites contaminated by chlorinated solvents. In addition, we found that DOD is actively involved in researching and testing new approaches to groundwater remediation, largely through its efforts to develop and promote the acceptance of innovative technologies. For example, DOD maintains several programs—such as the Strategic Environmental Research and Development Program—to support the research, development, and testing of innovative cleanup approaches. This program, a DOD-funded basic and applied research program, supports public and private research on contaminants of concern to DOD and innovative methods for their treatment, as well as a variety of other activities. DOD also pursues innovative solutions to groundwater remediation through its Environmental Security Technology Certification Program. This program field-tests and validates promising innovative environmental technologies and transfers these technologies to the commercial sector. DOD also works with various stakeholders, including the regulatory community, to promote understanding and acceptance of innovative remediation approaches. For example, DOD participates in the Interstate Technology and Regulatory Council, a state-led coalition that works with the private sector, regulators, and other stakeholders to increase the regulatory acceptance of new environmental technologies.

Background

DOD sites that require cleanup are often contaminated by many different types of hazardous materials, have contamination in more than one medium (e.g., soil, surface water, or groundwater), and may encompass several acres or even square miles. Groundwater stored in subsurface formations called aquifers can become contaminated in a number of ways. For example, contamination can occur when a liquid hazardous substance soaks down through the soil. Often, groundwater contamination is difficult to address because of the complexity of groundwater systems. The subsurface environment can be composed of numerous layers of diverse types of material—such as sand, gravel, clay, and solid rock—and fractured layers through which groundwater flows. These variations in the subsurface often affect how groundwater flows through a contaminated site and can influence how contaminants are spread and accumulate in the subsurface. Chemical properties of the contaminant also influence its distribution in the subsurface. Typically, contaminated sites consist of a source zone where the bulk of the contaminant is concentrated and a plume of contamination that develops beyond the source of contamination as a result of groundwater flowing through the contaminated site. See figure 1 for an illustration of a site with contaminated groundwater.

Figure 1: Example of a Site with Contaminated Groundwater



Source: Adapted from EPA, Fact Flash #5, Groundwater.

DOD Facilities Can Have Significant Groundwater Contamination

According to DOD, the Air Force has identified more than 2,500 sites on its active and closing installations with contaminated groundwater; the Navy has identified more than 2,000 sites; the Army has identified about 800 sites; and the Defense Logistics Agency has identified 16 sites. In addition, DOD has identified more than 500 contaminated groundwater sites on formerly used defense sites for which the Corps is responsible for cleanup. Contamination on DOD facilities can pose a threat to military personnel, the public, and the sustainability of DOD's training and testing ranges. DOD first initiated its environmental restoration efforts in 1975. Over the last 10 years, DOD has invested approximately $20 billion for the environmental restoration of contaminated sites, including remediation of contaminated groundwater on and around active, closing, and formerly used defense facilities.[7]

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[7] Some of DOD's sites are considered megasites—defined by EPA as sites requiring investments of over $50 million to achieve cleanup.

DOD Cleanup Activities Generally Follow the CERCLA Process

DOD's policies for administering cleanup programs are outlined in its guidance for managing its environmental restoration program and generally follow the CERCLA process for identifying, investigating, and remediating sites contaminated by hazardous materials.[8] According to DOD's guidance, department officials are required to involve EPA, relevant state and local government officials, and the public, among others, at specified points in the cleanup process. See figure 2 for more information on the phases of DOD's environmental cleanup process.

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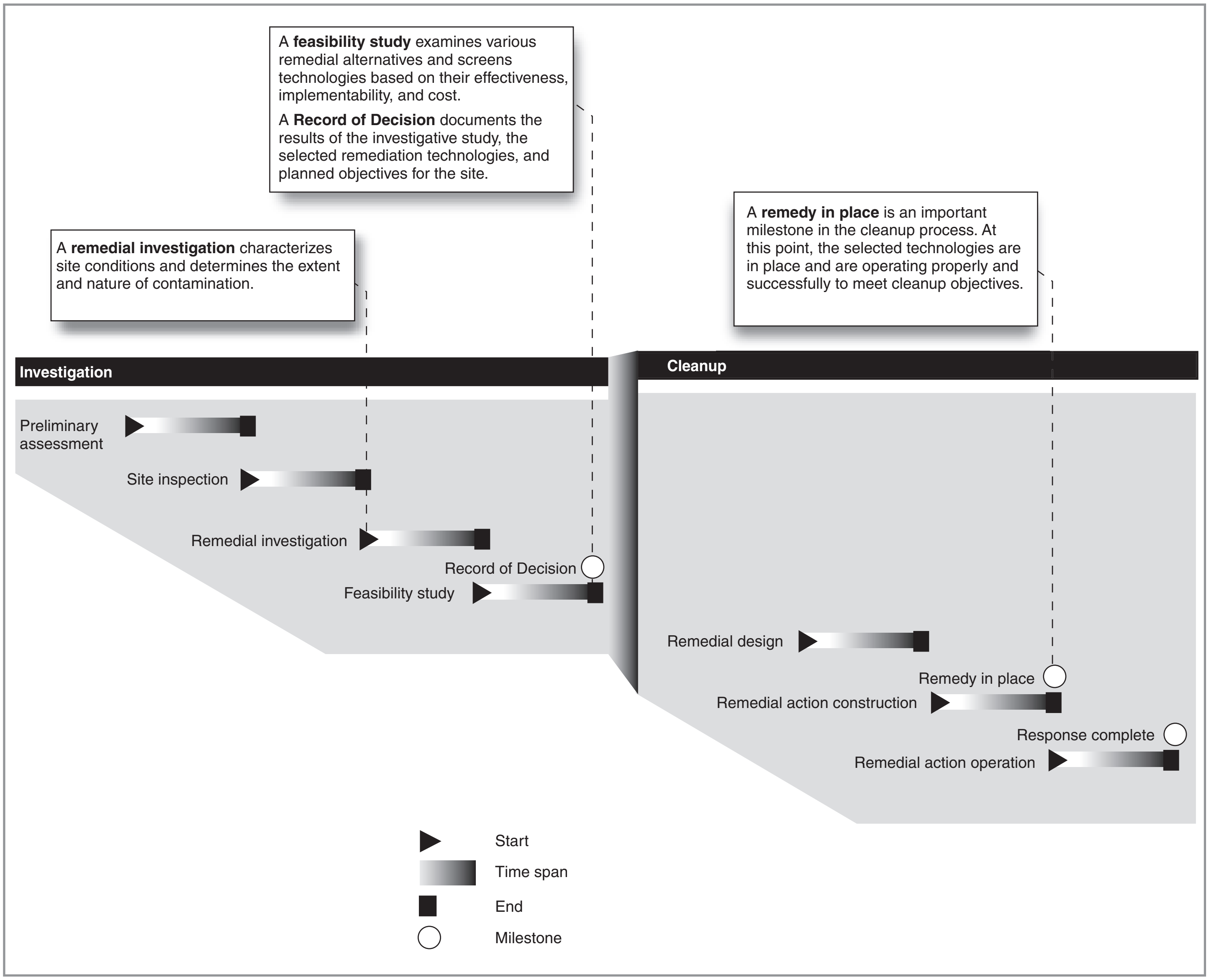
[8] DOD carries out some groundwater remediation as corrective action under the Resource Conservation and Recovery Act of 1976 (RCRA). According to DOD, while RCRA and CERCLA contain somewhat different procedural requirements, these differences do not substantively affect the outcome of remedial activities.

Figure 2: Selected Phases and Milestones in DOD's Environmental Cleanup Process



Source: Department of Defense, *Defense Environmental Programs, Annual Report to Congress, Fiscal Year 2004*.

Note: These phases may overlap or occur simultaneously, but cleanup activities at DOD facilities generally occur in the order shown.

Once DOD identifies potential contamination on one of its facilities, it initiates a preliminary assessment to gather data on the contaminated site. If DOD finds evidence that the site needs remediation, it consults with EPA to determine whether the site qualifies for inclusion on the National Priorities List.[9] If EPA places a DOD facility on the National Priorities List, CERCLA requires DOD to begin the next phase of cleanup within 6 months. During this next phase, called a remedial investigation/feasibility study, DOD characterizes the nature and extent of contamination and evaluates the technical options available for cleaning up the site.

DOD also pursues a remedial investigation/feasibility study for sites that do not qualify for the National Priorities List but require decontamination. Data collected during the remedial investigation influences DOD's development of cleanup goals and evaluation of remediation alternatives. During the feasibility study, often conducted concurrently with the remedial investigation, DOD identifies applicable regulations and determines cleanup standards that will govern its cleanup efforts. CERCLA requires that sites covered by the statute be cleaned up to the extent necessary to protect both human health and the environment. In addition, cleanups must comply with requirements under federal environmental laws that are legally "applicable" or "relevant and appropriate" as well as with state environmental requirements that are more stringent than the federal standards. Furthermore, CERCLA cleanups must at least attain goals and criteria established under the Safe Drinking Water Act and the Clean Water Act, where such standards are relevant and appropriate under the circumstances.

