Appendix B

Groundwater Contamination

INTRODUCTION

Groundwater contamination has been detected at all of the Nuclear Weapons Complex sites. The extent and types of contamination have not yet been fully characterized. It is not known with sufficient accuracy where the contamination is located, where it is moving, how it is changing, and how soon it might begin to cause problems for human health or the environment, to allow an appraisal of remediation alternatives. However, characterization is underway through the regulatory processes of the Resource Conservation and Recovery Act (RCRA) and Superfund. Work is underway at some sites to correct some contamination problems, and the Department of Energy (DOE) has identified an ambitious research program to develop more cost-effective techniques for characterizing and correcting groundwater and soil contamination problems. Investigations by the Environmental Protection Agency (EPA) and DOE Tiger Teams of some of the characterization and remediation efforts have revealed deficiencies.

This appendix discusses the state of the art of groundwater characterization and cleanup as well as DOE activities.

CHARACTERIZATION OF GROUNDWATER CONTAMINATION

Site characterization is important for understanding the nature and extent of a contamination problem (including pathways to exposure of people). It is also important for designing remediation measures and monitoring their effectiveness. Characterization of groundwater contamination problems has three major elements: detecting the presence of contaminants, understanding their movement and change since entering the subsurface, and predicting their subsequent fate and transport. That is, these elements are simply what they are, where they are and in what concentration, and where they are going and how fast. Data requirements depend on the objectives of cleanup, specific sites, and the remedial technologies that will be considered.

Characterization is a difficult task that requires a high level of expertise to implement properly. Poor characterization is a result of poor field procedures, unjustified choice of methods, and poor initial planning. However, even by following the best approaches, the results concerning fate and transport may be highly uncertain. This uncertainty is a particular problem for certain contaminant ts (e.g., dense, nonaqueous-phase liquids and complex mixtures of contaminants) and certain hydrogeologic environments (e.g., fractured rock systems, karst, and unsaturated zones).

The basic data to characterize groundwater contamination problems come from properly constructed and sampled wells. Wells offer a window into the subsurface that can provide information on the physical, chemical, and biological properties of both the aquifer media and the water. Such information is useful in predicting the occurrence, fate, and transport of contamination. However, wells can be expensive to construct and still provide a very limited view of the subsurface. Skilled hydrogeologists can extrapolate information between wells, but methods that provide a more comprehensive view of the subsurface are always preferred. Geophysical and remote sensing techniques and computer modeling provide additional means of gaining information about the subsurface, but they also have limitations.

Detecting Contaminants

Detecting contaminants is an iterative process. Samples are taken and analyzed. The results are interpreted to identify additional sampling needs. This procedure can be followed repeatedly until information needs are satisfied. Traditionally, the process can take many months, partly because of delays associated with obtaining laboratory results.

A major difficulty in detecting contaminants is the lack of accepted analytical and safety procedures for many of the contamination problems likely to be encountered at DOE sites; these include the number of radionuclides, the presence of radionuclides mixed with other chemicals or materials (mixed waste), and the specialty chemicals used by DOE (l). This is an issue that has been identified by DOE and is currently being addressed in its Research Development, Demonstration, Testing, and Evaluation (RDDT&E) program. There is also a special problem of detecting small quantities of highly potent chemicals. These situations may remain undetected for years, but suddenly show up at a point of use. Currently available sampling techniques for such problems are either prohibitively expensive because of the large numbers of samples required or not accurate enough to detect such low concentrations.

However, technologies to identify the types and concentrations of materials present are changing. Techniques are becoming available for on-site and in situ measurements. On-site measurements require that samples be extracted, but measured in the field rather than transported to a laboratory. In situ measurements are made directly in wells or boreholes, without the need to extract a sample. On-site and in situ techniques have both advantages and limitations. These new techniques avoid some of the time and expense associated with laboratory analysis and can help maintain sample integrity (2). However, it may be difficult to ensure adequate quality control for these techniques, and instruments may require modification to be effective in different types of aquifer materials (3).

On-site techniques are valuable because they allow for rapid evaluation of results and the ability to take additional measurements at the same or different locations when needed, without waiting for results from a laboratory. In situ techniques are also useful because many problems are associated with obtaining representative samples, particularly from groundwater, due to chemical and physical changes that may occur when groundwater is extracted. For example, dissolved gases or volatile contaminants can be lost, or the presence of oxygen can change the sample. Yet, no technique is likely to be capable of identifying the full range of contaminants present at the Nuclear Weapons Complex. In addition, some problems are always likely to require laboratory analysis.

The application of new monitoring technologies to problems at the Nuclear Weapons Complex depends on whether the technique can detect the contaminants of concern with the necessary sensitivity. Information gained in laboratory tests of an instrument may not always be indicative of field performance. In the field, other chemicals may interfere with instrument readings. The instrument must also be capable of detecting the contaminant at the level of concern; ideally an instrument should be able to detect a contaminant from below any regulatory standard to its volubility limit in water (4). However, this ideal range is rarely achieved. Other concerns include response time for on-site measurements, reversibility of in situ measurements to allow readings as the concentrations of contaminants decrease, and field operability.

In a study for DOE, Pacific Northwest Laboratory prepared an evaluation of chemical sensors for on-site and in situ monitoring of high priority contaminants found in groundwater at the Hanford Reservation (5). Table B-1 shows the contaminants of concern and the sensitivity of various instruments to those contaminants, based on laboratory analysis. Of the 14 contaminants considered, the authors found that each contaminantt could be detected by several types of technologies. Detection of only five types of contaminants has been demonstrated in the laboratory (cyanide, chromium, uranium, trichloroethylene (TCE), and hydrocarbons). Detection of seven contaminants (carbon tetrachloride, methyl ethyl ketone (MEK), nitrate, perchloroethylene (PCE), 1,1-dichloroethane (DCA), 1,1,1-trichloroethane (TCA), and 1,2-dichloroethylene (DCE) by in situ methods appears feasible but has not been demonstrated by the instrument systems studied. Continued technology evaluations of this type, as more contaminants are identified at other sites, would help to focus DOE sensor development research.

The report concludes that technology for chemical sensing is in an early stage of development and will probably remain so in the near term. This is an active area of research by universities, government, and industry that is rapidly changing. However, few technologies have been commercialized, and even those have not been tested sufficiently under field conditions. Also, private companies are apparently reluctant to field test prototype sensors because of the fear of adverse publicity if they do not work as well as advertised in the specific testing environment (6). Pacific Northwest Laboratory has a field testing program to demonstrate, test, and evaluate new or prototype sensors. Testing is scheduled for two prototype sensors developed with the support of DOE for two contaminants of concern, uranium and ferrous cyanide. Such a testing program is necessary to allow DOE to identify and ensure the development and availability of instruments that will meet the needs at the Nuclear Weapons Complex. The study further identified the need for DOE to concentrate future research support on the development of sensor coatings that are highly selective for contaminants of concern.

