Subsurface Containment and Monitoring Systems: Barriers and Beyond

(Overview Report)

March 1999

Prepared by

Leslie Pearlman

National Network of Environmental Management Studies Fellow

for

NOTICE

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FOREWORD

Within the past several years, the application of containment technologies to remediate contaminated subsurface zones has increased. EPA's Technology Innovation Office (TIO) provided a grant through the National Network for Environmental Management Studies (NNEMS) to prepare a technology assessment report on subsurface barrier technologies that prevent the migration of contaminated material. This report was prepared by a graduate student from Duke University during the summer of 1998. It has been reproduced to help provide federal agencies, states, consulting engineering firms, private industries, and technology developers with information on the current status of this technology.

About the National Network for Environmental Management Studies (NNEMS)

NNEMS is a comprehensive fellowship program managed by the Environmental Education Division of EPA. The purpose of the NNEMS Program is to provide students with practical research opportunities and experiences.

Each participating headquarters or regional office develops and sponsors projects for student research. The projects are narrow in scope to allow the student to complete the research by working full-time during the summer or part-time during the school year. Research fellowships are available in Environmental Policy, Regulations, and Law; Environmental Management and Administration; Environmental Science; Public Relations and Communications; and Computer Programming and Development.

NNEMS fellows receive a stipend determined by the student's level of education and the duration of the research project. Fellowships are offered to undergraduate and graduate students. Students must meet certain eligibility criteria.

About this Report

This report is intended to provide a basic summary and current status of subsurface barrier technologies for hazardous waste sites. It contains information gathered from a range of currently available sources, including project documents, reports, periodicals, Internet searches, and personal communication with involved parties. No attempts were made to independently confirm the resources used.

The report is available on the Internet at **http://www.clu-in.org.**

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1.0 INTRODUCTION

1.1 PURPOSE AND SCOPE
This document is intended to provide information on the past, present, and future of subsurface barriers—vertical and horizontal—with an emphasis on the emerging and innovative vertical barrier technologies. It is not intended to be an inclusive report; it merely provides an overview of the existing work in the field of underground barriers.

1.2 ORGANIZATION
Each section of this report provides the following information and format: (1) a brief description of the technology, (2) advantages, (3) disadvantage/limitations, (4) cost, (5) state of the technology, and (6) points of contact. For several technologies, there is such a wealth of knowledge available that additional references are provided.

1.3 OVERVIEW OF SUBSURFACE CONTAINMENT
Subsurface contamination poses a continuing risk to human health and the environment. Liquid contaminants can migrate through the soil matrix and leach into groundwater, while solid and semi-solid pollutants may be transported and dispersed through the subsurface (GETF, 1996). Because cleanup technologies, when available for subsurface containment, can be costly and time consuming, it is necessary to examine other, possibly cheaper, ways to reduce the risk and protect human health and the environment at contaminated sites.

According to the 1996 Global Environment and Technology Foundation (GETF) market assessment, containment technology is "poised for significant, if not enormous growth." Underground containment barriers are an important method of limiting and/or eliminating the movement of contaminants through the subsurface. Subsurface barriers can maintain the volume of waste and reduce the potential for migration into the surrounding geologic media, or groundwater. In the past, containment has been used at sites where there was no other efficient and cost-effective option. However, subsurface barriers can be used in any number of situations where it is necessary to prevent the migration of contamination. Barriers are currently used for the containment of contaminated waste, as an interim step while final remediation alternatives are developed (or decided), and in coordination with treatment technologies. In many instances, subsurface barriers are able to effectively confine the contaminant for extended time periods and provide a cost-effective method of remediation.

There are many subsurface barrier technologies commercially available and others in various stages of development. The purpose and function of the containment system must be determined prior to designing and constructing the barrier. Site characterization is an essential part of choosing an appropriate barrier. Rumer et al. (1996) suggests some factors that should be considered when designing a subsurface barrier. First, it is important to establish the barrier geometry—alignment, depth, and thickness. Second, a stress-deformation analysis should be performed on the surrounding area in order to assess the potential impacts of barrier construction. Third, compatibility testing must be done to select the most effective barrier materials and when necessary, appropriate mixture combinations. Fourth, it is necessary to determine the most effective and feasible construction methods. Finally, construction quality assurance/quality control, along with monitoring, is a crucial component of subsurface barrier design.

Construction quality assurance (CQA) and construction quality control (CQC) are essential for the successful design, implementation, and performance of a subsurface barrier (Rumer et al., 1996, EPA 1998). The U.S. Environmental Protection Agency (EPA) defines quality control as "the contractor's observations, sampling, measuring, and testing to establish conformance to plans and specifications" (1987). Quality assurance, as defined by the EPA, is conducted by or for the project engineer and provides further confirmation that the construction complies with the specifications of the design. Quality assurance is not mandated by the EPA (Rumer et al., 1996).

Different types of subsurface barriers have different CQC criteria, however there are two primary concerns. First, the installed barrier must have a hydraulic conductivity equal to or less than that specified in the design (Rumer et al., 1995). The second concern is barrier continuity, which is difficult to assess; the methods available have had varying degrees of success. Appendix A provides a brief overview of the standard industry practices for slurry walls. For additional information on CQA/CQC, see Evaluation of Subsurface Engineered Barriers at Waste Sites (EPA 542-R-98-005); Quality Assurance and Quality Control for Waste Containment Facilities (EPA 600-R-93-182); Construction Quality Management for Remedial Action and Remedial Design Waste Containment Systems (EPA 540-R-92-073); and Construction Quality Control and Post-Construction Performance Verification for the Gilson Road Hazardous Waste Site Cutoff Wall (EPA 600-2-87-065).

There is currently no method of guaranteeing the continuity of a subsurface barrier (Sullivan et al., 1998). Discontinuities may occur during grout application/installation and joint formation. Cracking due to curing, settling, and wet/dry cycling may occur over time. Proper emplacement of a subsurface barrier is critical to ensure overall effectiveness of the containment system. Once a barrier is installed, verification and monitoring are crucial. At this time, there is no uniform method of monitoring the emplacement, long-term performance, or integrity of the barrier. The Department of Energy (DOE) has acknowledged this problem and incorporated different monitoring techniques into containment projects.

2.0 ESTABLISHED TECHNOLOGY

2.1 SLURRY WALLS

Slurry walls are the most common type of subsurface wall and are considered baseline barrier technology (Heiser et al., 1997). "It is the expert consensus" that if properly designed and constructed, slurry walls can successfully contain waste at contaminated sites (Rumer et al., 1996). For over 45 years, these walls have been used in the construction industry to contain and direct water, and as a result, the requirements and practices for designing and installing a slurry wall are well established. Slurry walls have been used for pollution control since 1970, and the technology is accepted and regarded as an effective method of isolating hazardous waste and preventing the migration of pollutants (Gerber et al., 1994). Excavation under a slurry filled trench provides stability and prevents the trench from collapsing. Figure 1 is a diagrammatic representation of a typical slurry wall keyed into the subsurface.

Figure 1: Cross Section of a Typical Keyed-In Slurry Wall
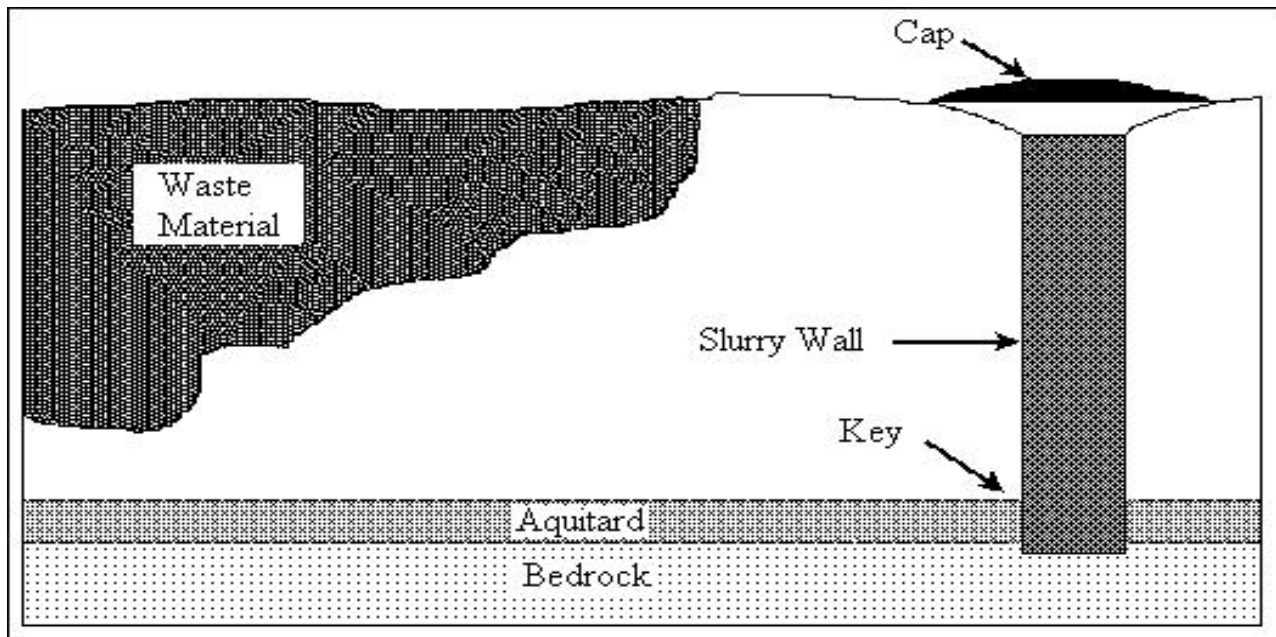
Source: Adapted from the Department of Energy (DOE) website