Once cleanup standards have been established, DOD considers the merits of various actions to attain cleanup goals. Cleanup actions fall into two broad categories: removal actions and remedial actions. Removal actions are usually short term and are designed to stabilize or clean up a hazardous site that poses an immediate threat to human health or the environment. Remedial actions, which are generally longer term and usually costlier, are

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[9] This list represents EPA's highest priorities for cleanup nationwide, including public and private sites considered by EPA to present the most serious threats to human health and the environment. To make its determination, EPA uses a hazard-ranking system to evaluate the severity of the contamination by examining the nature of the contaminants, the pathways through which they can move (such as soil, water, or air), and the likelihood that they may come into contact with a receptor—for example, a person living nearby. According to DOD's *Defense Environmental Programs, Annual Report to Congress, Fiscal Year 2004*, DOD has 152 facilities that are listed or proposed for listing on the National Priorities List.

aimed at implementing a permanent remedy. Such a remedy may, for example, include the use of groundwater remediation technologies. Also during the feasibility study, DOD identifies and screens various groundwater remediation technologies based on their effectiveness, feasibility, and cost. At the conclusion of the remedial investigation/feasibility study, DOD selects a final plan of action—called a remedial action—and develops a Record of Decision that documents the cleanup objectives, the technologies to be used during cleanup, and the analysis that led to the selection. If EPA and DOD fail to reach mutual agreement on the selection of the remedial action, then EPA selects the remedy. If the cleanup selected leaves any hazardous substances, pollutants, or contaminants at the site, DOD must review the action every 5 years after the initiation of the cleanup.[10] According to DOD policy, this may include determining if an alternative technology or approach is more appropriate than the one in place. DOD continues remediation efforts at a site until the cleanup objectives stated in the Record of Decision are met, a milestone referred to as "response complete." Even if DOD meets the cleanup objectives for a site, in some cases the site may require long-term management and monitoring to ensure that it does not become contaminated from residual sources of pollution.

DOD Has Implemented or Field-tested a Wide Range of Technologies to Remediate Sites Contaminated with Groundwater

DOD has implemented or field-tested all of the 15 types of generally accepted technologies currently available to remediate groundwater. These 15 technologies include 6 ex-situ and 9 in-situ technologies, each of which can be used to treat a variety of contaminants. All of these groundwater remediation technologies rely on a variety of biological, chemical, or physical processes to treat or extract the contaminant. DOD guidance directs department officials to consider cost-effectiveness and performance when selecting technologies for cleanup.

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[10] 42 U.S.C. § 9621(c). The applicable EPA regulation differs from the statute: It requires the five-year reports only if contaminants will remain at the site "above levels that allow for unlimited use and unrestricted exposure." 40 C.F.R. § 300.430(f)(4)(ii).

Fifteen Ex-situ and In-situ Technologies Are Currently Available for Groundwater Cleanup

We identified a range of ex-situ and in-situ technologies that DOD can employ to clean up a contaminated groundwater site. Ex-situ technologies rely on a pump-and-treat system to bring the contaminated water above ground so that it can be treated and the contaminants removed. Some ex-situ technologies destroy the contaminant, while others remove the contaminant from the groundwater, which is subsequently disposed of in an approved manner. The decontaminated water can be discharged to surface water, used as part of a public drinking water supply, injected back into the ground, or discharged to a municipal sewage plant. We identified 6 categories of ex-situ technologies:

- *Advanced oxidation processes* often use ultraviolet radiation with oxidizing agents—such as ozone or hydrogen peroxide—to destroy contaminants in water pumped into an above-ground treatment tank.
- *Air stripping* separates volatile contaminants from water by exposing the water to large volumes of air, thus forcing the contaminants to undergo a physical transformation from liquid to vapor (volatilization). There is no destruction of the contaminant; therefore, the contaminant must be removed and disposed of properly.
- *Bioreactors* are above-ground biochemical-processing systems designed to degrade contaminants in water using various microorganisms, an approach similar to that used at a conventional wastewater treatment facility. Contaminated groundwater flows into a tank or basin where it interacts with microorganisms that degrade the contaminant.
- *Constructed wetlands* are artificially built wetland ecosystems that contain organic materials, plants, microbial fauna, and algae that filter or degrade contaminants from the water that is pumped into the wetland.
- *Ion exchange* involves passing contaminated water through a bed of resin media or membrane that exchanges ions in the contaminants, thus neutralizing them into nonhazardous substances.
- *Adsorption (mass transfer)* involves circulating contaminated water through an above-ground treatment vessel containing a sorbent material—such as activated carbon—that removes the contaminant from the water.

Use of Pump-and-Treat Systems

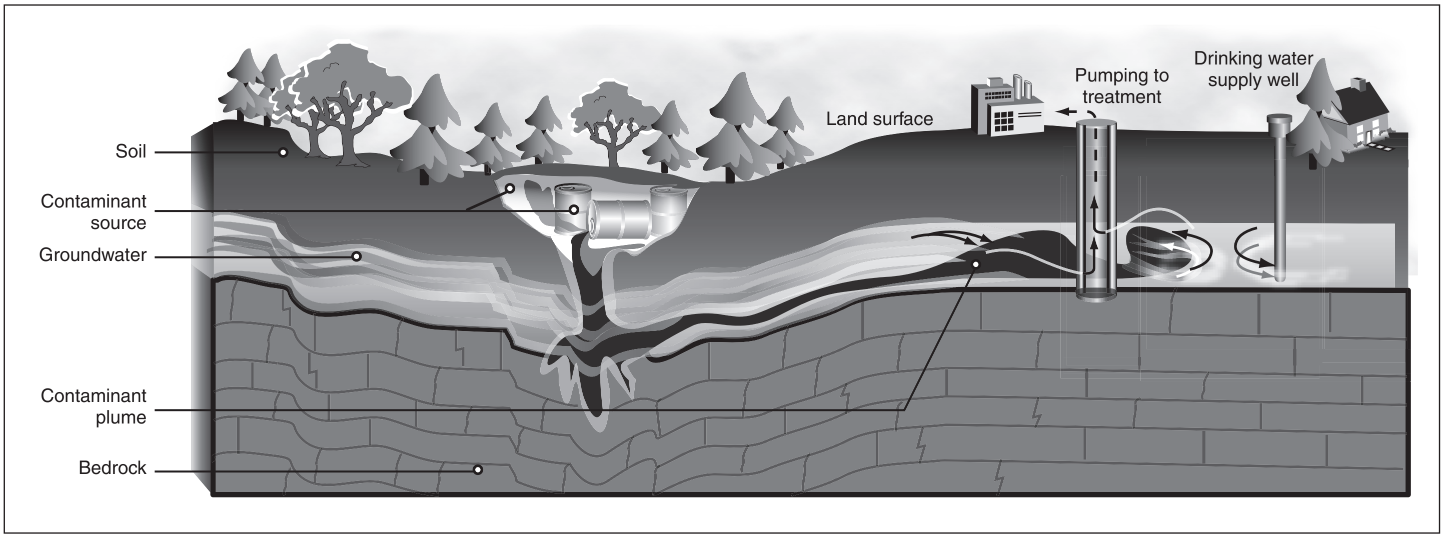
Some groundwater remediation experts believe that pump-and-treat systems may be the best option in situations such as the following:

- the contaminant is located so deep in the subsurface that site characterization and potential remediation can be prohibitively expensive;
- the subsurface is so complex that the effectiveness of in-situ approaches is limited (e.g., highly fractured systems);
- in-situ approaches are not viable or sufficiently proven to remediate a site (e.g., contamination by chlorinated solvents in fractured bedrock);
- the interim cleanup goal is to mitigate risk by containing the contaminant plume (e.g., to protect a public drinking water supply), while an in-situ approach is developed for the site; and
- an ex-situ system is needed to augment or support an in-situ technology.

See figure 3 for an illustration of a pump-and-treat system.

(See app. II for more information on key characteristics of these ex-situ technologies.)

Figure 3: Example of a Conventional Pump-and-Treat System



Source: Federal Remediation Technologies Roundtable Treatment Technologies Screening Matrix, 2002.

Similarly, we identified nine in-situ technologies that can be used to remediate contaminated groundwater. In contrast to ex-situ technologies, in-situ technologies treat contaminants within the subsurface. Some in-situ technologies—such as bioremediation and chemical treatment—destroy the contaminant within the subsurface by altering the contaminant's chemical structure and converting the toxic chemical to a nontoxic form (e.g., benzene to carbon dioxide). Other in-situ technologies—such as multiphase extraction and enhanced recovery using surfactant flushing—facilitate the removal of the contaminant from the subsurface for treatment above ground. Still other technologies—such as air sparging—combine in-situ treatments with extraction techniques.

