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VAMOS

The Verification and Monitoring Options Study: Current Research Options for In-Situ Monitoring and Verification of Contaminant Remediation and Containment within the Vadose Zone

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ABSTRACT

The Verification and Monitoring Options Study Project (VAMOS) was established to identify high-priority options for future vadose-zone environmental research in the areas of in-situ remediation monitoring, post-closure monitoring, and containment emplacement and verification monitoring. VAMOS examined projected needs not currently being met with applied technology in order to develop viable monitoring and verification research options. The study emphasized a compatible systems approach to reinforce the need for utilizing compatible components to provide user friendly site monitoring systems.

To identify the needs and research options related to vadose-zone environmental monitoring and verification, a literature search and expert panel forums were conducted. The search included present drivers for environmental monitoring technology, technology applications, and research efforts. The forums included scientific, academic, industry, and regulatory environmental professionals as well as end users of environmental technology. The experts evaluated current and future monitoring and verification needs, methods for meeting these needs, and viable research options and directions. A variety of high-priority technology development, user facility, and technology guidance research options were developed and presented as an outcome of the literature search and expert panel forums.

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CONTENTS

ACKNOWLEDGMENTS iiii
CONTENTS v
ACRONYMS vii
EXECUTIVE SUMMARY ES-1
1.0 VAMOS PURPOSE AND METHODOLOGY 1
2.0 VERIFICATION AND MONITORING DRIVERS: TECHNICAL AND OTHER CONSIDERATIONS 3
3.0 OVERVIEW OF CURRENT INDUSTRY VADOSE-ZONE MONITORING APPROACH 5
4.0 VADOSE-ZONE MONITORING AND VERIFICATION TECHNOLOGY OVERVIEW 7
4.1 Currently Available Technology 7
4.2 Products in Research and Development 8
4.3 Future Trends in Monitoring and Verification 10
5.0 VERIFICATION AND MONITORING OPTIONS 11
5.1 Technology Development Options 11
5.1.1 General Monitoring Options that Apply to Most Remediation and Containment Verification Technologies 11
5.1.2 In-Situ Remediation and Post-Closure Monitoring Options 12
5.1.3 Barriers and Covers Verification and Performance Monitoring Options 12
5.1.4 Tracer Technology Monitoring Options 13
5.1.5 Geophysical Monitoring Options for Barrier Verification and Performance 14
5.1.6 In-Situ Bioremediation Monitoring Options 15
5.2 Monitoring and Verification Technology User Facility Options 16
5.3 Technical Guidance Options 16
6.0 CONCLUSIONS AND RECOMMENDATIONS 19
6.1 Development Options 19
6.1.1 Technology Development Options Recommendations 19
6.1.2 Monitoring and Verification Technology User Facility Options Recommendations 20
6.1.3 Technical Guidance Options Recommendations 20
6.2 Recommendations for VAMOS Follow-On 21
6.3 VAMOS Options Summary 22
7.0 REFERENCES 23

APPENDIX A STUDY METHODOLOGY A-1
APPENDIX B PARTICIPANTS AND REVIEWERS B-1
APPENDIX C DRIVERS AND TECHNICAL GUIDANCE DOCUMENTS C-1
APPENDIX D LITERATURE REVIEW D-1

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ACRONYMS

ASI	Advanced Sciences, Inc.
ASTM	American Society for Testing and Materials
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CSCT	EPA Consortium for Site Characterization Technology
DoD	Department of Defense
DOE	Department of Energy
EnTice	Environmental Technology Innovation, Commercialization, and Enhancement Program
EPA	Environmental Protection Agency
HAZWRAP	Hazardous Waste Remedial Actions Program
m	meter
NRC	Nuclear Regulatory Commission
OTD	Office of Technology Development
PLC	programmable logic controller
ppb	parts per billion
ppm	parts per million
RCRA	Resource Conservation and Recovery Act
VAMOS	Verification and Monitoring Options Study
VOC	volatile organic compound

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EXECUTIVE SUMMARY

Overview

Significant effort is presently being directed toward remediation of Department of Energy (DOE) sites where contaminants, or future migration of contaminants, could pose a risk to human health and the environment. Monitoring these remedial processes is necessary to validate the performance and effectiveness of selected remedial or corrective actions as well as collect data to be used for site modeling and risk analyses. Monitoring the remediation process typically requires in-situ sampling and quantitative analysis of soil, gas, and/or water over time to demonstrate reduction and/or stabilization of contaminant concentrations.

Currently, post-closure monitoring of groundwater is required at Resource Conservation and Recovery Act (RCRA) sites to assess the long-term effectiveness of corrective actions. It is also frequently used at Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), also known as Superfund, sites to assess remedial actions. A disadvantage of using groundwater monitoring as a post-closure monitoring method is that it allows contamination to reach the groundwater table before detection. Failure to detect contamination before it reaches the water table can lead to expensive soil and groundwater remediation activities. Early contaminant detection and prompt remedial actions will typically result in smaller volumes of soil and groundwater being affected, with a bonus of significantly reduced remediation costs.

Vadose-zone monitoring technology has traditionally focused on soil moisture, soil chemistry, and vapor monitoring primarily for agricultural and water resources purposes. The need for early detection of contaminant releases above the water table has generated an interest in using vadose-zone methods to monitor contaminant transport. Various sensors and other technologies are currently under development to measure and quantify specific contaminants, in situ, for site assessment activities. A need exists to emphasize the adaptation of these technologies for use in remediation process monitoring, post-closure monitoring, and verification and performance monitoring of subsurface barriers, liners, and covers (i.e., containment).

Another consideration behind in-situ monitoring and verification technology development is the need to find ways to perform monitoring that are less expensive than traditional methods. Current monitoring and verification practices are expensive with respect to personnel and laboratory analysis services. These expenses can be reduced through the development and use of vadose zone monitoring systems that utilize geophysical, tracer, and chemical sensor technology and methods.

To identify options for future research that address projected needs for vadose-zone monitoring, a Verification and Monitoring Options Study (VAMOS) project was conducted to investigate methods for remediation process monitoring, post-closure monitoring, and containment verification and performance monitoring. This study was conducted using a literature search of current technology applications and research efforts in conjunction with an expert panel. The expert panel was composed of scientific, academic, industry, and regulatory environmental professionals, as well as end users of environmental technology. This panel evaluated current and future monitoring and verification needs, considered how these needs could best be met, and formulated viable research options.

The scope of the study and the expert panel evaluation focused on (1) the drivers for environmental monitoring technology (regulatory and economic), (2) current industry monitoring approaches, (3) currently available monitoring technology, and (4) needs and research options pertaining to remediation and containment verification not being met with existing technology.

Throughout the study an emphasis was placed on a compatible systems approach for sensor selection, emplacement, spacing, network design, automated querying, data collection, and data analysis and interpretation. This approach, when coupled with appropriate data archiving and retrieval technologies, ensures that components are compatible and provide a user friendly site monitoring system. Integrating archiving and retrieval technology ensures easy access to data at the time of collection as well as in the future. Sensor development and transfer of technology from other industries, as well as development of monitoring networks, querying systems, and data interpretation and archiving technologies, present numerous research options for specialists working on remediation monitoring and containment verification.

VAMOS Research Options

Through the course of this study several themes relating to technology development, technology user facilities, and technical guidance for verification and monitoring recurred. A summary of the highest priority research options related to these themes are given below. These themes are more fully described in the body of this report. These options are also presented in Table ES-1 at the end of the Executive Summary. The research options presented in this report represent high-priority options identified during the study. Options of lower priority, although evaluated, are not presented in this report in order to focus on options that address what was considered the most urgent needs throughout the DOE complex.