There are different materials, and combinations of materials, that can be used to construct slurry cutoff walls including soil-bentonite, cement-bentonite, and plastic concrete. The backfill and composite typically contain a mixture of materials such as cement, bentonite, fly ash, ground-blasted furnace slag, and clay. Other types of cutoff walls include mix-in-place, grout, and composite walls. For a comparison of cutoff walls, see Table 1. Both organic and inorganic contaminants can have a negative impact on bentonite (in the wall and/or in the backfill). To help reduce this problem, additives can be used to alter the characteristics of the slurry wall. For example, additions of fly ash can potentially reduce the degradation of concrete by an alkali-silica reaction or sulfate attack.

Table 1: Comparison of Selected Cutoff Walls

Type	Advantages
Cement-bentonite (CB)	Strength, low compressibility Can be used on steep slopes with unstable soil Hydraulic conductivity around 10^{-6} cm/s
Soil-bentonite (SB)	Lower hydraulic conductivities than CB Cheaper than CB Hydraulic conductivity typically around 10^{-7} cm/s, but as low as 5.0×10^{-9} cm/s
Soil-cement-bentonite (SCB)	Similar to CB in strength and SB in hydraulic conductivity
Plastic concrete (PC)	Stiffer and stronger than cement-bentonite Preferred type of cutoff wall for deep walls (clam-shell or hydromill is used to excavate the trench)
Mix-in-place	Soil is not excavated
Composite slurry	Improved impermeability and resistance
Grouting	Can be used for barrier construction by injecting grout into holes or to seal fractures in impermeable layers

Source: EPA, 1992

2.1.1 Soil-Based Slurry Walls

The application of soil-bentonite slurry walls involves excavation to the desired depth and eventual displacement of the slurry by a permanent backfill, which forms the hydraulic barrier. Varying the composition of the backfill can alter the properties of the barrier to obtain the desired strength or permeability. For example, the addition of plastic fines helps decrease the effect of contaminants on the barrier.

Advantages
- Construction techniques well understood, practiced, and accepted
- Depths of up to 200 ft
- Installed quickly (Heiser et al., 1997)
- Can be used in conjunction with other remediation technologies such as capping

Disadvantages
- Installation requires excavation, produces substantial quantities of spoils that must be disposed of, and requires a mixing area
- Difficult to ensure proper emplacement
- May degrade over time due to contaminants in the soil (Gerber et al., 1994)
  – Silica and aluminum in the bentonite and/or soil may dissolve in the presence of strong organic and inorganic acids (pH < 1) and bases (pH > 11) increasing the porosity of the barrier

– Inorganic salts and some neutral polar and nonpolar organic compounds result in the shrinkage of bentonite clay particles
- Wet/dry cycles and freeze/thaw cycles can cause deterioration such as cracking
- Limited to vertical orientation
- Assessment of performance is difficult

Cost

The cost ranges from $5 – $7/ft^2, not inclusive (Rumer et al., 1996). Cost varies depending on site conditions, type of slurry/backfill, depth, cleanup of spoils, and treatment of spoils.

Sources of Additional Information

1997 International Containment Technology Conference Proceedings. St. Petersburg, FL. February 9-12.

Rumer, R.R. and J.K. Mitchell, eds. 1996. Assessment of Barrier Containment Technologies *A Comprehensive Treatment for Environmental Remedial Application.* Product of the International Containment Technology Workshop. National Technical Information Service, PB96-180583.

Rumer, R.R. and M.E. Ryan, eds. 1995. Barrier Containment Technologies for Environmental Remediation Applications. Reproduced by the International Containment Technology Workshop. John Wiley and Sons, Inc., New York.

EPA. 1992. "*Engineering Bulletin* Slurry Walls." EPA 540-S-92-008.

2.1.2 Cement-Based Slurry Walls

A self-hardening slurry trench is a type of slurry wall that uses cement-bentonite as the permanent backfill. Cement-bentonite walls are advantageous when there is a lack of suitable soil for backfill, insufficient space available for mixing of backfill, a steep slope on site, or a very strong wall is required (shear strength) (Gerber et al., 1994). However, cement-bentonite walls tend to be more permeable than soil-bentonite walls. Permeabilities of cement-bentonite walls range from 10^{-5} – 10^{-6} cm/s, and the typical permeability required for site remediation is a minimum of 10^{-7} cm/s.

Self-hardening slurries typically consist of mixtures of Portland cement and bentonite clay. The bentonite is blended with water producing a hydrated slurry of approximately 6% bentonite by weight. Cement is added just prior to pumping the slurry into the trench. The cement content is usually 10 – 20% by weight (Mutch et al., 1997). Alternative self-hardening slurries incorporate ground-blast slag in with the cement to increase impermeabilities to 10^{-7}– 10^{-8} cm/s. Additions of slag can also increase the chemical resistance and strength of the barrier. Typically, the mixing ratio of Portland cement to slag is 3:1 or 4:1 (Mutch et al., 1997).

Advantages
- Installed quickly because construction requirements and practices are well understood (Heiser et al., 1997)
- Much stronger than soil-based vertical walls
- Self-hardening slurries do not require backfill, so walls can be constructed in limited access areas and at a lower cost

- Little or no slurry displaced

Disadvantages
- Difficult to ensure panel continuity
- High permeability of some mixes (e.g., Portland cement can adversely affect the swelling of bentonite clay)
- Often difficult to achieve sufficiently low permeability
- Cracking due to shrinkage, thermal stress, and wet/dry cycling (Heiser et al., 1997)

Cost
Cost ranges from \$10 – \$20/vertical ft^2 for a 2-ft wide barrier of less than 100 ft (Mutch et al., 1997)

Sources of Additional Information
1997 International Containment Technology Conference Proceedings. St. Petersburg, FL. February 9–12.

Rumer, R.R. and J.K. Mitchell, eds. 1996. Assessment of Barrier Containment Technologies *A Comprehensive Treatment for Environmental Remedial Application.* Product of the International Containment Technology Workshop. National Technical Information Service, PB96-180583.

Rumer, R.R. and M.E. Ryan, eds. 1995. Barrier Containment Technologies for Environmental Remediation Applications. Reproduced by the International Containment Technology Workshop. John Wiley and Sons, Inc., New York.

EPA. 1992. "*Engineering Bulletin* Slurry Walls." EPA/540/S-92-008.

2.1.3 Soil-Cement-Bentonite Slurry Walls
Soil-Cement-Bentonite (SCB) slurry walls are an adaptation of traditional soil- or cement-based walls. Fundamentally, the SCB wall is a soil-bentonite slurry wall with cement added to the backfill (less than 10%). The benefit of the SCB slurry wall is that it is similar to the cement-bentonite wall in strength and to the soil-bentonite wall in hydraulic conductivity (Rumer et al., 1996).

2.2 SHEET PILE WALLS
Sheet pile cutoff walls are constructed by driving vertical strips of steel, precast concrete, aluminum, or wood into the soil forming a subsurface barrier wall. The sheets are assembled before installation and driven or vibrated into the ground, a few feet at a time, to the desired depth. A continuous wall can be constructed by joining the sheets together. The joints between the sheet piles are vulnerable to leakage, and a number of patented techniques have evolved to seal them. In addition to different types of joints, a variety of sealants including grout, fly ash, and cement have been used to seal joints.

Advantages
- Sheet piling is very strong and successful in containing both soil and water
- Chemical resistance

- Excavation is not required (minimum waste to dispose of)
- Installation procedures are well established
- Able to construct irregularly shaped barriers in confined area
- Consistent hydraulic conductivity
- Potential for removal and reuse at another site

Disadvantages
- Joints can leak
- Piling can potentially corrode if used for long-term containment (Rumer et al., 1996), and amount of corrosion depends on the amount of oxygen in the soil
- Expensive compared to alternative types of vertical barriers
- Difficult to install in hard, rocky soil
- Depth of penetration of sheet piles is limited to approximately 30 – 45 m depending on soil type and drilling equipment (Smyth et al., 1995)
- Noise and vibration associated with drilling

State of the Technology
1. While the technology is well understood, sheet pile walls has had limited use in the United States and the United Kingdom.
2. Private companies such as Waterloo Barrier Inc. have successfully adapted the general sheet pile barrier for containment uses. Waterloo Barrier Inc. has developed a unique method of sealing the joints between the sheet piles to reduce leakiness, which has been a problem in the past. See Section 2.2.1 on the Waterloo Barrier^{TM}.