- *Air sparging* introduces air or other gases into the subsurface to remove the contamination from the groundwater through volatilization (converting a solid or liquid into a gas or vapor that may be treated at the surface), and in some configurations may also introduce oxygen into the contaminated area to stimulate in-situ biological breakdown (i.e., bioremediation) or ozone to achieve chemical oxidation of the contaminant.

- *Bioremediation* relies on microorganisms living in the subsurface to biologically degrade groundwater contaminants through a process called biodegradation. Bioremediation may be engineered and accomplished in two general ways: (1) stimulating native microorganisms by adding nutrients, oxygen, or other electron acceptors (a process a called biostimulation) or (2) providing supplementary pregrown microorganisms to the contaminated site to augment naturally occurring microorganisms (a process called bioaugmentation).

- *Enhanced recovery using surfactant flushing* involves the injection of active agents known as surfactants[11] into contaminated aquifers to flush the contaminated groundwater toward a pump, which removes the contaminated water and surfactant solution to the surface for treatment and disposal of the contaminants.

- *Chemical treatments* inject various substances into the groundwater that can chemically oxidize or reduce contaminants into less-toxic or nonhazardous materials.

- *Monitored natural attenuation* involves using wells and monitoring equipment in and around a contaminated site to track the natural physical, chemical, and biological degradation of the contaminants. Although not necessarily considered a treatment technology, this approach is often used to monitor contaminant concentrations to ensure that human health and the environment are not threatened.

- *Multiphase extraction* uses a series of pumps and vacuums to simultaneously remove from the subsurface combinations of contaminated groundwater, free product (i.e., liquid contaminants floating on top of groundwater), and hazardous vapors. This technology can be used to remove contaminants from above and below the

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[11] Surfactants, or surface active agents, are molecules with two structural units: one with an affinity for water and one with an aversion to water. This molecular combination is useful for dissolving some contaminants and enhancing their mobility by lowering the interfacial tension between the contaminant and the water.

groundwater table, thereby exposing more of the subsurface for treatment.

- *Permeable reactive barriers* are vertical walls or trenches built into the subsurface that contain a reactive material to intercept and remediate a contaminant plume as the groundwater passes through the barrier.
- *Phytoremediation* relies on the natural hydraulic and metabolic processes of selected vegetation to remove, contain, or reduce the toxicity of environmental contaminants in the groundwater.
- *Thermal treatments* involve either pumping steam into the aquifer or heating groundwater to vaporize or destroy groundwater contaminants. Vaporized contaminants are often removed for treatment using a vacuum extraction system.

(See app. II for more information on key characteristics of these in-situ technologies.)

Although most in-situ technologies have the advantage of treating a contaminant in place, these technologies may afford less certainty about the extent and uniformity of treatment in contaminated areas when compared with some ex-situ technologies. For example, enhanced recovery using surfactant flushing has not been used extensively and has limited data on its remediation effectiveness, whereas air stripping has been widely used for several decades to remove certain contaminants, and its benefits and limitations as a water treatment technology are well-understood. In some cases, a combination of in-situ and ex-situ technologies may be used (either concurrently or successively) to clean up a site if a single technology cannot effectively remediate an entire site with its range of contaminants and subsurface characteristics. According to the National Research Council, integration of technologies is most effective when the weakness of one technology is mitigated by the strength of another technology, thus producing a more efficient and cost-effective solution.[12]

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[12] For more information, see National Research Council, Water Science and Technology Board, *Contaminants in the Subsurface: Source Zone Assessment and Remediation* (Washington, D.C., 2004).

DOD Has Used the Full Range of Groundwater Remediation Technologies Identified

As shown in table 1, the DOD components involved in groundwater remediation activities reported using the full range of technologies that we identified as currently available for groundwater remediation. Specifically, the Navy reported that it has used all 15 of the currently available technologies; the Air Force, Army, and Corps reported using 14 each. The Defense Logistics Agency has used 9 of the available technologies for the cleanup of the limited number of contaminated groundwater sites for which it is responsible.

Table 1: Technologies DOD Components Used for Groundwater Remediation

Technology	Air Force	Army	Army Corps of Engineers	Defense Logistics Agency	Navy
In-situ					
Air sparging[a]	X	X	X	X	X
Bioremediation[b]	X	X	X	X	X
Enhanced recovery/surfactant flushing[c]	X			X	X
Chemical treatments[d]	X	X	X	X	X
Monitored natural attenuation	X	X	X	X	X
Multiphase extraction[e]	X	X	X	X	X
Permeable reactive barriers[f]	X	X	X	X	X
Phytoremediation[g]	X	X	X		X
Thermal treatments[h]	X	X	X		X
Ex-situ					
Advanced oxidation processes[i]	X	X	X		X
Air stripping	X	X	X	X	X
Bioreactors		X	X		X
Constructed wetlands	X	X	X		X
Ion exchange[j]	X	X	X		X
Adsorption (mass transfer)	X	X	X	X	X

Source: Department of Defense responses to GAO data collection instrument.

Notes: This table focuses on technologies used to treat contaminants found in groundwater. It excludes technologies used (1) to treat and dispose of the byproducts of groundwater remediation—such as emissions of potentially harmful volatile gases; (2) exclusively to treat contaminated soil (such as soil washing or excavation), although soil remediation is often conducted in conjunction with groundwater remediation; and (3) primarily to physically contain a contaminant—such as soil capping. See appendix II for more information on the key characteristics, benefits, and limitations of each of these technologies.

[a] Includes related remedial approaches and technologies, such as co-metabolic air sparging, oxygen and ozone sparging, in-well air stripping, and soil vapor extraction. Soil vapor extraction, although not

technically a groundwater remediation technology, is often used with air sparging to extract or capture emissions that result from treating contaminated groundwater.

[b] Includes related bioremedial approaches, such as bioaugmentation, biostimulation, co-metabolic treatment, enhanced aerobic biodegradation, enhanced anaerobic biodegradation, and biobarriers.

[c] Includes related remedial approaches that use co-solvents to improve the solubility of surfactants in the subsurface, and other technologies, such as hydrofracturing and pneumatic fracturing, that attempt to increase the permeability of the subsurface.

[d] Includes various remedial approaches and technologies that chemically oxidize or reduce contaminants in-situ, as well as the in-situ immobilization and stabilization of soluble metals.

[e] Includes the related technologies of bioslurping and dual-phase extraction.

[f] Includes both biotic and abiotic passive and reactive treatment barriers.

[g] Includes the related technologies of phytostabilization, phytoaccumulation, phytoextraction, rhizofiltration, phytodegradation, rhizosphere degradation, organic pumps, and phytovolatization.

[h] Includes related heating technologies, such as steam flushing, conductive heating, and electrical resistance heating.

[i] Includes the related technologies of ultraviolet oxidation, ultraviolet photolysis, and photocatalysis.

[j] Includes technologies that use ion exchange resins or membranes to remove contaminants from groundwater, including dissolved metals and nitrates.

According to department officials, DOD selects the most suitable technology to clean up a contaminated site based on a number of factors, including the type of contaminant, its location and concentration at different levels in the subsurface, and its chemical and physical composition.[13] These officials identified a number of contaminants of concern, such as federally regulated chlorinated solvents (commonly found in metal degreasers) and fuels used for military aircraft and vehicles. DOD officials also consider some other hazardous materials that are not regulated by the federal government—such as the rocket propellant perchlorate—to be contaminants of concern because they are regulated by some states, such as California, where DOD has active, closing, or formerly used defense sites that need groundwater remediation.

According to the groundwater remediation experts we consulted, some of DOD's contaminants of concern, such as chlorinated solvents, can potentially be treated using 14 of the 15 technologies, while others, such as metals, can be treated with only 7 of the 15 technologies. For example, many chlorinated solvents do not readily dissolve in water; and because they are often more dense (heavier) than water, they migrate downward and pool at the bottom of aquifers, thereby limiting the number of technologies that can treat them. Alternatively, some contaminants

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[13] A contaminant may exist in aqueous (dissolved in water), nonaqueous, solid (sorbed), or gaseous form.

composed of petroleum hydrocarbons (e.g., jet fuel, diesel fuel, and motor gasoline) float on top of the water table because they are less dense (lighter) than water, and technologies such as air sparging or multiphase extraction can often effectively treat or extract them through processes such as volatilization or free product recovery. See table 2 for information on which of the 15 technologies can potentially treat each of DOD's contaminants of concern.