Technology Development Options

A limited segment of vadose-zone monitoring technology is specifically aimed at fulfilling current government and industry needs for remediation monitoring, post-closure monitoring, and containment verification and performance monitoring. Much of the current environmental technology research and development has focused on site assessment and remediation process methods. A viable next step is to develop technologies and methods for verifying the effectiveness and performance of the remedial actions used for contaminant reduction, stabilization, and/or containment. VAMOS revealed that priority should be placed on technology development for the following areas:

- Cover and liner emplacement and performance monitoring
- Tracer technology for remediation, barrier, liner, and cover verification as well as monitoring
- Development of nonintrusive and minimally intrusive geophysical methods for remediation and containment monitoring and verification
- Monitoring network design, sensor selection and location, emplacement, automated sensor querying, data management, and data analysis tools using a compatible systems approach
- Conversion of existing site characterization sensors and development of new sensors for remediation and containment monitoring
- Modification of industry technology (e.g., aerospace, manufacturing, mining, and petroleum) for use in vadose-zone monitoring and containment verification
- In-situ bioremediation monitoring of remediation effectiveness, viability indicator parameters, and primary and secondary breakdown products.

Monitoring and Verification Technology User Facility Options

Successful technology development programs require a rigorous field testing program to determine the effectiveness and reliability of developed technologies under realistic field conditions. VAMOS revealed that priority should be placed on the development and/or expansion of existing programs to produce specialized user facilities and procedures that can be used to evaluate monitoring and verification technologies. These specialized facilities should address the following performance variables and applications:

- Differing climatic and hydrogeologic settings
- Sensor effectiveness and performance
- Sensor emplacement techniques
- Monitoring network performance
- Tracer applications
- Geophysical applications
- Subsurface barrier emplacement verification and performance monitoring
- Landfill liner and cover emplacement verification and performance monitoring.

The user facilities should also be flexible and adaptable in order to be used to evaluate new monitoring and verification technologies as they are developed. Rigorous field testing of developed technologies is necessary to facilitate technology acceptance by end users (i.e., environmental professionals).

Following field testing at a suitable user facility a new monitoring technology would be a candidate for further field validation through the EPA Consortium for Site

Characterization Technology (CSCT), being developed in association with DoD and DOE, to validate the performance of mature monitoring and verification technologies.

Technical Guidance Options

Technical guidance is typically developed to assist site managers and environmental professionals to comply with regulatory and corporate rules and regulations. VAMOS revealed that limited technical guidance is presently available to industry professionals and site managers specifically for verification and monitoring of remedial actions and closures in the vadose zone. To address this situation the EPA has technical guidance under development that addresses vadose-zone monitoring for the RCRA program (EPA, 1995). Industry is also developing vadose-zone monitoring standards through organizations such as the American Society for Testing and Materials (ASTM Section D - 18.21.02).

Technical guidance can also help define needs that lead to subsequent monitoring technology research and development. The VAMOS project identified the following guidance activities for possible consideration:

- Updated vadose-zone monitoring guidance
- Guidance for tracer monitoring methodology
- Nonintrusive and minimally intrusive geophysical barrier verification methods
- Remediation technology monitoring methods based on direct and/or indirect, i.e., indicator, remediation process parameters
- Operational reliability and performance specifications for in-situ remediation and containment monitoring systems
- Integrated systems approaches to monitoring system network design, installation, and data handling.

To be effective, guidance should be flexible and revised periodically to incorporate the capabilities of new monitoring and verification strategies, technologies, and methods once they are shown to be reliable through research, development, and field validation. The ease with which guidance is able to incorporate new strategies, technologies, and methods is important for timely acceptance by the environmental community.

Recommendations for VAMOS Follow-On

During the VAMOS project, excellent option study capabilities were developed for assessing research and development issues and directions in the area of monitoring and verification of in-situ remediation and containment activities. Follow-on to VAMOS is recommended. This follow-on should focus on specific technologies and serve as a resource to assist the DOE, national laboratories, and other governmental agencies as they address specific needs within their assigned sphere of responsibility.

Specifically, the insights and expertise developed through VAMOS are recommended for use in follow-on activities that provide technical and guidance input to support in-situ remediation monitoring and containment initiatives under development by the DOE Office of Technology Development (OTD). VAMOS follow-on should be used to provide both technical resources and a mechanism to assist OTD Focus Groups and other internal or external sub-committees, work groups, and/or, study groups, as needed. The implementation of follow-on activities would result in cost savings for future research and development. These cost savings would be realized by providing critical information used to evaluate and direct cost-effective monitoring and verification technology development, testing, and technical guidance useful at DOE environmental restoration sites.

In summary, VAMOS follow-on recommendations for in-situ remediation monitoring and barrier verification include:

- In-depth, detailed option studies for specific, high-priority technologies
- Providing formal and/or informal technical expertise, review, and guidance to work groups or study groups throughout the DOE complex on an as needed basis
- Providing test plan review and evaluation of monitoring and verification technology demonstrations.

The recommended technical areas for VAMOS follow-on include tracers, geophysics, sensors, networks, data evaluation, user facilities, and technical guidance.

VAMOS Options Summary

A summary of the primary monitoring and verification research options revealed during the VAMOS project is presented in Table ES-1. Note that only the highest-priority options are summarized in the table. These options are more fully described in the body of the report.

Table ES-1. Summary of High-Priority VAMOS Monitoring and Verification Research Option Areas, their Applications, and Estimated Time to Complete Research & Development.

VAMOS Option Area	Potential Applications	Estimated Time to Complete Research and Development*
TECHNOLOGY DEVELOPMENT		
Cover and liner monitoring	- Verifying emplacement and continuity - Monitoring effectiveness of containment	Near-to-Mid-Term
Tracer technology for remediation, barrier, liner, and cover monitoring	- In-situ remediation monitoring - Barrier effectiveness monitoring - Liner effectiveness monitoring - Cover effectiveness monitoring	Near-to-Mid-Term
Nonintrusive and minimally intrusive geophysical methods for subsurface remediation, containment, and verification	- Verifying barrier emplacement and continuity - Monitoring effectiveness of containment - In-situ remediation monitoring	Mid-to-Long-Term
Monitoring network design, emplacement, automated querying, data management, and data analysis	- In-situ remediation monitoring - Post-closure monitoring - Containment monitoring	Near-to-Mid-Term
Conversion of site characterization sensors and development of new sensors for remediation and containment monitoring	- In-situ remediation monitoring - Post-closure monitoring - Containment monitoring	Near-to-Mid-Term
Modification of other industry sensors for monitoring and verification	- In-situ remediation monitoring - Post-closure monitoring - Containment monitoring	Near-to-Mid-Term
In-situ bioremediation monitoring	- Remediation effectiveness - Viability indicator parameter monitoring - Primary and secondary breakdown product monitoring	Near-to-Mid-Term
USER FACILITIES		
Facilities specifically designed for testing and evaluation of methods and hardware used in the verification and monitoring area	- Sensor emplacement, effectiveness and performance, monitoring network design and performance, geophysical applications, tracer applications, and subsurface barrier, landfill liner, and cover emplacement verification and performance	Near-to-Long-Term
TECHNICAL GUIDANCE		
Development and updating of guidance for vadose-zone monitoring	- Tracer and geophysical monitoring and verification methods, in-situ remediation monitoring and verification, and the design, installation, and data handling of monitoring and verification networks	Near-to-Long-Term
VAMOS FOLLOW-ON		
Technical Expertise Resources	- Provide expertise for monitoring and verification issues to assist focused work groups and steering groups	Near-to-Mid-Term

* Time required for applied monitoring and verification research and development based on current best estimates.
Near-term = <2 yr; Mid-term = 2-4 yr; Long-term = >4 yr.

