In Situ Remediation Integrated Program

Evaluation and Assessment of Containment Technology

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Preface

The In Situ Remediation Integrated Program (ISRIP), instituted by the U.S. Department of Energy's Office of Technology Development, focuses research and development on the in-place treatment of contaminated environmental media, such as soil and groundwater, and the containment of contaminants to prevent them from spreading through the environment. Using in situ technologies to clean up DOE sites minimizes adverse health effects to workers and the public by reducing contact exposure. The technologies also significantly reduce the costs for cleanup by eliminating the need for waste excavation, transport, and disposal; and enable the remediation of relatively inaccessible areas, such as the deep subsurface and areas beneath structures.

This document was prepared under the ISRIP and describes technologies in one of four program areas within the ISRIP. The four program areas are in situ physical/chemical treatment technologies, bioremediation, containment technologies, and in situ manipulation/enabling technologies. In situ physical/chemical treatment technologies address processes that will remove or extract, destroy, and immobilize contaminants. The bioremediation area includes biological processes to destroy organic contaminants and mobilize or immobilize heavy metals and radionuclides. Containment technologies encompass both surface and subsurface barriers, as well as sorbent or permeable barriers and drainage systems. The in situ manipulation/enabling technologies include those technologies that will enable the addition, mixing, and transfer of reagents or energy into the subsurface, and those that can be used to monitor and measure the performance of in situ technologies. These documents summarize the current state-of-the-art for each program area and the research and development requirements to advance the technologies to the point of demonstration and deployment. These documents will be used by the ISRIP as planning guides and will be revised and updated annually.

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Summary and Conclusions

The In Situ Remediation Integrated Program (ISRIP) was established by the U.S. Department of Energy (DOE) to advance the state-of-the art of innovative in situ remediation technologies to the point of demonstration and to broaden the applicability of these technologies to the widely varying site remediation requirements throughout the DOE complex. This program complements similar ongoing integrated demonstration programs being conducted at several DOE sites.

The ISRIP also complements ongoing remediation activities managed by the Environmental Restoration (ER) Division of DOE. The ER Division currently manages more than 3000 inactive waste sites that have been identified at 18 DOE research and production facilities, including both engineered disposal facilities and unplanned releases.

The ISRIP has been conducting baseline assessments on in situ technologies to support program planning. Pacific Northwest Laboratory conducted an assessment and evaluation of subsurface containment barrier technology in support of ISRIP's Containment Technology Subprogram. This report summarizes the results of that activity and provides a recommendation for prioritizing areas in which additional research and development is needed to advance the technology to the point of demonstration in support of DOE's site restoration activities.

Containment technology can be used in a variety of site restoration applications at contaminated sites throughout the DOE complex. Some examples of containment applications are: providing short-term containment for potentially leaking underground storage tanks during retrieval of high-level waste; providing an interim to long-term cover for buried waste disposal sites to prevent infiltration of surface water; providing interim isolation of sources of contamination until site remediation can be implemented; and providing for temporary containment of reagents used in certain in situ treatment technologies, such as soil flushing and in situ biotreatment.

Subsurface containment barrier technology refers to physical barriers installed in the ground around a contaminated matrix (soil, sediment, solid waste, etc.). The purpose of these barriers is to limit containment migration from the matrix and subsequently offsite by reducing hydraulic flow and contaminant diffusion at the barrier. The containment methods evaluated in the report are listed below:

- caps installed above the contaminated zone but generally covered with overburden
- vertical barriers installed around the perimeter of the contaminated zone
- floors placed horizontally immediately below the contaminated zone
- angled barriers installed around the perimeter of the contaminated zone and extending underneath the zone to serve as both a floor and a lateral barrier
- sorbent barriers that do not control water flow but retard contaminant migration to acceptable rates

- gravel layers and curtains that can serve as barriers, drains, or vapor vents depending on the design.

These methods are briefly described in Section 2.0 of this report and assessed in more detail in the appendix.

Section 3.0 provides an overview of the state-of-the art for containment methods, including a discussion of ongoing development projects; identifies the technical gaps that require resolution prior to moving the technology forward toward deployment; discusses the priorities for resolution of the technical gaps; and identifies the site parameters which affect the application of a specific containment technology. DOE's needs are mostly driven by issues concerning the large number of sites requiring remediation, the wide variation among the sites themselves, and the wide variation of contaminants at these sites. Many of the sites contain a mixture of organic and inorganic hazardous waste and radioactive waste in a variety of media, including groundwater, soil, underground storage tanks, and buried waste. Containment is expected to play a role in site remediation in the following ways:

- short-term containment during remediation of a contaminated matrix
- interim containment action pending a Record of Decision (ROD) for site remediation
- intermediate-term isolation typically of at least 30 years as required by the U.S. Environmental Protection Agency for waste landfills regulated by the Resource, Conservation, and Recovery Act of 1976.
- long-term isolation to provide protection over an indefinite period as is currently being developed for nuclear waste
- long-term retention of residual contamination
- as a secondary or redundant barrier, which acts as a backup to a primary barrier.

Current remedial action strategies for hazardous waste sites utilize containment mostly as an interim action to prevent migration of contaminants from the site until an ROD is made. In some cases, containment is also considered as a remedial action alternative where it is determined to be the best compromise between cost and effectiveness over a relatively short period of time (about 30 years).

In general, a number of strategic activities are needed to fully realize the use of containment technology in the remediation of the various DOE sites. These activities are listed below:

- Identify and quantify containment functional requirements for DOE site applications.
- Verify ability of containment methods to meet functional requirements for DOE site applications.
- Integrate research and development involving containment and treatment technologies.
- Assess barrier material requirements for containment of concentrated leachate solutions.

- Develop barrier designs for management of gas phase transport of water and volatile organic compounds.
- Identify, develop, and assess alternative advanced techniques for verifying satisfactory barrier installation and performance monitoring.

The priorities for the containment technology subprogram of the ISRIP are largely dictated by the lack of information regarding site-specific technology opportunities. High priority is given to those activities needed to better assess technology opportunities both in regards to site needs and a general broadening of applications.

One high priority area identified is the need to integrate containment technology with in situ treatment applications. In particular, there is a great need for the development of technology for installing reliable floors below contaminated soil to be treated in situ.

Another high priority area is the development of containment methods for vadose zones at arid sites. There is a significant need for barriers for this application, but current technology is primarily oriented towards high-moisture-soil containment. Much of the need focuses on validating barrier materials such as asphalt, synthetic organic polymers, and vitrified soil that do not require a high-moisture environment in order to maintain their containment performance. Management of vadose zone water vapor also needs to be better understood for vadose zone applications in order to assess performance requirements for containment systems.

Sorbent barriers and gravel layers and curtains are both technology areas that mainly offer improvements to existing containment and in situ treatment strategies, but are not critical to current containment methods. Research in these areas is considered to be of medium priority for the program.

A related high priority activity is the development and application of technologies that can be used for verifying the performance of barriers. Acceptance of containment for many of the applications contemplated for DOE sites depends on demonstrating, with a high degree of confidence, that current and potential containment methods will perform as expected, provided they are properly installed. Acceptance further depends on verifying, again with a high degree of confidence, that barriers have been properly installed and continue to perform over time. In conjunction with this priority, research is needed to develop and validate models to predict barrier performance under specific site conditions and periods of use. Also required is the development of improved methods for verifying barrier integrity while maintaining reasonable monitoring costs over time.

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1.0 Introduction

Containment technology refers to a broad range of methods that are used to contain waste or contaminated groundwater and to keep uncontaminated water from entering a waste site. The U.S. Department of Energy's (DOE) Office of Technology Development has instituted the In Situ Remediation Integrated Program (ISRIP) to advance the state-of-the-art of innovative technologies that contain or treat, in situ, contaminated media such as soil and groundwater, to the point of demonstration and to broaden the applicability of these technologies to the widely varying site remediation requirements throughout the DOE complex. The ISRIP Containment Subprogram focuses on research and development (R&D) related to subsurface containment barriers. This document was developed by Pacific Northwest Laboratory (PNL)^(a) to support planning for this subprogram.

The information provided here is an overview of the state-of-the-art of containment technology and includes a discussion of ongoing development projects; identifies the technical gaps that require resolution before moving the technology toward deployment; discusses the priorities for resolution of the technical gaps; and identifies the site parameters affecting the application of a specific containment method. The overview of the state-of-the-art was obtained by reviewing and evaluating numerous technical publications. Technical gaps were identified with the help of technical experts familiar with containment technology.

This document provides the foundation for the ISRIP to develop a program for addressing R&D needs for containment methods and provides a mechanism for communication among the ISRIP, the technical experts, and the DOE end-users responsible for site remediation. The end-users responsible for site remediation require knowledge on the latest technological advances so that containment methods can be considered and appropriately evaluated for site-specific remediations. The technology developer requires site-specific characterization data and constraints for focusing the research on "real life" situations. This document will continue to be updated.

The containment technology described in this document cover surface caps; vertical barriers such as slurry walls, grout curtains, sheet piling, frozen soil barriers, and vitrified barriers; horizontal barriers; sorbent barriers; and gravel layers/curtains. Within DOE, containment technology could be used to prevent water infiltration into buried waste; to provide for long-term containment of pits, trenches, and buried waste sites; for the interim containment of leaking underground storage tanks and piping; for the removal of contaminants from groundwater to prevent contamination from migrating off-site; and as an interim measure to prevent the further migration of contamination during the application of an in situ treatment technology such as soil flushing. The ultimate goal is the implementation of containment technology at DOE sites as a cost-effective, efficient, and safe choice for environmental remediation and restoration activities. The technical details of the containment methods evaluated in this report are highlighted in the main text and more fully discussed in the appendix.

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2.0 Overview of Containment Technology

Containment technology includes a broad range of methods for managing water and contaminant migration around waste sites. These methods include active hydraulic controls using wells and pumps; various barriers for diverting rivers and streams; and barriers for controlling water infiltration and groundwater flow over a specific site. This report is concerned only with those barriers used to control water infiltration and groundwater flow around a contaminated zone in the ground.

Containment technology can be used in a variety of site restoration applications at contaminated sites throughout the DOE complex. Some examples of containment applications are: providing short-term containment for potentially leaking underground storage tanks during retrieval of high-level waste; providing an interim to long-term cover for buried waste disposal sites to prevent infiltration of surface water; providing interim isolation of sources of contamination until site remediation can be implemented; and providing for temporary containment of reagents used in certain in situ treatment technologies, such as soil flushing and in situ biotreatment.

Major categories of barriers used in containment applications are defined according to their orientation in the soil:

- caps installed above the contaminated zone but generally covered with overburden
- vertical barriers installed around the perimeter of the contaminated zone
- floors placed horizontally immediately below the contaminated zone
- angled barriers installed around the perimeter of the contaminated zone and extending underneath the zone to serve as both a floor and a lateral barrier.

These barriers, discussed further in this section and detailed in the appendix, are generally designed to provide for hydraulic control of water in the soil and sediment. Caps inhibit infiltration of surface water. Floors inhibit transport of leachate from the contaminated zone usually located in the vadose zone. Vertical barriers inhibit groundwater from entering a contaminated zone and leachate from leaving the zone. Angled barriers placed around a contaminated zone meet underneath the zone, serving the functions of both vertical barriers and floors. An important measure of the performance of hydraulic barriers is their resistance to the flow of water as measured by their hydraulic conductivity (permeability).

Barriers used around hazardous waste sites regulated under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 are not specifically required to achieve a certain hydraulic conductivity. However, U.S. Environmental Protection Agency (EPA) guidance for hydraulic barriers, including caps and liners, around disposal sites regulated under the Resource, Conservation, and Recovery Act (RCRA) of 1976, recommends achieving an average hydraulic conductivity of 10^{-7} cm/sec. This value is generally accepted as a benchmark for evaluating barriers at CERCLA sites, since comparable containment would be achieved. However, higher values may be acceptable depending on the specific application for the barriers, i.e., short- or

intermediate-term interim action, or long-term containment as part of a Record of Decision (ROD), and is determined during the remedial investigation/feasibility study (RI/FS) leading to the ROD. While lower hydraulic conductivities can be achieved for some barrier materials, values below 10^{-8} cm/sec are not as important because contaminant migration due to diffusion becomes the dominant transport mechanism.

Containment barriers may also need to resist vapor phase transport of water and hazardous volatile organic compounds (VOCs) in the vadose zone, as measured by their diffusivity properties for gases. This mechanism is currently under investigation, and specific barrier requirements for this transport mechanism are not established at this time.

In addition to the categories described above, there are two special categories of containment barriers based on their properties and special functions:

- sorbent barriers that do not control water flow but retard contaminant migration to acceptable rates
- gravel layers and curtains that can serve as barriers, drains, or vapor vents depending on the design.

These last two categories are specialized barriers that could, in principle, be part of many other configurations in an integrated system.

2.1 Caps

Caps cover contaminated materials to prevent direct contact with receptors (humans and animals); to control the infiltration of surface water, snow and ice melt water, or rainwater; and to control the release of soil vapors. Capping can also be used to control radon releases or to attenuate radiation from radioactive contaminants. Capping is commonly used in conjunction with other surface water controls and subsurface barriers, and with certain treatment strategies involving groundwater or soil gas extraction.

Various cap designs and capping materials are available. The selection of the cap design and materials depends on the nature of the waste to be covered, the function of the cap, the local climate and hydrogeology, the availability of materials, and the intended use of the capped area. The main types of caps include the multi-layered caps used at waste disposal sites regulated by RCRA, and single-layered caps.

The RCRA multilayered caps are used for RCRA hazardous waste disposal applications and are designed to provide a useful life of 30 years or more. The design of a RCRA multilayered cap is based on the premise that the placement of materials with different design functions will achieve the necessary containment over the life of the barrier. The various layers generally consist of an upper vegetative (topsoil) layer; a drainage layer; and a low-permeability layer, which may include a synthetic liner covering a layer of compacted clay (EPA 1985). The top soil layer generally serves as a barrier to protect the underlying layers from erosion, frost, and incidental excavation. The topsoil

may support vegetation for erosion control or be covered by gravel where climate does not support adequate vegetation. The drainage layer serves to provide a path for any water to flow off of the low-permeability layer. A filter fabric separates this layer from the native soil layer. In addition, cobbles may be placed above the drainage layer to prevent animal intrusion. The low-permeability layer usually consists of compacted clay placed in a way to provide a 3% to 5% grade for drainage. A synthetic liner is placed between the drainage layer and the low-permeability layer.

Fairly rigorous design specifications must be met for a RCRA cap, and although specific materials used in the different layers may vary, proof of equivalency is generally required before substitutions can be made. Some examples of substituted materials in the low-permeability layer are mixtures of soil and asphalt or Portland cement.

Single-layered caps may consist of soil, asphalt, concrete, or Portland cement. These caps are generally used in interim actions where short-term containment is desired during the RI/FS process for a site, pending selection of a preferred remedial action alternative in the ROD for a site, but they are not normally accepted in an ROD. However, in areas where precipitation (rainfall) is low, and transpiration of soil water is very high and/or the contamination is very deep, a single-layered cap may be suitable for longer-term containment. Similarly, single-layered caps, such as one made of asphalt, that can frequently be inspected and maintained, may also be acceptable as a longer-term containment measure (EPA 1985).

All caps require periodic inspection and maintenance for subsidence (settling), ponding of surface water, erosion, and naturally occurring invasion by deep-rooted vegetation and burrowing animals. The climate, flora, and fauna of the site impacts the frequency of inspection and maintenance. In addition, ventilation may be required if organic contaminants under the cap produce gas.

2.2 Vertical and Angled Barriers

Vertical barriers are used as cut-off walls to divert groundwater flow around a contaminated zone and contain contaminated water within the barrier. Types of vertical barriers include slurry walls, grout curtains, sheet piling cut-off walls, and cryogenic barriers. The technology for constructing vertical barriers has been well developed for management of underground water; for soil stabilization during site construction and excavation; and for mining applications.

Similarly designed barriers are sometimes installed at an angle so that the angled barriers on opposite sides of a contaminated zone meet underneath the zone. This provides both lateral containment and serves as a floor for vertical containment underneath the zone. Angled barriers can be used as an alternative to installing a separate horizontal barrier underneath the contaminated zone or extending vertical barriers to bedrock. Angled barriers are a variation of vertical barriers in terms of construction, differing only in orientation and the added requirement that a good seal be achieved between opposite panels that meet underneath the contaminated zone.

2.2.1 Slurry Wall

A slurry wall is a vertical trench excavated under a slurry and then back-filled with cement, grout, or soil-bentonite mixtures to form a hydraulic barrier. The low hydraulic conductivity of the material in the trench (typically 10^{-7} cm/sec to 10^{-6} cm/sec) reduces lateral flow of groundwater to manageable levels. Trenches are typically 2 to 4 ft in width (PNL 1991) and constructed to depths of 200 ft. Slurry walls are limited to vertical orientation.

Slurry wall trench excavation and backfilling are done entirely underneath the slurry in the trench. The slurry in the trench, which usually consists of a mixture of bentonite and water, is kept 2 to 4 ft above the level of the groundwater to provide a net outflow of water from the slurry into the groundwater. This creates a low-permeability filter cake on the trench walls that prevents large fluid losses into the adjacent ground. Whenever the design requires that the slurry trench be keyed into an underlying impervious zone, a keyway of approximately 2 to 3 ft in depth is constructed.

The most common slurry wall is composed of a soil-bentonite mixture. Where possible, the soil used in the mixture consists of soil excavated from the trench and treated as necessary to ensure sufficient fines content (generally 10% to 30% of soil finer than a No. 200 sieve). The backfill is mixed thoroughly and returned to the trench using a bulldozer. In some cases, offsite soil must be used if the character of the onsite material or the nature of the contaminants in the excavated soil makes the onsite material unsuitable. The completed slurry wall is usually provided with a compacted soil cap. A hard (asphalt or concrete) cap is sometimes placed wherever traffic is expected to cross the containment site.

Cement-bentonite slurry walls are very similar to soil-bentonite slurry walls. The main difference is that the cement slurry is left in the trench, in place of backfilled soil, and allowed to harden into a solid wall. Cement-bentonite slurry cut-off walls provide greater structural strength than soil-bentonite cut-off walls, but their hydraulic properties are less favorable.

2.2.2 Grout Curtain

Grout curtains are a relatively new type of subsurface barrier used in a manner similar to slurry walls. The main difference is that the grout curtain is created by injecting grout directly into the soil or by in situ mixing of soil and grout using special equipment. Consequently, it is possible to install angled grout curtains. Grout curtain technology is based on a related technology where grouting is routinely used to fill voids in earthen dams, rock formations, and in soil-based foundations. Grout curtains are usually not preferred for containment of hazardous waste because other barriers, specifically slurry cut-off walls, are less costly to install and possess comparable or better hydraulic properties. In some applications slurry walls are not suitable, however, and grout curtains may be adequate. Some examples include barriers extending up a slope and barriers installed at an angle.

Grout curtains can be placed in unconsolidated soils by permeation injection. In a typical system (called a stage-up system), a borehole is drilled to full depth of the wall prior to injection. The drill is withdrawn a specific distance, and grout is injected into the exposed borehole and adjacent soil. This process is repeated until the entire length of borehole is treated. Boreholes are spaced about 20 to 40 ft apart (EPA 1985).

Other grout curtain systems using a borehole include the stage-down system and the grout port system. In the stage-down system, the borehole is partially drilled and injected with grout as before. The borehole is redrilled to a greater depth and grout injected again. This procedure is repeated until the desired depth is achieved. The grout port method uses a slotted injection pipe sealed in the borehole. Slots are sequentially open and grout injected until all portions of the borehole have been treated.

Another method of creating a grout curtain is called the vibrating beam method. In this method, an I-beam is vibrated into the ground to the desired depth. It is then slowly withdrawn, and grout is injected into the empty space through injection nozzles at the bottom of the beam. The I-beam is then vibrated into a location overlapping the first placement, and the process is repeated until a complete curtain is produced (EPA 1985).

Grout curtains can also be installed by in situ mixing of grout with soil. In one process, called deep soil mixing, a guided auger system consisting of two or four hollow stem augers are fed vertically into the soil. As the augers penetrate the soil, grout is fed through the tip of the hollow and mixed with the soil. About 80% of the grout is added as the auger system penetrates the soil to the desired depth, and the remainder is injected and mixing is repeated as the system is withdrawn (Jasperse 1989). In a second method, called jet grouting, the grout is injected at high velocity into the soil at the bottom of the well, causing a chamber to be excavated and the loose soil to be mixed with the grout. As the well casing and jet are withdrawn, a column of grout-soil mixture is formed.

2.2.3 Sheet Piling Cut-off Walls

Sheet piling cut-off walls are made of precast interlocking sheets of steel or concrete. The piles are first assembled and driven a few feet into the soil to ensure that they interlock. The piles are then driven a few feet at a time over the entire length of the wall until the desired depth is reached. Spaces in the interlocking joints initially leak but are slowly sealed with fine particles over time (EPA 1985). Some newer sheet piling designs have provisions for injecting grout at the joints to ensure suitable sealing. Sheet piling cut-offs can also be installed to form an angled barrier provided the bottom of the barrier, where the pilings meet, can be adequately sealed.

2.2.4 Frozen Soil Cut-off Walls

Frozen soil barriers consist of a wall of water-saturated soil that has been frozen to produce a temporary barrier. Frozen soil barriers have been used for many years in the construction industry to prevent cave-in of the walls around an excavation site. In a typical application, holes spaced about 1 to 3 m apart are bored into the soil to the desired depth (K&M Engineering and Consulting Corp. and BDM International, Inc. 1993). Cooling pipes are installed in the holes and refrigerant is injected into the well, causing the soil to freeze and form a growing annulus of frozen soil around the pipe. Eventually, the frozen annuli of adjacent pipes merge to form a continuous wall of frozen soil. When the barrier is no longer needed, the refrigeration is stopped and the barrier slowly melts, returning the soil approximately to its original condition. Using directional drilling techniques it is possible to create angled frozen soil barriers, but the containment method has yet to be tested in the field.

2.2.5 Vitrified Barriers

Vitrified barriers are an advanced concept in which vadose zone soil is melted in situ using electrodes in a configuration that produces a vertical cut-off wall consisting of vitrified soil. The concept is an adaptation of in situ vitrification (ISV) technology, which is currently undergoing site demonstrations to immobilize inorganic and radionuclide contaminants in the soil. The properties of vitrified barriers are relatively insensitive to the properties of the soil and do not require the addition of materials in order to construct the barrier. However, the installation of vitrified barriers is limited to unsaturated soil applications. This concept is still in the early stages of development, and its performance has yet to be verified.

2.3 Floors

A floor is a horizontal barrier placed beneath a contaminated site to prevent downward migration of contaminants. Floors have been installed in dam foundations in situations where it was not practical to install a vertical barrier to an impermeable layer directly beneath the dam. In this application, the floor reduces the rate that water could flow underneath the vertical structures constituting the main dam structure. Floors have not been proven as a containment measure for hazardous waste. There are, however, several grouting techniques that in principle could be used for installing floors.

One grouting technique for bottom sealing is very similar to forming a grout curtain, except that the holes are bored on a slant from the perimeter and meet at the center. In another method, holes are first drilled through the contamination zone. High-pressure air or a water jet is then lowered to the bottom of the borehole and rotated 360° horizontally to create a circular cavity, which is filled with grout. A matrix of boreholes with intersecting grouted cavities forms the bottom seal.

A third method called fracture bounded grouting involves drilling specially notched holes at the desired depth and injection grout at the notch to propagate a thin (0.5-in. to 2.0-in.-thick), large-diameter horizontal fracture that is filled with the grout to form an impermeable barrier. A modification of this method is called block displacement. In this method, a vertical barrier is first constructed around the perimeter of the site; then specially notched holes are bored and the grout is injected. Continued grout injection causes vertical displacement of the soil isolated inside the vertical wall, producing a grout floor as much as 12 in. thick.

2.4 Sorbent Barriers

Sorbent barriers are an innovative containment method for retarding the migration of contaminants while allowing for the normal flow of groundwater through the barrier. Sorbents have been used to a very limited extent in immobilizing organic contamination in surface soils in which sorbent materials are tilled into the soil (Sims and Bass 1984). The application of subsurface barriers had not progressed beyond bench- and pilot-scale as of early 1990 (EPA 1990a).

In situ sorption involves the addition of sorbent materials to the soil in order to adsorb contaminants. It is based on the principle that the concentration of certain chemicals and ions will be higher

on the surfaces of certain solids than in the bulk liquid phase. Sorption materials utilize several mechanisms, including physical adsorption, specific adsorption, chemisorption, and ion exchange, to achieve this preferential partitioning of contaminants to the sorbent materials.

Any barrier can, in principle, contain sorbent materials that retard the migration of contaminants. However, sorbent barriers are typically described in the context of a barrier that is considered to be at least as permeable to water as the soil surrounding the barrier. Permeable barriers can be installed either in the groundwater sediments as a barrier to groundwater flow or in the vadose zone below contaminated soils to contain downward migration of leachate.

Permeable barriers to treat contaminated groundwater can be constructed by filling trenches with a mixture of soil and one or more adsorbents. This method is limited to the treatment of groundwater near the surface. However, it should be possible to use slurry wall construction techniques with a biopolymer slurry to construct deeper trenches (see Appendix A.2.3.4). When a sorbent barrier is to be used to contain leachate migration in the soil, the barrier would be installed using one of the grouting techniques described in Appendix A.3.

