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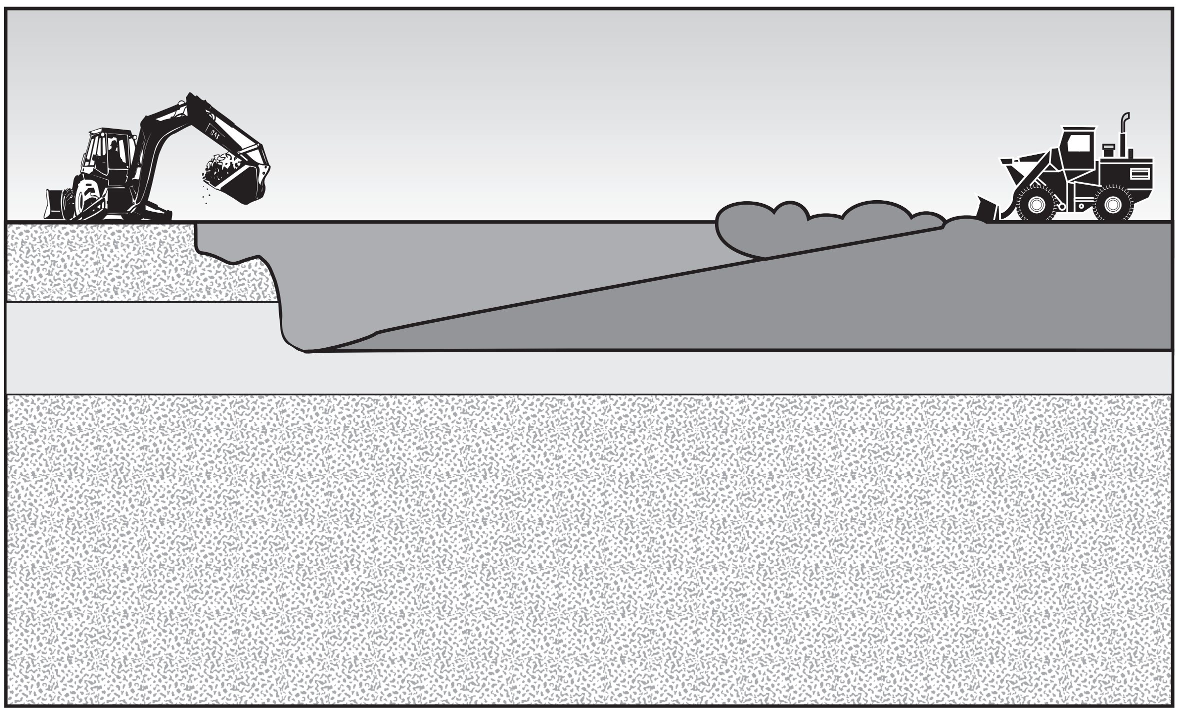
Evaluation of Subsurface Engineered Barriers at Waste Sites



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EVALUATION OF SUBSURFACE ENGINEERED BARRIERS AT WASTE SITES

NOTICE

This document was prepared for the U.S. Environmental Protection Agency's (EPA) Office of Solid Waste and Emergency Response (OSWER) under Contracts No. 68-W5-0055 and No. 68-W4-0007. The work assignments preparing this document were led by the EPA Office of Research and Development's (ORD) National Center for Environmental Assessment (NCEA), in cooperation with the EPA Office of Emergency and Remedial Response (OERR).

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FOREWORD

Subsurface engineered barriers have been used to isolate hazardous wastes from contact, precipitation, surface water, and groundwater. The purpose of this report is to provide the U.S. Environmental Protection Agency's (EPA) waste programs with a national retrospective analysis of barrier field performance, as well as information that may be useful in developing guidance on the use and evaluation of barrier systems. The report focuses on vertical barriers; evaluation of caps was a secondary objective.

The overall approach to the report was to assemble existing performance monitoring results from a number of sites, and examine those results in light of remedial performance objectives and factors that may influence performance, specifically, design, construction quality assurance/construction quality control (CQA/CQC), types of monitoring programs, and operation and maintenance (O&M) activities.

This performance evaluation report describes the performance of subsurface engineered barriers at each of 36 sites. The report discusses the performance evaluation process, including the site identification and selection process, and the availability of information upon which to base judgment of the performance of existing barriers and presents findings and conclusions, including observed similarities or trends among sites.

This document is available on the Internet at *www.clu-in.com*. A limited number or Appendices (document No. EPA-542-R-98-005a) are available from the EPA National Center for Publications and Information (NCEPI) at 1-800-490-9198.

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LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
AWQC	Ambient Water Quality Criteria
bgs	Below Ground Surface
BOD	Biochemical Oxygen Demand
BRA	Baseline Risk Assessment
BTEX	Benzene, Toluene, Ethylbenzene, and Xylene
CB	Cement-Bentonite
CCL	Compacted Clay Liner
cm	Centimeter
COD	Chemical Oxygen Demand
CQA	Construction Quality Assurance
CQC	Construction Quality Control
DBCP	Dibromochloropropane
DCA	Dichloroethane
DCE	Dichloroethene
DCPD	Dicyclopentadiene
DIMP	Diisopropylmethyl Phosphonate
DNAPL	Dense Nonaqueous-Phase Liquid
EPA	U.S. Environmental Protection Agency
FMGP	Former Manufactured Gas Plant
FML	Flexible Membrane Liner
FS	Feasibility Study
ft	Foot
GCL	Geosynthetic Clay Liner
GM	Geomembrane
gpd	Gallon Per Day
gpm	Gallon Per Minute
HDPE	High-Density Polyethylene
hr	Hour
IPA	Isopropyl Alcohol
ISSM	In Situ Soil Mixing
L	Liter
lb	Pound
LDPE	Low Density Polyethylene
LNAPL	Light Nonaqueous-Phase Liquid
MCL	Maximum Contaminant Level
mg	Milligram
msl	Mean Sea Level
NAPS	Nonaqueous-Phase Substance
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
NPL	National Priorities List
NSF	National Science Foundation

LIST OF ABBREVIATIONS (Continued)

O&M	Operation and Maintenance
OU	Operable Unit
PAH	Polynuclear Aromatic Hydrocarbon
PC	Plastic Concrete
PCA	Primary Containment Area
PCB	Polychlorinated Biphenyl
PCE	Tetrachloroethene
PCP	Pentachlorophenyl
POP	Project Operations Plan
ppb	Part Per Billion
ppm	Part Per Million
PRP	Potentially Responsible Party
psi	Pound Per Square Inch
PVC	Polyvinyl Chloride
QA	Quality Assurance
QC	Quality Control
RCRA	Resource Conservation and Recovery Act
RI	Remedial Investigation
ROD	Record of Decision
RPM	Remedial Project Manager
SB	Soil-Bentonite
SCB	Soil-Cement-Bentonite
sec	Second
SVE	Soil Vapor Extraction
SVOC	Semivolatile Organic Compound
SWMU	Solid Waste Management Unit
TAL	Target Analyte List
TCA	Trichloroethane
TCE	Trichloroethene
TCL	Target Compound List
TCLP	Toxicity Characteristic Leaching Procedure
THF	Tetrahydrofuran
TPHC	Total Petroleum Hydrocarbon
TVOC	Total Volatile Organic Compound
VLDPE	Very Low Density Polyethylene
VOC	Volatile Organic Compound
yd	Yard
mg	Microgram

EXECUTIVE SUMMARY

Subsurface engineered barriers have been used to isolate hazardous wastes from contact, precipitation, surface water, and groundwater. The objective of this study was to determine the performance of such barriers installed throughout the United States over the past 20 years to remediate hazardous waste sites and facilities. The study focused on vertical barriers; evaluation of caps was a secondary objective. This study provides the U.S. Environmental Protection Agency's (EPA) waste programs with a national retrospective analysis of barrier field performance, and information that may be useful in developing guidance on the use and evaluation of barrier systems.

The overall approach to the study was to assemble existing performance monitoring results from a number of sites, and examine those results in light of remedial performance objectives and factors that may influence performance, that is, design, construction quality assurance/construction quality control (CQA/CQC), types of monitoring programs, and operation and maintenance (O&M) efforts.

A national search was launched to locate hazardous waste sites (i.e., Superfund sites, Resource Conservation and Recovery Act [RCRA] facilities, and other hazardous waste management units) at which vertical barrier walls had been used as the containment method during a remedial or corrective action. An initial list of 130 sites was developed. A subset of sites was then selected on the basis of availability of monitoring data to enable a detailed analysis of actual field performance. Where caps were present at these sites, they were included in the study as well. Two available nonhazardous waste sites and one cap-only site with extensive data were also included to further inform the study. A total of 36 sites were analyzed in detail. It should be noted that because sites were chosen on the basis of sufficient performance-related information being available to enable detailed analysis, these sites were likely to represent the better-managed sites nationally and do not necessarily represent all sites.

For the 36 sites selected, data on design, CQA/CQC, monitoring systems, O&M, and performance results were obtained by contacting regulatory agencies, contractors, and owners of sites. Cost data were also noted where available. In some cases, owners required anonymity before releasing data to be used in the study.

Benchmarks for acceptable industry practice were then developed to enable evaluation of design, CQA/CQC, and monitoring systems. Designation of acceptable industry practices was based on a literature review, reinforced by discussions with barrier construction contractors, designers of barriers, university researchers and the best professional judgment of the project team. Each site was evaluated against acceptable practices for design, CQA/CQC, and monitoring programs. These factors were then analyzed in light of remedial goals and performance monitoring results for each site.

Performance objectives varied among the sites, from maintenance of a specific hydraulic head differential to achievement of a specific groundwater quality standard downgradient. Thus, the performance of the barriers cannot be compared to an absolute standard. The evidence showed that of the 36 sites, 8 had met and 17 may have met the performance objectives established by the owner or regulatory agency for that system. (Of the 17 sites at which performance objectives may have been met, 4 sites met the remedial objective, but long-term performance data was unavailable.) Seven may not have met performance objectives, and 6 had insufficient evidence to determine if objectives had been met. Of those that had met objectives, acceptable or better elements of design and CQA/CQC were generally utilized. Of those that had not met objectives, elements of design, CQA/CQC, and monitoring were less consistently acceptable, with insufficient monitoring programs being a common problem. Barrier failures were primarily due to underflow from the key-in horizon, and did not always correlate with insufficient design or CQA/CQC.

Major differences were found in the monitoring of the containment systems. At some sites, very little monitoring of groundwater quality and levels was carried out, while at others, monitoring well networks downgradient of the site were used to measure trends in groundwater quality and paired piezometers at a given spacing were used within 50 feet of the barrier to monitor groundwater levels. Essentially no long-term monitoring of physical samples was performed to examine mechanisms of degradation affecting the barrier. Geophysical surveys along the wall alignment were used at several sites, but were inconclusive because the available techniques cannot detect small changes in the permeability of the wall. Stress testing of the wall after construction was performed infrequently. However, monitoring data allowed the detection of leaks at four sites, and the leaks were repaired.

Of the 36 sites, 22 had caps in addition to the barrier wall. In many cases, the caps were tied into the barrier wall. One site had only a cap. Cap design varied little among the sites, and most sites met the design requirements set forth under RCRA Subtitle C. Monitoring data for caps generally were not detailed enough to evaluate performance.

Recommendations in this report to improve the performance and evaluation of subsurface engineered barriers include:

- The design of subsurface barriers and caps should be based on more complete hydrogeological and geotechnical investigations than are usually conducted. In addition, designs should be more prescriptive (as appropriate) in terms of contaminant diffusion and compatibility that could affect long-term performance.

- The CQA/CQC effort for subsurface barriers requires further development and standardization, including nondestructive post-construction sampling and testing.

- The importance of a systematic monitoring program in evaluating long-term performance of subsurface barriers cannot be overemphasized.

- Measures should be implemented to ensure the integrity of the barrier throughout its life including comparative data reviews at 5-year intervals. Such reviews should address 1) hydraulic head data (specifically, the development and maintenance of a gradient inward to the containment), 2) trends in downgradient groundwater quality, and 3) data from monitoring points at the key horizon.

A sampling protocol for use in performance evaluation of vertical barriers is provided as an appendix to this report. The protocol recommends evaluation of the performance of vertical barriers using proven and innovative monitoring techniques.

1.0 INTRODUCTION

Under Contracts No. 68-W5-0055 and 68-W4-0007, support was provided to the U.S. Environmental Protection Agency's (EPA) Office of Solid Waste and Emergency Response (OSWER) to conduct nationwide field performance evaluations of existing subsurface engineered barriers.

The purpose of this report is to provide EPA's waste programs with a national retrospective analysis of barrier field performance, and information that may be useful in developing guidance on the use and evaluation of barrier systems. The overall approach was to compile existing design, construction quality assurance/construction quality control (CQA/CQC), operation and maintenance (O&M), and performance monitoring data from a number of sites, and evaluate the data using benchmarks for acceptable industry practice relating to design, CQA/CQC, and monitoring systems. Based on this evaluation, the site's performance was determined with respect to the remedial performance objectives.

This performance evaluation report describes the performance of subsurface engineered barriers at each of 36 sites. It discusses design, installation, operation and maintenance, and overall performance. The report describes the performance evaluation process, including the site identification and selection process, and the availability of information upon which to base judgment of the performance of existing barriers and presents findings and conclusions, including observed similarities or trends among sites.

The report contains two volumes. Volume I presents the objective and scope of the evaluation report; describes the site selection process, collection and analysis of data, and evaluation of performance of subsurface engineered barriers and caps; and sets forth conclusions and recommendations. Volume II contains appendices that present a summary of engineered barriers, cap types, and construction techniques; an individual summary of each of the 36 sites included in the study; and a field sampling protocol, including sites recommended for future field investigations.

1.1 INTRODUCTION TO ENGINEERED BARRIERS

Engineered barriers are constructed containment systems that control one of the following:

- Horizontal migration of groundwater. Such barriers are referred to herein as vertical barriers. Vertical barriers typically used to control sources of hazardous waste are soil-bentonite, soil-cement-bentonite, cement-bentonite, sheet pile (steel or high-density polyethylene [HDPE]), and clay barriers. Soil-bentonite barriers are the most widely used in the United States.

- Downward migration or seepage of surface runoff and rain. Such barriers are referred to herein as caps. The caps used satisfy the design requirement set forth under Subtitle C of the Resource Conservation and Recovery Act (RCRA) and are built of clay or geosynthetic material.

1.1.1 Historical Development of Engineered Barriers

Historically, vertical barriers have been used on construction projects to prevent inflow of groundwater into deep excavations, as well as to support excavation. Sheet pile walls (first of wood and later of steel) have been installed throughout the world for many decades. The 1950s saw the development of slurry trenching technology, in which bentonite was used to support the sides of trenches under excavation before they were backfilled. That development took place independently in Europe and in the United States.

A market existed in Europe for the construction of deep excavations in urban areas adjacent to existing buildings, even historical structures. That demand created a need to develop technologies for rigid support systems and for limiting the drawdown of the water table outside the excavation to minimize subsidence. Secant pile walls first were used after World War II; later, in the 1950s, concrete slurry wall technology was developed. That development was a natural evolution of the secant wall technology, with the goal of decreasing the number of joints between piles, thereby minimizing the risk of blowouts in the mass excavation through faulty joints. By the end of the 1960s, cement-bentonite cutoff wall technology also had been developed in Europe to allow deep excavation below the groundwater table for power plants and locks, or to act as a cutoff through pervious overburden soils on dam projects. In Europe to date, the use of cement-bentonite (quite often in conjunction with a geomembrane) remains the preferred technique for seepage control, with applications including hazardous waste sites.

The development of slurry trenching technology in the United States, occurring independently from its development in Europe, took place in the late 1940s and early 1950s and was based on the use of the soil-bentonite technique (still unused in Europe). The main goal was to prevent the flow of water into deep excavations for lock and dam projects, or to minimize seepage beneath and through dams and dikes. The first industrial application of the soil-bentonite technique took place in 1950 at the Terminal Island project in California. Slurry trenches then were used extensively in the 1960s and 1970s for dam projects as permanent cutoff walls and for the construction of the Tombigbee Waterway.

More recently, by the late 1970s and early 1980s, vertical engineered barriers have been used in the United States to isolate hazardous wastes from groundwater, as slurry walls, primarily soil-bentonite cutoffs, began to be used to contain hazardous wastes. Initially, the goal was to contain contaminated groundwater for a “limited” period of time. A 30-year life span for the containment was often the objective. By the late 1980s, the concept of establishing a reverse gradient appeared. In such applications, an extraction or pumping system is installed in the contaminated zone, in addition to the peripheral cutoff wall. This approach allows maintenance of an inward flow through the wall at a very low rate. This approach has its advantages, since it decreases, if not eliminates, the risk arising from deficiency in design or installation or even localized anomalies in the aquitard layer.

In recent years, new concepts and developments in subsurface engineered systems have been introduced. Among them are:

- The funnel and gate, or permeable reactive wall: A contaminant plume is channeled between impervious vertical walls, referred to as the funnel, and flows naturally through a permeable reactive barrier gate, where the pollutants are treated in situ during the flow process.

- The use of slurry trenching technology to install a deep groundwater extraction trench, instead of an impervious cutoff wall: The slurry used to support the trench is made from a biodegradable material (instead of bentonite, which would reduce flow to the trench). After excavation, the trench is backfilled with a pervious material, and the slurry filling the voids of the pervious material biodegrades. Drains installed by this biopolymer method typically are from 20 to 50 feet deep, and sometimes deeper.

Quite recently, engineers began to be concerned not only about the hydraulic transport of contaminants, but also about the diffusion of contaminants through vertical barriers, a chemical process. This issue is crucial for the long term (usually considered to be well in excess of 30 years), in terms of the integrity of vertical barriers. New technologies are emerging to increase the sorption capacity of vertical barriers, primarily through the use of additives in the backfill materials.

In addition, improvements in barrier construction technology allow the installation of vertical barriers to depths as much as 400 feet, through various soil and rock conditions, and in hostile environments (such as brackish water and water contaminated with chemicals).

Caps have been used to prevent the downward flow of surface runoff and precipitation inside contaminated sites. The concept is similar to the use of impervious blankets on the upstream slope of a dam. At first, caps included clay blankets. The introduction of chemically resistant geosynthetic materials that have minimal diffusive conductivity has significantly improved the quality and the ease of installation of caps. Caps have been used at sites as large as 400 acres.

1.1.2 Types of Engineered Barriers

Engineered barriers, as discussed in this report, are vertical barriers and caps. Appendix A provides details of the design, construction, and construction quality assurance (CQA) and construction quality control (CQC) for vertical barriers and caps. Significant features of vertical barriers and caps are discussed below.

Note: This study does not include engineered bottom barriers, a recent development in which an impervious horizontal stratum is created below a hazardous waste site, when no aquitard exists, by grouting or other techniques now in the developmental phase.

Vertical Barriers

Vertical barriers control the subsurface flow of water into or out of a hazardous waste site. They are classified into various categories. The most common ones are briefly discussed below:

Barriers Installed with the Slurry Trenching Technology: Such barriers consist of a vertical trench excavated along the perimeter of the site, filled with bentonite slurry to support the trench and subsequently backfilled with a mixture of low-permeability material (1×10^{-6} cm/sec or lower) (see Figure 1-1). Such walls are keyed into an aquitard, a low-permeability soil or rock formation, or a few feet below the groundwater elevation when the objective is to contain light nonaqueous phase liquids (LNAPL). Significant features of a vertical barrier are, at a minimum:

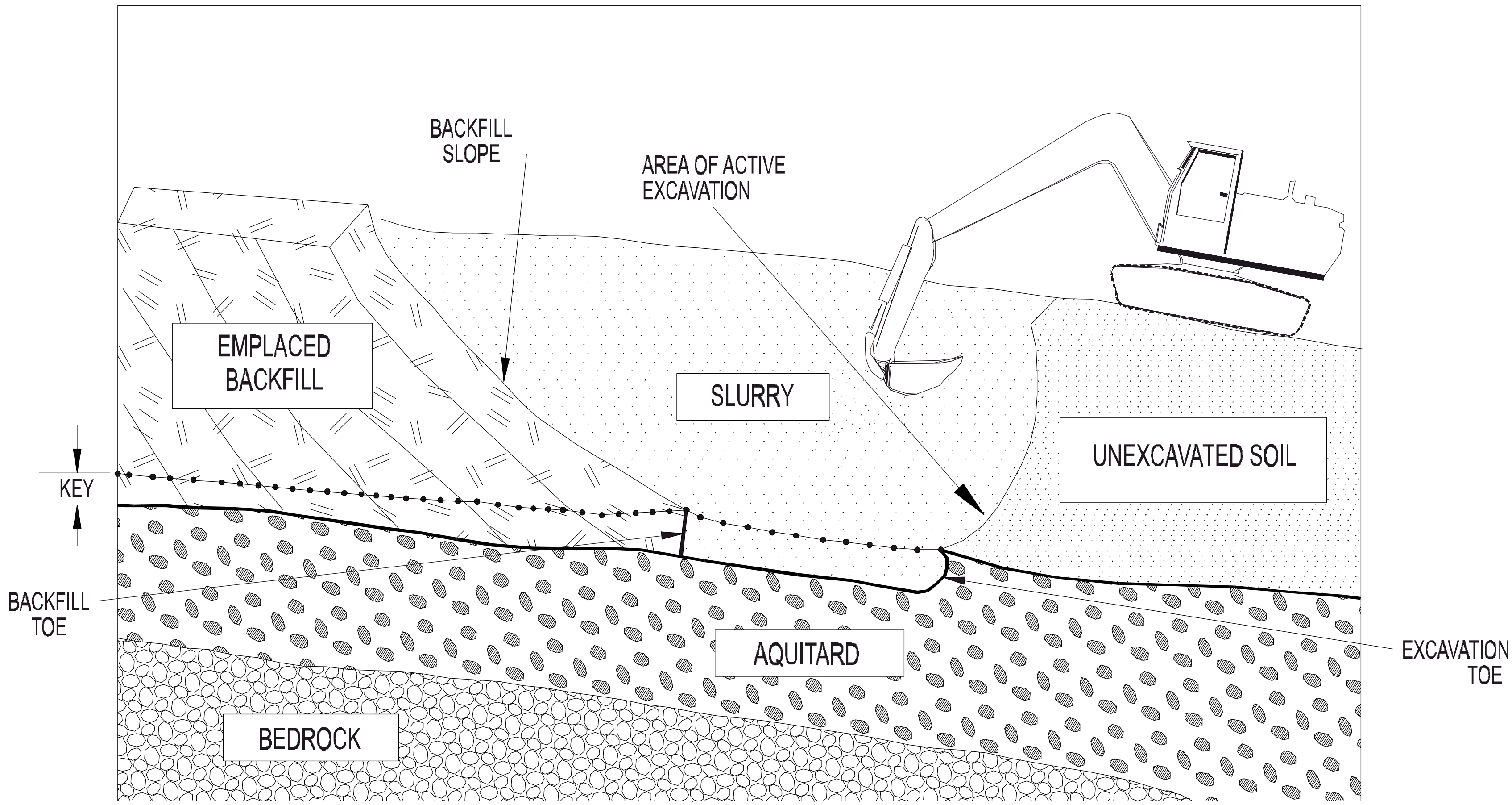

FIGURE 1-1

SOIL-BENTONITE SLURRY

TRENCH CROSS-SECTION

- Continuous wall of uniform low permeability
- Sufficient thickness to withstand earth stresses and hydraulic gradients and to provide long-term sorption capacity
- Wall backfill compatible with the groundwater quality and chemistry in the vicinity of the wall
- Continuous key, typically of 2 to 5 feet into the low-permeability soil or rock formation, if feasible (the quality of the key material can be verified continuously during excavation of the trench)

As stated previously, the most widely used technique for containment is the soil-bentonite slurry wall. It is typically the most economical, utilizes low-permeability backfill, and usually allows reuse of all or most of the material excavated during trenching. The low-permeability backfill is prepared by mixing a bentonite slurry with the excavated native soils. Sometimes, additional borrow materials or dry bentonite is added to the mixture to meet the design requirements. Recently, specialty additives have been used to increase the sorption capacity of the backfill.

In the United States, cement has been added to the soil-bentonite backfill on a few projects to impart strength to the wall, when that attribute was required by the site conditions. Such walls are called soil-cement-bentonite walls. The technique also has been used on a few conventional civil engineering projects at which loading conditions require a stronger barrier. Unfortunately, the addition of the most common types of cement, such as Portland, increases the permeability of the backfill.

Cement-bentonite and even concrete slurry walls also are used for containment when they are required by the site conditions. The techniques reduce the length of excavations held open under slurry at any given time and provide a backfill that exhibits strength. Typical applications would be trench excavation adjacent to an existing structure or through soft or unstable soil.

Thin Walls: These walls usually are installed by vibrating a beam to the aquitard that injects a backfill mixture, usually cement grout, when the beam is extracted. The design concept provides for overlap between beam imprints. Recent technological developments have allowed improved control of the overlap between joints and increased driving depth and thickness by the use of jetting. The effective width of such barriers is in the range of 8 to 10 inches.

Deep Soil Mixing: These barriers consist of overlapping columns created by a series of large diameter counter rotating augers mixing in situ soils with additives, usually bentonite or cement grout, which is injected through the augers.

Grout Walls: These barriers are installed by grouting or jet-grouting the soils. Grout walls or "curtains" have been used extensively in the past for civil engineering projects, but less frequently at hazardous waste sites. They are usually more expensive than other techniques and the barriers have higher permeability. However, grout walls are capable of extending the key of other types of subsurface barriers through bedrock.

Sheet Pile Walls: These barriers traditionally have consisted of steel sheeting with some type of interlock joint. Recently, such sheeting includes an improved interlock design to accommodate sealing of joints; several innovative techniques have been developed recently to seal and test the joints between sheet piles. In addition, plastic has been substituted for steel in a number of applications (see Figure 1-2).

Liners: Liners also have been used as vertical barriers, either alone or in conjunction with slurry walls.

A main concern in the application of these technologies is control of the key into the aquitard. It should be noted that the slurry trench excavation method is the only one that permits visual inspection of the key material and assurance of the key-in depth during construction. Appendix A describes construction methods used to install vertical barriers.

The applicability of a particular method at a site depends on the in situ groundwater conditions, soil and rock conditions, permeability desired, depth of installation, presence of adjacent structures, and cost considerations. For example, at one site studied, two walls were installed. The outer wall was constructed by the slurry trench excavation and backfill method as the primary barrier to migration of contaminated groundwater. An inner wall also was constructed by the vibrating beam method to limit the area of active (that is, pumping) containment.

Caps

To meet the performance standards set forth under RCRA Subtitle C, the cap design should include the following layers (EPA 1989):

- A base soil layer to support the other layers
- A low-permeability layer (1 x 10^{-7} cm/sec or less)
- A drainage layer
- A soil cover, including a vegetative layer

A gas collection and venting layer maybe required to control contained gases, such as methane. The gas collection layer typically is constructed of granular soils and collection and vent pipes. The low-permeability layer is constructed of clays and geosynthetic material (geosynthetic clay liners as a substitute for clay and geomembranes). The drainage layer is constructed of granular soils, or geosynthetic materials, and the soil cover usually is silty soils. The vegetative layer consists of topsoil that supports vegetation. In industrial areas, a parking lot or other alternative surface can be constructed over the soil cover. Appendix A provides details of typical cap design, construction, CQA/CQC, and cost.

1.1.3 Previous Studies

Previous studies have focused on the performance of caps, especially the stability of caps in cases in which geosynthetic materials are used (EPA 1993). The performance of different low-permeability soil mixtures for use in vertical barriers has been studied to a lesser degree, but some notable works are available (U.S. Army Corps of Engineers [USACE] 1996; Evans 1994).

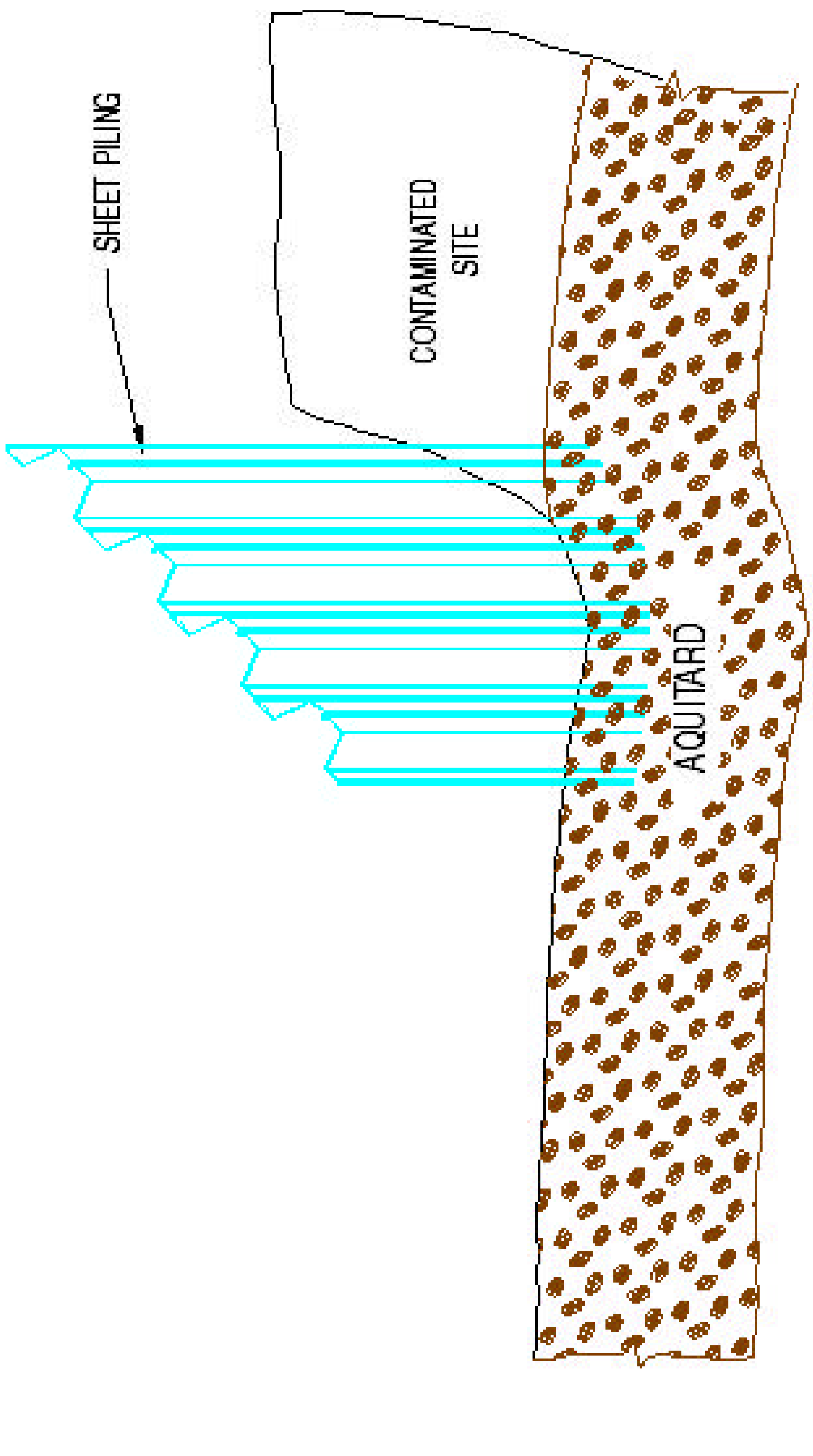

FIGURE 1-2

SHEET PILE BARRIER

This study strives to build upon those early works, rather than repeating them, and draws heavily upon the results of the identification of more than 160 sites and performance of detailed evaluations of 36 sites.

1.2 OBJECTIVE OF THE STUDY

The objective of this study is to perform a national retrospective analysis of the field performance and effectiveness of engineered containment barriers, including innovative and emerging technologies. The emphasis of the study is on the performance of vertical barriers; however, the performance of caps used in conjunction with vertical barriers also is evaluated. The factors that affect performance of containment systems, especially design, CQA/CQC, and operation and maintenance, are evaluated in detail for 36 sites and their performance determined. The study also analyzes monitoring techniques used to measure performance.

1.3 SCOPE OF STUDY

The scope of this study is to analyze performance of vertical barriers and caps (if present at the site) at sites for which sufficient data on performance were available. The four primary tasks completed during the study are described briefly below.

1.3.1 Site Selection

A nationwide search was launched to identify representative contaminated sites at which vertical barriers or caps had been used as the containment method during the remedial action. To determine what lessons could be learned about the performance of vertical barriers, a few nonhazardous waste sites for which large quantities of performance data related to the vertical barrier were available also were identified. An initial list of 162 sites was developed. On the basis of availability of performance data and several other criteria, 36 sites were selected from among them for detailed analysis of actual field performance.

1.3.2 Data Collection

For the 36 sites selected, data on design, CQA/CQC, performance monitoring, operations and maintenance (O&M), and cost were obtained by contacting regulatory agencies, contractors, and owners of the sites. Very large quantities of performance data were obtained for certain sites that had been constructed in the 1980s, while only limited performance data were obtained for other sites.

1.3.3 Determination of Existing Industry Practices

The project team reviewed available literature, in conjunction with the analysis of data obtained from the 36 sites. That research was reinforced further by discussions with constructors and designers of vertical barriers and with university researchers. The team established standard industry practice through examination of the information collected and the authors' experience and professional judgment. For the performance evaluation, a matrix of industry practice was developed and used as a reference in comparing the performance of individual sites.

1.3.4 Performance Evaluation

The performance evaluation included assessment of the performance of barriers at individual sites in light of regulatory performance standards, as well as comparison of standards and performance among the several sites. Available historical monitoring data, primarily those on groundwater quality and hydraulic head, were reviewed to determine the short-term and long-term environmental improvement provided by the containment and to determine whether regulatory standards and performance objectives were being met effectively. Performance, as measured against these standards and objectives, was compared among the sites.

In addition, available data describing criteria for containment design, CQA/CQC, monitoring, and O&M were evaluated to assess how each criterion affected performance of the containment barrier. All sites were compared to assess any trends between the site criteria and performance among the sites studied. The results of the performance evaluation were summarized to identify common elements among the sites or containment types that contribute to performance as well as noted pitfalls of performance or contributory criteria.

1.4 LIMITATION OF THE STUDY

This study focused on U.S. sites for which data were readily available. In addition, most barriers in the study have been in place for fewer than 10 years; therefore, long-term performance can only be extrapolated.

All sites included in the study were existing sites that had vertical barriers and, in many cases, caps. None of the sites has an engineered bottom barrier. Therefore, the effect of leakage through aquitards was not evaluated in this study.

Another limitation of the study was that existing available data rather than primary data were used; therefore, the analysis in this report is based on the assumption that published or publicly available data used for this study were collected and reported properly. In addition, surrogate factors or indicators of performance, such as design, CQA/CQC, and monitoring results, were used to evaluate sites. However, releases have occurred from sites that have exemplary design, CQA/CQC, and monitoring systems. Further, some releases may go undetected.

Some site owners required anonymity before they would release data; therefore, sites evaluated in this study are not identified by name.

2.0 SITE SELECTION

Selecting sites for the nationwide assessment of field performance of existing subsurface engineered barriers involved identifying sites at which engineered barriers are in use and determining whether performance data are available for those sites. After identifying sites that have engineered barriers, the project team developed criteria for selecting as many as 40 sites for evaluation of the performance of the barriers. Sites were selected on the basis of the amount and type of performance data available, as well as pertinent criteria, such as type of barrier technology, installation techniques, geographic and geologic distribution, age of the barrier containment system, and nature of the contamination at the site.

This section describes the identification and selection process used in choosing the sites at which the performance of subsurface engineered barriers would be evaluated. This section also discusses the limitations of the site selection process.

2.1 SITE IDENTIFICATION

To choose appropriate sites that had subsurface engineered barriers, the project team identified more than 160 sites at which subsurface engineered barriers were known or believed to be in place. The project team identified the sites through an open international literature search, as well as through extensive academic, industry, and government contacts and published sources.

2.1.1 Literature Search

An international open literature search was conducted to identify information available about the use and performance of subsurface engineered barriers. The purpose of the literature search was to document the status of existing subsurface engineered barriers, as well as to identify available information on the design, installation, operation and maintenance, and overall performance of subsurface engineered barriers. Terms commonly associated with subsurface engineered barriers (such as slurry walls) were used in conducting the literature search.

The DIALOG service of Knight-Ridder Information, Inc. was used to conduct the on-line literature search. DIALOG provides a one-step search that covers millions of documents drawn from scientific and technical literature, as well as from trade journals, newspapers, and news services. According to Knight-Ridder, DIALOG draws from more sources than any other on-line service.

The group of files selected for the on-line literature search was "all science," consisting of 174 files. Each of the 174 files was searched for the following key words and phrases:

- Engineered barriers
- Groundwater barriers
- Hydraulic barriers
- Subsurface barriers
- French drains
- Slurry wall(s)
- Groundwater cutoff wall(s)
- Groundwater dewatering

The project team searched for the years 1980 to the present. To identify available international bibliographic information. the search covered sources in English and in other languages, such as French, German, and Japanese.

The key words and phrases identified above were found in 81 “all-science” files. Most of those files showed few matches and were eliminated from further searches. Some files were newsletter files that, although they identified companies that used subsurface barriers, were not technical in nature. Those files also were eliminated from further searches. Five files were selected for the continuation of the on-line search National Technical Information Service (NTIS), Compendex Plus, Fluidex (Fluid Engineering Abstracts), Energy Science and Technology, and Water

Resources Abstracts. In the second step, the matches obtained through the first search were searched using the following key words:

- Performance
- Monitoring
- Evaluation
- Effectiveness
- Efficiency

The project team printed and reviewed the bibliographic results of the second search. The team then requested abstracts of 92 of the documents for further review. In addition to conducting the on-line literature search, the project team identified a number of applicable reference texts, guidance documents, and journal articles.

The project team also conducted an on-line search of the EPA Record of Decision System (RODS) database for the years 1980 to the present, using the same key words that were used for the DIALOG search. Abstracts obtained from RODS were reviewed to determine the status of remedy implementation and to identify sites at which engineered barriers had been installed.

2.1.2 Industry Sources

The project team also contacted a number of academic, industry, and government sources to identify sites at which existing subsurface engineered barriers were in use. Industry sources included:

- Site owners and operators
- Barrier design and engineering firms
- Barrier installation contractors
- Environmental consultants

Those sources, as well as the academic and government sources contacted, not only were able to identify sites at which subsurface engineered barriers had been installed, but also were able to identify sources of data for the sites and information about the performance of engineered barriers.

2.2 SITE SELECTION CRITERIA

To select approximately 40 sites for more detailed evaluation, the project team screened the sites identified to ascertain the extent and type of performance data that were available for each. Specifically, the criteria that represent factors crucial to the evaluation of the performance of engineered barriers were applied to screen the sites. The principal criteria represent data on monitoring, design, and CQA/CQC. Monitoring data provide a measure of the performance of a barrier at a specific location or point in time. Data on barrier design and CQA/CQC are extremely important because of the direct relevance that design and CQA/CQC have on performance of the barrier. Other relevant (but not crucial) criteria include type of barrier; geologic setting and distribution; whether the barrier is integrated with a cap or active pumping; and other considerations or features, such as innovative or emerging barrier technologies. The intent of the selection process was to identify a cross-section of barrier technologies and locations. The criteria are described below.

2.2.1 Availability of Adequate Monitoring, Design and CQA/CQC Data

Accurate and adequate monitoring data are essential to the evaluation of the performance of subsurface engineered barriers. The extent of monitoring varies from site to site, depending on the purpose for which the wall was installed. Types of monitoring data collected at sites include:

- Hydraulic head, within and outside the wall
- Groundwater quality, within and outside the wall
- Settlement of the top surface of the wall
- Verticality of the wall

At some cutoff walls installed at dam sites, geotechnical instruments, such as inclinometers, stress cells, electric piezometers, and survey markers, are installed to monitor the long-term behavior of the wall. However, at most hazardous waste containment sites, only the first two types of data (that is, hydraulic head and groundwater quality) are collected. The frequency with which such data are collected depends on how recently the barrier was installed and the stage of monitoring. Groundwater level and groundwater quality data generally are collected quarterly or even monthly after installation of the barrier. The frequency of data collection is reduced once a data trend or new baseline has been established.