The EPA Measurement and Monitoring Technologies Development Program has focused its attention on immunoassay techniques and the development of fiber optic sensing for in situ analysis. Immunoassay techniques are not applicable for most of the contaminants identified at Hanford as shown in table B-1.[1] Fiber optic systems are an integral part of many in situ detection techniques, but further work is required to develop the appropriate sensor for contaminants of concern.[2]

In situ methods are limited by the need to develop new sensors to detect the contaminants of concern. Many of these emerging methods will provide the opportunity for real-time analysis and remote transmission of data. Real-time analysis may allow monitoring of disposal sites for signs of containment failure and monitoring around well fields for incoming contaminant plumes.

Techniques that are currently available for on-site or in situ measurements include field gas chromatography (GC) and specific conductance electrode screening (7). GC is useful for low-molecular-weight organics and for

[1]EPA has initiated work on immunoassays for benzene, toluene, ethylbenzene, phenol, chlorobenzene, and nitroaromatic compounds.

[2]Fiber optic sensors have been developed for chloroform, oxygen, carbon dioxide, pH, trihalomethane, and gasoline. EPA is currently working to develop sensors for benzene, cyanide, iron, nitrate, phosphate, toluene, and xylene.

Table B-1—Applicability of Chemical Sensors to Contaminants at Hanford

	Chemical sensors[a]									
Selected Hanford contaminants	Fluorescence spectroscopy	Surface-enhanced Raman spectroscopy	Spark excitation—FOSES[b]	Chemical optrodes	Stripping voltammetry	Catalytic S-M ion electrode[c]	Immunoassay sensors	Resistance/ capacitance	Quartz piezobalance	SAW devices[d]
Organics										
Carbon tetrachloride	NA	?	NA	?	NA	?	NA	?	?	?
Trichloroethylene	NA	?	NA	ppb	NA	?	NA	?	?	?
PCE, DCA, TCA, DCE[e]	NA	?	NA	?	NA	?	NA	?	?	?
Chloroform	NA	?	NA	ppb	NA	?	NA	?	?	?
Cyanide	NA	ppm	NA	?	?	ppb	NA	?	?	?
Methyl ethyl ketone	NA	?	NA	?	NA	?	?	?	?	?
Hydrocarbons	ppb	?	NA	ppb	NA	?	?	ppm	?	?
Inorganics										
Chromium(IV)	NA	ppm	?	?	ppb	ppb	NA	?	?	?
Fluoride	NA	NA	NA	?	?	ppb	NA	?	?	?
Nitrate	NA	?	NA	?	NA	?	NA	?	?	?
Uranium	NA	?	?	ppm	ppb	?	NA	?	?	?

[a]NA = Not applicable; ppm = parts per million; ppb = parts per billion; ? = Unknown.
[b] Fiber optic spectrochemical emission sensors
[c]Surface-modified
[d] Surface acoustic wave
[e] PCE = perchloroethylene; DCA = 1,1-dichloroethane; TCA = 1,1,1-trichloroethane; DCE = 1,2-dichloroethylene.

SOURCE: E.M. Murphy and D.D. Hostetler, "Evaluation of Chemical Sensors for In-Situ Ground-Water Monitoring at the Hanford Site," PNL-6854 DE89 011306 (Richland, WA: Pacific Northwest Laboratory), March 1989.

Table B-2—Relationship Between Remedial Technologies and Site Characterization

Technology	Specialized site/contaminant data
In situ vitrification of contaminants in soil	Soil electrical conduction and glassification properties, presence of groundwater, soil permeability, presence of metals
Soil washing to remove trace metals and radionuclides in soil	Distribution of contaminants as a function of soil particle size and density
In situ removal of gasoline in soil and groundwater by vacuum-induced venting	Clay content of soil, depth to groundwater
In situ destruction of 1,1,2-trichloroethylene and perchloroethylene in groundwater by using microbes	Soil nutrient content, soil ion-exchange capacity
Ultraviolet/ozone treatment of groundwater contaminated with 1,1,2-trichloroethylene	Iron and manganese content of groundwater; presence of long-chain organics
Reducing the natural rate of conversion of metallic mercury to organic mercury through biological processes	Characterizing the physical and chemical conditions in the environment that favor mercury-resistant microbes
Chemical extraction of contaminants from soil	Presence of refractory minerals in soil
Soil washing to remove organic contaminants	Amount of sand present in soil matrix
Ion-exchange processes to remove heavy metals from groundwater	Water hardness
In situ steam cleaning of soil contaminated with volatile organics	Vapor pressure of contaminant
In situ electroacoustical soil cleaning[a]	Clay content of soil

aThis system is an example of the application of coupled processes.

SOURCE: S. Cohen&Associates, 'Technologies for Identification, Characterization, and Remediation of Environmental Contamination at U.S. Department of Energy Defense Complex Sites," contractor report prepared for the OTA, unpublished, October 1989.

solution or vapor analysis. It is an on-site technique that requires that samples be extracted; therefore, it is subject to problems with sample integrity. Many compounds could be missed with this technique because it is not sensitive to high-molecular-weight organics, and it is difficult to interpret readings for complex mixtures of contaminants on the available field equipment. Specific conductance electrodes are useful for dissolved ionic contaminants and generic plume definition. Results reflect total concentration of metal salts in water, but the method is not specific and thus cannot distinguish between different sources of contaminants and natural background levels. Also, the technique does not give information on organics that may move through aquifers at different rates than dissolved metals. These limitations highlight the need for well-qualified people to use and interpret the results.

Predicting Fate and Transport

Predicting fate and transport of contaminants in groundwater is very site-specific and inherently uncertain. It depends on understanding the characteristics of the source of contamination, the nature of the geologic environment, the rate and direction of groundwater movement, and the behavior of contaminants in the subsurface.

Investigations of fate and transport performed in accordance with guidance documents and sound science are conducted to take full advantage of existing data and to incorporate many methodologies-including aquifer tests, modeling, treatability studies, and geophysical surveys--- prior to, and in conjunction with, drilling and sampling. Proper use of these methods requires a high level of expertise. Specific data requirements depend on the site, the nature of the problem, and remedial alternatives. Examples of data needs for specific remedial alternatives are shown in table B-2. Guidance from EPA describes strategies and methods for determining the hydrogeology, characterizing the contamination, evaluating plume movement and response, assessing design parameters for potential treatment technologies, and considering technical uncertainty (8).