1.0 VAMOS PURPOSE AND METHODOLOGY

Monitoring the performance and effectiveness of remediation efforts is necessary during remedial or corrective-measure implementation to ensure that the actions taken are performing as intended. Presently, post-closure groundwater monitoring is required at Resource Conservation and Recovery Act (RCRA) sites to assess the effectiveness of remedial actions. This monitoring method can be effective if the water table is relatively close to the ground surface. However, this method could be considered flawed since it allows contaminants to reach the groundwater before detection (Wilson, 1983 and Everett, 1995), which can lead to expensive soil and groundwater remediation activities. Monitoring within the vadose zone (the soil column overlying the water table) can help limit soil and groundwater contamination through earlier detection of contaminant releases. Early detection can result in smaller volumes of contaminated soil and groundwater being affected and significantly reduced subsequent remediation costs.

The purpose of the Verification and Monitoring Options Study (VAMOS) project is to identify options for future vadose-zone research in the areas of in-situ remediation monitoring, post-closure monitoring, and containment emplacement and verification monitoring. VAMOS examined projected needs not currently being met with applied technology in order to develop viable monitoring and verification research options. The study emphasized a compatible systems approach. Such an approach would include selecting appropriate sensors; developing appropriate spacing, network design, emplacement, querying, data collection, and data analysis strategies and technologies; and developing an appropriate archiving and retrieval technology so that components are compatible and provide a user friendly site monitoring system.

To identify the needs and research options related to vadose-zone environmental monitoring and verification, a literature search and expert panel forums were conducted. The search included present technology applications and research efforts. The forums included scientific, academic, industry, and regulatory environmental professionals as well as end users of environmental technology. The experts evaluated current and future monitoring and verification needs, methods for meeting these needs, and viable research options and directions. VAMOS concentrated its efforts in four areas:

1. The drivers for environmental monitoring technology (regulatory and economic)
2. Current industry monitoring approaches
3. Currently available monitoring technology
4. Needs pertaining to remediation and containment monitoring and verification that are not being met with existing technology.

The identification of needs and research options focused on three areas: (1) in-situ remediation monitoring, (2) barrier and cover (i.e., containment) monitoring, and (3) emplacement and performance of components. Each area was subdivided into the following categories:

1. In-Situ Remediation Monitoring, which included:
   - In-situ waste stabilization
   - In-situ treatment and immobilization of heavy metals and organics
   - Bioremediation
   - Vapor extraction
   - Alternative in-situ treatment (such as reactive barriers, etc.).

2. Barrier and Cover Monitoring, which included:
   - Subsurface barriers
   - Landfill covers
   - Landfill liners
   - Other topical areas.

3. Emplacement and Performance Monitoring, which included:
   - Barriers
   - Covers
   - Networks and systems.

The remaining sections of this report will discuss the regulatory and technical drivers for technology development, monitoring approaches and technologies presently used by industry, and verification and monitoring options identified by this study. The appendices contain a more detailed description of the study methodology, a list of the study group participants, and a compilation of the literature review.

2.0 VERIFICATION AND MONITORING DRIVERS: TECHNICAL AND OTHER CONSIDERATIONS

Presently no specific regulations under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) or the Resource Conservation and Recovery Act (RCRA) explicitly address the issue of vadose-zone monitoring and verification for remediation and containment activities. Considerable flexibility in approach is provided by the National Contingency Plan and RCRA regulations, which drive monitoring at Superfund (i.e., CERCLA) sites and solid waste management units at RCRA sites, respectively. Case-by-case decisions are typically made for site-specific monitoring.

There is limited technical guidance currently available that addresses vadose-zone monitoring. Technical guidance for vadose-zone monitoring was introduced during the 1970s as a part of hazardous waste land treatment farms that, by design, were open systems that impacted the vadose zone. The concept of vadose-zone monitoring was not applied at that time to RCRA landfills, waste piles, and empoundments because these facilities were designed with a double liner system (i.e., closed systems) and therefore were not expected to leak (Everett, 1995). Recent evaluation of RCRA facilities in regions of the country have demonstrated that RCRA facilities in reality can leak and that vadose-zone monitoring systems are necessary to monitor the performance of these facilities (Everett, 1995). Currently there is technical guidance being developed by the EPA to address vadose-zone monitoring at RCRA Subtitle C facilities (EPA, 1995). This technical guidance is expected to be available later in 1995.

Technical guidance is also being developed for vadose-zone monitoring through the American Society for Testing and Materials (Section D-18.21.02). A listing of final ASTM standards and standards in progress is given in Appendix C. The emphasis on vadose-zone monitoring is also resulting in the development of technical information such as the recent publication entitled "Handbook of Vadose Zone Characterization and Monitoring" by L.G. Wilson, et al., released by Lewis Publishers (Wilson, 1995).

A future source of technical guidance is The Superfund Initiative on Long Term Reliability of Containment that is currently being initiated through the EPA Office of Emergency and Remedial Response. This initiative's goal is to develop technical guidance and programmatic information on the subject of containment. The EPA plans to work with other agencies and entities (including the Department of Defense, DOE, and DuPont) to jointly develop technical information that site managers may use when evaluating containment systems. Another future source of technical information is the EPA Environmental Technology Innovation, Commercialization, and Enhancement Program (EnTice). This program was recently formed to validate innovative technology performance and credibility of technology development data prior to releasing newly developed technology for general field use. Monitoring systems were listed as one of the top four of the fourteen initial program classes identified. As part of EnTice, the Consortium for Site Characterization (CSCT) has been formed specifically to validate the performance of mature innovative measurement and monitoring technologies.

Another consideration behind in-situ monitoring and verification technology development is the economic need to find ways to perform monitoring and verification activities that are less expensive than traditional methods. Current monitoring and verification practices are expensive with respect to personnel, sampling, and laboratory analysis services. These expenses can be reduced through the development and use of vadose zone monitoring systems that utilize:

- In-situ sensors that can be automatically queried through a remote terminal (minimizes field personnel expenses, frequent trips to the field for sampling, and potential expense related to field personnel exposure to hazards)
- Reversible sensors that can measure both increases and decreases in contaminant concentrations (minimizes laboratory analysis and sample disposal expenses)
- Tracer methodology for verifying remediation processes and containment performance
- Geophysical methods for verifying subsurface barrier emplacement and containment performance so that soil and groundwater contamination and future remedial actions can be avoided
- Dual use of systems for remediation and closure monitoring
- Modified sensors from other industries
- Data management, analysis, and archiving systems.

Some of the other regulatory, economic, technical, and stakeholder drivers and guidance for vadose-zone monitoring identified during VAMOS include Nuclear Regulatory Commission (NRC) monitoring requirements, state and local requirements, public perception of the appropriate need for monitoring, the cost-effectiveness of verifying and monitoring remediation and containment effectiveness and performance, and the early detection of failures or releases. These and other drivers are more fully described in Appendix C.