Design data also are crucial in evaluating the performance of the barrier. Indeed, barrier design objectives establish performance standards, as well as performance monitoring approaches. For most sites, a complete design report is available that includes the drawings and specifications. However, the quality of the design report varied from site to site. The report might set forth the basis of the design, calculations, value engineering, and performance monitoring requirements after construction.

The performance of a barrier wall is also highly dependent on the CQA/CQC program followed during installation. For example, if a subsurface barrier is keyed into a substratum incorrectly, the containment system ultimately could fail, despite adequate design. Therefore, sufficient CQA data are crucial in assessing the performance of a barrier. The installation contractor's quality control testing, independent CQA/CQC inspection and testing, and documentation by the engineer are components of the CQA/CQC program.

2.2.2 Representativeness Regarding Types of Barriers

Several types of barriers were considered for the study, including soil-bentonite walls and variations of such walls, funnel-and-gate systems, and sheet piling systems. A range of typical performance characteristics is associated with each type of barrier. Although most of the sites considered for detailed evaluation had soil-bentonite subsurface barriers, an attempt was made through application of this criterion to select examples of different barriers.

2.2.3 General Geologic Distribution

Ideally, the performance of subsurface engineered barriers should be evaluated in a variety of geologic settings. However, a majority of the sites that were identified for this study are located in the eastern United States, because barrier walls have been used more often for waste containment at Superfund sites in EPA Regions 1, 2, 3, and 4 than in other areas of the country.

Nevertheless, to ensure a wide geographic distribution, some sites in the Midwest, Rocky Mountain states, California, Washington, and the South were identified and selected. (Because the geologic setting would be determined during the detailed evaluation phase of the project geographic distribution was used as a surrogate for geologic setting in screening sites.)

2.2.4 Unique Features

Other features, such as a unique hydrogeologic setting or a relatively new technology incorporating geomembranes, were considered in selecting the sites. Consideration of those features was used as a screening criterion to reflect state-of-the-art developments, such as innovative and emerging technologies. This criterion also includes other factors, such as lessons learned from the use of a variety of containment systems in specific applications and settings.

In addition, availability of cost information and determination that the engineered barrier was part of an integrated system (including a cap and active pumping from within the wall) were used as screening criteria.

2.3 SELECTION PROCESS

The project team was able to identify 162 sites at which engineered barriers were known or believed to be in place. They included sites listed on the National Priorities List (NPL), as well as municipal landfills and sites at which corrective actions had taken place under RCRA. Several sites identified were dam sites or other sites that required cutoff or containment of water, but did not contain any hazardous constituents or contaminants. The project team assembled a list of items about which information was to be collected, including the name and location of each site, the type of barrier present, the type of monitoring conducted, and other pertinent information.

2.3.1 Results of Initial Search

Of the 162 sites identified, 10 had only a cap as an engineered barrier; that is, there was no vertical barrier at the site. Although one of those sites would be included for detailed evaluation of performance, it would be evaluated separately from sites having vertical barriers. A number of other sites were eliminated because of such factors as:

- The record of decision (ROD) had been changed to specify a different remedy.
- Hydraulic control was achieved through pumping alone (usually because of a change in remedy); no subsurface engineered barrier existed.
- The owner or operator of the site was not obliged to and did not wish to participate in the study.

In all, 32 sites were eliminated from further consideration. Thus, the number of sites considered for more detailed evaluation for subsurface engineered barriers became 130.

2.3.2 Sites Selected for Detailed Evaluation of Performance

For each criterion discussed above, the site was ranked on a scale from 1, indicating that data were not available or were not well defined, to 5, indicating that good quality data were available. For each site, the ratings were assigned by the project team member who was most familiar with the site. Project team members relied upon professional judgment to determine the rating under each criterion. As a result, only those sites for which sufficient data were or were likely to become available for analyzing the performance and effectiveness of the subsurface engineered barrier were retained for detailed evaluation.

The criteria have different degrees of importance in evaluating the performance of containment systems. Therefore, a weighting system was used to reflect the relative importance of each criterion. Availability of monitoring data is crucial to a meaningful evaluation of the performance of the barrier wall; that criterion therefore was given a weighting of 35 percent. The weighting of the criteria related to availability of data was established as follows:

Criterion	Weighting (percent)
Monitoring data	35
CQA/CQC data	15
Design data	15
Barrier type	10
Unique features	10
Cost data	5
Geographic distribution	5
Integrated system	5

As a result of the ranking and weighting of criteria, the 130 subsurface engineered barrier sites were assigned a priority according to their high, medium, or low potential for selection as one of the 40 sites for which detailed evaluation of performance would be conducted. Assignment of priority was based on the professional judgment and experience of the project team. In addition, some sites that had been designated as medium potential were included in the high potential category (at least through the data collection phase of the project) to increase the geographic distribution of sites or types of barrier included. Ultimately, 36 sites were selected for detailed evaluation, including one cap-only site.

2.4 LIMITATIONS OF THE SELECTION PROCESS

The list of 162 sites at which engineered barriers were believed to be in place was not considered a comprehensive compilation of sites at which subsurface engineered barriers may have been installed. Rather, the list reflects the consensus of the project team about a representative sample of enforcement, RCRA, municipal landfill, and dam sites at which subsurface barriers are in use.

Further, because the selection process emphasized the availability of adequate monitoring, design, and CQA/CQC data (as well as the other criteria), the sites selected for detailed evaluation generally represent the best monitored and documented sites. Therefore, the sites selected for detailed evaluation are, by definition, not representative of subsurface engineered barrier sites. For example, although 10 cap-only sites originally were identified, only 1 cap-only site was selected for detailed evaluation because little (if any) performance monitoring data were available for the other cap-only sites. In addition, because data collection ceased for a site once it had been categorized as medium or low priority, it would be difficult to quantify the amount of data that do not exist for sites not selected for detailed evaluation.

3.0 DATA COLLECTION AND ANALYSIS - VERTICAL BARRIERS

The site selection process described in Section 2 identified 36 sites to be analyzed in detail. Data collection and analysis were performed for those 36 sites so that site summaries could be prepared. The summaries, provided in Appendix B, highlight:

- Description and history of the site
- Geologic setting
- Nature and extent of contamination
- Containment remedy
- Performance evaluation

General site information, as described above, provided the background necessary to evaluate more specific performance-related criteria. Data were collected that describe four specific performance-related criteria: design, CQA/CQC, monitoring, and O&M. Those data were analyzed to determine performance of the containment and compare it with design objectives. Monitoring data, typically surrogate information about groundwater quality and hydraulic head, provided the measurements that were analyzed to estimate the containment performance relative to the established regulatory performance standards. In addition, monitoring was reviewed to assess the ability of the prescribed monitoring to measure performance adequately. Design, CQA/CQC, and O&M were analyzed to evaluate their contribution to short- and long-term performance.

An industry standard baseline was established for design, CQA/CQC, and monitoring to aid in the comparison and evaluation of the sites. The baseline was determined from experience, data sources, and published guidelines. The baseline enabled the project team to assign a comparative rating to specific criteria for an individual site. The evaluation team then could identify unique aspects of the three criteria that could be viewed readily in the subsequent performance evaluation. The objective was to recognize the possible contribution of criteria or subcriteria to containment performance. A secondary objective of the analysis was to better understand the variability of specific subcriteria among the sites evaluated.

Section 3.1 briefly describes the content of each of the categories listed above. Sections 3.2, 3.3, 3.4, 3.5, and 3.6 describe the design, CQA/CQC, performance monitoring, O&M, and cost of barriers.

3.1 GENERAL INFORMATION ABOUT THE SITES

Geotechnical and hydrogeological investigation reports, remedial design documents, remedial action completion reports (including as-built drawings), quarterly monitoring reports, and other available data were obtained for 36 sites, as described above. The data in those reports were analyzed to prepare the site summaries, with particular emphasis on performance evaluation criteria. Table 3-1 provides a summary of the sites by type of barrier, cap, and extraction system.

TABLE 3-1
CONTAINMENT SYSTEMS SUMMARY

Site	Barrier Type									Cap				Extraction System		
	Year Installed	SB	CB	SCB	Clay	Concrete	Sheet Pile	Plastic Concrete	Vibrating Beam	RCRA	Clay	Soil	Asphalt	Pumping Wells	Leachate Collection	Drains
1.	1989	●									●			●	●	
2.	1981	●									Under Construc-tion		●			
3.	1987/89	●								●						
4.	1993	●								●					●	
5.	1991				●						●				●	
6.	1993	●								●				●		
7.	1990	●									●				●	
8.	1989/94						●								●?	
9.	1995	●													●	
10.	1983	●												●		
11.	1992	●		●						●				●	●	●
12.	1991								●			●				
13.	1984									●				●		●
14.	1987							●						●		
15.	1984/89	●										Proposed		●	●	
16.	1981		●				Existing					●				
17.	1991	●								●				●	●	●
18.	1994	●								●				●		
19.	1982	●								●				●	●	
20.	1996	●								Under Construction				Under Construction		
21.	1994	●								●						
22.	1991	●								●						

TABLE 3-1 (Continued)
CONTAINMENT SYSTEMS SUMMARY

Site	Barrier Type									Cap				Extraction System		
	Year Installed	SB	CB	SCB	Clay	Concrete	Sheet Pile	Plastic Concrete	Vibrating Beam	RCRA	Clay	Soil	Asphalt	Pumping Wells	Leachate Collection	Drains
23.	1984															
24.	1990	•								•				•		
25.	1989	Hanging wall •														
26.	1977	•									•					
27.	1990	•								•				•		
28.	1986	•											•	•		
29.	1986	•								•				•		
30.	1991	• Primary							• Intermediate	•				• Intermittent		
31.	1986	•												•		•
32.	1989	•								•				•	•	
33.	1994		•	• Treat-ment Wall												
34.	1988	•														
35.	1994					•		•		•				•		
36.	1992									•					•	

Note: SB = Soil bentonite
CB = Cement bentonite
SCB = Soil cement bentonite
RCRA = Resource Conservation and Recovery Act Subtitle C

The summaries in Appendix B, Volume II contain the following sections, based on information available by mid-April 1997.

3.1.1 Site Description and History

This section describes the history of waste disposal activities at the site and the physical setting of the site. The dates of investigation, remedial design, and remedial action are presented, and the remedy is described.

3.1.2 Geologic and Hydrogeologic Setting

The geologic setting, site stratigraphy, and hydrogeologic units present at the site are described. The rate and direction of groundwater movement, the existence of an aquitard formation, and any surface-water features are indicated in this section.

3.1.3 Nature and Extent of Contamination

The types and concentrations of contaminants found in the soil and groundwater at the site are described in this section. The amount of contamination found in monitoring wells outside the containment system also is indicated.

3.1.4 Containment Remedy

Key components of the remedy implemented at the site are identified in this section, with emphasis on any unique features. The objective of the containment remedy also is stated, so that the performance could be evaluated on the basis of the remedial objective.

3.1.5 Performance Evaluation

This section contains all the information available about the design, CQA/CQC, monitoring, O&M, and cost of the remedy, rated against the "established" industry practice for design, CQA/CQC, and monitoring of vertical barriers and caps (if data on a cap were applicable and available). The monitoring data were examined, often replotted, and analyzed. Performance was indicated by monitoring data reviewed and evaluated against the remediation objective, and the contributions of design, CQA/CQC, monitoring methods, and O&M to performance were determined.

3.2 DESIGN

The design of an engineered barrier system outlines the functional criteria and objectives of the system. The design documents provide the constructor of the system with the detailed drawings, specifications, CQA and CQC requirements during implementation of the design, and O&M requirements, as well as a monitoring plan and a schedule for the installation. Therefore, understanding the design and analyzing the design data are important in evaluating the performance of the barrier.

The importance of proper design to achieving the intended objective and performance of a barrier wall cannot be overemphasized. USACE recognized that fact in its guidance document for barrier walls (1996). This section will define the components of the design and discuss the design matrix that was used in this study to evaluate the design of the engineered barriers.

The primary objective of subsurface barriers is to provide hydraulic isolation of the material enclosed by the barrier. (As discussed in Section 1.1.1, recent uses of permeable reaction walls and deep extraction trenches are notable exceptions.) The barrier must limit lateral inflow or outflow and must neither degrade nor allow diffusion of target contaminants through the barrier during its design life. The design should consider the following factors, which will be described in this section.

- Hydrogeologic investigation
- Determination of feasibility
- Geotechnical investigation
- Details of the barrier design, such as alignment and depth of key
- Development of monitoring program

For this study, those factors and associated subfactors were identified, and the acceptable industry practice was identified for each factor and subfactor. Acceptable industry practice was obtained from several sources, including available guidance documents or texts (USACE 1996; Evans 1994; D'Appolonia 1980; Barvenik 1992; McCandless and Bodocsi 1987; EPA 1984), discussions with engineers and contractors, findings of reviews of sites investigated, and the authors' experience. Table 3-2 presents a matrix summarizing acceptable industry practice. The matrix was used to evaluate the 36 sites selected for the study to determine whether the design effort for the site was acceptable, less than acceptable, or better than acceptable, when compared with industry practices. Subsection 3.2.5 discusses the range of findings about the sites.

The following discussion of barrier design focuses on slurry trench constructed soil-bentonite barriers because such barriers are most prevalent and represent the majority of the evaluated sites. However, many of the design subcriteria are equally applicable to other vertical barrier designs.

3.2.1 Hydrogeologic Investigation

The hydrogeologic investigation should define the subsurface stratigraphy and the hydraulic conductivity of the aquifer and underlying impermeable zones. The hydrogeologic investigation of a typical site includes, at a minimum:

- Soil and rock borings to define stratigraphy, particularly the extent and properties of an aquitard bottom (that is, a confining unit)

- Groundwater sampling from monitoring wells and piezometers to define the water quality and aquifer heads

- Testing of aquifers to define the hydraulic conductivity of the water-bearing zones and the extent of the contaminant plume

TABLE 3-2
MATRIX FOR EVALUATING BARRIER DESIGN AGAINST ACCEPTABLE INDUSTRY PRACTICES

Category	Less than Acceptable	Acceptable	Better than Acceptable
Hydrogeologic Investigation	None	Yes*	>
Feasibility Determination	None	Yes**	>
Geotechnical Design Investigation			
Borings along alignment	1 boring/>200 ft	1 boring/100-200 ft***	1 boring/<100 ft
Geotech. physical testing	None	Yes****	>
Barrier Design			
Groundwater modeling	No Modeling	Feasibility Modeling	Design Performance Modeling
Alignment & key depth+	<2 ft	2-4 ft Key	>4 ft
Wall thickness/hydrofracture	<2 ft	2-4 ft	>4 ft
Trench stability & analysis	None	Analytical	Numerical
Backfill permeability			
testing/optimization	<3	3 Tests	>3
Trench slurry compatibility	<3	3 Tests	>3
Long term backfill compatibility	<3	3 Tests	>3
Barrier penetration details	None	Contractor Designed	Designer Designed
Cap/barrier interface	None	Component Overlay	Physical Connection
Protection from dessication	<1 ft	1-2 ft Clay Cap	>2 ft
Protection from surface loading	None	Spanning Elements	>
Protection from subsurface breach	None	Physical Protection	>
Sediment & erosion control	None	Contractor Designed	Designer Designed

* Documentation of hydrogeological investigation necessary to establish design parameters was available .

** The feasibility determination was based on adequate geological and hydrogeologic site data.

*** Spacing of borings depends on geologic variability at the site

**** Representative gradation, limits, unit weight and key permeability.

\+ Soil key shown. Rock key rated less than acceptable (to fractured bedrock-no grouting), acceptable (0.5-1.0 ft into sound rock) better than acceptable (more than 1 ft into sound rock).

Most remediation projects at hazardous waste sites use a design life of 30 years. The durability of construction materials used to install barrier walls at contaminated sites still is being evaluated for that period.

At a minimum, the investigation report should include the direction and rate of groundwater flow and the extent and properties of the low-permeability zone, as those properties will affect the key-in of the vertical barrier.

At 23 of the sites, thorough hydrogeological investigations were conducted to identify the aquifer and aquitards; at 11 of the sites, the hydrogeological investigations was adequate. For 2 of the sites, the extent of the hydrogeological investigations could not be determined.

3.2.2 Determination of Feasibility

The hydrogeologic investigation provides the data necessary to determine whether a vertical barrier is technically and economically feasible for the site. Determination of feasibility is completed before, or sometimes during, the geotechnical investigation.

3.2.3 Geotechnical Investigation

The successful design and construction of a barrier wall requires that geotechnical data be collected along the alignment of the barrier wall. Typical industry practice is to obtain closely spaced soil samples from the surface to the bottom of the wall, usually an impermeable layer necessary to establish a good key-in and prevent underflow. The primary objectives of the geotechnical investigation are to:

- Determine that a continuous aquitard exists and determine its elevation along the slurry wall alignment

- Determine the elevation of the groundwater and the presence of any artesian conditions

- Determine the physical properties of the soils through which the trench will be excavated

To collect the soil samples, borings usually are drilled at 100- to 200-foot intervals along the alignment so that the variations in soil horizons can be established. Tests completed on soil samples generally include those for gradation, Atterberg limits, unit weight and moisture content, and permeability of the key-in horizon. For sites that are found to have geologic variability, the borings are completed at intervals of less than 100 feet, and extensive testing of soil samples is conducted to establish the subsurface conditions. Similarly, borings may be farther apart if geologic strata are consistent. For sites having very uniform geology, the spacing between borings may exceed 200 feet.

The information obtained through the geotechnical investigation is extremely important. It allows the designer to determine that the use of a vertical barrier is technically and economically feasible and to select the most appropriate type of barrier. The contractor also uses the information to select the equipment required for the excavation of the barrier trench, as well as the rate of production, and to estimate whether all or some of the excavated material can be reused for the impervious backfill.

Of the sites studied, 10 had borings at approximately 100-foot spacing, 4 had borings at 200-foot spacing, and 1 had borings at 300-foot spacing. For the other sites, the design report did not specify the spacing of the geotechnical borings; however, for all the sites, the geotechnical investigations were adequate to thorough. At some sites, a geophysical survey was used to supplement the geotechnical drilling program.

3.2.4 Detailed Design of the Barrier

The design of the barrier is dependent on the remedial objective for the site. The study identified several important elements involved in barrier design; those elements are discussed below.

Groundwater Modeling

The extent of groundwater modeling for a site can vary from no modeling to detailed finite-element modeling to predict the performance of the design. Highly complex hydrogeology may require extensive modeling, while small sites or simple hydrogeological conditions may require no modeling. However, acceptable industry practice is to use modeling to establish the feasibility of constructing the barrier wall. If performance modeling of the design is completed, and the modeling was further calibrated using postconstruction data, the site was considered better than acceptable, compared with industry practices.

For 15 of the sites studied, groundwater modeling was completed as part of the design effort. The extent of the modeling varied from a limited amount to define the flow pathways to a numerical model to predict the effect of a reactive barrier on groundwater quality downgradient of the site. The use of modeling and the extent of the modeling effort seems to have been dependent on site conditions and requirements imposed by the state or federal regulatory authority.

Alignment of the Wall

The alignment of the vertical barrier should be outside the contaminated zone. Such alignment is not always possible because of specific constraints, such as presence of adjacent streams or structures and sharp changes of topographic features. In such cases, the purpose of the groundwater monitoring system outside the barrier is to verify long-term improvement in groundwater quality.

Key in the Aquitard

An adequate key is crucial to eliminate the risk of leaking of contaminants below the vertical barriers. Key depth must allow for seating the barrier in competent low-permeability soil or rock. The key should not provide a preferential pathway for groundwater flow relative to the remaining barrier or bottom of the site.

The key must be deep enough to accommodate:

- Localized variations in the elevation and quality of the aquitard (transition from silty material to clay material, for example)

- Variations in the measurement of key depth

- Conditions inherent in the type of wall and installation technique (such as thickness of the wall)

Acceptable depth of the key usually ranges from 2 to 4 feet and depends on site-specific geology and barrier depth. The design of a slurry wall key into bedrock is a complex issue. The degree of fissuring and the increased in situ permeability of the upper rock stratum should be assessed. In addition, the degree of difficulty and cost of excavating into the bedrock should be evaluated. Keys in the 1- to 3-foot range usually can be achieved relatively economically in most shale and limestone formations. For more competent rock, no key or only a very small key can be excavated economically. In some cases it is economical to extend the wall below the key by grouting.

Most barrier techniques other than slurry walls will have more stringent limitations than slurry walls on the execution of the key into competent materials or bedrock or at increased depths. For example, it is difficult to drive a sheet pile or vibrate a beam at depths exceeding 70 to 80 feet. In addition, barrier techniques other than slurry walls do not provide for continuous visual inspection of the aquitard formation, as is the case with slurry trenching.

Measures should be specified to ensure that slurry wall keys are cleaned properly before backfilling. Some designers and contractors increase the key depth to accommodate some buildup of soil that can settle out of suspension during the construction, but that could not be removed before backfilling. This practice is not recommended, since such “muck” is pushed forward during backfilling by the toe of the backfill, similar to a mud wave. Eventually, the accumulation of soil and sand becomes too great to be displaced by the backfill, leaving higher-permeability material at the bottom of the trench.

The importance of the key cannot be overemphasized, since most vertical containment barriers that do not meet the design objective (that is, that leak) are deficient in either design (usually the assessment of the quality of the aquitard) or CQA/CQC during excavation and cleaning of the key.

Of the sites studied, 1 site was not keyed in to an aquitard (hanging wall), 8 sites had 2-foot keys, 14 sites had 3-foot keys, 6 sites had 5-foot keys, and 1 site had an 8-foot key. The industry has recognized the importance of the key depth. The greatest difficulty in achieving adequate key depth was encountered at sites at which fractured bedrock occurred at depths of more than 70 feet below ground surface.

Thickness of the Wall

Under typical conditions the thickness of the slurry wall varies from 2 to 4 feet to provide an adequate containment barrier. The thickness is determined primarily by head differential across the barrier and concern for hydrofracture, transport of contaminants, the practical limits of excavation equipment, and consideration of future settlement. The sorption capacity of the barrier also should be considered when determining the thickness of the wall. The designer must balance the need for a thick barrier to withstand high hydraulic heads and retard leaking through advection and diffusion with the need to minimize construction cost. Depending on the site conditions and construction methods for earthen barriers, some walls can have a thickness of less than 2 feet and others can have a thickness of more than 4 feet. However, for typical slurry-based installations, a thickness of less than 2 feet is considered less than acceptable, and a thickness greater than 4 feet is considered better than acceptable.

The thickness of the wall was in most cases 3 feet and not less than 30 inches at 33 of the 36 sites evaluated. The exceptions were a sheet piling site, a site at which an emergency action was undertaken using a 1-foot-wide backhoe bucket, and an interim remedy site at which a vibrating beam construction method was used, resulting in a 4-inch thick wall. At one site, a 10-foot-thick clay wall was used.

Analysis of Trench Stability

The stability of a slurry-installed trench is crucial to successful construction of the wall. In most cases, a bentonite slurry-filled trench will be stable if there is at least 3 to 5 feet of slurry head above the surrounding groundwater table and artesian conditions are not present. If stable soil or rock characteristics are encountered, detailed analysis of trench stability may not be required. Concerns about stability may arise under conditions of soft native soil, high water tables, openwork gravels, artesian conditions, long open trenches, excessive surcharge (for example, from adjacent dikes), or construction loads. If any of the above conditions exists and a stability analysis was not done, the site is considered less than acceptable; if empirical or analytical techniques were used, the site is considered acceptable; and if numerical techniques were used, the site is considered better than acceptable.

Alternative barrier types, not based on slurry trench installation, offer inherent advantages in some cases by eliminating the need for an open trench and the possibility of trench sloughing.

At all the sites studied, trench stability was analyzed; however, at some sites that had steep slopes or unstable soils, the stability analysis was rigorous and measures were taken to prepare the site adequately before excavation of the trench.

Compatibility of Trench Slurry

The fresh or new bentonite slurry is prepared by mixing the bentonite with water from an adequate source. Additives are required in such cases as:

- When the water source does not have the required characteristics to make an adequate bentonite slurry (for example, when the water is too hard)

- When chemically active groundwater or contaminants present in the subsurface soils have the potential to affect the rheological characteristics of the slurry (such as viscosity, gel strength, and filter loss)

- When trenching through contaminated groundwater, which could cause flocculation of the slurry and instability of the trench

In general, three trench slurry compatibility tests should be conducted (unless incompatibility is known not to exist). Conducting more than three tests was considered better than acceptable, and fewer than three, less than acceptable.

The compatibility of trench slurry was evaluated at most of the sites studied; the number of tests varied from 2 to 5.

Testing of Backfill Permeability

The permeability of the backfill used to construct the barrier wall is a key design parameter that should be tested adequately. For the soil-bentonite technique, the objective is to establish proportions of on-site or imported materials needed to achieve the target permeability and physical properties of the barrier backfill. References and sources differed significantly on what constitutes standard practice. Site conditions, availability of borrow materials, and procedures for testing permeant compatibility affect the number of tests required. However, the consensus average was approximately three permeability tests of the backfill (the same or similar batches), using acceptable laboratory procedures that simulate in situ conditions. Conduct of three tests was considered acceptable. Conduct of more than three tests was considered better than acceptable, and of fewer than three, less than acceptable.

The permeability of backfill at the sites studied varied from 1×10^{-6} to 9×10^{-9} cm/sec. The number of tests conducted to verify the permeability varied from 2 to 5.

Long-Term Compatibility of Backfill

Since chemical reaction with contaminants can increase the permeability of the backfill, the long-term compatibility of backfill with the in situ soils and groundwater should be analyzed. Typically, several permeability tests of multiple pore volumes are performed to simulate a long-term condition and identify degradation through changes in permeability with time. Such tests often are combined with the testing of permeability of the backfill. Conducting three tests was considered acceptable. Conducting more than three tests was considered better than acceptable, and fewer than three, less than acceptable.

Compatibility testing was done at all sites at which leachate or contaminants were encountered. The extent of testing varied from site to site, with rigorous testing done at some sites and very limited testing at other sites.

Barrier Penetration

Subsurface utilities present along the barrier wall alignment and located below the water table must be delineated, rerouted, or protected with watertight connections. If such conditions were not considered, the site was rated less than acceptable; if the contractor designed solutions during construction, it was rated acceptable; and if the engineer investigated the problems and designed solutions during design, it was rated better than acceptable. Barrier penetrations were encountered at only a few of the sites studied. In all those cases, the barrier penetrations were investigated and accounted for in the design by the engineer.

Interface between Barrier and Surface Cap

The cap and barrier wall form an integrated containment system that minimizes entry of water into the waste area or its migration out of the area. If no surface cap was provided, the site was rated less than acceptable; if a cap was provided but the components of the cap simply were laid over the barrier wall, the site was rated acceptable. If there was a physical connection between the cap and the barrier wall, the site was rated better than acceptable. The physical connection usually is a tie-in of the geomembrane and soil components of the cap to the wall or cap.

Of the sites studied, 21 had a cap and barrier interface. At only 2 sites was there no physical connection of the cap with the barrier.

Protection from Dessication

The surface cap over the barrier wall alignment must protect against erosion, desiccation, and long-term physical disturbance of the barrier. Since the earthen barrier materials are primarily clays and bentonite, they are susceptible to desiccation that leads to the development of macropores and secondary permeability in the upper section of the barrier. If the barrier wall was protected from desiccation with less than 1 foot of cover soil, the wall was rated less than acceptable; if the wall was protected with 1 to 2 feet of clay cap, the wall was rated acceptable. If the wall was protected with more than 2 feet of clay cap placed in a controlled manner, the wall was rated better than acceptable.

Protection from Surface Loading

Uncemented earthen backfill is generally of low to moderate strength and subject to consolidation. Protection from static and dynamic loading should be provided through engineered fill, geosynthetics, structural concrete slabs, or other suitable material. If no protection from surface loading was designed, the site was considered less than acceptable; if spanning elements or soil improvement methods were provided, the site was considered acceptable. If designed structural elements were provided, the site was rated better than acceptable.

At all the sites studied, a surface cap had been provided over the barrier wall alignment.

Protection from Subsurface Breach

Breaching by subsurface utilities or other structures in the vicinity of the barrier wall can create permeable zones in the wall and adversely affect performance. If the possibility of such a breach was not analyzed, the site was rated less than acceptable; if physical protection was designed to protect the wall from the potential effects of such breaches, the site was rated acceptable. If redundant systems to prevent such breaches were designed, the site was rated better than acceptable.

Construction Sediment and Erosion Control

The flow of construction sediment from the vicinity of the trench into the trench can create permeable windows in the barrier wall. If control of erosion and sediment flow was not designed, the site was rated less than acceptable; if the contractor designed the control method during construction, the site was rated acceptable. If the engineer designed the method of flow diversion and sediment and erosion control during design, the site was rated better than acceptable.

Construction sediment and erosion control had been provided by the contractor at most of the sites studied.

Weighting

The 18 categories listed in Subsection 3.2.1 were assigned weights, according to the importance of each to the performance of the barrier wall. As discussed above, the design categories that are crucial to performance are the hydrogeology investigation, geotechnical borings along the alignment, depth of the key, and thickness of the wall. Therefore, each of those categories was given a weight of 10. Next in importance are the determination of feasibility, geotechnical physical testing, groundwater modeling, analysis of the trench stability, and long-term compatibility of the backfill. Each of those categories was given a weight of 5. All other categories are of approximately equal importance; each was given a weight of 2.

Each site described in Appendix B, Volume II was evaluated in each category as acceptable (2), less than acceptable (1), or better than acceptable (3). The resulting number (1, 2, or 3) was multiplied by the weight assigned to that category, and the total for all categories was obtained. The total was normalized by dividing the total by the total of weights for all categories. A site that had a normalized total lower than 1.8 was deemed less than acceptable, and any site having a total higher than 2.2 was deemed better than acceptable. Although this procedure may not reflect the design weakness at a particular site, it treats all sites alike and represents the weighted average design ratings for the sites.

3.2.5 Range of Findings

Subsurface barrier design for most sites was either acceptable or better than acceptable, when evaluated according to the methodology described above. (Table 3-3 summarizes key features and overall design rating for the sites evaluated.) Only 1 site was rated less than acceptable. At Site 1, the design was rated less than acceptable because a thorough hydrogeologic investigation had not been performed, nor had compatibility testing.

For most of the study sites, the geotechnical and hydrogeologic investigation was adequate to thorough, with spacing of borings varying from 75 to 300 feet. Groundwater modeling had been performed for sites 7, 10, 18, 19, 20, 21, 22, 26, 28, 29, 30, 31, 32, 33, and 35. Thickness of the wall varied from 1 foot to 10 feet, with the walls at most sites having a thickness of 3 feet. The wall at Site 16 had a thickness of 1 foot, and the wall at Site 12 had a thickness of 4 inches because of equipment constraints. The remedy for Site 16 was an emergency action, and that at Site 12 was considered an interim remedy that had been constructed by the vibrating beam method. The wall at Site 5 was a 10-foot-thick shallow barrier wall (10 feet deep), constructed of clay.

Table 3-3
Summary of Barrier Designs

Site	Geotechnical Investigation	Hydrogeological Investigation	Groundwater Modeling	Wall Thickness (ft)	Wall Depth/Key	Permeability	Compatibility Testing	Cap/Barrier Interface	Other	Rating
1	N/A	N/A	Not performed	3 feet	15 ft deep, 2 ft key	1 x 10^{-7} cm/sec	Not performed	Yes	Gas and leachate collection	Less than Acceptable
2	Borings at 300 ft spacing, thorough investigation	Thorough investigation	Not performed	3 feet	Wall is 20 to 30 feet deep, with 3 foot key	1 x 10^{-7} cm/sec	N/A	Impermeable fill cap over cutoff wall	Cutoff wall to dewater landfill site	Better than Acceptable
3	Borings at 100 ft centers	Adequate	Not performed	3 feet	18 ft deep At least 2 foot key	Target: 1 x 10^{-7} cm/sec	NA	Cap and walls are not physically connected	--	Acceptable
4	Borings at 100 ft	Thorough	Not performed	40 ft deep, 3 feet	3 feet	1 x 10^{-7} cm/sec	Yes	Yes	Grout curtain underneath SB wall	Better than Acceptable
5	Adequate	Adequate	Not performed	10 feet	10 ft deep, 2 ft key	1 x 10^{-7} cm/sec	Not performed	Yes	Leachate collection system was designed to handle maximum anticipated flows from perched GW table	Acceptable
6	Thorough	Thorough	Not performed	2.5 feet	15 to 25 ft deep, 3 ft key	1 x 10^{-7} cm/sec	Yes	Yes	Waste solidified within barrier	Better than Acceptable
7	Thorough	Thorough	Detailed hydrogeologic models of area were completed	3 feet	Wall is 20 to 70 feet deep, with a 5 foot key	1 x 10^{-8} to 9 x 10^{-9} cm/sec	Leachate-backfill compatibility testing	Yes	--	Better than Acceptable
8	Thorough	Thorough	Not performed	Sheet pile thickness	Sheet piles are 65 to 75 feet long, with 5-foot key	Target permeability of 1 x 10^{-7} cm/sec	N/A	N/A	Flood wall and cutoff wall at site (both are sheet piles)	No rating criteria
9	Adequate	Adequate	Not performed	3 feet	Wall is 15 to 45 feet deep, with 3-foot key	1 x 10^{-7}cm sec	Backfill-leachate compatibility testing	No cap at site	--	Acceptable

Table 3-3
Summary of Barrier Designs (Page 2 of 5)

Site	Geotechnical Investigation	Hydrogeological Investigation	Groundwater Modeling	Wall Thickness (ft)	Wall Depth/Key	Permeability	Compatibility Testing	Cap/Barrier Interface	Other	Rating
10	Thorough	Thorough	Modeling supported the design	3 feet	Wall averages 52 feet in depth keyed in 5 feet into bedrock	Design conductivity 1×10^{-7} cm/sec	Yes	No cap at site	Site is combination hydraulic barrier and cutoff wall	Acceptable
11	Soil borings at 100 foot intervals	Thorough	Not performed	3 feet each	Walls are 20 feet deep, with 3-foot key	Requirement: 1×10^{-7} cm/sec	Thorough testing	Yes	300 feet SCB wall and 5,240 feet SB wall	Acceptable
12	Soil borings at 100 foot spacing	Thorough	Not performed	4 inches	Wall is 19 to 29 feet deep, with 3-foot key	1×10^{-7} cm/sec	Yes	Yes	Geophysical screening survey was conducted	Acceptable
13	< 100 ft spacing	Thorough	Not performed; information available	3 feet	2 feet	1×10^{-7} cm/sec	Yes	Yes	--	Acceptable
14	100 ft	Thorough	Yes		8 feet in Till	4×10^{-7} cm/sec	Yes, with sea water	No Cap	Seepage cutoff for deep open pit mine	Better than Acceptable
15	Adequate	Adequate	Not performed	3 feet	Wall is 20 feet deep, with 2 foot key	1×10^{-7} cm/sec	NA	N/A	Inclinometer installed	Acceptable
16	Adequate	Adequate	Not performed	1 foot	Wall is 23 feet deep, with 2 foot soil key	1×10^{-6} cm/sec target permeability	Several hydrogeologic and feasibility studies were performed before construction	N/A	Barrier was essentially contractor-designed since part of an emergency action	Acceptable
17	Borings at 200-ft spacing	Thorough investigation of aquifers	Not performed	3 feet	Wall is 15 to 33.5 feet deep, with 2-foot key	1×10^{-7} cm/sec required	Yes	Yes	--	Acceptable

Table 3-3
Summary of Barrier Designs (Page 3 of 5)

Site	Geotechnical Investigation	Hydrogeological Investigation	Groundwater Modeling	Wall Thickness (ft)	Wall Depth/Key	Permeability	Compatibility Testing	Cap/Barrier Interface	Other	Rating
18	Borings at 100 ft spacing	Thorough	Modeling to define flow pathways	30 inches	Wall is 80 to 86 ft deep, with 0.1 foot key into bedrock	1 x 10^{-7} cm/sec	Trench slurry tested	Cap is physically connected to barrier	Geotechnical physical testing conducted; borings aligned along barrier at 100 ft intervals	Better than Acceptable
19	Geophysical survey along alignment and soil borings	Thorough	Feasibility study and design-level groundwater modeling performed	3 feet	Averages 50 feet, 0.1 ft into weathered rock	1 x 10^{-7} cm/sec	Significant compatibility testing performed	Yes	Barrier designed to reuse excavated material	Better than Acceptable
20	Borings spaced at 90 ft along barrier	Thorough	Yes	3 feet	60 to 80 feet, with 3 foot rock key	1 x 10^{-7} cm/sec	Rigorous compatibility testing with on-site GW and brackish harbor water	Yes	Tidal surface water fluctuation successfully managed	Better than Acceptable
21	Borings at 100 ft spacing	Thorough	Yes	3 feet	Wall is 40 to 70 feet deep with 3-foot key	1 x 10^{-6} cm/sec	Rigorous	Provision for erosion control measures	--	Better than Acceptable
22	Borings at 100 to 200 ft	Thorough	Conducted	3 feet	Wall is 12 to 19 feet deep with 3 ft key	Requirement of 1 x 10^{-7} cm/sec	Yes	Yes	HDPE membrane inserted through center of wall	Acceptable
23	Adequate	Adequate	Not performed	3 feet	Wall ranges from 10 to 60 feet deep, with a 3 foot key	1 x 10^{-7} cm/sec	Yes	Cap is yet to be constructed	Piezocone testing and pumping tests conducted; wall is hydraulically adequate	Better than Acceptable
24	Limited amount of data collected	Adequate	Not performed	2.5 feet	Wall is 35 feet deep, with 5-foot key	N/A	No information found.	Cap covers slurry wall	--	Acceptable

Table 3-3
Containment Barrier Design Matrix (Page 4 of 5)

Site	Geotechnical Investigation	Hydrogeological Investigation	Groundwater Modeling	Wall Thickness (ft)	Wall Depth/Key	Permeability	Compatibility Testing	Cap/Barrier Interface	Other	Rating
25	Thorough	N/A	N/A	30 inches	Wall is 40 to 50 feet deep, not keyed into aquitard	Target permeability of 1 x 10^{-7} cm/sec for cutoff wall	More than 3 tests performed	N/A	Hanging wall, penetrates a silty clay layer	Better than Acceptable
26	Thorough	Thorough	Yes	3 feet	Wall ranges from 20 to over 45 feet deep, with 1-foot key into bedrock	Target permeability of 1 x 10^{-7} cm/sec for cutoff wall	Not performed	N/A	Most critical deficiency of wall design was key depth	Better than Acceptable
27	Borings at less than 100 ft spacing	Thorough	Not performed	3 feet	Wall is 25 feet deep, with 5-foot key	1 x 10^{-7} cm/sec required	Thorough testing	Yes	More than 60 soil samples were tested during geotechnical investigation	Better than Acceptable
28	Thorough	Thorough	Yes	3 feet	3 feet	1 x 10^{-7} cm/sec	Yes	Asphalt parking lot	Parking Lot	Better than Acceptable
29	Adequate	Adequate	Limited	3 to 11 feet	Wall has 2-foot key	1 x 10^{-7} cm/sec	NA	Yes	--	Acceptable
30	Soil borings every 100 to 200 feet	Thorough	Yes	3 feet	Wall is 30 feet deep with 3 ft-key	1 x 10^{-7} cm/sec	Compatibility study of two SB slurry wall backfill mixtures	Yes	Soil vapor extraction in progress Intermittent pumping	Better than Acceptable
31	Soil borings every 75 to 200 feet	Thorough	Regional and site scale models were performed	Minimum thickness 30 inches	Wall ranges from 10 to 77 feet deep, with 2-foot key	Target: 1 x 10^{-7} cm/sec	Conducted	N/A	River channel was relocated 150 feet west prior to construction of barrier wall	Acceptable
32	Soil boring at 100 foot spacing	Thorough	Hydraulic modeling performed.	3 feet	Wall is 50 feet deep, with 3-foot key	Target: 1 x 10^{-7} cm/sec	Yes	Earth fill cover overlies the barrier wall	--	Acceptable

Table 3-3
Summary of Barrier Designs (Page 5 of 5)

Site	Geotechnical Investigation	Hydrogeological Investigation	Groundwater Modeling	Wall Thickness (ft)	Wall Depth/Key	Permeability	Compatibility Testing	Cap/Barrier Interface	Other	Rating
33	49 cone penetrometer tests were performed to develop a geotechnical model	Thorough	Numerical GW flow model developed	1.5 ft and 3 ft	Wall excavated to design elevation to correspond to minimum 2-foot key	<5 x 10^{-6} cm/sec	Long-term tests performed on selected CB mixes	N/A	Site contains a treatment wall	Better than Acceptable
34	Thorough	Thorough	Yes	3 and 5 feet	76 feet deep 5 feet	1 x 10^{-6} cm/sec	Yes	NA	Civil structure	Better than Acceptable
35	Thorough	Thorough	Modeling completed	32 inches	Wall averages 138 feet in depth	Target: 1 x 10^{-7} cm/sec	N/A	N/A	Modeling was performed to determine dimensions of pumping system and to predict deformation of wall during mass excavation	Better than Acceptable
36	Adequate	Adequate	Not performed	N/A	N/A	N/A	N/A	N/A	--	Better than Acceptable

Notes: Acceptable industry practices in Table 3-2 were used to evaluate site designs. However, only key design parameters are discussed in this table.