Cost
The cost of a sheet pile barrier ranges from \$15 – \$40/ft^2 depending on the depth, equipment used, type of joint, and type of sealant (Smyth et al., 1995).

Sources of Additional Information
International Containment Technology Conference Proceedings. 1997. St. Petersburg, FL. February 9–12.

Rumer, R.R. and J.K. Mitchell, eds. 1996. Assessment of Barrier Containment Technologies *A Comprehensive Treatment for Environmental Remedial Application.* Product of the International Containment Technology Workshop. Available through the National Technical Information Service, PB96-180583.

Design of Sheet Pile Walls: Engineering and Design. Technical Engineering and Design Guides as adapted from the U.S. Army Corps of Engineers, No. 15. ISBN: 0-7844-0135-7, Stock number 40135-7

2.2.1 Waterloo Barrier[TM]

The Waterloo Barrier[TM] is an adaptation of the sheet pile wall that addresses the problem of leaky joints. The Waterloo Barrier[TM] is specially designed to interlock sealable joints. See Figure 2 for a schematic of interlocking, sealable joints. Installation involves driving sheet piles into the ground, flushing the interlocking joint cavity to remove soil and debris, and injecting sealant into the joints. Depending on site conditions, the cavity may be sealed with a variety of materials including clay-based, cementitious, polymer, or mechanical sealants. Video inspection of the joint cavity prior to sealing ensures that the joint can be sealed. The Waterloo Barrier[TM] can achieve bulk hydraulic conductivities of less than 10^{-8} cm/s (Mutch et al., 1997). The barrier can easily be installed to depths of 75 ft and possibly deeper if piles are spliced together.

Figure 2: Waterloo Barrier[TM] Sealable Joint Steel Sheet Piling (WZ 75 profile)
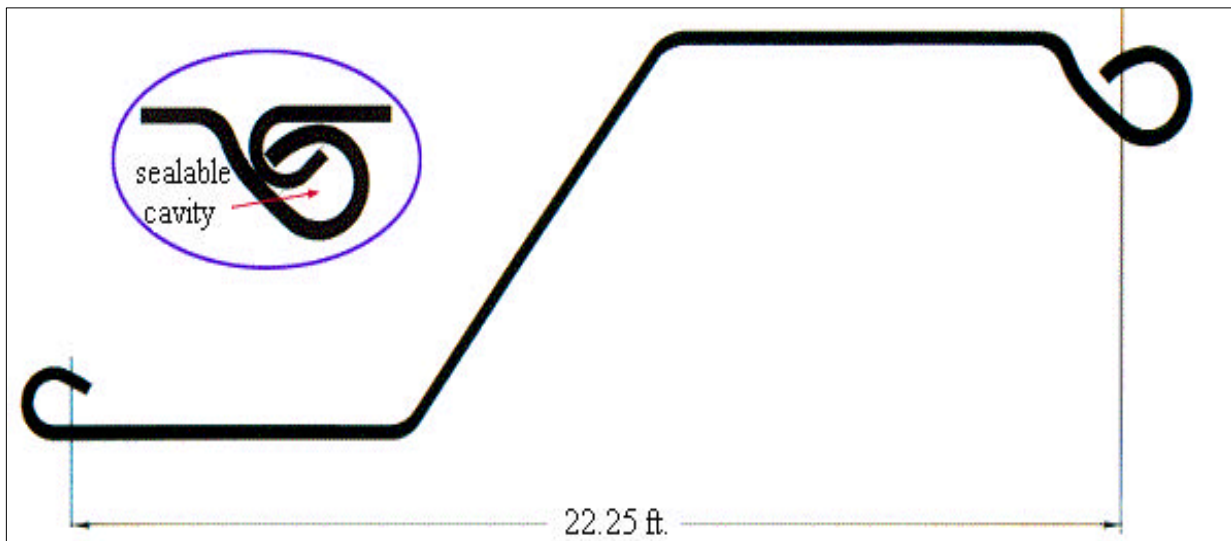
Source: Oceta website

Advantages
- No excavated soil
- Minimal disturbance of site required for construction
- Rapid installation and sealing
- Easily installed in areas with high water tables and surface water
- Easy to inspect and monitor during construction
- Joint separation or blockage can easily be repaired
- Installation uses the same equipment and techniques as used to install conventional sheet piling (vibration equipment or impact equipment)
- Provides a structural wall, groundwater barrier, and/or gas barrier
- Cost effective for small- to mid-size barriers (10,000 – 30,000 ft^2)
- Service life in excess of 30 years
- Consistent hydraulic conductivity
- Design flexibility – adaptable to irregular layouts such as corners
- Keyed into aquitard, hanging or grouted in bedrock
- Potential for removal and reuse at another site

<u>Disadvantages</u>
- Limited to depths of approximately 75 ft
- Driving pile has limitations based on soil characteristics
    – Difficult to install in rocky or very dense soils
    – Unable to key into rock
- Noise and vibration associated with drilling

<u>State of the Technology</u>
1. Between 1988 – 1992, 21 field trials occurred.
2. In 1993, the technology became commercially available.
3. In February 1997, the technology was installed at 19 sites.

<u>Cost</u>
Cost ranges from \$15 – \$25/ft^2 including installation, materials, mobilization, and QA/QC reports (Robin Jowett, personal communication).

<u>Points of Contact</u>
Waterloo Barrier Inc.
Robin Jowett
P.O. Box 385, Rockwood, Ontario
N0B 2K0, Canada
Phone: 519/856-1352
Fax: 519/856-2503
http://www.waterloo-barrier.com

3.0 INNOVATIVE BARRIER TECHNOLOGY

3.1 FROZEN BARRIERS

Frozen barrier walls, also called cryogenic barriers, are constructed by artificially freezing the soil-pore water. As the moisture freezes, the permeability decreases thereby forming an impermeable barrier. Once the wall is frozen, it remains impermeable and can prevent the migration of contaminants. When the barrier is no longer needed, the refrigeration system can be turned off, allowing the barrier to melt. In the past, this technology has been used for groundwater control and to strengthen walls at excavation sites.

The construction of a frozen barrier wall involves installing pipes called thermoprobes into the ground and circulating refrigerant (cryogenic) through them. As the refrigerant moves through the system, it removes heat from the soil and freezes the pore water. In arid regions, water can be injected into the soil to provide the moisture necessary to form the barrier or to repair the frozen wall. The thermoprobes can be placed in different configurations depending on the geologic media and the desired shape of the barrier. For example, if the pipes are installed at a 45° angle along the sides of the area to be contained and installed vertically on the ends, a V-shaped barrier will be formed providing complete containment.

The choice of refrigerant is site and contaminant specific. For example, if the site is polluted with a low freezing point contaminant like trichloroethylene (TCE), a refrigerant such as liquid nitrogen may be required. Other possible refrigerants include calcium chloride brine and carbon dioxide. Alternative refrigerants can have a dramatic effect on the overall cost due to different efficiencies in their refrigeration cycles (Erv Long, personal communication). In addition, friction or thermal resistance within the circulation systems can also reduce the efficiency.

Advantages
- Environmentally safe
- Lower risk and cost
  – Contaminated soil is not excavated
  – No by-products (Arctic Foundations website)
- Contaminants are contained in situ with frozen soil as the containment medium
- Thermoprobes may be installed in different positions to create a wall of almost any shape and size to fully contain contaminants
- Application for long-term containment depends on the half life of the contaminant
  – e.g., a frozen wall would be a good choice for a site contaminated with tritium. The wall could be installed while the tritium decays and unfrozen when the site is clean (Elizabeth Phillips, personal communication)
- Ice does not degrade or weaken over time (Arctic website)
- Can be used to contain a variety of materials including radioactive, heavy metal, and organic contaminants (DOE website)
- Once installed, easy to maintain
  – In situ repair by injecting water into the leakage area
  – Low maintenance costs

> – e.g., at Oak Ridge National Laboratory (ORNL), it costs $15/day for electricity to maintain the frozen barrier. "No other technology can be run at this low of a cost" (Elizabeth Phillips, personal communication)
- Easily removed by thawing
- In the laboratory, able to obtain hydraulic conductivities of less than 4×10^{-10} cm/s in soils contaminated with chromate and TCE

Disadvantages
- No long-term data
- Amount of energy and time to freeze the wall depends on the soil matrix (Layne Christensen Company information)
- Drilling may be a constraint (EPA SITE website)