Table 2: Technologies Available for the Treatment of DOD's Contaminants of Concern

Technology	Chlorinated solvents[a]	Explosives[b]	Fuels[c]	Metals[d]	Oxygenates[e]	Propellants[f]
In-situ						
Air sparging	X		X		X	
Bioremediation	X	X	X	X	X	X
Enhanced recovery/surfactant flushing	X		X		X	
Chemical treatments	X	X	X	X	X	X
Monitored natural attenuation	X	X	X	X	X	X
Multiphase extraction	X		X		X	
Permeable reactive barriers	X	X	X	X	X	X
Phytoremediation	X	X	X		X	X
Thermal treatments	X		X		X	
Ex-situ						
Advanced oxidation processes	X	X	X		X	
Air stripping	X		X		X	
Bioreactors	X	X	X		X	X
Constructed wetlands	X	X	X	X	X	X
Ion exchange				X		X
Adsorption (mass transfer)	X	X	X	X	X	

Sources: Department of Defense and several groundwater remediation experts.

Notes: This table presents the contaminants of concern to DOD. Depending on their concentrations, these contaminants can pose health risks to humans. The ability for any one technology to effectively treat a contaminant is greatly influenced by site-specific conditions. Some technologies are generally less effective or currently less utilized to treat contaminants.

[a] Includes, but is not limited to, perchloroethene (PCE), trichloroethene (TCE), dichloroethene (DCE), vinyl chloride (VC), and chloroform (CF).

[b] Includes, but is not limited to, trinitrotoluene (TNT); dinitrotoluene (DNT); cyclotrimethylene trinitramine, cyclonite, and hexogen (RDX); and octogen and cyclotetramethylene-tetranitramine (HMX).

[c] Includes gasoline, diesel fuel, jet fuel, and BTEX. BTEX is an acronym for benzene, toluene, ethylbenzene, and xylene—a group of volatile organic compounds commonly found in petroleum hydrocarbons, such as gasoline.

[d] Includes, but is not limited to, arsenic, barium, cadmium, chromium, copper, lead, mercury, selenium, silver, and zinc.

[e] Includes, but is not limited to, oxygen-bearing chemicals that can be added to fuel to bring additional oxygen to the combustion process. These include ethers such as methyl tertiary butyl ether (MTBE) and its related compounds.

[f] Includes, but is not limited to, materials such as ammonium perchlorate and potassium perchlorate that are used in the manufacturing and testing of solid rocket propellants and other munitions such as flares.

Technology Selection Is Also Influenced by Cost and Performance

According to DOD guidance on groundwater remediation, department officials should consider cost-effectiveness and performance of various groundwater remediation options when selecting the most suitable cleanup technology. A number of factors influence total cleanup costs for a given site, such as how long the cleanup is expected to take and the horizontal and vertical extent of the contamination. In addition, according to the National Research Council, actual cleanup costs associated with each technology depend on site-specific hydrogeologic, geochemical, and contaminant conditions.[14] Thus, a particular technology may be the most cost-effective solution for one site and not necessarily for another similarly contaminated site. The National Research Council and others have also found that performance of most technologies, including time for total cleanup, also depends on complexities within the site's subsurface (i.e., site heterogeneities) as well as contaminant characteristics. For example, the effectiveness of certain in-situ technologies—such as air sparging—decrease as site heterogeneity increases because the air will naturally follow certain pathways that may bypass the contaminant. Similarly, the effectiveness of many in-situ technologies may be limited by the presence of some chlorinated solvents that, if heavier than water, can migrate into inaccessible zones in the subsurface. Alternatively, in-situ thermal treatments that use conductors to heat the soil are not as sensitive to heterogeneity in the subsurface and contaminant characteristics because thermal conductivity varies little with the properties of subsurface materials and certain contaminants are more easily volatilized at elevated temperatures. However, equipment and energy costs may make this approach more costly than other in-situ technologies.

While overall conclusions on the cost-effectiveness of each groundwater remediation technology are difficult to reach, a few groups have attempted

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[14] For more information, see National Research Council, *Contaminants in the Subsurface: Source Zone Assessment and Remediation* (Washington, D.C., 2005).

to estimate costs for various technologies. For example, EPA has developed a technology cost compendium for several technologies based on cost data from various public and private remediation projects.[15] Similarly, the Federal Remediation Technologies Roundtable—a federal consortium of representatives from DOD, EPA, and other federal agencies—has attempted to evaluate the relative overall cost and performance of selected remediation technologies in general terms.[16] However, according to DOD officials and other experts we consulted, these efforts to compare technologies are of only limited utility because of the site-specific nature of technology decisions.

DOD Is Proactively Using and Developing New Approaches to Groundwater Remediation

We did not identify any alternative groundwater remediation technologies being used outside the department that DOD has not already either employed or tested on some scale (laboratory or pilot). However, we did identify a number of new approaches to groundwater remediation being developed by commercial vendors, but these approaches are based on modifications of or enhancements to existing technologies. Most of these new approaches are being used or field-tested by DOD and involve novel materials that are applied to contaminated sites using existing technologies. In addition, we found that DOD is generally aware of new approaches to groundwater remediation, in part through its efforts to develop remediation technologies with the commercial sector. DOD also works with various stakeholders, including the regulatory community, to promote understanding and acceptance of innovative remediation approaches. Some DOD officials and groundwater remediation experts believe additional resources may be needed in order to develop and advance DOD's process for selecting the most appropriate technology at a site.

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[15] For more information, see EPA, Office of Solid Waste and Emergency Response, *Remediation Technology Cost Compendium—Year 2000* (Washington, D.C., 2001).

[16] For additional information, see the online version of the Federal Remediation Technologies Roundtable Treatment Technologies Screening Matrix at http://www.frtr.gov/scrntools.htm.

Most New Approaches Employ Novel Materials or Modifications to Existing Technologies

Most of the new remediation approaches commercial vendors have developed and made available to DOD use existing technologies to apply novel materials to contaminated sites. These materials typically accelerate the breakdown of contaminants through biological or chemical processes. In particular, multiple commercial vendors have developed proprietary compounds used during bioremediation to stimulate microorganisms in the subsurface to biodegrade contaminants. Some of these compounds are designed to slowly release oxygen or other nutrients into the subsurface in an effort to prolong their availability, which microorganisms need to biodegrade the contaminants. DOD has also field-tested several novel compounds for bioremediation that are derived from food-grade materials such as molasses or vegetable oils. These compounds can be injected into the contaminated site using pre-existing wells or other existing techniques such as direct push injection:

- The Army used a compound developed by a commercial vendor to stimulate the bioremediation of chlorinated solvents at a contaminated site at its Rocky Mountain Arsenal. This compound reacted with the contaminated groundwater to produce lactic acid, which native microorganisms used to produce the hydrogen that ultimately led to the biological degradation of the contaminants. In addition, the Air Force reported using oxygen-releasing compounds to stimulate aerobic biodegradation at several of its cleanup sites, including a site in Florida contaminated by spilled fuel.

- DOD has also field-tested the use of molasses during bioremediation to treat chlorinated solvents at Vandenberg and Hanscom Air Force bases. In addition, DOD reported using vegetable oils to stimulate microorganisms in order to treat groundwater contaminated by chlorinated solvents and perchlorate at a variety of locations, including naval facilities in Massachusetts, Rhode Island, and South Carolina.

Commercial vendors have also developed innovative approaches for chemically treating contaminants in the subsurface. For example, several vendors have developed proprietary approaches for delivering oxidants, such as molecular oxygen and ozone with or without hydrogen peroxide, into the subsurface to achieve in-situ chemical oxidation of a variety of contaminants, including fuels and chlorinated solvents. These oxidants are often delivered underground using variations of existing air sparging technologies and a variety of injection technologies. In addition to achieving in-situ chemical oxidation of target contaminants, the use of ozone with or without hydrogen peroxide can enhance the aerobic biodegradation of contaminants because it increases oxygen levels in the subsurface. Commercial vendors have also developed approaches to directly injecting other chemicals that are oxidizing agents, such as persulfate and permanganate, into the subsurface using existing technologies such as injection wells and direct push-probe technologies.

DOD is exploring with the commercial sector other innovative approaches to groundwater remediation that involve modifying the engineering, design, or application of existing technologies. For example, DOD is currently working with the commercial sector to explore innovative uses of nanoscale metallic materials—such as zero-valent iron and palladium impregnated iron—to improve the efficacy of in-situ chemical treatments of chlorinated solvents commonly found on DOD facilities.[17] In the past, DOD used metallic materials, such as zero-valent iron in granular form, to fill trenches dug into the ground (a form of a permeable reactive barrier) to chemically reduce chlorinated solvent plumes. The iron reacts with chlorinated solvents, transforming them into benign products, such as ethane and ethene. Treating contaminant plumes located deep within the subsurface is often difficult, costly, and technically impossible using this approach. Because of their size, nanoscale particles can be mixed with other materials—such as vegetable oil and water—and injected deep into the subsurface using existing technologies to treat contaminant sources or plumes. Furthermore, nanoscale particles have high surface areas relative to their volume (i.e., more metal is available to contact and react with the contaminants), which will lead to increased rates of reaction and more effective treatment.