N/A Not applicable
NA Not available

The key depth at most sites varied from 2 to 3 feet. The only exceptions were sites 18 and 19, which were deep (50 to 90 feet) and each had a key of 0.1 foot into bedrock, and Site 26, which had a key of 1 foot into bedrock. For most of the sites, the barrier wall and cap were connected physically by extending the cap over the top of the barrier wall.

Compatibility of backfill with the contaminated groundwater had been tested at all sites except sites 1, 5 and 26. The type of compatibility testing to be conducted to ensure long-term compatibility has not been standardized, and the level of effort varied among the sites.

Site conditions varied among the 36 sites, and barriers were designed to accommodate those varying conditions. Two of the barriers studied (those at Site 2 and Site 35) were designed to withstand head differentials greater than 60 feet for several months during dewatering operations. The barrier at Site 34 also was designed for a high head differential and accommodated settlement and hydrofracture concerns with a two-stage construction of barriers of different thickness. At Site 4, because of concern about a permeable bedrock key, the base of the soil-bentonite barrier was a grout curtain in the native shale bedrock. At Site 26, a pilot barrier was constructed; later, wing walls to the barrier were designed and constructed to better capture migrating contaminants. At Site 33, detailed cone penetrometer investigations and groundwater modeling were used to characterize subsurface conditions, and a test cell was constructed to prove the reaction wall design. At Site 11, a soil-bentonite and soil-cement-bentonite barrier was designed to accommodate significant grade changes.

The design for Site 19 was rated above acceptable. Determination of feasibility and design-stage groundwater modeling had been performed. A geophysical survey had been performed along the entire barrier alignment and had been supplemented by a thorough geotechnical drilling and testing program. A significant amount of compatibility testing of slurry and backfill had been performed. The construction specifications for the barrier wall were based on performance and design. A bedrock key had been used; however, flow in the bedrock had been underestimated, and leaking from the key-in horizon had occurred. The leaking subsequently was repaired by grouting.

The study of designs at 36 sites showed the significant effect of design on field performance. The key design elements that require the most attention are the investigation of the key horizon, hydrogeological assessment of groundwater gradients, and compatibility testing of the backfill with the groundwater at the site.

3.3 CONSTRUCTION QUALITY ASSURANCE AND CONSTRUCTION QUALITY CONTROL DATA

The CQA/CQC program is important to the successful implementation of the design and to the performance of the barrier wall. Experience gained over the past 20 years in the installation of barrier walls and caps at hazardous waste sites has established typical industry practices for performing CQA/CQC at such sites. This subsection describes the typical industry practices and the range of findings for the 36 sites analyzed in this study.

CQA refers to quality assurance testing that the designer or independent CQA engineer performs to confirm that construction complies with the design specifications, while CQC refers to quality control testing that the constructor performs to verify the constructed product. In the following evaluation, CQA and CQC have been combined for ease and considered a single criterion.

Because postconstruction verification tests for the entire barrier are difficult, if not impossible, adequate CQA/CQC is a crucial element in achieving the design objective. The typical industry practice was determined through examination of several sources, including available guidance documents or texts (USACE 1996; EPA 1984; EPA 1987a; Xanthakos 1979; American Petroleum Institute [API] 1980), discussions with engineers and contractors, findings of reviews of sites investigated, and the authors' experience. Table 3-4 presents a matrix that summarizes the standard industry practice. The matrix was used to evaluate the 36 sites selected for the study to determine for each site whether the CQA/CQC effort was acceptable, less than acceptable, or better than acceptable. The range of findings for the sites is discussed in Section 3.3.21.

The following discussion of barrier CQA/CQC focuses on slurry trench soil-bentonite barriers because those barriers are most prevalent and represent the majority of the evaluated sites. However, several of the subcriteria are equally applicable to other vertical barriers that are installed using the slurry trenching method.

3.3.1 Experience of the Specialty Contractor

Subsurface barriers require specialized geotechnical construction. The more complex the project, the more important it is to use a specialty contractor. If the specialty contractor that installed the wall had completed four to six comparable projects in the recent past, the site was rated acceptable. If the contractor had completed fewer than four such projects, the site was rated less than acceptable. If the contractor had completed more than six such projects, the site was rated better than acceptable. At 75 percent of the sites studied, the barriers were constructed by one of four major specialty contractors.

3.3.2 Methods of Trench Excavation

The excavation of slurry wall trenches can be accomplished with various equipment, such as a backhoe, specially-modified clamshell, dragline, chisel, or hydrocutter. Selection of the trenching equipment depends upon several factors, such as the type, thickness, and depth of the slurry wall, as well as the nature of the materials to be excavated. Currently, most soil-bentonite slurry trenches are excavated with backhoes. Some specialty contractors own large backhoes that can excavate to depths in excess of 80 feet. When the trench is deeper than the reach of the backhoe, the excavation usually is extended to the final depth by clamshells. CQA/CQC related to the excavation should address at least the following items:

- **Excavation Equipment.** The equipment selected by the contractor must be able to excavate the trench according to the design criteria (such as width and depth) and through the anticipated geological formations. Indeed, to provide for localized anomalies in the elevation of the aquitard, the excavation equipment should be able to reach depths deeper than that required by the design. In addition, the digging power available at the bottom of the trench is important when the key must be excavated through very dense materials. For example, additional equipment might be needed to key the wall into bedrock.

At the majority of the sites studied, conventional or extended stick backhoes were used to excavate barrier trenches.

TABLE 3-4
MATRIX FOR EVALUATING BARRIER CQA/CQC AGAINST ACCEPTABLE INDUSTRY PRACTICES

Category	Less than Acceptable	Acceptable	Better than Acceptable
Specialty Contractor Experience	<4	4-6 Comparable Projects	>6
Trench Excavation Methods	No Inspection	Periodic Inspections	Constant Inspection
Trench Width, Verticality & Continuity *	No Inspection	Periodic Inspection	Measured
Trench Sounding (slope & bottom)	>20 ft	per 10-20 ft	<10 ft
Trench Bottom Cleaning	None	Yes *	>
Trench Key Confirmation	No Sampling	Sampling every 20ft	Sampling < 20 ft
Slurry Mixing	<	Agitation >12 hrs. Hydration	>
Slurry Viscosity Testing	<2	2 per shift	>2
Slurry Viscosity	<40	40+seconds (marsh funnel)	40-50 seconds (marsh funnel)
Slurry Sand Content Tests	<2	2 per shift	>2
Slurry Sand Content	>15%	<15 %	<<15%
Backfill Slump Testing	<	1 per 400-600 cy	>
Backfill Slump	<3" or >6"	Most tests 3"-6"	All tests 3"-6"
Backfill Gradation Testing	< 1	1 per 400-600 cy	> 1
Backfill Permeability Testing	< 1	1 per 400-600 cy	> 1
Backfill Target Permeability	>	5x10-7 - 1x10-7 cm/sec	<
Backfill Mixing/Placement	Loosely Controlled	Controlled Mix/Place	Central Mix/Guided Placement
Capping Confirmation	None	Cap confirmed	>
Barrier Continuity	Interrupted	Continuous	Continuous & Confirmed
Post Construc. Barrier Sampling/Testing	None	Minimal	Regular & Documented
As-Built Records	None	Const. Completion Report	Report, Drawings, Test Results
Groundwater Head Monitoring	None	Monitored Fluctuation	Periodic & Across Barrier
Final barrier alignment survey	None	Surveyed	Surveyed & Monumented
Barrier construction specification	None	Barrier	Barrier & CQA Plan
CQA/CQC program & testing spec.	None	Designer Specified	Independent Duplicate QA
Groundwater Chemistry Monitoring	None	Minimal	Periodic & Across Barrier

* Observation of trench width and equipment verticality.

Note: The categories, slurry sand content and backfill slump, are site-specific, and the numbers given above are typical for soil-bentonite slurry walls.

- **Trench Inspection**. The trench should be inspected regularly, to ensure that it is aligned as specified in the design and to detect any sloughing, since such sloughing may indicate the need to clean the bottom of the trench or top of the backfill. Moreover, an inspection will establish whether the trench is continuous through its full depth.

If the excavation was inspected regularly (for example, daily), the site was rated acceptable. If no inspection was conducted, the site was rated less than acceptable. If frequent inspection was provided, the site was rated better than acceptable.

3.3.3 Width and Verticality of the Trench

As a general rule, the trenching tool at a minimum should have the width specified in the design to ensure that the width of the barrier will conform with the design. Excavation buckets should be monitored regularly, and such items as teeth and side cutters should be replaced as needed before they exhibit excessive wear.

Verticality of the trench also must be monitored. Verticality is particularly important when the design and construction methods involve joints, such as those between slurry wall panels, stabilized columns, or vibrating beam imprints. For example, monitoring the verticality of the excavation helps ensure that the minimum design width is achieved at full depth if adjacent panels deviate from the vertical in opposite directions. Verticality is less critical for continuous excavation of the trench if the construction procedure provides for a positive method to control the continuity of the trench between adjacent excavated sections. If periodic inspections were conducted to monitor the width and continuity of the trench and verticality of the equipment, the site was considered acceptable. If no inspections were conducted, the site was rated less than acceptable. If actual measurements such as physical measurements of width and measurements of the level of the excavator, were obtained periodically, the site was rated better than acceptable.

Inspection of the width and verticality of the trench was conducted at all the sites studied. The frequency of inspections varied from one to two times per day, or from 10 to 25 feet of trench advance. The type of inspection varied from visual to actual measurements of the width of the trench and verticality of the wall. At one site, a mechanical caliper device was used to measure width at different depths. Information about the site revealed that the width of the trench remained relatively constant, except for the upper sections of the excavation and in areas of sloughing caused by weak soil or the presence of waste.

3.3.4 Confirmation of Key and Aquitard

Confirming the key of the trench into the aquitard is crucial to the successful installation of the barrier wall and to its subsequent performance. Confirming the key consists of measuring the depth of the trench (1) when the top of the aquitard is encountered and (2) after completion of the trench. In addition, samples of the aquitard formation should be taken at regular intervals with the excavator or some suitable sampling tool. The engineer of record then can use the results of such sampling to confirm that the key is within the selected formation. If sampling was performed every 20 feet, the site was rated acceptable. If sampling was not performed and only sounding was performed, the site was rated less than acceptable. If the sampling was performed at a frequency of less than 20 feet, the site was rated better than acceptable.

At most of the sites studied, confirmation of the trench key was accomplished by visually inspecting the trench bottom cuttings. At Site 8, the measured resistance to sheet pile driving was used to confirm the key. At Site 27, the key was confirmed by inspecting samples of trench bottom cuttings for every 25 feet of trench advance. Confirmation of the trench key was dependent on the qualifications of the inspection personnel; at sites at which a distinct aquitard was not present or weathered bedrock was present, confirmation of the key was difficult. The importance of a qualified geologist or geotechnical engineer verifying adequate key-in cannot be overemphasized. Inadequate key-in zones were discovered during postconstruction sampling at some sites, and appropriate corrective action was taken. At some sites, inadequate key-in was revealed only when leaking from the bottom occurred.

3.3.5 Sounding and Cleaning of the Bottom of the Trench

During excavation, soil materials become suspended in the slurry. In addition, if no adequate surface erosion or sediment control barriers are in place, surface sediments can flow into the slurry-filled trench during storms. These materials can settle from suspension and accumulate at the bottom of the trench or on the slope of the backfill. Usually, soils and sediments are more permeable than the backfill and must be removed before backfilling. Therefore, any accumulation of sediment must be monitored before the trench is backfilled. The depth of the trench must be measured (sounding) to verify that it is equivalent to the specified key depth. If any material has accumulated, additional cleaning of the bottom of the trench must be completed before backfilling. Cleaning the bottom of the trench may be accomplished with excavation equipment or with air-lift or special pumps. If accumulation of sediment occurred and such cleaning was performed periodically, the site was rated acceptable. If cleaning was not performed, the site was rated less than acceptable. If cleaning was performed frequently (once a day or more), the site was rated better than acceptable.

At many of the sites studied, cleaning of the trench bottom was accomplished with desanding pumps. When this procedure was not performed regularly, permeable windows were observed during postconstruction testing. At Site 18, the sand runs into the trench were not detected, and cleaning of the trench bottom was not performed regularly. The permeable windows in the wall were repaired by the deep soil mixing method.

3.3.6 Sounding of the Trench and Cleaning of the Backfill Slope

The slope of the backfill in the trench also must be monitored. Sounding of the backfill slope should be done at a minimum of twice daily, before work in the morning and after work at night, to detect cave-ins between shifts. Such soundings are relatively imprecise because of the soft consistency of the soil-bentonite backfill. The periodic measurements allow detection of any major anomaly in the backfilling process. Some specialty contractors use a special device to verify that no sediments have settled on the backfill slope.

Cleaning of the backfill slope is rarely required, if the rheological characteristics of the slurry are well maintained. Nevertheless, the need for cleaning the backfill slope exists. Since it would be risky to straddle the open trench with a backhoe, such cleaning often will require the use of a crane-mounted clamshell or special procedures developed by the specialty contractor.

Note: In light of the above discussion of cleaning the bottom of the trench and the backfill slope, it is recommended that a crane-mounted clamshell or other approved special cleaning tool be mobilized or readily available to sites at which there are deep trenches.

If the observations and measurements described above were made every 10 to 20 feet along the barrier wall excavation, the site was rated acceptable. If they were made at intervals of more than 20 feet, the site was rated less than acceptable, and if they were made at intervals of less than 10 feet, the site was rated better than acceptable.

Trench sounding was performed at least daily at all the sites studied. The frequency of trench sounding varied from 10 to 25 feet of trench advance. At Site 6, the backfill profile was measured twice daily to verify that the trench had not sloughed in. At Site 15, the depth of the trench was determined by measuring the depth of auger in the trench.

3.3.7 Bentonite Slurry

CQA/CQC of the bentonite slurry is important to ensure the constructability, as well as the performance, of the slurry wall. The slurry plays an important role in determining:

- The stability of the trench under excavation
- The cleanliness of the trench bottom and backfill slope, as a result of the ability of the slurry to keep soil material in suspension
- The quality of the backfilling operation

Mixing of Fresh Bentonite

The mixing water should be tested to ensure that it is suitable for mixing with the bentonite material. Typically, tests are performed for pH, hardness, and dissolved solids. Most project specifications require the use of bentonite materials that meet standards set forth in API 13A and B. It is good practice to mix the water and bentonite in a high-shear mixer and allow the slurry to hydrate fully in storage tanks or ponds for a minimum of 12 to 24 hours. The slurry should be kept agitated during storage. This procedure will produce a slurry that has the optimum rheological characteristics (viscosity, gel strength, density, and filter loss). If the agitation of the slurry was maintained to achieve hydration in more than 12 hours or high-speed shear mixers were used, the site was rated acceptable. However, if hydration time was significantly less than 12 hours, with very little quality control, the site was rated less than acceptable. If the typical agitation was such that hydration time was significantly more than 12 hours, the site was rated better than acceptable.

At all sites for which data were available, slurry was mixed thoroughly in a pond or tank before it was introduced into the trench. However, for most of the sites studied, rating for this criterion was not possible because of lack of data.

Ex Situ Testing of Bentonite Slurry

The rheological characteristics of the fresh slurry should be measured before it is introduced into the trench. On-site testing of the gel strength of the slurry rarely is required because the viscosity of bentonite slurry is also an indication of its gel strength. The higher the viscosity, the higher the gel strength.

However, gel strength does not always correlate with viscosity for slurry produced with materials other than bentonite.   For example, typical biopolymer slurries used for the installation of (leachate) collection trenches by the slurry trenching method exhibit viscosity, as a function of the content of biopolymer material, but have a very low gel strength regardless of the viscosity of the slurry. Such slurries therefore do not keep solids in suspension.

The Marsh funnel is the standard used to measure the viscosity of slurry; the time required for a measured amount of slurry to flow through the Marsh funnel is an indication of its viscosity. Viscosity may be less than 40 seconds if the trench is excavated through stable material. But typical values specified will be:

Marsh viscosity	∃	40 seconds
Density	∃	64 lb/ft^3
Filter loss	#	15 to 25

These rheological characteristics should be tested at least twice per shift before the fresh slurry is introduced into the trench, and corrective action taken if the results should be lower than the values set forth above.

If these measures were taken twice per shift, the site was rated acceptable. If they were taken less often than twice per shift, the site was rated less than acceptable. If they were taken more than twice per shift, the site was rated better than acceptable.

For the sites studied, the frequency of testing of slurry for viscosity varied from 1 to 4 times per shift, and conformed to contract specifications for the site. At the sites studied, the Marsh slurry viscosity generally ranged from 40 to 50 seconds.

Testing of the Bentonite Slurry in the Trench

It is good practice to test the rheological characteristics of the bentonite slurry in the trench at least twice per shift, to ensure that no degradation of the required characteristics occurred. Such degradation could be caused by dilution of the slurry with groundwater (that is, from excavation through material having a high water content, localized artesian conditions, or surface runoff into the trench), or by chemical reactions. The measurements also are made to ensure that trench slurry is appropriate for backfilling of the trench. In particular, if the density of the slurry is similar to that of the backfill, the bentonite slurry may not be displaced completely by the backfill; pockets of slurry then would remain inside the backfill, creating higher permeability zones. The slurry therefore should be sampled at different elevations in the trench, including close to its bottom.

In addition to viscosity, density, and filter loss, the sand content of the slurry also must be measured, since the action of excavation suspends soil materials in the slurry, thereby increasing the density of the slurry. As discussed above, increased density of the slurry not only can impair the backfilling operation, but also can cause sand sedimentation at the bottom of the trench. Typical maximum sand content as specified varies between 15 and 20 percent. (For concrete walls, sand content should be less than 5 percent.) There are several ways to solve such problems. Standard practice is to control the density of the slurry in the trench so that its density is at least 15 lb per ft^3 less than the density of the backfill. That result is achieved either by adding fresh slurry in the trench or by withdrawing the slurry at the bottom of the trench and circulating it through a desanding or desilting unit. Cleaning of the trench bottom was discussed in Subsection 3.3.5.

If the trench slurry was tested twice per shift, the site was rated as acceptable. If fewer than two tests per shift were performed, the site was rated less than acceptable. If more than two tests per shift were performed, the site was rated better than acceptable.

At the sites studied, testing of the trench slurry conformed to contract specifications, and the number of tests varied from 1 to 3 per shift.

For many of the sites studied, no information about the sand content of the slurry was available.

3.3.8 Mixing and Testing of the Backfill

The objective of the CQA/CQC for backfill mixing is to ensure that the mixed backfill meets the approved design for backfill mix before it is introduced into the trench. Typical specifications require:

- **Backfill Mixing Method and Equipment –** The method and equipment used should achieve thorough mixing of the backfill materials into a relatively homogeneous mass that will meet the gradation and consistency requirements identified for the selected mix design. Typical methods and equipment for soil-bentonite trenches are (1) mixing along the trench with the tracks of a bulldozer, (2) remote mixing with a bulldozer on a pad, or (3) mixing in a plant such as pugmill. Past experience has shown that well-controlled mixing along the trench, which is the most economical method for most sites, yields a satisfactory backfill. In general, the use of remote mixing depends upon considerations related to the particular site, such as lack of sufficient space adjacent to the trenches.

- **Gradation Tests –** Gradation tests are used to determine that the backfill, in particular the content of fines, meets the specified gradation requirements. Such tests should be conducted once for every 400 to 600 cubic yards, or once per shift, if production is lower.

- **Dry Bentonite Content –** The mix design may specify the addition of dry bentonite to the bentonite slurry. If so, the contractor should ensure that the percentage of dry bentonite required is added to the backfill.

- **Consistency of the Backfill –** Consistency of backfill is verified by slump testing. If the slump is too low, typically lower than 3 to 4 inches, the backfilling process may be impaired. That is, the backfill mixture is likely to contain pockets of slurry. If the slump is too high, higher than 6 to 7 inches, the backfill may not displace the slurry completely. Moreover, the backfill slope will be excessive (more than 12 horizontal to 1 vertical) and the trenches therefore longer than necessary, increasing the risk of construction difficulties (such as sloughing and sedimentation). In addition, high slump increases the potential for excessive consolidation of the backfill over the long term. Backfill slumps also should be measured once for every 400 to 600 cubic yards, or once per shift, if production is lower.

3.3.9 Permeability of the Backfill

The design permeability of a barrier can vary greatly, depending on the type of barrier and the design objective. Generally, 1×10^{-7} cm/sec ± is an industry-accepted achievable permeability for soil-bentonite barriers. Permeabilities of 1×10^{-6} cm/sec ± generally are accepted for cement-bentonite barriers of various types, such as soil-cement-bentonite and cement-bentonite. Grout barriers have permeabilities of approximately 5×10^{-6} cm/sec. Sampling, type of test conducted, and testing parameters can influence permeability values significantly.

Standard specifications require that an independent approved laboratory perform testing of backfill permeability. The tests should be run in a flexible-wall permeameter. Typically, the sample first will be prepared under a consolidation pressure equivalent to half the depth of the barrier. The frequency of the tests varies according to the project; however, for this analysis, a test once for every 400 to 600 cubic yards was considered standard.

Note: It takes approximately one week or longer from the time of sampling to obtain the results of a flexible-wall permeability test. For that reason, a few contractors conduct daily on-site permeability tests in a fixed-wall permeameter (filter press). That approach was not used as a rating criterion for this study. However, the project team recommends the practice, even if such tests are less accurate than laboratory tests, because its application allows the detection of deficient backfill within a few hours, rather than a week.

If all the above tests on the mixed backfill were performed once for every 400 to 600 cubic yards, the site was rated acceptable. If the tests were performed less frequently, the site was rated less than acceptable. If the tests were performed more frequently, the site was rated better than acceptable.

At the sites studied, backfill gradation was tested once for every 400 to 600 cubic yards unless the backfill borrow material was obtained from a relatively uniform source. In such a case, testing was less frequent. The backfill slump at most of the sites studied was tested once for every 400 to 600 cubic yards and varied from 3 to 6 inches. Testing of the backfill permeability at the sites varied from once every 250 cubic yards to once every 600 cubic yards.

3.3.10 Placement of the Backfill

Control of the placement of the backfill in the trench is an important component of successful barrier construction.

First, the bottom of the trench should be sounded and approved by the engineer before the backfill is placed. Once the initial slope of the backfill has been established appropriately, the mixed backfill should be pushed on top of the backfill previously placed on the top of the trench. Free-dropping of the backfill through the slurry should not occur. The slope of the backfill should be measured at least once per shift and, if the backfill operation was stopped for more than 24 hours, at a minimum, the slope should be sounded prior to backfill placement for potential sedimentation on its surface.

If the mixing was controlled loosely and the backfill placed in the trench, the site was rated less than acceptable. If the mixing was controlled at a central location and the backfill placed in a manner that prevented segregation, the site was rated better than acceptable.

Central mixing was used in completing 80 percent of the soil-bentonite barriers.

3.3.11 Confirmation of Capping

The surface of the barrier wall is capped to protect against physical damage, to limit desiccation, and to accommodate settlement of backfill materials. If the cap was tested to verify placement and compaction and the design specifications were met, the site was rated acceptable. If the cap was not placed on the wall surface in a controlled fashion, the site was rated less than acceptable. If the cap was placed under stringent CQA/CQC requirements, the site was rated better than acceptable.

For all sites studied, the cap was placed on the surface of the barrier wall in accordance with the design specification.

3.3.12 Barrier Continuity

The barrier wall should be constructed in a continuous sequence, with joints, seams, or connections minimized, thereby minimizing possible areas of preferential flow. If the construction sequence had been interrupted, the site was rated less than acceptable. If the continuity of the wall had been confirmed through the CQA process, the site was rated better than acceptable.

At all the sites studied except Site 2, continuity of the barrier was ensured through a continuous construction sequence. At one site, construction started, stopped, and restarted after a 12- to 18-month delay, creating potential problems.

3.3.13 Postconstruction Sampling and Testing of the Barrier Wall

The quality of the construction of the barrier wall sometimes is confirmed by sampling the barrier wall at regular intervals and testing the permeability and physical properties of the retrieved samples. If a limited amount of postconstruction sampling and testing of the barrier wall was performed, the site was rated acceptable. If no sampling and testing was performed, the site was rated less than acceptable. If the sampling and testing was done at approximately 100-foot intervals along the length and depth of the barrier wall, the site was rated better than acceptable.

Postconstruction sampling and testing of the barrier varied widely from site to site. At Site 11, confirmation testing was done every 100 ft for the soil-bentonite wall and every 50 ft for the soil-cement-bentonite wall, while at Site 1, samples were tested at 500-foot intervals. At Site 23, 17 dissipation tests were performed in addition to the permeability tests on undisturbed samples. Section 3.4 discusses these differences further.

3.3.14 As-Built Records

If the barrier wall construction was documented in a construction completion report, the site was rated acceptable. If no construction completion report was prepared, the site was rated less than acceptable. If the report included drawings and results of analysis of samples and of tests from both the construction and the postconstruction periods, the site was rated better than acceptable.

For all the sites studied, as-built records documented the construction effort.

3.3.15 Monitoring of Groundwater Head

Groundwater heads within and outside the barrier wall should be measured periodically during and immediately after construction to determine the groundwater response outside the barrier and groundwater rise within the barrier. Rapid changes in water level can affect the stability and constructability of the trench. If the heads were monitored to determine the head fluctuation during and immediately after construction, the site was rated acceptable. If the heads were not monitored, the site was rated less than acceptable. If the heads were monitored regularly in paired wells within and outside the barrier and trends analyzed, the site was rated better than acceptable.

At all the sites studied, the groundwater head was monitored after construction.

3.3.16 Final Survey of Barrier Alignment

The final survey of barrier alignment should be documented because some changes are likely to occur during construction. If the alignment survey was completed, the site was rated acceptable. If no survey was completed, the site was rated less than acceptable. If the survey was completed and monuments were set in place to identify the barrier alignment and facilitate future surveys, the site was rated better than acceptable.

3.3.17 Construction Specifications for the Barrier

The construction specifications the designer prepares for the barrier can be based on design or performance, or on a combination of the two. If the specifications were based primarily on design, the site was rated acceptable. If the specifications were based primarily on performance, with little specificity, the site was rated less than acceptable. If the specifications were based on design and detailed, and if they addressed barrier testing and ancillary construction, the site was rated better than acceptable.

For most of the sites studied, the construction specifications were based on design. Because the effort at Site 5 was an emergency action, the contractor designed the wall for the site; the specifications were based on performance.

3.3.18 CQA/CQC Program and Testing Specification

If the contractor maintained a CQC program and an independent consultant provided QA of the contractor's CQC and performed some additional QA tests, the site was considered acceptable. If no formal CQA program was used and limited CQC was performed, the site was considered less than acceptable. The site was considered better than acceptable if the designer specified CQC and independent CQA and CQC programs were followed strictly, with at least one-third duplicate CQA testing.

3.3.19 Monitoring of Groundwater Chemistry

The groundwater chemistry downgradient of the site is monitored after construction to determine whether the wall is preventing the flow of groundwater across the barrier wall. If some monitoring relative to the constituents of concern was performed downgradient of the wall, the site was rated acceptable. If such monitoring was not performed, the site was rated less than acceptable. If it was monitored periodically and in paired wells located inside and outside the barrier wall, the site was rated better than acceptable.

At all the sites studied except the two civil cutoff walls (Sites 34 and 35), the groundwater chemistry was monitored downgradient of the site. Section 3.4 discusses groundwater monitoring further.

3.3.20 Weighting of the Elements

The 26 elements described above are of different degrees of importance in the evaluation of barrier wall CQA/CQC. The elements were weighted to reflect their importance, as determined by the project team, with trench key confirmation given the greatest weight, 15 points of a total of 116 points. The next 4 elements, with weights of 10 points each, are use of an experienced specialty contractor, trench width and verticality, trench sounding, and construction specifications for the barrier. The next 6 elements, with a weight of 5 points each, are trench excavation methods, cleaning of the trench bottom, confirmation of capping, postconstruction sampling and testing of the barrier, as-built records, and CQA/CQC program and testing specification. The next 3 elements, with a weight of 3 points each, are gradation testing of the backfill, permeability testing of the backfill, and target permeability of the backfill. The next 10 elements, with a weight of 2 points each, are mixing of the slurry, viscosity testing of the slurry, viscosity of the slurry, sand content testing of the slurry, sand content of the slurry, slump testing of the backfill, slump of the backfill, mixing and placement of the backfill, continuity of the barrier, and head monitoring of the groundwater. The last 2 elements, with a weight of 1 point each, are final alignment survey of the barrier and monitoring of groundwater chemistry.

For each site, each rating of less than acceptable (1), acceptable (2), or better than acceptable (3) was multiplied by the weight for the CQA/CQC element and totaled. The ratings then were normalized by dividing by 116. If the result was lower than 1.8, the site CQA/CQC was rated less than acceptable; if the result was between 1.8 and 2.2, it was rated acceptable. If the result was higher than 2.2, it was rated better than acceptable. Table 3-5 shows the ratings for the sites.

3.3.21 Range of Findings

CQA/CQC for the barrier wall differed widely among the sites studied. For 24 sites, CQA/CQC was rated better than acceptable. For 2 sites, CQA/CQC was rated less than acceptable; for 7 sites, CQA/CQC was rated acceptable.

The CQA/CQC methods used at each site are described in the individual site summaries (see Appendix B, Volume II). For most sites, a majority of the CQA/CQC elements were applied, with sites that were rated better than acceptable completing and documenting the

Table 3-5
Containment Barrier CQA/CQC Matrix

Site	Trench Sounding	Key Confirmation	Slurry Testing	Backfill Testing	Backfill Permeability	Post-Construction Testing	Rating
1	Yes	Visually	Yes	Yes	Met requirement of 1 x 10^{-7} cm/sec	Samples collected every 500 lf	Less than Acceptable
2	Every 10 feet	Visual	Yes	Yes	6.3 x 10^{-8} cm/sec; target was achieved	Annual geophysical survey	Acceptable
3	Yes	Visually	Yes	Yes	1 x 10^{-7} cm/sec	NA	Acceptable
4	Conducted every 10 to 20 feet	Confirmed every 20 feet	USACE performed independent tests on grout and grout curtain	Yes	1 x 10^{-7} cm/sec	None	Better than Acceptable
5	N/A	Visually	N/A	Thorough testing of clay backfill	Wall met permeability requirement of 1 x 10^{-7} cm/sec	Undisturbed samples every 400 feet	Better than Acceptable
6	No	Visually	Daily	Daily	1 x 10^{-7} cm/sec	Samples taken to measure permeability	Better than Acceptable
7	Daily	Visually	Yes	Yes	1 x 10^{-8} cm/sec to 9 x 10^{-9} cm/sec	Post construction borings	Better than Acceptable
8	N/A	Visual observation of driving of sheet piles	N/A	N/A	N/A	Permeability certification test performed	No rating criteria
9	Constant trench-side inspections of trench	Constant trench-side inspections of key depth	NA	Backfill was mixed in centrally located, mobile pubmill to optimize characteristics of backfill	NA	NA	Acceptable
10	Every 10 feet	Sampling every 20 feet	Once to twice per shift	Once per 300 cu yd	1 x 10^{-7} cm/sec	NA	Better than Acceptable
11	Daily	Thorough	NA	Backfill was mixed in centrally located pugmill; test of hydraulic conductivity of backfill were conducted	Wall met permeability requirement of 1 x 10^{-7} cm/sec	Confirmation testing	Better than Acceptable

Table 3-5
Containment Barrier CQA/CQC Matrix (Continued)

Site	Trench Sounding	Key Confirmation	Slurry Testing	Backfill Testing	Backfill Permeability	Post-Construction Testing	Rating
12	Wall continuity and depth were demonstrated by putting a steel bar horizontally through the entire wall		Slurry density and viscosity were measured every 2 hours during well construction		Hydraulic conductivity was determined every 200 feet	None	Better than Acceptable
13	Thorough	Thorough	Yes	Thorough	1 x 10^{-7} cm/sec	None	Better than Acceptable
14	Every 10 feet	Thorough	Yes	Very elaborate mix design and QC program	4 x 10^{-7} cm/sec	Instrumentation inside and outside barrier	Better than Acceptable
15	Adequate	Thorough	Yes	Yes	3.4 x 10^{-8} cm/sec	50 permeability tests performed on undisturbed wall samples	Better than Acceptable
16	Adequate	Adequate	Yes	4 standard-sized bags of bentonite and 11 bags of cement for each 3 cu. yds. of backfill	1 x 10^{-6} cm/sec	None	Less than Acceptable
17	Slurry wall backfill profile was measured twice daily to verify that the trench had not caved in	Adequate	4 tests per day	3 tests per day for slump and density, 3 tests per 400 lf for permeability	All samples had permeabilities equal to or less than 1 x 10^{-7} cm/sec.	Samples of the wall taken for permeability testing	Better than Acceptable
18	Every 10 feet	Insufficient during trench excavation and backfilling, insitu soil mixing required to complete the key in	2 times per shift	28 backfill samples tested after wall completion	1 x 10^{-7} cm/sec requirement met	Samples taken every 100 feet along wall.	Better than Acceptable
19	Adequate	Thorough	Yes	Thorough	NA	Samples taken along wall. Piezocone testing performed for window detection, pump testing across barrier, and geophysical survey along barrier.	Better than Acceptable
20	Thorough	Thorough	Before and after trench placement	Yes - for each batch	1 x 10^{-7} cm/sec	Hydraulic testing	Better than Acceptable

Table 3-5
Containment Barrier CQA/CQC Matrix (Continued)

Site	Trench Sounding	Key Confirmation	Slurry Testing	Backfill Testing	Backfill Permeability	Post-Construction Testing	Rating
21	Auger depths measured	Visually	Daily	Daily	1 x 10^{-6} cm/sec	Samples taken to verify key	Better than Acceptable
22	Daily	Visually	Yes; 18 hour slurry mixing period	Yes	1 x 10^{-7} cm/sec	None	Better than Acceptable
23	Daily	Visually	Yes	Yes	1 x 10^{-7} cm/sec; requirement met	17 dissipation tests performed measure permeability. Undisturbed barrier samples collected every 500 feet	Better than Acceptable
24	Daily	Visually	Tested for density, Marsh viscosity, and filtrate loss	Tested for liquid limit, gradation, and permeability	NA	Samples were collected from completed trench for permeability testing	Acceptable
25	Adequate	N/A-hanging wall	Twice per shift	Slump testing and slope testing performed on every 250 to 300 cu. yd. of backfill	3 backfill samples tested using flexible wall permeameter; all met 1 x 10^{-7} cm/sec requirement	N/A	Acceptable
26	Depth sounding every 10 feet	Yes	Yes	Yes	1 x 10^{-7} cm/sec	No information available	Not evaluated; no data available
27	Adequate	Confirmation sampling every 25 feet	Thorough	Yes	Avg. permeability = 2 x 10^{-8} cm/sec; wall met permeability requirement	NA	Better than Acceptable
28	Yes	Yes	Yes	Yes	1 x 10^{-7} cm/sec	Stress Test	Better than Acceptable
29	Average	Yes	Yes	Slump testing average	1 x 10^{-7} cm/sec	Stress testing	Acceptable
30	Yes	Yes	Yes	Extensive testing	1 x 10^{-7} cm/sec	Sampling and testing after slurry wall completion	Better than Acceptable
31	Every 15 to 20 feet	Visual analysis of trench bottom samples	Twice per shift	Once every 400 to 600 cy	Wall met requirement	Regular and documented	Better than Acceptable
32	NA	NA	NA	NA	NA	NA	Not assigned; no data available
33	Depth sounding every 25 feet	Continuous visual inspection of cuttings to ensure at least 2 feet of penetration into aquitard	Daily testing	Daily testing	Required permeability was <5 x 10^{-6} cm/sec 3 C-B; 3 S-C-B backfill tested.	Unconfined compressive strength	Better than Acceptable

Table 3-5
Containment Barrier CQA/CQC Matrix (Continued)

Site	Trench Sounding	Key Confirmation	Slurry Testing	Backfill Testing	Backfill Permeability	Post-Construction Testing	Rating
34	Every 10 feet	Visually plus top and bottom sounding	2-3 times per shift	Daily testing	K $\leq 5 \times 10^{-7}$ cm/sec	Settlement plates Stress cells	Better than Acceptable
35	Yes; < 10 ft.	Visual inspection of cuttings	Slurry viscosity density, sand content prior to concreting	Plastic concrete mix was designed and tested with materials and site mixing plant	Permeability test	NA	Better than Acceptable
36	N/A	N/A	N/A	N/A	N/A	N/A	Acceptable (Cap only)

Note: Acceptable industry practices in Table 3-4 were used to evaluate site CQA/CQC. However, only CQA/CQC parameters are discussed in this table.

N/A = Not Applicable
NA = Not Available

postconstruction sampling and testing of the barrier and ensuring continuity of the barrier. For sites that were rated less than acceptable, postconstruction sampling and testing of the barrier was limited, and the barrier wall was interrupted during construction because of obstructions along the alignment. In general, CQA/CQC problems were encountered in the areas of cleaning and confirmation of the trench key.

The CQA/CQC matrix presented in Table 3-5 illustrates the differences among the sites studied. At Site 1, which is rated less than acceptable, confirmatory samples were taken from the barrier wall at intervals of 500 linear feet (lf), while at Site 11, which is rated better than acceptable, confirmatory samples were taken at intervals of 50 lf for the soil-cement-bentonite wall and 100 feet for the soil-bentonite wall. Site 16 is rated less than acceptable because construction was interrupted when a gas line was encountered during excavation, and because postconstruction sampling was not performed.

Key confirmation was done visually at most sites. Trench sounding was performed daily at all sites, with measurements at intervals of 10 to 25 feet. The slurry testing and backfill testing was adequate at all sites studied, with the number of tests varying according to requirements at the particular site. Evaluation of the CQA/CQC efforts at the sites studied revealed that the acceptable industry practice detailed in Table 3-4 was followed at most sites and the differences are related to the requirements of the Sites. Only at Site 16, where the barrier wall was constructed for an emergency action, was acceptable industry practice not followed.