State of the Technology
1. On May 12 to October 10, 1994, a successful demonstration of the technology occurred at a clean site at Oak Ridge National Laboratory. Cryocell® RKK, Ltd. installed a V-shaped containment system measuring 28 ft. The wall was 12 – 15 ft thick in the sandy areas and 5 – 9 ft thick in the clayey areas (DOE website). The volume of frozen soil in the barrier was 35,694 ft^3 and the volume of soil contained by the barrier was 8,175 ft^3. The integrity of the barrier was assessed using diffusion studies with the tracer rhodamine (tracer studies done by Los Alamos National Laboratory (LANL)). The total cost of installation was $481,427. The estimated "real" cost for installation at a non-demonstration site was $332,754. Maintenance costs were approximately $3,322/month. A large number of pumps were required to circulate the brine through the pipes, and additional pipes require more electricity to freeze and maintain the wall. Electricity costs required to pump the brine used by Cryocell® is higher than other refrigerants (Elizabeth Phillips, personal communication).
2. In 1997 – 1998, a full-scale demonstration occurred at an ORNL site contaminated with strontium 90. Arctic Foundations, Inc. (AFI) installed a frozen barrier using a unique system of "hybrid thermosyphons," which can be used in either an active or passive mode. In warmer climates, with ambient air temperature above freezing, the active mode is used. This mode includes the use of a refrigeration unit. The passive mode involves heat removal from the soil without an external power source and therefore without a refrigeration unit. The wall was frozen for at least one year. During nine months of that time, the wall thickness was 12 ft. AFI used a standard refrigeration unit and standard refrigerants (R404A and carbon dioxide) that are readily available and less expensive than a super-cooling liquid (brine) (Scott McMullin, personal communication). See Table 2 for physical design data. The electrical costs are much lower than the wall installed in 1994 because of the choice of refrigerants. Two refrigerants were necessary at ORNL because the ambient air temperature is high. In cooler regions, with temperature below 32° C, the system can run passively. The EPA SITE Program is responsible for verifying barrier integrity (SITE Program website: http://www.epa.gov/ORD/SITE).

The Arctic system, which is commercially available, uses an innovative thermoprobe consisting of the following components (Arctic Foundations, Ltd. website):

- Multiple thermoprobes
- Active, electrically powered refrigeration unit
- Two-phase passive refrigerant
- Interconnecting piping system
- Control system
- Remote monitoring system

Table 2: Frozen Barrier: Physical Design Data for ORNL Project

Parameter	Design Data
Initial Soil Temperature	Approximately 66° F
Length	300 ft
Depth	30 ft
Wall Thickness	12 ft
Frozen Volume	108,000 ft^3
Frozen Barrier Surface	9,000 ft^2
Contained Volume	1,658,750 ft^3
Number of Freeze Probes	50
Freeze Probe Spacing	6 ft
Active Refrigerant	R-404A
Passive Refrigerant	Carbon dioxide
Evaporator Temperature	-25° F (capable of -40° F)

Source: Arctic Foundation, Inc.

Cost

There is a large difference in cost between the Cryocell® technology and the Arctic Foundation, Inc. technology (applied at ORNL). The main expense at ORNL was for drilling because the site was radiologically contaminated (Elizabeth Phillips, personal communication). For summary information of installation and maintenance costs of the frozen barrier wall installed at Oak Ridge, see Table 3.

The following cost estimates include waste disposal (Rumer et al., 1996):
- Standard non-directional drilling costs are \$60/ft^2 to emplace and \$2/ft^2 to maintain.
- Directional drilling costs are \$65 – \$75/ft^2.

Table 3: Frozen Barrier: Cost of Installation and Maintenance for ORNL Project

Cost Element	Cost
Project installation ($)	1,252,778
Power to freeze barrier ($) [67,000 kilo watt hour (KWH)]	3,500
Site power ($ per KWH)	0.052
Freezeback ($ per ft^2) [Freezeback to 12 ft (61,416 KWH or 1.758 ft^2/KWH)]	139.20
Freezeback ($ per ft^3) [Freezeback to 12 ft (61,416 KWH or 1.758 ft^3/KWH)]	11.60
Power only ($ per month)	477
Total maintenance ($ per day)	54.59
Maintenance ($ per ft^2/day)	0.0061
Maintenance ($ per ft^3/day)	0.0005
Total maintenance ($ per ft^2/day)	2.21
Total maintenance ($ per ft^3/day)	0.18

Source: Arctic Foundations Inc.; all other data from Arctic Foundations Inc., website

<u>Points of Contact</u>

RKK Ltd.
Cryocell® ground freezing technology
(Patent No. 4,860,544)
8410 154th Ave., NE
Redmond, WA 98052
Phone: 425/861-6010
Fax: 425/558-5865
e-mail: rkk@cryocell.com

Arctic Foundations, Inc.
5621 Arctic Blvd.
Anchorage AK 99518-1667
Phone: 907/562-2741
Fax: 907/562-0153
e-mail: info@arcticfoundations.com

Tom Roberts, Environmental Drilling Manager
W229 N5005 DuPlainville Road
Pewaukee, WI 53072
Phone: 414/246-4646

Elizabeth Phillips, Principal Investigator
DOE-OR
Oak Ridge Operations Office
P.O. Box 2001, EW-923
Oak Ridge, TN 37830
Phone: 423/241-6172
Fax: 423/576-5333
e-mail: phillipsec@oro.doe.gov

Layne Christensen Company

Annette Gatchett, Associate Director for Technology
U.S. EPA
National Risk Management Research Laboratory
26 W. Martin Luther King Dr.
Cincinnati, OH 45268
Phone: 513/569-7697
Fax: 513/569-7620
e-mail: gatchette.annette@ epa.gov

Steven A. Rock, Environmental Engineer
U.S. EPA
National Risk Management Research Laboratory
26 W. Martin Luther King Dr.
Cincinnati, OH 45268
Phone: 513/569-7149
e-mail: rock.steven@epa.gov

3.2 IN SITU SOIL MIXING

In situ soil mixing is a construction technology where the subsurface barrier is mixed-in-place. This method yields a smaller quantity of excavation spoils compared to external methods such as slurry walls.

3.2.1 Deep Soil Mixing (DSM)

Deep soil mixing (DSM), which was originally developed in Japan in the early 1960s, involves mixing an additive into the soil to produce a hard mass that acts as a barrier. The technology uses a special auger with a mixing shaft to simultaneously drill and inject the desired material, resulting in a column of soil and material. As the augers move through the earth, they loosen the soil, lift it into the mixing paddles, blend it with slurry, and inject it back out through the augers (Mutch et al., 1997). Possible slurry materials include bentonite, cement, lime, and additives (e.g., fly ash and slag that change the composition/durability of the material). DSM can be used to construct continuous walls by overlapping individual columns. Walls can be built up to 100 ft in depth.

Advantages
- In situ technique
  – Minimal disposal costs
  – Reduced worker exposure
- Less danger of collapse because wall is constructed in small sections
- Can be installed in confined areas
- Able to contain any type of waste as long as "a chemical or physical reagent is applicable" (Geo-Con, Inc., website)

Disadvantages
- Interconnected, short panels
  – Difficult to verify continuity
  – Care must be taken to ensure gaps are not present between panels
  – Verticality is crucial
- Contaminated soil is incorporated into the slurry mixture and into the wall
- Rocks mixed into the slurry can cause construction problems
- Hard ground or large boulders in the subsurface limit drilling ability

- Depth limitations

– Effective mixing to depths of 40 ft (DOE website), but commercial vendors claim they have reached depths of 100 ft

Cost

The cost varies depending on the soil characteristics and the grout material used. For example, soil-cement is more expensive than soil-bentonite (Rumer er al., 1996). The following are some cost estimates:

- $10 – $20/vertical ft^2 (Mutch et al., 1997)
- $40 – $50/$yd^3$ (cost does not include reagent) (Geo-Con, Inc.)
- Cost ranges from $6 – $15/$ft^2$ for deep mixing, and $15 – $30/$ft^2$ for DSM structure (Rumer and Mitchell, 1996)

State of the Technology

1. In April 1988, an EPA SITE demonstration occurred at the General Electric Service Shop in Hialeah, FL. This site was contaminated with PCBs. The project ended in 1990 with remediation of the site.
2. Geo-Con has used soil mixing at over 40 sites in the United States.

Points of Contact

Geo-Con, Inc.
4075 Monroeville Boulevard
Corporate One, Building II, Suite 400
Monroeville, PA 15146
Phone: 412/856-7700
Fax: 412/373-3357

U.S. EPA's Vendor Information System for Innovative Treatment Technologies (VISITT) 6.0 database has additional vendor information at http://www.epareachit.org.