2.5 Gravel Layers and Curtains

Gravel layers and curtains are not considered to be a containment measure by themselves. Instead, they are incorporated into cap and cut-off wall designs as part of an integrated containment barrier system to facilitate the management of water.

Gravel layers and curtains can be used in containment systems in one of several ways to either impede or redirect flow in the ground. These materials behave as capillary breaks that impede unsaturated flow from an adjacent layer of fine soil as a result of the differences in hydraulic conductivity in unsaturated conditions. Gravel layers and curtains can also serve as either vertical or horizontal drains that direct the flow of water under saturated conditions away from the zone of ground being contained. Gravel layers and curtains may also serve as a conduit for active or passive vapor extraction from the soil. In this capacity, they may serve to remove water from the soil in the form of vapor.

3.0 Assessment of Containment Technology

This section provides an assessment of subsurface containment barrier technology. Section 3.1 discusses issues that affect the applicability of containment technology at DOE sites. Section 3.2 summarizes the status, technology gaps, and ongoing R&D for the methods described in Section 2.0 and more fully detailed in the appendix. Section 3.3 identifies R&D that is needed to advance these methods to the point of demonstration and to broaden their application at DOE waste sites. Section 3.4 provides a recommendation for prioritizing those R&D areas of interest to the ISRIP Containment Subprogram.

3.1 Issues Affecting Applicability of Containment Technology to DOE Needs

The state-of-the-art for constructed barriers depends more on the specific application and associated performance requirements than on the individual elements comprising the design and installation of the barrier. Caps, for example, rely on construction techniques and materials used by industry for designing liners installed in water-retaining lagoons and in other nonhazardous waste applications where surface erosion or gas migration to the surface must be controlled. Similarly, much of the underlying technology for cut-off walls is well understood in the restricted context of underground water management in site construction, excavation, and mining applications. Much of the technology has a strong foundation in the construction and maintenance of river dams. Temporary barriers are routinely used to control surface and groundwater flow in river beds during excavation of subsurface foundations, and for controlling water flow into open pit mines that are below the water table.

Even though constructed barrier technology is well developed for the construction applications described above, it is not directly adaptable to hazardous waste containment because it generally has involved reducing the flow of clean water to levels that can be handled by a pump. Since the water is clean, it can immediately be discharged to the environment without treatment. In hazardous waste containment, it is not desirable to have water flowing through the barrier and into the zone of contamination at rates that require significant pumping. If the barrier is to prevent the migration of contaminated water offsite, then flow reduction can be even more critical.

The applicability of subsurface barriers to site restoration and the state of the art for the technology for these applications depend on several factors:

- compatibility with site remediation objectives and activities
- amenability to site constraints
- performance verification
- life-cycle cost
- institutional criteria.

3.1.1 Compatibility with Site Remediation Objectives and Activities

Both the application and the performance requirements are determined by the site remediation objectives and all activities associated with meeting those objectives. The two primary parameters that must be considered in assessing application and performance requirements are the containment function and the site-specific constraints.

3.1.1.1 Applicability to Containment Function

Containment function refers to the manner in which the barrier is used in an overall remediation strategy for a site. The containment function is determined by a number of factors, including its design life span, integration with other containment measures being implemented, and any treatment activities utilizing the containment function.

3.1.1.2 Design Life Span

The design life span has an important effect on the performance requirements of the barrier. These life spans are determined by the overall remediation strategy involving the following types of containment:

1. short-term containment during remediation of a contaminated matrix
2. interim containment action pending an ROD for site remediation
3. intermediate term isolation typically of at least 30 years as regulated by EPA for RCRA waste landfills
4. long-term isolation to provide protection over an indefinitely long period as is currently being developed for nuclear waste
5. long-term retention of residual contamination
6. as a secondary or redundant barrier.

Current remedial action strategies at hazardous waste sites mostly utilize containment as an interim action until an ROD is made. In some cases, containment is also considered as a remedial action alternative where it is determined to be the best compromise between cost and effectiveness over a relatively short period of time (about 30 years). Containment technology for RCRA landfill sites also generally falls into the third category in terms of performance.

Three situations where containment could be considered in the actual remediation of a site are: for long-term containment; for short-term containment as part of a treatment; and as a secondary or redundant barrier constructed in conjunction with a primary barrier system. In a long-term application, the containment system would be designed and installed so that it could be left unattended for indefinite periods of time. In this application, the barrier would either serve to permanently

isolate the waste in a geologically sound enclosure or it would allow a slow but finite migration of wastes from the site so that the waste eventually is released but at inconsequential concentrations.

As part of a treatment strategy involving soil, a trench or a leaking tank, for example, containment could also be used for relatively short periods of time, such as a few weeks to several months, to prevent contaminant migration during the treatment operations.

3.1.1.3 Integration with Other Containment Measures

Other containment measures that are needed in a site remediation also affect the performance requirements of a specific barrier. In some cases, several types of barriers are needed to provide complete containment. For example, a cap, vertical barrier, and a bottom sealing barrier may be required to isolate a contaminated zone. In other cases, a barrier may be used for secondary containment to a barrier such as an underground storage tank, which provides primary containment. Similarly, a barrier may be needed as a temporary containment measure during the installation of a more durable barrier.

3.1.1.4 Applicability to Treatment Activities

Containment barriers may also need to be integrated into remedial actions involving in situ treatment processes. In fact, containment is considered to be a necessary element in applications where the addition of reagents to the ground could cause contaminants or excess reagents to migrate from the site prior to completion of the treatment. However, at the present time there has been little effort to integrate treatment and containment technologies. Caps have been placed over contaminated soil to manage the infiltration of air from the surface during soil gas extraction. Hydraulic containment of groundwater has been accomplished during soil flushing using injection and extraction wells. Lateral barriers could potentially be applicable in this latter application. Floors and lateral barriers are potentially applicable for treating contaminated vadose zone soils during soil flushing to facilitate retention and subsequent recovery of solvents and contaminants during treatment. Similarly, other chemical and biological treatment processes requiring the addition of liquids to the vadose zone may require barriers to prevent migration of contaminants and excess reagents from the site. In these cases, the barrier must also be compatible with the reagents added in the treatment process.

3.1.2 Amenability to Site Constraints

The applicability and performance requirements of specific containment barriers to specific hazardous and mixed waste sites within the DOE complex depend to a large extent on the characteristics of each site. These characteristics include the type, location, and extent of the contaminated matrix to be treated; site topography, geology, and hydrology; weather; and space needed for equipment and to manage excavation spoils produced during barrier installation.

Eighteen research and production facilities are operated by DOE throughout the United States. These facilities occupy approximately 2800 square miles (DOE 1986). More than 3000 inactive waste sites have been identified at these facilities, including both engineered disposal facilities and unplanned releases (GAO 1988a,b). These sites vary considerably in regard to the type and location of contamination within each facility as well as climate, topography, and geology. Table 3.1, which

is based on ongoing PNL environmental characterization studies, lists the major DOE sites and indicates some of the general characteristics of these sites regarding climate and geology. However, even within each site there is considerable variation in the geological setting at specific sites because of their proximity to stream and rivers, canyons and gullies, and rock outcroppings.

The DOE sites also vary considerably in the type of mixed and hazardous waste produced and the methods used for disposal at individual hazardous waste sites because of different missions for the various DOE facilities. Several of the larger facilities have a complex history of waste-disposal practices resulting from large-scale chemical processing for nuclear fuel fabrication and spent fuel processing. Over the years, the nature of the chemical wastes changed as these technologies matured. Other facilities primarily engaged in fabrication and testing of nuclear and nonnuclear weapons, and construction and testing of nuclear reactors. The method of disposing of waste streams at these facilities varied by the type of waste, ranging from high-level radioactive waste stored in underground storage tanks to large volumes of water containing low levels of radioactive and chemical contamination disposed of in cribs, French drains, infiltration ponds, and trenches to containers of small quantities of chemical and mixed waste disposed of in onsite landfills.

Many of the site constraints affect barriers by requiring certain methods for installation of the barrier, which in turn affects the applicability of certain barrier designs. The amount of moisture in the soil and/or sediment may also limit the applicability of specific designs if moisture affects the performance of materials used in the barrier.

3.1.2.1 Type, Location, and Extent of the Contaminated Matrix

Constructed barriers can be used to isolate and contain contamination within several different types of matrices that may be encountered at a hazardous waste site:

- soil (vadose zone)
- groundwater
- tanks, pipelines
- buried waste, barrels, debris, etc.
- cribs, trenches, ponds.

The type and location of the contaminated matrix also affects the type of barrier design required. An important factor is the location of impermeable bedrock relative to the surface and the contaminated matrix. For example, ponds, tanks, pipelines, and buried waste are usually located at or near the surface. If impermeable bedrock is relatively near the surface then vertical barriers can be keyed into the bedrock to provide lateral containment of the waste matrix, while the bedrock serves as a floor. However, if the bedrock is very deep it may be impractical to extend the vertical barriers all the way to the bedrock if contamination is confined near the surface. In this case, it may be more practical to install shallow vertical barriers and a separate floor, or install angled barriers to serve both functions. The latter option, however, may be impractical if the areal extent of contamination is very large or a relatively large structure lies over the site. Alternatively, it may be practical to place a subsurface vertical barrier in the groundwater zone connecting to the bedrock in order to divert groundwater away from the plume above it.

Table 3.1. General Characteristics of DOE Sites^(a)

Site	Annual Rainfall (cm)	Soil Layer	Soil Texture Name	Soil Layer Thickness (m)	Soil Bulk density (g/cm ³)	Soil porosity (%)	Soil Field Capacity (%)	Hydraulic conductivity (cm/sec)	Percent (vol) sand/silt/clay/ organic
Fernald Environmental Management Project (OH)	102.0	Unsaturated - 1	Loam	1	1.4	50	40	1.2 (10) ⁻⁵	33/43/24/0.46
		Unsaturated - 2	Loamy Sand	1	1.7	42	5	1.6 (10) ⁻²	77/20/3/0.39
		Saturated - 1	Loamy Sand	45	1.7	42			77/20/3/0.39
Paddy's Run Area									
Fernald Environmental Management Project (OH)	102.0	Unsaturated - 1	Silt Loam	4	1.4	46	28	2.0 (10) ⁻³	11/63/26/0.58
		Unsaturated - 2	Loamy Sand	2	1.5	44	15	6.5 (10) ⁻²	75/20/5/0
		Unsaturated - 3	Loam	4	1.4	48	38	1.2 (10) ⁻⁶	33/43/240
Southwest Production Area		Unsaturated - 4	Loamy Sand	8	1.7	42	5	1.6 (10) ⁻²	77/20/3/0.39
		Saturated - 1	Loamy Sand	45	1.7	42			77/20/3/0.39
Fernald Environmental Management Project (OH)	102.0	Unsaturated - 1	Loam	1	1.4	47	24	5.3 (10) ⁻³	40/39/21/0
		Unsaturated - 2	Loam	3	1.4	50	40	1.2 (10) ⁻⁵	33/43/24/0.46
		Unsaturated - 3	Loam	8	1.4	48	38	1.2 (10) ⁻⁶	33/43/24/0
East-Northeast		Unsaturated - 4	Loamy Sand	11	1.7	42	5	1.6 (10) ⁻²	77/20/3/0.39
		Saturated - 1	Loamy Sand	45	1.7	42			77/20/3/0.39
Hanford Site (WA)	16.0	Unsaturated - 1	Sand	33	1.8	36	19	1.5 (10) ⁻³	90/9/1/0
		Unsaturated - 2	Sand	50	1.6	42	8.5	5.0 (10) ⁻³	95/3/2/0
200 East Area		Unsaturated - 3	Sand	19	1.8	36	19	1.5 (10) ⁻³	90/9/1/0
		Saturated - 1	Loamy Sand	9	1.6	18			86/12/2/0
Hanford Site (WA)	16.0	Unsaturated - 1	Sand	25	1.8	36	11	1.2 (10) ⁻²	95/3/2/0
		Unsaturated - 2	Loam	15	1.7	40	13	2.3 (10) ⁻³	45/55/0/0
200 West Area		Unsaturated - 3	Loamy Sand	5	1.7	40	18	6.8 (10) ⁻³	86/12/2/0
		Unsaturated - 4	Sandy Loam	6	1.9	31	7	2.0 (10) ⁻³	73/25/2/0
		Unsaturated - 5	Loamy Sand	21	1.8	36	12	2.1 (10) ⁻³	87/11/2/0
		Saturated - 1	Loamy Sand	9	1.8	36			87/11/2/0
Hanford Site (WA)	16.0	Unsaturated - 1	Sand	18	2.0	30	9	1.4 (10) ⁻²	90/7/3/0
		Unsaturated - 2	Loamy Sand	6	1.9	30	12	2.1 (10) ⁻³	87/11/2/0
100N Area		Saturated - 1	Loamy Sand	11	1.9	30			87/11/2/0
Hanford Site (WA)	16.0	Unsaturated - 1	Sand	12	2.1	26	7.5	1.4 (10) ⁻²	92/6/2/0
		Saturated - 1	Sand	10	2.1	26			92/6/2/0
300 Area									

Table 3.1. (contd)

Site	Annual Rainfall (cm)	Soil Layer	Soil Texture Name	Soil Layer Thickness (m)	Soil Bulk density (g/cm ³)	Soil porosity (%)	Soil Field Capacity (%)	Hydraulic conductivity (cm/sec)	Percent (vol) sand/silt/clay/ organic
Idaho National Engineering Laboratory (ID)	23.0	Unsaturated - 1	Silty Clay	12	1.5	35	24	7.1 (10) ⁻⁶	20/50/60/0
		Unsaturated - 2	Loam	53	1.9	20	5	7.1 (10) ⁻⁴	100/0/0/0
		Unsaturated - 3	Sand	3	1.6	43	32	2.4 (10) ⁻⁵	20/20/60/0
Technical Area North		Saturated - 1	Clay Sand	75	1.9	20			100/0/0/0
Idaho National Engineering Laboratory (ID)	23.0	Unsaturated - 1	Silty Clay	12	1.5	35	24	7.1 (10) ⁻⁶	20/50/60/0
		Unsaturated - 2	Loam	53	1.9	20	4.5	7.1 (10) ⁻⁴	100/0/0/0
		Unsaturated - 3	Sand	2	1.6	43	32	2.4 (10) ⁻⁵	20/20/60/0
Playas		Saturated - 1	Clay Sand	75	1.9	20			100/0/0/0
Idaho National Engineering Laboratory (ID)	23.0	Unsaturated - 1	Sandy Loam	18	1.5	45	18	6.9 (10) ⁻⁵	60/25/15/0
		Unsaturated - 2	Sand	27	1.9	20	5	2.9 (10) ⁻²	100/0/0/0
		Unsaturated - 3	Silt	15	1.5	45	28	6.9 (10) ⁻⁵	10/80/10/0
Central Facilities Area		Unsaturated 4	Sand	76	1.9	20	5	2.9 (10) ⁻²	100/0/0/0
		Saturated - 1	Sand	75	1.9	20			100/0/0/0
Idaho National Engineering Laboratory (ID)	23.0	Unsaturated - 1	Silt	3	1.5	49	28	7.6 (10) ⁻⁵	10/80/10/0
		Unsaturated - 2	Sand	10	1.9	23	5	3.4 (10) ⁻²	100/0/0/0
		Unsaturated - 3	Silt	73	1.5	49	28	7.6 (10) ⁻⁵	10/80/10/0
Radioactive Waste Management Complex		Unsaturated 4	Sand	93	1.9	23	5	3.4 (10) ⁻²	100/0/0/0
		Saturated - 1	Sand	75	1.9	20			100/0/0/0
Idaho National Engineering Laboratory (ID)	23.0	Unsaturated - 1	Sandy Loam	18	1.5	45	18	6.9 (10) ⁻⁵	60/25/15/0
		Unsaturated - 2	Sand	27	1.9	20	5	2.9 (10) ⁻²	100/0/0/0
		Unsaturated - 3	Silt	15	1.5	45	28	6.9 (10) ⁻⁵	10/80/10/0
Argonne National Laboratory-West		Unsaturated 4	Sand	76	1.9	20	5	2.9 (10) ⁻²	100/0/0/0
		Saturated - 1	Sand	75	1.9	20			100/0/0/0
Mound (OH)	--	Unsaturated - 1	Clay Loam	3	2.1	30		1.2 (10) ⁻³	10/10/8/1.7
Hill		Unsaturated - 2	Sandy Loam	9	1.6	42		3.5 (10) ⁻²	65/25/10/0.5
		Saturated - 1	Sandy Loam	8	1.6	44			65/25/10/0.5
Mound (OH)	--	Unsaturated - 1	Silt Loam	8	2.1	21		1.2 (10) ⁻²	15/25/60/1.7
		Saturated - 1	Sandy Loam	28	2.1	38			70/25/5/1.7
Buried Valley Aquifer									
Oak Ridge National Laboratory (TN)	139.2	Unsaturated - 1	Silt Loam	0.5	1.3	50	42	1.3 (10) ⁻²	30/50/20/1.5
		Unsaturated - 2	Sandy Loam	3	1.7	37	33	4.6 (10) ⁻³	60/25/15/0.3
		Unsaturated - 3	Silt Loam	0.5	1.3	42	30	1.9 (10) ⁻²	35/50/15/2.0
X-10 Site, (Knoxville Water Table Zone)		Unsaturated - 4	Clay Loam	4	1.6	45	40	3.6 (10) ⁻³	30/40/30/0.1
		Saturated - 1	Loam	3	2.7	1			45/40/15/0.1

Table 3.1. (contd)

Site	Annual Rainfall (cm)	Soil Layer	Soil Texture Name	Soil Layer Thickness (m)	Soil Bulk density (g/cm ³)	Soil porosity (%)	Soil Field Capacity (%)	Hydraulic conductivity (cm/sec)	Percent (vol) sand/silt/clay/ organic
Oak Ridge National Laboratory (TN)	139.2	Unsaturated - 1	Silt Loam	0.5	1.3	50	42	1.3 (10) ⁻²	30/50/20/1.5
		Unsaturated - 2	Sandy Loam	3	1.7	37	33	4.6 (10) ⁻³	60/25/15/0.3
		Saturated - 1	Clay/Fill	6	1.5	40			5/10/85/0.1
K-25 Site		Saturated - 2	Clay Loam	5	2.7	50			45/40/15/0.1
Oak Ridge National Laboratory (TN)	139.2	Unsaturated - 1	Silt Loam	0.5	1.3	50	42	1.3 (10) ⁻²	30/50/20/1.5
		Unsaturated - 2	Sandy Loam	3	1.7	37	33	4.6 (10) ⁻³	60/25/15/0.3
		Unsaturated - 3	Silt Loam	0.5	1.3	42	30	1.9 (10) ⁻²	35/50/15/2.0
Y-12 Site, E. Fork		Unsaturated - 4	Clay Loam	4	1.6	45	40	3.6 (10) ⁻³	30/40/30/0.1
Poplar Creek/Bear Creek Drainages		Saturated - 1	Clay Loam	2	2.6	20			30/40/30/0.1
Paducah Gaseous Diffusion Plant (KY)	119.1	Unsaturated - 1	Silt	5	1.4	40	28	9.9 (10) ⁻⁷	15/55/30/0.05
		Unsaturated - 2	Sand	5	1.8	30	10	1.5 (10) ⁻⁵	75/15/10/0.05
		Unsaturated - 3	Clay	5	1.6	40	28	9.9 (10) ⁻⁸	15/35/50/0.05
		Saturated - 1	Loamy Clay	12	1.8	30			80/15/5/0.05
Portsmouth Gaseous Diffusion Plant (OH)		Unsaturated - 1	Silty Clay	5	1.7	40	40	8.1 (10) ⁻⁸	8/44/48/2.5
		Unsaturated - 2	Silty Clay	2	1.4	39	38	1.5 (10) ⁻⁶	12/50/38/1.1
		Saturated - 1	Loam	1	1.7	42			84/12/4/0
			Loamy Sand						
Rocky Flats Plant	48.7	Unsaturated - 1	Sandy Clay	5	1.8	30	10	1.6 (10) ⁻⁴	50/8/42/0
		Saturated - 1	Sandy Clay	3	1.8	30			50/8/42/0
Rocky Flats Alluvium									
Rocky Flats Plant	48.7	Unsaturated - 1	Sandy Clay	2	1.8	30	10	2.5 (10) ⁻⁴	50/8/42/0
		Saturated - 1	Sand	2	1.8	30			95/3/2/0
Colluvium									
Rocky Flats Plant	48.7	Saturated - 1	Sand	2	1.8	30			95/3/2/0
Woman's Creek Drainage									
Rocky Flats Plant	48.7	Saturated - 1	Sand	4	1.8	30			95/3/2/0
Walnut Creek Drainage									

(a) Based on ongoing environmental characterization work conducted by PNL for the Programmatic Environmental Impact Statement project.

If the matrix is buried waste, installation of a reliable cap to prevent surface water infiltration may not be practical if the waste contains voids susceptible to collapse or subsidence over the life span of the cap, causing it to deform and subsequently crack. In this case, it may be more practical to install a sorbent barrier beneath the site to contain the contaminants while allowing surface water to infiltrate the barrier.

3.1.2.2 Site Topography

Site topography can be an important issue in the installation of certain barriers. For example, slurry walls need to be staged if they slope down a grade; otherwise, the slurry would flow out of the trench. Similarly, a cap located on a hill must consider water running downhill onto the cap.

3.1.2.3 Weather

Weather can be a very important consideration in the design of a barrier. The amount and form (snow or rain) of annual precipitation and the timing can directly affect site water infiltration rates and transpiration rates (due to seasonal temperature and vegetation) that, in turn, affect water inventory in the vadose zone. These factors then affect the materials used in the construction of a cap or vertical barrier in the vadose soils. For example, in arid climates, soil water inventory can be relatively low, which is undesirable for a barrier relying on water-saturated clay for hydraulic containment, because the clay may shrink as it loses water to the surrounding soil and cause cracks to appear in the barrier. Wind and flooding can also affect the designs by placing special requirements on erosion control. As shown in Table 3.1, the annual rainfall varies from about 16 cm to as much as 139 cm at DOE sites.

3.1.2.4 Space for Equipment and Spoils Management

Space at the site for the location and movement of equipment as well as for spoils management can become an issue in the feasibility of certain barrier designs. For example, slurry walls using soil-bentonite mixtures need a staging area for receiving soil and mixing it with bentonite. If this space is not available, another material will be required. Similarly, if the area where the barrier is to be installed has a limited load-bearing capacity due to buried tanks or other features, either special arrangements for access and installation of the barrier may be required, or the barrier may need to be located farther away.

3.1.3 Performance Verification

There are two overriding issues determining the performance of a specific barrier: 1) the ability to install a tight barrier consistent with the containment requirements and 2) the ability to maintain performance over the design life span for the barrier.

Barrier integrity must consider two factors, water transport and contaminant diffusion. Barrier integrity is considered primarily by its ability to impede water flow, particularly if the water is contaminated. There are several parameters that must be considered in assessing the hydraulic integrity of a constructed barrier: intrinsic hydraulic conductivity; tightness of joints; and continuity of macropores, fissures, and cracks through the barrier. Liquid and gas phase contaminant diffusion can

also become important transport mechanisms in certain applications, even though the barrier is hydraulically sound. In these cases, knowledge about the diffusion and adsorption properties of the barrier materials need to be assessed.

Two major factors affecting the long-term performance of constructed barriers are resistance to crack formation and propagation and resistance to degradation due to contaminants and soil constituents. The applicability and performance of different barriers also depend on the type, combination, and concentration of contaminants that may contact the barrier.

Performance verification is an issue because verification often cannot be determined during installation of the barrier, but eventually must be determined after the barrier has been installed. Thus, indirect techniques must be applied for verifying performance. Furthermore, in those cases where the extent of the barrier is large, it may be necessary to make assumptions on the uniformity of the barrier in assessing its integrity.

Performance verification also becomes an important issue if the barrier is to perform over a long period of time. Long-term monitoring is necessary to ensure that the barrier performs as designed and to detect the need for barrier maintenance. However, long-term monitoring adds to the total cost of the barrier.

3.1.4 Life-cycle Cost

Life-cycle costs must be applied to a barrier to assess its true cost in comparison with other alternatives. These costs can be roughly divided into initial barrier cost, regular operating costs, and periodic maintenance costs. The relative contribution of each category depends both on the design and life span of the containment measure. For proper comparison, all barrier elements in an integrated design, such as cap, vertical or angled barrier, and/or bottom sealing barrier elements, must be considered.

Initial costs can be divided into materials of construction and installation. The cost of materials depends both on the unit cost and on quantity. Unit costs (EPA 1985) for various grout and slurry wall materials range from about \$1/gal to \$4/gal (1985 dollars) for inorganic materials (cement, bentonite, and silicate material) to about \$8/gal to \$40/gal (1985 dollars) for organic materials (epoxy, acrylamide, and urea formaldehyde). The quantities required for these materials are dictated by the ratio of reagents to inert solids, such as soil, and the dimensions of the barrier. For example, slurry walls are typically 3 ft wide. Installation costs depend on several activities, including site preparation, equipment setup, excavation and installation, spoils management and/or disposal, and site cleanup.