3.0 OVERVIEW OF CURRENT INDUSTRY VADOSE-ZONE MONITORING APPROACH

Current remediation practices (i.e., stabilization, immobilization, bioremediation, etc.) as well as monitoring these practices are site-specific and activity-specific. However, to date, most vadose-zone monitoring has dealt primarily with determining soil properties that control movement of liquids and gases (Everett et al., 1984a, 1984b; Wilson, 1980, 1982 and 1983; US EPA, 1993; US EPA, 1995). Current approaches to monitoring these practices, as well as some of their perceived shortcomings, are discussed briefly below.

Monitoring of in-situ remediation usually involves in-situ sampling of soil for contaminant concentrations followed by quantitative analysis at a laboratory. At sites being remediated for volatile organic compounds (VOCs), vapor-monitoring wells are also used to monitor remediation progress. This labor-intensive and expensive procedure provides only isolated sets of data, and the procedure must be repeated many times to develop trends that verify contaminant reduction. Efforts to develop real-time, vadose-zone remediation monitoring systems, which could provide direct verification of contaminant level increases or decreases in the unsaturated soil column, have been minimal. Such systems could not only monitor the progress of the remediation but also be used to optimize the remediation process in real-time.

Post-closure monitoring practices for in-situ remediation, subsurface barriers, and landfill liners and covers currently do not address conditions specifically in the vadose zone, either. RCRA stipulates that post-closure monitoring be accomplished by monitoring for groundwater contamination by using a minimum of one groundwater well located hydraulically upgradient and three wells hydraulically downgradient from the site. These wells are to be sampled and analyzed for contaminants on a regular schedule. This practice allows contamination of the soil and groundwater prior to detection. This delayed detection results in costly additional remediation.

Subsurface barriers are also not currently monitored for the presence of contaminants within the vadose zone. Subsurface barriers (i.e., grout curtains, slurry walls, and containment structures) have typically been considered temporary barriers designed to reduce the migration or flow of contaminants within the vadose zone and/or below the water table. The need for verification monitoring has been compensated through the use of "over-engineering" practices such as increased overlap during jet grouting and deep soil mixing operations, or the use of very low permeability slurry mixes. However, a need exists to develop non-destructive verification methods (such as tracer and geophysical methods) for the emplacement and performance monitoring of subsurface barriers, especially if those barriers are intended for long-term containment.

For landfill liners and covers, performance is typically monitored by evaluation of leachate collected by on-site systems and post-closure groundwater monitoring requiring a minimum of one well upgradient and three downgradient. If these systems are not present, as is often the situation at older landfills, this evaluation is not possible. To verify liner and cover emplacement and quality, these landfill components are generally constructed according to RCRA technical guidance for installation and construction (US EPA, 1982; US EPA, 1991). This guidance focuses on quality assurance and quality control of materials and construction practices. As with subsurface barriers, reliance is typically placed on "over-engineering" practices.

4.0 VADOSE-ZONE MONITORING AND VERIFICATION TECHNOLOGY OVERVIEW

4.1 Currently Available Technology

The vadose zone is comprised of the soil column overlying the water table, including the top-soil zone. Until recently the vadose zone has been monitored primarily to determine water movement in the soil. Monitoring activities have focused on water content, water flow, and chemical changes as the groundwater infiltrates through soil (Everett et al., 1984a). The resulting data are used to assess the quantity and quality of agricultural moisture and groundwater recharge. More recently, investigations have examined vadose-zone water as a mechanism for contaminant transport.

Several methods are currently utilized to characterize soil moisture and water flow within the vadose zone. The most prevalent methods are listed below. Note that the listed technologies either collect water or measure water content or movement, but do not specifically measure changes in contaminant levels within the unsaturated zone (Everett et al., 1984a;b and Wilson, 1982 and 1983).

- Neutron moisture logging is used to measure the volumetric water content of soil in situ. This technique has also been used to monitor water storage, delineate perched water layers and mounds, and estimate flow rates within the vadose zone.
- Permeameters are used to measure the intrinsic permeability and hydraulic conductivity of a soil or rock sample.
- Lysimeters are used to collect soil pore water.
- Tensiometers are used to measure soil-water pressures during saturated and unsaturated flow and also to provide estimates of soil-water content.
- Electrical resistance blocks are used to measure either soil-water content or soil-water pressure. These blocks are calibrated for site-specific soil conditions.
- Psychrometers are used to measure soil-water pressure below one-half to one atmosphere.
- Tracer technology has been utilized to measure flow rates in the vadose zone.

Soil vapor is another important component of the vadose zone and can also be a mechanism for contaminant transport. Vapor monitoring can be used to evaluate volatile organic contamination in the vadose zone as well as in the groundwater. Soil vapor can also be extracted in an effort to remediate soil and groundwater. Three soil-vapor monitoring technologies are listed below.

- Soil-gas vapor probes (passive and active) are utilized to assess vapor contamination concentrations in the soil.
- Vapor monitoring wells are currently used to monitor volatile organic compound (VOC) concentrations in soils; these wells provide a low pressure sink to which the vapors can migrate from areas of higher vapor pressure in the soil column.
- Vadose-zone monitoring systems have been recently developed to allow continuous, real-time monitoring of soil-gas contaminants in vertical boreholes.

Although soil water and soil vapor may be controlling mechanisms for the transport of contaminants in the vadose zone, the ability to directly monitor the contaminants in situ is also important. Some of these capabilities currently under research and development are discussed in the following section.

4.2 Products in Research and Development

To date, environmental restoration research and development efforts have emphasized site characterization and treatment methods so that appropriate remediation technologies can be selected and/or developed for site cleanup. However, little work has focused specifically on in-situ vadose-zone monitoring; methods, systems, or sensors to verify remediation processes or barrier emplacement verification and performance; or long-term, post-closure site monitoring. Although recent research has included drilling, emplacement, data manipulation, and visualization technologies, the major emphasis to date for in-situ vadose-zone monitoring and verification technology development has focused on chemical sensors and network system sensors. Government agencies such as DOE and EPA are now recognizing the increased importance of improved in-situ vadose-zone monitoring methods and technologies (Gerber et al., 1994, Heiser 1994, and Koglin, et al., 1995).

Seven reports on the current status of chemical sensor research and development activities were compiled by Advanced Sciences, Inc. (ASI) under the Hazardous Waste Remedial Actions Program (HAZWRAP) for the Department of Energy (US DOE, 1993a, 1993b, 1993c, 1993d, 1994a, 1994b, 1994c). A review of this compendium indicated that probably no more than 25 chemical sensor companies exist in the United States. During the study, ASI identified no commercially available chemical sensors capable of in-situ measurements in soil or rock, except for gasoline and diesel vapor sensors utilized for underground storage tanks (US EPA, 1988). Interviews with sensor researchers revealed a common belief that the long-term stability and performance of sensors is a crucial area of chemical research necessary to perform post-remediation monitoring. These interviews indicated that little if any work related to this problem was being conducted (US DOE, 1993c). Specific conclusions and recommendations from the ASI study include:

- Chemical sensor research for environmental restoration and waste management must be secondary to well-defined programs of sensor development and testing.
- A sensor-user facility is needed to test sensor technology in real-time "dirty" environments that simulate real field conditions rather than a sterile laboratory environment.
- Existing chemical sensors for laboratory and air quality monitoring need to be evaluated for potential use and development as field monitoring sensors.