DOD Supports the Development of New Technologies with the Commercial Sector through Several Programs

We found that DOD is actively involved in researching and testing new approaches to groundwater remediation, largely through its efforts to develop and promote the acceptance of innovative groundwater remediation technologies. According to the National Research Council, research on innovative remediation technologies is sponsored almost exclusively by federal agencies such as DOD and, in some circumstances, by individual companies and industry groups that have joined with federal

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[17] Nanoscale refers to miniscule particles that measure less than 100 nanometers in diameter. In comparison, an average human hair typically measures 10,000 nanometers in diameter.

agencies in seeking more cost-effective solutions to common problems.[18] In particular, the DOD-funded Strategic Environmental Research and Development Program (SERDP) supports public and private research on contaminants of concern to DOD and innovative methods for their treatment, among other activities. Created in 1990, the program primarily focuses on issues of concern to DOD, although it is jointly managed by DOD, EPA, and the Department of Energy.[19] In fiscal year 2004, SERDP spent about $49 million to fund and manage projects in a variety of areas, including 27 projects related to groundwater remediation.

In response to technology needs and requirements generated by each of the DOD components, SERDP funds research projects in private, public, and academic settings on the fundamentals of contaminant behavior, environmental toxicity, and the advanced development of cost-effective innovative groundwater remediation technologies, among other things. For example, SERDP has funded research projects to examine such issues as the innovative use of vegetable oils for bioremediation; zero-valent iron based bioremediation of explosives; and the behavior of, and treatment options for, several emerging groundwater contaminants not yet regulated by the federal government, such as 1,4-Dioxane (found in solvents), N-Nitrosodimethylamine (found in rocket fuel), and trichloropropane (used as a degreaser and paint stripper). In addition, SERDP holds workshops with the scientific, engineering, academic, regulatory, and DOD-user communities to discuss DOD's issues and identify needs for future research, development, and testing of groundwater remediation techniques.

DOD also pursues innovative solutions to groundwater remediation through its Environmental Security Technology Certification Program (ESTCP). This program, founded in 1995, field-tests and validates promising innovative environmental technologies that attempt to address DOD's highest-priority environmental requirements, including groundwater

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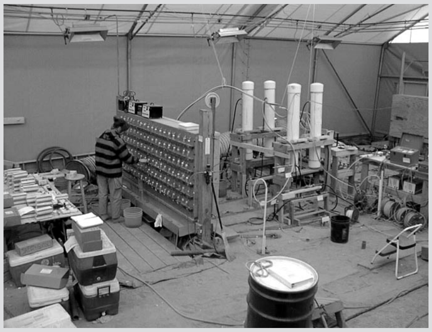
[18] See National Research Council, Water Science and Technology Board, *Environmental Cleanup at Naval Facilities: Adaptive Site Management* (Washington, D.C., 2003).

[19] SERDP's goals include supporting basic and applied research and development of environmental technologies; providing information and data on environmental research and development activities to other governmental and private organizations in an effort to promote the transfer of innovative technologies; and identifying technologies developed by the private sector that are useful for DOD's and DOE's environmental restoration activities.

National Environmental Technology Test Site at Dover Air Force Base



Source: Dover National Environmental Technology Test Site, Tim McHale.

At Dover Air Force Base, DOD has constructed three double-walled underground test areas (referred to as cells) that enable researchers to inject common soil and groundwater pollutants into a natural geologic setting as test constituents, without allowing the test constituents to come into contact with the surrounding environment. These test cells, known as the Groundwater Remediation Field Laboratory, include one large test cell and several smaller ones, all sharing the same outer containment cell area. The cells are constructed of interlocking steel sheet pilings with sealed grouted joints that extend from the ground's surface to a depth of 40 feet. This safe testing area is in an area with "ideal geology," according to the site program manager, because it has a shallow aquifer contained by a clay layer, which prevents the migration of contaminants. This laboratory is the only place in the United States that offers such a test setting. A variety of technologies have been tested here for cleaning up a range of contaminants. For example, tests for cleanup of TCE are under way using a combination of three technologies: soil vapor extraction, bioremediation, and air stripping.

remediation.[20] Using a process similar to that of SERDP, ESTCP solicits proposals from public and private researchers to field-test laboratory-proven remediation technologies that have broad DOD and market application. Once ESTCP accepts a proposal, it identifies a military partner, which provides a site on a DOD installation where the researcher can field-test the technology and document the technology's cost, performance, and reliability. In fiscal year 2004, ESTCP spent about $35 million to fund and manage its program, including 36 projects on groundwater remediation. These projects include the demonstration of an enhanced recovery technology using innovative surfactants, emulsified zero-valent nanoscale iron to treat chlorinated solvents, and an ion exchange technology for the removal and destruction of perchlorate. ESTCP and SERDP have co-located offices and, according to DOD officials, the two programs work together to pursue the development of innovative groundwater remediation technologies from basic research through advanced field-testing and validation. ESTCP often funds the demonstration of technologies that were developed by private or public researchers with financial support from SERDP.

In addition to funding the development of innovative technologies, DOD works with various stakeholders, including the regulatory community, to promote the understanding and acceptance of these technologies. For example, DOD participates in the Interstate Technology and Regulatory Council (ITRC), a state-led coalition that works with the private sector, regulators, and other stakeholders to increase the regulatory acceptance of new environmental technologies. ITRC develops guidance on innovative environmental technologies and sponsors training for regulators and others on technical and regulatory issues related to environmental cleanup technologies and innovative groundwater remediation approaches. According to ITRC, these efforts are designed to help regulators streamline their review process and enable wider acceptance of innovative environmental technologies across state boundaries. In 2004, ITRC and DOD signed a memorandum of understanding on the relationship between the two organizations. As a result of the agreement, DOD now provides several liaisons to the ITRC's board of advisers and helps the group develop materials and training courses on innovative groundwater remediation technologies. According to a DOD official, the department's partnership

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[20] According to ESTCP, the program "provides an independent, unbiased evaluation of the cost, performance, and market potential of state-of-the-art environmental technologies based on field demonstrations conducted under DOD operational conditions."

with ITRC has led to enhanced cooperation among state regulators, DOD personnel, and community stakeholders and increased the deployment of innovative technologies at DOD cleanup sites.

Although DOD is actively involved in the research and development of innovative technologies, some groundwater remediation experts and some DOD officials with whom we consulted believe that additional resources may be needed to develop and advance DOD's process for selecting the most appropriate technology at a site. These individuals believe that a better understanding of the nature and extent of contamination at a site is critical for selecting appropriate technologies for cleanup. Furthermore, these experts and some DOD officials believe that additional resources may be appropriate for examining and improving methods and engineering approaches for optimizing the performance of the 15 types of groundwater remediation technologies that are currently available. Other groundwater remediation experts and some DOD officials suggested that more resources may be needed to further develop innovative approaches to emerging groundwater remediation issues, and to educate DOD personnel and regulators on these approaches.

Agency Comments

DOD generally agreed with the content of the report, stating that the report is an accurate summary of DOD's use and field tests of remedial technologies; DOD also provided technical clarifications that we have incorporated, as appropriate.

We are sending copies of this report to appropriate congressional committees; the Secretary of Defense; the Administrator of EPA; and other interested parties. We will also make copies available to others upon request. In addition, the report will be available at no charge on GAO's Web site at http://www.gao.gov.

If you or your staff have any questions about this report, please contact me at (202) 512-3841 or mittala@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made major contributions to this report are listed in appendix V.

Anu K. Mittal

Anu K. Mittal
Director, Natural Resources
and Environment

Objectives, Scope, and Methodology

This report (1) describes the groundwater remediation technologies that the Department of Defense (DOD) is currently using or field-testing and (2) examines whether any new groundwater remediation technologies are being used outside the department or are being developed by commercial vendors that may have potential for DOD's use, and the extent to which DOD is researching and developing new approaches to groundwater remediation. In addition, this report provides limited information on the key characteristics, benefits, and limitations of selected groundwater remediation technologies.

To address the first objective, we developed a questionnaire that we sent to the DOD components responsible for DOD's groundwater cleanup efforts—the Air Force, Army, U.S. Army Corps of Engineers, Defense Logistics Agency, and Navy. In the questionnaire, we listed groundwater remediation technologies and asked these DOD components to indicate which technologies they have implemented and still currently use. We also asked the components to provide examples of specific groundwater remediation projects. We developed the list of technologies based on a review of reports and existing lists developed by the National Research Council, Environmental Protection Agency (EPA), Federal Remediation Technology Roundtable, and others, as well as through discussions with a groundwater remediation consulting firm and several nationally recognized groundwater remediation experts. To better understand DOD's processes for environmental cleanup and technology development, we met with officials from the offices of the Deputy Undersecretaries of Defense for Installations and Environment and for Science and Technology. We also reviewed documents, reports, and guidance on groundwater remediation from the Office of the Secretary of Defense and the various DOD components involved in groundwater remediation. To obtain information on how DOD uses groundwater remediation technologies to treat contaminants of concern, we toured several bioremediation projects at Dover Air Force Base and spoke with a groundwater remediation program manager for the Air Force.