Technical uncertainty is inherent in the prediction of the fate and transport of groundwater contaminants. It arises from inadequate knowledge in the following areas:

- the source of contamination (e.g., volume, concentration, and timing of contaminant release; physical, chemical, and biological characteristics of contaminants; contaminant dispersion and diffusion),
- the movement of contaminants through the unsaturated zone (e.g., hydraulic conductivity and potential moisture content of soil, chemical and biological characteristics of soil), and
- the rate and direction of groundwater flow (e.g., hydraulic conductivity; viscosity, density, permeability, anisotropy, and heterogeneity of hydrogeology; aquifer characteristics such as porosity and organic carbon content; aquifer stresses arising, for example, from groundwater pumping at other wells and natural or artificial recharge; seasonal variation in groundwater levels; tidal and pressure effects; storage characteristics of the aquifer; aquifer thickness, and areal extent) (9).

An example of these technical uncertainties that is directly applicable to several sites in the Nuclear Weapons Complex is poor understanding of the physical, chemical, and biological processes that affect contaminant movement. The mobility of certain radionuclides with colloidal organic material is poorly understood. Other parameters are impossible to measure with sufficient detail to provide accurate predictions of the magnitude and direction of contaminant transport, such as geologic heterogeneities (10). Because the long-term behavior of radionuclides can be highly dependent on local soil chemistry, which makes accurate prediction from generic models unlikely, radionuclide mobility is an active area of research for DOE and the Nuclear Regulatory Commission (NRC) (11). The use of innovative sampling methods, such as sampling vegetation to detect groundwater contamination in fractured or inhomogeneous media, is also an important area of research (12).

EPA guidance on technical uncertainty focuses on how to address it so that cost-effective decisions can be made about data collection to support cleanup decisions (13). EPA notes that reducing uncertainty should be weighed against time and resource limitations and that, often, remedy selection should move ahead by using the best professional judgment even if the level of uncertainty is high. Additional data are justified to the extent they can help distinguish the performance and uncertainty of remedial alternatives.

Recognition of uncertainty in both characterization and performance of remedial alternatives has led EPA to recommend modifying the Superfund approach to groundwater remediation (14). The major recommendation is to initiate early action on a small scale, while gathering more detailed data prior to committing to full-scale restoration. This approach is discussed in more detail under a following section, cleanup of groundwater contamination.

Geophysical and Remote Sensing Techniques

Geophysical and remote sensing techniques can potentially serve as a screening tool to describe the geological environment, identify areas of contamination, and monitor the performance of some remediation measures (15). Perhaps the greatest value of these methods is to characterize the heterogeneity of the environment, rather than to detect contamination (16). Box B-1 presents examples of the use of various techniques to characterize environmental contamination. These techniques can potentially provide continuous information on a site, and many can be applied remotely without exposing the operator to contamination. Most practitioners argue that drilling will always be necessary to interpret the resulting data accurately. However, these techniques can limit the number of wells required by helping to locate the wells so as to maximize information gained.

Different techniques are not applicable to all sites due to limitations such as rock and soil type, depth of penetration, and interference from natural or manmade features. Based on a relatively fast geophysical survey (completed in a matter of days), wells can be located to investigate anomalies, which can lead to more rapid identification of unknown or unexpected problems. The accessibility of these techniques, however, is constrained by the lack of qualified people and the availability of equipment.

Considerable basic research is needed to develop equipment and applications in this area. The greatest need, according to some practitioners, however, is to educate people to use available techniques in appropriate ways. The subject is highly complex, and each site presents its own challenges as to what approaches to use, in what sequence, and how to interpret the results. Flexibility is important in applying the techniques.

Some of the technology applied today was developed 30 to 40 years ago for the mining and oil industries. Applying this technology to environmental restoration problems in many cases requires reinventing old techniques, refining equipment for more portable field applications, making it feasible for use in contaminated areas, and modifying new computer imaging tools to aid in interpretation at the depths of interest.

Some geophysical techniques are widely used and accepted. Technologies that are sufficiently developed to be suggested by the U.S. Geological Survey as possible techniques for characterizing hazardous waste sites are described in box B-2. Borehole techniques are also widely used; these involve lowering a sensing device into a well or borehole to collect data that can provide information on the characteristics of geologic formations that affect the availability of water and the water quality. The use of borehole techniques is quite extensive in the petroleum industry. Hydrogeologic applications emphasize the use of electrical techniques (17).

Significant improvements continue to be made in the sensitivity and interpretative ability of geophysical techniques. Prospects for new geophysical technologies are good, although most will represent improvements on existing techniques and detection. The detection of organic compounds is problematic. Many remote sensing systems are rapidly being developed and improved for air, surface, and near-surface detection of contamination, including organics. New technologies being developed and identified by government experts as showing great promise for environmental restoration problems include infrared reflectance spectroscopy, complex resistivity, and geophysical diffraction tomography.

Computer Modeling

Modeling of groundwater flow and contaminant transport has a definite role to play in characterizing a contaminated site and in planning and implementing remedial activities. To play that role in an effective manner, users of the models must know their limitations,

Box B-1—Examples of Use of Geophysical Techniques in Site Characterization

1) Gravity and seismic methods to determine detailed bedrock structure and to identify buried bedrock channels filled with permeable deposits that provide a pathway for migration of contaminants. Helpful in selecting drilling sites.[1]

2) Seismic methods to define bedrock topography and terrain conductivity survey to locate possible leaching field or buried drums. Combination of two techniques was necessary to help interpret results.[2]

3) Seismic methods for investigating boundaries of glacial units.[3]

4) Ground-penetrating radar to map water table in glacial outwash. Accuracy was within 2 feet (would not meet EPA standards for accuracy under RCRA).[4]

5) Ground-penetrating radar to provide information on the scale of heterogeneity of the aquifer and to monitor plume position and movement from a municipal landfill in glaciolacustrine sand. The upper surface of the plume was readily monitored.[5]

6) Magnetic methods and computer mapping to design a program of excavation and drum removal. Analysis took 6 days to complete and resulted in reducing excavation area from 2.5 to 0.3 acres.[6]

7) Electromagnetic and resistivity methods to monitor groundwater at a sanitary landfill. To design monitoring program, various geophysical methods were tested, interferences were identified, and seasonal fluctuations were defined. Similar area with known contamination was compared, showing significant differences from uncontaminated areas.[7]

8) Surface electrical resistivity to map fractures in bedrock and identify areas open to movement of groundwater in a crystalline bedrock formation.[8]

9) Promising field tests on the use of geophysical diffraction tomography to identify buried waste such as drums or trenches and to detect and locate leaks in buried hazardous liquid storage facilities.[9]

[1]E.B. Rodriguez, "Application of Gravity and Seismic Methods in Hydrogeological Mapping at a Landfill Site in Ontario," *Proceedings of the First National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods,* May 1987.

[2]D.W. Hall and D.L. Pasicznyk, "Application of Seismic Refraction and Terrain Conductivity Methods at a Ground Water Pollution Site in North-Central New Jersey," Ibid., pp. 505-524.