One of the areas of environmental research and development within the US DOE Office of Technology Development (OTD) is the development and testing of in-situ and on-site chemical and radiochemical sensors for the monitoring of organics, transuranics, and metals (US DOE, 1994d). Several technologies that have been developed or are currently under development and refinement include:

- Sensors for use with the cone penetrometer for site characterization activities, including soil moisture and chemical concentration measurements
- Down-hole X-ray fluorescence metals analysis
- Reversible, fiber-optic sensors for detection of select VOC contaminants (e.g., methelene chloride) in the parts per billion (ppb) range
- Measurement while drilling for the detection of radionuclides and other contaminants
- Organic vapor monitors developed and made robust for harsh field environments and conditions
- On-site analysis of metals using adsorptive stripping analysis
- Portable vapochromic/fiber optic detector for VOCs in air and water—a potential sensor with alarm for initial detection in field applications
- Crosshole seismic and electromagnetic surveys for site characterization and remediation process monitoring
- Surface geophysics to identify contamination sources and guide removal and remediation actions
- Borehole liners with real-time VOC monitoring systems.

The OTD utilizes the resources of the national laboratories, universities, and private industry throughout the United States to fulfill its mission to develop environmental technologies that enables the DOE meet goals for environmental restoration. Until recently, research has emphasized technology and sensors primarily applicable to site characterization and remediation. Currently, however, characterization sensors have been developed that could potentially be transferred or developed into systems deployable as vadose-zone monitoring systems for remediation processes, long-term post-closure monitoring, and barrier verification and performance monitoring.

Sensor research conducted by private industry is another potential source of monitoring development. For example, at the Microswitch Division of Honeywell, researchers have developed the concept of smart sensors for heavy manufacturing. These sensors use on-board intelligence to link themselves to programmable logic controllers (PLCs) and transmit information regarding their working status (e.g., calibration data) to evaluate the system's ability to function within designated parameters (Murray, 1994). Other companies, such as Motorola, Philips Components, and Texas Instruments, are working on smart sensor technology (Ormund, 1993). Although smart sensors are currently utilized primarily for heavy manufacturing, the technology may provide insight for developing "smart" monitoring sensors for environmental applications.

A significant amount of research and development has also resulted in development of methodologies for the design and analysis of sensor failure networks in the aerospace industry (Chou et al., 1993). These methodologies are potentially transferable to environmental monitoring systems. Progress has been made to integrate this technology into personal-computer-based monitoring systems (US DOE, 1994e,f; Guthrie and Bakios-Daines, 1994).

Additionally, research at the University of California-Davis has focused on developing appropriate integrative models (i.e., models that use combinations of measured field data) for field sensor networks and automated monitoring of soil water sensors (Grismer, 1992). This research resulted in a conceptual model for an integrated soil-plant-atmosphere sensor network that included a remote sensing system.

4.3 Future Trends in Monitoring and Verification

Presently available vadose-zone monitoring technology has traditionally focused on soil moisture and vapor monitoring. Some recent efforts have assessed monitoring contaminant transport via water and water vapor movement. Various sensors to measure and quantify specific contaminants in situ are under development. However, the monitoring of remediation and containment in the vadose-zone needs to be emphasized. To address the needs pertaining to remediation and containment verification and monitoring, research is needed that involves (1) the development, integration, and transfer of sensors, and (2) the development of monitoring networks, querying systems, emplacement techniques, and data analysis and archiving technologies.

A variety of work is being conducted in the environmental monitoring arena. Much progress has been made in the development of in-situ and on-site sensors and analytical equipment for site investigations and characterization. The trend is now shifting toward monitoring and verification. Continued research emphasis in this area will aid development of in-situ remediation and containment monitoring and verification technologies. The research options of these and other topics developed during the course of the VAMOS project will be discussed in Section 5.

5.0 VERIFICATION AND MONITORING OPTIONS

During the course of the VAMOS project, many verification and monitoring options were identified through the expert panel meetings, literature research, and a review of OTD research and development being conducted by Focus Groups and Cross-Cutting Programs. These options were then refined to address the explicit need for monitoring and verification of remediation and containment actions at both DOE and non-DOE sites. A description of the options identified for the verification and monitoring of in-situ remediation and containment are outlined in the following subsections. The research options presented in this report represent high-priority options identified during the study. Other options, although evaluated, are not presented in this report in order to focus on options that address what was considered the most urgent needs in this area throughout the DOE complex.

5.1 Technology Development Options

The options for technology development specifically aimed at remediation monitoring, post-closure monitoring, and verification and performance monitoring of containment are presented below.

5.1.1 General Monitoring Options that Apply to Most Remediation and Containment Verification Technologies

Evaluation of monitoring technology reveals some research options that encompass virtually all remediation and containment verification technologies. These options center around the development and emplacement of integrated and compatible monitoring systems. General monitoring research options identified through this study include developing:

- Interval to continuous monitoring systems with real-time querying capabilities able to track changes in contaminant concentrations, i.e., reversible sensors that can detect increases and decreases in contaminants
- Compatible sensors, data collection devices, and networks
- Methodologies to select appropriate sensors, design networks, and optimize sensor placement and querying schedules
- Dual-purpose monitoring systems that can serve as both remediation monitoring and post-closure monitoring systems
- Systems that will not provide pathways for contaminant migration beyond current extent when emplaced
- Passive monitoring systems that signal if they malfunction
- Data management and archiving systems that eliminate excessive duplicate data sets and allow for simple future data retrieval and analysis
- Automated data and sample collection analysis systems that will record and evaluate contaminant levels

- Data analysis systems that can identify out-of-compliance situations
- Sensor contaminant detection sensitivity in the range of ppb to ppm
- Sensors specifically developed for monitoring unsaturated flow and transport properties in unconsolidated and fractured systems

5.1.2 In-Situ Remediation and Post-Closure Monitoring Options

Developing both in-situ remediation monitoring and post-closure monitoring systems allows for timely and cost-effective monitoring of the remediation process and post-remediation effectiveness over time. Vadose-zone monitoring conducted during remediation activities and continued after closure increases the likelihood that groundwater contamination will be limited because of earlier detection. VAMOS identified research options for in-situ remediation and post-closure monitoring which include developing:

- Vadose-zone performance monitoring specifications of remediation systems and processes
- Monitoring systems amenable to cost-effective emplacement technologies (i.e., cone penetrometers, etc.)
- Interval to continuous, real-time site monitoring systems
- Dual-use monitoring systems that could be utilized for additional purposes (e.g., neutron logging access pipe under a site that could also be used for vapor extraction remediation)
- Robust, reliable sensors that can handle variable field conditions
- Monitoring system emplacement methods that do not produce uncontrolled pathways for contaminant migration
- Passive monitoring systems and alarms; "smart sensors" that alert personnel of failures or malfunctions; and fail-safe backups
- Sensors for early detection and alarm
- Tracer and geophysical technology methods to monitor in-situ remediation and containment actions.

5.1.3 Barriers and Covers Verification and Performance Monitoring Options

An evaluation and assessment of containment technology by Gerber and Fayer (1994) indicated that subsurface barriers/containment systems are currently not monitored for verification of emplacement or performance within the vadose zone. Since subsurface barriers are being used for containment, a need exists to develop non-destructive verification methods for their emplacement and performance.

Identified research options relating to both subsurface barriers/containment systems and the emplacement and performance of landfill liners and covers include development of:

- Methods for leak detection of leachate, water, water vapor, and gasses in landfill covers, landfill liners, and subsurface barriers/containment systems
- Design specifications for long-term reliability of containment systems
- Methods to verify landfill cover effectiveness that will monitor the conductivity of the low hydraulic-conductivity layer
- Methods to monitor subsidence of landfill covers
- Non-intrusive geophysical methods for barrier monitoring and verification
- Reference markers and benchmarks for long-term identification of site boundaries and contaminant plumes
- Tracer and geophysical technology methods to monitor containment actions.