Regular operating costs are those costs associated with monitoring the barrier and, if needed, water management. Any barrier used to contain hazardous materials needs to be equipped with monitoring wells to verify performance of the barrier over its lifetime. These wells are located either immediately outside the barrier to detect contaminant leakage or inside the barrier to measure water infiltration. In those cases where the barrier cannot completely stop water infiltration, it may be necessary to pump water from inside the barrier to minimize leaching of the contaminants.

Periodic maintenance costs are those costs incurred generally for both scheduled and unscheduled barrier maintenance. Scheduled maintenance includes maintenance of monitoring wells and equipment, extraction pumps (if they are used), and in certain cases replacement of barrier materials if they are used to adsorb contaminants. Unscheduled maintenance occurs when monitoring equipment indicates degraded barrier performance.

By knowing the life-cycle cost of various barrier designs for a specific site application, it is easy to assess those designs that are less costly and to make comparisons with other remediation alternatives involving treatment. However, it is difficult to obtain sufficient information on the life-cycle costs for barriers because the design life span is not certain, and most cost estimates are limited to the installation of individual barriers. Table 3.2 summarizes the range of cost estimates for installing various barriers. Some of these estimates may or may not include overhead costs and/or contingencies, and are based on original data that are as much as 10 years old. However, the data in the table do provide an indication of the expected costs and a relative comparison of barriers with similar function. In evaluating the various cost estimates it was apparent that common parameters such as material costs, barrier thickness, or the scale of application did not show any clear trend and that site-specific factors likely had a major influence on the cost ranges. Thus, it is not possible to apply generalizations regarding the cost comparisons among various containment and treatment alternatives that do not consider specific geology of a waste site and the geometry of the contaminated matrix.

One of the most important considerations for comparing containment and treatment options is that treatment costs depend directly on the (three-dimensional) volume of material to be treated, and containment costs depend on the (two-dimensional) area surrounding the contaminated zone (perimeter length and depth of the contaminated zone). Tables 3.3 and 3.4 provide a rough guide on the effect of the geometry of the waste site on the cost of the various barriers. Table 3.3 shows the relationship between the site perimeter and the areal surface area of the site and the unit cost (\$/yd³ soil) for containing the soil inside the barrier. Also shown in the table are the corresponding areal surface areas that would produce specific ratios assuming that the site was either square or circular in shape. The table shows that the perimeter-to-areal-surface ratio has a direct effect on the cost of containment. It also suggests that containment costs on a unit-volume-of-ground-contained basis becomes insignificant for most barrier designs for sites of a few acres.

Table 3.4 shows the relationship between the unit cost of a floor or a cap (\$/ft² of barrier surface) and the unit cost of containing contaminated soil distributed from the surface to a range of depths (\$/yd³ soil). This table shows that as the depth of contamination increases, the unit cost (\$/yd³ soil) for containing the soil decreases. For contamination depths greater than about 30 ft, the cost of a relatively expensive Hanford engineered cap at \$23/ft² and a floor costing \$20/ft² would produce a containment cost of about \$21/yd³ and \$18/yd³ of soil, respectively. If this cap covered a circular site of 11.54 acres (from Table 3.3), then adding a slurry wall, at \$10/ft² (from Table 3.4), would produce a total containment cost of approximately \$40/ft³ of soil contained. This is a relatively modest cost.

Table 3.2. Summary of Estimated Costs for Containment Methods

Method	Estimated Cost Range (\$/ft ²) (1992 Dollars) ^(a)	Reference
Cap		
RCRA Cap	6.5	EPA (1985)
Hanford Engineered Cap	23.0 ^(b)	
Vertical Barriers		
Bentonite Slurry Wall	2.50 - 10.00	Yang et al. (1987) Spooner, Wetzel, and Grube (1982) SCS Engineers (1986)
Grout Curtain		
Permeation Grouting	14.5 - 95.5	Yang et al. (1987)
Deep Soil Mixing	17.0 - 30.0 ^(c)	EPA (1990b)
Vibrating Beam	8.0 - 18.0	Yang et al. (1987)
Sheet Piling	7.5 - 21.5	EPA (1985) Yang et al. (1987)
Frozen Soil Barrier	4.5 ^(d)	Sullivan, Lynch, and Iskandar (1984)
Vitrified Soil Barrier	27.5 - 37.5 ^(e)	EPA (1985)
Floor		
Permeation Grouting	11.5 - 148.0	Yang et al. (1987)

(a) All costs corrected to 1992 using a 2.5% annual inflation rate, and rounded to nearest half dollar.

(b) Unpublished estimate of cost.

(c) Barrier cost estimated from cost for in situ fixation application.

(d) Cost does not include estimated annual cost of \$4/yr/ft² to maintain the frozen barrier.

(e) Barrier cost estimated from cost for in situ vitrification application.

3.1.5 Institutional Criteria

Institutional criteria are more qualitative in their influence on the applicability of a particular barrier. These criteria include short- and long-term health and safety concerns, public acceptance, and permitability. Short-term health and safety concerns can be important during the installation of a barrier if excavation spoils are contaminated. Measures may be required to protect workers and to prevent these spoils from moving offsite by wind or water erosion.

Table 3.3. Calculation of Containment Costs for Vertical Cut-off Walls

	Perimeter/Areal Surface Ratio, 1/ft				
	0.1	0.05	0.01	0.005	0.001
	Acreage				
Square Geometry	0.04	0.15	3.67	14.69	367.31
Circular Geometry	0.03	0.12	2.88	11.54	288.48
Barrier Cost, \$/ft ²	Containment Cost, \$/yd ³				
1	\$2.70	\$1.35	\$0.27	\$0.14	\$0.03
5	\$13.50	\$6.75	\$1.35	\$0.68	\$0.14
10	\$27.00	\$13.50	\$2.70	\$1.35	\$0.27
15	\$40.50	\$20.25	\$4.05	\$2.03	\$0.41
20	\$54.00	\$27.00	\$5.40	\$2.70	\$0.54
30	\$81.00	\$40.50	\$8.10	\$4.05	\$0.81
50	\$135.00	\$67.50	\$13.50	\$6.75	\$1.35
75	\$202.50	\$101.25	\$20.25	\$10.13	\$2.03
100	\$270.00	\$135.00	\$27.00	\$13.50	\$2.70
150	\$405.00	\$202.50	\$40.50	\$20.25	\$4.05

Assumptions: Soil containment costs do not differentiate between clean and contaminated soil inside barrier.

Table 3.4. Calculation of Containment Costs for Caps or Floors

Barrier Cost		Depth of Soil Contained, ft				
		10	20	30	40	50
\$/ft ²	\$/acre	Containment Cost, \$/yd				
1	\$43,560	2.70	1.35	0.90	0.68	0.54
5	\$217,800	13.50	6.75	4.50	3.38	2.7
10	\$435,600	27.00	13.50	9.00	6.75	5.4
15	\$653,400	40.50	20.25	13.50	10.13	8.1
20	\$871,200	54.00	27.00	18.00	13.50	10.8
30	\$1,306,800	81.00	40.50	27.00	20.25	16.2
50	\$2,178,000	135.00	67.50	45.00	33.75	27
75	\$3,267,000	202.50	101.25	67.50	50.63	40.5
100	\$4,356,000	270.00	135.00	90.00	67.50	54
125	\$5,445,000	337.50	168.75	112.50	84.38	67.5

Assumptions: Soil capping costs do not differentiate between clean and contaminated soil underneath cap.

Long-term health and safety relate primarily to the risk imposed on the public and environment by the contaminants once the barrier is in place, as well as the potential release of toxic barrier constituents if they are used. Short- and long-term health and safety risks are addressed in characterization studies of the waste, leachate, barrier material chemistry, and site geochemistry as called for in EPA guidance documents (Siskind and Heiser 1993). Public acceptance, on the other hand, often relates more to perceived risk than actual risk. Barriers have been specified in prior RODs as part of the remedial action. Finally, permitability can become an issue if certain laws prevent installation. Some examples of laws that can affect permitability are those dealing with flood plains, geologic faults, and historic artifacts preservation.

3.2 Containment Technology Status and Gaps

While containment barrier technology has been fairly well developed for industrial applications such as construction and mining, its adaptation to hazardous waste has not been fully realized, except in a few cases. The presence of contaminants places much greater constraints on water migration rates. Also, the financial risk can be a drawback because there is considerable reluctance to demonstrate an unproven application of containment when there are other proven remedial action strategies available. The purpose of this section is to give a more global perspective to the main configurations of containment in terms of function (i.e., caps, lateral migration containment, floors, and sorbent barriers), breadth of potential application, and limitations offered by the application of available and developing technologies; and to identify the status of development and/or adaptation of key elements of design and installation for these applications.

3.2.1 Caps

3.2.1.1 Proven Technology

At the present time the baseline standard for cap construction are the RCRA cap design criteria. A key element in this set of criteria is that any cap to be used in an application regulated by RCRA demonstrate equivalency to EPA's RCRA design regardless of the design used. This places considerable burden on the validation of engineered designs that do not follow the EPA's guidance for constructing a RCRA cap, even for those circumstances where the RCRA cap design guidance is not well matched to the site characteristics. Thus, the driving force for cap construction is toward accepted design and construction practices regardless of the consequences, rather than towards a truly optimized barrier.

3.2.1.2 Technology Gaps

One of the principal gaps in cap technology relates to the practicality of achieving a good match of the cap design to the site characteristics and remediation objectives. There is growing concern that RCRA caps are not always maintaining their performance specifications for their required 30-year life span. It has been noted that both animal burrowing and root penetration are failure mechanisms that must be fully appreciated in designing a cap (Ely et al. 1982; Sutter, Luxmoore, and Smith 1993). Cracking in clay liners that has occurred due to desiccation is another possible failure mechanism for caps that needs to be better understood in arid soils, where the average soil moisture is much lower

than that in a newly installed clay liner. Additional research is needed in understanding all of the mechanisms that can lead to cap failure over various time periods, and in the context of key site characteristics.

Achievement of cap design properties in the field and verification of those properties are two key gaps in the technology, particularly in regards to water management. One area that has received some attention is the effect of field installation of clay layers on the permeability of the clay. Common engineering practice has been the sequential layering of clay, called lifts, until the desired thickness is obtained. What was not fully appreciated was that the lateral transport of water between the lifts could be substantial. As a result, the water is free to seek the most permeable path through the next lower layer. The increased connectivity of flow paths offered by the interface produces a much greater effective permeability of the clay than would be calculated from a single lift.

Verification of Performance. Compacted clay layers are an important component of the currently accepted cap design. For these layers, quality control is critical if the performance standard of 10^{-7} cm/sec is to be met. What has not been clearly resolved is how to verify that the large areal extent of a compacted layer meets the standard. The same question applies to any natural material used as part of the cap and having to meet some performance standard. Natural materials have a variability of properties that are difficult to characterize, let alone ensure that they meet a performance standard.

Because their manufactured quality can be controlled, manmade alternate barriers (e.g., clay blankets) are factored into many cap designs. However, the in situ performance of these barriers remains to be demonstrated (Daniel and Estornell 1990). Furthermore, the longevity of these barriers must be demonstrated for the design life of the caps, which may exceed 1000 years for some DOE applications. Although 1000-year tests cannot be performed, alternative tests must be devised and performed to credibly demonstrate that these barriers can survive and function for 1000 years.

In the final analysis, the performance of a cap reflects the integrated performance of its various components. The only way to judge integrated performance is to test full-scale caps. Case studies of actual waste site caps (Ely et al. 1983) demonstrate the value in monitoring complete cover systems. Instrumented field tests like those in Germany and in the U.S. (Utah and Washington) are expected to provide performance data on a level rarely seen. The results generated can then be used to update and improve cap designs.

While individual components might be rated for longevity, it remains to be shown how the cap, which is the integration of the components, will fare. Monitoring schemes to track performance of caps are needed for as long as capping is considered an acceptable option for waste disposal sites. Caps that are representative of each of the major designs can be chosen for long-term monitoring. Measurement types and frequency should be chosen to guarantee useful conclusions regarding performance 10, 20, even 30 years following construction. Furthermore, such data can be used to evaluate conceptual models and validate their usefulness, in some cases even driving modeling changes (e.g., Nyhan 1989; Fayer, Rockhold, and Campbell 1992).

Equivalency Demonstration. Given the rapid changes in technology, there is every reason to expect that better cap designs will emerge in the years ahead. An important need is to demonstrate that these newer designs are as good as or better than the EPA standards, i.e., demonstrate RCRA equivalency. Acceptable methods are needed to accomplish such a demonstration.

The need exists to facilitate the exchange of cap information across agencies such as EPA, DOE, and the U.S. Nuclear Regulatory Commission (NRC). These agencies all have a stake in the design and construction of caps that meet their performance objectives. To be successful and cost effective, cap designs must incorporate the latest information. Perhaps a lead role for one of the agencies would bring some continuity to the development and verification of acceptable cap systems. Whatever entity takes on the coordinating role, it should quickly establish ties with the cap development activities of the international community. Finally, the envisioned coordinating agency could maintain a clearinghouse of current news on development issues, construction lessons, and field observations. For example, word-of-mouth information gives a RCRA-cap failure rate of one per month, but no documentation appears available to substantiate that claim. The task of disseminating the latest news on caps could be handled as a newsletter or electronic bulletin board.

3.2.1.3 Ongoing R&D

DOE has two major ongoing programs involving caps. These caps are fully instrumented and should provide the type of data needed to gauge the true performance of caps. If monitored for more than 3 years, these instrumented caps should begin yielding data on the maturation of caps that should improve our confidence in their long-term performance.

Pacific Northwest Laboratory and Westinghouse Hanford Company are engaged in a program to develop and demonstrate a full profile cap for long-term containment of waste at Hanford Site. This program, which was initiated in FY 1986, has involved the systematic testing and evaluation of various cap materials and material combinations for infiltration, biointrusion, and wind and water erosion control, with the object of designing a cap that will last for 1000 years. A full-scale protective barrier cap (footprint area roughly 2.5 ha) that is based on these results is scheduled for construction in the spring of 1994 at the Hanford Site, Richland, Washington (Wing 1993). The cap will be monitored to verify performance under field conditions. This activity is part of a treatability study for the 200-BP1 operable unit at the Hanford Site.

Los Alamos National Laboratory is conducting follow-on research at Hill Air Force Base in Ogden, Utah, to evaluate the hydrologic performance of four cap designs. This program has been in progress since January 1990, originally funded by the United States Air Force. The cap designs (each with an area roughly 4.6 by 9.8 m) include a RCRA cap, two capillary barrier designs, and a conventional soil cap. The results of this research will be used to recommend cap designs to demonstrate at the Mixed Waste Landfill Integrated Demonstration at Sandia National Laboratory. It is anticipated that this program will include the full-profile cap being developed at Hanford in order to evaluate the effect of the rainfall profile on the cap performance of this design.

DOE is also conducting a study at Sandia National Laboratory to investigate the lateral migration of water in unsaturated soil underneath a cap. The main concern is that strong capillary pressure gradients in highly stratified heterogeneous dry sediments can cause significant lateral migration from

the outer margins of the cap. This, in turn, could create a condition in which the water inventory underneath the cap is much greater than expected and thus defeats the purpose of the cap to control water infiltration.

Successful application of the results of DOE's ongoing R&D will still require a rigorous assessment for any resulting designs proposed for full-scale field demonstration to prove equivalency to the RCRA design. Ultimately, it will also be necessary to perform similar assessments that project performance for time periods up to 1000 years to gain public acceptance of caps for long-term containment.

3.2.2 Vertical and Angled Containment Barriers

3.2.2.1 Proven Methods for Containing Contaminated Soil and Groundwater

Certain methods proven for hydraulic containment in construction and mining applications appear to be attractive in a number of hazardous waste containment applications. Some examples are slurry and sheet piling cut-off walls and grout cut-off walls installed using vibrated beam and deep-soil mixing techniques.

Slurry walls constructed using soil-bentonite mixtures are considered by industry to be relatively low-cost, high-performance hydraulic barriers that can be installed with a fairly high degree of certainty regarding the expected performance. However, slurry walls constructed using cement-bentonite mixtures are not considered to be a suitable variation of this technology for hazardous waste applications.

Slurry cut-off walls warrant serious consideration at those sites where they can be applied. The barriers have excellent hydraulic properties, good quality control during installation, and have been used in construction applications for both short- and long-term groundwater management. Slurry walls can be readily integrated with other forms of containment, including caps and floors.

Slurry walls are not practical under conditions of sloped topography, unavailability of suitable soil or nearby bentonite sources, and inadequate space for mixing the soil and bentonite. In addition, the construction technique requires excavation of the soil that presents a short-term health and safety risks, and some of the soil may require treatment and/or disposal.

In most applications where slurry walls are not considered applicable because of topography and/or availability of space, grout-cut-off walls constructed using deep soil mixing offer comparable performance. Jet grouting using soil-cement grout mixtures appears to be another technique for forming grout cut-off walls with reportedly comparable hydraulic properties to soil-bentonite slurry walls. However, this newer method is not as proven as deep soil mixing. At the present time, permeation grouting of unconsolidated soils does not appear to merit further consideration, as it routinely produces an inferior barrier and is costly to install.

3.2.2.2 Technology Gaps

All of the above barriers appear to be suitable for containing groundwater, over life spans ranging from a few months to many years. Each can be readily integrated with caps and floors, and are generally tolerant of dilute concentrations ($< 1\%$ by volume) of most organic and inorganic contaminants. However, special instances exist where the barriers have not been proven reliable:

- permanent containment (> 300 years)
- elimination of excavation spoils during installation that could pose a safety and health risk
- containment of soil flushing solutions during in situ treatment
- scenarios requiring barrier removal.

In addition, barrier technology has not been proven for containment applications in vadose zones:

- intermediate to long-term containment of contaminants in vadose zone soils
- containment of gas phase transport of VOCs in vadose soils.

Technology needs of the bulleted items are discussed in the following sections.

Permanent Containment. Permanent containment of contaminated soils and sediments is an attractive option for many DOE sites, where the areal extent of the contamination is large but at relatively low levels. In these circumstances, containment and/or in situ immobilization of the contaminants may be more cost effective than treatment requiring excavation of soils or extraction of groundwater. While all of the proven vertical barriers discussed above appear to be capable of long-term containment, and many have been successfully used in dam construction, there has been no concerted effort to validate them for permanency on the order of hundreds to thousands of years as might be required for containment of radionuclides.

Elimination of Excavation Spoils. Many of the proven methods for installing lateral containment barriers require soil removal during installation. In the case of slurry walls, this quantity of soil can be substantial since the walls are typically 3 ft wide and can be up to hundreds of feet deep. Jet grouting and deep soil mixing produce spoils from both borehole drilling and displacement of soil during the mixing of grout and soil. Deep soil mixing, for example, increases the volume of treated soil by about 8.5% (EPA 1990b).

Spoils produced from permeation grouting are limited to the amount produced during borehole drilling. However, the spoils produced from drilling boreholes can produce a significant safety and health hazard if the soils contain radionuclides. Thus, techniques that further minimize spoils generation by reducing the number of boreholes required for permeation grouting could improve short-term health and safety and reduce remediation costs incurred by the need to treat and dispose of the spoils.

Some of the installation methods can eliminate the generation of contaminated spoils. Both steel sheet piling and grout installed using the vibrating beam technique can be installed without generating spoils for shallow barrier applications in unconsolidated soil. Neither method is suitable in soils containing large cobbles and boulders that can deflect the sheet piles or vibrating beam, resulting in

poor joints. While both are proven technologies, neither has undergone sufficient demonstration to verify their reliability of proper installation and performance in hazardous and mixed waste applications.

Vitrified barriers are an unproven, but potentially attractive, concept that eliminates spoils generation and would work in vadose zone soils. The concept is based on ISV technology currently in the demonstration stage of development. However, there are a number of issues that need to be addressed and resolved if ISV is to be adapted for the generation of subsurface barriers. One issue is the depth that a barrier can reach. The maximum depth demonstrated by the ISV process is 5.8 m. To generate a vertical barrier wall using ISV (with two or more electrodes in a linear array), a substantial increase in this depth capability may be possible.

Research efforts are currently focused on increasing ISV depth through a variety of modifications to the equipment and process. The engineering-scale ISV barrier experiments showed that an enhanced melt rate can be achieved, thereby limiting outward melt growth and resulting in a relatively planar vertical vitrified structure. Numerical modeling of this technique shows that it significantly increases the heat transfer through the bottom of the melt into the soil below at the expense of heat transfer through the sides of the melt into surrounding soil. However, it is currently unknown if this method, or others in concert, are sufficient to increase the melt depth in the field by a factor of 2 or more.

A second issue is whether underground startup is feasible at full scale. While the capability to generate a subsurface melt has been demonstrated in the laboratory, it has not yet been attempted in the field. Horizontal drilling technology is offered by a variety of vendors and is increasing in its use in supporting a variety of waste remediation activities (EPA 1991). It is believed that the horizontal drilling technology has the capability to accurately deliver the required starter path material to a desired subsurface location. It will be necessary to link the horizontal drilling technology with the ISV technology in the field in order to initiate and maintain a subsurface melt at the target location.

Research is also needed to determine the porosity and hydraulic conductivity of the vitrified soil in a barrier configuration. However, geologic analogs such as dense and vesicular basalts and obsidian suggest that ISV barriers will have very favorable properties compared with other constructed barriers.

Containment of Concentrated Chemical Solutions. While the proven barriers are expected to handle contaminated groundwater containing trace quantities of various contaminants without degrading the barrier, it has not been demonstrated that they can stand up to concentrated chemical solutions, such as those generated by in situ soil flushing.

There has been a considerable amount of research on the performance of certain barrier materials used as impermeable liners in landfill applications. This data base needs to be extended to the above applications and in the context of specific contaminants of concern to DOE.

Scenarios Requiring Barrier Removal. For most containment applications involving temporary or interim containment, a barrier can be left in place after it is no longer needed, provided it does not adversely affect water flow in the soil and sediment. However, in some circumstances, leaving a barrier in place may not be desirable. For example, both a vertical barrier and floor left in place

following an in situ treatment may form a basin that could fill with water, eventually forming a surface body of contaminated water. A better method would be to use barriers that can be removed or otherwise altered over the long term. Frozen soil cut-off walls appear to be suitable but have not been proven as a containment barrier for contaminated soil and have not been used in conjunction with in situ treatment technologies. Biodegradable barrier materials, such as the biopolymer slurry used in excavation, may also fit this application, but additional research is needed. Finally, methods for permanently fracturing more conventional barriers also need to be investigated as a possible alternative.

Intermediate to Long-Term Containment of Contaminants in Vadose Zone Soils. All proven vertical barriers are currently used to control groundwater. Thus, the portion of the barrier that performs the containment function is in the ground, saturated with water; and the materials used in these barriers generally are inorganic materials, such as bentonite, that derive important characteristics from being fully hydrated.

When barriers are used for containment in vadose zone soils, the surrounding unsaturated soil may wick water from the barrier, particularly near the soil surface where the amount of soil moisture approaches zero. A limited amount of research has shown that caps consisting of clays can be subject to drying out and increased susceptibility to cracking under deformation forces near surface (Corser, Pellicer, and Cranston 1992; Sutter, Luxmoore, and Smith 1993). In principle, the same phenomenon will apply to vertical barriers in the same soil. Information is needed to assess the long-term durability of vertical barriers consisting of clay or other materials that depend on water for their properties. Research is also needed to identify and validate the long-term performance of barrier materials composed of natural and synthetic organic polymer materials that do not require water for their properties.

Containment of Gas Phase Transport of Volatile Organic Compounds in Vadose Soils. All proven applications of vertical barriers for hazardous waste are limited to containment of leachate and contaminated groundwater. The only known proven application of barriers to gases is in the containment of methane from landfill sites. However, in this application, the methane is in relatively large concentrations and the gas is collected at a vent within the barrier system. Furthermore, methane is a very light gas with a maximum solubility of about 40 ppm in water at standard temperature and pressure.

Many hazardous waste sites contain VOCs, including fuel hydrocarbons and chlorinated solvents. An important soil transport mechanism for these compounds is in the gas phase, albeit at very low partial pressures.

It is also a significant transport mechanism for water in vadose zone soils. These vapors can migrate in any direction since the effects of gravity are minimal. Research is needed to better define the gas phase transport mechanism for VOCs of interest to DOE to quantify this transport mechanism and to determine mitigation strategies for this form of migration. This research needs to assess the ability of various barrier materials to reduce gas phase diffusion rates from a site and to demonstrate the performance of vertical barriers in combination with other containment measures to contain VOCs over a long period of time.

3.2.2.3 Ongoing R&D

Neither DOE nor EPA has been very active in the development of vertical barriers, partly because several types of barriers for containing groundwater are commercially available, and certain types, most notably slurry walls, have been selected in RODs as a part of a remedial action. However, most of the barrier types have not been proven in the field for containment of contaminated groundwater or for containment of contaminated vadose zone soil, particularly at arid sites. The main area of research sponsored by DOE has been in evaluating new grout materials that are capable of achieving greater performance for grout barriers.