Millgard Environmental Corporation
Phone: 313/261-9760

3.2.2 In Situ Enhanced Soil Mixing (ISESM)

In situ enhanced soil mixing (ISESM) is a modification of the deep soil mixing technology (DSM). ISESM is advantageous because it can include a number of treatment technologies (DOE website). The following list illustrates the types of treatment technologies that can be used in conjunction with DSM technologies:

- Soil mixing with vapor extraction combined with ambient air injection (vaporizes volatile organic compounds (VOCs))
- Soil mixing with vapor extraction combined with hot air injection
- Soil mixing with hydrogen peroxide injection (hydrogen peroxide oxidizes the VOCs)
- Soil mixing with grout injection for solidification/stabilization (the grout immobilizes the contaminant in solid form)

Advantages

- Soil mixing with vapor extraction combined with ambient air injection, soil mixing with vapor extraction combined with hot air injection, and soil mixing with hydrogen peroxide injection have been shown to remediate VOCs
- Can be used in low (or high) permeability soils

- Good for small sites

Disadvantages
- Requires surface access
- Expensive

Cost
The estimated cost for the four technologies ranges from \$120 – \$175/yd^3.

State of the Technology
1. In 1992, DOE conducted field demonstrations of the four types of ISESM technologies at the Portsmouth Gaseous Diffusion Plant near Piketown, OH.
2. In 1996, at the Kansas City Plant (a DOE project), technicians were able to mix at depths of 45 ft.

Points of Contact

Geo-Con, Inc.
4075 Monroeville Boulevard
Corporate One, Building II, Suite 400
Monroeville, PA 15146
Phone: 412/856-7700
Fax: 412/373-3357

U.S. EPA's Vendor Information System for Innovative Treatment Technologies (VISITT) 6.0 database has additional vendor information at http://www.epareachit.org.

Millgard Environmental Corporation
Phone: 313/261-9760

3.3 COMPOSITE WALLS
In 1979, the first composite cutoff wall was installed in the Jordanian section of the Dead Sea (Rumer and Mitchell, 1996). A composite cutoff wall is formed by inserting a geomembrane liner into the trench of a slurry wall. The geomembrane adds reinforcement to the integrity of the wall and increases resistance to chemical attack. Construction techniques may vary, but installation generally involves mounting the geomembrane on an installation frame, lowering the frame plus geomembrane into the trench using weights, and then withdrawing the frame (Rumer and Ryan, 1995). Geomembrane panels are typically emplaced using the vibrating beam technology. See Section 3.5 for a description of this technology. The addition of the geomembrane can decrease the hydraulic conductivity up to five orders of magnitude (Jessberger, 1991). Geomembranes are particularly beneficial above the water table where soil-bentonite walls are susceptible to cracking due to wet/dry cycles. Geomembranes can be used with other types of walls (soil-cement, cement-bentonite, or soil-cement-bentonite) to provide added assurance against discontinuities. Application of this technology needs additional field-testing.

3.3.1 Geomembrane Composite Walls
Geomembranes were first used as vertical barriers in the early 1980s. They can be used alone or in conjunction with other containment systems. Although geomembranes are extremely impermeable when used in a composite wall, they can potentially provide an added level of protection. The permeability depends on the thickness of the geomembrane and the contaminant. While there are many kinds of geomembranes available, vertical walls are typically constructed of high density

polyethylene (HDPE). Methods of installation include a trenching machine; vibrated insertion plate; slurry supported, segmented trench box; and vibrating beam (Rumer et al., 1996). There are different types of interlocks that can be used to connect the panels. The cost of HDPE ranges from $10 – $30/ft^2 (Mutch et al., 1997).

Long-term durability of HDPE is not yet known. However, under normal conditions, HDPE is expected to have a lifetime exceeding 300 years (Belinda Burson, personal communication). The Drexal University Geosynthetic Research Institute is studying eight factors that influence HDPE degradation: oxidation, chemical attack, hydraulic effects, ultraviolet radiation, nuclear radiation, biological attack, stress effects, and temperature effects (Rumer and Mitchell, 1996). See Tables 4, 5, and 6.

Table 4: General Assessment of Geomembranes as Vertical Walls

Method Name	Typical Cost		Some Advantages	Some Disadvantages
	$/ft^2	$/m^2		
Trenching machine	2-5	20-50	No seams Rapid installation No slurry	Depth limitations Soil type limitations Trench stability necessary
Vibration insertion plate	3-7	30-70	Rapid installation Narrow trench No material spoils No slurry	Soil type limitations Possible panel stressing Bottom key is a concern
Slurry supported	5-15	50-150	No stress on panels Conventional method Choice of backfill	Requires slurry Buoyancy concerns Slow process
Segmented trench box	16-18	160-180	Can weld seams Visual inspection No stress on panels No slurry	Depth limitations Soil type limitations Slow incremental process
Vibrating beam	18-25	180-250	Narrow trench No material spoils No stress on panels Usually CB slurry	Requires slurry Slow incremental process Soil type limitations

Source: Rumer et al., 1996

Table 5: Installation Methods for Geomembrane Walls

Method or Technique	Geomembrane Configuration	Trench Support	Typical Trench Width mm (in.)	Typical Trench Depth m (ft)	Typical Backfill
Trenching machine	Continuous	None	300-600 (12-24)	1.5-4.5 (5-15)	Sand or native soil
Vibrated insertion plate	Panels	None	100-150 (4-6)	1.5-6.0 (5-20)	Native soil
Slurry supported	Panels	Slurry	600-900 (24-36)	No limit, except for trench stability	SB, SC, CB, SCB, sand or native soil
Segmented trench box	Panels or continuous	None	900-1200 (36-48)	3.0-9.0 (10-30)	Sand or native soil
Vibrating beam	Panels	Slurry	150-220 (6-9)	No limit	SB, SC, CB, SCB slurry

Source: Rumer et al., 1996

Table 6: Case Studies of Geomembrane Vertical Barriers

Reference	Type of Contained Waste	Type of Installation	Depth of Wall		Length of Wall		Type of Interlock	Backfill
			m	ft	km	mi		
Burnette & Schmednecht	Hazardous	Vibrating beam	10	35	0.3	0.2	Curtain Wall Interlock[TM]	Clay/cement slurry
Bliss & Burnette	Earth dam cutoff	Slurry supported	15	50	20	12.5	Curtain Wall Interlock[TM]	Sand
Burnette & Pierce	Petroleum	Slurry supported	4.5	15	0.4	0.2	Curtain Wall Interlock[TM]	Sand
Burnette & Pierce	Hazardous	Slurry supported	14	45	0.5	0.3	Curtain Wall Interlock[TM]	Sand
Scuero, et al.	Earth dam cutoff	Slurry supported	9	30	0.1	0.1	Geolock[TM]	CB slurry
Michalangeli	Ash & MSW	Slurry supported	Various		Various		Grouted	CB slurry
Hansen & Crotty	Contaminated drilling waste	Trenching machine	3	10	34	21	Welding	Natural soil

Source: Rumer et al., 1996

3.3.2 GSE GundWall®

The GundWall® system uses sheets of 2 mm high density polyethylene (HDPE) to form barrier walls. The method of installation depends on the depth and length of the wall, contaminant, and soil type. Groundwater Control, Inc. (GCI) uses a patented interlock developed in Holland and a unique hydrophilic rubber cord to seal the interlocks. The interlocks are joined to the HDPE by fusion welding and then sealed with a chloroprene-based hydrophilic seal (Burson et al., 1997). The seal is 8 mm in diameter and expands, up to eight times its original volume, when exposed to water (Belinda Burson, personal communication). The seals are monitored for continuity during panel installation. Because the interlock is designed to be stronger than the geomembrane, the HDPE will stretch under stress (Burson et al., 1997). The barrier can be keyed into clay, but if the confining layer is rock, keying in will fracture rock and cause leakage. For additional protection, jet grouting can be used to prevent leakage between the geomembrane and the bedrock.

The two primary methods of installation are a trencher system and vibratory pile-driving (trench-less) method. GCI has developed a unique deep trencher that is simultaneously able to cut a narrow trench, support the sidewalls, and install HDPE walls. As the trencher moves through the soil, it cuts a narrow trench (ranging from 16 – 22 inches in diameter) and places HDPE in the trench. The special interlock system allows an HDPE wall to be placed using vibratory instal-lation, with conventional vibratory pile-driving equipment.

Advantages
- HDPE is flexible and will elongate and conform to soil deformation rather than crack under stress
- Able to obtain permeabilities as low as 2.7 x 10^{-13} cm/s (Burson et al., 1997)
- Durable and resistant to a variety of chemicals
- Provides a barrier to liquid and gas flow
- Has a long service life
- Quick and economical installation
- Patented interlocks that swell when exposed to water
- Thin
- Composite wall (employed with conventional barriers such as a slurry wall) or as a geomembrane wall installed using a patent-pending technology known as "vibro-jetting"

Disadvantages
- Depth limitation depending on installation method
- Lifetime of HDPE is unknown

Cost
Cost varies depending on soil characteristics, depth and length of wall, and drilling technique. The trencher method costs $9 – $15/ft^2 and the vibratory method costs $12 – $25/ft^2 (Belinda Burson, personal communication).