5.1.4 Tracer Technology Monitoring Options

Gas, liquid, and colloid tracers have been used in the past for atmospheric, surface water, groundwater, and oceanographic studies. Tracers have been used for indoor air quality tests and for detecting leaks in pipelines, underground storage tanks, and landfill liners. Potential applications of tracer monitoring technology include monitoring the performance and effectiveness of remediation processes such as in-situ waste stabilization, treatment, and immobilization; in-situ bioremediation; pump and treat systems for soil gas and groundwater; and containment systems such as covers, liners, and subsurface barriers.

Currently, tracer technology is not being fully utilized due to lack of knowledge and insufficient research and development. A need exists to better understand the interactions of the tracers with soils, contaminants, and the remediation or containment activity that the tracer is to monitor.

Some current limitations of tracer applications include selection and development of appropriate tracers for in-situ remediation and containment monitoring; methodologies for emplacement, detection and use; and automated tracer collection, analysis, and reporting systems. Tracer monitoring technology needs to be improved in the areas of remediation performance evaluation to produce tracer analogs for contaminants that mimic the waste but are more easily detectable. Additionally, tracers that move rapidly through containment structures are needed to provide a way to evaluate how well barriers, liners, and covers are emplaced, and to provide an early warning of leaks that may develop in the future. Also needed are methods and techniques that can identify and locate small containment discontinuities and leaks (Heiser, 1994, suggests that resolution to fractions of an inch may be possible). The development of tracers and methodologies that are representative and well-matched for the contaminant or process being monitored are needed (e.g., Does the tracer adequately mimic the containment? Is the tracer appropriate for monitoring the remediation or containment activity?).

Environmental monitoring tracers include a wide range of conservative and non-conservative compounds. Radioisotopes have been used in the past, but due to environmental concerns, even short-lived radioisotopes are unlikely to be acceptable for environmental monitoring. Therefore, chemical tracers hold the most promise for environmental monitoring and verification. To enhance tracer technology acceptance, toxicology studies are needed to confirm the safety of various chemical tracers. Because there is curently limited understanding of tracers and their toxicology, as well as a resistance to injecting unfamiliar or foreign materials into the soil column, many environmental scientists and regulators are hesitant to use tracers. Public and stakeholder acceptance of this method can be difficult to obtain due to this lack of knowledge concerning tracer technology.

To overcome these obstacles and limitations, as well as fully utilize tracer technology, the following research options were identified by VAMOS:

- Research to develop tracers and methods that mimic the behavior of selected contaminants of regulatory concern
- Toxicology studies to assure that tracers being used are environmentally safe
- Research to develop tracers and methods specifically suited for verification and monitoring of in-situ remediation processes and long-term barrier emplacement, performance, and integrity
- Development of appropriate emplacement methods, sensors, and monitoring network designs
- Development of tracers for colloid and microorganism transport monitoring
- Automated tracer sample collection and analysis monitoring systems capable of measuring and recording concentrations in the ppb range.

5.1.5 Geophysical Monitoring Options for Barrier Verification and Performance

Most subsurface geophysical characterization techniques originated in the petroleum and mining exploration industries. Geophysical methods have been utilized to identify subsurface stratigraphy based on variations in soil and rock density/velocity responses and electrical responses to fluids within pore spaces. Seismic reflection has been used in gravel exploration to assist in mapping the distributions of high quality deposits.

Potential environmental monitoring applications of geophysical methods include in-situ remediation and containment. For instance, subsurface geophysics has been used to monitor remedial actions during steam injection to remove petroleum hydrocarbon contamination. Heiser (1994) concluded that acoustic seismic logging methods show promise for environmental applications to monitor the emplacement and performance of containment structures once resolution capabilities have been enhanced. Carpenter et al. (1991) presented work related to assessing fractured landfill covers using electrical resistivity and seismic refraction techniques. Although refinement of resolution is needed, the electrical resistivity technique allowed cover thickness estimates to within 0.7 m over unfractured cover areas. Seismic refraction techniques indicated that higher p-wave velocities characterized areas of intact covers while lower velocities characterized highly fractured cover. Work at Sandia National Laboratories evaluated the applicability of geophysical techniques for non-intrusive or minimally intrusive methods to verify the emplacement and performance of subsurface barriers and concluded that high-density networks of sensors, closely spaced vertical and/or directionally drilled access holes, and high-frequency geophysical methods are among those items needed to achieve appropriate resolution (e.g., decimeter) for containment monitoring (Borns, 1995).

The primary limitations for the use of subsurface geophysics that must be addressed include resolution (size and location of problem areas), applicable geophysical sensors and tools, heterogeneties in the subsurface, and the density, emplacement, and configuration of monitoring networks.

VAMOS identified the following technology development and research options related to geophysical methods needed for successful barrier verification and performance monitoring:

- Development of appropriate geophysical methods, configurations, and instrumentation for in-situ remediation and containment monitoring
- Defining and addressing appropriate spatial resolution (e.g., decimeters)
- Monitoring continuity and emplacement of subsurface barriers during installation
- Containment deterioration zone identification
- Long-term containment performance verification
- Development of appropriate emplacement methods, sensors, and network designs.

5.1.6 In-Situ Bioremediation Monitoring Options

In-situ bioremediation technologies are cost-effective options that are currently being used at a number of sites. Bioremediation has been proposed and/or used for diverse applications such as in-situ remediation of organic contaminants, the in-situ precipitation of metal species, and the denitrification of nitrate-contaminated groundwater. Many of these naturally occurring processes can be augmented by the addition of critical nutrients and/or additional microorganisms. However, in-situ monitoring of the effectiveness of the remediation or the ability to evaluate whether components added to the system are reaching the entire contaminated area is lacking.

Technology development options for bioremediation include monitoring systems that evaluate bioremediation effectiveness based on evidence of primary and secondary microbial activity at the remediation site (MacDonald and Rittman, 1993), monitoring contaminant concentrations and breakdown or "daughter" compounds, and monitoring the addition of nutrients and microorganisms.

The bioremediation monitoring options include in-situ sensors and methodologies that:

- Document the degradation of contaminants from the site

- Evaluate the presence or absence of microorganisms capable of degrading site contaminants
- Detect indicator parameters regarding the health and viability of microorganisms (e.g., respiration products)
- Detect secondary or "daughter" compounds of contaminants to indirectly assess the effectiveness of the remediation
- Use tracers to evaluate if contaminated areas receive injected nutrients and microorganisms.

5.2 Monitoring and Verification Technology User Facility Options

Successful development of monitoring and verification technologies requires rigorous field testing to determine effectiveness and reliability under realistic conditions. After field testing, evaluation programs (such as the EPA CSCT) might be used to evaluate the performance of these technologies. VAMOS participants suggested developing and/or expanding existing programs to produce specialized user facilities and procedures for evaluating monitoring and verification technologies prior to their performance testing by regulatory and other testing entities. These user facility sites and programs could address the following performance variables and applications:

- Differing climatic and hydrogeologic settings
- Sensor effectiveness and performance
- Sensor emplacement techniques
- Monitoring network performance
- Tracer applications
- Geophysical applications
- Subsurface barrier emplacement verification and monitoring
- Landfill liner and cover emplacement verification and monitoring.

If developed, these user facilities should be flexible and sufficiently adaptable to evaluate new monitoring and verification technologies that are developed in the future.