[3]A. Streitz, "Off-End Surface Seismic Reflection Sounding With Vertical Seismic Profiling in Glacial Terrain," Ibid., pp. 525-537.

[4]D.G. Johnson, "Use of Ground-Penetrating Radar for Determining Depth to the Water Table on Cape Cod," Ibid., May 1987, pp. 541-554.

[5]T.M. Cosgrave, J.P. Greenhouse, and J.F. Baker, "Shallow Statigraphic Reflection from Ground Penetrating Radar," Ibid., pp. 555-569.

[6]J.F. Blasting, "Characterization of an Abandoned Waste Site Using Proton Magnetometry and Computer Graphics," Ibid., pp. 573-584.

[7]J.O. Rumbaugh, III, J.A. Caldwell, and S.T. Shaw, "A Geophysical Ground Water Monitoring Program for a Sanitary Landfill: Implementation and Preliminary Analysis," Ibid., pp. 623-641.

[8]G.A. Johnson and T.E. Saylor, "Detailed Subsurface Mapping of Fracture Closure in a Crystalline Bedrock Formation," Ibid., pp. 643-657.

[9]A. Witten and W.C. King, "Sounding Out Buried Waste," *Civil Engineering,* May 1990, pp. 62-64.

apply them in appropriate situations, and interpret the results accordingly.

Models can be useful tools for understanding some elements of groundwater and contaminant transport at a site. Because of the complex nature of the subsurface, models can be used to evaluate data and to form and test hypotheses of subsurface behavior. For example, modeling studies at the Feed Materials Production Center in Femaid, OH, contributed to understanding the role of the storm sewer outfall and the waste storage pit area as sources of contamination; identified the possible presence of a previously unknown groundwater divide that could affect local contaminant transport; and helped to refine groundwater monitoring programs (18). Models have also been used to compare remedial alternatives.[3] However, modeling alone is not sufficiently refined to confidently predict the transport and fate of complex mixtures of contaminants, exposure pathways, and effectiveness of remediation technologies.

Moiels differ in purpose, complexity, data requirements, and level of skill required of the user. Screening models have minimal data requirements and are useful for

[3]For example, drains, a slurry wall, and a clay cap were evaluated by using models for a landfill, and pump and treat technology has been modeled at several sites. See P.F. Andersen, C.R. Faust, and J.W. Mercer, "Analysis of Conceptual Designs for Remedial Measures at Lipari Landfill, N.J.," *Ground Water*, vol. 22, No. 2, March-April 1984, pp. 176-190; D.S. Ward et al., "Evaluation of a Groundwater Corrective Action at the Chem-Dyne Hazardous Waste Site Using a Telescopic Mesh Refinement Modeling Approach," *Water Resources Research*, vol. 23, No. 4, April 1987, pp. 603-617; C.R. Faust et al., "Simulation of Three-Dimensional Flow of Immiscible Fluids Within and Below the Unsaturated Zone," *Water Resources Research*, vol. 25, No. 12, December 1989, pp. 2449-2464; and J.W. Mercer et al., "Modeling Ground-water Flow at Love Canal, New York," *Journal of Environmental Engineering*, vol. 109, No. 4, August 1983, pp. 924-941.

Box B-2—Geophysical Methods

Radiometric Methods—Radiometric techniques measure the radiation emitted from radioactive isotopes. Radioactive contaminants may be masked by high background levels of natural radioactivity or by roughly a meter of overlying soil cover (depending on the type and strength of the source). These are generally useful only at radioactive waste disposal sites. However, they may be useful in locating natural radioactive hazards (e.g., radon gas sources), early radium processing plants, mining mill tailings, and other similar sites.

Magnetic Methods—Magnetic techniques measure perturbations in the earth's natural magnetic field near magnetic objects such as iron drums or barrels. Large concentrations of iron or steel fences, utilities, culverts, vehicles, or buildings may interfere with the technique. Soils with high iron content (e.g., greensand, basalt, red hematitic soil) may be sufficiently magnetic to hide objects detectable under other soil conditions.

Electromagnetic Methods Induction (EMIs)—EMIs are electromagnetic techniques that induce currents in the earth. They measure the magnetic field generated by the induced currents. The electrical conductivity of the earth is proportional to the magnetic field generated from the induced currents. The depth of investigation is a function of the instrument coil spacing and orientation, the frequency of measurement, and the electrical conductivity of the ground. By measuring and mapping the changes in electrical conductivity, EMI may directly locate plumes of inorganic contaminants, clay lenses, metallic objects such as buried drums, and inhomogeneities in geology such as fractures. EMI techniques are ineffective in areas with many fences, pipelines, telephone cables, or other metallic interference. EMI requires topographic correction. EMI techniques are readily available commercially, relatively inexpensive, and require one- or two-worker crews. EMI methods gather data very quickly over large areas, whereas resistivity methods are preferred for sounding to acquire depth information

Soil Gas Methods—Soil gas techniques measure the variation in concentration of gaseous vapors collected just below the ground surface. Collected vapors are analyzed by portable gas chromatographs or mass spectrometers to identify particular compounds of interest. The sampling zone may be at or within a few meters of the surface. Airborne or near-surface contamination may bias interpretation of underground contaminants. Permeability variations at the site from utility corridors, clay layers, or fractures will modify the apparent contaminant patterns at the surface, requiring careful interpretation. Driving gas sampling probes into the ground to avoid surface or airborne contamination may pose a safety hazard if utilities or near-surface barrels are punctured. Soil gas sampling is insensitive to nonvolatile organics and cannot detect inorganic contaminants.

Complex Resistivity Methods—Resistivity techniques use electrodes in contact with the ground to measure electrical resistivity (the reciprocal of conductivity). The depth of investigation is a function of electrode spacing and geometry (larger spacings probe more deeply). By measuring and mapping the changes in electrical resistivity, these techniques may directly locate plumes of inorganic contaminants, clay lenses, metallic objects such as buried drums, and inhomogeneities in geology such as fractures. Resistivity techniques are ineffective in areas with many fences, pipelines, telephone cables, and other metallic interference. Resistivity techniques may require topographic correction, are readily available commercially, are relatively inexpensive, and require one- or two-worker crews. Resistivity measurements are preferred for sounding to acquire depth information, whereas EMI provides easier and faster areal mapping. Complex resistivity methods measure resistivity as a function of frequency, and may be able to detect organic contaminants when they react with clay minerals. However, this is much more time-consuming and expensive.

Ground-Penetrating Radar (GPR) Methods—GPR measures changes in the velocity and mode of propagation of electromagnetic energy in the ground. Such changes typically occur from changes in water content and bulk density. Thus, GPR is a sensitive indicator of soil stratigraphy and bedrock fracturing and is an excellent way to map the water table. GPR may sometimes directly detect organic contaminants, either by changes in scattering properties (the texture of the radar record) or by dielectric contrast (e.g., oil floating on water). GPR works well in high resistivity environments such as dry or freshwater saturated coarse sand or granite. Low-resistivity salt water and clays such as montmorillonite severely limit the depth of penetration and the effectiveness of GPR.