To address our second objective, we contracted with consultants from the Washington, D.C., office of Malcolm Pirnie Inc. to gather information from commercial vendors on the range of currently available groundwater remediation technologies. We also attended a national groundwater remediation conference, where we spoke with a number of vendors of groundwater remediation technologies about their products, efforts to develop innovative approaches to groundwater remediation, and remediation work they may have performed for DOD. In addition, we collected and reviewed reports and studies from these vendors to better understand the range of technologies available to DOD. We also consulted with four nationally recognized groundwater remediation experts—two from academia and two from industry—to provide information on innovative remediation technologies currently available or under development by the commercial sector. We selected these experts on the basis of their independence, knowledge of and experience with groundwater remediation technologies, and recommendations from the National Academy of Sciences and others. In addition, we consulted with a senior groundwater remediation official from EPA's Groundwater and Ecosystem Restoration Division, who is an expert on technologies used for groundwater remediation.

Through these sources, we identified 15 technologies that are currently available commercially for the treatment of contaminated groundwater. For the purposes of this report, we defined a technology as a distinct technical method or approach for treating or removing contaminants found in groundwater. We did not consider any modifications or enhancements to a technology, such as variations in the material or equipment used during treatment, to be a separate technology. To determine whether there were any technologies currently being used outside of DOD, we compared the list of 15 currently available technologies with information provided to us by DOD officials on technologies currently used by DOD for groundwater remediation.

To identify the extent to which DOD supports the research and development of new approaches to groundwater remediation, we interviewed officials from the Strategic Environmental Research and Development Program and the Environmental Security Technology Certification Program. We reviewed reports, project portfolios, and other documents developed by these two programs. To gain a better understanding of DOD's efforts to field-test innovative approaches to groundwater remediation, we visited a DOD National Environmental Technology Test Site, located in Delaware, where private and public researchers can test innovative groundwater remediation technologies. We observed several ongoing research projects and interviewed an official responsible for managing the test facility. To gain a better understanding of DOD's relationship with the Interstate Technology and Regulatory Council, we reviewed a memorandum of understanding between the two organizations and interviewed an official that serves as DOD's liaison to the council.

Information presented in this report is based on publicly available documents and information provided by government officials, independent consultants, and experts. We did not review nonpublic research and development activities that may be under way in private laboratories. We reviewed data for accuracy and consistency, and corroborated DOD-provided data to the extent possible. We assessed the reliability of the DOD-provided data by reviewing related documentation, including DOD's annual reports to Congress on its Defense Environmental Restoration Program and information provided by consultants.

We performed our work from January 2005 through May 2005, in accordance with generally accepted government auditing standards.

Technologies for the Remediation of Contaminated Groundwater

Ex-situ Technologies

1. *Advanced oxidation processes* often use ultraviolet light irradiation with oxidizers such as ozone or hydrogen peroxide to produce free radicals, which break down and destroy chlorinated solvents, fuels, and explosive contaminants as water flows through a treatment reactor tank. Depending on the design of the system, the final products of this treatment can be carbon dioxide, water, and salts. An advantage of advanced oxidation processes is that it destroys the contaminant, unlike some other technologies, which only shift the phase of the contaminant into something more easily handled and removed. There are some limitations to these processes; for instance, maintenance of the treatment equipment can be a problem if certain substances—such as insoluble oil or grease—are allowed into the system. Also, the handling and storage of oxidizers can require special safety precautions. The cost of this type of remediation is largely dependent on the volume and flow rate of groundwater to be treated, energy requirements, and chemicals utilized. Operations and maintenance costs are also a factor in the overall cost of this approach. For the purposes of this report, advanced oxidation processes also include the related technologies of phyotolysis and photocatalysis.

2. *Air stripping* involves the mass transfer of volatile contaminants from water to air by exposing contaminated water to large volumes of air, so that the contaminants, such as chemical solvents, undergo a physical transformation from liquid to vapor. In a typical air stripper setup, called a packed tower, a spray nozzle at the top of a tower pours contaminated water over packing media or perforated trays within the tower. At the bottom of the tower, a fan forces air up through the tower countercurrent to the water flow, thus stripping the contaminants from the water. The contaminants in the air leaving the tower must then be removed and disposed of properly. Air strippers can be combined with other technologies for treatment of groundwater. Advantages of this technology include its potential to effectively remove the majority of the volatile organic contaminants of concern. Moreover, this mature technology is relatively simple and design practices are standardized and well-documented, and, in comparison with other approaches, this technology is often less expensive. However, maintenance can be an issue with this technology if inorganic or biological material clogs or fouls the equipment, and process energy costs can be high.

3. *Bioreactors* are biochemical-processing systems designed to degrade contaminants in groundwater using microorganisms, through a process

similar to that used at a conventional wastewater treatment facility. Contaminated groundwater flows into a tank or basin, where it interacts with microorganisms that grow and reproduce while degrading the contaminant. The excess biomass produced is then separated from the treated water and disposed of as a biosolids waste. This technology can be used to treat, among other things, chlorinated solvents, propellants, and fuels. Potential advantages of bioreactors include relatively low operations and maintenance costs and the destruction, rather than mass transfer of, the contaminants. Moreover, regulators and other stakeholders generally accept bioreactor technology as a proven approach for remediation. Nonetheless, there are some limitations to the use of bioreactors, including decreases in effectiveness if contaminant concentrations in the influent water are too high or too low to support microorganism growth and if nuisance microorganisms enter the system. Additionally, the sludge produced at the end of the process may need further treatment or specialized disposal. Bioreactor cost is influenced by the upfront capital needed for installation, setup, and start-up, as well as the operations and maintenance costs associated with longer-term treatment.

4. *Constructed wetlands* use artificial wetland ecosystems (organic materials, microbial fauna, and algae) to remove metals, explosives, and other contaminants from inflowing water. The contaminated water flows into the wetland and is processed by wetland plants and microorganisms to break down and remove the contaminants. Wetlands, intended to be a long-term remediation approach, can be created with readily available equipment and generally can operate with low maintenance costs. Furthermore, because this technology provides a new ecosystem for plant and animal life, it is generally popular with the public. However, this approach is often more suitable for groundwater that is ultimately discharged to the surface rather than reinjected into the ground. Also, the long-term effectiveness of this treatment is not well-known, as aging wetlands may lose their ability to process certain contaminants over time. Temperature, climate, and water flow rate may negatively impact the processes that break down the contaminants. Applicability and costs associated with constructed wetlands vary depending on site conditions, such as groundwater flow rate, contaminant properties, landscape, topography, soil permeability, and climate.

5. *Ion exchange* involves passing contaminated water through a bed of resin media or membrane (specific to the particular contaminant) that

exchanges ions in the contaminants' molecular structure, thus neutralizing them. This approach can be useful for dissolved metals (e.g., hexavalent chromium) and can be used to treat propellants such as perchlorate. Once the ion exchange resin has been filled to capacity, it can be cleaned and reused (following a process called resin regeneration). Ion exchange is usually a short- to medium-term remediation technology. This technology allows contaminated water to be treated at a high flow rate and can completely remove the contaminants from the water. However, some substances—such as oxidants or suspended solids—in the incoming water may diminish the effectiveness of the ion exchange resins. Furthermore, different resin types can be needed for different contaminants. Among the factors influencing costs are discharge requirements, the volume of water to be treated, contaminant concentration (as well as the presence of other contaminants), and resin regeneration. For the purposes of this report, ion exchange includes technologies that use ion exchange resins or reverse osmosis membranes to remove contaminants from groundwater, including dissolved metals and nitrates.

6. *Adsorption (mass transfer)* technologies involve passing contaminated water through a sorbent material—such as activated carbon—that will capture the contaminants (through either adsorption or absorption), thus removing or lessening the level of contaminants in the water. The contaminated water is pumped from the aquifer and passed through the treatment vessel containing the sorbent material. As the contaminated water comes into contact with the sorbent surface, it attaches itself to that surface and is removed from the water. Benefits of this technology include its ability to treat contaminated water to nondetectable levels and its potential for treating low to high groundwater flow rates as well as multiple contaminants simultaneously. However, some contaminants may not be sorbed well or the sorbent unit may require disposal as hazardous waste. Furthermore, this approach is impractical if the contaminant levels are high due to higher costs resulting from frequent changing of the sorbent unit. If the concentrations of contaminants are low or flow rates for treatment can be kept low, then adsorption technology may be a cost-effective approach.