Sandia National Laboratory is conducting research to evaluate two grout materials being developed in Europe for in situ barrier construction. The grouts are composed of a bentonite clay/natural paraffin mixture developed by German companies and an inorganic grout developed by a French company. The two materials will be evaluated under a range of soil conditions found at DOE sites. Tests will be conducted to resolve questions concerning the compatibility of the barrier materials and anticipated waste forms, the ability to construct a barrier that is laterally extensive, and the physical and hydraulic integrity of the barrier.

Brookhaven National Laboratory is conducting research to identify the regulatory issues, drivers, and key assumptions associated with aspects of barrier installation. Specific barrier materials will be developed and tested for durability: permeability to water; ionic diffusivity; wet/dry cycling; freeze/thaw cycling; and chemical resistivity to acid, base, and solvent conditions under typical waste site conditions. All formulations will be capable of being placed as vertical barriers through conventional construction methods to depths of at least 20 ft.

In a study on different materials, Lawrence Berkeley Laboratory is conducting research to identify and evaluate liquids with temperature-dependent viscosity and sets of two fluids which, when mixed and heated to a desired temperature, create nearly inert impermeable materials that solidify at average aquifer temperatures. The ability of these substances to provide an effective containment of the contaminated zone by entrapping and immobilizing both the contaminant source (if any) and the plume will be investigated. The containment ability of this approach will be evaluated by means of numerical simulation, large-scale laboratory experimentation, and field testing/demonstration.

Barrier materials being developed by DOE are oriented primarily to permeation grouting and vibrating beam installation of grout barriers. The integration of these techniques and materials will need to be demonstrated at one of DOE's Integrated Demonstration sites.

3.2.3 Floors

3.2.3.1 Proven Technology

The state-of-the-art of floors is considered proven for certain applications that do not involve hazardous waste containment. However, the state-of-the-art of floors for hazardous waste containment is not considered to be proven at this time for any application, regardless of the design life span.

In nonhazardous applications, floors, also called blankets, have been installed using permeation grouting techniques in dam construction to impede water flow under a dam where the bedrock has an unacceptably high permeability, and to connect cut-off walls in dams to suitable bedrock that is not located immediately below the cut-off wall. Other techniques for installing floors have been commercially applied in mining applications, although not necessarily for hydraulic containment. These technologies include kerfing, long-wall mining, horizontal drilling, and hydraulic fracturing.

3.2.3.2 Technology Gaps

The main technology gap for floors for hazardous waste containment applications is that no single technique has been demonstrated to consistently produce a reliable flawless barrier. Furthermore, there are no reliable techniques for verifying proper installation of floors. Another technology gap is that the resistance of floor materials to concentrated chemicals has not been demonstrated. Technology gaps also exist for installing temporary barriers for scenarios requiring barrier removal and for containment of gas phase transport of VOCs in vadose soils.

Reliable Installation Methods. Further development is needed to improve the reliability of installing floors suitable for hazardous waste applications. At this time, all techniques except long-wall mining warrant further investigation along with techniques for general sealing of a floor to eliminate flaws.

Verification of Performance. Short of performing a hydrostatic pressure test, no reliable method appears to be available for verifying proper installation of a floor. The main deficiency in alternative methods is that they are not sufficiently sensitive to identify the location and/magnitude of a flaw that may create unacceptable performance. Research is needed to develop more sensitive techniques for verifying proper installation.

Resistance to Concentrated Chemicals. Floors will almost always be used when there is a potential for contact with concentrated leachate. However, it has not been demonstrated whether materials used to construct floors can stand up to concentrated chemical solutions. There has been a considerable amount of research on the performance of certain barrier materials used as impermeable liners in landfill applications that provides a good indication of how various barrier materials will perform under these conditions. This data base needs to be extended to the above applications and in the context of specific contaminants of concern to DOE.

Scenarios Requiring Barrier Removal. As discussed earlier, it may be desirable to use barriers that can be removed or otherwise altered to defeat their function over the long term. Angled frozen soil cut-off walls appear to fit this criterion very well. However, frozen soil cut-off walls have not been proven as a containment barrier for contaminated soil, and have not been used in conjunction with in situ treatment technologies. Biodegradable barrier materials such as the biopolymer slurry used in excavation may also fit this application, but additional research is needed. Finally, methods for permanently fracturing more conventional barriers also need to be investigated as a possible alternative.

Containment of Gas Phase Transport of VOCs in Vadose Soils. As already discussed, many hazardous waste sites contain VOCs, including fuel hydrocarbons and chlorinated solvents. An important soil transport mechanism for these compounds is in the gas phase, albeit at very low partial

pressures. It is also a significant transport mechanism for water in vadose zone soils. These vapors can migrate in any direction since the effects of gravity are minimal. Research is needed to better define the gas phase transport mechanism for VOCs of interest to DOE, to quantify this transport mechanism, and to determine mitigation strategies for this form of migration. This research needs to assess the ability of various barrier materials to reduce gas phase diffusion rates from a site and to demonstrate the performance of floors in combination with other containment measures to contain VOCs over a long period of time.

3.2.3.3 Ongoing R&D

The development of technologies for placing floors in situ is receiving only peripheral support by DOE. The main areas of activity are in the development of horizontal drilling techniques that can be used for a number of applications, including soil gas extraction, soil flushing, and the placing of floors via permeation grouting. EPA does not have an active program in the development of floors. However, EPA is sponsoring research on hydraulic fracturing for soil gas extraction applications.

3.2.4 Sorbent Barriers

3.2.4.1 Proven Technology

Sorbent barriers are an innovative containment technology for retarding the migration of contaminants while allowing for the normal flow of groundwater through the barrier. Sorbents have been used to a very limited extent in immobilizing organic contamination in surface soils in which sorbent materials are tilled into the soil (Sims and Bass 1984). The application of subsurface barriers had not progressed beyond bench- and pilot-scale as of early 1990 (EPA 1990a).

3.2.4.2 Technology Gaps

Sorbent barrier technology has progressed very little past the concept stage for hazardous waste containment. There are two applications of sorbents in barriers that dictate technology needs: hydraulic barriers and permeable barriers. Coupled to both applications is the need for more data on the physical and chemical behavior of various combinations of sorbent materials that directly impact design parameters for barriers incorporating these materials. Also, the methods for installing and maintaining sorbent barriers and their associated costs are important issues that need to be developed.

Sorbent Material Behavior. An important gap in sorbent barrier technology is the dearth of data relating sorbent behavior to the contaminants of interest to DOE, in the context of in situ application. A number of sorbents have been developed and tested for treating wastewater containing radionuclides, heavy metals, and/or organic compounds. However, these sorbents were used in ex situ applications where they could be taken off line and replaced or regenerated as frequently as daily. In addition, in most of these studies, the wastewater was much simpler in composition because the water did not contain complex mixtures of contaminants or did not contain common hardwater constituents that would compete for sorption sites on a given sorbent. Furthermore, many of the sorbents evaluated are expensive or otherwise unsuitable for in situ applications. There is a need to both reevaluate sorbents that have been used in ex situ applications, as well as to evaluate low-cost natural sorbent

materials that may be more suitable for in situ applications. These evaluations need to consider not only selectivity and sorption capacity for the desired contaminants but, also, competition of sites for other constituents that may be several orders of magnitude more concentrated. In addition, these sorbents need to be evaluated for resistance to reactions that could lead to degradation of the sorption or hydraulic behavior of the barrier over time.

Performance of Sorbent-impregnated Hydraulic Barriers. There have been some modeling studies conducted that suggest that the addition of sorbents to hydraulic barrier materials can significantly retard the migration of certain contaminants through the barrier, thereby extending the time before breakthrough for the barrier. Research is needed to identify sorbents specific to the contaminants of concern to DOE that are compatible with likely barrier materials, such as cement, bentonite, and silicates.

Permeable Barrier Applications. The design and maintenance of permeable barriers depend on the specific application. However, there are a number of design considerations that can apply to certain classes of applications. Research is needed to identify the likely applications for permeable barriers within the DOE complex in order to determine the categories for designing an R&D program. Examples of applications are: as a secondary barrier underneath an engineered lined disposal trench; as a barrier to a groundwater plume; and as a barrier below a contaminated zone in vadose soil (arid or nonarid sites). This information is needed in conjunction with information on specific sorbent material behaviors to establish the key design parameters that must be met in order to fulfill the desired applications. This information is needed to determine technical feasibility of the concept and to compare alternative approaches to implementing the concept.

Other technology needs closely related to the type of application are the design requirements for installing and maintaining permeable barriers that require periodic replacement to maintain their function. Further development is needed to identify and evaluate different methods for replacing the sorbents in a trench or floor application that minimize cost and exposure to contaminated sorbent materials.

3.2.4.3 Ongoing R&D

DOE is funding two projects to develop sorbent barrier concepts. One of the projects is being conducted by Chem-Nuclear Geotech, Grand Junction, Colorado, to determine the feasibility of injecting a ferric oxyhydroxide colloidal suspension into an aquifer. Ferric oxyhydroxide is a naturally occurring sorbent that has been shown to be effective on contaminants common to DOE sites. The project will involve designing and evaluating a low-cost field demonstration of an in situ permeable treatment system to demonstrate the performance of a ferric-oxyhydroxide-based system to control radionuclide and metal contamination in a groundwater plume. The test will involve the injection of an in situ permeable treatment system containing ferric oxyhydroxide into a contaminated aquifer at a depth of 50 ft.

The second project is being conducted by PNL to develop and determine the effectiveness of 1) hydraulic and diffusion barriers and 2) permeable barriers to be used in vadose or aquifer sediments to minimize contaminant migration. These barriers will be created by mixing chemical reagents directly within the barrier materials or placing a layer of reagents next to the barriers. The

chemical reagents tested will include quaternary alkyl ammonium salts bound by cation exchange to clay, capable of adsorbing uncharged organics such as chlorinated hydrocarbons; hydrotalcite-like minerals for binding anions such as iodide, cyanide, and pertechnetate; and reducing agents such as sodium sulfide and ferrous salts to convert mobile oxyanions and oxycations to immobile reduced forms.

3.2.5 Gravel Layers and Curtains

3.2.5.1 Proven Technology

Gravel layers are often used to drain water either away from or towards certain locations. Gravel drains are often integrated with cut-off walls to prevent buildup of water on the upstream side of the barrier. Gravel has also been used in columns to accelerate vertical drainage of water from the surface.

3.2.5.2 Technology Gaps

Gravel layers and curtains have not been used extensively in hazardous waste applications as a capillary break, which serves as a barrier to water infiltration or lateral migration. This technique needs to be demonstrated to be a viable method for managing water flow in the vadose zone. A key element in verifying performance is demonstrating that the long-term integrity of the gravel-soil interface can be created and maintained. This task may be more difficult to accomplish and/or verify for existing waste sites than for new sites.

3.3 Requirements for Filling Technology Gaps

A number of areas of R&D activities could be used to address the technology gaps identified to date. These areas are discussed in the following sections.

3.3.1 General

In evaluating the state-of-the-art and technology gaps, it is apparent that there are several strategic activities that need to be investigated in order to fully realize the use of containment technologies in remediation of various sites. These activities are general in nature mainly because they apply to more than one area of the technology. These activities are listed below:

- Identify and quantify functional requirements for containment methods for DOE site applications.
 - Identify potential applications and performance requirements for containment.
 - Evaluate available site data for DOE facilities for possible applications.
- Verify ability of containment technologies to meet functional requirements for DOE site applications.

- Integrate R&D involving containment and treatment technologies.
 - Demonstrate adequate hydraulic containment of nonviscous reagents for horizontal floor/vertical wall systems.
 - Demonstrate adequate hydraulic containment of nonviscous reagents for angled barrier technologies.
 - Evaluate containment barrier material compatibility with reagents.
 - Demonstrate removal of excess treatment reagents from ground.
 - Develop concepts to eliminate barrier function following treatment.
- Assess barrier material requirements for containment of concentrated leachate solutions.
- Develop barrier designs for managing gas phase transport of water and VOCs.
 - Conduct transport modeling of key VOCs and water vapor.
 - Validate transport modeling in pilot-scale systems.
 - Evaluate barrier materials and installation methods needed for vapor containment.
- Identify, develop, and assess alternative advanced techniques for in situ verification of proper barrier installation and performance monitoring.
 - Identify and assess existing and potentially applicable methods and instrumentation, including sensitivity requirements.
 - Develop and validate applicable improved methods and instrumentation for detecting flaws in the various barriers.

3.3.2 Cap

It is expected that the primary application of caps at DOE sites will be for long-term containment of contaminated soils and sediments and for capping engineered disposal sites. Accordingly, activities need to be conducted to verify the adequacy of RCRA cap designs for DOE long-term applications, as well as validate alternative designs for RCRA equivalent or more stringent requirements. The following activities are identified for cap technology development:

- Consolidate cap design and performance information of existing caps.
 - Hold a state-of-art conference on cap technology.

- Conduct a technology needs workshop.
- Prepare an in-depth assessment of capping methods.
- Verify RCRA equivalency of integrated cap designs.
- Verify longevity of cap components for periods exceeding RCRA equivalency.
 - Conduct fully instrumented field-scale demonstrations to obtain multi-year performance data.
 - Develop and validate models with field data to predict performance over long time periods.

3.3.3 Vertical and Angled Barriers

Lateral barriers are expected to be used for a variety of applications ranging in life span requirements of a few months to a thousand years, and be used to contain contaminants in either vadose zone or groundwater zone sediments. Some of these applications will require containment of concentrated leachate that may interact with the barrier. Key activities needed to address technology gaps are shown below:

- Verify longevity of alternative designs for groundwater zone applications.
 - slurry wall
 - deep soil mixing
 - vibrated beam
- Develop and verify barriers for long-term vadose soils applications.
 - vitrified barriers
 - asphalt barriers
 - synthetic organic material barriers

3.3.4 Floor

The development of technology for installing floors is considered essential for in situ treatment involving fluid addition to the soil, specifically soil flushing and immobilization using low viscosity grout. In addition, remediation of underground storage tanks that are potential leakers will require the installation of floors before retrieval of tank contents, if the retrieval method involves the addition of fluids to the tanks. In many respects, the technology gaps for floors are the same as those for lateral barriers. However, at the present time, no floor designs are comparable in performance to

lateral barriers. Thus, the level of effort for developing adequate designs is expected to be much greater. The following activities are needed for floors:

- Develop and verify alternative floor containment designs.
 - angled barriers
 - horizontal barriers
- Develop and verify barriers materials for long-term vadose soils applications.

3.3.5 Sorbent Barriers

Sorbent barriers offer a means for improving the ability of a barrier to retard the migration of contaminants to the extent hydraulic containment is less critical. However, sorbent barrier technology has not been sufficiently developed for demonstration. A key gap is a clear understanding of the functional requirements of these barriers for likely applications. Within this understanding is the need to clearly understand the capabilities of various sorbents in a sorbent barrier context, as well as the functional requirements for maintaining the barrier over its design life span. The following activities are identified for addressing these needs:

- Assess sorbent barrier functional requirements for application at DOE sites.
- Assess sorbent barrier material physical and chemical behavior in sorbent barrier applications.
- Develop permeable barrier installation and maintenance designs.
- Develop and verify hydraulic/sorbent barrier designs.

3.3.6 Gravel Layers and Curtains

Gravel layers and curtains are potential components of integrated containment systems involving caps and/or lateral barriers. The main area of uncertainty in the use of gravel is as a capillary barrier. The following activities are considered necessary for addressing technology gaps for this application:

- Develop and verify capillary barrier layer and curtain designs.
- Verify longevity of capillary barriers.

3.3.7 Interfacing Technologies

Two supporting technologies were identified that are considered important to containment technology feasibility and thus warrant investigation. These areas need to be either addressed through experimental research or through careful assessment of ongoing activities:

- Assess technologies for treatment of excavation spoils.
- Verify adequacy of drilling technologies for placing floors and angled barriers using permeation grouting techniques.

3.4 Technology Research and Development Priorities

The priorities for the containment technology subprogram are largely dictated by the lack of information regarding site-specific technology opportunities. In this context, high priority is given to those activities needed to better assess technology opportunities both in regards to site needs and a general broadening of applications. Near-term opportunities for technology development generally lie in supporting the demonstration of those barriers proven for similar applications. These applications generally are for groundwater control and containment of engineered landfills.

Another high priority area is integrating containment with treatment applications. However, this area will require a longer timeline for development. It also has a greater degree of uncertainty of success because certain treatment technologies need some form of floor for containment, but floors are not considered proven at this time.

Another high priority area is the development of containment methods for vadose zones at arid sites. There is a significant need for barriers for this application, but current technology is primarily oriented towards high-moisture-soil containment. Development will require intermediate time periods to develop, but there are several candidate approaches for certain containment elements. For example, advanced cap designs mostly require validation of performance and longevity of design function. Lateral barrier and floor concepts using materials such as asphalt, synthetic organic polymers, and vitrified soil need to be investigated for feasibility for these applications because these materials do not require water to maintain their containment performance. Management of vadose zone water vapor also needs to be better understood for these applications in order to assess performance requirements for the containment systems and to determine whether floors will be necessary for containment systems.

Sorbent barriers and gravel layers and curtains are technology areas that mainly offer improvements to existing containment and in situ treatment strategies. Both are expected to provide significant improvements in technology but are not critical to current containment methods. Research in these areas is considered to be of medium priority and development risk.

High priority is concurrently given to the development and application of techniques that can be used for verifying the performance of barriers. Acceptance of containment for many of the applications contemplated for DOE sites depends on demonstrating, with a high degree of confidence, that current and developing containment methods will perform as expected provided they are properly installed. This demonstration will require both the development and application of performance models that account for all important parameters affecting performance over the design life span of the various barrier and barrier applications, as well as the acquisition of data from field-scale containment systems needed to validate these models. In addition, experimental data are needed to support the projection of future barrier material properties resulting from chemical and biological

degradation over the design life span of the various barriers. Similarly, acceptance depends on demonstrating, also with a high degree of confidence, that barriers are properly installed and that they are performing as intended. This demonstration will require the development of improved methods for verifying barrier integrity over time while at the same time maintaining reasonable monitoring costs.

4.0 References

- Corser, P., J. Pellicer, and M. Cranston. 1992. "Observations on Long-term Performance of Composite Clay Liners and Covers." *Geotechnical Fabrics Report*. November 1992, pp. 6-16.
- Daniel, D. E., and P. M. Estornell. 1990. *Compilation of Information on Alternative Barriers for Liner and Cover Systems*. Cooperative Agreement No. CR-815546-01-1, University of Texas, Austin, Texas.
- Ely, R. L., G. L. Kingsbury, M. R. Branscome, L. J. Goldman, C. M. Norheim, J. H. Turner, and F. O. Mixon. 1983. *Performance of Clay Caps and Liners for Disposal Facilities*. EPA Contract No. 68-03-3149, Research Triangle Institute, Research Triangle Park, North Carolina.
- Fayer, M. J., M. L. Rockhold, and M. D. Campbell. 1992. "Hydrologic Modeling of Protective Barriers: Comparison of Field Data and Simulation Results." *Soil Sci. Soc. Am. J.* 56:690-700.
- Jasperse, B. H. 1989. "Soil Mixing." *Hazmat World*. November 1989, pp. 20-23.
- K&M Engineering and Consulting Corp. and BDM International, Inc. 1993. *Evaluation of Alternative Drilling Technologies and Subsurface Confinement Barriers for Single Shell Tanks at Hanford, Phase I Draft Summary*. Prepared under Contract No. DE-AC21-90MC27346 for the U.S. Department of Energy, Morgantown Energy Technology Center, Morgantown, West Virginia.
- Nyhan, J. 1989. *Hydrologic Modeling to Predict Performance of Shallow Land Burial Cover Designs at the Los Alamos National Laboratory*. LA-11533-MS, Los Alamos National Laboratory, Los Alamos, New Mexico.
- Pacific Northwest Laboratory (PNL). 1991. "Technology Modules for the Remedial Action Assessment System (RAAS)." PNL-SA-7842, Richland, Washington.
- SCS Engineers Inc. 1986. *Cost of Remedial Actions at Uncontrolled Hazardous Waste Sites Worker Health and Safety Considerations*. EPA/600/2-86/037, Hazardous Waste Engineering Laboratory, U.S. Environmental Protection Agency, Cincinnati, Ohio.
- Sims, R., and J. Bass. 1984. *Review of In-place Treatment Techniques for Contaminated Surface Soils - Volume 1, Technical Evaluation*. EPA-540/2-84-003a, NTIS, PB85-124881, U.S. Environmental Protection Agency, Cincinnati, Ohio.
- Siskind, B., and J. Heiser. 1993. *Regulatory Issues and Assumptions Associated with Barriers in the Vadose Zone Surrounding Buried Waste*. BNL-48749, Brookhaven National Laboratory, Upton, Long Island, New York.

Spooner, P. A., R. S. Wetzel, and W. E. Grube, Jr. 1982. "Pollution Migration Cut-Off Using Slurry Trench Construction." In *Proceedings from the National Conference on Management of Uncontrolled Hazardous Waste Sites*. Hazardous Materials Control Research Institute, Silver Spring, Maryland.

Sullivan, J. M. Jr., D. R. Lynch, and I. K. Iskandar. 1984. "The Economics of Ground Freezing for Management of Uncontrolled Hazardous Waste Sites." In *Proceedings of The 5th National Conference on Management of Uncontrolled Hazardous Waste Sites*. Hazardous Materials Control Research Institute, Silver Spring, Maryland.

Sutter, G. W., II, R. J. Luxmoore, and E. D. Smith. 1993. "Compacted Soil Barriers at Abandoned Landfill Sites Are Likely to Fail in the Long Term." *Journal of Environmental Quality* 22(2):217-226.

U.S. Department of Energy (DOE). 1986. *Capsule Review of DOE Research and Development Field Facilities*. DOE/ER-0305, Washington, D.C.

U.S. Environmental Protection Agency (EPA). 1985. *Handbook: Remedial Action at Waste Disposal Sites (Revised)*. EPA/625/6-85/006, Washington D.C.

U.S. Environmental Protection Agency (EPA). 1990a. *Handbook on In Situ Treatment of Hazardous Waste-Contaminated Soils*. EPA/540/2-90/002, Office of Research and Development, Cincinnati, Ohio.

U.S. Environmental Protection Agency (EPA). 1990b. *SITE Superfund Innovative Technology Evaluation*. EPA/540/5-90/006, Risk Reduction Engineering Laboratory, Office of Research and Development, Cincinnati, Ohio.

U.S. Environmental Protection Agency (EPA). 1991. *Design and Construction of RCRA/CERCLA Final Covers*. EPA/625/4-91/025, Office of Research and Development, Cincinnati, Ohio.

U.S. General Accounting Office (GAO). 1988a. *Nuclear Waste Problems Associated with DOE's Inactive Waste Sites*. GAO/RCED-88-169, Washington, D.C.

U.S. General Accounting Office (GAO). 1988b. *Nuclear Waste, Supplemental Information on Problems at DOE's Inactive Waste Sites*. GAO/RCED-88-229FS, Washington, D.C.

Wing, N. R. 1993. *Permanent Isolation Surface Barrier Development Plan*. WHC-SA-0000 (formerly RHO-RE-PL-35 P), Westinghouse Hanford Company, Richland, Washington.

Yang, E. C., D. Bauma, L. Schwartz, and J. D. Werner. 1987. *Compendium of Costs of Remedial Technologies at Hazardous Waste Sites*. EPA/600/2-87/087, Hazardous Waste Engineering Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, Ohio.

Appendix

Description of Containment Barrier Technology

Appendix

Description of Containment Barrier Technology

The containment barrier methods described in this appendix involve caps, slurry cut-off walls, grout barriers, sheet piling cut-off walls, frozen soil cut-off walls, vitrified barriers, floors, sorbent barriers, and gravel layers and curtains. The discussion includes installation and performance factors.

A.1 Caps

Of all the barriers, caps are the most complex both in design and in function. The primary function of a cap is to limit water infiltration from the surface. Water that infiltrates the waste zone can transport soluble contaminants to regions where biotic contact can occur. Generally, this contact occurs when the contaminants enter the groundwater and travel to wells or nearby streams or rivers. This mode of exposure to contaminants is referred to as the groundwater pathway. Water infiltration may be due to precipitation, water run-off from an nearby slope, or periodic flooding of a nearby body of water such as a pond or stream. Caps can be designed to prevent or limit the infiltration of water in several ways:

- divert surface water off the waste site with impermeable material (e.g., plastic, concrete, asphalt) or compacted clay
- allow water to infiltrate the soil surface, but divert the water in the subsurface
- store water in the surface soil, and allow evapotranspiration to remove it.

Caps must also be designed to prevent intrusion by plants, animals, or humans so that a direct pathway from the contaminated soil to the surface environment will not occur. Methods to control intrusion include thick caps, impenetrable layers, layers that are hard to drill through, and warning markers.

In some instances where volatile organic compounds (VOCs) are in the soil, the cap may need to serve as a barrier to gas-phase migration of the contaminants to the surface of the site. The exfiltration of volatile contaminants can be controlled with a cap in both passive and active modes. In the passive mode, the cap can retard the migration of volatiles to the surface, allowing time for decay (e.g., radon) and/or degradation. Alternatively, in the active mode, caps may be used as part of a remediation scheme. For example, a cap can enable the exertion of subatmospheric pressure between the waste zone and the cap, allowing the volatiles to be drawn to a zone where they could be collected and disposed.