3.4 PERFORMANCE MONITORING

Performance monitoring as a performance evaluation criteria is a direct measurement of the system's ability to meet the containment objective. The preceding sections, 3.2 and 3.3, discussed containment design and containment CQA/CQC issues that contribute to performance. Monitoring does not contribute directly to performance, but monitoring approaches may contribute to the perceived performance of the containment. Therefore, the following discussion evaluates monitoring methods as measuring mechanisms, both in general and relative to the studied sites. It describes as well variations in the methods and possible pitfalls in monitoring containment performance.

Performance monitoring focuses on demonstrating the ability of the containment system to meet the design objective in both the short term and the long term. The objective of the containment system monitoring is to measure three factors: cutoff of outflow (contamination); cutoff of inflow (leachate generation); and maintenance entombment. Therefore, monitoring should measure flow or flux into and out of the containment system and measure long-term degradation mechanisms that affect the flow or flux, as well. The following discussion examines the monitoring methods unique to either barriers or caps, as well as those common to both, for the investigated sites.

Monitoring to assess performance must be viewed in terms of the established performance criteria for the site. Performance goals varied widely among the sites studied, even within similar types of containment categories. These various goals are compared in Section 4.0 and discussed in the individual site summaries listed in Appendix B, Volume II. Equally important is the period within which the performance objective is reached. Monitoring must consider time required to attain performance, with long periods of flow and flux equilibration often needed before the site meets its performance goal. The reader is referred to the generic model Methods for Evaluating the Attainment of Cleanup Standards (EPA 1992).

To aid in consistently assessing performance monitoring of a site, matrices were developed to compare and rank the site monitoring (see Section 3.4.1). A qualitative ranking was determined on the basis of available data, and a reference to an industry baseline standard was established. The baseline standard was based on personal experience, consultation with industry contacts, published information, and site review. Discussions of monitoring methods, findings from site evaluations, and several significant monitored sites follow.

Subsurface barriers traditionally have monitoring elements common with those for caps, but also require unique monitoring. For subsurface barriers, monitoring immediately after construction is more important because of the effect barriers have on dynamics of groundwater flow and the process of flow equilibration. The subsurface nature of barriers makes monitoring more difficult and performance measurement more ambiguous, compared with monitoring of surface barriers or caps. Evaluation of monitoring at the selected sites revealed that monitoring methods varied. Groundwater head and quality were monitored routinely, while monitoring to detect long-term degradation was less prevalent. The following subsections discuss monitoring methods for vertical barriers and the range of findings among the studied sites.

3.4.1 Typical Industry Practices

The most successful way to ensure adequate performance in the long term is to conduct thorough design studies and provide competent field quality control during construction (Evans 1993). However, monitoring is necessary to confirm and document performance. EPA provides general guidance for monitoring (EPA 1984) and discusses specific applications of conventional and some less typical CQA and monitoring techniques (EPA 1987b). In previous industry research (EPA 1987a), a reasonable performance monitoring program was outlined. It included the following key features:

- The installation of observation wells and periodic performance pumping tests to measure the average as-built hydraulic conductivity
- Periodic comparisons of baseline and postconstruction groundwater quality at key downgradient locations
- Monitoring of deformation when the barrier is subjected to significant loading

Subsequent work additionally advocated the use of noninvasive or nondestructive testing and predictive mathematical modeling for fate and transport of contaminants across barriers (Rumer and Ryan 1995). Finally, the range of applicable monitoring methods and a discussion of current technology are presented below and summarized in proceedings of the first International Containment Workshop (Rumer and Mitchell 1996).

Table 3-6 describes the monitoring categories for vertical barriers evaluated as part of this study. The established industry baseline standard also is defined. Individual monitoring categories are described further below.

TABLE 3-6

EVALUATION OF CONTAINMENT BARRIER MONITORING CATEGORIES

Category	Below Industry Baseline Standard	Industry Baseline Standard	Above Industry Baseline Standard
Groundwater Quality	<3 wells	at least 3 wells downgradient	>3
Hydraulic Head	None	Piezometer pairs across barrier	Equally spaced pairs
Hydraulic Stress Tests	None	Postconstruction at barrier	Several periodic tests
Physical Samples and Analysis	None	At select locations	At regular intervals
Surface Water Quality	None	At select locations	At several locations
Monitoring of Settlement and Earth Stress	None	Near structures	Near structures and regularly
Inclinometer and Barrier Movement	None	At problem slopes	At problem slopes and regularly
Nondestructive Testing (geophysics and other)	None	None	Some
Environmental Degradation	None	None	Some

Groundwater Quality

Groundwater quality is the most widely used method of monitoring containment performance. This surrogate measurement of barrier performance enables us to estimate the flux leaving the containment. Groundwater quality typically is measured outside the barrier, with more emphasis in the downgradient direction.

Performance monitoring through evaluation of groundwater quality should consider the number of locations, well placement, the screen intervals of monitoring wells, frequency of readings, and laboratory analysis performed. Typically, the sites studied had more than the minimum number of monitoring wells located downgradient. For the sites studied, an average of one well per 500 lf of barrier (ranging from 1 per 50 ft to 1 per 1,440 ft) had been installed. Spatially, an average of one well per 7 acres (ranging from 1 per 0.3 acre to 1 per 62 acres) had been installed. At a few sites, strata below the barrier key were monitored. Most wells were sampled and analyzed quarterly. Of 20 sites, groundwater quality was measured quarterly at 14, semiannually at 3, and annually at 3. At 1 site, frequency of monitoring decreased with increasing depth below the zone of interest, and 2 sites showed a decreased frequency when few elevated levels were detected. The analytes varied with each site and with the contaminants present. For most sites, indicator compounds had been chosen for monitoring. In addition, at a few of the sites studied, quality of groundwater was measured inside the containment, and, in most of those cases, the interior concentrations decreased over time.

Hydraulic Head

Hydraulic head refers to water level or piezometric readings inside or outside the barrier, preferably in locations paired across the barrier. Hydraulic head is the second most widely used monitoring technique for measuring the containment performance of a vertical barrier. The hydraulic head often is used as a direct measurement of advective inflow or outflow by measuring head differential across the vertical barrier and the consequent gradient.

Performance monitoring with hydraulic head should consider measurement locations (both cross-barrier and along the barrier), frequency of measurements, precision of measurements, and the dynamics of groundwater flow. Head should be measured in correlative strata on opposite sides of the barrier at multiple locations. Locations along the barrier should be more uniform for an active (intragradient) containment system or more concentrated downgradient for a passive system. Hydraulic head also should be monitored in the barrier key or sub-key strata, if there is concern about the uniform low permeability of the keying interval, or floor, of the containment. The industry baseline standard was established as paired piezometers as described above, adjusted for active or passive containment.

For 13 of the 36 sites studied, there are active intragradient containment systems. At all but one of the 13 sites, paired piezometers were used to measure hydraulic head. Most of the paired piezometers were spaced equally across the barrier and within 25 feet of the barrier. At most of the 13 sites, pairs were spaced somewhat equally along the barrier, on average every 750 lf (160 lf minimum to 2,250 lf maximum). Only a few of the passive containment sites had paired piezometers. Hydraulic head was measured monthly at 5 of the 9 sites for which significant historical head data were available. For 3 of the sites, head was measured and reported quarterly, while for 1, head was measured hourly and reported quarterly. The measured values were used to assess whether cross-barrier head differentials specified in the regulation, typically greater than 1 foot, were achieved. At a few sites, control of vertical gradients also was required, and at 1 site, maintenance of head below the contained waste material was required.

Hydraulic Stress Tests

Pumping tests provide a means to subject a region in the vicinity of pumping to increased stress conditions, thereby accentuating flow through imperfections in the barrier. Such imperfections may be zones of high permeability (windows) or inadequate contact between vertical barrier and key. A stress test should be run adjacent to the barrier to achieve maximum stress, within allowable limits. Test monitoring should include monitoring of cross-barrier water level near the pumping center and along the alignment. Tests can be run either inside or outside the containment. Disposal of water, potential to induce leaks outside the vertical barrier, and potential for excessive head differential and hydrofracture during testing should be considered. Hydraulic stress also can be induced through injection of water or natural stress, such as tidal influence of groundwater outside the vertical barrier. For sites studied, tests have been run immediately after barrier construction, as part of the 5-year review of the site, or as a diagnostic test to evaluate suspected leaks identified by another surrogate monitoring technique. The industry baseline standard for this monitoring method was established as some postconstruction pumping tests, as Table 3-6 shows.

Evaluation of the selected sites indicated that some form of active stress test was performed after construction or as part of postconstruction evaluation tests at only 8 of 36 sites. For 4 of those sites, tests were conducted at multiple locations with monitoring in several strata, including the key stratum. At 3 of the 4 sites at which the more elaborate tests were used, leaks had been suspected and were confirmed by the testing. Tests were run either inside or outside the containment. At a few sites, initial site dewatering was used as a stress-testing alternative. At 2 of the non-waste-containment sites, head differential was from 60 to 100 feet and leaks of less than 100 gpm were measured to confirm the low permeability of the vertical barrier. At 1 site, pumping and injection tests and flow simulations were used to prove attainment of required permeability of the vertical barrier. At 1 site, testing was conducted by conventional falling head permeability testing through the earthen barrier backfill.

Testing varied significantly among the sites. Logistical issues appear to be the deterrent to stress testing. However, evaluation pumping tests on sites at which leaks were suspected proved conclusive.

Physical Samples and Analysis

Physical sampling and laboratory testing of vertical barriers, typically earthen barriers, provide a direct measurement of the constructed permeability. However, such direct measurement is affected by the representativeness of the sample, differences of scale between laboratory and field, disturbance of the sample, and concerns about disturbance of the barrier during sampling. Some additional complications arise from differences in laboratory procedures for permeability testing. Despite some disadvantages, sampling and testing often are used. Correspondingly, the industry baseline standard shown in Table 3-6 includes some physical sampling and testing at select locations.

Physical sampling and testing should include samples collected at different depths in the earthen barrier and, at a minimum, from zones at which construction difficulties occurred. Several drilling and sampling methods have been used to retrieve samples with minimal disturbance (such as Shelby tubes). Testing should include physical inspection, select physical tests comparable to previous CQA/CQC testing, and permeability testing.

Postconstruction sampling and testing were performed at 9 of the 36 sites studied. Spacing of borings averaged every 300 lf along the barrier alignment, with a maximum of one boring every 100 lf and a minimum of one boring every 500 lf. At most sites, conventional flexible wall permeameters were used to test samples for physical parameters and permeability.

Surface-Water Quality

Monitoring of adjacent or downgradient surface-water quality monitoring is sometimes used in addition to or in lieu of groundwater quality monitoring. Dilution factors make this monitoring method problematic for assessing the direct performance of a vertical barrier. However, measurements of surface-water quality and comparison of the results with risk-based surface-water standards can measure the efficacy of the containment in managing risk to surface-water receptors. Location and analysis of surface-water monitoring vary significantly according to the features of the site monitored.

The industry baseline standard was established simply as surface-water quality monitoring at selected locations, if a body of surface water is near the site.

Of the sites studied, approximately one-third were located adjacent to surface-water bodies; typically, surface water was measured to determine for containment performance. In just a few cases, data on surface-water quality were submitted to regulatory agencies in place of corresponding groundwater data. In addition, in a few cases, samples of sediment or biota supplemented surface-water quality data.

Monitoring of Settlement and Earth Stress

Physical distortion of the earthen barriers can be measured by monitoring settlement, either at the surface or at depth. Earth stress (modified geostatic stress) in an around the barrier also can be measured. While these are not direct measurements of containment performance, they can provide data that indicate potential regions of physical distortion or excessively high stress. Generally, this type of monitoring is more prevalent in cases in which barriers are located near structures or high loads. Similarly, this monitoring is performed near barriers subjected to high hydrostatic stresses, such as those associated with dewatering operations or dam cutoffs.
The industry baseline standard for this monitoring was established as performance of some monitoring of settlement and earth stress when vertical barriers are located adjacent to structures or in areas of high induced stresses. At 4 of the sites studied, such monitoring was performed. Of those sites, 3 were dam cutoffs or dewatering operations

Inclinometer and Barrier Movement

Inclinometers or similar devices can be used, either in the barrier or on the adjacent native ground, to monitor lateral movement. While monitoring of movement is not a direct measure of performance, it can measure physical distortion that may affect performance. Concerns about movement may arise because of adjacent steep slopes or excessive head differentials on the vertical barrier, contributing to slope instability. Conventional containment barrier installations cause minimal concern for postconstruction instability unless the installation is near unstable steep slopes. Therefore, the industry baseline standard was established for application at problem slopes.

The study of 36 selected sites revealed that lateral movement of the barrier was measured at only 5. Two of those sites were dam cutoffs at which movement was monitored because of high hydrostatic head differentials across the dam core or vertical barrier. At the remaining sites, movement was measured because of excessive load from adjacent landfilling, concern for movement of adjacent railroad lines caused by lateral consolidation of the soil-bentonite backfill, or steepness of the slope downgradient of a containment barrier having high internal heads.

Concerns about lateral movement of barriers is minimal in conventional containment installations. However, certain conditions warrant such monitoring, which can be accomplished with several devices, such as inclinometers or survey bench marks.

Nondestructive Tests (Geophysics and Piezocones)

In addition to destructive sampling, nondestructive geophysical techniques can be used to monitor the subsurface vertical barrier. Such monitoring methods might provide a means to measure the integrity of the barrier directly, and perhaps continuously, at costs that appear reasonable, compared with the cost of intrusive sampling. However, such use has been limited.

Geophysical methods of monitoring vertical barriers include electromagnetic, seismic/acoustic, magnetic, and gravity techniques. There is growing interest in cross-hole seismic imaging, surface seismic refraction, ground penetrating radar, ultrasonic and electromagnetic/resistivity surveying (Rumer and Mitchell 1996). Of the 36 sites studied, a geophysical method was used as a monitoring tool at only 3. At 2 of those sites, resistivity surveying was used, and streaming self potential was used at the third. At 1 of the two sites at which resistivity surveying was performed, measurements are collected annually to identify changes in resistivity and suspected leaks. The results of resistivity surveying have been inconclusive. At the site at which streaming self potential is being performed, this technique is being used a few years after initial construction to assess leaking. The information is being correlated with information about groundwater quality and hydraulic head. Use of self potential methods involves measuring potentials generated by electrochemical reactions between the native materials and groundwater, with potential differences between areas of contamination and those at which there is no contamination. No obvious correlative trends were identified through this effort.

While geophysics may provide intriguing monitoring methods, the data revealed only minimal successes.

Another form of monitoring used is the piezocone and pore pressure dissipation testing. This test is intrusive but does not necessarily require extraction of a soil or water sample to evaluate the integrity of the barrier. The system consists of a cone penetrometer fitted to induce and measure pore pressure dissipation over time. Results offer information about variations in soil or barrier backfill and estimates of permeability. This monitoring method was used successfully at 2 sites after initial barrier construction. It proved useful in defining the location of the barrier, identifying windows, and measuring permeability in situ.

Environmental Degradation of Barrier Construction Materials

Monitoring environmental degradation of barrier construction materials is not practiced widely. Detection of degradation processes would allow the introduction of corrective measures or perhaps lead to preventive design modifications. Degradation mechanisms can include chemical attack (for example, a high concentration of chlorinated solvents), inhibited bentonite hydration caused by saline or hard water, desiccation of earthen barriers in a cyclic vadose zone, and corrosion of metal-sheeted structures. The established industry baseline standard for postconstruction degradation monitoring is that none is performed. Testing for degradation would involve some form of direct monitoring.

Often during the design phase, chemical compatibility testing is performed if there is concern about chemical attack on the vertical barrier, especially in the case of earthen barriers. This laboratory testing typically involves permeating backfill samples with 3 to 5 pore volumes of contaminated permeant. Such tests may not simulate adequately in situ, long-term conditions at the barrier. For approximately half the barriers studied, some compatibility test was performed in the design phase (see Section 3.2). However, postconstruction analysis of chemical breakthrough and degradation was reported for only 2 of the 36 sites studied. At no site were periodic long-term degradation monitoring data collected.

Nonearthen barriers, particularly geomembrane and sheeting, are monitored for degradation differently than are earthen barriers. At 1 site having steel sheeting containment, conventional ultrasonic testing was performed after years of operation to determine corrosion. No decreased performance was noted. Vinyl or plastic sheeting offers obvious corrosion advantages over steel. Geomembrane vertical barriers have benefited from research on landfill liners, including extensive laboratory simulations and field efforts that involve exhuming installed geosynthetics.

Such tests have indicated lives of hundreds of years for geomembranes buried underground and not subject to degradation caused by ultraviolet (UV) light.

Historical data that define the effects of long-term attack on vertical barriers are necessary to better understand the true functional life of such barriers.

3.4.2 Range of Findings

Monitoring of the subsurface barrier varied widely among the sites studied, as described in the previous section. Monitoring efforts at each site were compared in the various monitoring categories with the industry baseline standard, as described above. A rating was provided by site for the monitoring effort as a whole. Measured against the established industry baseline standards, 11 were considered acceptable, 8 sites were considered less than acceptable, and 16 were considered better than acceptable.

The monitoring methods used at each site are described in some detail in the individual site summaries in Appendix B, Volume II of this report. Table 3-7 presents a summary of the barrier monitoring performed at the sites studied.

At most sites, hydraulic head and groundwater quality were monitored. Typically, if surface water was adjacent to the site, it also was monitored. At most of the sites where active containment was performed, paired piezometers across the barrier were used to measure head differential. In almost all cases, the pairs were located within 25 feet of the barrier and, in most cases, were spaced every 200 to 400 feet along the barrier. At approximately one-third of the sites, postconstruction confirmation borings and analysis had been performed. Several of those sites were in New Jersey, where closure or permit regulations require confirmation borings and testing. At only a few of the sites were pumping tests performed to measure the effectiveness of the barrier during stressed conditions. In only a few cases were geophysical methods used to estimate the integrity of the barrier. In no case were tracers used to monitor leaks in the barrier.

Among the 36 sites studied, some noteworthy monitoring efforts were revealed. Those efforts are outlined below and described in more detail in the site summaries in Appendix B, Volume II.

Site 19 was the most extensively monitored site. Significant postconstruction monitoring and testing, as well as subsequent performance evaluation and testing, had been conducted there. Notably, monitoring at the site included piezocone testing to detect windows and pumping tests at three suspect locations, with multilevel cross-barrier monitoring to measure barrier underflow.

Although Site 23 was monitored adequately during construction, postconstruction monitoring detected problems in groundwater quality. Borings and piezocone dissipation tests were used to measure the continuity and integrity of the barrier. Subsequent pumping tests showed interior head response while the outside groundwater was being pumped. A remedy was put in place to correct the problem.

Table 3-7
Containment Barrier Monitoring Matrix

Site	Groundwater Quality	Hydraulic Head	Hydraulic Stress Tests	Physical Samples	Surface Water Quality	OTHER Settlement, movement, desiccation, stress, NDT-geophysics, other	Rating
1	3 outside & 1 inside wells	Not conducted	Not conducted	Taken during post-construction verification	2 outside	Leachate quality	Acceptable
2	5 outside (1 up and 4 down gradient)	Not measured	Not conducted	None	None	Annual electrical resistivity survey outside barrier	Better than Acceptable
3	Semiannual monitoring	N/A	Not conducted	Post-construction borings (100 ft centers)	None	None	Less than Acceptable
4	8 pairs of nested wells with screens in shallow and deep aquifers	3 inside & 1 outside are monitored monthly for water level. Hydraulic gradient could not be determined because of deficiencies in data	Not conducted	None	None	None	Better than Acceptable
5	Several wells downgradient	Paired piezometers	Not conducted	Samples obtained at 400 lf spacing	Several adjacent points	None	Better than Acceptable
6	Quarterly monitoring in 6 wells	N/A	Not conducted	Yes	No	Waste was solidified	Acceptable
7	8 wells outside, and leachate sampled	Head outside only, inside head monitoring pending;	Not conducted	None	3 locations	Leachate quality and quantity is measured	Less than Acceptable
8	100 monitoring wells	None	Pump Test to certify permeability of sheetpile cutoff	NA	Several locations	None	Less than Acceptable
9	6 pairs across barrier; inside leachate collection system	6 pairs across barrier	Not conducted	None	None	None	Less than Acceptable
10	21 wells both sides of barrier	150 wells measuring local head	Not conducted	Post-construction permeability tests	None	None	Acceptable
11	Not yet implemented	Not yet implemented	Not yet implemented	CQA undisturbed samples and testing per 100 lf	None	None	Insufficient Data
12	5 pairs across barrier	>7 Alluvial monitoring wells	Not conducted	None	None	None	Better than Acceptable
13	49 wells both sides of barrier	Paired piezometers	Not conducted	None	Several locations	None	Better than Acceptable

Table 3-7
Containment Barrier Monitoring Matrix (Continued)

Site	Groundwater Quality	Hydraulic Head	Hydraulic Stress Tests	Physical Samples	Surface Water Quality	OTHER Settlement, movement, desiccation, stress, NDT-geophysics, other	Rating
14	N/A	43 vibrating wire piezometers 15 multiple level standpipe piezometers	Permanent high gradient across barrier	Visual inspection of key	N/A	12 inclometers/extensometers in barrier to control deformation. Monitoring of settlement and movement on top of wall	Better than Acceptable
15	11 outside wells	Not conducted	Only during ground water withdrawal	50 taken during post-construction verification	None	Inclinometers	Better than Acceptable
16	Several wells up and down gradient; DNAPL & dissolved phase measured	4 pairs across cutoff for measuring gradient	Not conducted	None	Several down gradient	Streaming self-potential geophysics for detecting leakage, unsuccessful	Better than Acceptable
17	Quarterly monitoring of several wells	6 pairs across barrier, and 2 wells downgradient	Not conducted	Post-construction backfill samples taken	None	None	Acceptable
18	Quarterly monitoring at 9 wells, 2 inside and 7 outside	4 pairs across barrier	Not conducted	28 samples taken after wall installation	None	None	Better than Acceptable
19	38 single level and 33 multi-level wells	Several pairs across barrier to measure of zero net gradient differential	1 CQA post-construction pump test; 3 evaluation pump tests with multi-level cross-barrier monitoring	Post-construction evaluation samples and breakthrough analysis	>3 down gradient location	Electrical resistivity; piezocone sounding for widow detection	Better than Acceptable
20	Quarterly monitoring of wells outside barrier	16 pairs across barrier measured hourly, two levels	Pre- and post-barrier pumping tests with cross barrier monitoring	None	Several locations outside the wall	Settlement plate monitoring	Better than Acceptable
21	Quarterly monitoring	4 pairs across barrier	Not conducted	Samples obtained to verify key	Yes	None	Less than Acceptable
22	13 wells, quarterly sampling	Slight inward gradient	Not conducted	None	4 onsite points	None	Less than Acceptable
23	15 wells outside	21 pairs across barrier	3 pump test outside the barrier with multi-level cross barrier monitoring	Samples collected every 500 lf	None	Post construction evaluation with piezocone for continuity and dissipation tests for permeability	Better than Acceptable
24	3 outside (1 down and 2 up gradient) in shallow and 4 in deep zones	No piezometer pairs; measured head in 6 pumping wells	Not conducted	Samples collected for permeability testing	Several locations	None	Less than Acceptable

Table 3-7
Containment Barrier Monitoring Matrix (Continued)

Site	Groundwater Quality	Hydraulic Head	Hydraulic Stress Tests	Physical Samples	Surface Water Quality	OTHER Settlement, movement, desiccation, stress, NDT-geophysics, other	Rating
25	27 wells monitoring monthly	24 paired piezometers	Not conducted	None	6 stations sampled monthly	None	Acceptable
26	54 withdrawal wells, 38 recharge wells; quarterly monitoring	10 equally spaced piezometers on both sides of barrier	Not conducted	Post-construction backfill permeabilities	None	None	Acceptable
27	>5 well outside	8 pairs across barrier measuring head differential quarterly	Groundwater extraction and cross-barrier monitoring	CQA post-construction sampling and permeability test per 250 lf	None	Leachate quality and quantity	Better than Acceptable
28	Yes	Yes	Yes	Yes	None	Pump test for 1 year	Better than Acceptable
29	6 paired monitoring wells	6 pairs of piezometers	Yes	Yes	None		Acceptable
30	Monitored	Monitored	Not conducted	CQA undisturbed samples and testing per 400 lf at various depths	Monitored for NPDES	None	Acceptable
31	21 wells and piezometers; quality no measured if head gradient is met	8 sets of paired wells across the barrier	Not conducted	None	River sediments, fish	None	Acceptable
32	16 wells inside and outside	4 pairs monitoring cross-barrier; interior monitoring for >5 ft differential below waste	None, except initial sitewide drawdown.	None	None	None	Better than Acceptable
33	1 up gradient, 4 down in iron filter, 2 downgradient of filter	Flow through reactive wall	N/A	None	None	Protective cap	Acceptable
34	N/A	Electric piezometer inside and outside of wall	Permanent high gradient across dam	None	N/A	Stress cell, settlement plate, and inclinometer	Better than Acceptable
35	N/A	Several paired piezometers across cutoff	Head differential across wall is close to 100 feet	CQA testing only	N/A	Dewatering rates, tieback loading, deformation monitoring during construction	Better than Acceptable
36	N/A	N/A	N/A	N/A	N/A	N/A	Acceptable (Cap only)

N/A = Not Applicable NDT = Non-destructive testing

Because of concerns about possible outward flow conditions caused by tidal fluctuations in surface water and groundwater, paired piezometers at Site 20 were monitored hourly to confirm head differentials. Exterior groundwater and surface-water quality also were measured monthly.

In contrast to the efforts at the sites mentioned above, minimal to no monitoring was performed at several sites. Although, at several sites, barrier compatibility was investigated during design efforts, at only 2 of the sites studied was the barrier reevaluated to assess long-term degradation of the barrier or contaminant breakthrough. The two studies were prompted by the identification of other problems related to the barrier. Electrical resistivity surveying of the subsurface barrier is performed at Site 2 annually in an attempt to measure changes over time in the integrity of the barrier.

3.5 OPERATION AND MAINTENANCE

O&M of subsurface barriers consisted of scheduled preventive maintenance and repair of components to ensure the continued effectiveness of the remedial system. Most O&M activities at the sites studied consisted of operating the pumping systems required to maintain the design gradient across the barrier wall.

O&M activities for subsurface barriers included monthly site inspections, quarterly readings of water levels in monitoring wells and water quality sampling, and sampling required under the facility's National Pollutant Discharge Elimination System (NPDES) permit.

3.5.1 Typical Industry Practice

Because O&M activities are site-specific, it is difficult to establish acceptable practice. However, the elements of O&M that should be conducted for vertical barriers include:

- Monitoring the pumping systems within and outside the barrier wall and adjusting the treatment system for variations in water quality, either monthly or quarterly

- Inspecting the surface of the barrier wall for settlement or erosion, either monthly or quarterly

3.5.2 Range of Findings

For most of the sites studied, O&M activities were related to the pumping and treating of contaminated water within the barrier wall. Table 3-8 provides a summary of the O&M information that was available. O&M activities were not compared with acceptable industry practice; however, sites at which O&M practices were noteworthy are discussed below.

Site 11 was visited 10 years after the installation of the barrier wall and cap. The investigation involved extensive head monitoring for horizontal and vertical gradients at the barrier, conduct of pumping tests at the barrier, advancement of 11 borings to obtain data on the integrity of the barrier, and evaluation of the groundwater flow in the vicinity of the barrier.

As a result of O&M activities at Site 25, it was determined that the concentrations of contaminants in groundwater within the wall increased with time, and the treatment system required modification to accommodate the increased concentrations.

Table 3-8
Containment Barrier and Cap O&M and Cost Matrix

Site	Barrier O&M	Cap O&M	Pumping System O&M	Barrier Capital Cost	Cap Capital Cost	Barrier O&M Cost	Cap O&M Cost
1	Monthly inspection	Surface erosion control	Quarterly effluent sampling	NA	NA	NA	NA
2	NA	NA	NA	$444,000 in 1981	NA	NA	NA
3	NA	Monthly inspections	N/A	NA	NA	NA	NA
4	Yes	Yes	On-site treatment system	$6.8 million total for grout curtain, slurry wall, landfill cap, and treatment plant	Included as lump sum	NA	NA
5	Regular inspection	Monthly inspection	Yes	NA	NA	NA	NA
6	Regular inspection	Regular inspection	NA	NA	NA	NA	NA
7	NA	Inspection of cap	Maintenance of leachate pretreatment facility	$3,120,885=barrier ($7.81/sq. ft)	$17,073,616=cap $4,154,859=gas collection system $1,833,841=leachate collection system	NA	NA
8	Cathodic protection may be needed	N/A	NA	NA	N/A	NA	N/A
9	NA	N/A	N/A	NA	N/A	NA	N/A
10	NA	N/A	Information not available	$242,000 cost estimate for cutoff wall extension (650 feet)	N/A	NA	N/A
11	NA	NA	N/A	$8,900,000	NA	$1,200,000/year	NA
12	Periodic visual inspections	Vegetative cover maintenance		$456,000	$432,000	$59,000/year total	Information not available
13	NA	As needed	As needed	$4,500,000	Included in barrier	NA	NA
14	NA	NA	NA	NA	NA	NA	NA
15	None	NA	Quarterly effluent sampling	NA	NA	NA	NA
16	NA	N/A	NA	$500,000	N/A	NA	N/A
17	NA	Monthly inspection	Monthly inspection	NA	NA	NA	NA

Table 3-8
Containment Barrier and Cap O&M and Cost Matrix (Continued)

Site	Barrier O&M	Cap O&M	Pumping System O&M	Barrier Capital Cost	Cap Capital Cost	Barrier O&M Cost	Cap O&M Cost
18	Monthly inspection	Monthly inspection	$200,000/year	$5.5 million	$2.7 million	Minimal	$10,000/year
19	Barrier integrity evaluated after 10 years	Monthly inspection	Groundwater treatment: $1,644,000 wells: $50,000	$1,000,000 - slurry wall ($4.65 per sq. ft)	$436,000=cap $65,000 = gas vents	NA	NA
20	Inspection of barrier surface	NA	Regular inspection	$5,000,000	NA	$400,000/year	NA
21	Regular inspection	Regular inspection	Monthly	$3,000,000	$1,300,000	NA	$10,000/year
22	Quarterly monitoring for three years	Monthly inspection	NA	$2,550,000	NA	NA	NA
23	Regular inspection	Quarterly water level readings, monthly site inspections	NA	NA	NA	NA	NA
24	NA	Quarterly visual inspections, annual benchmark surveys, monthly mowing of vegetative cover as needed	NA	$400,000	NA	NA	NA
25	Regular inspection and checking water levels	N/A	NA	NA	N/A	NA	N/A
26	No information available	N/A	No information available	No information available	N/A	No information available	N/A
27	Monthly site inspections, quarterly effluent sampling and well water level readings, and annual well water sampling	NA	NA	$4,500,000 = total	NA	$30,000/year =total	NA
28	NA	N/A	NA	NA	N/A	NA	N/A
29	Information not available	Information not available	Information not available	Information not available	Information not available	Information not available	Information not available

Table 3-8
Containment Barrier and Cap O&M and Cost Matrix (Continued)

Site	Barrier O&M	Cap O&M	Pumping System O&M	Barrier Capital Cost	Cap Capital Cost	Barrier O&M Cost	Cap O&M Cost
30	Yes	Yes	Yes	$14,200,000	Included as lump sum		
31	Weekly site inspection; monthly barrier inspection	N/A	NA	$2.5 million for construction and CQA/CQC	N/A	Information not available	N/A
32	Periodic pumping to maintain water table level inside containment	NA	NA	No cost information available	NA	NA	N/A
33	Monthly water sampling	N/A	N/A	NA	N/A	NA	N/A
34	Continuous monitoring of seepage	N/A	N/A	$2 million for installation only ($6/sq ft)	N/A	NA	N/A
35		N/A	N/A		N/A	N/A	N/A
36	N/A	NA	N/A	N/A	NA	N/A	NA

Notes: N/A = Not applicable
NA = Not available

3.6 COST

The cost information obtained during the study could not be segregated as design and construction costs. Completion reports for the remedial actions provided lump-sum costs for the barrier wall, cap, and groundwater treatment system. In some reports, O&M costs were provided for the barrier wall, cap, and treatment plant. Details are provided in the individual site summaries in Appendix B, Volume II.

The costs of installing subsurface barriers vary widely, depending on the unique conditions at each site (see Table 3-8). Costs also vary because of the construction method and the type of barrier wall. In general, use of the vibrating beam method of barrier wall construction resulted in the lowest cost, and use of the trench excavation method resulted in the highest cost. However, it should be emphasized that the vibrating beam method produces a thinner wall than the trench excavation method. Soil-bentonite walls cost less than cement-bentonite walls. If off-site borrow clays are used in soil-bentonite walls, the cost is higher than the cost would be if a bentonite slurry were sufficient.

The capital cost for construction of a barrier wall is expressed in dollars per square foot of sidewall area. Such costs vary from $5 to $15 per square foot. The O&M cost is usually very small, unless the design includes a treatment plant. The O&M cost will depend on the monitoring requirements specified by the state regulatory agency.

4.0 DATA COLLECTION AND ANALYSIS - CAPS

Data collection and analysis for caps was done in conjunction with that for barriers. The site summaries in Appendix B provide information for the barrier and cap systems; site 36 was a cap only site. This section describes the present design, CQA/CQC, performance monitoring, O&M, and cost of the caps evaluated.

4.1 DESIGN

The design of a cap defines the functional criteria performance objectives of the cap. The design documents provide the design calculations, detailed drawings and specifications, CQA and CQC requirements during cap construction, O&M requirements, a performance monitoring plan, as well as construction costs and schedule. Therefore, understanding the design objective and analyzing design documents are important for evaluating cap performance.

Guidance has been provided by USEPA (1989, 1993) and USACE (1993) for the proper design of caps. This subsection will define the design components of the cap and discuss the matrix that was used to evaluate the design of caps.

The primary objective of capping is to minimize infiltration into the waste materials and isolate waste from human contact. At sites for which the cap is a component of the containment system, the cap typically is interconnected with the vertical barrier wall. The design of the cap should consider the following factors, which are described in this section.

- Stability of the waste
- Settlement
- Stability of the cap system

- Drainage
- Infiltration
- Gas management

The project team identified the factors listed above and subfactors associated with them and defined the typical industry practice for each factor and subfactor through discussions with engineers and contractors, the project team's experience, and review of published literature. Table 4-1 presents a matrix that summarizes standard industry practice. The matrix was used to evaluate the 36 sites selected for this study to determine whether the design effort was acceptable, less than acceptable, or better than acceptable. The range of findings from that evaluation is discussed in Subsection 4.2.5.

4.1.1 Stability of the Waste

The stability of the waste mass must be analyzed to determine whether it will remain stable under all potential loading conditions. Several analytical and numerical techniques can be used to analyze global stability of the waste mass. Several loading conditions must be analyzed to determine the stability of a waste mass. They are:

- **Cap loads -** A cap can vary in thickness from 3 to 5 feet. The effect of that loading on stability must be analyzed by accepted slope stability methods.

- **Seismic stability -** The National Oceanic and Atmospheric Administration (NOAA) publishes the earthquake database for all parts of the United States. The seismic loading recommended by the database should be used to conduct psuedostatic seismic stability analysis of the waste mass. EPA (1995) should be used for conducting seismic stability analysis.

- **Construction loading -** During construction of the cap, loads are applied by stockpiles of soil and construction equipment. The worst-case short-term loading conditions should be analyzed.

If the loading conditions described above had not been analyzed and the reliability of the data had not been verified before the stability analysis was performed, the site was rated less than acceptable. If stability was analyzed and the results incorporated into the design, the site was rated acceptable. On the other hand, if the reliability of the data was verified during the analysis and a sensitivity analysis performed, the site was rated better than acceptable.

4.1.2 Settlement Analysis

The foundation and the waste materials may consolidate under the loading conditions described in Subsection 4.1.1, with settlement of the waste mass differing accordingly. Because such differential settlement can have adverse effects on the cap, it must be analyzed. The analyses to be completed are:

TABLE 4-1
MATRIX FOR EVALUATING CAP DESIGN AGAINST ACCEPTABLE INDUSTRY PRACTICES

Design Items	**Less Than Acceptable**	**Acceptable**	**Better Than Acceptable**
1. Global Waste Stability			
General		Check reliability of input data	Sensitivity analysis on waste properties
Under cap loads	None performed	Computer modeling done	Sensitivity analysis
Seismic stability	Not performed	NOAA data used and pseudostatic analysis completed.	Sensitivity analysis
Construction loading	Not performed	Consider worst case short term loading conditions during construction, apply equipment and stockpile loads	Sensitivity analysis
2. Settlement Analysis			
Refuse materials	Not considered	Representative data used for analysis/estimate	Settlement plates included in monitoring plan
Foundation materials	Not considered	Traditional soil mechanics analysis completed	
Impact of differential settlement considered	Not considered	Impact on cover materials analyzed	
3. Stability of Cap System			
Interface stability analysis	No analysis performed or analysis performed using assumed data	Analysis performed using data generated from laboratory testing of site specific geosynthetics and soils	Analysis performed with additional sensitivity checks performed
Cover soil tension above geomembrane lined slope	No analysis performed	Analysis performed to determine need for tension reinforcement using appropriate laboratory generated data	
Stresses within cap components	No analysis performed	Analysis performed using cap loads and construction loads	
Impact of differential settlement on geosynthetics	No analysis performed	Calculate stresses in geosynthetics due to subsidence	
Stability of slopes steeper than 3:1	Not considered	Slope protection designed	

TABLE 4-1
MATRIX FOR EVALUATING CAP DESIGN AGAINST ACCEPTABLE INDUSTRY PRACTICES (Continued)

Design Items	**Less Than Acceptable**	**Acceptable**	**Better Than Acceptable**
4. Drainage Analysis			
Drainage capacity of cover system evaluated (transmissivity)	No analysis performed	Evaluate drainage requirements of cap system using models such as HELP and size drainage medium accordingly	
Geotextile filtration	No analysis performed	Evaluate cover soil compatibility with separation geotextile to prevent clogging and encourage filtration	
Runoff control	No analysis performed	Evaluate piping and discharge structure requirement for appropriate peak storm	
Erosion potential	No analysis performed	Universal soil loss equation used	
5. Leachate Management			
Leachate generation rate	Not considered	Analysis completed using site-specific data	
Collection/treatment system	Not considered	Collection/treatment system designed and documented	
6. Gas Management			
Well design/placement	Not considered	Pilot data from site used as design basis	
Passive system design	Not considered	Lateral piping and vertical vents designed	
7. Miscellaneous/Other Items			
Frost depth	Not considered	Soil barrier layer placed beneath maximum frost depth	
Puncture vulnerability	Not considered	Potential for waste material and cover soil to puncture cap system evaluated	

- **Waste materials -** The variability of the waste materials must be considered, and accepted analytical techniques should be used to estimate the long-term settlement of waste material.

- **Foundation materials -** The properties of the foundation materials should be determined, and traditional soil mechanics analysis should be completed to estimate settlement of the foundation.

- **Effects of differential settlement -** The effects of differential settlement on the cap materials, especially geomembranes, should be analyzed.

If the analyses described above were not performed, the site was considered less than acceptable. If the analyses were performed, the site was considered acceptable. If the long-term settlement was analyzed, sensitivity analysis completed, and the results accommodated by the design, the site was considered better than acceptable.

4.1.3 Stability of the Cap System

The stability of the cap system, which consists of different types of soils and geosynthetic materials, must be analyzed. Any failure of the components of the cap system can affect performance adversely. The analyses to be completed to determine the stability of the cap system are:

- **Interface stability -** The critical interfaces within a cap system are those of the soil and geosynthetic clay liner (GCL); the GCL and geomembranes; and the geomembrane, drainage layer, and cover soils. Stability along these interfaces should be analyzed using soil from the site, and reliable data should be obtained from independent laboratories that test geosynthetic materials.