State of the Technology
1. The technology was developed in 1991.

2. The wall has been installed at more than 35 sites in the United States. Thirty-four of the walls were installed for contaminant control, and one was installed for groundwater control.

Points of Contact
Groundwater Control, Inc.
Belinda Burson, Vice President of Vertical Barriers Division
Jeff Haluch, Executive Vice President
11511 Phillips Highway
Jacksonville, FL 32256
Phone: 904/886-3700 or 800/843-6133
Fax: 904/886-377
e-mail: BBGCI@aol.com

GSE Lining Technologies, Inc., HDPE supplier
19103 Gundle Rd.
Houston, TX 77073
Phone: 281/443-8564
Fax: 281/875-6010

3.3.3 EnviroWall

The EnviroWall barrier technology combines six patented techniques for emplacing subsurface vertical barriers of high-density polyethylene (HDPE). See Figure 3 for a schematic diagram of the EnviroWall. The barrier may be installed for containment purposes, as a groundwater recovery system, or in conjunction with a treatment system for remediation. The system is flexible and can be altered to meet many needs. For example with a treatment wall, contaminated groundwater can be collected upgradient of a HDPE barrier, and treated groundwater can be discharged down-gradient of the barrier.

The installation system is a patented process involving trench and guide-box construction. Interconnected guide boxes (8 ft long) are temporarily placed in the trench to provide support and to permit the panels to be emplaced at the desired depth. Stacking guide boxes allows deeper walls to be installed (Buddy Breaux, personal communication). Spools of HDPE geomembrane are inserted into the guide box and unrolled along the length of the barrier forming panels up to 240 ft in length (EnviroWall brochure). Insert-beams, located inside the guide boxes, help hold the geomembrane in a vertical position. Geomembranes are sealed together using a specially patented interlocking system. The joints have an elastomeric seal with a double mechanism on the interlocking joints (Buddy Breaux, personal communication). Joining the interlocks "creates a virtually impervious barrier" (Dunn, 1994). A downhole video camera is used to visually inspect the integrity of the geomembrane and interlock system before backfill is added.

Figure 3: EnviroWall Barrier
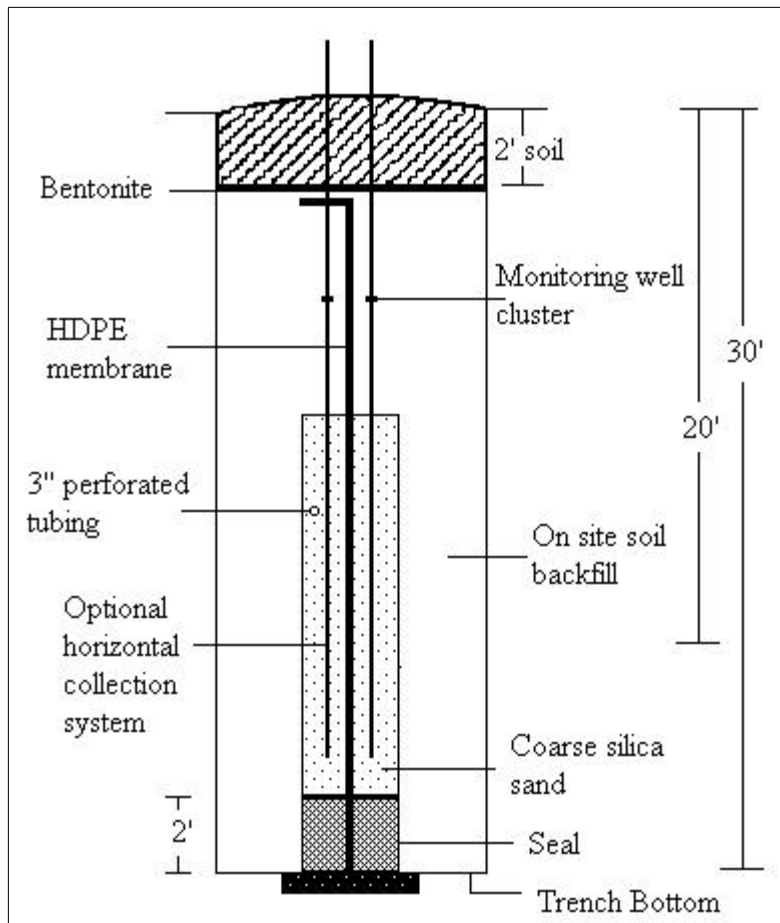
Source: EnviroWall Ltd. Information

A Bentonite "Hole Plug^{TM}" is poured into the guide box forming a seal along the bottom of the barrier. Backfill is added to the top of the guide box before the guide box is removed. The backfill material is site and contaminant specific and can be used to control water flow or act as a treatment wall. For long-term monitoring, it is easy to install multi-level monitoring wells, pressure transducers, and in situ monitoring instruments such as pH sensors, flow meters, and vadose zone lysimeters on both sides of the barrier wall.

Advantages
- Minimal number of joints
- Unaffected by fluctuations in the water table
- Relatively simple system (Buddy Breaux, personal communication)
- Very adaptable and can be used with multiple treatment systems
- Special cameras to verify emplacement (Don Johnson, personal communication)
- Can be installed in trenches as narrow as 24 inches
- Interlock system instantly provides a tight seal

Disadvantages
- Depth limitations of 40 – 50 ft

- Long-term durability of HPDE is not yet known
- Boulders in the subsurface increase cost

Cost
See Table 7 for estimated costs for the funnel and pass through gate system (inclusive).

Table 7: Estimated Installation Costs for EnviroWall

Depth (ft)	Length of Wingwalls	
	100 ft	**500 ft**
8	$47426.00	$103,178.00
11	$59,269.20	$132,862.00
14	$71,670.00	$165,333.20
17	$85,185.60	$203,380.00
20	$100,559.60	$250,718.40
23	$116,863.20	$302,703.20
26	$138,184.00	$379,776.00
29	$155,905.20	$456,849.20
32	$180,826.00	$533,922.00
35	$202,147.20	$610,995.20

Source: EnviroWall Ltd.

State of the Technology
1. In 1995, a full-scale "cold" demonstration occurred at the Savannah River Site.
2. In 1998, a wall was installed at a clean site in Texas.

Points of Contact

Buddy Breaux (patent holder)
EnviroWall Ltd.
2217 RidgeLake Drive
Metairie, LA 70001
Phone: 504/398-0501
Fax: 504/328-3997

Robert McLeod
Hydrology and Water Resources
Engineering Consultants
130 Timbercrest Drive
Oak Ridge, TN 37830
Phone: 423/482-9385

3.4 GROUT BARRIERS (OR CURTAINS)

3.4.1 Jet Grouting

Jet grouting was developed in the early 1970s in Japan and was introduced into Europe in the late 1970s and into the United States in the 1980s (Dwyer, 1998). It was developed for use on conventional civil engineering problems such as excavation support. Methods of jet grouting are based on a water cutting technology that includes a single-rod system (injecting grout alone), a double-rod system (injecting grout and air) or a triple-rod system (injecting grout, air, and water) (Rumer et al., 1995, Mutch et al., 1997). Typically, a Portland cement grout or cement-bentonite grout is used. Larger diameter columns can be constructed with the triple-rod system.

Jet grouting involves injecting a grout mixture at very high pressures (up to 5,000 – 6,000 pounds per square inch) and velocities (as great as 800 – 1,000 ft/s) into the pore spaces of the soil or

rock. The jetted grout cuts, replaces, and mixes the soil with cementing material to form a column. Rotation of the drill rod, as it is being removed, will form a column. A panel is formed by leaving the drill rod in place (EPA, 1998). The soil structure is destroyed as grout and soil are mixed, forming a homogeneous mass. Jet grouting can be used in soil types ranging from gravel to clay, but the soil type can alter the diameter of the grout column. Soil properties also are related to the efficiency. For instance, jet grouting in clay is less efficient than in sand (Heiser et al., 1997).