Gravity Methods—Gravity techniques measure changes in the gravitational field of the earth. These changes are interpreted in terms of changes in density and porosity in the ground. Gravity techniques require accurate location and topographical surveying, removal of regional gradients, and correction for tidal effects. They cannot directly detect contaminants. Microgravity techniques may be useful in locating trenches, voids, and incipient subsidence problems.

Seismic Methods—Seismic techniques measure changes in the propagation of elastic compressional or shear energy in the ground. They may be operated in reflection or refraction modes. They are sensitive to changes in density and water content. They are most useful in defining subsurface geological or hydrological structure. They cannot detect contaminants directly, although they may locate trenches or other disturbed burial zones in the ground. In urban environments, high noise or difficult coupling (through concrete or asphalt) may render them useless. Seismic and radar techniques are complementary because seismic methods work well in clay soils, whereas radar does not, and radar works well in loosely compacted sandy soil, whereas seismic techniques do not.

SOURCE: G.R. Olhoeft, "Geophysics Advisor Expert System," U.S. Geological Survey Open File Report 88-399, June 1988.

elucidating the role of specific processes in controlling system behavior and for providing guidance in early data collection efforts. More complex, data-intensive models can be used to test the validity of assumptions made about the site by a comparison of past and present system behavior with model predictions.

Before models can be used to predict the transport and fate of contaminants, exposure pathways, and effectiveness of remediation alternatives, a detailed understanding of the site is required. In particular, the processes controlling groundwater flow and contaminant transport must be identified. Mathematical modeling is not a substitute for data collection, and successful forecasting of detailed system behavior requires good quality, site-specific data.

Selection of an appropriate model requires consideration of the purpose for which the model is to be used, the characteristics of the site and the contaminants, the site-specific data available, the extent to which the model has been validated, the education and experience of the person using the model, and the computational facilities necessary. Selection and use of a model also requires training and experience. However, it is more important for the model user to have a good understanding of the basic geologic, hydrologic, physical, chemical, and biological processes that control groundwater flow and contaminant transport than to be a skilled mathematician or numerical analyst.

There are very definite limitations on the use of models to predict contaminant fate and transport and to plan site remediation. The extreme heterogeneity of the natural environment can make the use of models extremely difficult (19). Other limitations include the large amount of site-specific data required as a result of heterogeneity, incomplete understanding of some of the processes controlling contaminant transport and fate, an inability to solve the resulting mathematical equations in an efficient manner, and the unavailability of people with the ability to select, use, and interpret the models (20).

The effect of these limitations can vary with the characteristics of the site and the contaminants being modeled. Problems involving a small number of completely soluble, noninteracting contaminants in a relatively homogeneous subsurface environment can be modeled with a high degree of confidence. Most sites, however, do not meet such conditions. Deviations from these conditions will reduce the level of confidence that can be placed in model results, particularly if one is looking for a detailed description of system behavior.

Uncertainties in model predictions result largely from a lack of detailed information about the site. Research is currently underway on methods of characterizing this uncertainty in a useful manner and on techniques to combine modeling and data collection in order to reduce uncertainties in the most efficient way. Research is also being carried out on the use of stochastic modeling techniques as a possible means of dealing with uncertainties in model predictions, but their applicability to waste site remediation projects has not been tested (21). One of the most advanced approaches involves combining computer simulation techniques for predicting contaminant migration with advanced mathematical and statistical methods for determining the most effective and economical pumping locations and rates to withdraw water for treatment (22).

Flow and transport through fractured rock environments, problems involving multiphase fluid systems (nonaqueous liquids), and chemical reactions other than simple appearance or disappearance of a chemical are examples of conditions for which good models are not available and little successful experience exists. These are all active areas of research, and the situation is slowly improving (23).

Modeling will be most effective when used in an interactive manner with data collection and site cleanup activities. Modeling can be used *to* guide data collection activities; in this way, the additional data can be used to refine the model, which, in turn, can provide guidance for further data collection, until a good understanding of system behavior is obtained. Modeling can be used in a similar manner to guide the operation of a cleanup system at the site.

CLEANUP OF GROUNDWATER CONTAMINATION

Once contamination has reached groundwater, it may be very difficult, expensive, and time-consuming to clean up. In some cases, cleanup maybe an unrealistic goal, and alternatives such as containment or treatment at the point of use may be appropriate.

The first steps in remediating a groundwater contamination problem, after initial characterization, are to prevent the spread of the contamination plume with a containment system and to eliminate the source. In addition to eliminating the source of contamination, such as leaking tanks or a surface impoundment, contaminated soils must often be cleaned up or isolated so that water moving through a contaminated unsaturated zone does not carry contaminants to the groundwater.

The major difficulty in restoring groundwater quality is associated with gaining access to the contamination—either by extracting the groundwater for treatment at the surface or by reaching contamination with in situ methods.

Recognizing these difficulties, EPA has made several recommendations for modifying the Superfund approach to groundwater remediation (24). The primary goal of

Superfund-to return groundwater to its beneficial uses within a reasonable timeframe-is retained. Recommendations encourage data collection to allow the design of an efficient cleanup approach that more accurately estimates the time required for remediation and the practicability of achieving cleanup goals. This entails initiating staged action and collecting specific data to optimize design and performance. It also entails recognizing the uncertainties associated with remediating contaminated groundwater, informing the public of these uncertainties, and developing contingencies to respond to new information and performance problems. EPA rec--ommendations are described in box B-3.

The new recommendations are directed to responsible EPA regional officials. DOE headquarters has endorsed this basic approach, also known as the observational method, and now has consultants educating field office personnel on use of the observational method in remediation programs. The approach has been criticized for application to non-Federal Superfund sites as primarily an effort for cleanup contractors to minimize their liabilities (25). Contractors contest these criticisms by stating that the motivation for applying the observational approach is to avoid conducting studies and collecting data for no useful purpose, and to move ahead with remedial activities while recognizing the inherent technical uncertainties (26).

There is a need to be explicit with the public about the uncertainties posed by characterization and cleanup, to optimize resources for characterization and cleanup, and to recognize that cleanup efforts must be monitored for their effectiveness so that modifications to remedial activities can be implemented when problems are recognized.