- **Cover soil tension above geosynthetic-clay lined slopes -** The cover soil tension above the geosynthetic-clay lined slope should be analyzed to determine the need for tension reinforcement. This analysis should use data generated by an independent laboratory.

- **Stresses within components of the cap -** The stresses within the components of the cap should be analyzed through the use of cap loads and construction loads to determine whether the cap system will remain stable.

- **Effect of differential settlement on geosynthetics -** The differential settlement caused by subsidence of the waste materials can induce stresses in the geosynthetic materials. The properties of the geosynthetics selected should be appropriate for those induced stresses.

- **Stability of slopes -** Stability of all slopes should be analyzed; however if slopes steeper than 3 horizontal to 1 vertical are required, they should be analyzed to determine whether slope protection measures are needed.

If the analyses described above were not performed, the site was considered less than acceptable. If the analysis were performed, the site was rated acceptable. If the analyses and additional sensitivity analyses were performed, the site was rated better than acceptable.

4.1.4 Drainage Analysis

Drainage of storm water at the site is important to prevent the buildup of hydraulic head on the low-permeability impermeable cap. The design of the drainage system should be subjected to the following analyses:

- **Drainage capacity analysis -** The Hydrologic Evaluation of Landfill Performance (HELP) model is used widely to determine the drainage capacity of the cap. The results obtained from the HELP model are used in designing the drainage layer that overlies the low-permeability cap.

- **Geotextile filtration -** A geotextile is placed over the drainage layer so that the cover soil does not clog the drainage layer. The compatibility of the cover soil with this separation geotextile should be analyzed to ensure the maximum efficiency of the drainage layer.

- **Runoff control -** The 25-year, 24-hour peak storm typically is used to determine the amount of runoff from the site. Piping and discharge structures should be adequate to handle the storm.

- **Erosion control -** The universal soil loss equation is used to analyze the amount of soil erosion at the site. This analysis should be completed to support the design of erosion control measures.

If the analyses described above were not performed, the site was rated less than acceptable. If the analyses were performed, the site was rated acceptable. If the analyses were conducted and a sensitivity analysis of the various input parameters used was performed, the site was rated better than acceptable.

4.1.5 Infiltration

The prevention of leaching at a hazardous waste site is important to the success of remediation. The infiltration design of a cap system should be evaluated according to the following considerations.

The water balance model predicts water percolation through the cap. Several computer models are available to evaluate the hydraulic performance of the landfill cap. The HELP model mentioned in Section 4.1.4 is used to estimate the amount of infiltration into the waste. The effect of compacted clay or the GCL should be analyzed to predict long-term infiltration through the cap. In addition, any improvement of the cap by use of a geomembrane in addition to the clay or GCL should be analyzed.

If the HELP analysis did not use the representative values for the different components of the cap, the site was rated less than acceptable. If the HELP analysis was completed properly, the site was rated acceptable. If the HELP analysis included sensitivity analysis for the various components of the cap, the site was rated better than acceptable.

4.1.6 Gas Management

Decomposition of waste materials may produce methane and other gases. The gases must be collected and vented to the atmosphere or treated, depending on the concentration of contaminants present. The design analyses to be completed are:

- **Design and placement of wells -** A pilot test usually is conducted to determine the quality of gas from the waste and the rate at which it is generated. Design of the depth and spacing of the wells and gas treatment are based on the resultant data.

- **Design of the passive system -** If a passive venting system is required, the locations of lateral piping and vertical vents are designed as the waste characteristics indicate is necessary.

If generation or management of gas was not considered adequately, the site was rated less than acceptable. If the analyses used input data that were not site-specific, the design was considered acceptable. If site-specific input data were used in performing the design analyses described above, the site was considered better than acceptable.

4.1.7 Other Factors

Other factors important to the successful performance of the cap are frost penetration of the cover soils and vulnerability of the geosynthetic materials to puncture. The Soil Conservation Service of the U.S. Department of Agriculture publishes information on the depth of frost in different parts of the country. If that factor was not accounted for in the design, the site was considered less than acceptable. Waste material, construction equipment, and cover soils have the potential to puncture such geosynthetic materials as geotextiles and geomembranes. If these factors were not considered in the design, the site was rated less than acceptable.

4.1.8 Range of Findings

Of the 36 sites, 22 have caps. Cap design varied little among the sites, and most sites met the design requirements set forth under RCRA Subtitle C. The major differences among the designs were in documentation of the settlement analysis, seismic stability analysis, and interface stability analysis. Infiltration analyses and gas management design was handled as required for the site.

At most of the sites, geosynthetic materials were used in the cap. Sites 1, 7, 27, and 30 had compacted clay liners. Sites 28 and 33 were covered with paved parking lots. For most of the sites, the design was rated acceptable, incorporating the following design elements:

- Geotechnical testing of the materials used for the cap
- Analysis of global stability of the waste, based on the properties of materials used at the particular site
- Analysis of potential for settlement
- Analysis of the stability of the cap system

- Analysis of drainage and infiltration through application of the HELP model
- Adequate design of the gas management system
- Protection of the cap against frost penetration

Site 27 was rated less than acceptable because no analyses of seismic stability and interface stability were performed, and no leachate management system was designed. At Site 18, a test section was incorporated into the design to determine the long-term behavior of the geosynthetic clay liner.

Other variations among caps were noted, usually in response to conditions at the particular site. Site 15 had a soil cover only. At Site 1, the side slopes were covered with clay only and the top of the landfill area with geomembrane. At Site 36, a capillary break layer was incorporated in the cap section to control capillary rise. The design for Site 36 was a "consumptive use" cap consisting of specified soil types and vegetation to promote consumptive use of rainfall and limit infiltration.

At most sites, the cap design provided an interconnection with the barrier wall to form a containment system. In addition, erosion control features were designed to protect the cover soils.

4.2 CONSTRUCTION QUALITY ASSURANCE/CONSTRUCTION QUALITY CONTROL DATA

On January 29, 1992, EPA issued final regulations for CQA/CQC in 40 Code of Federal Regulations (CFR) Part 264.19 (57FR3486). Those regulations apply to the design and construction of surface impounded waste piles and landfills, including the construction of caps. However, the state of the art of cap installation has changed since 1992, with geosynthetic materials replacing natural clays and drainage soils. For CQA/CQC, the following factors, which are described in this section, should be considered:

- Borrow soil
- Compacted clay liner
- Soil drainage layer
- Geomembrane barrier

Development of a matrix that describes the typical industry CQA/CQC practices for caps was based on the experience of team members, review of published literature, and discussions with academic and industry practitioners; Table 4-2 presents that matrix. The matrix was used to evaluate the 36 sites selected for the study to determine whether CQA/CQC activities at each site were less than acceptable, acceptable, or better than acceptable. The range of findings for the sites is discussed in Subsection 3.3.21.

EPA has funded several research projects and published reports that summarize the state of the art for installing caps (EPA 1988, 1989, and 1993). The National Sanitation Foundation (NSF) has published standards for the manufacture of flexible geomembranes, and the American Society of Testing and Materials (ASTM) has developed several testing methods that are used widely during the installation of caps. These standards are discussed in the following subsections.

TABLE 4-2
MATRIX FOR EVALUATING CAP CQA/CQC AGAINST ACCEPTABLE INDUSTRY PRACTICES

Category	Less than Acceptable	Acceptable	Better Than Acceptable
BORROW SOIL (Subgrade & Cover Soil)			
Soil Prequalification Testing:			
Classification ASTM D2487	Not performed	1 test per 5,000-6,580 c.y.	More frequent
Compaction Curve ASTM D698/D1557	Not performed	1 test per 5,000-6,580 c.y.	More frequent
Soil Construction Testing:			
Density Testing/Lift ASTM D2922/1556	Not performed	5 per acre	More frequent
Moisture Content Testing/Lift ASTM D3017/2216	Not performed	5 per acre	More frequent
COMPACTED CLAY LINER			
Clay Prequalification Testing:			
Classification ASTM D2487	Not performed	1 test per 5,000-6,580 c.y.	More frequent
Compaction Curve ASTM D698/D1557	Not performed	1 test per 5,000 c.y.	More frequent
Remolded Permeability Test ASTM D5084	Not performed	1 test per 10,000-13,160 c.y.	More frequent
Clay Test Pad Construction/Testing/Evaluation	Not performed	Not performed	Performed and well documented
Clay Construction Testing:			
Compaction Curve ASTM D698/D1557	Not performed	1 test per 5,000 c.y.	More frequent
Density Testing/Lift ASTM D2922/1556	Not performed	5 per acre	More frequent
Moisture Content Testing/Lift ASTM D3017/2216	Not performed	5 per acre	More frequent
Undisturbed hydraulic conductivity ASTM D5084	Not performed	1 per acre per lift	More frequent
Atterberg Limits ASTM D4318	Not performed	1 per acre per lift	More frequent
Grain Size ASTM D422	Not performed	1 per acre per lift	More frequent
Undisturbed Dry Density	Not performed	1 per acre per lift	More frequent
SOIL DRAINAGE LAYER			
Prequalification Testing			
Grain Size Analysis ASTM D422	Not performed	1 per 1,500-2,630 c.y.	More frequent
Hydraulic Conductivity ASTM D2434	Not performed	1 per 2,630-3,000 c.y.	More frequent
Carbonate Content Testing ASTM D4373	Not performed	1 per 2,630-3,000 c.y.	More frequent
Construction Testing			
Grain Size Analysis ASTM D422	Not performed	1 per 2.5 acres	More frequent
Hydraulic Conductivity ASTM D2434	Not performed	1 per 7.5 acres	More frequent
Carbonate Content Testing ASTM D4373	Not performed	1 per 2,630 c.y.	More frequent

TABLE 4-2
MATRIX FOR EVALUATING CAP CQA/CQC AGAINST ACCEPTABLE INDUSTRY PRACTICES

Category	Less than Acceptable	Acceptable	Better Than Acceptable
GEOMEMBRANE BARRIER			
Manufacturing Quality Control Testing			
Resin Testing:			
Melt Index ASTM D1238	Not performed	1/180,000 lbs	More frequent
Resin Density ASTM D1505	Not performed	1/180,000 lbs	More frequent
Environmental Stress Crack ASTM D1693/5397	Not performed	1/lot(1,800,000 lbs)	More frequent
Compliance with NSF 54 Standard	Not performed	Performed	---
Geomembrane Conformance Field Testing:			
Thickness, Tensile, Elongation, Puncture, Tear	Not performed	1/100,000 s.f. - 1/lot	More frequent
Construction quality Control Inspection:			
Material Delivery Inspection	Not performed	Every roll	More frequent
Material Handling and Storage Inspection	Not performed	Every roll	More frequent
Pre-deployment Panel Layout Diagram	Not performed	Every roll	More frequent
Pre-deployment Written Subgrade Inspection Certificate	Not performed	Every roll	More frequent
Construction Quality Control Seam Testing:			
Trial Seams Testing	Not performed	a.m. & p.m.	More frequent
Non-destructive Seam Testing:			
Vacuum Box on Extrusion Welded Seams	Not performed	100% of seams	---
Air pressure testing on Fusion Welded Seams	Not performed	100% of seams	---
Destructive Seam Testing:			
Peel and Shear Testing ASTM D4437, D3083, D751	Not performed	250-750 linear ft. of seam	More frequent

4.2.1 Borrow Soil

Borrow soil is used for preparing the subgrade and installing the cover soil. Tests are conducted to prequalify the borrow source, as well as during the placement of the soils. The standard frequencies for testing the borrow soils are:

- **Soil classification (prequalification test) -** One test per 1,000 to 6,580 cubic yards. The ASTM D2487 test is conducted, and the frequency is lower (1 per 6,580 cubic yards) if the borrow soil is relatively uniform.

- **Compaction test (prequalification test) -** One test per 5,000 to 6,580 cubic yards. The ASTM D698 or D1557 test is conducted, and the frequency is lower (1 per 6,580 cubic yards) if the borrow soil is relatively uniform.

- **Density test (construction test) -** Five per acre per lift placed. The ASTM D2922 or D1556 test is conducted.

- **Moisture content test (construction test) -** Five per acre per lift. The ASTM D3017 or D2216 test is conducted.

4.2.2 Compacted Clay Liner

If natural clays are more economical to use than a geosynthetic clay liner, natural clays are used to construct the low-permeability layer. The source of the clay must be prequalified, and, during construction, the quality of the layer must be tested to determine that the design permeability is achieved. A test pad generally is used to determine the moisture requirement and the compactive effort needed to achieve the design permeability. According to the results from the test pad, the clay layer is placed, and tests are conducted on each lift placed to confirm the quality of the layer. The standard frequencies for these tests are set forth below:

- **Soil classification (prequalification test) -** One test per 1,000 to 6,580 cubic yards. The ASTM D2487 test is conducted on the borrow soil.

- **Compaction curve (prequalification test) -** One test per 5,000 cubic yards, using the ASTM D696 or D1557 test.

- **Permeability (prequalification test) -** One test for each compaction curve.

- **Density -** Five per acre per lift placed, using the ASTM D2922 or D1556 test.

- **Moisture content -** Five per acre per lift placed, using the ASTM D3017 or D2216 test.

- **Undisturbed hydraulic conductivity and moisture content -** One test per acre per lift. This test is conducted on a Shelby tube test sample, using the ASTM D5084 test.

- **Atterberg Limits -** One per acre per lift, using the ASTM D4318 test.

- **Grain size test -** One per acre per lift, using the ASTM D422 test.

- **Undisturbed dry density and moisture content -** One test per acre per lift. This test is performed on the sample obtained for the hydraulic conductivity test.

4.2.3 Soil Drainage Layer

The soil drainage layer is used to drain the cover soils and prevent buildup of hydraulic head on the low-permeability layer. The borrow source for this granular soil must be prequalified, and, during construction, the quality of this layer must be tested. The standard frequencies of these tests are set forth below:

- **Grain size analysis (prequalification test) -** One per 1,500 to 2,630 cubic yards. The ASTM D422 test is performed.

- **Hydraulic transmissivity (prequalification test) -** One per 2,630 to 3,000 cubic yards. The ASTM D2434 test is performed.

- **Carbonate content test (prequalification test) -** One per 2,630 to 26,300 cubic yards. The ASTM D4373 test is performed. This test is used for limestone quarry sources; the frequency depends on the variability of the rock in the quarry.

- **Grain size analysis -** One test per 2.5 acres.

- **Hydraulic conductivity test -** One test per 7.5 acres.

- **Carbonate content tests -** One test per 2,630 cubic yards.

4.2.4 Geomembrane Barrier

The Industrial Fabrics Association and the NSF have developed several standards to ensure manufacturing quality control for geomembranes. Over the past decade, geomembrane barriers have been used extensively as either primary or secondary barriers to the infiltration of water into waste. The EPA has developed CQA/CQC guidelines for the installation of geomembranes (EPA 1993). The standard frequency of testing for ensuring the quality of the geomembrane barrier is described below.

Manufacturing Quality Control

The following tests are conducted in the manufacturing plant;

- **Resin melt index -** One per 180,000 pounds, using the ASTM D1238 test.

- **Resin density -** One per 180,000 pounds, using the ASTM D1505 test.

- **Environmental stress crack -** One per lot (1,800,000 pounds), using the ASTM D1693 or D5397 test.

- **NSF test -** One per lot, using NSF 54 Standard tests.

Field Quality Control Inspection and Tests

The field inspection procedures and tests that are conducted to ensure that geomembranes are installed properly are described below:

- **Thickness, tensile strength, elongation, puncture and tear resistance -** One per 100,000 square feet or 1 per lot. These properties usually are certified by the manufacturer; however, on large projects, these properties are field tested.

- **Material delivery inspection -** Every roll.

- **Materials handling and storage inspection -** Every roll.

- **Predeployment panel layout inspection -** Every roll. The exact field location of the roll and its relation to the other rolls is verified, and conformance to the approved layout diagram is checked.

- **Predeployment written subgrade inspection certificate -** Every roll. This inspection verifies that there are no defects in subgrade preparation that could damage the geomembrane. The written inspection certificate is checked before the membrane is deployed.

- **Seam testing -** The seam is the weakest link in the geomembrane barrier; therefore, only experienced personnel perform this test. The frequency of such tests and types of tests conducted are:

    - **Trial seams -** Two per day. Trial seams are tested for peel and shear strength by application of the ASTM D4437, D3083, and D751 tests.

    - **Nondestructive tests -** All seams are checked, using the vacuum box (extrusion welded seam) or air pressure (fusion welded seam) test.

    - **Destructive tests -** 1 per 250 to 750 lf of seam. Samples of the seam are cut to run, and peel and shear strength tests are performed, as for trial seams. A patch of membrane then is fusion-welded over the sampled areas. Such tests are kept to a minimum.

If testing described in Subsection 4.2.1, Subsection 4.2.2, Subsection 4.2.3, and Subsection 4.2.4 was not performed with the frequency indicated, the site was rated less than acceptable. If the testing was conducted as described, the site was rated acceptable. If tests were conducted more frequently than set forth above, the site was rated better than acceptable.

4.2.5 Range of Findings

Of the 36 sites evaluated during the study, 22 had caps in addition to the barrier wall. One site had only a cap. The CQA/CQC elements (that is, borrow soil, clay liner, drainage layer, and geomembrane) are crucial to the successful performance of the cap, and most of the sites studied were rated acceptable. In many cases, the caps were tied in to the barrier wall to form a containment system.

Caps had been installed at 22 sites. For a majority of those, a GCL had been used for the low-permeability layer, and a geonet for the drainage layer. (At 2 sites, the caps had yet to be installed.) Four sites had compacted clay liners, and, at each of 2 sites, a parking lot had been constructed over the site. The CQA/CQC procedures at those sites consisted of the following elements:

- Borrow soil testing to verify that the soil met specifications
- Field and laboratory testing to verify that the compactive effort met or exceeded the design specification and that the design permeability had been achieved
- Geomembrane barrier testing that conformed to standard industry practice

For two of the sites, the use of cap test pads had been documented, as well as the use of quality control procedures using field permeability tests and undisturbed samples for laboratory permeability tests. At site 7, the cap CQA consisted of six settlement monitors to evaluate settlement during and after installation. Compaction and settlement were evaluated to identify optimum construction practices, such as equipment weight and number of passes.

The soil drainage layer was usually a geonet, even at sites at which the low-permeability layer was a compacted clay liner. The ease of using geosynthetic materials and improved quality control at the manufacturing facilities have brought about widespread use of such materials in the past five years.

The weakest link in the components of a cap is the seam that connects each roll of geomembrane. The QC seam testing described in Subsection 4.2.4 is crucial to performance of the cap. Although both nondestructive and destructive seam-testing techniques are time-consuming, such tests are necessary to ensure that the cap is performing as designed. At all the sites studied, the installer had followed standard industry practice, and the regulatory agency had provided oversight of this key construction activity.

4.3 PERFORMANCE MONITORING

Horizontal surface barriers or caps prevent dermal contact, limit infiltration or vertical inflow, and contain upward migration (that is, vectors, diffusion, capillary action, or evapotranspiration). Effective monitoring focuses on those functions. As is the case with vertical barriers, in ensuring the performance of caps, most emphasis historically has been put on adequate CQA/CQC to ensure a quality constructed product (EPA 1993). However, postconstruction monitoring is required by regulations for closure of municipal solid waste and hazardous waste facilities. Monitoring of groundwater quality, hydraulic head, and surface quality are common elements in monitoring performance of vertical barriers. Those elements are described in the preceding subsection. Specific approaches to the monitoring of caps are discussed in subsequent subsections.

Generally, limited information about monitoring of the cap was available for the sites studied. Typically, the visible grading and drainage and erosion control features were inspected. Less typically, settlement and other structural features of the cap were monitored. In few cases was contamination within or above the cap monitored. The following subsection discusses industry standards and elaborates on the range of cap monitoring efforts identified in this study.

4.3.1 Typical Industry Practices

Industry guidance for monitoring caps can be found in several sources, most notably EPA publications on landfills (EPA 1990 and EPA 1992). The established monitoring categories are groundwater, leachate generation, gas concentration, subsidence, surface erosion, and air quality. These and other sources fail to provide specific monitoring requirements because of the site-specific nature of the monitoring needs. Federal solid waste landfill regulations, 40 CFR Part 258, describe in some detail requirements for groundwater monitoring (subpart E) and other closure (subpart F) considerations (40 CFR 264.228, 264.310, 270.21e). Bagchi (1989) provides a concise discussion of performance monitoring requirements for landfills.

Monitoring data for caps were not detailed enough for the sites reviewed to support a numerical ranking similar to that prepared for the vertical barrier monitoring matrix (Table 3-7). Groundwater quality monitoring data were common to vertical barriers. Other noteworthy monitoring data for caps are described in the site summaries in Appendix B, Volume II and are discussed briefly in the following subsection.

4.3.2 Range of Findings

Of the 36 sites having vertical barriers, 22 also had caps in place. In some cases, the uncapped sites were operating landfills; at others the cap had not yet been constructed. The remainder simply were not capped. Of the capped sites, periodic visual inspections of the cap surface had been performed as part of ongoing operation and maintenance procedures, and the usual problems with erosion, drainage, and vegetation had been documented. Investigation and compilation of data yielded only limited cap-specific monitoring data, other than those on groundwater quality.

At Site 36, soil moisture and vegetative growth had been monitored periodically because the design of the cap was based on consumptive use to limit infiltration into the containment. At Site 12, water quality in the drainage layer and long-term settlement will be monitored regularly in response to a regulatory requirement.

4.3.3 System Monitoring

In collecting the monitoring data described in previous sections, it became clear that, if data had been reviewed, they seldom had been evaluated to determine performance of the complete containment system. Typically, one reporting entity received groundwater quality data, and another received head and other information specifically related to the barrier.

Generally, at the sites studied, the system as a whole was monitored and data collected that cannot identify leaks attributable to defects in either cap or barrier. The monitoring categories reviewed show a wide variety of methods and frequencies, even in light of differences in applications. The more diagnostic stress tests were found to be run infrequently, typically only when a problem was detected.

Testing for long-term degradation, physical sampling for diffusion through the barriers, and testing for the effect of desiccation on permeability effectively were absent.

Design of the containment system is dependent on conditions at the site, particularly the hydrogeology. Standardized monitoring therefore is difficult. However, measurement of performance could benefit significantly from more consistent monitoring approaches and more periodic reporting than currently are the norm. Such recommendations are discussed in more detail in subsequent sections of this document.

4.4 OPERATION AND MAINTENANCE

O&M for caps require correction of surface erosion problems and inspection of the leachate and gas management systems (EPA 1989). Acceptable industry practice is to follow the O&M plan that EPA and the pertinent state agency have approved for the site. The O&M plan may include:

- Visual inspection of the cap and mowing of the grass during the growing season
- Repairs of any erosion or surface slumping
- Repairs of any damage to drainage control structures
- Quarterly monitoring of leachate levels and monitoring wells
- Quarterly or semiannual monitoring of leachate quality
- Monthly inspection of the components of the leachate collection system
- Cleanout of leachate collection pipes, as required
- Monitoring of the gas vents to clear any obstructions
- Quarterly or semiannual monitoring of the quality of gas

No unusual O&M practices were identified at the sites studied.

4.5 COSTS

Caps are constructed with compacted clay, geosynthetics, and combinations thereof. The cost of construction of a cap depends on the local availability of soils for the grading layer and cover soils. In general, compacted clay liners may cost more than geosynthetic clay liners, especially if the clay borrow source is a few miles from the site. The cost of a cap also depends on the extent of leachate and gas management the site requires.

For the sites studied, the capital cost of installation of a cap varied from $200,000 to $400,000 per acre (see Table 3-8). The O&M cost varied from $10,000 to $50,000 per year, excluding administrative and reporting costs. The O&M cost depended on the amount of groundwater and surface-water sampling required by the state regulatory agency.

Obtaining cost information on subsurface barrier walls and caps was not the primary objective of this study. However, when cost information was provided in the site reports, that information is included in the individual site summary in Appendix B, Volume II. In most cases, O&M costs could not be obtained. Capital costs mentioned in the reports are engineer’s estimates, rather than actual construction costs. For a few sites, the remedial action report provided the actual construction costs for the remedy components, such as barrier wall, cap, and wastewater treatment plant.

5.0 PERFORMANCE EVALUATION

A primary objective of the study is to assess performance of containment as a remedy in controlling contamination in the subsurface. The term "controlling" here refers to holding the source for subsequent removal, reducing off-site migration, reducing leachate generation, or simply containing exposure to the source. The general objective of containment is to control inflow to and outflow from the system and contact with the source to minimize its effect on the environment for a significant design life. Measurement of a site's specific performance was based upon data related to site-specific criteria, compared with regular monitoring data, which at most sites studied consisted of those on hydraulic head and groundwater quality. Because of the site-specific criteria and types of monitoring data available for the sites studied, a comparative evaluation is problematic. Nevertheless, the following subsections present evaluation findings by identifying and describing the basis for measuring performance, presenting a summary and evaluation based on 4 considerations, and describing factors that contribute to performance.

5.1 PERFORMANCE BASIS

The performance basis varied considerably among the sites evaluated. The performance basis can be viewed first by containment type and second by specific monitoring standard. Table 5-1 below summarizes the basic containment type and standards for the sites studied.

TABLE 5-1

CONTAINMENT CATEGORIES AND PERFORMANCE MONITORING

Category	Number of sites	Performance Based on Groundwater Quality Monitoring	Performance Based on Hydraulic Head Monitoring	Performance Based on Other Monitoring
Active	18	15	15	3
Passive	12	12	--	--
Reactive	1	1	--	--
Cutoff	4	1	2	1

Section 3-4 describes the various monitoring methods used for the sites studied. The monitoring method used and the performance criteria depend on the category of the site and often on site-specific features.

Active containment is the most prevalent containment type among the sites studied. Further, site selection research (see Section 2.0) indicates it is the most prevalent form of containment. Active containment includes a vertical subsurface barrier, often a surface horizontal barrier (cap), and some form of groundwater or leachate withdrawal inside the containment to maintain the groundwater elevation at a level lower inside the barrier than outside. This hydraulic head differential or gradient criterion varied among the active containment sites, sometimes influencing performance. Table 5-2 summarizes the head differences among the 18 active sites.

TABLE 5-2
VARIATION IN ACTIVE CONTAINMENT HEAD DIFFERENTIAL

Head Differential	Number of Sites	Remarks
Inward, < 1 foot	2	See Table 3-7 for locations of readings
Inward, 1 - 10 foot	7	
Inward, >10 foot	5	
Inward, below waste elevation	1	
Inward, unknown difference	3	

Hydraulic head monitoring commonly is used to monitor performance at active containment sites. The necessary groundwater head differential across the vertical barrier is established to maintain inflow and control flux. Head differential may be sufficient to overcome diffusion through the vertical barrier or keep contaminants away from the barrier. Vertical gradients may be induced as well to contain contamination. For example, thin barriers of low permeability may require increased head differential to counteract diffusion mechanisms (Devlin 1996).

To measure performance, passive and reactive containment types usually rely on monitoring of groundwater quality, rather than hydraulic head. Often, the requirement for monitoring of groundwater quality is more rigorous for passive and reactive containment than for active containment because improvements in groundwater quality are the only measure of performance. Similarly, monitoring of groundwater quality is important as a measure of whether active containments achieve and maintain standards for groundwater quality outside the containment. Section 3-4 presents and Table 3-8 lists other site performance criteria and corresponding monitoring.

In addition to compliance with performance standards, performance of the containment system should be measured by its success in meeting the design intent of providing a system that minimizes long-term O&M costs to the owner. For example, at several active containment sites, actual groundwater extraction to maintain performance standards was greater than had been predicted; the system therefore had been more costly to the owner than it had been predicted.

5.2 PERFORMANCE STAGES

Containment performance can be viewed as occurring in stages. The stages have parallels to the generic model for cleanup of groundwater (EPA 1992). Figures 5-1A and 5-1B present a graphical display of typical groundwater quality and hydraulic head responses for containment scenarios. Several stages can be defined: the construction stage, the equilibration stage, the demonstration stage, the short-term performance stage, and the long-term performance stage. After the initial construction stage, groundwater inside and outside the containment adjusts to new flow conditions during the equilibration stage. This stage may be complete within months to a year after construction, depending on the flow regime. The demonstration period consists of several quarters of monitoring, during which system operation is fine-tuned and final equilibration continues. This period generally lasts from 1 to 2 years. The end of the period triggers operation and performance monitoring, as required by the regulatory agency. The short-term performance period ends after 5 years of continued operation and generally overlaps somewhat with the demonstration period. The long-term performance stage includes operations

Performance Stages for an Engineered Barrier

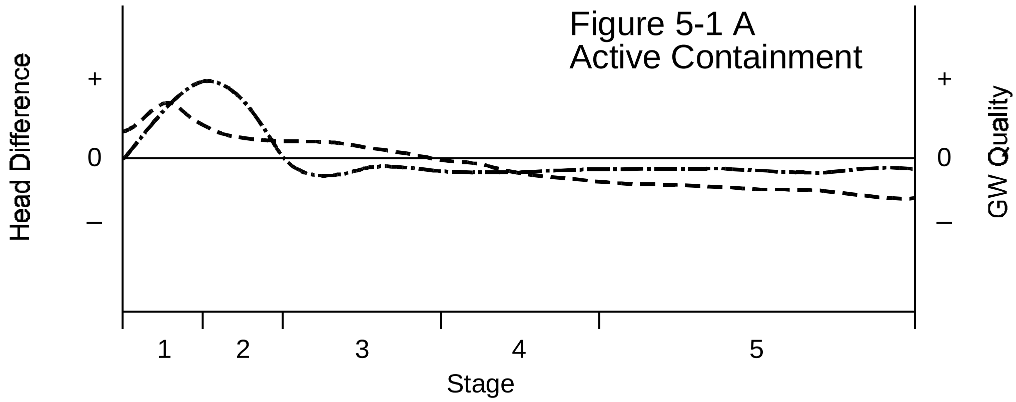

Figure 5-1 A
Active Containment

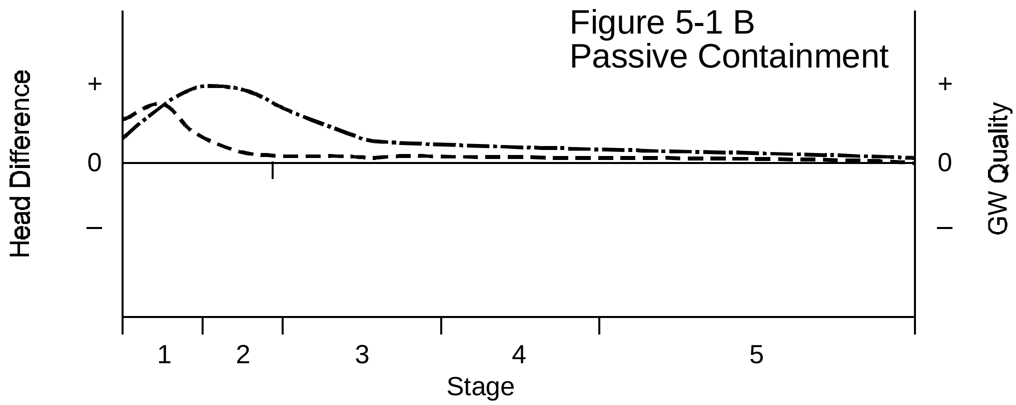

Figure 5-1 B
Passive Containment

Head Differential (+ Outward) (- Inward)

GW Quality (+ Contaminant Down Gradient)

Stages:
1. Construction
2. Equilibration
3. Demonstration
4. Short-Term Performance
5. Long-Term Performance

and some monitoring, presumably at a reduced frequency, over a 30-year period. Figure 5-1 illustrates performance response for both active and passive containment. Performance for both remedies converges toward no or some *de minimus* leaking during the performance period. Specific performance results are discussed in the following subsection.

5.3 RANGE OF FINDINGS

Table 5-3 provides a summary of the range of findings. The table lists the remedial objective for the particular containment system and identifies elements of short- and long-term performance. The preceding subsection described short- and long-term performance periods. Generally, short-term performance is covered by monitoring during the first 5 years by sampling and testing after installation of the containment system. Long-term performance is identified through monitoring over the design life of the containment system, for example 30 years; possible effects of degradation of the containment system should be considered. Assessment of long-term performance may include evaluation of data from hydraulic stress testing, periodic testing of barrier integrity, and long-term compatibility testing of the barrier materials with the site contaminants, as well as evaluation of the effectiveness of any redundancy measures installed.

Table 5-4 also presents a rating of the performance of a particular site's containment. The performance rating was based on available data and considerations related to several containment systems. Standard 5-year review reports were used, when available. Quarterly and annual reports of monitoring data also were used. Monitoring data were reviewed to determine whether regulatory criteria were being met, as required. Hydrogeologic features of the site and the type of containment were weighed during the evaluation. Site contacts also were queried about the operational performance of the containment.

The ratings listed in Table 5-4 and in the individual site summaries in Appendix B of Volume II were based on several considerations:

- Did the site meet performance criteria (water quality, head differential, or other)?
- Did performance improve continually over time?
- Were any problems detected, and, if so, were they remedied readily?

Was the owner satisfied with the performance and protectiveness of the containment?

Using site data and evaluating performance according to the above considerations, the review team assigned each site one of four ratings, as defined below:

1 = Remedial objective was met.

2 = Evidence suggests that remedial objective may have been met.

3 = Evidence suggests that remedial objective may <u>not</u> have been met.

X = Data are insufficient to determine whether the remedial objective was met.

Table 5-3
Performance Evaluation Matrix

Site	Remedial Objective	Containment System	Short-Term Performance	Long-Term Performance	Remarks
1	Surface water and down gradient water quality to meet MCL; no head standard	SB barrier, leachate collection, cap-geomembrane over compacted clay liner (CCL)	Groundwater quality improvement; visible improvement in adjacent surface water	No long-term data available	Site has fulfilled the remedial objective
2	GW cutoff to allow for landfill excavation	Passive SB barrier	Dewatered in 1 year	Landfill is still dry after 15 years	Site is performing as designed
3	Source control Prevent offsite migration	7 SB walls, multimedia cap	GW quality outside well has reached steady state	GW monitoring program being modified to assess performance	2 hanging walls
4	Containment of inflow	Grout curtain, SB barrier; RCRA cap	Pumping rates as designed; down gradient water quality improvement	Insufficient information	No groundwater gradient criteria
5	Intercept landfill seepage; achieve groundwater gradient and MCL	Clay barrier, leachate drain, clay cap, active gas collection	Shallow groundwater met MCL standards	Decreasing VOC concentrations	Compacted clay barrier
6	Minimize off site migration	SB barrier, multimedia cap	Works as designed	Insufficient information	Contained area is solidified
7	No head gradient criteria, reduce the potential for downward vertical migration	SB barrier, leachate drain, CCL cap, active gas collection	Surface and shallow groundwater improvements	System not yet able to dewater and develop inward gradient	--
8	DNAPL containment	Steel pile, GW bioremediation	Design criteria met	Insufficient information	DNAPLs monitored in wells
9	Contain landfill leachate; enable further landfill expansion	SB barrier; leachate collection system	Undetermined; system not active; rising leachate levels	Not applicable	Active landfill
10	Capture and remove organic contaminants	Active system consisting of SB cutoff wall, withdrawal and recharge wells	Improved groundwater quality, but groundwater contaminants were detected moving around both edges of the linear cutoff wall	Groundwater quality continues to improve down gradient of the cutoff wall	The cutoff wall was extended in 1990; additional extraction and recharge wells were added in 1991 to prevent contaminant movement around the wall
11	Improved surface water and groundwater quality	SB & SCB barrier; RCRA type cap, up gradient groundwater interceptor; leachate extraction; gas collection	Improved surface water monitoring data unavailable	No data	SB/SCB barrier
12	Reduce lateral migration of groundwater contamination from source trenches	Passive system consisting of SB barrier, soil and vegetative cap	Inward gradient developed along the up gradient side; outward on down gradient side.	Groundwater quality has showed little change over time.	Vibrating beam thin wall
13	Limit migration of contaminants	SB barrier, cap, pump/treat leakage collection	GW quality outside improved	GW quality outside improved	Extraction (flushing system)
14	Seepage cutoff wall	Plastic concrete; run-on extraction wells	Performance as designed for 4 years of mining operation	No data	Very well instrumented at site
15	Maintain inward gradient around landfill	SB barrier and leachate collection, no cap	Groundwater quality improved	Performing as designed since 1984	2 phase barrier installation, 1984 and 1989

Table 5-3
Performance Evaluation Matrix (Continued)

Site	Remedial Objective	Containment System	Short-Term Performance	Long-Term Performance	Remarks
16	Contain DNAPL; improve surface water quality; maintain head gradient across barrier	CB barrier; to permit DNAPL extraction	Immediate surface water improvement; enabled DNAPL extraction	Constant head gradient with time; decrease in down gradient concentration	Good example of DNAPL cutoff; emergency response installation
17	Maintain inward gradient and leachate collection	SB barrier, multimedia cap, extraction wells, interceptor trench	Inward gradient established	Insufficient information	Site is performing as designed
18	Maintain head differential of 1 ft	SB barrier; RCRA cap	Inward gradient developed; pumping rates as designed	Insufficient information	Post construction testing revealed improper key-in, which was corrected with in situ soil mixing
19	Zero net gradient across barrier; downgradient water quality to meet MCL	SB barrier; RCRA type cap, well extraction and trench recirculation	Immediate shallow groundwater improvement	Possible barrier underflow; downward gradient to bedrock aquifer	Good design and CQA/CQC; extensive 10-year review
20	Inward 0.01 ft head differential	SB barrier, multi-media cap, extraction wells; auto monitor for head differential	Immediate surface and ground water improvement; good hydraulic test response	Well installed in 1996	Head differential and surface and groundwater quality requirements
21	Maintain head differential of 1 ft	SB barrier, multi-media cap	Inward gradient developed	Well installed in 1994	Fate and transport modeling completed
22	Maintain inward gradient	SB barrier, multimedia cap, extraction wells	Inward gradient not developed as yet	Remedy is interim measure	HDPE membrane placed through center of the wall
23	Improve groundwater quality outside barrier; inward head gradient differential of 1 ft.	SB barrier, no cap, wells and drain, groundwater extraction	Head differential achieved in most locations; ground water quality improvement	Some down gradient contamination detected; barrier underflow identified at one location	2 phase construction; active landfill; containment leakage easily rectified
24	Prevent further degradation of SW and GW quality	Active SB barrier, RCRA cap, extraction wells	Inward gradient maintained	Insufficient information	
25	Inward gradient in shallow groundwater zone	Active system consisting of SB barrier, groundwater infiltration and extraction system	Inward gradient developed	Groundwater quality improved and inward gradient maintained along most of the wall	Owners seek to change from active to passive remediation and cap the site
26	Intercept, treat, and discharge contaminated groundwater	Active system consisting of SB cutoff wall, withdrawal wells	Groundwater contamination migrated under and through the wall due to poor key and high hydraulic gradient	Improved recharge capacity has decreased the hydraulic gradient to near zero	Recent water quality data is not available but the removal of the high gradient should curtail or reduce plume movement beyond the wall
27	Groundwater standard; maintain regional gradient; source separation	SB barrier; CCL/geomembrane cap; extraction wells	Immediate groundwater improvement; reduced pumping; head difference easily met	Continued monitoring; protective of human health	Good CQA/CQC; sustained dewatering of source
28	Minimize off-site migration	SB barrier, extraction wells	Performing as designed	Seems to have accomplished design objective	Waste inside barrier has been solidified

Table 5-3
Performance Evaluation Matrix (Continued)

Site	Remedial Objective	Containment System	Short-Term Performance	Long-Term Performance	Remarks
29	Maintain inward gradient	Active SB wall, multimedia cap, extraction wells	Inward gradient established, GW quality improved	No information	--
30	Maintain head differential of 1 ft.	SB barrier, multi-media cap	Inward gradient developed on up gradient side, outward on down gradient side	Well installed in 1993 testing	Outward gradient developed after pumping from inside wall was stopped in 1995.
31	Maintain head differential of about 1 ft. to control contaminant source and groundwater cleanup	Active system consisting of SB barrier, collection and treatment system	Inward gradient developed; pumping rates as designed	Inward gradient maintained	System has successfully reduced onsite levels of contamination and prevented contaminants from reaching the nearby river.
32	Maintain head differential	S-B/RCRA cap with groundwater extraction	Inward gradient throughout site	Inward gradient for 7 years	System performed better than expected by design.
33	Channel plume to flow through reactive wall	C-B/S-C-B reactive wall	Performing as designed	System operational for only one year	VOC not detectable in downgradient well
34	Cut off seepage through and below dam	SB barrier	Very effective	Maintains large head differential across cutoff	Automated electronic monitoring
35	Dewatering for construction of power plant	Plastic concrete and dewatering	Excellent - based on predicted and actual pumping rates	Well operational for 2 years	Plastic concrete wall subject to high gradient
36	Prevent migration of contaminant plume	Multimedia cap, leachate collection and treatment	Contaminant plume contained	Insufficient information	“Cap only” site

Notes:

MCL = Maximum contaminant limit

TABLE 5-4
PERFORMANCE RATING VERSUS CRITERIA RATING

Site	Design*	CQA/CQC*	Monitoring*	Performance#	Containment Category
1	3	3	2	2	Passive
2	1	2	1	1	Passive
3	2	2	3	X	Passive
4	1	1	3	X	Passive
5	2	1	1	1	Passive
6	1	1	2	1	Passive
7	1	1	3	2	Passive
8	X	X	3	X	Passive
9	2	2	3	X	Passive
10	2	1	2	2	Passive
11	2	1	X	X	Passive
12	2	1	1	2	Passive
13	2	1	1	2	Active
14	1	1	1	1	Cutoff
15	2	1	1	1	Active
16	2	3	1	2	Cutoff
17	2	1	2	2+	Active
18	1	1	1	2	Active
19	1	1	1	3	Active
20	1	1	1	2	Active
21	1	1	3	X	Active
22	2	1	3	3	Active
23	1	1	1	2+	Active
24	2	2	3	3	Active
25	1	2	2	2	Active
26	1	X	2	2	Active
27	1	1	1	2+	Active
28	1	1	1	2+	Active
29	2	2	2	2	Active
30	1	1	2	3	Active
31	2	1	2	2	Active
32	2	X	1	1	Active
33	1	1	2	2	Reactive
34	1	1	1	1	Cutoff
35	1	1	1	1	Cutoff
36	1	2	2	X	Cap Only

* Criteria Rating: 1= Better than Acceptable; 2= Acceptable; 3= Less than Acceptable;
X = Insufficient Data

Performance Rating: 1= Remedial objective was met; 2= Evidence suggests objective may have been met; 3= Evidence suggests objective may not have been met; X= Insufficient data to determine if remedial objectives have been met.