Advantages
- Soil heterogeneity has much less of an impact on wall placement than permeation grouting (See Section 3.4.2 for a description of permeation grouting)
- Versatile – jet grouting can stabilize a wide variety of soil types ranging from gravel to heavy clays (Mutch et al., 1997)
- Starting from a small borehole, large diameter columns or panels can be created
- Can install wall (inject) in confined places that might otherwise limit installation – for instance, cut-off walls can be constructed beneath buildings without disrupting the structure (Mutch et al., 1997)
- Installed at depths up to 150 – 200 ft
- Can drill at any angle forming both vertical and horizontal water control barriers (Dwyer,1998)
- Jet grout unit is mobile, permitting drilling with rotation and percussion (Dwyer,1998)
- Down-the-hole (DTH) percussion hammer coupled with the drill string results in more reliable drilling alignments (straight and parallel), faster drilling rates, and a quieter operation (Dwyer, personal communication)
- Innovative equipment allows injection of multiple fluids or gases (Dwyer, 1998)
  – DTH percussion hammer
  – Multi-nozzle grout injection unit increases the efficiency of injection
- Can be used in coordination with treatment

Disadvantages* (Heiser et al., 1997, Mutch et al., 1997)
- Difficult to ensure panel continuity (verticality is critical to ensure that gaps will not occur between panels)
- Boreholes can become misaligned
- Obstruction of jet nozzle can be a problem
- Different soil types and densities affect ability to grout
- Gaps between panels or thin spots may lead to cracking
- Separation or tears may occur as barriers harden
- Potentially large amount of spoils to clean up (Rumer et al., 1995)
- Injection pressure and volume must be closely monitored

* A solution to many of the disadvantages is to inject two overlapping rows of barrier material.

Cost
Cost ranges from \$15 – \$30/vertical ft^2 (Mutch et al., 1997).
3.4.1.1 Close-coupled Subsurface Barriers (Cement-Polymer Composite)
A close-coupled barrier combines a thin (inner) lining of polymer grout with a conventional, low-

cost cement-grout containment barrier. The resultant barrier is a cement-polymer composite deriving economic benefits from the cement, and performance benefits from the polymer (Heiser et al., 1997). See Figure 4 for a diagrammatic representation of a close-coupled subsurface barrier. Close-coupled subsurface barriers are installed using jet grouting with a dual fluid injection system. The dual pump system was devised to avoid problems with rapid gel times. The system allows split streams of two different grouting media to be jetted simultaneously. Polymerization occurs when the two parts are mixed. The grouts mix together only after leaving the drill equipment. This avoids clogging the drill system. Mixing occurs normally as a result of the high pressure jetting. Dual fluid injection is preferred when using thermosetting polymers that gel after about 30 minutes (Heiser et al., 1997).

Figure 4: Cross-Section of the Close-Coupled Subsurface Barrier
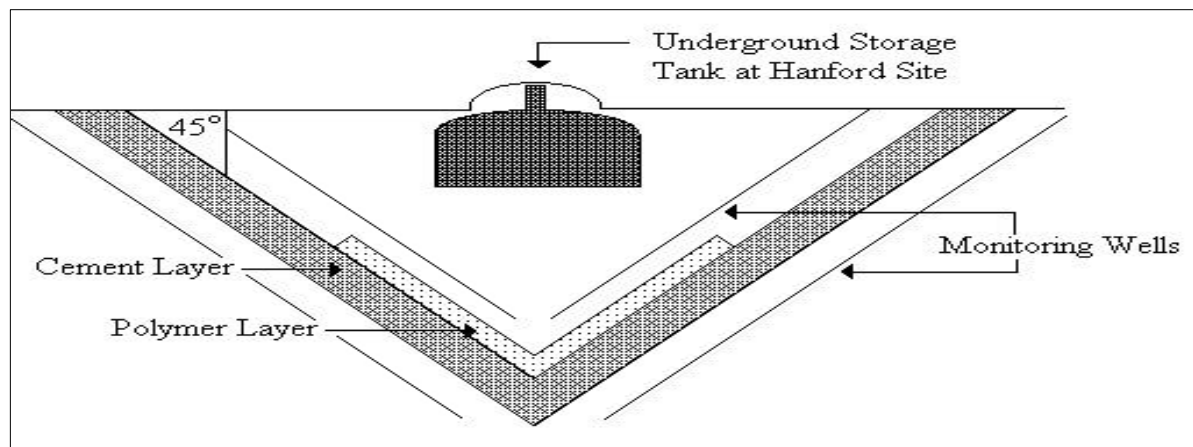
Source: Adapted from Heiser et al., 1997

Advantages
- Benefits of using cement (Dwyer, personal communication)
    – Adequate for the containment of the majority of waste forms
    – Readily available
    – Easy to work with
    – Low cost
- Savings are associated with composite barrier (vs. all polymer) – cement is inexpensive and helps reduce the amount of polymer needed (Heiser, et al., 1997)
- Performance benefits attributed to the durable and chemically resistant polymer layer
    – Compatible with virtually any waste form (SCFA, 1996)
- Emplacement of vertical, angled, and/or horizontal subsurface barriers
- Designed to cost substantially less than any known alternative remedial action such as cryogenic, soil-saw or circulating air barriers, excavation and treatment, or vapor extraction (Heiser et al., 1997)
- Barrier can provide short-term or permanent containment
- Can be used in coordination with other remedial options
- Applicable to a wide range of geohydrologic conditions

Disadvantages
- Polymer grout is expensive and cost is often a limiting factor (Heiser, 1997)

- Compatibility depends on the contaminant and grout combinations for both the cement and polymer layers

Cost

The cost of the barrier grout increases with performance and durability (Heiser et al., 1997). The chosen grout is site and contaminant specific. The estimated cost for a standard DOE site that is 2 acres and 20 ft deep is $24/m^3 (Heiser et al., 1997 and Dwyer, personal communication).

State of Technology

1. In 1993, Brookhaven National Laboratory (BNL) began investigating different advanced polymer materials for subsurface barriers.
2. In 1993, DOE conducted laboratory testing on different polymer materials including high molecular weight acrylics, polyester styrene, a furfuryl alcohol based furan polymer, vinyl ester styrene, sulfur polymer cement, and bitumen (Heiser et al., 1997).
3. In 1994, DOE continued testing polymer materials for strength and hydraulic conductivity.
4. In 1994, Sandia National laboratory (SNL) and Idaho National Engineering and Environ-mental Laboratory (INEEL) conducted several pilot scale tests including individual jet-grouted cement columns, conical and V-trough shaped configurations, and a 7 X 7 matrix of columns placed at a clean site near the Chemical Waste Landfill at SNL. Dual fluid injection was used at SNL.
5. In 1995, a full-scale "cold" demonstration occurred at the Hanford Site in Washington. A barrier was emplaced beneath a 20,000 L tank. The primary barrier was injected using jet-grouting with a dual wall drill pipe and a two-part polymer grout. The grout used was a high molecular weight acrylic material. A secondary cement layer was constructed using conventional jet grouting techniques. A cone shaped barrier was formed by drilling at a 45° angle to the ground (Heiser et al., 1997).
6. In July 1996, a full-scale demonstration was completed at a remediation site at Brookhaven National Laboratory, Long Island, NY. A V-trough barrier was installed at the Glass Hole Waste Site using construction techniques identical to Hanford. The primary layer was an acrylic-gel polymer manufactured by Geochemical Corporation (AC-400) and the secondary layer was conventional cement grout. The contents of the pit were stabilized into 4 ft square retrievable monoliths (SCFA, 1996). The integrity and hydraulic conductivity of the close-coupled barrier was determined. Methods used to evaluate the performance were excavation with visual evaluation, hydraulic testing of core samples, water flooding, and gas tracer verification. Both perfluorocarbon gas tracers (PFTs) and SEAtrace^{TM} were used to validate barrier integrity after emplacement, repair or seal a breach, and assess long-term integrity.

   Results from the Hanford and BNL projects:
   - The use of a dual-wall drill pipe to inject two fluid and thermosetting-polymer grouts proved to be safe and reliable (Heiser et al., 1997).
   - Jet grouting was used effectively to install a continuous barrier.
   - Jet grouting did not affect the waste form.
   - A barrier integrity verification system was demonstrated successfully. The barrier was excavated and found to be "fault free."
   - Both the close-coupled barrier concept and the dual-fluid injection of thermosetting polymers are considered ready for commercial application (Heiser et al., 1997).

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Points of Contact
John Heiser
Environmental and Waste Technology
Center
Brookhaven National Laboratory
P.O. Box 5000, BLDG 830
34 N Railroad
Upton, NY 11973-5000
Phone: 516/344-4405
Fax: 516/344-4486
e-mail: heiser@bnl.gov

Brian Dwyer
Sandia National Laboratories
MS 0719
Albuquerque, NM 87185-0719
Phone: 505/845-9894
Fax: 505/844-0543
e-mail: bdwyer@sandia.gov

3.4.1.2 Thin Diaphragm Barrier

The thin diaphragm barrier is emplaced using high pressure jet grouting. While this grouting technique has been used for years in civil engineering applications, it has only recently been considered for environmental/remediation related purposes (SRT, 1997). Installation involves drilling a horizontal or angled borehole, inserting a rod-string to the desired depth, and removing the string at a constant speed. As the string is removed, grout material is injected through the nozzle at a pressure of approximately 5,700 pounds per square inch. To facilitate the penetration of grout through the subsurface, a cone of air surrounds the grout as it is injected through the nozzle (Carey Johnston, personal communication). The resultant thin diaphragm barrier is composed of a mixture of grout and parent material. Excess soil and fluid, forced to the surface surrounding the drill rod, are contained in a "spoils box." The drill consists of two injection nozzles positioned 180° apart. This configuration enables the formation of thin panels approximating 4 – 8 inches thick and 10 ft wide. See Figure 5 for diagrammatic representation of the emplacement of a thin diaphragm barrier.