5.3 Technical Guidance Options

Technical guidance (i.e., practical suggestions and technical information related to accomplishing a task) is often used to direct and guide the implementation of technical activities. This type of guidance can be found in journal articles, the guidance documents of regulatory entities, corporate operating procedures, and the standards, guidelines, and test methods set by professional organizations.

Vadose-zone monitoring has been utilized for many years in agriculture and groundwater management to measure soil properties that control water infiltration and moisture retention. In the environmental area, this monitoring method has been recommended for use primarily in site-specific applications to monitor moisture movement at landfill sites and contamination at hazardous-waste land treatment units

(Koerner and Daniel, 1992; US EPA, 1986). Recently the use of vadose-zone monitoring for in-situ remediation, post-closure activities, and barrier verification and performance has also generated attention.

The following options for technical guidance development were identified by VAMOS as useful for defining and directing technology development in vadose-zone verification and monitoring.

- Technical guidance for site managers and industry personnel, including updates of previous (1980s) vadose-zone monitoring technical guidance
- American Society for Testing and Materials (ASTM) committee development of guidelines and test methods for monitoring and verification techniques
- Performance specifications for use in technology development
- Reliability and performance-based standards for evaluating remediation effectiveness
- Parameters needed to support risk assessments
- Technical guidance for the use of tracer and geophysical technology
- Guidance for actively monitoring closed landfill sites
- Integrated systems approaches to monitoring system network design, installation, and data handling.

Some of these areas are currently in the process of being developed and should help define and direct monitoring technology development in the future.

To be effective, guidance should be flexible and revised periodically to address the capabilities of new monitoring and verification strategies, technologies and methods once they are shown to be reliable through research, development, and field validation. The ease with which guidance is able to incorporate new strategies, technologies or methods is important for timely acceptance of these technologies by the environmental community.

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6.0 CONCLUSIONS AND RECOMMENDATIONS

Vadose-zone monitoring technology has traditionally focused on soil-moisture and soil-vapor monitoring. The monitoring of contaminant transport specifically in the vadose zone is a relatively recent development. Various sensors are under development to measure and quantify specific contaminants in situ for characterization purposes. However, remediation and containment monitoring in the vadose zone needs to be specifically emphasized. VAMOS showed that numerous research options exist for the development, implementation, and transfer of vadose-zone monitoring technology.

6.1 Development Options

As with any developing technology area, many research development options, which address a wide spectrum of topics, can be identified. However, this study observed three prevalent recurring themes: technology development, user facilities, and technical guidance. It is recommended that priority emphasis be placed on the research options identified in those themes, as summarized below.

6.1.1 Technology Development Options Recommendations

To date, environmental technology research and development has focused on performing site assessment and remediation. However, limited vadose-zone monitoring technology is specifically aimed to address government and industry needs in the remediation and containment monitoring area. Needed now are technologies and methods to verify that selected remedial actions are effective in contaminant reduction and/or containment. Development of vadose-zone monitoring and barrier verification technologies should involve both new technology and the conversion of compatible existing technology. It is recommended that priority should be placed on technology development in these areas:

- Cover and liner emplacement and performance monitoring to evaluate installation techniques and anticipate failures or breaches
- Tracer technology research and development that includes (1) development of tracers and methodologies to monitor and evaluate contaminant transport, in-situ remediation, and provide early warnings of containment leaks or failures; (2) toxicology studies that will allow industry professionals and site managers to select with confidence safe and appropriate tracers for site-specific conditions
- Development of geophysical instrumentation and methods capable of monitoring in-situ remediation and assessing cover, liner, and subsurface barrier emplacement, continuity, and long-term performance
- Monitoring networks designed with a compatible systems approach to ensure that appropriate sensors are selected so that spacing, emplacement, querying, data collection, data analysis, and appropriate archiving and retrieval technologies are compatible, automated, and provide a user-friendly site monitoring system
- Modification of existing site characterization sensors and development of new sensors for application to the remediation and post-closure monitoring and barrier verification arena

- Modification of other industry sensor technologies (e.g., aerospace, mining, manufacturing, and petroleum) for use in vadose-zone monitoring and barrier verification
- Development of monitoring techniques to assess in-situ bioremediation effectiveness, viability indicator parameters, and primary as well as secondary breakdown products.

6.1.2 Monitoring and Verification Technology User Facility Options Recommendations

Successful technology development and transfer requires a rigorous field testing program. As new technologies for monitoring and verification of remediation and containment become available, field testing could be expedited by developing and/or expanding existing programs to produce specialized user facilities. These facilities could evaluate new technologies prior to validation by regulatory and other testing entities. These user facilities should be capable of assessing the following variables and applications:

- Differing climatic and hydrogeologic settings
- Sensor effectiveness and performance
- Sensor emplacement techniques
- Monitoring network performance
- Tracer applications
- Geophysical applications
- Subsurface barrier emplacement verification and monitoring
- Landfill liner and cover emplacement verification and monitoring.

The user facilities should also be flexible and adaptable in order to evaluate new technologies as they are developed.

6.1.3 Technical Guidance Options Recommendations

Technical guidance documentation is typically developed to assist site managers with compliance procedures. Currently, limited technical guidance for verification and monitoring in the vadose zone is available for use by industry professionals and site managers. The most recent vadose-zone technical guidance identified was published in the 1980s. Areas of guidance which would help define and guide technology development directions might include:

- Update of vadose-zone monitoring guidance published in the 1980s
- Tracer monitoring methodology
- Nonintrusive and minimally intrusive geophysical barrier verification methods
- In-situ remediation technology monitoring methods that are based on remediation process indicator parameters

- Integrated systems approaches to monitoring system network design, installation, and data handling
- Development and institution of standards for reliability/performance specifications of technologies used for remediation and post-closure monitoring.

These guidance documents should be flexible and periodically revised to address applications of new monitoring and verification technologies, strategies, and methods after they are shown to be reliable through field validation.

6.2 Recommendations for VAMOS Follow-On

During the VAMOS project, excellent option study capabilities were developed for assessing research and development issues and directions in the area of monitoring and verification of in-situ remediation and containment activities. Follow-on to VAMOS is recommended. This follow-on should focus on specific technologies and serve as a resource to assist the DOE, national laboratories, and other governmental agencies as they address specific needs within their assigned sphere of responsibility.

Specifically, the insights and expertise developed through VAMOS are recommended for use in follow-on activities that provide technical and guidance input to support in-situ remediation monitoring and containment initiatives under development by the DOE Office of Technology Development (OTD). VAMOS follow-on should be used to provide both technical resources and a mechanism to assist OTD Focus Groups and other internal or external sub-committees, work groups, and/or, study groups, as needed. The implementation of follow-on activities would result in cost savings for future research and development. These cost savings would be realized by providing critical information used to evaluate and direct cost-effective monitoring and verification technology development, testing, and technical guidance useful at DOE environmental restoration sites.

In summary, VAMOS follow-on recommendations for in-situ remediation monitoring and containment verification include:

- In-depth, detailed option studies for specific, high-priority technologies
- Providing formal and/or informal technical expertise and guidance to work groups or study groups throughout the DOE complex on an as needed basis
- Providing test plan review and evaluation of monitoring and verification technology demonstrations.

The recommended technical areas for VAMOS follow-on for in-situ remediation and barrier verification include:

- Tracer technology
- Geophysical technology
- In-situ sensors

- Monitoring networks
- Data evaluation
- Monitoring and verification technology user facility design
- Technical guidance development for monitoring and verification technologies.

