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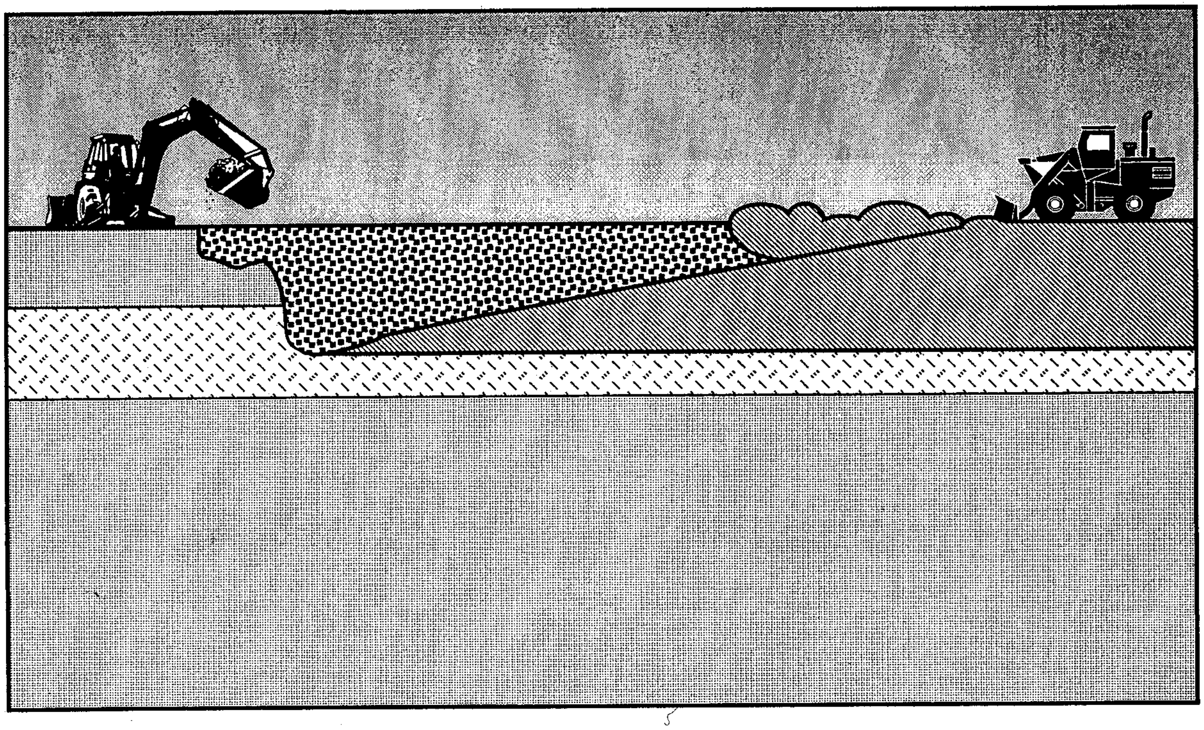
Evaluation of Subsurface Engineered Barriers at Waste Sites



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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.

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 and monitoring data. 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.

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

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.

- **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.

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.