Groundwater Extraction

Extraction of groundwater for treatment is currently the primary method of groundwater remediation. Technologies to extract contaminated groundwater for treatment have limitations that make it difficult to predict the amount of time required to remove sufficient concentrations of contaminants. Limitations include adsorptive partitioning of contaminants between the aquifer and aquifer materials, and diffusion of contaminants into the small pores of the aquifer materials, which increase the amount of time required for remediation; aquifer heterogeneity, which makes it difficult to control groundwater flow; and residual contaminant sources in the soil or in a nonaqueous phase, which replace the dissolved contaminants as they are removed. In some cases, when sources of contamination cannot be eliminated, it may be necessary to operate pump and treat systems for long periods to achieve the desired reductions in contaminant concentrations.

Box B-3—EPA Recommendations To Modify the Superfund Approach to Groundwater Remediation

1. *Initiate Response Action Early*—"Response measures may be implemented to prevent further migration of contaminants if they will prevent the situation from getting worse, initiate risk reduction, and/or the operation of such a system would provide information useful to the design of the final remedy." EPA provides examples of when such an approach is warranted, e.g., when contamination is migrating rapidly and when sites are located near drinking water wells that can potentially be affected by the plume. Advice is also given on implementing remediation measures in a staged process when data collected during the remedial investigation/feasibility study were insufficient to optimize design. By monitoring the response of contamination to the staged remedy, the system can be modified to address the problem efficiently.
2. *Provide Flexibility in the Selected Remedy To Modify the System Based on Information Gained During Its Operation*—EPA's discussion of this recommendation focuses on the uncertainty associated with reducing groundwater contamination to specified levels. EPA emphasizes the importance of informing the public of these uncertainties, developing contingency plans within the framework of a record of decision (ROD), and recognizing when it may be necessary to modify a ROD. EPA also discusses the importance of continuing monitoring activities after remediation measures have been completed to ensure that contaminant levels do not recover. EPA plans to develop future guidance on when it is appropriate to terminate groundwater extraction activities if some portion of groundwater cannot be returned to its beneficial uses.
3. *Collect Data To Better Assess Contaminant Movement and Likely Response of Groundwater to Extraction*—EPA's discussion of this recommendation lists the types of data required to improve the design and predict the performance of groundwater pump and treat systems. Evaluation of ongoing systems has revealed many deficiencies.

SOURCE: U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, "Considerations in Ground Water Remediation at Superfund Sites," OSWER Directive 9355.4-03, Oct. 18, 1989.

There are two basic methods for extracting groundwater: pumping systems and passive systems. Both are based on two assumptions: 1) that it is possible to design a system that will withdraw all the contaminated water (this can be a problem in aquifers of low transmissivity, which do not release much water to wells, or in aquifers that have zones of low permeability, such as clay lenses); and 2) that the contaminants will come out of the aquifer with the water (this can be a problem if contaminants are sorbed onto aquifer materials or are present in a nonaqueous phase). Nonaqueous-phase contaminants may be either more or less dense than the groundwater. When dense nonaqueous-phase liquids (e.g., TCE and some other solvents) are present, they may be difficult to locate, and aquifer restoration may be judged impossible (27). When less dense, nonaqueous phase liquids (e.g., many petroleum products) are present, prospects for cleanup are improved by the use of additional restoration techniques such as vapor extraction or bioremediation.

Pumping systems, or wells, can extract or divert groundwater at virtually any depth. The system should be optimized to remove contaminated groundwater while extracting only a limited volume of uncontaminated water. More information on the design of pumping systems is discussed under a following section, *Containment and Flow Control.*

Passive interceptor systems can be excavated to a depth below the water table with the possible placement of a pipe to collect contaminated water or to lower the water table beneath a contamination source. These systems are relatively inexpensive to install, have low operating costs because flow is by gravity, and provide a means for leachate collection without impermeable liners (28). Although these systems can be more effective than wells for extracting water from some lower permeability materials, they are not suited to all low permeability conditions. They are limited in depth to the capabilities of trenching equipment (about 100 feet) and require continuous and careful monitoring to ensure adequate leachate collection (29).

Treatment After Extraction

Surface treatment techniques developed for water or wastewater are available for most contaminants.[4] However, treatment systems for extracted water must be designed to deal specifically with the mixtures of contaminants and varying concentrations present at a site. Combinations of treatment processes may be required, and there is little experience designing systems to handle the mixtures of organics, radionuclides, and inorganics that may be present. Some processes are not applicable to the low concentrations of contaminants in question. Measures are required to discharge treated water back to the subsurface, to surface water, or to further treatment at a treatment plant. Some processes also generate residuals that must be handled as hazardous waste.

A description of various physical, chemical, and biological treatment techniques and some of their important limitations are presented in the EPA handbook on groundwater (30).

DOE has sponsored research on several technologies for groundwater treatment including supercritical water oxidation, solar destruction, and ultraviolet ozonation. Many of the new technologies are potentially applicable to a range of organic waste streams with a high destruction efficiency. The applicability of technology developed by DOE for waste treatment and minimization is also being tested for groundwater treatment.

In Situ Biological Treatment

Technologies to treat contaminated groundwater in situ are at an early stage of development and, for the most part, will face many of the same technical limitations as efforts to extract groundwater for treatment. There is little field experience with actually restoring groundwater quality using in situ biological methods. However, recent pilot-scale field studies have provided enough data to show that the approach is feasible for some contaminants (especially hydrocarbons) and sites, if proper site characterization and feasibility studies are carried out (31). Sites with complex hydrogeology will greatly reduce the chances of successful biorestoration, regardless of the nature of the contaminants.

In situ biorestoration usually involves stimulating microorganisms that are present in the environment so that they transform contaminants into (ideally) harmless compounds more rapidly than they would under natural conditions. The technique can potentially transform contaminants sorbed to the aquifer material, dissolved contaminants, and nonaqueous-phase liquids.[5] Stimulation involves injecting oxygen or nutrients into the environment, but the characteristics of the environment may make it impossible for the stimulants to reach the appropriate areas (32). Again because of variations in the environment, microorganisms, if they are present, may not be able to gain access to all the contaminants. Another problem associated with the technique is possible formation of byproducts that are more toxic or mobile than the original contaminants. For example, TCE has been shown to degrade into vinyl chloride, although it has been demonstrated that vinyl chloride can be oxidized by other organisms (33).

Implementing in situ biorestoration requires several factors: very detailed site characterization, laboratory feasibility tests to determine both the nutrient requirements of the microorganism and the compatibility of the nutrients with the subsurface environment, system design, and monitoring (34). Moving from the laboratory to the

[4]Although treatment techniques are not available for tritium, many scientists believe that this is not a problem because means can be used to Prevent its migration while it decays naturally. Others, however, are concerned that migration could be more serious than currently understood.

[5]Biorestoration also has the potential to remediate the unsaturated zone. 'f'his is necessary to prevent contaminants that are trapped in pore spaces above the water table from being continually leached into the groundwater below.

field is very difficult, and field conditions can vary significantly, changing expected results (35). Research by ERA has shown that laboratory experience can be extrapolated successfully to field scale if performed in conjunction with a thorough site characterization study (36). These steps require a high degree of expertise in both hydrogeology and microbiology.