6.3 VAMOS Options Summary

A summary of the important options revealed during the VAMOS project is given in the Executive Summary. Only the highest-priority options identified are summarized in the table; those options judged as having a lower priority are not included in this report or table.

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APPENDIX A

STUDY METHODOLOGY

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STUDY METHODOLOGY FOR THE VERIFICATION AND MONITORING OPTIONS STUDY (VAMOS)

Literature Review

To identify the needs related to monitoring and verification, a literature review was performed. The review included current technology applications and research efforts related to monitoring remedial processes, as well as associated regulatory and technical guidance. Appropriate documents were secured and reviewed. A bibliography of the references secured and reviewed is located in Appendix D. The literature search accessed the following data bases:

- EPA on-line database
- Compendium of Superfund Program Publications
- Catalogue of Hazardous and Solid Waste Publications
- University of New Mexico Library System database
- New Mexico State University Library System database
- CARL expanded database for Journals

Expert Panel

In conjunction with the literature review, authoritative guidance was solicited from an expert panel composed of scientific, academic, and regulatory environmental professionals as well as end users of technology. This group met twice to evaluate current and future monitoring and verification needs and to establish methods for fulfilling these needs through research options. The first meeting focused on initial brainstorming to identify needs; the second focused on individual panel member presentations of identified monitoring needs. The expert panel evaluation focused on the topics listed below.

1. Regulatory and economic drivers for environmental monitoring technology
2. Current industry monitoring approaches
3. Commercially available monitoring technology
4. Needs pertaining to remediation and containment monitoring and verification that are not being met with existing technology.

The study topic, for needs identification included:

In-Situ Remediation Monitoring

- In-situ waste stabilization
- In-situ treatment and immobilization of heavy metals and organics
- Bioremediation
- Vapor extraction
- Alternative in-situ treatment (such as reactive barriers, etc.)
- Emplacement and performance of remediation and monitoring systems.

Barriers and Covers Monitoring

- Subsurface barriers
- Landfill cover
- Landfill liners
- Other topical areas
- Emplacement and performance of barriers, covers, and monitoring systems.

During the course of this study, participants found it useful to use a question-and-answer approach. The following questions represent some of those assembled; these questions must be addressed to effectively develop technology that will be applicable in the field.

Remediation monitoring:

Is the site adequately characterized to utilize existing remediation technology?
Is vadose-zone monitoring necessary?
What are the criteria for selecting a monitoring system?
What are the criteria for completing remedial action?
Are the criteria for completing remedial action risk-based?
Is the remediation localized?
How effective is the remediation during implementation?
Has remediation been achieved after implementation?

Containment Technology:

Where is the barrier?
Has containment been achieved?
Is the barrier suitable for the level of containment required?
Is the barrier deteriorating (in localized areas or in general)?

How badly is the barrier deteriorating?
Is the barrier failing (where and how badly)?
Can monitoring be used to determine the rate of deterioration and/or failure?

System Performance:

How long does the system need to function?
How long is "long-term" in relation to monitoring?
What is the consequence of monitoring system failure?
Are redundant monitoring systems needed?

Completion Report

After completion of the literature review and the panel meetings, the present report was completed to document the monitoring and containment verification needs identified during the course of the literature search and the panel meetings. The report was submitted for technical review by the panel members and others (see Appendix B) prior to finalizing.

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APPENDIX B

LISTING OF PANEL MEETING PARTICIPANTS AND DOCUMENT REVIEWERS

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APPENDIX C

DRIVERS AND TECHNICAL GUIDANCE DOCUMENTS

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DRIVERS AND TECHNICAL GUIDANCE DOCUMENTS

Some of the regulatory, economic, technical, and stakeholder drivers and technical guidance for vadose-zone monitoring identified during VAMOS are described below.

Drivers

Various drivers generate the need for vadose-zone monitoring and verificaiton of in-situ remediation and containment activities. These include regulatory, economic, technical, and stakeholder drivers as noted.

Regulatory Drivers for Vadose-Zone Monitoring

- Regulations for radioactive waste and mixed waste that require monitoring of the site for 10,000 years.
- Individual state environmental department perceptions of the appropriate need for monitoring.
- RCRA and CERCLA site-specific Environmental Protection Agency (EPA) agreement or approval of monitoring methods that are appropriate to the site conditions and have the ability to demonstrate "no migration" at the time of closure.
- The Federal Facilities Compliance Act and the EPA and Department of Energy (DOE) interpretations of compliance with the Act.

Economic Drivers for Vadose-Zone Monitoring

- The economic need to find methods for performing in-situ monitoring and verification of containment that are less expensive and more rapid than traditional methods. Current monitoring and verification practices are expensive and time consuming with respect to personnel and laboratory analysis and interpretation services.
- DOE consideration that containment could be used as a long-term remediation solution (US DOE, 1994g).

Technical Drivers for Vadose-Zone Monitoring

- Vadose-zone monitoring technical guidance documents produced by the EPA.
- The Superfund Initiative on Long Term Reliability of Containment that is currently being initiated through the EPA Office of Emergency and Remedial Response. This initiative's goal is to develop technical guidance and programmatic information on the subject of containment. The EPA plans to work with other agencies and entities (including the Department of Defense, DOE, and DuPont) to jointly develop technical information that site managers may use when evaluating containment systems.
- The Environmental Technology Innovation, Commercialization, and Enhancement Program (EnTice) formed by the EPA as a program to validate

innovative technology performance and credibility of technology development data prior to releasing newly developed technology for general field use. Presently the testing protocols are in place for this program that will operate 20 to 25 validation centers. Monitoring systems are listed as the fourth priority of the fourteen initial program classes identified.

- The Consortium for Site Characterization Technology (CSCT), as part of EnTice, has been formed by the EPA to validate the performance, through rigorous field testing, of mature, innovative measurement and monitoring technologies.

Stakeholder Drivers for Vadose-Zone Monitoring

- Public perception of the appropriate need for monitoring
- Regulatory concerns on a site-specific basis.

Technical Guidance

The following documents were identified during the literature search to identify vadose-zone monitoring technical guidance produced by the U.S. Environmental Protection Agency and the American Society for Testing and Materials (ASTM). Much of the ASTM vadose-zone monitoring technical guidance is currently in "progress" or "draft" form. Those ASTM standards that are finalized are so noted.

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American Society for Testing and Materials

The following is a listing of ASTM vadose-zone monitoring standards and their current status.

- Vadose Zone Terminology (Final)
- Soil Pore-Liquid Monitoring (D 4696-92)
- Soil Core Monitoring (D4700-91)
- Matric Potential Determination (D 3404-91)
- Neutron Moderation (D5220-92)
- Flux Determination (Clean Draft)
- Soil Gas Monitoring (D5314-93)
- Air Permeability Determination (Outline)
- Hydraulic Conductivity (D5126-90)
- Field Screening (Outline)
- Soil Moisture Determination (Outline)
- Thermocouple Psychrometers (Outline)
- Water Content Determination (Outline)
- Time Domain Reflectometry (Clean Draft)
- Frequency Domain Capacitance (Clean Draft)
- Horizontal Applications of Neutron Moderation (Clean Draft)
- Decontamination of Field Equipment (Final)

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APPENDIX D

LITERATURE REVIEW

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LITERATURE REVIEW
(ORGANIZED BY SUBJECT CATEGORY)

A literature review of current technology applications and research efforts related to vadose-zone monitoring of remedial processes, subsurface containment, and associated regulatory and technical guidance was conducted as a part of this study. Selected references are presented below by primary subject category.

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