The cap must incorporate elements that preserve its integrity; prevent erosion of the cap or degradation of the underlying materials caused by geophysical forces such as earthquakes; or prevent penetration by animals or plant roots that impair the control of water infiltration.

A.1.1 Installation of Caps

Generally, construction practices for the installation of caps are routine, using standard road construction equipment and well-established engineering techniques. The main differences from ordinary construction are the higher level of quality assurance (QA) controls, documentation, and sampling; the installation of monitoring equipment; and likely some specialty techniques such as installation of geofabrics or the spraying of large areas of rubberized asphalt. An additional complicating factor is the possibility of contamination during construction. Specific guidelines are used for installing caps (EPA 1987). A complete discussion of the construction of caps can be found in EPA (1991a). Figure A.1 shows the primary components in a RCRA cap design.

A.1.2 Factors Affecting Siting and Design

The siting and design of a cap is at least equal in importance as the actual installation of a cap. The waste characteristics, site layout, topography, hydrology, vegetation, geology, climate, and

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Figure A.1. RCRA Cap Design

design life affect the performance requirements of the individual elements and how they integrate over the design life of the cap. These factors are described below.

A.1.2.1 Waste Characteristics

Waste characteristics have an important impact on the design of a cap. These characteristics include the depth, dimensions, shape, stability, and chemical composition.

The height of the waste above or below has a significant impact on the design of the cap. Old disposal units must be capped in place and perch above the existing waste (sometimes well above the surrounding terrain) unless the waste can be excavated and reburied. Newly engineered disposal sites, on the other hand, can be located to optimize depth and proximity to other site features in order to allow a cap to be installed at the desired elevation relative to the surrounding terrain.

The dimensions of the contaminated zone also affect the design. For example, increasing the areal extent of a cap will result in larger volumes of surface water that must be handled. The increased volumes must be handled through some combination of surface flow routing, storage in the cap, and subsurface capture and routing. Similarly, the shape is important because long and narrow disposal units have more side-slope exposure per area than square or circular units. This feature could result in added cost per unit volume of waste covered, depending on the height of the cap. Conversely, the long and narrow units would be easier to drain (shorter distance from the peak of the slope) and probably experience less water erosion.

Many wastes sites are known to have a settlement (subsidence) potential and will require a cap that maintains its stability. Subsidence typically causes the ground above the waste zone to collapse. Thus, a cap above the waste could be subjected to forces causing it to deform and possibly crack or form a basin. Where subsidence is expected, the cap must be designed to withstand these forces and be sufficiently flexible to undergo deformation without compromising the integrity of the barrier.

Some wastes have the potential to damage materials. Gases generated during decomposition of the wastes could build to pressures that disrupt one or more cap layers. Volatiles, such as organic compounds and radon, or mobile contaminants that diffuse from the waste could chemically or radiologically react with and degrade materials like the flexible membrane liners. Heat generated during organic decomposition or radioactive decay could degrade cap layer performance or longevity.

A.1.2.2 Site Layout

The site layout also impacts the design options for a cap. Nearby facilities may constrain the area available for constructing a cap. Such constraints may preclude having the cap overhang the waste zone, a case in which a cap may not be feasible. Overhang is necessary because a portion of the percolating water near the cap edge will migrate underneath the cap as it moves downward in the soil and could contact waste near the cap perimeter. Nearby facilities also may limit the available options for routing water from the cap, particularly if the nearby facilities are also waste disposal units.

A.1.2.3 Topography

Topography also affects the cap design by impacting the stability of the site and its erosion potential. The site stability depends on the slope of the ground at the site. As the slope increases, a waste disposal unit (and thus the cap) is exposed to increasing stresses that could cause failure such as creep or flow. For this reason, disposal units are generally placed on level and stable areas. Caps raised above the surrounding terrain are subject to increased wind erosion potential. Also, as the slope of the cap surface increases, the erosive force of surface water increases. Connections between the cap surface and upland areas may provide a conduit for water to flow onto the cap and increase the erosion potential.

A.1.2.4 Hydrology

The hydrology of a site includes sources of water such as precipitation, surface water, and groundwater. The major source of water on a cap is precipitation. It is primarily the variation in precipitation across the country that determines the differences in design between caps developed in the humid east versus the arid west. Precipitation that does not infiltrate the cap surface will move over the surface of the cap. This water must be safely routed off the cap without damaging its integrity. In some areas, disposal units may be adjacent to surface water bodies such as streams, rivers, or lakes, or to channels that have the potential to contain surface water (e.g., arroyos). Under these circumstances, more attention must be directed towards the stability of the cap side-slopes. The distance from the base of the disposal unit to the groundwater could impact the cap design. Shallow groundwater may require that excess water from the surface be routed well away from the site rather than recharge the groundwater beneath the disposal unit and possibly raise the water table into the waste unit.

A.1.2.5 Biota

Vegetation and animals, including humans, affect the design in different ways. Vegetation is used to reduce the potential for water infiltration of the waste by removing water stored in the cap and returning it to the atmosphere. Plants also serve to reduce the wind and water erosion potential of the cap. However, plant roots can penetrate the waste zone and transport contaminants to the environment. Roots are a food source and may attract burrowing animals. Roots also create preferential flow paths that increase the likelihood of water infiltration. This can be particularly troublesome when clays are used in the impermeable barrier, because clays retain water and the plant roots intrude the clay layer for the water. When plants are part of a cap design to prevent surface erosion, a rooting medium must be provided that is optimum for growth. While the 60-cm-thick layer of the RCRA cap may be sufficient for growth of native grasses in the eastern U.S., a much thicker layer is required in the arid western U.S., where deep-rooted grasses are prevalent.

Burrowing animals can increase the infiltration of surface water, may disrupt textural discontinuities engineered in certain barrier designs, and may puncture layers meant to be impermeable. Animals can be vectors if they penetrate the disposal unit, because they will carry the contamination to the surface environment.

Humans intrusion involves, for example, repeated traveling across a cap, which can degrade it. Digging can disrupt layering sequences and puncture impermeable features. Disposal units close to population centers will require more human controls than those units in remote areas.

A.1.2.6 Geology

Site geology affects the cap design in terms of the nature and structure of the sediments that serve as the foundation of the cap, as well as the availability of suitable materials onsite for constructing the cap. The latter can become an important consideration in the prospective cost of the cap if expensive measures must be taken to alter the materials to meet cap performance specifications, or if suitable materials must be transported from remote sites.

A.1.2.7 Climate

The total precipitation, its seasonal distribution and form (rain or snow), and its intensity all impact the performance of a cap (infiltration, erosion, supportable vegetation). Temperatures influence the cap directly through the action of weathering rates and freeze/thaw cycles. Thus the north-south temperature gradient in the U.S. can require design differences. The impact of wind on a cap is felt through erosion and deposition of airborne soil onto the barrier surface, causing irregularities that may adversely impact plant growth and cause undesirable channeling of surface water. Regional and local topography, elevation relative to the surroundings, source area (for depositional material), vegetation, and general wetness will determine the design features required. For those caps that are expected to function without maintenance, wind erosion control measures are especially important in arid settings and water erosion control measures are especially important in wetter settings.

A.1.2.8 Design Life

The design life for a cap depends on the type of waste and the regulatory requirements that apply. For institutional control of RCRA landfills, during which maintenance can occur, RCRA allows 30 years; the DOE through DOE Order 5820.2a allows for 150 years (DOE 1988); the NRC through 10 CFR 61 allows 100 years. For low-level waste (LLW) site stability, 10 CFR requires 500 years, while 40 CFR 193 requires 1000 years.

The design life places constraints on the use of certain materials in the cap. For example, man-made materials such as high-density polyethylene (HDPE) may satisfy the 30-year design life of a RCRA cap, but may not be able to satisfy a 1000-year design life of a LLW site. In fact, very little information is available for most materials that can be used to project their performance beyond 30 years with any confidence.

The design life also affects the assumptions that must be made on climate. Historical records clearly show large variations in climate (i.e., the statistical summary of the weather), even on a scale of decades. If the design life is to be longer, on the order of 100 to 1000 years, significant changes in climate must be anticipated. For example, the annual precipitation, seasonal distribution, and intensity level of the precipitation can each change. Similarly, the average temperature and seasonal temperatures change significantly. Either effect will cause substantial changes in vegetation types to occur so that the original vegetation used in the cap may no longer thrive and self propagate.

The design life also affects the assumptions regarding population and land use. The longer the design life, the more important it is to anticipate changes in nearby populations and land use. Such changes can cause a need for more investment in intruder control.

A.1.3 Performance of Caps

The overall performance of a cap derives from the performances of the individual elements in the cap acting together in an integrated fashion. Thus, the cap depends on the material properties as well as the arrangement and dimensions of individual elements in the cap. Other factors that influence the performance of a cap are integration with other remedial action measures, verification of performance following installation, and applicability of the cap to the site conditions. Each of these factors is discussed in the following sections.

A.1.3.1 Performance of Impermeable Materials

Impermeable materials (in reality, low-permeability materials), such as clay, asphalt, HDPE, etc., are used to redirect infiltration water away from the waste zone or to hold it close to the surface where it can be returned to the atmosphere by evapotranspiration. The performance of the manufactured materials tends to be more controllable than that of compacted clay layers.

The performance of clay layers at actual waste sites (e.g., Ely et al. 1983) will vary depending on type of clay, thickness, and compactive effort. The results of field studies showed a substantial variation in clay liner permeabilities (EPA 1989). In one experiment, covering about 214 m², in situ saturated conductivities ranged from 10⁻⁶ to 10⁻⁸ cm/sec (10⁻⁷ is the required saturated conductivity). In another experiment, the field conductivity of a 24-m² area of a 232-m² clay test pad was 10⁻⁵ cm/sec versus laboratory values averaging 10⁻⁹ cm/sec measured on 7.5-cm-diameter cores.

The performance of clay is also sensitive to the moisture in the surrounding soil. Corser, Pellicer, and Cranston (1992) showed that clay covers can lose moisture over a time period of a year or less, causing desiccation cracks to form in the cover as the clay shrinks.

Daniel and Estornell (1990) discussed the performance of alternate materials such as clay blankets. Less well documented are the longevity and performance of these blankets over many years. The long-term durability and aging of manufactured materials (e.g., geonets, geofilters, geomembranes) are also uncertain (EPA 1991a).

A.1.3.2 Performance of Other Barrier Materials

The vast majority of the materials that comprise a cap are earthen. While the intrinsic performance of an individual sample is measurable, the performance of a cap will be the integrated response of many "samples"; i.e., the earthen material properties vary spatially. Thus, the performance will depend on the mean, the standard deviation, and knowledge of the type of distribution (e.g., normal; log-normal) of each parameter.

Geotextiles are considered in some cap designs. In a field test in Ogden, Utah, a geotextile with a high conductivity is used on a sloping capillary barrier interface to redirect infiltrating water laterally to a drain. The long-term performance and longevity of such geotextiles are not known, however.

The earthen material properties will be subject to soil development processes. Such processes include leaching (higher in the east), burrowing, chemical reactions, and organic matter accumulation. These development processes are likely to be more significant for a 1000-year cap than a 30-year cap.

A.1.3.3 Verification of Performance of Cap Integrated Elements

The performance of a cap depends in part on achieving the expected performance of each cap element once installed. Verification of proper installation is readily achieved because each phase of installation can be visually inspected. However, visual inspection may not be sufficient to ensure proper performance, and samples of the barrier may need to be obtained and tested. The EPA recommends that a sampling frequency for density is 5 samples/acre, or roughly 1 sample per every 800 m² section (EPA 1991a). However, it is not clear that this frequency is sufficient. For example, Mundell and Bailey (1985) reported that a design permeability of 1 to 5 x 10⁻⁸ cm/sec could be achieved by controlling the compaction process. However, a field experiment in Klingerstown, Pennsylvania, 250 measurements obtained from an area of roughly 209 m² revealed that conductivity varied over 2 orders of magnitude (ranging from 10⁻⁶ to 10⁻⁸ cm/sec). Furthermore, the variation of the saturated conductivities could not be correlated to either water content or dry density (EPA 1989), two parameters normally associated with variations in hydraulic conductivity. Thus, EPA's recommended sampling frequency may be inadequate for verifying the average field performance of a cap.

Performance also depends on withstanding degradation and maintaining acceptable performance experienced over time. Degradation mechanisms include 1) erosion/deposition, 2) intrusion, 3) settlement, 4) waste impacts on material properties, 5) earthquakes, and 6) physical and biological weathering. The importance of each mechanism varies for different sites. Thus, given the setting of a particular cap, the important degradation mechanisms can be identified and their rates measured or estimated. Those mechanisms that are important are then addressed through design features. Thus, each disposal unit will require site-specific design features that will distinguish it from the generic cap designs.

Modeling studies can be used to provide relatively quick estimates of expected performance over time for a variety of configurations. These studies are also able to explore future performance given estimates of the boundary conditions (e.g., weather) and degradation of the component properties. A model was developed explicitly for designing caps and comparing alternate designs (Schroeder et al. 1984). Other models have been used to study specific cap issues (Johnson et al. 1983; Fayer, Rockhold, and Holford 1992).

Laboratory testing is required for many of the components of a cap. The EPA (1987) requires these tests to be conducted using approved procedures such as those issued by the American Society for Testing and Materials (ASTM). Daniel and Estornell (1990) discuss some of the laboratory tests used to evaluate the performance of manufactured alternate barriers such as clay blankets.

While modeling and laboratory studies provide useful information on expected performance of the elements of a particular cap, data obtained from the field provide the only information on the integrated performance of a cap as it was meant to function. Field data obtained from small-scale field tests (e.g., Nyhan et al. 1989; Cadwell 1991) can provide important pieces of information on the expected performance of caps. Similarly, case studies of actual disposal sites can provide important information on the expected performance of a cap if they are sufficiently instrumented and monitored. However, past case studies have only provided piecemeal information, some of which is not encouraging. Ely et al. (1983) reported that, of the 33 waste disposal sites studied, only 22 had sufficient information to judge performance. They also reported increased infiltration due to animal burrowing and root penetration of the cover, mechanisms that were not previously appreciated.

In 1988 in Germany, 500-m² caps were constructed to slopes of 4% and 20% to test three cap designs for landfills (Melchior and Miehlich 1989). All water balance parameters, including drainage, were monitored. Melchior et al. (1993) reported that desiccation and shrinkage have affected the unprotected compacted soil liner, and that thermally induced liquid and vapor movement beneath the flexible membrane liner desiccated the protected compacted liner in some locations.

A.1.3.4 Integration with Other Remedial Action Measures

Caps are often used in combination with vertical cut-off walls to control water infiltration to a site. The integration of caps with these barriers is described more fully in Sections A.2 through A.7. Caps may also be used at certain sites in conjunction with soil gas extraction technology to remove VOCs from the soil. In these instances the cap is used to increase the radius of influence of the extraction well by sealing off the surface near the extraction well. Hutzler, Murphy, and Glerke (1988) identified nine pilot- and field-scale soil gas extraction systems that used temporary caps composed of various individual materials, including plastic sheet, clay, concrete, and existing pavement.

A.1.3.5 Limitations to Applicability

The main factors limiting the applicability of caps to hazardous waste sites are the slope stability of the site, stability of the waste, the risk associated with the waste, and the design life span for the cap. In addition, climate, soil characteristics, and hydrology can affect the selection of candidate cap materials for the various cap components as well as the design of the cap. Caps can usually be used at new engineered hazardous waste disposal sites because they can be located in regions with low earthquake potential and in areas with no or stable slopes. Old hazardous waste sites that are too risky to exhume and that do not have a stable foundation will likely be difficult to cap successfully. Similarly, old waste sites that are prone to settlement are unsuitable for capping unless the waste can be treated to reduce the settlement potential.

Caps are not yet applicable for either permanent or long-term isolation of wastes from the biosphere until the wastes degrade to a nonthreatening state. No cap design has been demonstrated as capable of lasting for long periods of time. Some wastes, such as high-level nuclear waste and some hazardous wastes, have decay half-lives that are far in excess of the design life of caps. In these circumstances, caps should not be considered the primary control.

Even for caps design life spans of more moderate length, applicability is questionable at this time because active monitoring and maintenance may cease. Therefore, any assessment of the applicability of the cap must consider the period when active control and maintenance may stop and intrusion control measures would be passive. For some locations, and for some wastes, the loss of institutional control may not be acceptable considering the risk.

A.2 Slurry Cut-Off Walls

Slurry cut-off walls have been used in the U.S. for over 40 years to control the lateral groundwater flow in unconsolidated earth materials. They have also been used at numerous sites since 1970 for pollution control. Spooner et al. (1984b) provide excellent background information of slurry wall design fundamentals, typical slurry wall configurations, and installation methods, as well as some of the limitations to their application in the containment of pollutants. The most common type of slurry cut-off wall is composed of a soil-bentonite mixture.

A.2.1 Installation of a Soil-Bentonite Slurry Wall

Slurry cut-off walls are typically constructed using a slurry trenching method whereby a continuous trench is excavated under a bentonite water slurry. Figure A.2 illustrates this process. Depending on the depth required, a backhoe and/or a clam shell is used to excavate a narrow trench typically 2 to 4 ft wide. As excavation progresses, the trench is filled with a bentonite water slurry. By maintaining the level of the slurry above the groundwater level, an outwardly directed force is exerted on the trench walls, which stabilizes them and prevents their collapse. In addition, the resulting outward flow of water from the slurry into the surrounding soil and sediment causes the formation of a thin filtercake layer on the walls that both seals the walls, preventing slurry loss, and ultimately contributes to the low permeability of the completed wall. The wall itself is typically completed by backfilling the trench with a soil-bentonite slurry mixture.

The backfill mixture typically has a consistency of mortar or concrete that will flow easily, yet stands on a slope of about 10:1. This property is achieved by using a mixture with a slump of 2 to 7 in. on the ASTM C143-74 "Slump of Portland Concrete" Test (Spooner et al. 1984b). The flow characteristics are important because the mixture must not flow so easily that it results in a flat backfill slope, but also must not be so stiff that it forms voids within the wall. The slurry is also at least 15 lb/ft³ more dense than the slurry in the trench. Standard practice for backfill preparation is to use excavated material mixed with slurry from the trench for backfill. The excavated material is placed on a relatively level area near the trench; slurry is added; and a bulldozer is used to track and blade the material until it is mixed. Where there is insufficient space available, batch mixers or pug mills can be used, although they are slower (Spooner et al. 1984b). Once excavation progresses to the point where fill material added to the trench will not be re-excavated, backfill is added to the trench bottom, usually using a clam shell until the backfill is visible at the surface. Subsequent backfill is pushed into the trench using bulldozers or graders. Once in place the slurry wall forms a continuous monolith.

If the purpose of the slurry cut-off wall is to control groundwater flow, then it will need to be keyed into the confining layer below the aquifer to make a tight seal between the wall and the

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Figure A.2. Construction of a Slurry Wall

confining layer. If the purpose of the cut-off wall is to control a floating organic on top of the groundwater then the wall does not need to extend through the entire depth of the aquifer. This type of configuration is called a hanging slurry wall.

A.2.2 Performance of Soil-Bentonite Slurry Cut-off Walls

A.2.2.1 Physical/Chemical Properties

A typical soil-bentonite backfill material has a bentonite content of 1% to 2%, a moisture content of 25% to 35%, and a fines content of 20% to 60%. These proportions are necessary for achieving the proper density and flow properties discussed above, as well as to produce the necessary physical and chemical properties of the completed barrier. The primary physical and chemical properties that affect the performance of soil-bentonite slurry cut-off walls are low permeability, resistance to hydraulic pressure and chemical attack, low load-bearing strength, and moderate to high plasticity (Spooner et al. 1984b).

The typical hydraulic conductivities of completed soil-bentonite slurry cut-off walls range from 10^{-5} cm/sec to 10^{-8} cm/sec. The permeability of the backfill is directly related to the fines content with the lower permeability achieved from slurry with the higher fines content. However, much of that performance is achieved by the thin-layer filtercake of the slurry on the trench walls, which can have a hydraulic conductivity as low as 10^{-9} cm/sec. An analysis by Spooner, Wetzel, and Grube (1982) shows that even with relatively permeable backfill material (hydraulic conductivity >

10^{-4} cm/sec) the filtercake with a hydraulic conductivity of $2.5 (10)^{-8}$ cm/sec on only one of the trench walls can produce a barrier with a hydraulic conductivity of 10^{-6} cm/sec.

Slurry cut-off walls may need to be capable of withstanding large hydraulic gradients across the wall unless extraction wells, interceptor trenches, or drains are installed on the upgradient side of the barrier to redirect the water elsewhere. Otherwise, the barrier eventually erodes and fails. According to Spooner et al. (1984b), long resistance to hydraulic gradients as much as 200 ft can be achieved by using high concentrations of clayey materials in the backfill. Slurry cut-off walls can also fail if they are degraded by contaminants in the soil. According to Spooner, who references the work of D'Appolonia and Ryan (1979) and D'Appolonia (1980), strong organic and inorganic acids ($\text{pH} < 1$) and bases ($\text{pH} > 11$) can dissolve the silica and aluminum in the bentonite and/or soil components, thereby increasing the porosity of the barrier. Inorganic salts and certain neutral polar and nonpolar organic compounds can cause shrinking of bentonite clay particles by changing the amount of water in the interspatial layers of the clay particles, also resulting in increased permeability. Walls containing high concentrations of plastic fines in the backfill are generally more resistant to the detrimental effects of these contaminants.

In almost all applications, the load-bearing strength of the slurry wall is not important and should not be a consideration in the selection of materials. In the case of soil-bentonite slurry cut-off walls, the load-bearing strength of the wall is usually designed to be comparable to that of the surrounding ground. The plasticity of the wall is important, however, to prevent crack formation when the completed wall is subjected to shifts in nearby strata caused by overloading the ground surface near the wall. Soil-bentonite slurry cut-off walls undergo plastic deformation when stressed.

A.2.2.2 Integration with Other Remedial Action Measures

Slurry cut-off walls can be used for different purposes along with other remedial action measures. One purpose is to isolate the contaminant zone by forming a continuous wall around the perimeter of the contaminated zone. In this configuration the slurry wall is used in conjunction with a cap, which prevents infiltration of water from the surface. It is also usually used in conjunction with a leachate collection system inside the barrier to dewater the contaminated zone. This configuration reduces the generation of contaminant leachate generated at the site and directs the flow of water inward, thereby preventing contact of the wall with the contaminants that could degrade its performance over time. An important consideration of this configuration is the ability to withstand potentially large hydraulic gradients between the groundwater table and the dewatered interior.

Slurry cut-off walls placed upgradient of the contaminated zone can also be used to divert groundwater around the site. However, in order for the barrier to be effective, the diverted groundwater must be drained to a sufficiently lower elevation that it cannot flow around the barrier and return to the contaminated zone or, in some cases, overflow the wall. This type of barrier is generally limited to sites where there is a relatively steep gradient.

Slurry cut-off walls may also be placed downgradient of the contaminated zone. In this configuration, however, the purpose of the wall is not to reduce leachate generation but, rather, to confine it for subsequent recovery and onsite treatment. This particular configuration lends itself to a hanging

wall configuration to collect floating contaminants for recovery and treatment. An important consideration of this type of configuration is the compatibility between the wall materials and the contaminants.

Slurry walls have also been used in the past to control the migration of methane and other landfill gases. In this application the wall is placed on the downgradient side of the gas phase flow from the site and thus could entirely surround the site. In order to be truly effective, venting of the gases (preferably forced venting) is recommended (Spooner et al. 1984b). In this configuration the wall would extend down to the water table or a layer of fine moist soil, both of which serve as effective barriers to gas migration.

A.2.2.3 Verification of Performance

Verification of the performance of a soil-bentonite cut-off wall depends primarily on ensuring that the compositional requirements of the slurry and backfill materials are maintained throughout the installation of the wall. This is done by testing the dry bentonite, water, fresh slurry, in-trench slurry, backfill materials, and mixed back fill (Spooner et al. 1984b). The raw materials used in the cut-off wall, bentonite, water, and backfill material must meet specific requirements.

In the case of bentonite, the primary concern is whether the bentonite actually meets the specifications stated, including purity, dry-fineness, additives, pH, viscosity, and fluid loss. Water is usually tested for pH, hardness, total dissolved solids, and the presence of organics or other deleterious substances. Fresh bentonite slurry is tested for pH, bentonite content, viscosity, and fluid loss. In-trench slurry is tested using a sample from the bottom of the trench and evaluating its density and viscosity; other samples are taken from various depths and tested to verify uniformity of the slurry. Soil used as backfill is tested for its particle size distribution. Mixed backfill is tested for bentonite content, moisture content, fines content, and shear strength. In addition to these tests, wall construction is monitored to identify a number of potential problems that can lead to poor installation if not resolved. These include the presence of unstable soils, high water tables, hard rock and/or large boulders in the soil, sudden slurry loss, trench collapse, and inadequate backfill placement.

Once the cut-off wall is installed; its performance is monitored by measuring basal stability of the area, ground movement behind the wall, groundwater quality, and hydraulic head drop across the wall.