To date, most experience within situ biorestoration has involved remediating hydrocarbon spills in aerobic environments. Often, in situ remedies are combined with groundwater extraction and surface treatment, and integration into a welldesigned treatment system is considered by some researchers to represent the greatest potential of the technique (37).

Research is underway to define and stimulate other mechanisms for biotransformation, including anaerobic environments; organisms that use methane, nitrogen, sulfur, or lactate compounds as terminal electron acceptors; cometabolism and cooxidation; and proprietary microbes or genetically engineered organisms. Research in these areas has begun to demonstrate that some chemicak previously thought not to biodegrade can be biotransformed under the proper conditions. Research has also shown that the use of anaerobic biodegradation may be effective for aromatic hydrocarbons and may overcome the difficulty of providing sufficient oxygen to contaminated areas (38). However, the management of mechanisms such as cometabolism that do not use the contaminant as a growth substrate is very complex and will require considerable research before it is ready for field application (39).

Models are also being developed to predict contaminant transport affected by biodegradation to help design treatment systems and predict the time required for operation (40).

DOE contends that bioremediation is potentially the least costly of all groundwater treatment technologies for the destruction of organic contaminants (41). Although some costs will probably be much lower for in situ bioremediation compared with technologies that require extraction, other costs incurred by testing and analysis, potentially long treatment times, and the need to use containment technologies make it difficult to bakmce remediation costs (42).

In Situ Chemical and Physical Treatment

In situ physical and chemical techniques require very detailed site-specific knowledge of the contaminants present, their concentration, and extent. Problems include controlling the contaminants, the reactions that occur, and any chemicals that might be injected or placed in the environment to react with contaminants. Experience with these approaches is limited.

In situ chemical techniques involve adding chemicals to the groundwater to treat specific contaminants. Examples include making metals insoluble and immobile with alkali or sulfides, oxidizing cyanides with sodium hypoehlorite, encapsulating contaminants in an insoluble matrix, precipitating cations by adding anions or oxygen, and using reducing agents to render hexavalent chromium insoluble (43). Chemicals are either injected into wells or placed in shallow, permeable treatment beds. The use of treatment beds provides opportunities to remove contaminants by adsorption on activated carbon, zeolites, and synthetic ion-exchange resins.

As with biological techniques, problems include access to the contaminants of concern and the potential formation of toxic byproducts. The process may also interfere with groundwater flow patterns, and contaminants can be diverted to other areas.

In situ physical techniques include thermal or steam flooding (used to recover hydrocarbons at shallow depths), alcohol flooding to dissolve hydrocarbons, radio-frequency in situ heating, and in situ vitrification (44). These approaches are primarily applicable to soil.

Containment and Flow Control

Technologies to control contaminated groundwater either by containing plume movement or by ensuring discharge to surface water to provide for the dilution of contamination are subject to many of the same problems associated with characterization. However, the data requirements are generally fewer for containment than for actual cleanup. The basic data required to implement a containment system are the horizontal and vertical locations of the contaminant plumes and the gradient and flow rate of the groundwater. It is not necessary to evaluate factors that tend to slow the movement of contaminants, such as sorption characteristics or diffusion Imitations of the contaminants in the subsurface. More detailed data may be required for dense, nonaqueous-phase liquid contaminants that, depending on the hydrogeologic environment, may move in a direction different from groundwater. Another reason more detailed information is required for effective containment is the occurrence of unexpected forms and mixtures of contaminants that are more mobile than anticipated-a factor at sites within the Nuclear Weapons Complex.

Examples of unexpected contaminant forms include plutonium and americium contamination of groundwater within a canyon at Los Alamos National Laboratory (45). Laboratory studies had predicted that these substances would *move* less than a few meters, but both have been detected in monitoring wells 1,000 feet downgradient from the point of discharge. Investigation has shown that most of these radionuclides moved in association with colloids. The portion of americium unassociated with colloids exists in a low molecular-weight form and appears to be a stable, anionic complex of unknown composition. Another example of unexpected contaminant mobility is cobalt-60 at Hanford. In this case, cobalt-60, which is usually immobile, has probably been chemically complexed and mobilized by cyanide (46).

Migration control relies on the use of hydrodynamic or other physical barriers to affect the movement of contaminated groundwater. To establish such control, the groundwater flow system and spatial distribution of the contamination must be well understood. Control may also depend on establishing institutional regulations on water use.

Relatively simple analytical methods are available for designing control systems where groundwater flow is uniform and unidirectional, but this is rarely the case. Other groundwater wells, seasonal changes in surface water levels, heterogeneity in aquifer properties-all increase the complexity. The heterogeneity of aquifer properties is most severe in fractured rock or karst aquifers. In such systems, the design of remedial measures may be reduced to trial and error (47). Although computer models may be useful in designing such systems, very thorough site investigations may be required, and there will still be uncertainty about the model's accuracy. Nevertheless, models can be valuable, if calibrated and verified with site-specific data and sensitivity analyses conducted to determine appropriate safety factors immigration control system design. Monitoring is needed to verify the effectiveness of containment and flow control measures.

Hydrodynamic barriers involve changing groundwater flow patterns either by extracting or by injecting water to prevent contaminants from moving in an undesirable direction (e.g., toward a well field, another aquifer, or surface water) or at an undesirable rate. Depending on conditions, different techniques might be used, including well points, deep wells, and pressure ridge systems.

Physical barriers to control contaminated groundwater must be designed to be impervious to the combinations of contaminants that may be present. In general, these techniques are not considered to be proven, long-term solutions. Barriers include slurry trench walls, grout curtains, vibrating beam walls, sheet piling, bottom sealing, block displacement, and membrane and synthetic sheet curtains (48). The approach and design used depend on site-specific conditions. Basically these barriers work by preventing contaminated groundwater from moving beyond the area that is already contaminated. In many cases, this improves the efficiency of groundwater extraction and treatment because it limits the volume of clean water that is drawn into treatment systems along with contaminated groundwater. The integrity of these techniques can be verified by geophysical methods.

These physical barriers are often designed in conjunction with surface water controls to minimize infiltration of water from the surface to the groundwater. Surface controls include changing the contour to divert surface water from the area, installing a cover barrier to prevent water from entering the site, and revegetating to stabilize soils and reduce infiltration.

DEPARTMENT OF ENERGY ACTIVITIES

DOE recognizes the diflicdties **associated with characterizing** and cleaning up contarninated groundwater (49,50). It places a great deal of emphasis ontheprospects for developing: 1) characterization techniques that are not dependent on drilling wells or boreholes and 2) in situ techniques to clean up contaminated soil and groundwater. Given general progress in the field of groundwater remediation, great strides in these areas are likely to be made within the next decade. In fact, new characterization and monitoring equipment is becoming available. For example, an infrared sensor to detect liquid contaminants such as fuel oil or solvents within soil has been developed by the Pacific Northwest Laboratory and is available for commercialization and manufacture.