In-situ Technologies

1. *Air sparging* introduces air or other gases into a contaminated aquifer to reduce concentrations of contaminants such as fuel or chlorinated solvents. The injected air creates an underground air stripper that

removes contaminants by volatilization (a process similar to evaporation that converts a liquid or solid into a gas or vapor). This injected air helps to transport the contaminants up into the unsaturated zone (the soil above the water table, where pores are partially filled with air), where a soil vapor extraction system is usually implemented to collect the vapors produced through this process. This technology has the added benefit of often stimulating aerobic biodegradation (bioremediation) of certain contaminants because of the increased amount of oxygen introduced into the subsurface. Typically, air sparging equipment is readily available and easily installed with minimal disturbance to site operations. However, this technology cannot be used if the contaminated site contains contaminants that don’t vaporize or are not biodegradable. In some cases, this technology may not be suitable for sites with free product (e.g., a pool of fuel floating on the water table) because air sparging may cause the free product to migrate and spread contamination. Also, this technology is less effective in highly stratified or heterogeneous soils since injected air tends to travel along paths of least resistance in the subsurface, potentially bypassing areas of contamination. This technology can be less costly than ex-situ technologies because it does not require the removal, treatment, storage, or discharge of groundwater. For the purposes of this report, air sparging includes the related remedial approaches of co-metabolic sparging, sparging using other gases, and in-well air stripping.

2. *Bioremediation* relies on microorganisms to biologically degrade groundwater contaminants through a process called biodegradation. It may be engineered and accomplished in two general ways: (1) stimulating native microorganisms by adding nutrients, oxygen, or other electron acceptors (a process called biostimulation); or (2) providing supplementary pregrown microorganisms to the contaminated site to augment naturally occurring microorganisms (a process called bioaugmentation). This technology mainly focuses on remediating organic chemicals such as fuels and chlorinated solvents. One approach, aerobic bioremediation, involves the delivery of oxygen (and potentially other nutrients) to the aquifer to help native microorganisms reproduce and degrade the contaminant. Another approach, anaerobic bioremediation, circulates electron donor materials—for example, food-grade carbohydrates such as edible oils, molasses, lactic acid, and cheese whey—in the absence of oxygen throughout the contaminated zone to stimulate microorganisms to consume the contaminant. In some cases, pregrown microbes may be

injected into the contaminated area to help supplement existing microorganisms and enhance the degradation of the contaminant, a process known as bioaugmentation. A potential advantage of bioremediation is its ability to treat the contaminated groundwater in place with naturally occurring microorganisms, rather than bringing contaminants to the surface. By using native microorganisms, rather than injecting additional ones, cleanup can be more cost-effective at some sites. However, heterogeneous subsurfaces can make delivering nutrient/oxygen solutions to the contaminated zone difficult by trapping or affecting movement of both contaminants and groundwater.[1] Also, nutrients to stimulate the microorganisms can be consumed rapidly near the injection well, thereby limiting the microorganisms' contact with the contaminants, or stimulating biological growth at the injection site. In summary, this technology avoids the costs associated with bringing water to the surface for treatment; instead, the main costs associated with bioremediation include: delivery of the amendments to the subsurface (which varies depending on the depth of contamination), the cost of the amendments themselves, and monitoring of the treatment. For the purposes of this report, bioremediation includes the related bioremedial approaches of bioaugmentation, biostimulation, co-metabolic treatment, enhanced aerobic biodegradation, enhanced anaerobic biodegradation, and biobarriers.

3. *Enhanced recovery using surfactant flushing* speeds contaminant removal in conventional pump-and-treat systems by injecting surfactants[2] into contaminated aquifers or soil to flush the contaminant toward a pump in the subsurface (some distance away from the injection point); this pump removes the contaminated water and surfactant solution to the surface for treatment and disposal of contaminants. Surfactants are substances that associate with organic compounds such as fuels and chlorinated solvents and significantly

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[1] Heterogeneities can cause wide variability in hydraulic properties such as hydraulic conductivity—a measure of the volume of water that will pass through an area at a given time. These changes in hydraulic properties enhance the dispersion of a dissolved contaminant spread. Heterogeneities can also create preferential pathways for contaminant migration.

[2] Surfactants are molecules with two structural units: one with an affinity for water and one with an aversion to water. Surfactants are especially useful for dissolving some contaminants and enhancing their mobility by lowering the interfacial tension between the contaminant and water.

increase their solubility, which aids cleanup of contaminated aquifers with less flushing water and pumping time. This technology is applicable to both dense and light nonaqueous phase liquids (DNAPL and LNAPL).[3] Benefits of enhanced recovery approaches include the rapid removal of contaminants, which may significantly reduce cleanup times. However, regulatory issues may require special attention due to extra scrutiny for obtaining approvals to inject surfactant solutions; a greater degree of site characterization is often required to satisfy both technical and regulatory requirements. In addition, subsurface heterogeneities and low permeability can interfere with the effective delivery and recovery of the surfactant solution. Furthermore, to the extent that mobilization of organic liquid contaminants is achieved, this approach may be better for LNAPLs than DNAPLs, as LNAPLs tend to migrate upward and DNAPLs downward, possibly trapping them in previously uncontaminated subsurface areas. In addition to the high cost of surfactant solutions, another factor influencing the overall cost of this approach may be the treatment of the surfactant solution that is pumped out of the aquifer. For the purposes of this report, this technology includes related remedial approaches that use co-solvents such as ethanol to improve the solubility of surfactants in the subsurface.

4. *Chemical treatments* include remediation technologies that chemically oxidize or reduce contaminants when reactive chemicals are injected into the groundwater. This approach converts contaminants such as fuels and explosives into nonhazardous or less-toxic compounds. Depending on the extent of contamination, this process involves injecting chemicals into the groundwater and generally takes a few days to a few months to observe results in rapid and extensive reactions with various contaminants of concern. Additionally, this technology can be tailored to the site and does not require rare or complex equipment, which may help reduce costs. Generally, there are no unusual operations and maintenance costs; however, in-situ chemical treatment may require intensive capital investment for large contaminant plumes or zones where repeated applications or large volumes of reactive chemicals may be required; major costs are

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[3] Nonaqueous-phase liquids are liquids that do not mix with, or dissolve in, water. Dense nonaqueous-phase liquids (DNAPL) fall to the bottom of a body of water; chlorinated solvents are typical examples. Conversely, light nonaqueous-phase liquids (LNAPL) gather on top of the water. Gasoline and fuel oil are examples of LNAPLs.

associated with injection-well installation (cost influenced by well depth), procurement of the reactive chemicals, and monitoring. Additionally, site characterization is important for the effective delivery of reactive chemicals, as subsurface heterogeneities may result in uneven distribution of the reactive chemicals. For the purposes of this report, chemical treatment also includes various remedial approaches and technologies that chemically oxidize or reduce contaminants in-situ, as well as those that result in the in-situ immobilization and stabilization of soluble metals.

5. *Monitored natural attenuation* is a relatively passive strategy for in-situ remediation that relies on the naturally occurring physical, chemical, and biological processes that can lessen concentrations of certain contaminants in groundwater sufficiently to protect human health and the environment. The changes in contaminant concentrations are observed through various wells that are placed throughout the contaminated groundwater zone to monitor the level of contamination over time and its migration from its initial location in the subsurface. Some chlorinated solvents and explosives may be resistant to natural attenuation; however, it can still be used in cases of nonhalogenated chlorinated solvents and some inorganic compounds. If appropriate for a given site, natural attenuation can often be less costly than other forms of remediation because it requires less infrastructure, construction, and maintenance. Furthermore, it is less intrusive because fewer surface structures are necessary and it may be used in all or selected parts of a contaminated site, alone or in conjunction with other types of remediation. However, compared with active techniques, natural attenuation often requires longer time frames to achieve remediation objectives.

6. *Multiphase extraction* uses a series of pumps and vacuums to remove free product,[4] contaminated groundwater, and vapors from the subsurface, treat them, and then either dispose or reinject the treated groundwater. Specifically, one or more vacuum extraction wells are installed at the contaminated site to simultaneously pull liquid and gas from the groundwater and unsaturated soil directly above it. This type of vacuum extraction well removes contaminants from above and below the groundwater table, and can expose more of the subsurface for treatment, notably in low permeability or heterogeneous

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[4] Free products are liquid contaminants floating on top of groundwater.

formations. The contaminant vapors are collected in the extraction wells and taken above ground for treatment. This approach can be used to treat organic contaminants—such as chlorinated solvents and fuels—and can be combined with other technologies, particularly above-ground liquid/vapor treatment, as well as other methods of in-situ remediation such as bioremediation, air sparging, or bioventing. Potential advantages of this technology include its applicability to groundwater cleanup in low permeability and heterogeneous formations and its minimal disturbance to site-specific conditions. However, the system requires complex monitoring and specialized equipment, and it may be difficult or problematic to implement the most effective number of pumps. A major contributor to this technology's cost is operations and maintenance, which may run from 6 months to 5 years, depending on site-specific factors. For the purposes of this report, multiphase extraction includes the related technologies of bioslurping and dual-phase extraction.