Of the 36 sites studied, 8 are in Category 1, 13 are in Category 2, 4 are in Category 3, and 7 are in Category X. An additional 4 sites met the remedial objectives. However, because long-term performance could not be verified, those sites were rated as 2+.

The ratings show that the engineered barriers at 25 of the 36 sites studied generally performed as designed and significantly improved the quality of groundwater and surface water in the vicinity of the site. Unfortunately, for many of the sites, data are insufficient to determine long-term performance.

At 4 of the sites studied, leaks were detected at the key; however, the leaks were repaired with relative ease. For example, at Site 26, leaks were detected below the key. The problem was solved by installing a recharge trench. At Site 19, underflow was detected at the bedrock key; grouting was used to repair the problem. At Site 23, a leak was detected at one place and was repaired. At Site 27, downgradient leaks were detected; however, the leaks were interrupted and treated. At Site 30, downgradient leaks were observed when pumping from inside the wall was stopped. The extent of the leaks and their effect on downgradient water quality are being evaluated.

At the sites that have caps, the caps were integrated with the barrier walls to minimize the amount of surface water entering the waste. Installation of a containment system resulted in immediate reduction of contaminant transport and, in active systems, significantly reduced the amount of contaminated water pumped to a treatment plant. Leaks detected were located primarily at the key horizon. Such leaks could be the result of insufficient penetration into the low-permeability horizon, insufficient quality control, or poor quality of the key material.

5.4 FACTORS AFFECTING SYSTEM PERFORMANCE

Rated containment performance was compared with the evaluation criteria for the sites studied to determine whether some obvious correlation exists. No definitive correlation could be identified from the limited data available because both design and CQA/CQC significantly affect performance. Table 5-4 shows performance ratings for the sites studied and the previously assigned ratings for design, CQA/CQC, and monitoring criteria. Table 5-4 shows that the majority of the sites received favorable ratings (1 or 2). The sites rated 2+ appeared to meet the remedial objective, and data existed to prove the performance of the containment. However, data were unavailable for several consecutive periods of positive performance. At several, performance was poor. At several others, indicated by an X, data were insufficient to support assignment of a performance rating.

Review of the table reveals that most sites having positive ratings, 1 and 2, also were rated favorably for the other criteria shown. Good efforts at design, CQA/CQC, and monitoring generally led to positive performance, as often advocated and indicated by the data. However, less than optimum performance can occur even when significant design, CQA/CQC, and monitoring efforts are used, as the ratings for sites 19 and 30 indicate. Less than optimum performance under one subcriterion or criterion also can influence performance significantly. For example, a problem with keying a vertical barrier, lack of continuity, or low permeability of the site floor can decrease the performance of the system.

As discussed in Section 3.3 and 3.4, CQA/CQC testing and postconstruction physical testing showed that the constructed barriers were of consistently low permeability. At several sites, problems with the key of the vertical barrier and the floor, or the continuity of the floor, likely created leaks and less than optimum performance. For example, at sites 15, 19, and 26, key problems led to leaking. At Site 22, drawdown could not be achieved to maintain the needed head differential, a circumstance that most likely occurred because the bottom was more pervious than predicted.

However, it should be noted that, at most of the sites with known performance problems, leaks have been or are being rectified to achieve performance objectives. Those efforts are described in the individual site summaries in Appendix B of Volume II.

The discussion set forth above describes performance and relates performance criteria to observed performance. However, other criteria or subcriteria can contribute to short- or long-term performance. Some of the negative contribution mechanisms are diffusion, long-term degradation, abrupt physical failure, altered groundwater flow, and abrupt mechanical failure. Among positive mechanisms are natural attenuation and adsorptive capacity of the barrier. The reader is referred to the Rumer and Mitchell (1996) for further explanation of these and other mechanisms.

6.0 CONCLUSIONS AND RECOMMENDATIONS

This report evaluated engineered barriers used to isolate hazardous sites from their surroundings. Those barriers included:

- Subsurface barriers – that is, vertical cutoffs, that prevent the horizontal migration of the groundwater across the barriers

- Impervious caps that prevent the downward migration of surface runoff

Initially, subsurface engineered barriers were the major component of passive containment systems to prevent migration of contaminated groundwater from hazardous waste sites. Caps often were added to completely isolate such sites. In recent years, for the most part, active containment systems have been installed, where an inward gradient is maintained by extracting and treating contaminated groundwater from the contained area. Recently, the concept of active and reactive barriers has been introduced, and more thought has been given to the use of long-term (more than 30 years) passive containment systems that require much less maintenance than active systems and that therefore offer lower operating costs.

In this context, it is important to assess the performance of engineered barriers installed since 1980 as short-term and long-term remediation techniques. The conclusions and recommendations of the study are presented below, emphasizing subsurface barriers.

6.1 CONCLUSIONS

Nineteen of the 36 engineered barriers studied for this report met or may have met the intent of the design *and* have been effective to date in preventing migration of contaminated groundwater outside the contained zones or in meeting design objectives. At 4 of the 36 sites studied, additional corrective measures were needed to meet the design intent. This conclusion is limited to the scope of this study. In particular:

1. Thirty-six sites of the 130 sites identified were analyzed. The other sites were eliminated from the study because of the lack of availability of design, construction, or monitoring data. (It is likely that some those sites that were eliminated do not perform as expected.)

2. This study represents a majority of the sites that have been in operation for less than 10 years. It is difficult to extrapolate this performance evaluation for the 30-year design life of the barrier because of physical and chemical degradation of the backfill resulting from site contaminants.

Table 6-1 summarizes the ratings assigned to the factors that affect performance for the 36 sites included in this study. As the table shows, most sites were rated acceptable or better than acceptable for design, CQA/CQC, and monitoring. In particular, more sites were rated better than acceptable for CQA/CQC than for either design or monitoring. (Data were insufficient for the CQA/CQC factor at the greatest number of sites.) More sites were rated less than acceptable for the monitoring factor than for either design or CQA/CQC. The distribution of performance ratings most closely resembled that for the ratings based on monitoring.

Table 6-1
Number of Sites by Rating Criteria

Rating*	Design	CQA/CQC	Monitoring	Performance**
1	19	24	16	8
2+	-	-	-	4
2	15	7	11	13
3	1	2	8	4
X	1	3	1	7

Notes:
* Criteria Rating: 1= Better than Acceptable; 2= Acceptable;
3= Less than Acceptable; X= Insufficient Data

** Performance Rating: 1= Remedial objective was met;
2= Evidence suggests objective may have been met;
3= Evidence suggests objective may not have been met;
X= Insufficient data to determine if remedial objectives have been met.

The performance of a barrier is inferred by monitoring data obtained after installation; however, the performance depends on the design and CQA/CQC effort during installation. Of the sites studied, 94 and 86 percent had acceptable or better than acceptable design and CQA/CQC ratings respectively, but only 75 percent of the sites had a acceptable or better than acceptable monitoring rating. This finding suggests that monitoring, which is critical for determining the performance of a barrier, needs to be improved and based on site specific requirements. Sites that had a below acceptable rating for monitoring might be performing adequately because design and CQA/CQC were acceptable or better than acceptable at those sites; alternatively, some releases may be undetected

The general major conclusions of this study are:

- Based on data from 25 of the 36 sites studied, subsurface engineered barriers are effective containment systems for the short and middle term, if properly designed and installed. None of the monitoring data reviewed indicated a decrease in effectiveness as a function of time.

- In the 36 sites studied, monitoring systems for subsurface engineered barriers lack consistency in terms of scope, design, and implementation. This results in lack of credible data that can be used to evaluate performance. This study shows the need to standardize the design and implementation of monitoring systems. This need becomes even more crucial for engineered barriers used for long-term containment.

- The most likely pathway for leaking of continuous subsurface barriers is in the vicinity of their keys, as a result of defective installation (that is, insufficient cleaning prior to backfilling, insufficient key as specified by the design or lack of sounding, or defects in the aquitard layer below the key).

- The soil-bentonite slurry wall technology was the most widely used technique for the sites that were studied. Improvements in barrier technology, such as the development of active backfill material capable of degrading the site contaminants, should be encouraged.

The conclusions and the recommendations of the project team are discussed further below.

6.1.1 General Conclusions from Performance Evaluation

Active containment using soil-bentonite slurry walls is the most prevalent type of containment used at the sites studied. Sites showed positive performance despite variations in methods and the amounts of interior groundwater withdrawal required. Increased head differential across the barrier in active containment did not necessarily correlate with improved performance. Passive containment, without groundwater extraction, also showed positive performance results, primarily indicated by groundwater quality outside the containment.

Performance is measured by established standards. However, the implemetation of standards varied dramatically among the sites studied. Design, CQA/CQC, and monitoring can affect performance directly. Design was performed somewhat consistently among the common types of containment sites evaluated. CQA/CQC appeared to conform with industry standards, and, with some exceptions, was evaluated as acceptable or better than acceptable. Types and frequency of monitoring were less consistent among the sites studied. Since such criteria provide a measurement of performance, that circumstance implies that containment performance may be inconsistent. A more standard approach to monitoring and reporting that allows variations to accommodate site specific conditions, could improve the measurement of containment performance and ultimately lead to improvements in containment as a remedy.

The following discussions elaborate on the conclusions of the study by describing important findings related to the various evaluation criteria. Conclusions are justified further in the pertinent sections of the report. Preliminary recommendations follow the conclusions.

6.1.2 Design of Containment Systems

The design of subsurface barriers and caps is based on specific remedial objectives for the control of exposure to hazardous waste and prevention of migration of groundwater contamination. Section 3.2 defines the established standard for barrier design; design at most sites were determined to be acceptable or better than acceptable. Design standards for vertical barriers generally followed USACE guidance, and cap design generally was based on EPA guidance. For most site designs, hydrogeologic and geotechnical investigations had been undertaken to obtain data to support the design. In several cases, that effort was insufficient and resulted in poor containment performance because either the key or site bottom had not been defined adequately. For many sites, performance modeling was not performed as part of the design. While modeling results are often debatable, that tool is the best means of assessing effects on groundwater before actual operation. Compatibility testing of trench slurry and backfill to support the design had been conducted at most sites. However, the need for vertical barrier integrity and long design lives suggests that additional study of long-term performance should be performed.

The quality of design indirectly contributes to the performance of the containment system. The industry has adopted design guidelines. In some cases, the design subcriteria adopted are more stringent than the published design guidance.

6.1.3 Construction Quality Assurance and Construction Quality Control of Containment Systems

CQA/CQC contributes to containment performance. Because of the buried barrier elements of either caps or vertical barriers, postconstruction testing is difficult; further, a quality constructed product will improve performance. Construction quality assurance plans (CQAP) sometimes are prepared at the same time as the design documents, and inspection and testing requirements typically are specified in CQAPs. CQAPs are produced more often for caps than for vertical barriers. CQA/CQC guidance provided by USACE (USACE 1996) and EPA (EPA 1993) for vertical barriers and caps, respectively, and earlier guidance had been followed at most of the sites studied. Generally, CQA/CQC procedures for vertical barriers have improved less than those for caps. In many cases, CQA/CQC adjustments in testing frequency were made to accommodate site-specific conditions.

Performance at several sites was affected negatively by problems with the vertical barrier that might have been eliminated if CQA/CQC controls had been more stringent. Two such controls are:

- Trench key confirmation — At some sites, sampling and sounding were used to confirm the key, while, at a majority of the sites, only sounding was used; physical inspection of the key at regular intervals is important in minimizing poor key contact, regardless of the type of barrier.

- Trench bottom cleaning — Accumulation of sloughed or settled high-permeability material may create windows in the vertical barrier; at some sites, cleaning tools or desanding pumps were used to ensure a clean bottom in the key.

Other findings of the evaluations are:

- The most crucial measurable parameter of the vertical barrier, permeability, had been measured in several ways, producing significant differences

- For slurry trench barriers, physical inspection of the key material can be performed, while key inspection is difficult at most other barriers

- Water levels during and immediately after construction were not monitored or documented well, although such data often can help determine the integrity of the barrier

- Postconstruction testing of the barrier is prevalent and usually involves obtaining backfill samples at regular intervals. This procedure is performed and sometimes mandated, despite concern in the industry about the negative effects of such sampling efforts on the integrity of the barrier. Efforts are being made to develop nonintrusive post construction monitoring techniques.

- Barrier CQA/CQC has not been standardized to a level comparable to that for caps

6.1.4 Performance Monitoring

Major differences were found among the sites studied in the performance monitoring of the containment system. At some sites, very little monitoring of groundwater head and quality had been carried out, while, at others, paired piezometers at close spacing were used within 25 feet of the barrier to monitor groundwater head, and monitoring well networks downgradient of the sites were used to measure trends in groundwater quality.

Frequency of monitoring also varied among sites, with monthly monitoring at some sites and quarterly monitoring at most sites. At some sites, the monitoring data had been analyzed to determine performance and reports submitted quarterly to the regulatory agency, but at most sites, the monitoring data had been submitted with little or no analysis of performance.

At only a few sites, key or subkey soils had been monitored to identify any barrier underflow.

Essentially no long-term monitoring of physical samples had been performed to identify degradation mechanisms. Geophysics had been used at several sites, but the results were not conclusive. Cone penetrometer and pressure tests had been conducted at two sites and had yielded useful information. Stress testing and pumping tests after construction had been performed only infrequently. Stress cells and electronic wire piezometers have been installed in the barrier on some civil engineering projects. In addition, there appeared to have been no consistent method of establishing the groundwater monitoring network to obtain information about either quality or head.

On the basis of the information presented above and discussed in earlier sections of the report, the following conclusions can be drawn:

- Monitoring requirements differ for active, passive, and cutoff containment methods
- Rational and consistent monitoring is needed, including standards for well placement, accuracy of measurement, and frequency of sampling.
- Less frequent sampling should be allowed when trends indicated by data are consistently positive
- Long-term performance of containment is not adequately measured
- Geophysical methods, while intriguing, have not been demonstrated to be successful, but should be investigated because of their inherent value in providing spatially continuous testing
- Reporting of monitoring data is inconsistent, and the regulatory community does not use such data to the fullest extent possible to assess performance

6.1.5 Operation and Maintenance (O&M) at Containment Systems

O&M at containment systems consisted primarily of quarterly inspections of the cap for erosion and O&M of the treatment plant. The data available did not support measurement of the effect of O&M practices on performance.

6.2 RECOMMENDATIONS

Evaluation of the 36 sites indicates that containment can be an effective remedy for protection of human health and the environment. However, the conclusions presented above reveal that improvements could be made. Recommendations are discussed in general below and discussed specifically in light of design, CQA/CQC, and monitoring.

Active containment has become more prevalent than passive containment. Active containment performance standards should be made reasonably consistent. Passive containment should not be discouraged; it should be evaluated further to understand the efficacy and cost-benefit relationship, compared with active containment. Passive containment augmented by active barriers and reactive walls should also be considered. As an alternative, conversion of active containment systems to passive containment systems after the effectiveness of the system has been demonstrated could be considered.

Recommendations by containment criteria, focusing on vertical barriers, are presented in the following sections.

6.2.1 Design

The design of subsurface barriers and caps should be based on more complete hydrogeological and geotechnical investigations, focusing on depth of key and integrity of the floor. In addition, although cap design has been standardized, a more prescriptive design for a subsurface barrier should be developed. When appropriate, that design should include:

- Design performance groundwater modeling
- Geotechnical borings, at a maximum spacing of 200 feet, to define the stratigraphy and properties of the key-in horizon
- Design for the long-term compatibility of the containing barrier with aggressive contaminants
- Design for diffusion and desiccation mechanisms (as appropriate) that could affect long-term performance

In addition, it is recommended that design using innovative technologies for vertical barriers, such as trenching technologies, active barriers, and reactive barriers, be scrutinized to ensure that sound engineering and construction methods are used in their application. In the case of reactive barriers, groundwater modeling is a crucial element of the design. Monitoring of the groundwater flow is also required to ensure long-term performance.

6.2.2 CQA/CQC

Standardization of CQA/CQC for caps has been adopted by the industry. The CQA/CQC effort for subsurface barriers requires further development. Important CQA/CQC elements include:

- Trench key confirmation, using samples of the key-in horizon. The trench bottom and backfill surface should be profiled twice daily by a qualified geologist or geotechnical engineer.
- Consistent cleaning of the trench bottom and backslope to remove sediments from the slurry trench
- Controlled mixing and placing of the backfill to prevent segregation of materials
- Prescribed post-construction sampling and testing, preferably before construction demobilization, of the barrier through an approved method that preserves the integrity of the barrier or through some proven nondestructive testing methods.

CQA/CQC for vertical barriers should be developed to a level similar to that for caps. Preparation of construction quality assurance plans and inspection should become commonplace, as they have been for caps. This recommendation will become increasingly important as more innovative barrier technologies challenge CQA/CQC conventions.

6.2.3 Monitoring

The importance of a systematic monitoring program in evaluating long-term performance cannot be overemphasized. The sampling protocol provided in Appendix C details the suggested long-term monitoring program; monitoring recommendations also are listed below.

- Groundwater head monitoring in paired piezometers located within and outside the wall, at a minimum spacing of 400 lf along the wall alignment and within 30 feet of the barrier wall, automatic monthly or quarterly monitoring to assist in early detection of leaks

- Systematic quarterly monitoring of groundwater quality in downgradient wells to determine the improvement in water quality over time

- Hydraulic stress tests of the barrier wall after construction as compared with intrusive sampling and testing of the barrier to confirm the integrity of the barrier and identify areas that may require supplemental long-term monitoring

- Further development of nondestructive monitoring methods, such as geophysical surveys or piezocone testing along the barrier wall alignment, to detect permeable zones in the completed barrier

Collected data must be compiled and used for the purpose intended. A consistent reporting format should be developed for all regulatory required data. Archiving of data should be done consistently to allow future access to those data. Periodic reporting should compare required measurements consistently so meaningful judgment can be made from the data. Data should be cumulative and demonstrate clearly trends toward improvement or deterioration.

6.2.4 Long-Term Maintenance

Measures should be implemented to ensure the integrity of the barrier throughout its life, such as:

- Access should be provided and maintained along the perimeter of the barrier for periodic inspection

- Comparative data reviews should be performed periodically (for example, at 5-year intervals). Such reviews should address hydraulic head data, trends in groundwater quality, as well as data from monitoring points at the key horizon. Poor performance should trigger a pragmatic graduated response (i.e., additional monitoring, non-destructive testing, destructive sampling and analysis, hydraulic testing, and replacement).

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GLOSSARY

Anchor Trench—The terminus of most geosynthetic materials as they exit a waste containment facility, usually consisting of a small trench in which the geosynthetic material is embedded and backfilled.

Atterberg Limits—Liquid limit and plastic limit of a soil.

Backfill Slump—Settlement of a volume of backfill mix when it is introduced into a measuring device.

Barrier Underflow—Groundwater inflow or outflow under the containment system key.

Bentonite—Any commercially processed clay that consists primarily of the mineral group smecite.

Cap—Landfill cover system, consisting of several layers of various materials, that contains waste and prevents infiltration of water.

Clamshell Excavation—Method of excavating a trench that uses a bucket shaped like a clamshell.

Construction Quality Assurance (CQA)—Planned system of activities that provide assurance that a facility was constructed as specified in the design. CQA includes inspections, verifications, audits, and evaluations of materials and workmanship necessary to determine and document the quality of the constructed facility. CQA refers to measures taken by the CQA organization to assess whether the installer or contractor is in compliance with the plans and specifications for a project.

Construction Quality Control (CQC)—Planned system of inspections performed to directly monitor and control the quality of a construction project. CQC is necessary to achieve quality in the constructed or installed system. CQC refers to measures taken by the installer or contractor to determine compliance with the requirements for materials and workmanship, as stated in the plans and specifications for the project.

Contaminant Plume—Area of contaminated groundwater flowing downgradient of the site.

Contaminant Transport—Movement of contaminants by groundwater or surface water flow.

Deep Soil Mixing—Construction method in which augers are used to mix in place soils with a backfill slurry.

Drainage Layer—Portion of a landfill cap with a permeability of at least 0.01 to 1 centimeters per second (cm/sec) that promotes the movement of liquids, usually away from the impermeable layer.

Engineered Barrier—Vertical barrier walls and caps that are constructed to control the inflow of water.

Feasibility Determination—Investigation to determine whether construction of a barrier wall is both technically and economically feasible.

Fines—Portion of soil that passes through a No. 200 sieve (openings of 0.075 millimeters).

Foundation Materials—Soil materials used as a foundation for the layers of the cap.

Funnel and Gate Barrier—Permeable reactive barrier that consists of a permeable curtain (gate) that contains appropriate reactive materials, and a barrier wall (funnel) that directs the groundwater to the gate.

Gas Collection—System to collect landfill gases, typically methane, produced under the cap.

Geosynthetic Materials—Generic term for all synthetic materials used in geotechnical engineering applications.

Geotechnical Investigation—Investigation of soil mechanics; rock mechanics; and the engineering aspects of geology, geophysics, hydrology, and related services.

Gradation—Distribution of physical size in a granular soil.

Groundwater Dewatering—Removal of groundwater from within a barrier system; generally, the water is treated to remove contamination.

Groundwater Cutoff Wall—Another term for a vertical subsurface barrier.

Grouting—Introduction of cemenitous materials in porous soil and fractured rock.

Head Differential—Difference in water elevation within and outside the barrier wall.

Hydraulic Conductivity—Rate of discharge of water under laminar flow conditions through a unit cross-sectional area of a porous medium under a unit hydraulic gradient and standard temperature conditions.

Hydrofracture—Fracture within a vertical barrier wall caused by earth stresses that allows groundwater flow across the barrier.

Hydrogeologic Units—Water-bearing geological units.

Inclinometers—Measurement device to monitor the movement of soil and rock materials relative to a fixed point located along an inclined or vertical borehole.

Key-in—Section of the vertical barrier where the low-permeability barrier material intersects with in-situ low-permeability soil or a rock formation to restrict the movement of groundwater, typically at the greatest depth of the barrier.

Lateral Flow—Horizontal movement of groundwater.

Low Permeability Layer—Portion of a landfill cover, vertical barrier, or liner that restricts groundwater flow to less than or equal to 10^{-7} cm/sec.

Macropore—Discontinuity in barrier materials that allows groundwater flow.

Marsh Funnel—Measurement device used to determine the viscosity of bentonite slurry.

Monitoring Well—Groundwater well used to measure the water level and quality in a water-bearing horizon.

Operation and Maintenance—Scheduled inspections to prevent, repair, and maintain components of a remedial system to ensure its continued effectiveness.

Performance Monitoring Data—Data on groundwater head, quality, and other tests used to monitor performance of the containment system.

Permeability—Capacity of a material to conduct or transmit fluid.

Permeable Window—Permeable layer or area within an impermeable barrier wall.

Piezocone—Type of pentrometer used to measure the field resistance of soil horizons and pure pressure.

Piezometer—Monitoring point used to measure static groundwater levels.

Plastic Cement Barrier—Barrier system that uses cement and plastic (a material that contains organic polymeric substances of large molecular weight that is solid in its finished state) to form a flexible cement barrier.

Pump and Treat System—Generic term used to describe the removal of contaminated groundwater and its subsequent treatment in some type of treatment plant.

Remedial Investigation/Feasibility Study—Stages of the remedial process under CERCLA during which the nature and extent of contamination are determined and remedial action options are developed and evaluated.

Remedial Action—Last Stage of the CERCLA remedial program, following a remedial design, during which a permanent remedy is constructed.

Remedial Action Completion Reports—Reports that describe how the remedial action was completed, describing field changes and deviations from remedial design documents; also known as "as-built records."

Remedial Design Documents—Plans that describe how the remedial action will be completed.

Sheet Pile—Steel or high-density polyethylene geomembrane material used to construct a vertical subsurface barrier.

Site Stratigraphy—The geologic strata or layers present at a site.

Slurry—Suspension of bentonite clay and water.

Slurry Trench and Backfill—Construction method in which a backhoe or clamshell bucket is used to excavate a trench filled with bentonite slurry; subsequently, the trench is filled with a low-permeability backfill.

Slurry Wall—Vertical subsurface barrier constructed with a bentonite slurry and other low permeability materials.

Soil Horizons—Soil layers of various compositions.

Soil Cover—Layer of landfill cap that supports vegetation.

Source Control—Any of a number of methods that can be used to control the movement of contaminants.

Standard Industry Practice—Design, CQA/CQC, and monitoring practices for barrier walls and caps, as determined by work completed in this study.

Subsurface Barrier—Another term for vertical subsurface barrier.

Venting Layer—Layer of a landfill cap that aids the collection and venting of landfill gas.

Vertical Subsurface Barrier—Engineered barrier to restrict the horizontal movement of liquids.

Vibrating Beam Method—Construction method that consists of an I-beam that is vibrated into the ground and through which bentonite slurry is introduced to form an impermeable barrier wall.

Wall Sloughing—The raveling of soil materials from the walls of a trench caused by instability of the wall.

Appendix A

Summary of Existing Subsurface Engineered Barrier and Cap Types and Typical Construction Techniques

SUMMARY OF EXISTING SUBSURFACE ENGINEERED BARRIER AND CAP TYPES AND TYPICAL CONSTRUCTION TECHNIQUES

This appendix summarizes existing subsurface engineered barrier and cap types. The summary includes descriptions of current technologies, applications, design considerations, and construction methods. The information contained herein is thoroughly documented in current engineering literature.

1.0 SUBSURFACE ENGINEERED BARRIERS

Subsurface engineered barriers can be used (1) as barriers to groundwater flow, (2) to prevent off-site migration of contaminated groundwater, and (3) to prevent on-site migration of uncontaminated groundwater. Barriers may be circumferential or open and hanging or keyed. This section describes some current barrier technologies in terms of particular design, construction, and performance characteristics. The subsurface engineered barriers (walls) described in this appendix are grouped into five categories: slurry trench barriers, grouted barriers, deep soil mixed barriers, sheet-pile walls, and treatment walls. Slurry trench barriers were the most common barrier type identified in this study; therefore, slurry trench barriers are discussed in greater detail than the other types. In addition, the appendix briefly describes biopolymer drains which use barrier technology to engineer migration of groundwater.

1.1 SLURRY TRENCH BARRIERS

The most common subsurface barrier is the slurry wall. In general, slurry walls are constructed in a two-step process. First a trench is excavated, and a slurry is placed in the trench to maintain trench stability. When the trench is excavated to the designed depth and width, a permanent backfill material is placed in the trench, displacing the slurry. The permanent backfill forms a hydraulic barrier. A slurry wall can be constructed as one continuous trench or as a continuous series of panels. A bentonite-water slurry is commonly used in slurry trenches, although a variety of slurries and backfill materials can be used. Design considerations common to all slurry walls include the wall depth and key.

Slurry trenches can typically be excavated to depths of 50 to 80 feet using backhoes. Deeper continuous and panel slurry trenches can be excavated using a crane-mounted drag line or clamshell bucket. Trenches are usually 2.5 to 3 feet wide (the width of most backhoe buckets) but may be up to 5 feet wide. Unique site or project considerations, including hydrogeology, chemical compatibility, permeability, and budget, should be addressed in selecting the type of slurry trench to be used. The following subsections describe the different types of slurry trench subsurface barriers.

1.1.1 Soil-Bentonite Barriers

Soil-bentonite (SB) barriers are the most common barrier type identified in this study. The backfill used for SB barriers is 1 to 5 percent bentonite--a montmorillonitic clay that swells when hydrated--blended with soil fill. SB barriers can reliably achieve permeabilities of 10^{-7} to 10^{-8} cm/sec. The trench is excavated using a backhoe, dragline, or clamshell, depending on depth requirements. Figures A-1 and A-2 illustrate a typical slurry wall construction site and a trench cross section, respectively.

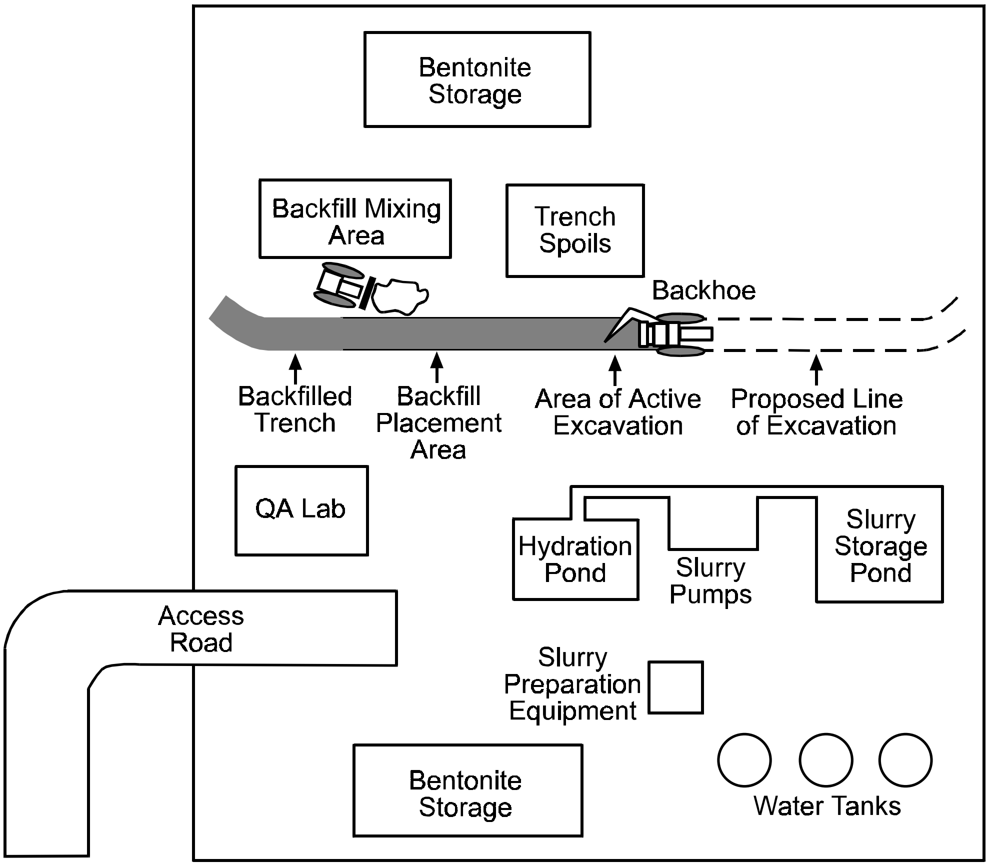


Figure A-1
Typical Slurry Wall
Construction Site

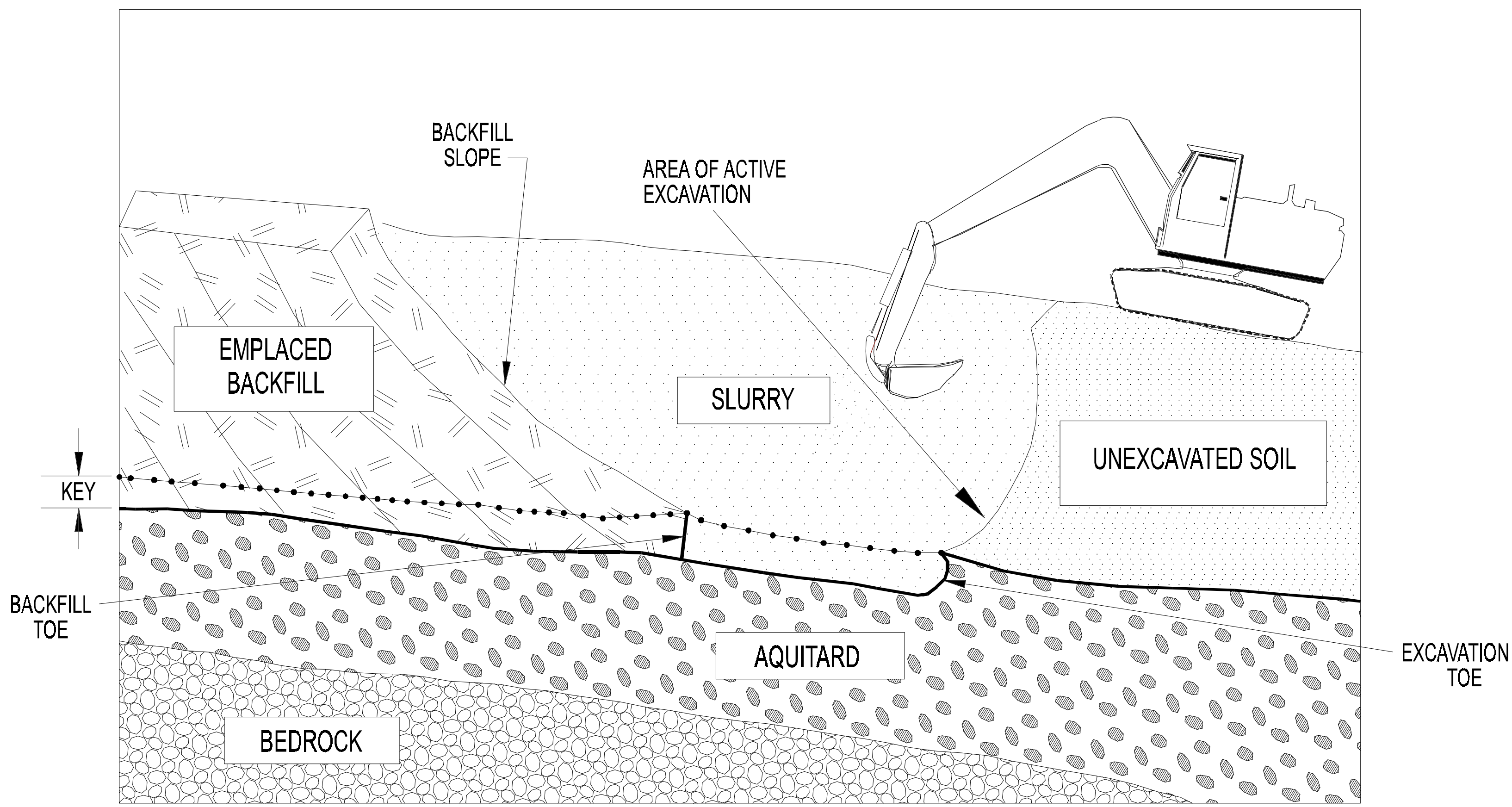


FIGURE A-2
SOIL-BENTONITE SLURRY
TRENCH CROSS-SECTION

During excavation, a bentonite-water slurry typically consisting of 1 to 5 percent bentonite is placed in the trench to support the sides of the trench. To support the trench, the slurry overcomes the active earth pressures in the soil adjacent to the trench and forms a filter cake along the trench walls. The bentonite slurry should be fully hydrated before being placed in the trench, typically for 12 to 24 hours. Therefore, temporary ponds or tanks are necessary for hydration and storage of the slurry. The slurry level in the trench is maintained at or near the top of the trench and above the surrounding groundwater table.

Soil excavated from the trench may be used for trench backfill unless physical or contaminant characteristics render it unsuitable. Amendments may be added to the soil to improve its physical characteristics (for example, fines could be added to improve the gradation of a coarse soil). Bentonite-water slurry is then mixed into the soil to form a mixture of SB backfill with a slump of approximately 4 to 6 inches. The backfill is then placed in the trench in such a way that it flows down a shallow slope (see Figure A-1). The backfill should not be free-dropped into the trench. Appropriate placement of SB backfill in the trench is necessary to displace the bentonite-water slurry without entrapping lenses of slurry within the backfill.

1.1.1.1 Design Considerations

This subsection describes some of the criteria that should be considered during the design of an SB barrier. In general, the design should consider site conditions, barrier requirements to meet design criteria, and general construction requirements.

Site Conditions. Predesign investigations should include a thorough evaluation of site conditions, including the (1) site geology and hydrogeology, (2) nature and extent of contamination, and (3) geotechnical properties of subsurface materials. Soil borings should be drilled along the potential alignment route or routes, and samples should be collected for geotechnical, physical, and contaminant analyses. Groundwater modeling may also be necessary.

Site Grade. SB barriers can generally be constructed only where surface grades are less than 1 percent. Because the slurry will flow, excavating down a slope will result in lower slurry levels within the upslope portion of the trench, reducing trench stability. Site grades may need adjustment before construction of the trench begins.

Site Access. The site should have adequate space available to mix, hydrate, and store the slurry, as well as to mix backfill and place it in the trench.

Trench Stability. Design studies of trench stability should be conducted to ensure proper determination of slurry parameters and other construction constraints.

Slurry Properties. The design evaluation of slurry mixes should establish weight, viscosity, and filtrate loss requirements for the slurry. The weight of the slurry should be sufficient to overcome active earth pressures in order to maintain an open trench, but the slurry must also be light enough to be displaced by the SB backfill.

Water Quality. The quality of the water that will be used to hydrate the bentonite should be determined. Compatibility testing of the water and bentonite may be required, although potable water supplies are usually acceptable.

Backfill Properties. The backfill design should specify criteria for unit weight, slump, gradation, and permeability. The backfill should consist of a well graded mixture of coarse and fine materials. The backfill should typically have approximately a 4-to 6-inch slump. Laboratory studies of backfill permeability should be conducted during the design phase to ensure that performance criteria can be met. The backfill should be of sufficient strength to prevent hydrofracturing under high stress.