A.2.2.4 Limitations to Applicability

A number of factors affect the applicability of slurry cut-off walls to hazardous waste containment. Site topography is a factor because both the excavation slurry and the backfill will flow under excessive stress, unless the trenchline is excavated to within a few degrees of level (EPA 1985). Cement-bentonite cut-off walls (see Section A.2.3.1) are not restricted, but a higher permeability of the wall will be a necessary tradeoff.

The availability of work area is also a limitation on soil-bentonite walls because of the need for a mixing area. Again cement-bentonite walls are not so restricted.

The compatibility of soil-bentonite slurry wall materials of construction with contaminants is another possible limitation. Contaminants of concern included strong acids and bases, strong salt solutions, and certain organic chemicals. An important caveat, however, is the level of concentration necessary to cause degradation of the barrier. In many cases, the levels in the groundwater may be much lower than the threshold levels required for significant degradation (EPA 1985).

A.2.3 Alternative Slurry Cut-off Wall Materials

In addition to soil-bentonite slurry cut-off walls, there are other materials that have been used in certain circumstances. These materials include cement-bentonite, diaphragm walls, and geomembranes. In addition, biopolymer materials have been developed to replace the bentonite slurry in trench excavation and thus can be considered as an alternate material.

A.2.3.1 Cement-Bentonite Slurry Cut-off Wall

The next most common barrier material is a cement-bentonite mixture. Cement-bentonite walls are used when there is a lack of suitable soil for backfill, insufficient space available for backfill mixing, excessive slopes at the site, or the completed slurry cut-off wall must possess a greater strength than that of a soil-bentonite wall. Cement-bentonite slurry cut-off walls are not as subject to cracking as a typical concrete wall. However, the hydraulic conductivity of a cement-bentonite slurry cut-off wall ranges from $1(10)^{-6}$ cm/sec to $5(10)^{-6}$ cm/sec. Thus, a compromise on hydraulic conductivity must be made if these other considerations are important.

The installation of a cement-bentonite slurry wall is similar to that for a soil-bentonite slurry except that backfill material is not used. Instead, a cement-bentonite slurry is added to the trench and allowed to set. A typical cement-bentonite slurry is about 6% bentonite, 18% ordinary Portland cement, and 76% water, and begins to set after about 2 to 3 hr. If the slurry wall can be completed in 1 day or less, then the cement-bentonite slurry also serves as the excavating slurry. If it takes longer to complete the excavation, either cement retarders must be used or excavation can take place using a bentonite slurry and then replacing the bentonite slurry with the cement-bentonite mixture. An alternative method for installing cement-bentonite walls under a bentonite slurry has been developed that uses a downhole drilling rig, which operates under a bentonite slurry and produces a rectangular hole about 2.5 to 4 m long and 0.4 to 1.2 m wide. This rig is capable of reaching depths to 130 m.

A.2.3.2 Diaphragm Wall

Diaphragm walls are concrete walls consisting of either precast panels or panels that are cast in place. In both cases, a trench is constructed under a bentonite slurry. If precast panels are used, they are lowered into the completed trench and secured. If the panel is cast in place, the trench is constructed in short sections; a reinforcing bar is lowered into place; and the cement is directed to the bottom of the trench using a funnel-like apparatus that is slowly raised as the cement is added, and the bentonite slurry is pumped out. Diaphragm walls are used where high strength is required and are not generally considered suitable for contaminants because they are susceptible to leakage between adjacent panels and to cracking in the panels, which are more brittle than the other walls.

A.2.3.3 Geomembranes

Spooner et al. (1984b) mentions the possible installation of synthetic membrane liners in a slurry trench to reinforce the integrity of the wall and to improve its resistance to chemical attack. However, they did not report any membranes having been installed. They do point out that placement of the liner would be difficult and would require overlap adjacent sections. Furthermore, backfilling the trench could cause the corners of the membrane to be displaced and leave behind a gap in the membrane barrier. Day (1991), on the other hand, mentions the installation of a geomembrane liner in a drainage trench using an overlap of at least 5 ft between adjacent sections.

A.2.3.4 Biopolymer Slurry Material

Trench excavation using biopolymer materials is a relatively recent commercial technique developed for the installation of deep drainage trenches (Day 1991). Like a bentonite slurry, the biopolymer slurry supports the sides of the trench during excavation. The principal difference is that the latter does not form a permanent impermeable filtercake on the walls but, rather, a temporary, impermeable, gelatin-like membrane on the walls. In a typical application for a drainage trench, the necessary monitoring and extraction wells are placed in the completed trench, and the trench is back-filled with pea gravel and/or other suitable material. Once construction (and necessary backfilling) is complete, the slurry is broken by lowering the pH of the slurry to below 7 and adding an enzyme breaker solution. The drain is then continuously pumped and recirculated for one to several days to complete degradation of the polymer and restore the permeability of the trench. This technique has been successfully employed at several sites and at depths to 70 ft.

A.3 Grout Barriers

Grout technology has three applications in the remediation of contaminated sites: 1) to form a barrier around a site in the form of a grout curtain; 2) to seal rock formations to reduce their permeability (rock grouting); and 3) to immobilize contaminants in the soil as a treatment. This section is primarily concerned with the state of technology for grout curtains. However, much of the discussion also pertains to rock grouting, which is discussed separately in Section A.3.3. The use of grout as an immobilization technology for waste treatment is not specifically discussed here.

A.3.1 Installation of Grout Curtains

Historically, grouting has served as a means for filling voids in earthen dams and in rock formations being mined to reduce water infiltration to acceptable levels. It has also been used as a means for stabilizing soil to support foundations by filling in voids in the soil. Its application as a curtain in soil is less well developed primarily because installation is a relatively slow, labor-intensive process that produces a barrier with hydraulic properties inferior in many cases to those achieved with a slurry wall. The principal methods for forming grout curtains are permeation grouting, jet grouting, deep soil mixing (also called hydrofraise), and vibrating beam injection. Each of these methods is described below.

A.3.1.1 Permeation Grouting

Permeation grouting is the most common method of installing grout curtains and is the primary method for rock grouting. In general, permeation grouting involves drilling a hole, withdrawing the drill a short distance and then pressure injecting grout into the open hole and surrounding soil. The repeated withdrawing of the drill and injecting grout until a entire column is completed is called the stage-up method as shown in Figure A.3. The stage-down method is similar except that the repeated sequence involves first redrilling through the grouted section to the next lower level, retracting the drill to a point near the bottom of the previous stage, and then injecting grout (Figure A.4). Another technique, the grout port method, uses a pipe with slots at different depths sealed in a borehole. A second injection pipe with inflatable seals above and below the injection point is lowered in the pipe to a level with a slot, and the seals are inflated to seal off that section. Grout is then injected through the slot and into the ground. The grout port method is more expensive to install, but it is more suitable for grout curtains in soil because the slots can be reused to inject different grouts into the same zone.

Permeation grouting is usually conducted in multiple stages involving the placement of holes. One method called the multiple row method involves the placement of two or more rows of grout to form the barrier. The spacing of the rows is such that the grout will ideally overlap, creating a broad point of contact between pillars within a single row and between pillars of different rows. This is necessary to compensate for the high permeability of the joints between adjacent pillars because they do not coalesce into a single monolith, and for subsequent grout shrinkage. In order for permeation grouting to be employed, sufficient overburden must be present to resist the injection pressures. Typically 5 to 10 m of overburden are required (Einstein and Barvenik 1975).

Since the void size distribution is very broad in soils, several different grouts are injected into the grout curtain. Highly viscous particulate grouts such as the clay-cement grouts are first injected into the soil to fill the larger pores. Less viscous but more expensive chemical grouts are then injected into the soil to fill the smaller voids. Another method involving multiple rows consists of two outer rows injected with particulate grout and an inner row injected with chemical grout. The two outer rows serve essentially as redundant barriers, while the inner rows in which all voids are filled with chemical grout serve as the primary barrier (Einstein and Barvenik 1975).

Construction of a single row may also involve a technique called split spacing. In this technique, primary holes spaced as much as 40 ft apart are filled with a particulate grout. The spaces between the holes are split with new holes and particulate grout added. This is continued until the amount of grout that can be injected into the new split of is reduced, indicating that adjacent pillars are being joined. Then subsequent splits use progressively less viscous grouts to fill progressively smaller voids. Because of the side range of void sizes in soil, some of the smaller voids are not filled even with the chemical grouts with viscosities close to that of water. To compensate for this, a typical grout curtain barrier in soil is 20 m or more wide (Einstein and Barvenik 1975).

A.3.1.2 Jet Grouting

Jet grouting is a technology used for forming columns of grouted soil. Jet grouting typically involves drilling a hole into the soil to the desired depth and placing a grouting pipe in it. A jet grouting head is then lowered to the bottom of the pipe, and a high-pressure (6000 psi) stream of air,

Figure A.3. Up-staging Method of Permeation Grouting

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Figure A.4. Down-staging Method of Permeation Grouting

water, and Portland cement is directed laterally into the soil. The high-pressure jet both excavates a hole and mixes the soil with the cement and water as shown in Figure A.5. As the jet rotates 365°, a flat disc of grouted soil is formed (K&M Engineering and Consulting Corp. and BDM International, Inc. 1993). The pipe is moved progressively upward, eventually leading to an entire column of grouted soil. The resulting column is typically 0.6 to 0.75 m in diameter (Allan, Kukacka, and Heiser 1992). Formation of a grouted soil column using a jet can also be accomplished by injecting a high-pressure fluid into the soil and removing the soil cuttings to the surface. After the column is excavated it is filled with grout and about 85% of the excavated soil (Allan, Kukacka, and Heiser 1993).

According to Allan, Kukacka, and Heiser (1993), Portland cement grouts typically have a water:cement ratio ranging from 1:1 to 3:1. They report that, according to Guatterri, Mosiici and Altan (1988), soil cements produced by jet grouting have permeabilities on the order of 10^{-7} cm/sec.

A.3.1.3 Deep Soil Mixing

Deep soil mixing is a technology originally developed during the 1960s for the construction industry that has recently been adapted to site remediation as both a means for in situ fixation of contaminated soil and for constructing cut-off walls. A typical deep soil mixing system consists of an assembly of two or more hollow stemmed auger and mixing paddles (Jasperse 1989). As the augers penetrate into the soil, grout is injected through the tip of the augers. The augers lift the soil and grout to mixing paddles that homogenize the two components. The mixing process takes place both during penetration of the soil in which about 30% of the grout is injected, and during withdrawal in which the remainder of the grout is injected. The entire assembly is guided by a crane-supported set of leads. The process minimizes the amount of soil that is actually excavated from the ground. When constructing a cut-off wall, secondary columns are placed between primary columns so that the secondary columns overlap both primary columns. Deep soil mixing is reported to be capable of constructing columns to a depth of about 100 ft (Jasperse 1989).

One such system being demonstrated by International Waste Technologies/Geo-Con, Inc., which produces a 36-in.-diameter column, was tested in EPA's SITE program as a soil stabilization process (EPA 1990b). Soil at two test sections was treated to depths of 14 and 18 ft, respectively. While the purpose of the demonstration was contaminant immobilization, the permeability of the treated soil was reported to be 10^{-6} to 10^{-7} cm/sec, compared with 10^{-2} cm/sec for the untreated soil. They also reported that the specific volume of the treated soil increased by 8.5%, which is an indication of the amount of spoils that might ultimately be produced in the construction of a cut-off wall.

A.3.1.4 Vibrating Beam

Another method of creating a grout curtain is called the vibrating beam method. In this method, an I-beam is either driven or vibration-driven into the ground to the desired depth. It is then slowly withdrawn and grout is injected into the empty space through injection nozzles at the bottom of the beam. The I-beam is then vibrated into a second location overlapping the first placement, and the process is repeated until a complete curtain is produced (EPA 1985). The I-beam shape provides for maintaining continuity of the wall between adjacent sections during installation by providing some additional tolerance for inaccurate placement as shown in Figure A.6.

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Figure A.5. Jet Grouting Schematic Diagram

This process is different from the other grouting methods in that the grout fills an empty space created by the beam rather than mixing with the soil. This feature provides for more control in the resulting properties of the barrier. The typical thickness of the wall is about 10 cm. Depth is limited to about 20 to 25 m. Two types of grout have been installed successfully using the vibrating beam method: cement-bentonite and asphalt emulsion. Field testing of a vibrated beam cut-off wall made from cement-bentonite indicated a hydraulic conductivity between 10^{-6} and 10^{-7} cm/sec (Glover 1982). Hydraulic conductivity values reported for asphalt are on the order of 10^{-9} cm/sec or less (Glover 1982).

A.3.2 Performance of Grout Curtain Materials

The performance of grout curtains depends on a number of factors: the initial permeability of the soil and heterogeneity of the soil, the choice of grouting materials used, and the method of placement. According to Einstein and Barvenik (1975) grout curtains, properly installed in soils using permeation grouting, seemed to achieve a hydraulic conductivity of between about 10^{-5} cm/sec and 10^{-4} cm/sec, regardless of their initial permeability. The most common materials used were a cement-clay mixture to grout the larger voids followed by sodium silicate grout to grout the smaller voids. However, depending on the type of soil to be grouted and the contaminants present in the soil, other grout materials may also be used. Figure A.7 illustrates the applicability of various grout materials based on soil grain size.

To some extent, the lower performance achieved with grout installed using permeation grouting is consistent with that achieved with slurry walls because the slurry wall achieves much of its performance from the bentonite filtercake on the walls of the trench. In addition, slurry walls can adjust the composition of the soil used to form the wall in terms of fines content, whereas grout barriers must use what is located in the soil to be grouted. The lower values reported for deep soil mixing and jet grouting can be attributed to the homogenization of the soil with the grout and the resulting increase in the pore size evidenced by the displacement of soil to the surface. Those values for vibrated beam cut-off walls are consistent with those reported for slurry walls.

Within the overall performance expected from grout cut-off walls there are other considerations that affect the performance of these barriers. These considerations are discussed below.

A.3.2.1 Physical/Chemical Properties

A large number of materials have been used in grout formulations. These materials can generally be grouped as suspension grouts, chemical grouts, hot melts, and emulsion grouts. Suspension grouts usually consist of solids, such as Portland cement, bentonite, and clays suspended in water. Small quantities of additives are used to adjust their properties. Chemical grouts include sodium silicate solutions and a number of organic chemicals (acrylamides, acrylates, polyurethanes, polyester styrenes, and vinyl ester styrene) and various promoters, catalysts, and additives. Hot melts include hot bitumen (asphalt) and hot sulfur. Emulsions include water-based asphalt.

The wide variety of grout materials is necessary to match the specific grout application. This is predominantly determined by the grain size and distribution of the soil, which, in turn, determines the pore size distribution of voids that need to be filled with grout. Figure A.7 also shows the general

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Figure A.6. Vibrating Beam Method Schematic Diagram

Adapted from: Bowen, 1981

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Figure A.7. Applicability of Different Classes of Grouts Based on Soil Grain Size

range of application of the various grouts for progressively finer-grained soil. Generally, the primary property controlling selection is the viscosity of the grout, with higher viscosity suspension grouts being used for coarser-grained soil, and lower viscosity emulsion and chemical grouts being required for finer-grained soils. A second property that is considered in selecting a grout material is its setting time. This is controlled to a large extent by the physical and chemical properties of the primary grout material but may be adjusted by additives that control the setting time.

The selection of a grout material is also influenced by its stability in the absence of water. The suspension grouts and the inorganic chemical grouts (sodium silicates) depend on water to hydrate these materials. In low-moisture soils, water may be wicked away from these materials causing them to shrink and crack. Organic grouts, as a rule, are hydrophobic and do not depend on water in the soil to maintain their properties.

An important consideration in the selection of a grout material is its resistance to various chemicals that might be found in leachates at a hazardous waste site, either as part of the waste or as a reagent used in situ treatment. Spooner et al. (1984a) provides a good overview of the compatibility of grout materials with hazardous waste. Two concerns identified are the ability of the grout to set in the presence of these materials, and the long-term effect of the chemicals on the permeability of the grout. This is an important consideration in the selection of grouts, but compatibility data are not complete for the various grouts. Therefore, chemical compatibility testing is required to verify performance of a specific grout for a specific site application.

A.3.2.2 Integration with Other Remedial Action Measures

Grout curtains are amenable to integration with other containment barriers as evidenced in their use in dam construction. Grout curtains when used in conjunction with floors also offer a means for containing chemical reagents and mobilized contaminants during in situ soil flushing. It is likely that grout resistance to degradation by specific chemical leachates can be achieved by selection of one of the variety of organic and inorganic materials used to create grout curtains.

A.3.2.3 Verification of Performance

Einstein and Barvenik (1975) describe three primary methods available for determining whether a grout curtain has been successfully installed. The three primary methods are permeability tests, piezometer method, and coring tests.

Permeability tests consist of either pumping tests or water pressure tests. In pumping tests, a section of the curtain is grouted and a hole drilled in the middle of the curtain in a position that is well away from the curtain boundaries and any previously drilled injection wells. Observation wells are drilled outside of the curtain and the water level in them is monitored as water is pumped from the middle well. In the water pressure test, no observation wells are installed and water is pumped into the middle hole for a specified period. The amount of water injected is correlated to the permeability of the grout curtain.

The piezometer method involves the installation of piezometers on both sides of the grout curtain. As grouting proceeds, the difference in the water levels is used to indicate the effectiveness of the barrier.

The coring test samples are taken from selected locations in the curtain and the surrounding soil. The cores are then examined for discontinuities, proper setting of the grout, and the percentage of voids filled. This particular method is very expensive and gives only indirect evidence of the expected grout curtain performance. It is primarily used for troubleshooting causes of unsatisfactory grouting.

Einstein and Barvenik (1975) also describe two secondary tests that are based on correlations between grout pressure and grout take. These parameters are obtained for previously installed grout that had been tested by one of the primary methods and found to be satisfactory. These controls are then used to monitor progress on subsequent grouting of individual holes. Basically these correlations assume that the pressure required to inject a certain volume of grout will be the same for all holes, or alternatively the grout take will remain the same for a certain pressure. If the actual values of these parameters deviate then the grouting procedure must be re-evaluated using the primary tests.

A.3.2.4 Limitations to Applicability

An important limitation in the applicability of grout curtains is that it is very difficult to grout voids in soils with a hydraulic conductivity less than about 10^{-4} cm/sec. Furthermore, particulate grouts containing cement are limited to soils with a hydraulic conductivity greater than about $5(10)^{-3}$ cm/sec and is ineffective if more than about 10% of the soil particles are finer than 3 mm. Other grouts, however, such as montmorillonite or colloid cement can be used with finer soils.

Bituminous emulsions are mentioned by Einstein and Barvenik (1975) as having been used to effectively treat soils with a permeability less than 10^{-3}

A.3.3 Rock Grouting

Rock grouting is considered to be a highly specialized and site-specific operation that is performed by a limited number of contractors (EPA 1985). Rock grouting is performed in rock to fill fractures, fissures, and large voids in a rock formation. It is used in situations to reduce groundwater flow through the rock formation. It may be used in conjunction with a grout curtain or slurry wall that is keyed into the rock formation in order to prevent flow around the bottom of the curtain.

Rock grouting is conducted in essentially the same method that was described for permeation grouting of soil, except that the grout formulation is determined by pressure testing each zone to be grouted using a nonsetting fluid of the same viscosity of the grout to be used (EPA 1985). Another important difference, however, is that the voids are often much larger than those found in soil, although they may tend to be somewhat uniform within the rock formation. Consequently, cement-based grout mixtures often incorporate fillers such as sand, flyash, rock flour, and clay (Einstein and Barvenik 1975) to reduce cost and to achieve a more viscous grout to fill the larger cavities and cracks.

A.4 Sheet Piling Cut-Off Walls

Sheet pile cut-off walls are preformed wall sections driven into the ground to form a hydraulic barrier. Preformed wall sections may be interlocking steel, precast concrete, or wood. However, wood walls are considered ineffective as hydraulic barriers, and precast concrete, though better than wood, is also considered inappropriate for containing contaminated groundwater, except in those instances where significant lateral resistance is needed (EPA 1991b). The discussion of sheet piling in this section is thus limited to steel walls.

A.4.1 Installation of Sheet Pilings

Installation of sheet pilings involves driving interlocking sheet piles around a contaminated zone and into an impervious strata beneath the site. Examples of sheet piling shapes and interlocks are shown in Figure A.8. The procedure involves connecting adjacent panels abovegrade at their edge interlocks (EPA 1985). The piles are then driven in a few feet at a time over the entire length of the wall by using a drop hammer or a vibratory hammer. The process is repeated until the desired depth is achieved for each pile. Piles are typically installed to depths of about 40 ft. However, under favorable conditions, sheet piles have successfully been driven to depths in excess of 100 ft (Glover 1982). By necessity the interlocking edges are not tight in order to drive individual piles without damaging the interlock. Consequently, the permeability of the wall at these joints can be very high. In many construction applications the seepage of water is allowed, which in turn carries fine soil particles into the joints, eventually reducing their permeability to acceptable levels. In some cases, the piles are provided with the means to inject grout into the interlock following installation. This provides for an immediate seal if it is successfully grouted. However, damage or misalignment of adjacent panels during installation could prevent successful grouting of some joints.

Straight Web Type

Arch Web Type

Deep Arch Web Type

Z-Type

Y-Fitting

T-Fitting

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Figure A.8. Some Steel Piling Shapes and Interlocks

A.4.2 Performance of Sheet Piling Materials

Steel sheet pile material is impermeable to water, although the permeability at the interlocking joints between individual sheets can be quite high. Thus, the performance of the sheet wall may rely mainly on the physical and chemical properties of the materials used to seal the interlock joints.

A.4.2.1 Physical/Chemical Properties

Steel is susceptible to corrosion, and the integrity of the individual panels could eventually fail over time. Inspections of steel piles placed in soils ranging from well-drained sand to impervious clay, with soil resistivities ranging from 300 ohm/cm to 50,000 ohm/cm and with soil pH ranging from 2.3 to 8.6, did not reveal any significant deterioration of the piles through corrosion. In cases where the potential for corrosion is significant, the piles can be galvanized or coated with a polymer and/or provided with cathodic protection (EPA 1985).

A.4.2.2 Integration with Other Remedial Action Measures

Sheet piles are considered applicable for short-term containment in conjunction with soil treatment schemes and for interim containment measures until a permanent remedial action is implemented. Although sheet piles are usually installed vertically, they can be installed at an angle to provide both lateral and bottom containment for a contaminated zone. However, in this orientation it will be necessary to grout the joint at the bottom since there is no other means for sealing the intersection of sheets from opposite sides of the barrier. Sheet piles can also be integrated with a cap.

A.4.2.3 Verification of Performance

There are no specific methods for verifying proper installation and operation of sheet pile cut-off walls other than by monitoring water levels on the two sides of the barrier and/or monitoring for the presence of contaminants.

A.4.2.4 Limitations to Applicability

Sheet piles cannot reliably be installed in soil containing cobbles, boulders, or other large obstructions because these materials can damage or deflect individual piles as they are driven. Glover (1982) reports that sheet walls exposed during construction have shown that an obstruction can move a sheet pile laterally for several feet or tens of feet, even though it appeared the pile was being driven to its intended position. Sheet piles are also typically limited to depths of about 40 ft, although much greater depths can be achieved in favorable soils. Sheet piles are also limited to a useful life of between 7 and about 40 years, depending on the condition of the soil.

A.5 Frozen Soil Cut-off Walls

Frozen soil cut-off walls are an established technology used in the construction industry as a temporary containment technique to consolidate ground during excavation. An advantage of the technique is that, in principle, it can be installed in all types of soil without requiring extensive

geologic data; and it is adaptable to practically any size, shape or depth. It is also a benign barrier in that, in some instances, it does not involve adding any material to the soil other than water, and once the barrier is removed the original properties of the soil are restored (Sullivan, Lynch, and Iskandar 1984).

As with other cut-off walls used in the construction industry the application of frozen soil cut-off walls to hazardous waste containment is a logical adaptation of the technology. However, this application was first suggested about 5 years ago and to date, field demonstration of the technology has not been reported, although there has been considerable interest in it.

A.5.1 Installation of Frozen Soil Cut-off Walls

Frozen soil cutoff walls are traditionally installed in a vertical orientation for construction applications. However, they also appear to be capable of being installed at an angle to provide containment to both the sides and the bottom of a contaminated zone.

Frozen soil walls are created by circulating refrigerated brine or injecting liquid nitrogen into a closely spaced pattern of wells, as shown in Figure A.9. As the soil around the pipe cools, water in the soil freezes and expands, filling most of the voids and thus reducing the permeability of the soil. A frozen soil wall that uses brine is constructed by installing steel casings in wells typically spaced about 2.5 to 5 ft apart, plugging the bottom of the hole, and placing a smaller-diameter pipe in the well. A calcium chloride brine solution is cooled in a refrigeration unit and injected down the pipe, up the annulus between the pipe and the well casing, and back to the refrigeration unit. Advantages of this technique include a relatively low initial and maintenance cost and the formation of regularly shaped frozen soil cut-off walls. The minimum temperature of the frozen soil wall is limited to about -55°C using this method. When liquid nitrogen at -196°C is used as the refrigerant it is vented to the atmosphere from the annulus. This method, though more expensive, creates a frozen wall much faster and can achieve frozen soil wall temperatures approaching -196°C . If there is insufficient moisture in the soil to produce a good barrier, then a set of injection wells near the freeze wells must be installed to inject water to the freezing zone.