Despite these plans and prospects for future technology development, contamination problems are being addressed now under the regulatory structure of RCRA and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and under agreements developed by DOE, EPA, and the States. According to EPA personnel, as of January 1990 all but the Nevada Test Site had completed the preliminary analyses under RCRA or CERCLA (51). Numerous solid waste management units continue to be identified as part of the ongoing effort to characterize problem areas. The regional site hydrogeology is reasonably well understood at all the sites. However, due to the size of the sites, complexity of the subsurface, complexity of the waste, or lack of sufficient reliable information, additional hydrogeologic characterization is required at all sites to understand the site-specific occurrence and use of groundwater and the movement of groundwater and contaminantts. This additional information will be collected as part of the RCRA facility investigation or CERCLA remedial investigation phase, which is expected to begin within the next 5 years. The status of groundwater investigations at each of the DOE weapons facilities is presented in appendix A.

Although characterization studies are underway, the extent of contamination, including potential off-site contamination, has not yet been identified at many sites. In most cases, the types and concentration of hazardous constituents have yet to be determined. Information on the fate and transport of contaminantts and the risks to human health and the environment will have to be developed under the continuing characterization process. Groundwater remediation has been initiated at a small number of sites by using either pump and treat systems, or pump and treat with French drains or interceptor trenches. Treatment consists of air stripping, ultraviolet light exposure, physical/chemical treatment, and ozonation.

Although the cleanup work is in its very early stages, investigations of ongoing efforts by both EPA and DOE reveal deficiencies in the handling of groundwater problems at DOE sites, as described below.

Groundwater Cleanup at the Savannah River Plant A/M Area

Groundwater remediation has been underway since 1983 at the Savannah River A/M Area. This is one of 19 pump and treat projects included in a recent EPA review of the effectiveness of pump and treat systems (52). The case study prepared for EPA on this project reveals many of the pitfalls common to pump and treat projects that must be overcome if this type of cleanup approach is to be successful.

The case study reveals numerous problems with the pump and treat system at the Savannah River Site. The site was not adequately characterized, and the system was not adequately designed to meet a goal that was set without consideration of health-based criteria. The study concluded that the pump and treat system would not achieve its goal of removing 99 percent of the estimated contamination dissolved in the groundwater within 30 years, nor was the system meeting its objectives of containing the spread of the plume and preventing the downward migration of contaminants (53). This is partly because the pump and treat system was not designed to account for contamination that was sorbed onto the soil. The pumping system was not adequately designed. Wells were not screened to capture contamination from lower permeability areas, and pumping rates were insufficient to prevent downward migration or to recover contamination except in areas close to the wells.

Despite these deficiencies, it is important to note that the pump and treat system has effectively treated significant quantities of contaminants, has been approved by the appropriate regulatory agencies, was put in place quickly, is reviewed on a regular basis, and is modified as required (54). It is also important to note that this project was initiated outside the RCRA/CERCLA regulatory framework (55). The goal of 99 percent removal within 30 years was never intended as the basis for a cleanup criterion or a deadline for turning off the system. Rather, it was intended as a simplified estimate for gauging performance. The final cleanup standards and overall system will be determined by periodic negotiations with regulators and by updating the system. Further study has revealed that the downward migration of contamination was caused by another source, and the remediation plan has been modified to address this problem. The technical deficiencies of the system have been recognized, and plans have been proposed to expand the system to include, forexarnple, vacuum extraction of the unsaturated zone to eliminate residual sources before they slowly leach into the groundwater. New remediation technologies will be tested in this area, including a process developed at the site-in situ air stripping by using horizontal wells; this represents the first application of directional drilling (frequently used in petroleum recovery) to environmental restoration activity.

This example of system implementation, evaluation, and modification including the use of new technologies, is typical of what is likely to be encountered as more efforts are made to clean up contaminated groundwater. As new information is obtained while the performance of remediation activities is being evaluated, it may be necessary to modify or expand system design and to modify agreements that have been reached about the level of cleanup or the time required to reach that level. To enhance the chances that these modifications will be accepted by the public, likely problems and deficiencies must be identified, along with possible contingencies, as early as possible when remedial measures are being planned.

Inadequate Performance on Groundwater Problems at Other Department of Energy Facilities

The problems identified at the Savannah River Site are not unique to that facility. The EPA study reveals similar problems at most of the pump and treat projects evaluated. Other investigations have revealed problems with groundwater monitoring programs at various DOE facilities, which include the following:

- Pantex Tiger Team---inadequate groundwater monitoring program and unknown integrity of underground storage tanks and pipes (56);
- Fernald-EPA inspection in August and October 1989 (57) found inadequate monitoring database (58);
- Rocky Flats Tiger Team inadequate characterization of soil and groundwater contamination at inactive waste sites, lack of adequate upgradient background monitoring wells, use of groundwater monitoring wells of unknown construction, lack of comprehensive organized groundwater database, deficiencies in groundwater sampling procedures, lack of adequate quality assurance/quality control of work products, deficiencies in well filter construction (59);
- Oak Ridge (Y-12) Tiger Team-inadequate monitoring of wells and sampling procedures, including access to wells, monitoring well conditions, ground-

water level measurement procedures; problems with alternate concentration limits program (60); and

. Mound Tiger Team inadequate monitoring wells and insufficient groundwater monitoring programs (61).

CONCLUSION

Given the limitations of current approaches to both characterization and cleanup of groundwater, it may be appropriate to consider a range of other methods for protecting this resource.

First, it is important to prevent contamination from occurring in the first place, by following best management practices and existing environmental regulations to avoid spills, accidents, or leaks and to identfy and address them when they occur. Efforts should be made to remove the sources of contamination to prevent further contamination from occurring.

Second, more people with sufficient expertise are needed to conduct and review any efforts to actively address groundwater contamination problems.

Third, characterizing the extent of contamination and preventing existing contamination from spreading by implementing containment measures early can provide useful information for the design and implementation of cleanup technologies. Cleanup should be approached in a realistic manner, by clearly communicating to the public the uncertainties associated with characterization and cleanup.

Fourth, it may be appropriate to consider treating groundwater at the point of use, rather than trying to restore some aquifers. Such an approach would require the development of low-cost water monitoring and treatment methods suitable for nonpublic water supplies, including private wells, irrigation wells, and wells used to obtain water for livestock. This approach may be inappropriate for radioactive contaminants but could be suitable for other hazardous contaminants. DOE could work together with EPA to develop appropriate point-of-use and point-of-entry water treatment technologies.

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