7. *Permeable reactive barriers* are vertical walls or trenches built into the subsurface that contain a reactive material to intercept and remediate a contaminant plume as the groundwater passes through the barrier. This technology can be used to treat a wide range of contaminants and is commonly used to treat chlorinated solvents and heavy metals. Reactive barriers usually do not require above-ground structures or treatment, allowing the site to be used while it is being treated. However, its use is limited by the size of the plume since larger contaminant plumes are often more difficult to intercept for treatment. Moreover, the barrier may lose effectiveness over time as microorganisms or chemicals build up on the barrier, making rehabilitation or media replacement necessary. The depth of the contaminated groundwater zone and the required barrier may also present some technical challenges. Underground utility lines, rocks, or other obstacles can increase the difficulty of installing a barrier and drive up capital costs. Additionally, because permeable reactive barriers do not treat the contaminant source, but simply the plume, treatment may be required for extended time periods, thus increasing overall cleanup costs. For the purposes of this report, permeable reactive barriers include biotic and abiotic, as well as passive and active treatment barriers.

8. *Phytoremediation* is the use of selected vegetation to reduce, remove, and contain the toxicity of environmental contaminants, such as metals and chlorinated solvents. There are several approaches to

phytoremediation that rely on different plant system processes and interactions with groundwater and contaminants. One approach to phytoremediation is phytostabilization, which uses plants to reduce contaminant mobility by binding contaminants into the soil or incorporating contaminants into plant roots. Another approach is phytoaccumulation, where specific species of plants are used to absorb unusually large amounts of metals from the soil; the plants are later harvested from the growing area and disposed of in an approved manner. A similar process is called rhizofiltration, where contaminated water moves into mature root systems and is circulated through their water supply. Another process can remove contaminants by evaporating or volatilizing the contaminants from the leaf surface once it has traveled through the plant's system. Phytoremediation offers the benefit of only minimally disturbing the environment and can be used for the treatment of a wide range of contaminants. However, specific plant species required for particular contaminants may be unable to adapt to site conditions due to weather and climate, and phytoremediation may not be an effective approach for deep contamination. While maintenance costs, including cultivation, harvesting, and disposal of the plants, are substantial for this technology, phytoremediation typically has lower costs than alternative approaches. For the purposes of this report, phytoremediation includes phytostabilization, phytoaccumulation, phytoextraction, rhizofiltration, phytodegredation, rhizosphere degredation, organic pumps, and phytovolitilization.

9. *Thermal treatments* involves either pumping steam into the aquifer or heating groundwater in order to vaporize chlorinated solvents or fuels from the groundwater. The vaporized contaminant then rises into the unsaturated zone and can be removed via vacuum extraction for treatment. There are three main approaches for heating the groundwater in-situ. The first, radio frequency heating, uses the electromagnetic energy found in radio frequencies to rapidly heat the soil in a process analogous to microwave cooking. The second, electromagnetic heating, uses an alternating current to heat the soil and may include hot water or steam flushing to mobilize contaminants. The third uses heating elements in wells to heat the soil. Thermal treatments may be applied to a wide range of organic contaminants and sites with larger volumes of LNAPLs or DNAPLs as well as sites with low permeability and heterogeneous formations. However, the presence of metal and subsurface heterogeneities in the contaminated site may interfere with this process. The heating and vapor collection

systems must be designed and operated to contain mobilized contaminants, to avoid their spread to clean areas. The major costs incurred for thermal treatments are for moving specialized equipment to the site, developing infrastructure to provide power, and providing energy to run the system. For the purposes of this report, thermal treatments include related soil-heating technologies, such as steam flushing, conductive heating, and electrical resistance heating.

Appendix III

Groundwater Remediation Experts Consulted

Dr. John Fountain
Professor and Head, Department of Marine, Earth and Atmospheric Sciences
North Carolina State University
Raleigh, North Carolina

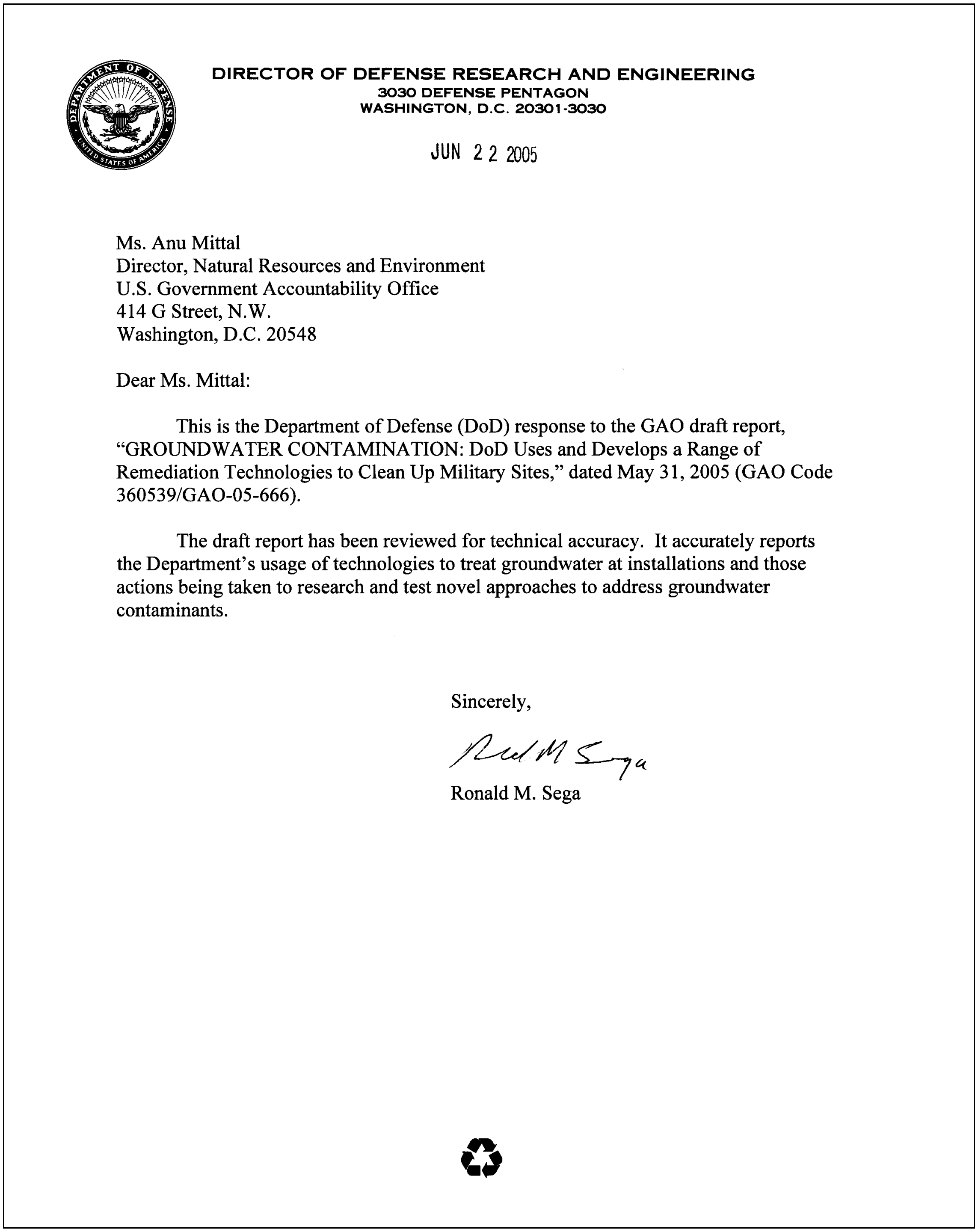
Dr. Robert E. Hinchee
Principal Civil and Environmental Engineer
Integrated Science and Technology Inc.
Panacea, Florida

Dr. Michael C. Kavanaugh
Vice President
National Science and Technology Leader
Malcolm Pirnie Inc.
Emeryville, California

Dr. Robert L. Siegrist
Professor and Division Director
Environmental Science and Engineering Division
Colorado School of Mines
Golden, Colorado

Dr. John T. Wilson
Senior Research Microbiologist
Ground Water and Ecosystems Restoration Division, National Risk Management Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Ada, Oklahoma

Comments from the Department of Defense



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JUN 22 2005

Ms. Anu Mittal
Director, Natural Resources and Environment
U.S. Government Accountability Office
414 G Street, N.W.
Washington, D.C. 20548

Dear Ms. Mittal:

This is the Department of Defense (DoD) response to the GAO draft report, "GROUNDWATER CONTAMINATION: DoD Uses and Develops a Range of Remediation Technologies to Clean Up Military Sites," dated May 31, 2005 (GAO Code 360539/GAO-05-666).

The draft report has been reviewed for technical accuracy. It accurately reports the Department's usage of technologies to treat groundwater at installations and those actions being taken to research and test novel approaches to address groundwater contaminants.

Sincerely,

Ronald M. Sega

GAO Contact and Staff Acknowledgments

GAO Contact

Anu K. Mittal, (202) 512-3841

Staff Acknowledgments

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