Contaminant Compatibility. Some contaminants, including some solvents and salts, have been shown to reverse the swelling characteristics of bentonite, which would result in a higher permeability. The compatibility of contaminated groundwater and SB backfill should be evaluated.

Integration with Other Remedy Components. If the SB barrier is one component of a multifaceted remedy, then the design should consider the integration of the various units. For example, if a cap is to be constructed, an appropriate interface between the SB barrier and the cap should be designed. Additionally, the SB barrier should be able to withstand changes in site conditions caused by other units of the remedy, such as the increased hydraulic stress resulting from use of a groundwater recovery system.

Barrier Protection. Protective measures should be taken to prevent backfill desiccation, excess surface loading, and potential subsurface breaches.

1.1.1.2 Construction Quality Assurance and Quality Control Considerations

This subsection describes some of the criteria that should be considered during construction of an SB barrier.

Testing of Slurry. Before being placed in the trench, the slurry should be sampled and tested for unit weight, viscosity, and filtrate loss to ensure that these parameters meet the design requirements. The slurry may also be tested for pH, sand content, and gel strength. Slurry samples should also be collected from the trench during excavation. Trench slurry samples should be tested for unit weight, viscosity, and filtrate loss. A mud balance, Marsh funnel, and filter press can be used to make field measurements of unit weight, viscosity, and filtrate loss, respectively. These tests should be conducted on a frequent and regular basis as specified in the site construction quality assurance (CQA) plan.

Inspection of the Trench. During construction, the trench should be inspected for width, depth, key penetration, verticality, continuity, stability, and bottom cleaning. The most critical factor is key penetration. The excavator operator should inform the inspector when the key stratum is encountered. Visual inspection of trench spoils can confirm that the key stratum has been encountered if the key stratum is visibly different from the overlying material. The inspector can measure the depth to the key stratum when it is encountered and as excavation continues to ensure that the required penetration is made. The depth of the trench can be measured with a rigid probe, and the measurements should be made at frequent intervals along the trench alignment. Repeated measurements made at the same location can also reveal accumulation of sloughed soil while the trench has remained open. The bottom of the trench should be cleaned to ensure a tight seal between the key and the backfill. The appearance of tension cracks in the ground surface parallel to the trench sides would indicate potential failure of the trench sides. Tension cracks may be avoided by limiting traffic near the trench, increasing the slurry density, or minimizing the depth to the slurry surface. For circumferential barriers, the end of the wall should be continued a certain distance into the beginning of the wall to ensure continuity.

Testing of Backfill. Before its placement in the trench, the backfill should be sampled and tested for unit weight, slump, gradation, and permeability to ensure that it meets the design requirements. The backfill unit weight should be at least 15 pounds per cubic foot greater than the slurry’s weight to ensure that the slurry will be displaced during backfill placement. Backfill samples should be collected during backfill placement on a frequent and regular basis as established in the CQA plan. When the barrier is completed, backfill samples should be collected at regular intervals and tested for permeability. This test will establish whether the completed barrier meets the design criteria.

Handling of Contaminated Materials. At sites where contaminated backfill or slurry may be handled, precautions should be taken to ensure that potential spills or releases are contained and recovered in order to prevent exposure of site workers or other receptors.

1.1.2 Cement-Bentonite Barriers

Cement-bentonite (CB) slurry trench cutoff walls are excavated using a slurry composed of water, cement, and bentonite. The bentonite-water slurry is prepared and allowed to fully hydrate before portland cement is added. Once the cement has been added, the CB slurry is pumped to the trench. The CB slurry is left to harden in place, forming a hydraulic barrier with a permeability on the order of 10^{-5} to 10^{-6} cm/sec. The relatively high permeability is the result of the portland cement reducing the swelling properties of the bentonite. Because of their relatively high permeabilities, CB barriers are typically not used as contaminant containment applications, which often require permeabilities of less than 10^{-7} cm/sec. However, CB barriers are commonly used as cutoff barriers where higher wall strengths are necessary and low permeability is not required. A CB barrier is a homogenous, isotropic cutoff wall; therefore, the likelihood of variations being present in the wall is lower than for SB barriers because no separate backfilling step is necessary.

Alternative cement mixes have been used that display lower permeabilities and improved chemical compatibility. Ground, granulated blast furnace slag mixed with portland cement at a ratio of 3:1 or 4:1 has displayed permeabilities of 10^{-7} to 10^{-8} cm/sec. Bentonite substitutes have also been used. One such substitute is attapulgite, a clay mineral that is more resistant to chemical degradation than bentonite. The use of such additives can significantly increase the overall cost of a barrier.

1.1.2.1 Design Considerations

In general, design considerations for CB barriers are similar to those for SB barriers (see Section 1.1.1.1). Unique aspects of CB barrier design are described below.

Permeability. CB barriers typically exhibit permeability on the order of 10^{-5} to 10^{-6} cm/sec. Because of their relatively high permeabilities, CB barriers are typically not used for contaminant containment applications.

Wall Strength. CB barriers have higher shear strengths than SB barriers. The hardened trench of a CB barrier will exhibit the consistency of stiff clay. Therefore, CB barriers can be used where higher strengths are needed.

Surface Grade. CB barriers can be constructed with steeper surface grades than can SB barriers. Grade steps can be easily accomplished because the CB slurry hardens daily.

Site Access. Construction of CB barriers does not require as large a working area as construction of SB barriers because backfill mixing areas are not used.

Construction Method. CB barriers can be constructed continuously or in panels. If a CB barrier is constructed continuously, retarding agents may have to be added to the CB slurry in order to prevent premature curing.

Chemical Compatibility. CB barriers typically have a cement to water ratio of 0.15 to 0.25. Therefore, CB barriers may be susceptible to increases in permeability resulting from the effects of contaminated fluids. The introduction of certain additives to the slurry, such as siliceous materials, special clays, or chemical additives, may improve the chemical compatibility of CB barriers.

Handling and Disposal of Excavated Material. Materials excavated from the trench of a CB barrier will require disposal. If the materials are contaminated, handling and disposal of the materials may represent a significant cost factor and may require additional design considerations. If applicable, use of these materials as site fill may be feasible.

1.1.2.2 Construction Quality Assurance Considerations

In general, CQA considerations for CB barriers are similar to those for SB barriers (see Section 1.1.1.2). Unique aspects of CB barrier construction are described below.

Slurry Testing. The hydrated bentonite-water slurry mixture should be tested for unit weight, viscosity, and filtrate loss before the addition of cement because the cement will begin to cure and these properties will change. The slurry should also be tested for the same parameters after the introduction of cement, and the test results should be compared to the design requirements. CB slurry test cylinders should be prepared in the field, allowed to cure (typically for 28 days in a 100 percent humidity environment), and tested in the laboratory for shear strength and permeability.

Trench Continuity. Because the CB slurry hardens in the trench, during each day of construction, a clean contact should be established with the previous day's hardened slurry. Therefore, at the beginning of each construction day, the end of the CB trench should be excavated to ensure a clean contact with the new CB slurry to be added to the trench.

1.1.3 Plastic Concrete Barriers

Plastic concrete (PC) barriers are constructed under a head of bentonite-water slurry and are backfilled with a lean concrete mix of water, cement, aggregate, and bentonite. PC barriers are usually constructed in panels (see Figure A-3). The PC backfill is placed by tremie pipe. PC barriers can achieve permeabilities ranging from 10^{-6} to 10^{-8} cm/sec.

1.1.3.1 Design Considerations

Design considerations for PC barriers are similar to those for SB barriers (see Section 1.1.1.1) and CB barriers (see Section 1.1.2.1). Because PC barriers are constructed under a bentonite-water slurry, the trench and slurry design criteria are similar to those for SB barriers. As with CB barriers, PC barriers (1) require disposal of excavated material, (2) can be constructed over steeper grades, and (3) have higher strengths that allow their use in situations requiring structural loading. Unique aspects of PC barrier design are described below.

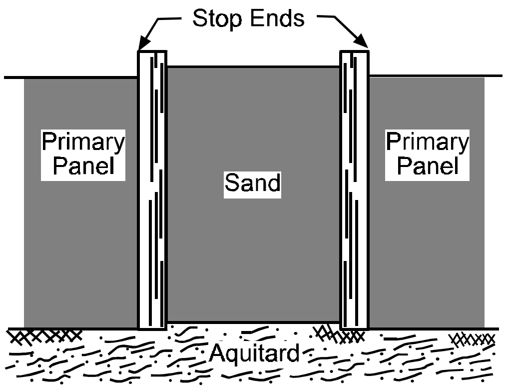


Figure 5(a)
Primary panels tremie concreted with stop ends in place

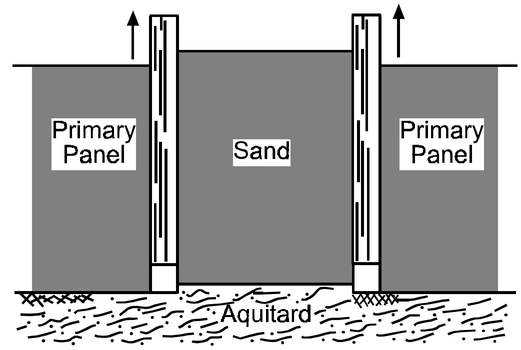


Figure 5(b)
Stop ends lifted

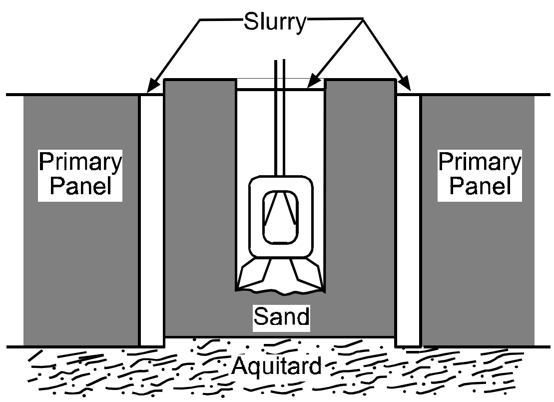


Figure 5(c)
Excavation of midsection of secondary panel

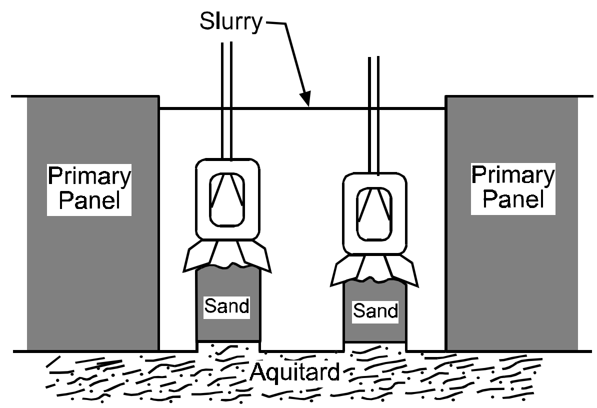


Figure 5(d)
Excavation of each end of secondary panel

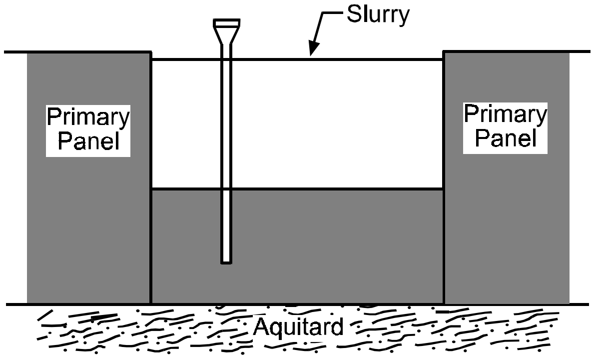


Figure 5(e)
Tremie concreting secondary panel

Figure A-3
Panel Construction Method for a Plastic Concrete Barrier

Strength. PC barriers are considerably stronger than SB and CB barriers. Therefore, PC barriers should be considered for applications where additional strength is desirable.

Compatibility. The limited data available indicates that PC barriers are more resistant to organic contamination than CB barriers.

Cost. PC barriers are more expensive than SB and CB barriers. The higher costs are the result of (1) disposal costs associated with excavated materials; (2) panel construction, which is more time-consuming than continuous trenching; and (3) the added cost of the aggregate used.

1.1.3.2 Construction Quality Assurance Considerations

In general, CQA considerations for PC barriers are similar to those for SB barriers (see Section 1.1.1.2) and CB barriers (see Section 1.1.2.2). Slurry, trench construction, and backfill parameters should be maintained in accordance with design requirements.

1.1.4 Geosynthetic Composite Barriers

Geosynthetic composite barriers have been constructed using a combination of geosynthetic materials and conventional barrier technology. Geosynthetic materials such as high-density polyethylene (HDPE) can improve the performance of a traditional SB barrier by (1) decreasing the permeability of the barrier by as much as two orders of magnitude and (2) improving the chemical resistance of the barrier. Interlocking geomembranes have been developed to improve joint seals (see Figure A-4). Hydrophillic gaskets that expand when in contact with water can be used in the interlocks.

Current methods for installing geosynthetic materials include the following:

- The geosynthetic material (geomembrane liner) is mounted on an installation frame, and the frame is lowered into the slurry-filled trench (see Figure A-5). Interlocking joints on either side of the geomembrane are sealed with a hydrophyllic gasket or by the slurry. The installation frame is then removed.

- The bottom of the geomembrane liner is weighted so that the liner sinks into the trench.

- Hardened geomembrane panels are driven into the ground using a pile driver

Geosynthetic composite barriers have been used to prevent gas migration from landfills and to protect the bentonite in SB barriers from moisture changes resulting from fluctuating water tables. A leak detection system can also be constructed by sandwiching a geonet fabric between two geomembranes.

1.2 GROUTED BARRIERS

Construction of grouted barriers involves injection of a grout into the subsurface. Pressure grouting and jet grouting are both forms of injection grouting, in which a grout mixture is injected into the pore spaces of the soil or rock. When a vibrating beam is used, the grout is injected through a special H-pile into the space created by the driven pile when the pile is removed.

Particulate or chemical grouts may be used for grouted barriers. Particulate grouts include slurries of bentonite, cement, or both and water. Chemical grouts generally contain a chemical base, a catalyst, and

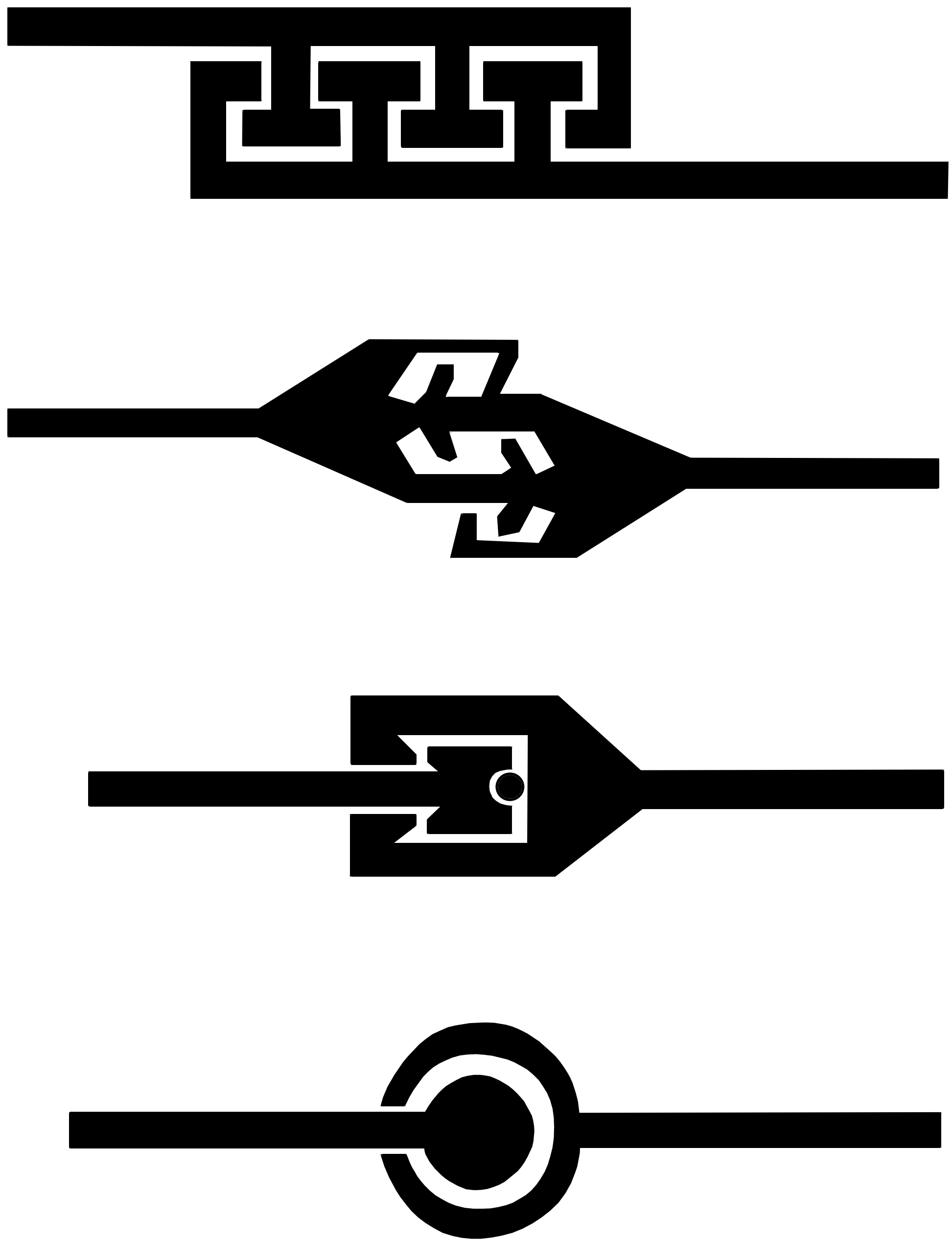


Figure A-4
Examples of Interlocks for
Goesynthetic Composite Walls

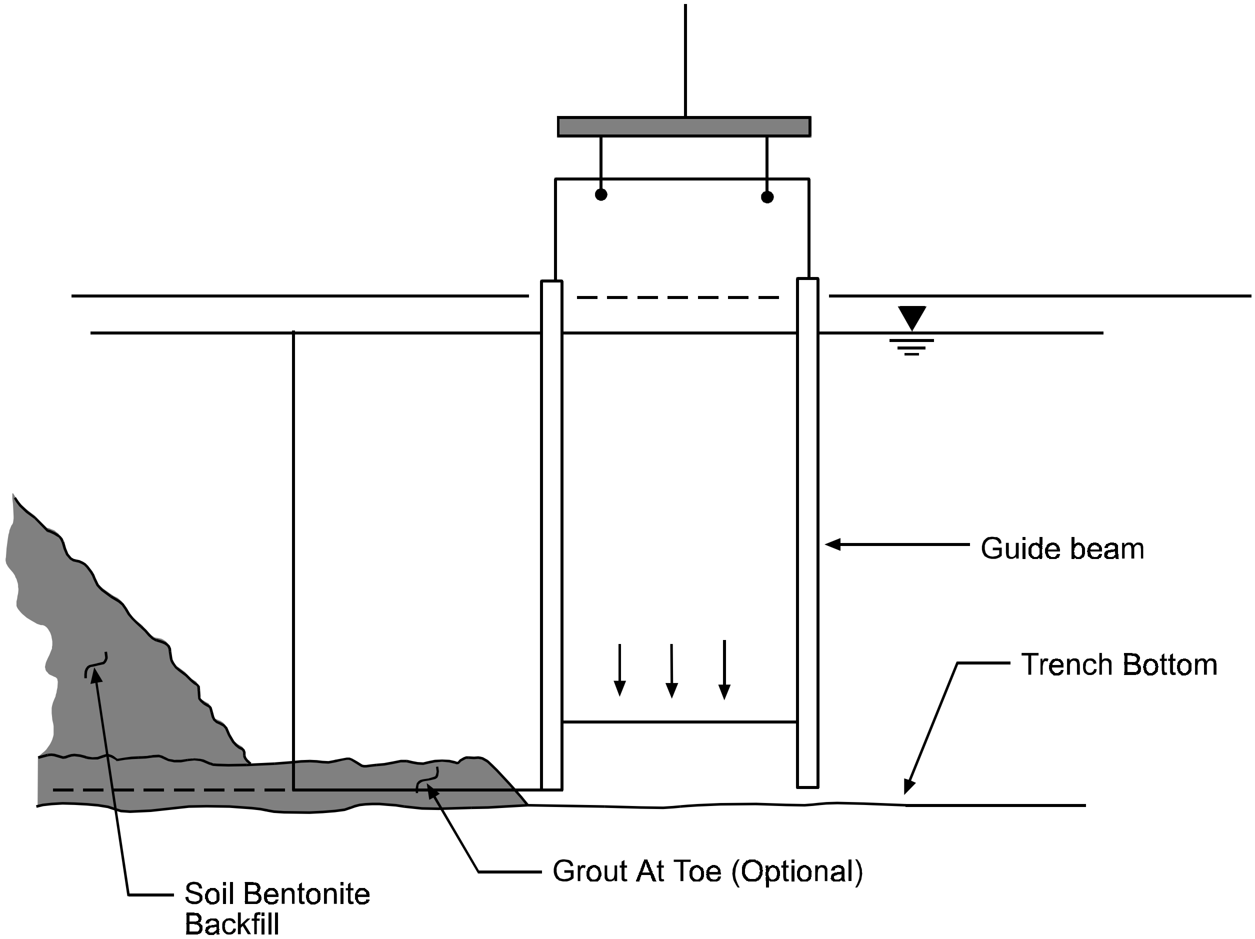


Figure A-5
Installation Method for a
Geosynthetic Composite Wall

water or another solvent. Common chemical grouts include sodium silicate, acrylate, and urethane. Particulate grouts have higher viscosities than chemical grouts and are therefore better suited for larger pore spaces, whereas chemical grouts are better suited for smaller pore spaces. Combinations of particulate and chemical grouts can also be used.

The following subsections describe the permeation (pressure) grouting, jet grouting, and vibrating beam technologies.

1.2.1 Permeation Grouting

Permeation grouting involves filling of soil voids with a sealing grout. To achieve low permeability, the soil voids must be completely filled, and the lateral extent of grout penetration must be controlled. The design of a permeation grouted barrier must consider soil permeability, grout viscosity, and soil and grout particle size. In general, soils with permeabilities greater than 10^{-3} cm/sec can be permeation grouted with chemical grouts, while particulate grouts can be used when soil permeabilities are greater than 10^{-1} cm/sec.

Two permeation grouting methods, point injection and tube-a-manchette, are currently used and are described below.

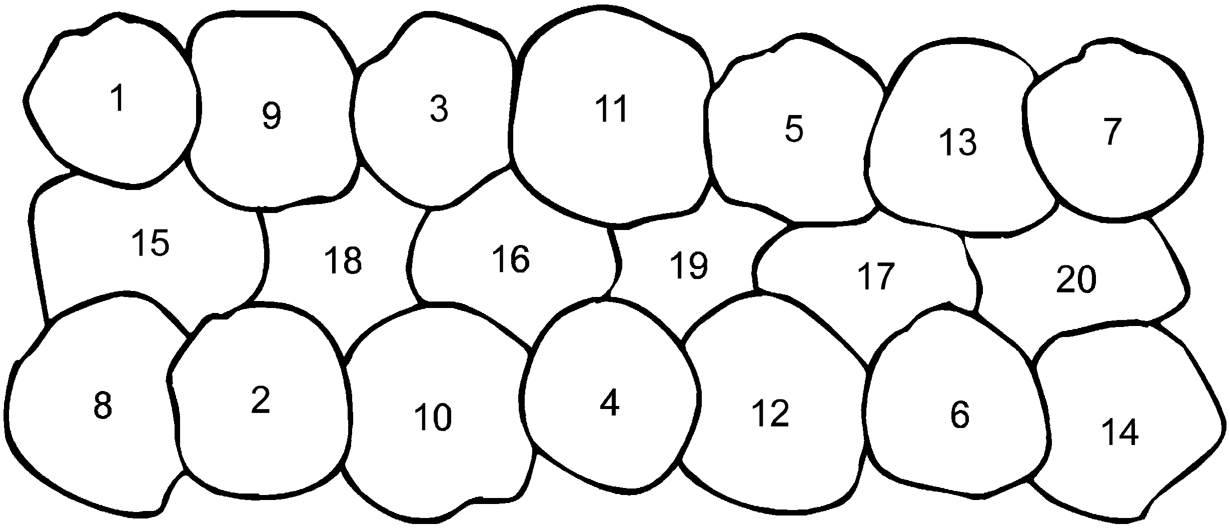
- Point Injection: The grout casing is advanced to the maximum depth of penetration, and grout is extruded through the end as the casing is withdrawn. A continuous barrier is formed by installing an array of at least two or three rows of overlapping injection holes, as shown in Figure A-6.

- Tube-a-Manchette: A sleeve pipe containing small holes at 1-foot intervals is grouted into a borehole with a weak grout. The small holes are covered by rubber sleeves (manchettes) that act as one-way valves, allowing grout to be forced into the formation (Figure A-7). A double packer is placed in the sleeve pipe in such a way that it straddles the manchettes, and grout is injected under pressure. If the required containment permeability is not achieved, the tube-a-manchette method allows for regrouting at the same location. Also, this method allows different grout types to be used at the same location (for example, a cement grout to fill larger voids and a chemical grout to fill smaller voids).

The design of a permeation grouted barrier must include a thorough evaluation of the grouting pressure to be used. Excessive pressure can cause hydrofracturing. If hydrofracturing occurs, the grout will be forced into the hydrofractures but may not adequately fill the natural soil voids, and therefore the barrier would not meet the permeability design requirement.

1.2.2 Jet Grouting

Jet grouted walls are constructed by injecting grout at very high pressure (up to 6,000 pounds per square inch [psi]) into the soil. The high-pressure grout is injected at rates of 800 to 1,000 feet per second, which cuts and mixes the native soil into a uniform barrier. Typically a portland cement grout is used, although a variety of grouts can be used. In general, a small-diameter pilot hole is drilled to the total depth of the barrier. The hole is jet grouted from the bottom to the surface. A column of soil can be created by rotating the jet grouting drill rod while it is being removed, and a panel can be created by not



(Numbers indicate order of injection).

Figure A-6
Injection Array and Sequence
for a Permeation Grout Barrier

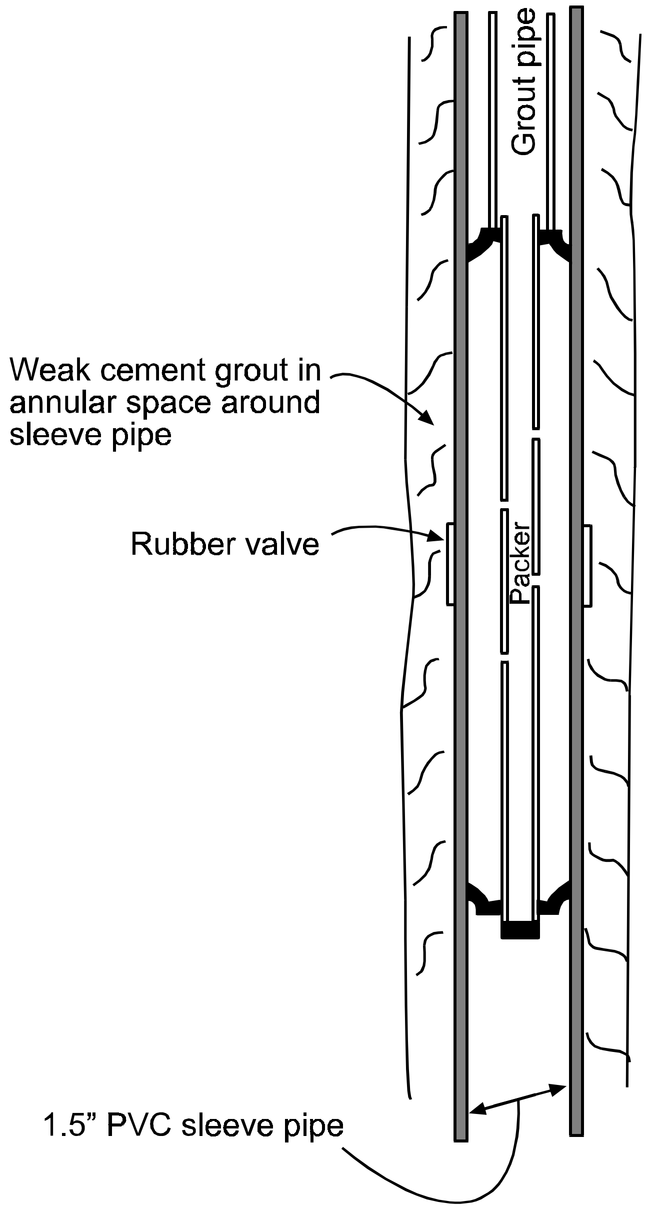


Figure A-7
Tube-A-Manchette
Permeation Grout Apparatus

rotating the rod. A horizontally continuous barrier can be created by successive installation of jet grouted columns or panels.

Jet grouting can be used to stabilize soils ranging from gravels to heavy clays. Jet grouted barriers have been built to depths of greater than 200 feet, although below about 100 feet the verticality and thus the continuity of jet grouted barriers are difficult to control or confirm.

Three types of jet grouting, single rod, double rod, and triple rod (all referring to the number of passageways in the drill rod), have been developed and are described below.

- Single Rod: Only grout is pumped through the rod and injected into the soil. After the soil-grout column is mixed, excess soil and water are displaced to the surface. Single rod columns can be up to 1.2 meters wide in granular soils and 0.8 meter wide in cohesive soils.

- Double Rod: Air is injected into the soil through the same jet as the grout. The injected air keeps the jet stream clear by holding back groundwater and the soil cut by the jet and helps lift the cut soil to the surface. Double rod columns can be up to twice as large as single rod columns. However, the high air content of a double rod column may result in higher permeability.

- Triple Rod: Air and water are injected through a cutting jet that cuts and lifts the soil, resulting in removal of most of the native soil. Grout is injected through a second jet, filling the column as the drill rod is lifted. The resulting column is therefore almost entirely grout. Triple rod columns can be up to 3 meters wide in granular soils and 1.5 meters wide in cohesive soils.

Like permeation grouting, jet grouting requires that injection pressure and volume be monitored closely. If spoil materials cannot be expelled to the surface, excess pressure can build and cause hydrofracturing. Excessive injection volume could indicate grout loss to the formation. Jet grouting can produce large volumes of spoil materials; if these materials are contaminated, they require special handling and disposal.

1.2.3 Vibrating Beam Technology

A vibrating beam barrier is a grouted barrier that is suitable for shallow soils. A modified H-pile is driven into the ground with a vibratory pile driver; the H-pile has been modified to inject grout through nozzles at the bottom end of the pile. During pile driving, a small amount of grout may be injected through the nozzles to provide lubrication. Grout is injected through the nozzles to fill the void created by withdrawal of the pile. A continuous barrier is created by overlapping grouted piles.

CB grouts are usually used for vibrating beam barriers, although bituminous (asphalt-based) grouts have also been used. Vibrating beam walls are only about 2 to 3 inches thick and therefore have a high potential to hydrofracture. The permeability of a vibrating beam wall depends on the grout used; for example, a permeability of 10^{-5} to 10^{-6} cm/sec may be expected where a CB grout is used.

Vibrating beam barriers have two primary advantages: (1) no handling or disposal of excavated material is required; and (2) vibrating beam barriers can be installed in relatively tight quarters. The primary disadvantage of vibrating beam barriers is that the H-piles may deflect from vertical, making the continuity of the barrier at depth uncertain. The bottom of a vibrating beam barrier cannot be inspected to confirm verticality or key penetration. Also, pre-auguring may be necessary to ensure ease of penetration into tighter soils.

1.3 DEEP SOIL MIXED BARRIERS

Deep soil mixing technology was developed in Japan and consists of in situ mixing of soil and a slurry. The specially designed equipment typically consists of three auger mixing shafts that inject and mix a water-bentonite or CB slurry into the soil as the augers are advanced, resulting in a column of thoroughly mixed soil. As shown in Figure A-8, the final mix is usually about 1 percent bentonite. A continuous barrier is created by overlapping penetrations.

Deep soil mixed barriers can achieve permeabilities of 10^{-7} cm/sec. As with a vibrating beam barrier, the bottom of a deep soil mixed barrier cannot be inspected to confirm key penetration. However, deep soil mixed barriers are considerably wider than vibrating beam barriers and can achieve lower permeabilities.

Because potentially contaminated materials are not excavated, the advantages of using deep soil mixing technology include reduction of health and safety risks and elimination of costs associated with handling and disposal of contaminated soils.

1.4 SHEET-PILE WALLS

Sheet-pile walls have long been used for a wide variety of civil engineering applications, but their use in environmental situations has been limited. Although sheet-pile walls are extremely strong and steel will not hydrofracture, the interlocking joints present a leakage problem. The ability of steel sheet piling to meet a typical 10^{-7} cm/sec design performance standard depends on the type of material used to seal the interlocking joints.

1.5 TREATMENT WALLS

The treatment wall is a relatively new technology in which a traditional barrier wall, such as a slurry trench wall, is used to direct contaminated groundwater through a treatment zone. The groundwater moves passively through the treatment zone, where the contaminants are degraded, precipitated, or absorbed by the treatment media. The treatment zone may contain metal-based catalysts for degrading volatile organics, chelators for immobilizing metals, nutrients and oxygen for microorganisms to enhance biodegradation, or other agents. Degradation reactions break down the contaminants in the groundwater into benign by-products. A precipitation wall reacts with the contaminants to form insoluble products that remain in the wall as the water passes. A sorption wall adsorbs or chelates contaminants to the wall surface.

To maintain the treatment zone reactions, parameters such as pH, oxidation/reduction potential, contaminant or nutrient concentrations, and kinetics must be maintained within certain limits. Therefore, the geologic, hydrogeologic, and contaminant environments must be adequately characterized.

Most treatment walls are designed to operate in situ for years with little or no maintenance. Some treatment walls are permanent, others are semipermanent, and still others are replaceable. The long-term stability of these walls has not been determined.

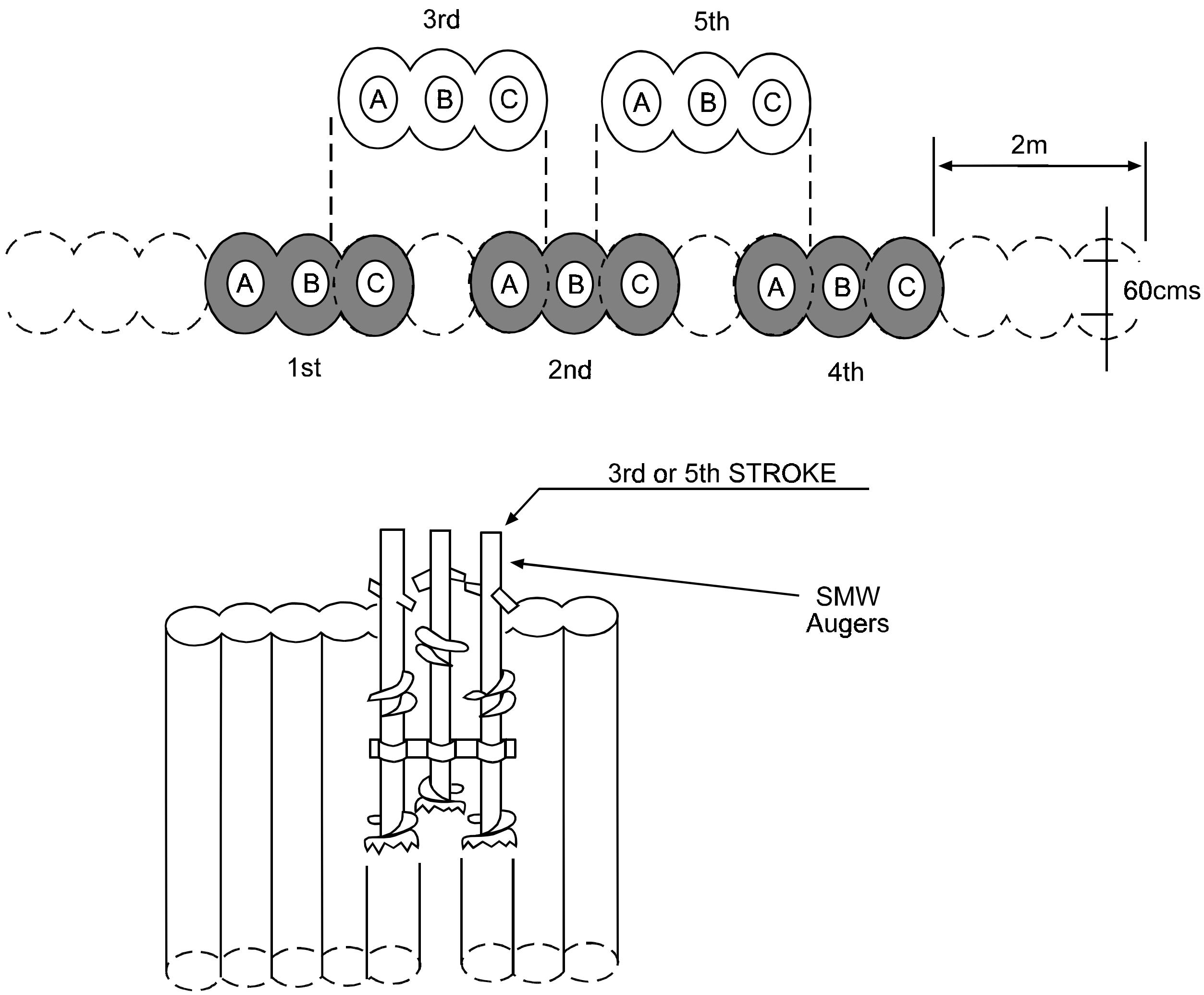


Figure A-8
Installation Sequence for a
Deep Soil Mixed Barrier

1.6 BIOPOLYMER DRAINS

Biopolymer drains are briefly discussed here to illustrate the use of conventional slurry trench construction methods to build permeable drains. Biopolymer drains are constructed using techniques similar to those used for SB walls, but instead of being barriers of low permeability, biopolymer drains have higher permeabilities than the surrounding strata.

During construction of the trench for a biopolymer drain, a biopolymer slurry such as a biodegradable drilling mud is used to maintain trench stability. The trench is backfilled with a coarse, granular material such as sand or gravel. As the mud biodegrades, the sand- or gravel-filled trench becomes a permeable drain. Groundwater flowing into the drain can be collected by pumps or gravity-drained to a collection point.

The advantages of installing biopolymer drains include the following:

- Reduced excavation effort because trench-side backslopes and trench shoring are not necessary

- Reduced health and safety risks because workers do not have to enter the trench

- Time and cost savings because construction proceeds rapidly

2.0 CAPS

Cap systems are used at landfills and other waste sites to prevent transfer of contaminants to the atmosphere and to prevent or minimize surface water infiltration. The vegetation and topsoil over a cap temporarily store the rainwater and ultimately evapotranspirate a large part of it. The remaining moisture percolates downward toward the waste and must be drained laterally above a liner.

Caps are used by themselves or in conjunction with other waste treatment technologies such as barrier walls, groundwater pump and treat systems, and in situ treatment. A cap by itself cannot prevent horizontal flow of groundwater through the waste, only vertical entry of water into the waste. Caps are most effective where most of the underlying waste is above the water table. Caps serve to isolate untreated wastes and treated hazardous wastes, prevent generation of contaminated leachate, contain waste while treatment is being applied, and control gas emissions from underlying waste. Moreover, a cap can be used to create a land surface capable of supporting vegetation.

Caps may be temporary (interim) or final. An interim cap can be installed before final closure of the site to minimize generation of leachate until a better remedy is selected. Caps are also used to cover waste masses too large for treatment, such as tailings piles at mining sites. Caps can be designed to divert water away from waste areas while minimizing erosion.