The nominal width of a frozen soil wall will be on the order of the spacing of the wells or greater in order to ensure sufficient overlap of adjacent frozen columns to produce a continuous barrier. The temperature of the barrier ranges from a minimum value at the centerline of the frozen soil wall to a point away from the wall where the temperature reaches the freezing point of the groundwater. Thus, the properties of the wall will vary from the centerline to the outer edge. Another configuration of well spacing involves two rows of wells. This configuration creates a zone of fixed dimension between the rows that will be uniform at the minimum temperature and will possess constant properties (Dash 1991).

A.5.2 Performance of Frozen Soil Cut-off Walls

Frozen soil cut-off walls are a well-established technology for temporary lateral support of an excavation and for temporary groundwater control. Their applications to containment of hazardous waste and as an angled barrier have not been demonstrated.

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Figure A.9. Schematic Diagram for Soil Freezing

A.5.2.1 Physical/Chemical Properties

Frozen soil cut-off walls are considered to be very impermeable structures, and because of their inherent strength and relatively wide dimensions are considered to be resistant to losing containment integrity. Documentation of the permeability of frozen soil was not found. However, Gilpin (1980) uses a value of $0.8(10)^{-11}$ cm/sec in an example for estimating the soil permeability at the frozen fringe of the soil. Dash (1991) references Barnaal and Slotfeld-Ellington (1983), who report the diffusion of inorganic molecules such as NaCl, HCl, and HNO₃ in crystalline ice at -15°C is in the

range of $4(10)^{-9}$ cm²/sec. However, Dash (1991) and others (Iskandar and Houthoofd 1985) point out that even in a frozen wall at temperatures well below the freezing point, a thin layer of water will exist between the ice and the soil. Dash estimates this layer to be 2 or 3 water molecules in thickness at -35°C, and about double that at -3.5°C. Dash discusses the behavior in the context of reduction of the diffusivity of contaminants caused by the reduced mobility of water in these layers compared with that in a bulk liquid and also the effect of reduced pore volume containing the mobile fluid. While not specifically stated it would appear that the effective diffusion coefficient of 1 of contaminants (about 10^{-4} cm²/sec in bulk water) would be reduced by about 3 orders of magnitude. Another phenomenon noted by both Dash (1991) and Sullivan, Lynch, and Iskandar (1984) is frost heave, which is due to the growth of ice lenses in the freezing soil. This phenomenon occurs as water from an unfrozen zone migrates towards an ice lens. Ice lenses may appear as interstitial ice or as larger discrete layers in the soil (Gilpin 1980). Modeling of frost heave by Gilpin shows that it is a continuous process and that frost heave rates on the order of 0.1 to 10 mm/day can be expected, with lower values occurring in coarse-grained soils with a large overburden pressure. This could be an important parameter if there are structures in the area of frost heave and the barrier is in place for a long period.

A.5.2.2 Integration with Other Remedial Action Measures

Frozen soil cut-off walls constructed on an angle have the potential for providing temporary containment around a contaminated zone while conducting treatment of the soil. In principle, treatment such as soil flushing should be possible, although a small portion of the flushing solvent (typically water) could be incorporated into the surface of the frozen soil barrier. Some of the frozen flush water may be recoverable as the barrier is allowed to thaw following completion of soil flushing.

Frozen soil barriers are not expected to serve as a long-term barrier because life-cycle costs would eventually be uncompetitive due to higher maintenance costs (Sullivan, Lynch, and Iskandar 1984). Similarly, integration of a frozen soil wall with a cap would not be straightforward because the cap must extend through partially frozen soil to the fully frozen wall. This area could be very susceptible to frost heave.

A.5.2.3 Verification of Performance

Information regarding verification of performance was not obtained for frozen soil barriers. Presumably, differences in hydraulic head and groundwater composition can be used as methods for verifying the integrity of the barrier much as other barriers are tested. It is also conceivable that predrilled test holes can be placed in the barrier zone for permeability testing subsequent to installation of the frozen barrier. Emplacement of thermocouple wells between freeze pipes enables verification of temperatures sufficient to create the frozen barrier.

A.5.2.4 Limitations to Applicability

Frozen soil cut-off walls are active barriers in that energy must continually be removed from the soil in order to maintain the necessary temperatures of the barrier. Consequently, this type of barrier becomes uncompetitive relative to the cost of other barriers for containment periods greater than about 5 months (Sullivan, Lynch, and Iskandar 1984), although other site-specific considerations may make the barrier attractive for longer-term applications. Frozen barriers are potentially limited to

soils that contain sufficient water. Although it is possible to add water to water-deficient soils, it has not been demonstrated that all of the water added would stay in the barrier zone and not migrate further into the soil where it could leach the contaminated soil or exacerbate the frost-heave problem.

A.6 Vitrified Barriers

Vitrified barriers are produced when vadose soil is heated in situ using electrodes to melt the soil in a configuration that produces a continuous vertical cut-off wall consisting of glass-like material. The concept is an adaptation of the in situ vitrification (ISV) technology developed by Pacific Northwest Laboratory to immobilize contaminants in soil. Using techniques developed for ISV, the installation of vitrified barriers will not require excavation of soil or drilling of wells to install the barrier.

The ISV process delivers electrical energy through an array of electrodes placed on the soil. Starting at the surface, electrical energy progressively heats the soil to temperatures above its melting point. Upon reaching the desired depth or shape of the glass melt, power is discontinued. Upon cooling, the soil and associated inclusions are converted to a stable glassy monolith.

A.6.1 Installation of Vitrified Barriers

Vitrified barriers have only been tested at the bench-scale level. Consequently, installation procedures have not been developed for a full-scale system. However, procedures that were developed for in situ vitrification of contaminated soil serve as guidelines for installing the barrier.

The process of installing a monolith of vitrified soil is shown in Figure A.10. The vitrification process is initiated by passing electrical current through two electrodes that are inserted into the ground a short distance. A conductive path is made between the two electrodes using graphite or some other conductive material. The electrodes are then energized using a 3- or 6-phase power source. As the soil between the electrodes melts, the electrodes are inserted into the ground until the desired depth is reached. The electrodes are then abandoned in place and the melt is allowed to cool. As the soil is vitrified, its porosity is reduced, causing subsidence, as shown in the figure. Based on information gained from ISV technology for vitrifying contaminated soil, the spacing between electrodes can be at least 17 ft and may be much greater. This is because the power is dissipated through a much smaller volume of soil than occurs when vitrifying large blocks of contaminated soil, due to a linear electrode arrangement. In the vitrification of contaminated soil, a hood is required above the soil being vitrified so that volatile contaminants cannot escape the melt. However, if the barrier is installed in clean soil, the hood may not be necessary.

Laboratory tests have been conducted using an engineering-scale system configured for generating a subsurface vitrified structure resembling a barrier (Tixier, Murphy, and Stottlemire 1991). The system uses electrodes spaced 30 cm apart in a 6-ft-diameter by 8-ft-high chamber containing soil, and produces vitrified blocks ranging from 50 to 500 kg in weight. The following results were obtained on the engineering-scale system:

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Figure A.10. Installation of a Vitrified Barrier

- A relatively planar melt was initiated at the surface and propagated to a target depth without significant outward growth.
- A subsurface melt was initiated and maintained at a significant depth.
- A vertical melt was propagated downward to the point of contacting a previously established subsurface melt such that the two were fused into one continuous monolith.

A laboratory test also established the feasibility of using ISV to melt through unconsolidated soils and into an underlying layer of basalt (Shade et al. 1991). In this test it was demonstrated that upon reaching the underlying rock layer, temperatures were sufficient to partially melt the basalt and fuse with the ISV melt.

A.6.2 Performance of Vitrified Barriers

The performance of ISV barriers has not been demonstrated, but they are expected to possess excellent resistance to water penetration. They are also expected to last very long periods of time without failure. In addition, should a portion of the barrier fail during construction, it can be repaired relatively easily by revitrifying it.

A.6.2.1 Physical/Chemical Properties

In applying ISV as a barrier in uncontaminated soils around a waste site, it will be important to evaluate the quality of the product not only in terms of its leach resistance and durability, but also in terms of its permeability characteristics. The vitrified soil product generated by ISV has been tested and analyzed on numerous occasions to determine its durability and leach resistance. Recently, leach tests were performed on vitrified soil products at the Idaho National Engineering Laboratory (Callow et al. 1991). These test results confirm that the vitrified soil product is comparable to obsidian and granite. Devitrified samples of ISV product showed a lower leach rate than for amorphous samples of equivalent bulk composition.

Structural testing has also been performed on the ISV product using ASTM methods (Buelte et al. 1987). Results show that the vitrified soil product is about 10 times stronger in both compression and tension than unreinforced concrete. Numerical analysis methods have also been developed for predicting thermal-structural performance during and after melt cooldown (Garnich 1990). The models show that a structurally favorable residual stress pattern develops in the vitrified barrier during cooldown to ambient conditions. This pattern consists of compressive stresses at the surface and tensile stresses at the center of the cooled vitrified product. This is identical to the residual stress pattern in tempered glass where the apparent strength is significantly increased. Field tests are still needed to verify the model for barrier applications.

A.6.2.2 Integration with Other Remedial Action Measures

Vitrified barriers by their very nature are permanent barriers. In principle, these barriers should be amenable to containment applications involving vadose zone soils and should be capable of integration with a cap. At the present time, ISV has not been shown to be capable of producing a floor under a contaminated zone in the vadose zone. Thus, vitrified barrier walls will need to be joined to a floor-forming barrier if total containment is desirable. The barrier should also be capable of being integrated with soil treatment technologies, such as in situ soil flushing to remove nonvolatile contaminants from the soil. The feasibility of using the ISV barrier technology in conjunction with treatment of VOCs is less certain because sufficient distance must exist between the contaminants and the melt during its construction to prevent premature volatilization of VOCs. The distance required has not been determined.

A.6.2.3 Verification of Performance

It is not possible at this time to assess methods needed to verify performance. However, excavation of vitrified soil has shown that properties remain uniform throughout the melt. This observation may reduce direct sampling and testing requirements, enabling inference of melt quality by controlling operating parameters within established limits.

A.6.2.4 Limitations to Applicability

In situ vitrification technology is currently limited to applications requiring depths of no more than about 30 ft. It may be possible to increase this depth limit with further development, however. Vitrified barriers are also not applicable to saturated soil and thus are generally not applicable to controlling groundwater flow.

A.7 Floors

Floors are installed as a containment measure to prevent or minimize downward migration of contaminants. They are used in conjunction with vertical barriers, which prevent lateral migration of contaminants. In combination the two barriers can provide containment during remediation activities such as soil flushing, or in conjunction with caps they can provide for isolation of the contaminants from the environment. Floors are necessary in situations when it is not possible or practical to key vertical barriers into an impervious stratum in the soil to achieve the desired containment. Sometimes the underlying impervious stratum is too permeable or the impermeable stratum is very deep relative to the contaminated zone.

A.7.1 Installation of Grout Floors

A floor can be installed as a separate horizontal barrier in the soil or as an angled barrier that also serves as lateral containment. Construction of angled barriers can be accomplished, in principle, using grout curtains, sheet piles, and frozen soil cut-off walls. The installation of these walls is described in the previous sections. Horizontal walls can be constructed using grout injection techniques similar to those described for grout curtains, i.e., permeation grouting, fracture-bounded grouting, and jet grouting. Longwall mining techniques can also be used, in principle, to install horizontal barriers. Each of these methods is described below. Also discussed are alternative drilling and boring techniques that can be used to access the soil underneath the contaminated zone.

A.7.1.1 Permeation Grouting

Permeation grouting to form a floor has been used in dam construction where the permeability of the bedrock formation is unsuitable and does not improve with depth. Floors have also been constructed to connect the core of a dam to a cut-off wall that is not immediately below it. Installing a floor using permeation grouting is very similar to installing a cut-off wall (Einstein and Barvenik 1975). The main differences are that only a narrow band is grouted at the predetermined depth, and the number of rows of injection wells is configured to place a flow under the entire area to be sealed. In principle, permeation grouting can also be conducted from horizontally drilled wells, although it has not been demonstrated. A key issue in using horizontal wells is accurate placement of the well to ensure proper spacing.

A.7.1.2 Fracture-bounded Grouting

Fracture-bounded grouting also involves the injection of grout in a thin layer at a prescribed depth to create a thin, large-diameter impermeable barrier. The installation technique is similar in many respects to permeation grouting except that a horizontal notch is formed in the side of each borehole at the prescribed depth, as shown in Figure A.11, and a particle slurry is injected under higher pressure than is used in permeation grouting. This causes the fracture to form in the notch and radiate horizontally a considerable distance from the borehole. The fracture is subsequently filled with grout. The thickness of the fracture is on the order of 0.5 to 2.0 in., and the radius of the grouted fracture extends as far as 150 ft away from the borehole (K&M Engineering and Consulting Corp. and BDM International, Inc. 1993). In actual installation the direction of the fracture is not exact, and the overlapping disks will not necessarily form a tight barrier. However, the barrier does

serve to limit downward flow of low-viscosity grouts injected above the fracture grouted floor and encourage horizontal flow instead. Thus, a low-viscosity grout will bridge the gaps between the grouted fractures and create a more uniform layer of grout above the fracture zone. This technique is based on well-established fracturing technology in the petroleum industry used to open up oil-bearing formations by injecting sand into the fractures. However, adaptation of the technology to creating impermeable floors in near-surface applications is still in the development stage and has not been validated in a full-scale demonstration.

A modification of fracture-bounded grouting is called block displacement. In this method, a vertical barrier is first constructed around the perimeter of the site, as shown in Figure A.12; then specially notched holes are bored at the desired depth, and the grout is injected. Continued grout injection causes vertical displacement of the soil isolated inside the vertical wall, producing a grout floor. A full-scale test of this method was conducted at Whitehouse, Florida, where a block of earth 60 ft in diameter and 25 ft deep was lifted as much as 12 in. using an array of seven holes to form the floor. The test showed the viability of the installation technique. However, only about 80% of the desired barrier was actually formed. This was attributed to the formation of an unsatisfactory vertical barrier using another experimental technique: drill, notch, and blast perimeter barrier construction.

A.7.1.3 Jet Grouting/Kerfing

Jet grouting (also referred to as kerfing in the literature) can also be used to place a floor under a site. The technique is similar to installing grout curtains using jet grouting, except that the grouting takes place at one depth. Installation involves boring a hole to the desired depth and inserting the jet. The jet is supplied with air or a water/bentonite mixture and an abrasive material such as sand. As the jet is rotated, a 1- to 3-m disk is carved out of the ground, with the cuttings recovered at the surface. The high pressure of the jet (3,000 to 30,000 psi) holds the cavity open during the process (Murdock et al. 1990). The chamber is subsequently filled with grout. As with permeation grouting, a pattern of holes is used to create the floor. However, by the nature of the cutting action of the jet, a portion of adjacent grouted holes will be recut and grouted to ensure a good joint between disks. This technology is still in the development stage. It appears to have some limitation in soils containing large cobbles that are too large to fall into the chamber because they block the jet. This technique has been commercially developed for mining ore bodies and has been capable of removing material from as far as 75 ft away from the borehole (Murdock et al. 1990).

A.7.1.4 Longwall Mining

In principle, longwall mining techniques could be applied to the installation of a floor. Longwall mining involves mining a horizontal layer as little as 2 to 3 ft thick in the ground. As the wall advances, the spoils are mixed with cement, water, and other additives and used to continuously fill the excavated chamber. This method can be installed remotely so that miners do not need to be routinely working at the mine face. Proper installation of the barrier can be verified by direct visual inspection and sampling. One major disadvantage with this method is that it requires some hands-on work by miners at the face of the wall and roof collapse is a distinct possibility in unconsolidated soils. Mining below the water table would also be an important limitation to this method.

Figure A.11. Formation of Notch for Fracture-bounded Grouting

A.7.1.5 Alternative Drilling and Boring Techniques

Many of the techniques for placing floors in the ground rely on wells bored from the surface to a predetermined depth, and then installing the floor at that depth. Consequently, a pattern of relatively closely spaced holes must penetrate the surface of the entire site, which causes the generation of contaminated spoils. This can be a major limitation if there is a structure such as a tank or large building over the site. Alternatively, grout and frozen soil barriers can be installed at an angle to form a barrier, but they also rely on drilling holes. However, if there is a large areal extent of contamination or a large structure on the site, the holes may need to be drilled to considerable depth in order to have holes from opposite sides intersect at their bottom.

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Figure A.12. Installation of a Floor Using Block Displacement

There are, however, several advanced drilling techniques that can be used to produce horizontal holes in the ground. These techniques include directional drilling techniques used in the oil and gas industries and the mining and mineral exploration industries; river crossing technology; and trenchless excavation technologies.

A.7.2 Performance of Grout Floors

The performance of grout floors has not been well documented, in part because many of the installation methods are unproven for hazardous waste containment applications. Einstein and Barvenik (1975) mention that floors are used in dam construction only when it is not feasible to accomplish the same results with a grout curtain because they are more difficult to construct and must cover large areas. Murdock et al. (1990) reference May et al. (1985), who state that the grouted zones from kerfing were not always the size and shape needed to produce a continuous and complete barrier. They also quote Huck, Waller, and Shimondle (1980), who note that the presence of large cobbles in the soil produces zones of unkerfed soil that result in incomplete barriers.

A.7.2.1 Physical/Chemical Properties

The materials available for creating grouted floors are the same as those available for constructing grouted cut-off walls. However, when grout is used in a floor for a hazardous waste site, the possibility that the grout will come in contact with concentrated contaminants is distinct.

A.7.2.2 Integration with Other Remedial Action Measures

Grout floors are amenable for integration with other containment barriers as evidenced in their use in conjunction with cut-off walls in dam construction. Grouted floors when used in conjunction with cut-off walls also offer the means for containing chemical reagents and mobilized contaminants during in situ soil flushing.

A.7.2.3 Verification of Performance

According to Einstein and Barvenik (1975), the methods used for verifying proper installation and performance of floors are essentially the same as those used for grout curtains. The only exception is that piezometers give no indication of performance until there is hydraulic head developed. Geophysical methods for monitoring the development of the floor during fracture-bounded grouting (block displacement) is mentioned by Brunsing (1987) as a possible method for verifying the integrity of the floor, and sonic detection methods are mentioned by K&M Engineering and Consulting Corp. and BDM International, Inc. (1993).

A.7.2.4 Limitations to Applicability

A clear advantage of the bounded fracture grouting technique is that fewer boreholes need to be drilled. Also, the barrier can be extended underneath fairly large structures by placing boreholes around the perimeter of the structure.

A.8 Sorbent Barriers

Sorbent barriers are an innovative containment technology for retarding the migration of contaminants while allowing for the normal flow of groundwater through the barrier. Sorbents have been used to a very limited extent in immobilizing organic contamination in surface soils in which sorbent materials are tilled into the soil (Sims and Bass 1984). The application of subsurface barriers had not progressed beyond bench and pilot-scale as of early 1990 (EPA 1990a).

In situ sorption involves the addition of sorbent materials to the soil in order to adsorb contaminants. It is based on the principle that the concentration of certain chemicals and ions will be higher on the surfaces of certain solids than in the bulk liquid phase.

Sorption involves several mechanisms including physical adsorption, specific adsorption, chemisorption, and ion exchange. This distribution of the contaminant between the solid and the solution is generally expressed by the Freundlich equation:

$$C_s = KC_e^n$$

where

- C_s = amount of contaminant adsorbed per unit dry weight of solid (g/g)
- C_e = contaminant concentration of solution in equilibrium with the solid (g/mL)
- K = contaminant distribution coefficient (mL/g)
- n = constant.

Physical adsorption occurs between the dissolved compound and the surface because of weak atomic and molecular forces such as Van der Waals forces. Specific adsorption is exhibited by anions involving the exchange of the ion with surface ligands to form partly covalent bonds. Chemisorption involves a chemical reaction between the compound and the surface of the solid. Ion exchange involves the exchange of cations and anions between the liquid and solid phases. In some cases, the adsorption involves precipitation or coprecipitation of inorganic contaminants on the adsorbent. These phenomena are also included in adsorption technology.

Sorbent barrier technology is based on the engineered retardation of contaminant flow through sediment by the addition of sorbent materials. In cases where the kinetics of adsorption are rapid and reversible, the velocity of a contaminant in a porous medium such as sediment can be related to the velocity of the water according to the equation (Freeze and Cherry 1979):

$$V_c/V_w = 1 + \rho/n(K_d)$$

where

- V_c = velocity of the contaminant (m/hr)
- V_w = the water velocity (m/hr)
- ρ = bulk mass density of the porous medium g/mL
- n = porosity
- K_d = distribution coefficient for the contaminant between the liquid and solid phases (mL/g).

The term $1 + \rho/n(K_d)$, on the right hand side of the equation, is called the retardation factor. For unconsolidated granular deposits, the retardation factor typically ranges from $(1 + 4K_d)$ to $(1 + 10K_d)$ (Freeze and Cherry 1979). Thus, for a K_d of 1 mL/g, the retardation factor would range from 5 to 11. By adding sorbents to a barrier it is possible to increase the value of the retardation factor substantially. This is the principle behind the use of sorbent barriers.

In principle, sorbent barriers operate in the same manner as an ion-exchange or an activated carbon adsorption column used in ex situ treatment of wastewater. As contaminated water enters the barrier, the adsorbents on the upstream side of the barrier adsorb most of the contaminants. As the adsorbent on the upstream face of the barrier reaches its capacity, the contaminated water passes further into the barrier and the contaminants are adsorbed. Eventually, when the adsorption capacity of the entire barrier is largely exhausted, the wastewater passes through only partially treated. At this time, the barrier would need to be replaced. However, if an entire plume passes through the barrier and is replaced by clean water before the adsorbent is exhausted, it is possible to leave the barrier in place and allow the contaminants to slowly elute from the barrier, provided they do not exceed concentration limits. In this case, the barrier is undergoing elution but at conditions that do not favor high concentrations of contaminants in the water.

A.8.1 Installation of Sorbent Barriers

Permeable barriers can be installed either at and/or below the water table as a barrier to groundwater flow or in the vadose zone below contaminated soils to contain downward migration of leachate. Permeable barriers to treat contaminated groundwater can be constructed by digging

trenches with a backhoe and filling in the trench with an adsorbent material or a mixture of materials. This method is limited to the treatment of shallow groundwater because of the potential for cave-in from deep soil walls. However, it should be possible to use slurry wall construction techniques with a biopolymer slurry to construct deeper trenches, as discussed in Section A.2.3.4. When a sorbent barrier is installed horizontally to form a floor for containing downward migrating leachate in the soil, the barrier would be installed using one of the grouting techniques described in Section A.7 for floors.

A number of adsorbent materials may be considered for in situ sorption, including activated carbon, agricultural residues, clays, zeolites, glauconitic greensand, and limestone. Activated carbon is generally used for the removal of organic compounds. However, it also may be used to remove certain heavy metals, such as Cr(III) and (VI), lead, cadmium, mercury, silver, copper, and cyanides (Lyman 1978; Huang 1984). It has also been shown to have good adsorption properties for cobalt (Freeman, Jones, and Depner 1989).

Agricultural residues are similar to activated carbon in many respects but are susceptible to biodegradation, which may reduce their initial performance as an adsorbent (Sims and Bass 1984). Clays are primarily used to adsorb cations and thus adsorb many dissolved metals and a number of cationic organic materials, including certain pesticides and herbicides. For example, specific materials that are adsorbed by montmorillonite clay include S-triazines, substituted ureas, phenyl carbamates, anilines, anilides, and picolinic acids (Sims and Bass 1984). Fuller's earth has been used as a carrier for insecticides and fungicides, and is well established as an adsorbent for greases, oil, and water (Patterson and Murry 1975). Certain clays have been shown to have good properties for adsorbing cesium (Freeman, Jones, and Depner 1989). Zeolites and glauconitic greensands (EPA 1985) have high-surface-area cation exchange properties and are used to remove a number of heavy metals and radionuclides in wastewater treatment applications. Crushed limestone and lime [$\text{Ca}(\text{OH})_2$] are used to neutralize acidic groundwater and to adsorb/coprecipitate certain metal cations such as iron, cadmium, and chromium. Calcite has been shown to coprecipitate strontium and/or plutonium with the phosphate ion in the water (Ames, McHenry, and Honstead 1958).

The selection of adsorbents for a specific application can be guided by information regarding their adsorption properties for various contaminants. However, bench-scale treatability tests are necessary for obtaining key design parameters relating to the distribution coefficients of candidate materials for each contaminant in the specific groundwater or leachate to be treated, and for obtaining breakthrough curves that indicate the point of exhaustion of the adsorbent material. These parameters must be conducted for actual water, or simulated water of the same composition, because of competition among the various organics and inorganic ions in the water for the same adsorption sites in the adsorbents.

Bench-scale tests using various combinations of adsorbents mixed with soil are also needed to determine the best combination and quantity of sorbent materials for a specific application. Key data include selectivity and capacity of each mixture for the contaminants and interactions among the sorbent, soil, and/or groundwater components. These components include natural adsorbents already in the soil and competing organic and ionic species indigenous to the soil.