Caps have been shown to successfully contain a variety of contaminants, including volatiles, semivolatiles, metals, radioactive materials, corrosives, oxidizers, and reducers. Storing materials containing these contaminants in landfills does not reduce their toxicity, mobility, or volume. However, when properly designed and maintained, landfills can isolate contaminated wastes from human and environmental exposure for long periods. Landfill caps and their components are expected to eventually fail, although their effective lives can be extended by long-term inspection and maintenance. Likely cap upkeep activities include vegetation control; construction-related repairs; and erosion, settlement, and subsidence adjustments. Long-term repairs and maintenance can be minimized if a rigorous CQA/CQC program is followed during cap construction.

The following sections discuss the basic configuration of a cap system, types of caps and materials of construction, cap design, construction of caps, CQA and CQC for caps, cap performance, and costs of cap systems.

2.1 BASIC CAP CONFIGURATIONS

Cap configurations range from a one-layer system of vegetated soil to a complex, multilayer system of soils and geosynthetics. The materials used in construction of caps include low-permeability and high-permeability soils and geosynthetic products. The low-permeability materials, such as geomembrane or soil layers, divert water and prevent its passage into the waste. The high-permeability materials, which are used in the drainage layer, carry away water that percolates into the cap. Other materials are used to increase cap slope stability.

The basic layout of a multilayer cap includes (from top to bottom) (1) a surface layer, (2) a protection layer, (3) a drainage layer, (4) a barrier layer, and (5) a gas collection layer. The surface layer usually promotes vegetative growth and evapotranspiration and consists of topsoil (at a humid site) or cobbles (at an arid site). Figures A-9 and A-10 show typical landfill configurations in humid and aired climates, respectively. The protection layer is designed to protect the underlying layers from intrusion, desiccation, and freeze-thaw damage and is usually made up of mixed soils. The drainage layer drains away infiltrating water and is made up of sands, gravels, or geotextiles. The barrier layer minimizes infiltration of water into the underlying waste and may direct gas to an emission control system. Barrier layers usually consist of compacted clay or geosynthetic liners, geomembranes, or composites. The gas collection layer transmits gas to collection points for removal or cogeneration and is usually made up of granular materials and piping.

2.2 CAP TYPES AND MATERIALS

Natural soil drainage materials are used in the construction of the drainage layer and the gas collection layer as well as a leachate collection layer, a leak detection layer, or drainage trenches as appropriate. Soil drainage systems are constructed of materials that will maintain high hydraulic conductivity over time and resist plugging or clogging. The hydraulic conductivity of drainage materials depends primarily on the grain size of the finest particles present in the soil. Drainage materials may also be required to serve as filters to protect a drainage layer from plugging.

Geomembranes used in barrier layers are supplied in large rolls and are available in varying thicknesses (20 to 140 mils), widths (15 to 100 feet), and lengths (180 to 840 feet). Most geomembranes are either polyvinyl chloride (PVC) or polystyrenes of various densities. Geomembranes are much less permeable than clays; geomembrane leakage is generally attributable to improper installation.

Soil barrier layers usually consist of clay that is compacted to a hydraulic conductivity of 1×10^{-6} cm/sec or less. Compacted soil barriers are generally installed in 6-inch (or smaller) lifts to achieve a thickness of 2 feet or more. Composite barriers use both soil and geomembrane; the geomembrane is essentially impermeable, but if a leak develops, the soil component prevents significant infiltration. Composite barriers (liners) have proven to be the most effective in decreasing hydraulic conductivity.

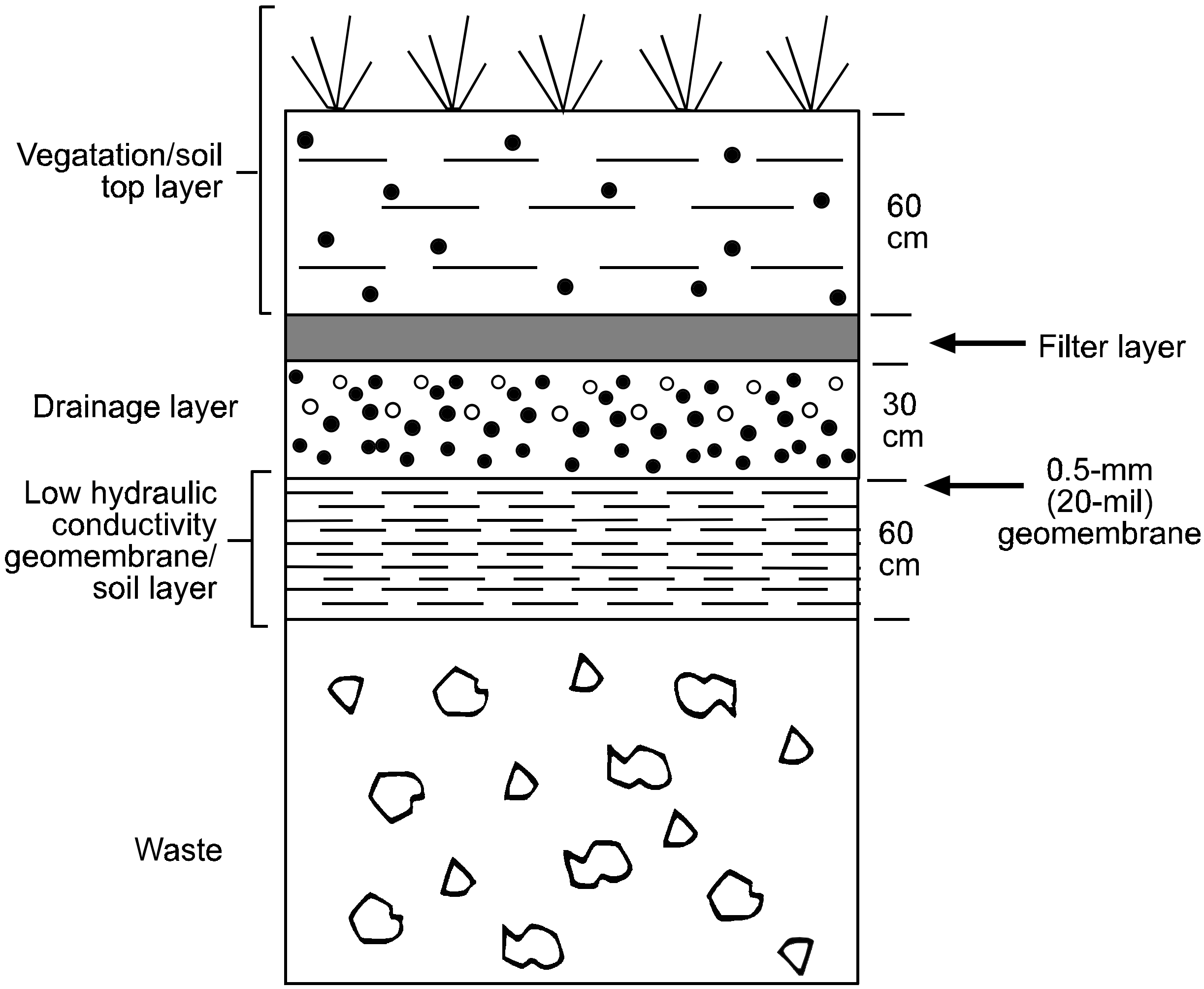


Figure A-9
Typical Landfill Cover
Design in Humid Regions

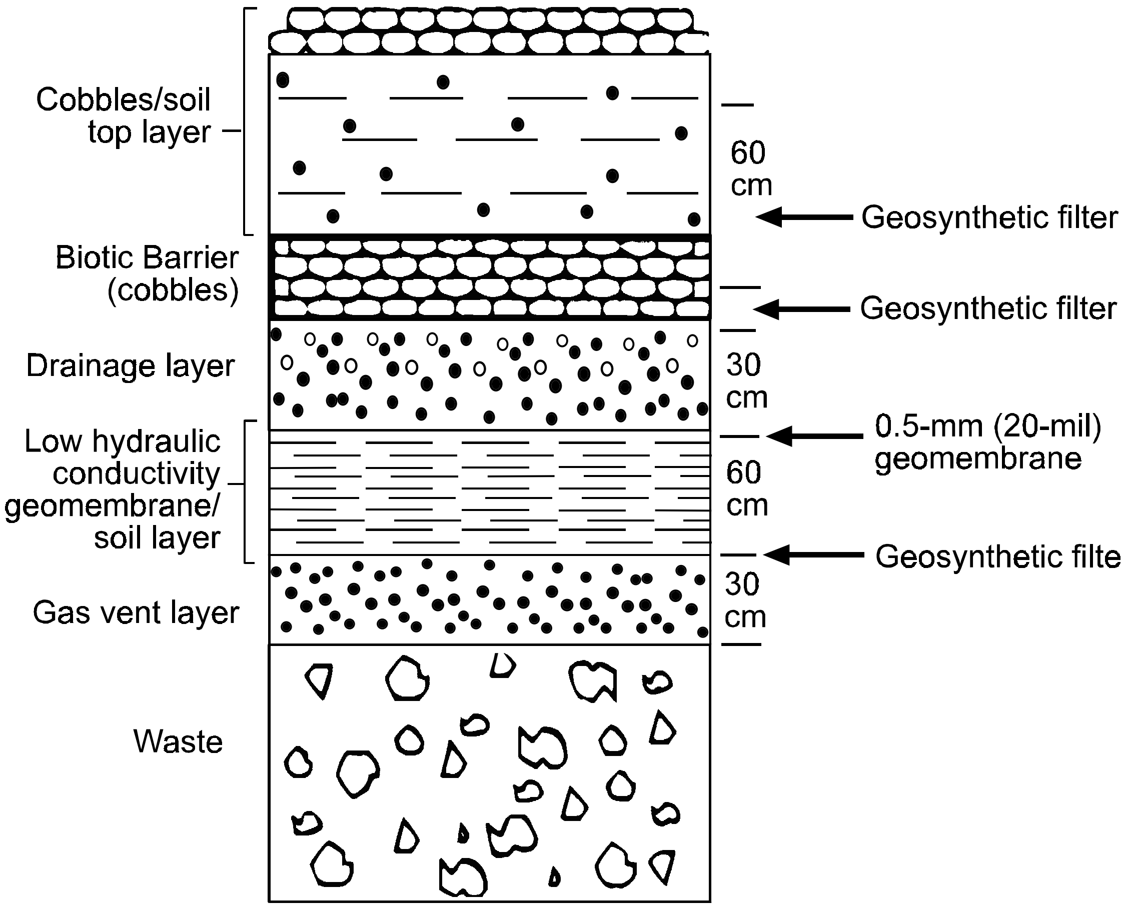


Figure A-10
Typical Landfill Cover
Design in Arid Regions

Geosynthetic clay barriers, which are composed of a thin layer of bentonite between two geosynthetic materials, can be used in place of both geomembrane and clay components. The bentonite expands to create a low-permeability, resealable barrier that is • self-healing.• The geosynthetic clay barrier material is supplied in rolls, but unlike geomembranes, it does not require seaming.

Other barrier materials include flyash-bentonite-soil mixtures, super-absorbent geotextiles, sprayed-on geomembranes and soil-particle binders, and custom-made bentonite composites made with geomembranes or geotextiles. These materials have various potential advantages, including quick and easy installation, better quality control, cost savings, reduction in the volume of material used, use of lighter construction equipment, and some self-healing capabilities.

2.3 CAP DESIGN

Major design factors that influence the effectiveness of a cap include (1) determination of global waste stability, (2) settlement analysis, (3) analysis of the stability of the cap system, (4) drainage analysis, (5) leachate management analysis, and (6) gas management analysis. Determination of global waste stability involves evaluating whether the waste mass will remain stable under all potential loading conditions. Waste mass stability is analyzed under several different loading conditions, including cap loads, seismic stresses, and construction loading. Settlement analysis evaluates the potential for the foundation and waste materials to consolidate under the loading conditions of a cap. Long-term settlement analysis should be conducted, and a monitoring plan should be developed to measure any settlement.

The stability of the cap system itself should be analyzed to determine its potential for failure. Analyses should address (1) interface stability, (2) cap soil tension above a geosynthetic-lined slope, (3) various stresses within cap components, (4) the impact of differential settlement on geosynthetic materials, and (5) the stability of slopes steeper than 3 horizontal to 1 vertical.

A drainage analysis is necessary to prevent buildup of hydraulic head on the nonpermeable cap. Drainage analyses should address (1) drainage capacity, (2) geotextile filtration, (3) runoff control, and (4) erosion control. Leachate management analysis involves evaluation of the leachate generation rate and the collection and transmission system to prevent buildup of leachate within the waste. Gas management analysis consists of an evaluation of the proposed gas collection well design and placement and usually includes a pilot test to determine the gas composition and generation rate. If a passive venting system is required, the locations of lateral and vertical vents are determined on the basis of waste characteristics (see Figure A-11). Other design considerations that affect the performance of the cap include frost penetration of cover soils and the puncture vulnerability of geosynthetic materials.

2.4 CAP CONSTRUCTION

Caps are usually constructed in a domed shape to enhance runoff. The base layer, which may be a gas collection layer, overlies the waste mass. The clay component of the barrier layer is constructed over this base layer. The clay is spread and compacted in lifts a few inches thick until the desired thickness is achieved. Each lift is scarified (roughed up) following compaction to remove any trace of a surface between it and the next higher lift. The top lift is compacted and rolled smooth so that the geomembrane can be laid on it with direct and uniform contact. The clay’s optimum moisture content must be maintained during construction to provide the necessary low permeability upon compaction.

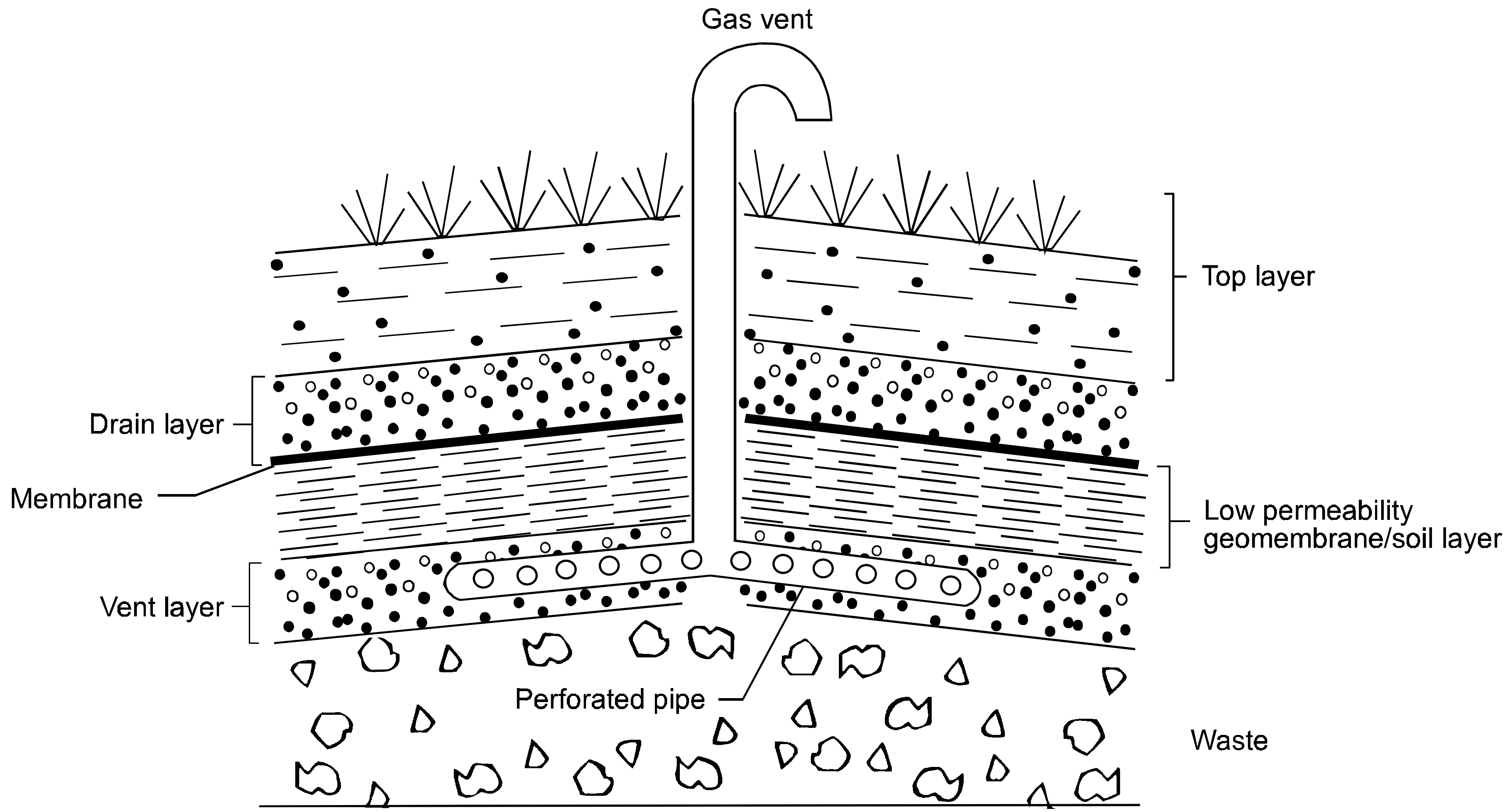


Figure A-11
Cover With Gas Vent
Outlet and Vent Layer

A geomembrane should be laid without wrinkles or tension. Its seams should be fully and continuously welded or cemented, and it should be installed before the underlying clay surface can desiccate and crack. If vent pipes are present, they should be carefully attached to the geomembrane in order to prevent tearing as a result of subsidence. Punctures and tears should be avoided during the geomembrane handling and installation procedure. In addition, the effects of air temperature and seasonal variations on the geomembrane should be taken into account; stiffness and brittleness are associated with low air temperatures. If installed while the air temperature is high, the geomembrane will expand and can then shrink to the point where seams rupture.

A geotextile may be laid on the surface of the geomembrane to protect it, particularly if coarse and sharp granular materials are to be used in the overlying drainage layer. The drainage layer is designed to carry away water that percolates down to the barrier layer. The drainage layer may be either a granular soil with high permeability or a geosynthetic drainage grid or geonet sandwiched between two porous geotextile layers. Another geotextile may be put on top of the drainage layer to prevent clogging of the drainage layer by soil from above. Fill soil and topsoil are then applied, and the topsoil is seeded with grass or other vegetation.

CQA/CQC, including testing, is estimated to increase the cap installation cost and completion time by 10 to 15 percent but is generally acknowledged as improving the performance of the cap. Materials considered for each of the cap components are tested to ensure their suitability. Both before and during construction, soils are tested to determine their grain size, Atterberg limits, hydraulic conductivity, and compaction characteristics. Geomembrane test strip seaming is performed on narrow pieces of excess geomembrane to ensure high seam quality. The test strips are subjected to strength (shear and peel) testing to simulate stress from equipment, personnel, or climatic changes. Seams should run up and down slopes rather than across them to reduce seam stress.

The slope of the cap top should be between 3 and 5 percent. Steeply mounded caps can present difficulties related to soil compaction, soil erosion, and anchorage of the geomembrane. High air temperatures and dry conditions during construction may result in loss of moisture from a clay barrier layer, causing desiccation cracking that can increase hydraulic conductivity. Desiccation cracking can be prevented by adding moisture to the clay surface and key installing the geomembrane in a composite barrier quickly after completion of the clay layer.

Construction equipment required during cap installation includes bulldozers, graders, various rollers, and vibratory compactors. Additional equipment is needed for moving, placing, and seaming geosynthetic materials. Storage areas are needed for the materials used in the cap. If site soils are not adequate for use in cap construction, other, low-permeability soils have to be trucked in. Water supplies need to be adequate to ensure that soils used in construction maintain their optimum soil density.

2.5 CAP CONSTRUCTION QUALITY ASSURANCE AND CONSTRUCTION QUALITY CONTROL

CQA/CQC is widely recognized as being critically important to overall quality management for waste containment facilities. Preparation of the best designs and adherence to regulatory requirements do not necessarily result in a superior cap system unless the cap is properly constructed. Additionally, when geosynthetic materials are to be used, manufacturing quality assurance and manufacturing quality control of the geosynthetic products are extremely important.

Cover soil and subgrade soil should be classified using American Society for Testing and Materials (ASTM) Method D-2488 to ensure that the soils have adequate plasticity. Adequately classifying soils is best accomplished by observing all excavations of borrow soil from the borrow pit. Borrow soil should also be periodically evaluated using compaction curves as well as testing of soil density and moisture content.

The soil used to construct the drainage layer should be periodically evaluated to determine its grain size, hydraulic conductivity, and carbonate content. Care should be taken during placement of the soil drainage layer to ensure that underlying materials are not punctured, and that fine-grained soil is not accidentally mixed with drainage material.

CQA/CQC processes for soil liners are intended to ensure that (1) soil liner materials are suitable, (2) soil liner materials are properly placed and compacted, and (3) the completed liner is properly protected. Clay prequalification testing is accomplished through periodic soil classification, generation of compaction curves, and remolded permeability tests. A test pad should be used to demonstrate that the materials and methods proposed will result in construction of a liner with the required large-scale, in situ hydraulic conductivity. Construction testing of the soil liner should include generation of compaction curves as well as testing of density, moisture content, undisturbed hydraulic conductivity, Atterberg limits, grain size, and undisturbed dry density.

Manufacturing quality control testing should be performed on geomembrane barriers to ensure that the geomembrane complies with National Science Foundation (NSF) 54 standard and displays the desired melt index, resin index, and resistance to environmental stress cracks. Field testing should be periodically conducted to evaluate geomembrane thickness, tensile strength, elongation, and resistance to punctures and tears. CQA inspections should be performed for every roll of geomembrane at the site. Seam testing should be performed using nondestructive (vacuum box or air pressure) and destructive (peel and shear testing) methods.

2.6 CAP PERFORMANCE

Cap systems usually perform well and require minimal maintenance. However, the impact of differential settlement and the stability of slopes steeper than 3 horizontal to 1 vertical should be monitored quarterly or semiannually. Additional monitoring of leachate quality, quantity, and leak detection; water infiltration; gas quality and quantity, and groundwater will ensure that the cap system is performing as intended.

2.7 CAP COSTS

The cost of a cap (0.5 to one acre) can vary from $500,000 for a one-layer system to several million dollars for a multilayer cap. The cost is highly dependent on the local availability of soils suitable for construction and the requirements for monitoring, leachate collection, and gas collection.

REFERENCES FOR FIGURES

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Figure A-6 Rumer, R.R. and M. E. Ryan. 1995. "Barrier Containment Technologies for Environmental Remediation Applications." John Wiley and Sons. New York.

Figure A-7 Karol, R.H. 1990. "Chemical Grouting." Marcel Dekker. New York.

Figure A-8 Ryan, C.R. 1987. *Vertical Barriers in Soil for Pollution Containment.* Geotechnical Practice for Waste Disposal '87. Geotechnical Special Publication No. 13. Edited by Richard D. Woods. ASCE. Pages 182-204.

Appendix B
Site Summaries

This appendix gives more detailed descriptions of the 36 sites evaulated in the retrospective report.
This is a separate document.
A limited number are available from NCEPI.
Please reference document EPA-542-R-98-005a.

Appendix C

Field Protocol

1.0 INTRODUCTION

This appendix sets forth a proposed approach to the preparation of a detailed protocol for field study of sites with subsurface engineered barriers. This discussion also summarizes the results of the performance evaluation report for subsurface barriers, as those results apply to current monitoring of such barriers, and puts forth a general approach to monitoring existing subsurface barriers for performance as containment systems.

Results of the evaluation of engineered barriers revealed that these barriers are monitored as containment systems, not as single entities within a containment system. The performance of a barrier wall therefore generally is not monitored singly, but the containment system is monitored for overall performance in meeting the design objective of a remedial system. The evaluation also showed that monitoring plans vary for passive and active containment systems. These systems are summarized below.

- Prevention or cutoff of outflow from the containment system (that is, stop or slow the rate of flow of the contaminant plume, for example, by installation of a vertical barrier). A containment system that uses such a design, with no associated groundwater extraction, can be referred to as a passive containment system.

- Maintenance of the entombment of the contaminants (that is, prevent the flow of contaminants from the system, for example, by the use of active containment measures like maintenance of a slight hydrologic flow through active groundwater extraction). A containment system that uses such a design is referred to as an active containment system.

Monitoring systems evaluate the functional performance of the containment system--that is, whether the containment system is performing the function that it was designed to perform. The study concluded that, at all the sites studied, once the containment barrier had been constructed and had become operational, performance monitoring consisted of collecting hydraulic head or groundwater quality data or a combination of the two. Additional testing was not completed unless problems in the performance of a barrier containment system were indicated. Diagnostic stress tests seldom were conducted, typically only when a problem affecting the containment system was suspected. Tests for long-term degradation, physical sampling for diffusion through barriers, and tests of the effect of desiccation on permeability also were performed very seldom at the sites studied. In addition, the study concluded that monitoring the performance of an engineered barrier is dependent on the conditions at the site, in particular, on the hydrogeological characteristics of the site. The site-specific nature of performance monitoring makes the establishment of a standard monitoring protocol difficult and impractical. However, performance monitoring can be made more consistent through the establishment of a general approach to monitoring.

The following sections put forth a monitoring or sampling protocol for engineered barrier containment systems. The protocol is presented in two categories. First, the consistent use and expansion of existing technology are discussed. Second, a view of more innovative technologies is presented. The application and field testing of the developed protocol then are reviewed.

2.0 PROPOSED PERFORMANCE MONITORING PROTOCOL

A review of the 36 sites studied showed significant variation in monitoring methods used to assess the performance of containment systems. That variation is discussed in greater detail in Section 3.4 of the report. An even greater inconsistency was identified in the reporting and tracking of performance monitoring data from the sites studied. The following section presents recommendations for the collection of performance monitoring data and the systematic review of those data. Figure C-1, Barrier Wall Containment System Performance Monitoring Decision Tree, presents a step-by-step general approach to determining the functional performance of a barrier wall containment system. The steps outlined in the figure are described below. Table C-1 presents a summary of studies recommended for the evaluation of the performance of a containment system. Table C-1 depicts the continuation of the process illustrated in Figure C-1: if the integrity of a barrier wall containment system is in question, integrity testing of barrier wall components should be completed. Table C-1 summarizes the tests and evaluations that should be completed for assessing the integrity of a barrier wall containment system. Below is a discussion of the recommended protocol for assessing the performance of existing engineered barrier containment systems. The discussion below is general in nature and is intended to outline the methods used to assess performance. As stated earlier, site-specific hydrogeological characteristics always should be considered before any containment and performance monitoring program is implemented. The appropriateness of monitoring techniques is site-specific and application-specific. Therefore, other than the use of hydrological monitoring techniques (monitoring of groundwater quality and head differential) and stress or pump testing, neither nondestructive nor destructive monitoring techniques are routinely recommended to assess the performance of barrier containment systems.

2.1 STEP 1: MONITORING OF GROUNDWATER QUALITY AND HEAD DIFFERENTIAL

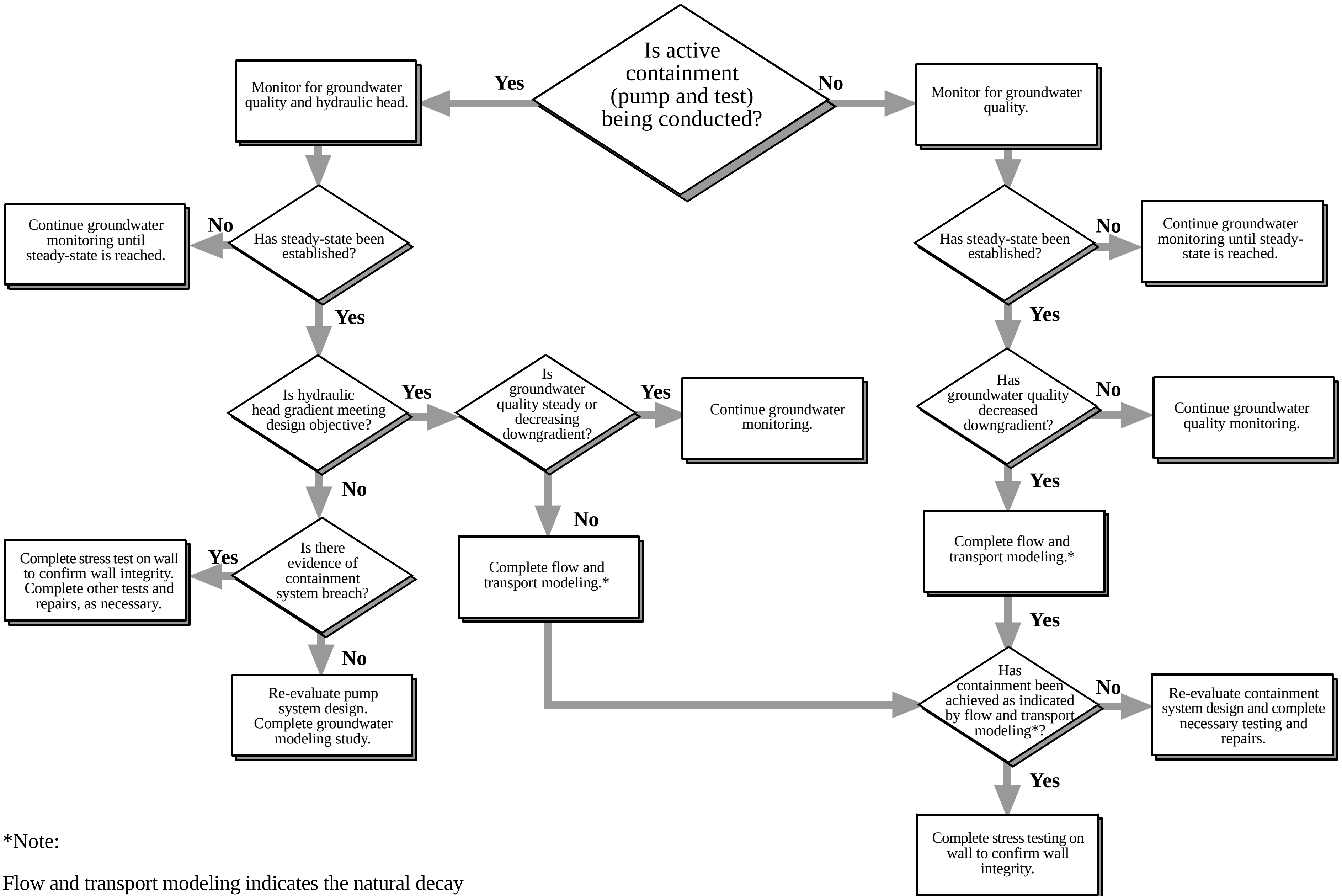
Monitoring of groundwater quality and head differential is the recommended method of assessing the functional performance of barrier containment systems. As seen in the evaluation study, monitoring of groundwater quality can range in complexity from very little monitoring (frequency of monitoring, number of monitoring points or wells, and analysis completed) to significant monitoring efforts. The type of containment system (active or passive) does not have a bearing on the complexity of the monitoring program. The complexity of the monitoring program is dictated by the hydrogeological characteristics of the site.

It is recommended that, for passive or partially active containment sites, monitoring of groundwater quality be used to assess the performance of a barrier wall containment system. For active sites, groundwater head differentials should be the primary element monitored to assess performance of the containment system.

Monitoring of Groundwater Quality

The first step in assessing the functional performance of a barrier wall containment system is monitoring the quality of groundwater outside the containment barrier. The effectiveness of a groundwater monitoring network in assessing the performance of a containment system depends on hydrogeological conditions at the site; therefore, no universal approach to the placement of a monitoring network is recommended. However, it is recommended that the location of monitoring wells for the assessment of groundwater quality be based upon a probabilistic approach to compliance monitoring. In addition, flow and transport mechanisms should be evaluated to assist in establishing the minimum necessary number and locations of monitoring points. Nests of monitoring wells, set at various depths in different strata, located close to the barrier system also should be used in identifying underflow or downward flow conditions that may allow the contaminants to migrate from the containment system.

Figure C-1
Barrier Wall Containment System



*Note:

Flow and transport modeling indicates the natural decay of contaminants outside the barrier wall.

Table C-1
Summary of Studies Commonly Used
to Evaluate the Performance of a Containment System

<u>Barrier Walls</u>

I Evaluation of Barrier Wall Integrity

- Reevaluate the groundwater modeling completed for design of the containment system.
- Complete nondestructive tests that could include one or more of the following: cone penetration (piezocone soundings), cross-hole seismic surveys, ground-penetrating radar, seismic surveys, tomography, surface-based seismic refraction survey, or dye tracing.
- Conduct destructive sampling of the barrier wall, such as destructive tests through boreholes or other means, to measure (1) degradation of components of the barrier wall by contaminants and (2) hydraulic conductivity.

II Evaluation of Containment Leaks

- Review CQA/CQC information and groundwater monitoring data.
- Conduct stress testing by means of pumping.
- Perform modeling of hydraulic efficiency and evaluation of hydraulic heads inside and outside the barrier wall.
- Evaluate groundwater quality through selection of a groundwater monitoring network and selection of indicator contaminants.

III Evaluation of Key-in of the Containment System

- Profile the bottom of the barrier wall.
- Compare data obtained from evaluation of leaks in the containment system to identify any leaks through the key-in.

Groundwater quality should be monitored or reviewed regularly, with weekly monitoring recommended, until the system has reached a steady-state condition. Once a steady-state condition has been reached, monitoring of groundwater quality should continue less frequently (for example, quarterly or semiannually). Tolerance of outlying data points and length of time periods for attaining cleanup levels should be allowed following the attainment of a steady-state condition of the containment system. Statistical trend analysis may be applicable for assessing the performance of the containment system.

Monitoring of Groundwater Head Differential

For active containment systems, monitoring of groundwater head differentials between piezometers inside and outside the barrier should be completed to assess functional performance. Monitoring of groundwater head differentials, along with groundwater quality, is the first step set forth in Figure 1 for the performance monitoring of active containment systems.

Interior wall or barrier monitoring wells should be used at active containment system sites to better evaluate the effect of pumping drawdown, if drawdown is occurring. To achieve efficient cross-barrier monitoring, monitoring well points should be spaced to approximate a line source. Equal spacing of monitoring wells or piezometers across the barrier has been shown to be the most efficient design for monitoring of head for active containment systems, but is less crucial for passive containment systems. However, for passive containment systems, interior water levels must be monitored to track groundwater flow through or under the vertical barrier. Again, fate and transport modeling should be used to assist in establishing the minimum necessary number and locations of monitoring points.

Monitoring groundwater head conditions at the bottom of the containment system, confining unit, or rock stratum, at or immediately underlying the containment system, is recommended. Such monitoring will help identify the presence of vertical gradients along the alignment of the subsurface barrier.

To better understand the influence of the barrier system on groundwater flow patterns, it is recommended that gathering of data begin during the design phase for the barrier containment system and continue through construction. Measurements of groundwater head should be collected frequently during and immediately after construction of the containment system, with frequency increasing from weekly to monthly as the containment system reaches a steady-state condition. Head monitoring can be performed less frequently when data values have become stable or steady. Monitoring of groundwater head through wells currently is the most widely used method of monitoring head; that approach is recommended. However, automatic data reporting may prove to be useful and, over the long term of site remediation, may prove to be more cost-effective.

2.2 STEP 2: HYDRAULIC TESTING

Step 2 in determining the performance of a containment system is to complete a hydraulic stress test. A stress test is recommended when a steady-state condition has not been reached within an acceptable time frame, based on design or fate and transport modeling data, or when design flaws or construction problems are identified or there is other evidence of a breach of the containment system (for example, a decrease in water quality downgradient of the system or changes in head differentials) that are not attributed to changes in the active containment system (for example, a decrease in pumping rates). Deficiencies in a containment system can become amplified when the contained area is stressed during pumping. When combined with cross-barrier monitoring of groundwater quality and head, stress tests can identify definitively leaks in the vicinity of the zone of influence. When combined with multilevel monitoring, stress testing of a vertical barrier can assess underflow effectively within a region of influence.

In addition to internally performed stress tests, stress tests can be performed by pumping outside the containment system. The benefits of external stress testing are the reduction of the concentrations of contaminants in the extracted water and the minimization of disposal requirements. It is recommended that, for newly constructed sites, stress testing be performed before or as part of the startup of any pumping system. Such testing will aid in the reporting and future comparison of data to be used in evaluating the performance of the barrier. In addition, it is recommended that periodic reviews (for example, a five-year regulatory review of a remedial remedy) include pumping tests or stress tests and that comparisons be made to evaluate changing hydraulic properties of the barrier (for example, degradation of components of the barrier system over time).

2.3 STEP 3: OTHER PERFORMANCE MONITORING METHODS

Once a stress test has been completed, hydraulic efficiency modeling of the head differentials, both inside and outside the barrier wall, should be completed. If the results of the hydraulic efficiency modeling indicate that the integrity of the containment system has been breached, destructive and nondestructive testing of barrier components should be considered. Below is a list of current and evolving monitoring techniques and technologies that can be used to monitor the performance of a containment system.

It is recommended that destructive and nondestructive testing be completed simultaneously on containment systems. Physiochemical processes (deterioration of the components of the containment system) that can lead to failure of the system can be quantified more effectively through destructive sampling and testing than through nondestructive testing.

Destructive Tests

Destructive sampling of a barrier containment system is recommended to measure degradation of components of the barrier. Collection of samples of test borings, undisturbed samplers, and other methods should be implemented. Samples collected should be tested for reconstituted permeability, gradation, moisture content, and chemical compatibility with components of the system. Determination of the location and number of samples to be collected should be based on site-specific information. Data obtained from destructive testing should be evaluated with the results of nondestructive testing.

Nondestructive Tests

Nondestructive tests that could be used to evaluate the integrity of a containment system include those listed below. (For more detail about the principles of operation of the technologies listed and their application and limitations, the reader is referred to Rumer and Mitchell (1996).)

- **Geophysical Testing Systems:** Geophysical techniques are based on the response of geomedia and pore fluids to the electromagnetic spectrum, seismic or acoustic energy, magnetic fields, or gravitational fields. Geophysical techniques measure the physical and chemical characteristics of geomedia and pore fluids that may change with chemical contamination or development of internal voids. Geophysical methods that can be used to assess the continuity of natural and emplaced barriers include: (1) cross-hole seismic imaging; (2) surface seismic refraction; (3) ground penetrating radar; and (4) microwaves, ultrasound, and radio waves. Geophysical techniques that are useful in tracking the extent of contaminant plumes include: (1) electromagnetic resistivity and (2) ground penetrating radar.

- **Electrochemical Systems:** Electrochemical sensing systems monitor the changes in the physiochemical characteristics of the sensor caused by contact with a fluid.

- **Electrical Systems:** These techniques use electric current impulses to monitor subsurface media or physical interactions between the embedded device and the surrounding media.

Table C-2
General Application of Monitoring Approaches

Monitoring Method / Barrier Monitoring Approach	Monitoring Well Network	Geophysical Methods	Electro-Chemical Methods	Mechanical and Electro-Chemical Methods	Electrical Methods
1. Barrier Integrity	N/A	G	R	C	G
2. Barrier Permeation Monitoring	N/A	R	G	R	C
3. External Monitoring	C	G	G	R	G

Key: C=conventional, G=growing application, R=rare, N/A=Not applicable

Note: These methods comprise several specific techniques, some of which may not necessarily fit into these three categories

Many of the technologies described are innovative in nature and require further refinement to achieve spatial resolutions necessary for containment system monitoring programs. Table C-2 presents a general application of approaches to performance monitoring.

2.4 REPORTING PROTOCOLS

Consistent and accurate reporting of monitoring data is vital to an accurate assessment of the performance of a containment system. It is recommended that a reporting format be established early in the performance monitoring program or, if possible, during design of the monitoring program. Establishment of a consistent reporting format will allow the comparison of data over time, and the consistency of the format will facilitate the identification of changes or trends in the barrier wall containment system that could lead to functional failure.