Soil characteristics are important in determining feasibility and design of bench-scale tests. Characteristics include pH; moisture; mineral and organic composition; saturation extract chemical

composition to determine competing ions; the presence of ligands that affect sorption tendencies of contaminants; cation exchange capacity; acid/base buffering capacity; soil permeability; and exchangeable cation composition. The tests should include all significant contaminant types and concentrations in order to determine the competition of the various contaminants for adsorption sites. These experiments also need to consider the adsorption properties of both candidate sorbents and soil.

A.8.2 Performance of Sorbent Barriers

Sorbent barriers are an innovative technology that has experienced very little actual application in the field. As mentioned before, a recent EPA study (1990a) reported that no sorbent barrier technology had progressed past the bench- and pilot-scale stage.

A.8.2.1 Physical/Chemical Properties

The performance of a sorbent barrier depends on a number of factors related to the physical and chemical properties of the barrier and its application site, including the effect of interactions of the adsorbents with the groundwater constituents. These factors include contaminants at varying concentrations with time; the thickness of the barrier; the concentration of adsorbents in the barrier; the permeability of the barrier; and the groundwater velocity.

A major drawback in using in situ sorption is the loss of adsorption capacity as the materials become fully loaded with contaminants and other adsorbed constituents. In addition, permeable barriers containing chemically reactive inorganic reagents may become clogged with precipitates, which would require that the permeable bed be periodically removed and treated and/or disposed of as a hazardous waste. This technology, then, should be considered only as a temporary containment measure.

A.8.2.2 Integration with other Remedial Action Measures

An important feature of permeable barriers for containing organic contaminants is an ability to serve as a host site for microorganisms that will eventually degrade the contaminants. The barrier itself may contain some of the trace nutrients needed to support the microorganisms. Others can be added through injection wells either within or just upstream of the barrier depending on where it is used. Permeable barriers also can be integrated with pump-and-treat or other in situ treatment options that remove most of the contaminants from zones of highest contamination, and then the barrier is used to ensure that residual levels of contamination are contained onsite, thus protecting the aquifers and/or surface waters located offsite.

A.8.2.3 Application of Sorbent Materials to Hydraulic Barriers

The major difference between a permeable barrier and a hydraulic barrier is the permeability of the barrier. In both cases the effect of sorbents in the barrier will cause retardation of contaminant migration. In the case of a hydraulic barrier, the water velocities are typically reduced to values so low that it takes several years for water to migrate through the barrier. By adding sorbents to the barrier it should be possible to increase the corresponding time for contaminants to migrate through the barrier to decades or even longer. For example, modeling of trichloroethylene (TCE) transport

through a 3-ft earthen barrier by Acar and Haider (1990) showed that increasing the retardation factor from 1 to 40 would increase the time to achieve breakthrough at 20% of the TCE concentration at the upstream side of the barrier, from 19.6 years to 783 years. In practice, however, consideration must be given to preferential flow through cracks and high-permeability zones within the barrier that will experience accelerated localized sorbent loading and premature breakthrough of contamination.

A.8.2.4 Verification of Performance

Methods for verifying proper installation and performance of sorbent barriers have not been developed. Periodic sampling of the barrier as it is installed should provide for quality control. Monitoring groundwater contaminant levels downstream of the barrier will provide information of performance. However, this method will not indicate whether the barrier will achieve its designed service life. Monitoring groundwater within a barrier may provide an early indication of impending premature breakthrough of contaminants.

A.8.2.5 Limitations to Applicability

As a general rule, sorbent barriers have limited applicability to most anions containing metals. This is primarily due to the limited number of adsorbents suitable for anions and the fact that adsorption is affected by the presence of other competing anions.

A.9 Gravel Layers and Curtains

Gravel layers and curtains are used in many containment systems to manage the flow of water in the soil. The use of gravel as a barrier is based on differences in permeability between coarse-textured and fine-textured sediments under saturated and unsaturated conditions. The flow of liquid or gas through sediments is a function of the sediment texture, which is a qualitative measure of the sediment particle size distribution. Some sediments are predominantly coarse-textured (e.g., gravels and sands), while others are fine-textured (e.g., silts and clays). Coarse-textured soils are highly permeable, whereas fine-textured soils are relatively impermeable. Because flow through them depends on their permeability, sediments can be segregated and placed to optimize flow properties.

A.9.1 Mechanisms Affecting the Behavior of Gravel Layers and Curtains in Vadose Zone Applications

The flow rates of liquids and gases through sediments are proportional to the respective pressure gradients (hydraulic or pneumatic), where the proportionality factors are called conductivities. The ability of a sediment to conduct liquid such as water decreases as the water content decreases, partly because the cross-sectional area available for flow decreases. Conversely, the ability of a sediment to conduct gas such as air increases as the water content decreases, partly because the cross-sectional area available for flow increases. According to Poiseuille's Law, the flow through a capillary pore (or pipe) is proportional to the pore radius to the fourth power. Therefore, larger pores have a much greater impact on flow than smaller pores, even if the total cross-sectional areas of the pores are the same.

Figure A.13 shows how the water retention and conductivity of two materials, a gravel and a silt loam, might vary over a range of matric potentials (i.e., capillary pressures). Water conductivities in gravel are extremely high near saturation, which occurs at a matric potential of zero, but drop rapidly as matric potential decreases only slightly. Conversely, silt loam has a much lower conductivity near saturation and the drop in conductivity as the matric potential decreases is much less rapid. The curves cross, and at lower matric potentials, the water conductivity of silt loam is orders of magnitude higher than that of gravel.

If a silt loam layer were to reside above a gravel layer, significant water movement through the gravel would not occur until the water content of the silt loam layer was fairly high. This can be illustrated using the curves in Figure A.13. The EPA-required saturated hydraulic conductivity for the impermeable layer of the RCRA cap is 10^{-7} cm/sec. This corresponds to a hydraulic conductivity of 3.6×10^{-4} cm/h, which is the assumed unit for hydraulic conductivity in this figure. Using Curve A, this value of hydraulic conductivity corresponds to a matric potential of -400 cm for the silt loam layer. However, the gravel conductivity at this matric potential is more than 8 orders lower than the EPA requirement. Using this matric potential value in Curve B the water content of the silt loam layer is about $0.23 \text{ cm}^3/\text{cm}^3$. If water content in the silt loam layer is increased to approximately $0.50 \text{ cm}^3/\text{cm}^3$, the new matric potential is -3 cm (point b of Curve A). At this new matric potential, the conductivity of the gravel is equal to the EPA-required 10^{-7} cm/sec value. Note that the water content in the silt loam greatly increases going from point a to point b. Agricultural interests use this phenomenon of fine soils over coarse soils to their advantage in retaining soil water in the root zone of their crops (Miller and Bunger 1963).

From a waste disposal perspective, if the excess water in the silt loam can be removed before the matric potential increases to or exceeds -3 cm, then flux through the gravel can be minimized to less than 10^{-7} . Removal options include evaporation and plant transpiration (e.g., the Protective Barrier), and lateral drainage (e.g., Frind, Gillham, and Pickens 1977).

The air conductivity of gravel is nearly constant over most of the range of matric potentials. Not until the potential is above -10 cm does air conductivity begin to drop significantly. Essentially, the gravel would have to be saturated to impact air conductivity. Air conductivities in silt loam are 3 or more orders of magnitude less than those of gravel throughout the range of matric potential values.

A.9.2 Flow Modifications Achieved Using Gravel Layers and Curtains

Gravel layers and curtains can be used to manage water in the ground in three distinct ways: capillary breaks, gravel drains, and gravel vents. The phrase "capillary break" refers to a textural discontinuity or contrast. For example, a silt loam layer above a gravel layer produces a capillary break at the interface. In actuality, there is no "break." Rather, the predominance of smaller pores in the silt loam changes to the predominance of larger pores in the gravel. The phrase "capillary barrier" refers to the situation where the unsaturated conductivity of one layer is much lower than an adjacent layer and, therefore, controls flow through the total system. As shown in the example in Section A.9.1, significant amounts of water will not flow from the silt loam into the gravel if the gravel is too dry. Thus, infiltrating water will be detained in the silt loam until it is sufficiently wet (the matric potential approaches zero) such that the gravel can conduct a higher flux of water.

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Figure A.13. Retention and Conductivities of Silt Loam and Gravel. Note: The air conductivity curves were generated by modifying the air conductivity of dry material by the air porosity, which decreases as the water content increases. The calculated values allow for comparison but do not represent actual values. For example, air conductivities are usually reduced to zero before complete saturation (in contrast to the finite values show here).

Gravel drains are vertical curtains or horizontal layers of gravel that serve as conduits for draining free water. Gravel is traditionally considered as a drainage material. Gabions on road embankments serve this purpose in addition to providing structural support for the embankment. Vertical curtains serving as gravel drains to direct water downward may also serve as a capillary barrier to lateral hydraulic flow when the drain is empty.

Some disposal facilities emit gases that must be vented. Pipes called risers are commonly used to vent the gases. When disposal facilities must be left unattended for hundreds of years, pipes may not be acceptable. Rather than use pipes, holes filled with gravel can serve as vents. As long as the gravel is not saturated, the permeability to gases will be very high. Whole layers, such as the gravel layer beneath some of the capillary barrier designs, can also serve as "layer" vents (EPA 1991a).

A.9.3 Installation of Gravel Curtains and Layers

Generally, installation of gravel curtains and vents involves standard construction practices. Gravel layers are installed by spreading a layer of gravel over the ground. If the layer is to serve as a capillary break then the gravel is covered with a layer of fine sediment. Gravel curtains can be installed by excavating a trench and filling it with gravel. Slurry wall construction techniques using a biopolymer slurry, as described in Section A.2.3.4, have been used to install gravel beds up to 70 ft deep.

A.9.4 Performance of Gravel Curtains and Barriers

Given the history of use in construction, gravel curtains and vents should perform as designed for long periods of time. However, the life span of the capillary break, i.e., the interface between the gravel and the surrounding material, is not clear. The largest concern will be ensuring the integrity of the capillary break so that fines do not fill the interstitial voids of the gravel. This would create preferential pathways for water drainage into the gravel bed from the fine-textured layer above it, at much lower matric potentials, thereby reducing its performance as a hydraulic barrier.

A.9.4.1 Integration with Other Remedial Action Measures

Gravel curtains and layers are generally used in conjunction with other containment measures. Gravel drains are often used to direct water away from a cut-off wall or prevent buildup of hydraulic head that either causes a failure of the cut-off wall or leads to overflowing the barrier.

A.9.4.2 Limitations to Applicability

Any structure involving gravel on or near the surface is likely to suffer infiltration of fines, either from root penetration, animal burrowing, or intrainment in percolating water. If the capillary break is not protected, fines could penetrate the gravel, leading to settlement and destabilization of the cap.

A.10 References

- Acar, Y. C., and L. Haider. 1990. "Transport of Low-Concentration Contaminants in Saturated Earthen Barriers." *Journal of Geotechnical Engineering* 16(7):1031-1052.
- Allan, M. L., L. E. Kukacka, and J. H. Heiser. 1993. *In Situ Containment and Stabilization Buried Waste, Annual Report FY 1992*. Brookhaven National Laboratory, Upton, Long Island, New York.
- Ames, L. L., Jr., J. R. McHenry, and J. F. Honstead. 1958. *Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy*. Volume 18, "Waste Treatment and Environmental Aspects of Atomic Energy, United Nations, Geneva.
- Barnaal, D., and D. Slotfeld-Ellington. 1983. "Pulsed Nuclear Resonance Studies of Doped Ice." *J. of Phys. Chem.* 87:4321.
- Brunsing, T. P. 1987. *Block Displacement Method Field Demonstration and Specifications*. EPA/600/2-87/023, U.S. Environmental Protection Agency, Hazardous Wastes Environmental Research Laboratory, Cincinnati, Ohio.
- Buelt, J. L., C. L. Timmerman, K. H. Oma, V. F. FitzPatrick, and J. G. Carter. 1987. *In Situ Vittrification of Transuranic Waste: An Updated Systems Evaluation and Applications Assessment*. PNL-4800, Supp. 1, Pacific Northwest Laboratory, Richland, Washington.
- Cadwell, L.L. 1991. *Hanford Site Protective Barrier Development Program: Fiscal Year 1990 Highlights*. PNL-7831, Pacific Northwest Laboratory, Richland, Washington.
- Callow, R. A., L. E. Thompson, J. R. Weidner, C. A. Loehr, B. P. McGrail, and S. O. Bates. 1991. *In Situ Vittrification Application to Buried Waste: Final Report of Intermediate Field Tests at Idaho National Engineering Laboratory*. EGG-WTD-9807, Idaho National Engineering Laboratory, Idaho Falls, Idaho.
- Corser, P., J. Pellicer, and M. Cranston. 1992. "Observations on Long-term Performance of Composite Clay Liners and Covers." *Geotechnical Fabrics Report*, pp. 6-16. November 1992.
- D'Appolonia, D. J. 1980. *Slurry Trench Cut-off Walls for Hazardous Waste Isolation*. Technical Paper, Engineered Construction International, Inc., Pittsburgh, Pennsylvania. April 1980.
- D'Appolonia, D. J., and C. Ryan. 1979. "Soil and Bentonite Slurry Trench Cut-off Walls." Presented at the Geotechnical Exhibition and Technical Conference, Chicago, Illinois, March 26, 1979.
- Daniel, D. E., and P.M. Estornell. 1990. *Compilation of Information on Alternative Barriers for Liner and Cover Systems*. Cooperative Agreement No. CR-815546-01-1, University of Texas, Austin, Texas.

- Dash, J. G. 1991. "Ice Technology for Hazardous Waste Management." *Waste Management* 11:183-189.
- Day, S. R. 1991. "Extraction/Interception Trenches by the Bio-polymer Slurry Drainage Trench Technique." *Hazardous Materials Control* 5(5):27-31.
- Ely, R. L., G. L. Kingsbury, M. R. Branscome, L. J. Goldman, C. M. Northeim, J. H. Turner, and F. O. Mixon. 1983. *Performance of Clay Caps and Liners for Disposal Facilities*. EPA Contract No. 68-03-3149. Research Triangle Institute, Research Triangle Park, North Carolina.
- Einstein, H. H., and M. J. Barvenik. 1975. *Grouting Applications in Civil Engineering*, Vol. 1. Soils Publication No. 334. Massachusetts Institute of Technology, Department of Civil Engineering, Cambridge, Massachusetts.
- Fayer, M. J., M. L. Rockhold, and D. J. Holford. 1992. *Model Assessment of Protective Barriers: Part III*. PNL-7975, Pacific Northwest Laboratory, Richland, Washington.
- Freeman, H. D., E. O. Jones, and J. P. Depner. 1989. *Technology Assessment Guide for Application of Engineered Sorbent Barriers to Low-level Radioactive Waste Disposal Sites*. PNL-6882, Pacific Northwest Laboratory, Richland, Washington.
- Freeze, R. A., and J. A. Cherry. 1979. *Groundwater*. Prentice-Hall International, Inc., London.
- Frind, E. O., R. W. Gillham, and H. F. Pickens. 1977. "Application of Unsaturated Flow Properties in the Design of Geologic Environments for Radioactive Waste Storage Facilities." In *Finite Elements in Water Resources*, eds. W. G. Gray and G. F. Pinder. Pentech Press, London.
- Garnich, M. R. 1990. "Thermal Stress Modeling of In Situ Vitrified Barriers for Hazardous Waste Containment." PNL-SA-19347S, Pacific Northwest Laboratory, Richland, Washington.
- Gilpin, R. R. 1980. "A Model for the Prediction of Ice Lensing and Frost Heave in Soils," *Water Resources Research* 16(5):918-930.
- Glover, E. W. 1982. "Containment of Contaminated Ground Water: An Overview." In *Proceedings Natl. Symp. Aquifer Restor. Ground Water Monit.* 2nd National Water Well Association, Worthington, Ohio.
- Guatterri, G., P. Mosiici, and V. D. Altan. 1988. "Jet Grouted Cut-off Walls." In *Proceedings of REMR Workshop in New Remedial Seepage Control Methods for Embankment-Dams and Soil Foundations*, ed., E. B. Perry, pp. 71-105. Vicksburg, Mississippi.
- Huang, C. P. 1984. *Concurrent Removal of Toxic Heavy Metals and Organic Substances By Activated Carbon Process from Contaminated Groundwater*. Pb85-218972, National Technical Information Service, Springfield, Virginia.

Huck, P., M. Waller, and S. Shimondle. 1980. "Innovative Geotechnical Approaches to the Remedial In-Situ Treatment of Hazardous Materials Disposal Sites." In *Proceedings of the 1980 National Conference of Hazardous Material Spills*. U.S. Environmental Protection Agency, Louisville, Kentucky.

Hutzler, N. J., B. E. Murphy, and J. S. Glerke. 1988. *State of the Art Technology Review Soil Vapor Extraction Systems*. Dept. of Civil Engineering, Michigan Technological University, Houghton, Michigan, under Cooperative Agreement CR-81431901-1, with Hazardous Waste Engineering Research Laboratory, U.S. Environmental Protection Agency, Cincinnati, Ohio.

Iskandar, I. K., and J. M. Houthoofd. 1985. "Effect of Freezing on the Level of Contaminants in Uncontrolled Hazardous Waste Sites - Part I: Literature Review and Concepts." In *Land Disposal of Hazardous Waste Proceedings of the Annual Research Symposium (11th) Held at Cincinnati, Ohio on April 29-May 1, 1985*. PB85-1963756. U.S. Department of Commerce, National Technical Information Service.

Jasperse, B. H. 1989. "Soil Mixing." *Hazmat World*, pp. 20-23. November 1989.

Johnson, T. M., K. Cartwright, B. L. Herzog, and T. H. Larson. 1983. "Modeling of Moisture Movement Through Layered Trench Covers." In *Role of the Unsaturated Zone in Radioactive and Hazardous Waste Disposal*, eds. J. W. Mercer, P.S.C. Rao, and I. W. Marine. Ann Arbor Science, Ann Arbor, Michigan.

K&M Engineering and Consulting Corp. and BDM International, Inc. 1993. *Evaluation of Alternative Drilling Technologies and Subsurface Confinement Barriers for Single Shell Tanks at Hanford Phase I Draft Summary*. Prepared under Contract No. DE-AC21-90MC27346 for the U.S. Department of Energy, Morgantown Energy Technology Center, Morgantown, West Virginia.

Lyman, W. J. 1978. "Carbon Adsorption." In *Unit Operations for Treatment of Hazardous Industrial Wastes*, ed. D. J. De Renzo. Noyes Data Corp., Park Ridge, New Jersey.

May, J. H., R. J., Larson, P. G. Malone, J. A. Boa, and D. L. Bean. 1985. *Grouting Techniques in Bottom Sealing of Hazardous Waste Sites*. EPA/600/2-86-020, U.S. Environmental Protection Agency, Cincinnati, Ohio.

Melchior, S., and G. Miehlich. 1989. "Field Studies on the Hydrological Performance of Multi-layered Landfill Caps." In *Proceedings of the 3rd International Conference on New Frontiers for Hazardous Waste Management*, Pittsburgh, Pennsylvania, September 10-13, 1989. EPA/600/9-89/-72, Office of Research and Development, Cincinnati, Ohio.

Melchior, S., K. Berger, B. Vielhaber, and Gunter Miehlich. 1993. "Results of the Long-term Monitoring of Different Types of Covers on the Georgswerder Landfill (Hamburg, FRG)." *Geoconfine 93*, eds. M. Arnould, M. Barres, and B. Come, pp. 325-330. Balkema, Rotterdam, ISBN 9054103302. Proceedings of the International Symposium/8-11 June 1993.

Miller, D. E., and W. C. Bunker. 1963. "Moisture Retention by Soil with Coarse Layers in the Profile." *Soil Sci. Soc. Am. Proc.* 27:586-589.

Mundell, J. A., and B. Bailey. 1985. "The Design and Testing of a Compacted Clay Barrier Layer to Limit Percolation Through Landfill Covers." In *Hydraulic Barriers in Soil and Rock*, Eds. A. I. Johnson, R. K. Frobels, N. J. Cavalli, and C. B. Pettersson, ASTM STP 874, American Society for Testing and Materials, Philadelphia, Pennsylvania.

Murdock, L., B. Patterson, G. Losonsky, and W. Harrar (University of Cincinnati). 1990. *Technologies of Delivery or Recovery for the Remediation of Hazardous Waste Sites*. EPA/600/2-89/066, Risk Reduction Engineering Laboratory, Office of Research and Development, U. S. Environmental Protection Agency, Cincinnati, Ohio.

Nyhan, J., B. Drennon, and T. Hakonson. 1989. *Field Evaluation of Two Shallow Land Burial Trench Cap Designs for Long-Term Stabilization and Closure of Waste Repositories at Los Alamos, New Mexico*. LA-11281-MS, Los Alamos National Laboratory, Los Alamos, New Mexico.

Patterson, S. H., and H. H. Murry. 1975. "Clays." In *Industrial Minerals and Rocks*, 4th ed., pp. 519-585, ed. S. J. Lefond. American Institute of Mining, Metallurgical, and Petroleum Engineers, New York.

Schroeder, P. R., J. M. Morgan, T. M. Walski, and A. C. Gibson. 1984. *Hydrologic Evaluation of Landfill Performance (HELP) Model: Vol. I. User's Guide for Version 1*. EPA/530-SW-84-009. U.S. Environmental Protection Agency, Washington, D.C.

Shade, J. W., R. K. Farnsworth, J. S. Tixier, and B. L. Charboneau. 1991. *Engineering-Scale Test 4: In Situ Vittrification of Toxic Metals and Volatile Organics Buried in INEL Soils*. PNL-7611, Pacific Northwest Laboratory, Richland, Washington.

Sims, R., and J. Bass. 1984. *Review of In-place Treatment Techniques for Contaminated Surface Soils - Volume 1, Technical Evaluation*. EPA-540/2-84-003a, NTIS, PB85-124881, U.S. Environmental Protection Agency, Cincinnati, Ohio.

Spooner, P. A., R. S. Wetzel and W. E. Grube, Jr. 1982. "Pollution Migration Cut-Off Using Slurry Trench Construction." In *Proceedings from the National Conference on Management of Uncontrolled Hazardous Waste Sites*. Hazardous Materials Control Research Institute, Silver Spring, Maryland.

Spooner, P. A., G. E. Hunt, V. E. Hodge, and P. M. Wagner. 1984a. *Compatibility of Grouts with Hazardous Wastes*. EPA-600/2-84-015, Municipal Environmental Research Laboratory, Cincinnati, Ohio, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, Ohio.

Spooner, P. A., R. S. Wetzel, C. E. Spooner, C. A. Furman, E. F. Tokarski, and G. E. Hunt. 1984b. *Slurry Trench Construction for Pollution Migration Control*. EPA-540/2-84-001, U. S. Environmental Protection Agency, Office of Emergency and Remedial Response, Washington, D.C.

Sullivan, J. M. Jr., D. R. Lynch, and I. K. Iskandar. 1984. "The Economics of Ground Freezing for Management of Uncontrolled Hazardous Waste Sites." In *Proceedings of The 5th National Conference on Management of Uncontrolled Hazardous Waste Sites*. Hazardous Materials Control Research Institute, Silver Spring, Maryland.

Tixier, J. S., M. T. Murphy, and J. A. Stottlemire. 1991. "Vitrified Underground Barriers." PNL-SA-19014, Pacific Northwest Laboratory, Richland, Washington.

Ueguhardt, L. C., et al. 1962. *Civil Engineering Handbook*. McGraw-Hill Book Company, New York.

U.S. Department of Energy (DOE). 1988. Radioactive Waste Management. DOE 5820.2a, Washington, D.C.

U.S. Environmental Protection Agency (EPA). 1985. *Handbook: Remedial Action at Waste Disposal Sites (Revised)*. EPA/625/6-85/006, Washington, D.C.

U.S. Environmental Protection Agency (EPA). 1987. *Design, Construction, and Maintenance of Cover Systems for Hazardous Waste, An Engineering Guidance Document*. PB 87-191656, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

U.S. Environmental Protection Agency (EPA). 1989. *Requirements for Hazardous Waste Landfill Design, Construction, and Closure*. EPA/625/4-89/022, Office of Research and Development, Cincinnati, Ohio.

U.S. Environmental Protection Agency (EPA). 1990a. *Handbook on In Situ Treatment of Hazardous Waste-Contaminated Soils*. EPA/540/2-90/002, Office of Research and Development, Cincinnati, Ohio.

U.S. Environmental Protection Agency (EPA). 1990b. *SITE Superfund Innovative Technology Evaluation*, EPA/540/5-90/006, Risk Reduction Engineering Laboratory, Office of Research and Development, Cincinnati, Ohio.

U.S. Environmental Protection Agency (EPA). 1991a. *Design and Construction of RCRA/CERCLA Final Covers*, EPA/625/4-91/025, Office of Research and Development, Cincinnati, Ohio.

U.S. Environmental Protection Agency (EPA). 1991b. *Handbook - Stabilization Technologies for RCRA Corrective Actions*. EPA/625/6-91/026, Office of Research and Development, Cincinnati, Ohio.