Advantages
- Minimal waste generated
- Grout can be altered for contaminant compatibility
- In situ technique
    – No excavation required
    – Grout is injected through a borehole into the ground to form the barrier
    – Expected to significantly lower risks (DOE, Technology Overview)
- Cost benefits anticipated
- Installation at depths up to 200 ft
- Vertical, angled, or curved barriers can be created
- Injection system can control the volume of grout and shape of the barrier
- Potentially able to inject two chemical agents simultaneously (Rumer et al., 1996)
- Injection system can also be used to repair defects in the wall

Figure 5: Thin Diaphragm Wall Emplacement

Slurry jet
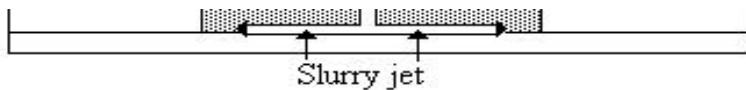
Source: Adapted from Carey Johnston, U.S. EPA, Radiation Protection Division

Disadvantages
- Difficult to orient nozzle (Carey Johnston, personal communication)
- Hard to form a continuous wall especially in heterogeneous soil
- Technique is not suited for rocky, fractured subsurface soils (Rumer et al., 1996)
- Subsurface obstructions may have a negative impact on drilling and injection

Cost

An estimated cost of installing a thin diaphragm barrier, using high-pressure jet grouting, is $10 – $15/ft^2 (Rumer and Mitchell, 1996). This estimate does not include the costs of waste disposal or materials.

State of the Technology
1. In 1991, Bruno Germi installed a hydraulic control barrier at the confluence of the River Po and the River Oglio in Northern Italy. Several other thin diaphragm walls have been installed in Italy and Germany.
2. In 1997, barrier emplacement occurred at the Groundwater Remediation Field Laboratory National Test Site (GRFL), Dover Air Force Base, DE. The project partners included DOE, Department of Defense (DoD), DuPont, and EPA. Technicians emplaced two thin diaphragm walls using high pressure jet grouting. The Phase I barrier was constructed of a cement-rich grout material, and the Phase II barrier contained a bentonite-rich material.

    The panels were installed at an angle in order to provide reinforcement at the overlapping areas. The verification methods included hydraulic testing (Westinghouse Savannah River Company), gas and groundwater tracers (Sandia National Laboratory and Science and Engineering Associates, Inc.), and geophysical testing (MSE-TA, Lawrence Livermore National Laboratory, Lawrence Berkeley National Laboratory). Results are expected by 1999.

Points of Contact
Carey Johnston
U.S. EPA, Office of Air and Radiation (6602J)
401 M Street, S.W.
Washington, DC 20460

Phone: 202/564-9341
e-mail: johnston.carey@epamail.epa.gov

3.4.2 Permeation (or Pressure) Grouting

Permeation grouting has been used extensively in the United States and overseas in the civil engineering, mining, and geotechnical fields (Mutch et al., 1997, Dwyer, 1994). This technique involves the injection of a low-viscosity grout into the soil at low pressure. The grout fills the soil voids to achieve low permeabilities without significantly changing the structure or volume of the soil. To avoid hydrofracture, the grout pressure should not exceed the soil fracture pressure (Rumer et al., 1995).

The first step of the process involves grouting the sleeve pipe annulus with a brittle grout material (weak) prior to injection with the selected grout(s). Once hardened, the "real" grout is injected at a pressure that will fracture the annulus grout thereby directing grout radially into the formation at the designated interval (Dwyer, 1994). Injection pressure is lowered as pressure decreases from fracturing of the annulus grout to ensure permeation and avoid hydrofracturing of the formation (Dwyer, 1994).

Permeation grouting is a feasible method for emplacing a low permeability subsurface barrier in semi-arid unconsolidated alluvial soils common in the southwest United States. The degree of grout permeation is a function of the grout viscosity, grout particle size, and the particle size distribution. These characteristics are directly correlated with the soil hydraulic conductivity. Understanding the relationship between these parameters is essential for predicting grout flow characteristics (Dwyer, 1994).

A variety of materials can be used in permeation grouting, and it is essential to select a grout that is compatible with the soil matrix. Particulate grouts are applicable when the soil permeability is greater than 10^{-1} cm/s (Karol, 1990). Chemical grouts can be used with soil permeabilities greater than 10^{-3} cm/s (Karol, 1990). For further information on groutability and compatibility, see Appendix B.

There are currently two main methods of permeation grouting: point injection and sleeve pipe injection (tube-a'-manchette). In the point injection method, the casing is driven to full depth and grout is injected as the casing is withdrawn (Rumer et al., 1995). Overlapping injection holes can be used to form a continuous barrier. The tube-a'-manchette method involves grouting a sleeve pipe in the grout hole and injecting grout through holes in the pipe (Rumer et al., 1995). The holes are covered and placed at 1 ft intervals along the pipe. The grout is injected under pressure into the soil. The advantage of the tube-a'-manchette method is that different grouts can be injected into different holes, and grout can be re-injected if there is a problem.

Advantages (Mutch et al., 1997 and Dwyer, 1994)
- In situ technique means lower costs because there is no excavated soil
- Directionally drilled boreholes allow access without disturbing the waste
- Can be used to emplace vertical or horizontal barriers for complete containment
- Short-term or long-term applications

- Barriers may enhance the effectiveness of in situ remediation while containing the volume of waste
- Applicable to rock

Disadvantages
- Limited to formations with moderate to high permeabilities
- Hard to ensure continuity
- Difficult to direct the flow of grout in heterogeneous soils because the grout tends to follow the path of least resistance
- Hard to predict grout penetration radius

Cost

The cost is often dominated by directional drilling. Cost estimates for directional drilling are $7 – $17/ft^2 (Rumer and Mitchell, 1996). These estimates do not include grouting materials, waste disposal, surface support equipment, and other contingencies.

State of the Technology
1. On October 1992 and September 1993, Brookhaven National Laboratory conducted laboratory tests on superplasticized grouts and soil cements (Allan and Kukacka, 1993).
2. In 1993 – 1994, Golder Associates tested montan wax and glyoxal-modified sodium silicate grouts.
3. In 1994, Sandia National laboratory (SNL) conducted a field-scale demonstration of BNL, Golder, and glyoxal grouts, and montan wax using the tube-a'-manchette permeation grouting method. The area has a dry, semi-arid climate and unconsolidated, unsaturated, silty-sand layers (Dwyer 1994).

Verification

Phase I (BNL microfine cementitious grout)
- A verification survey, before and after grout injection, involved crosswell seismic tomography. "This process is able to measure anomalies in the subsurface corresponding to changes in the velocity of seismic wave signals" (Dwyer, 1994).
- Verification also included excavation and physical comparison.

Phase II (montan wax and sodium silicate)
- Preliminary ground penetrating radar (GPR) surveys were of limited value because of interference from the caliche layer (Dwyer, 1994).
- Electromagnetic induction was employed before, during, and after wall installation.
- Neutron probe logging was used before, during, and after wall installation.

Results

The interconnection between soil pore spaces will determine groutability (Dwyer, 1994). Permeation grouting can be used with gravels and sands but is only marginally successful for silts and clays (Dwyer, 1994). Microfine cementitious grout can be used to grout high hydraulic conductivity soils. The penetration radius depends on soil heterogeneity, grout viscosity, and injection pressure (Dwyer, 1994). Non-uniform grout flow was attributed to soil characteristics

because viscosity and injection pressures were held constant. The grout tended to follow the path of least resistance and flowed primarily along the horizontal plane.

Results of Excavation (Dwyer, 1994)
- Grout permeated coarse sand and gravel soil, but the technology only displaced the fine sand and silty soil.
- Cement grouts attained hydraulic conductivities of $10^{-7} – 10^{-9}$ cm/s, which meets EPA guidelines requiring liners to have a minimum hydraulic conductivity of 10^{-7} cm/s.

Conclusions (Dwyer, 1994)
- Permeation grouting is a promising technique for emplacing low permeability barriers in unconsolidated, semi-arid vadose zone soils.
- Additional or new grout can be added at a later date because the tube-a'-manchette method uses injection piping that is permanent.
- Permeation grouting is most effective in relatively homogeneous soils.
- A minimum hydraulic conductivity of 10^{-4} cm/s is required for the injection of microfine cements, montan wax, and sodium silicate grouts. In lower hydraulic conductivity soils (less permeable), grout tends to displace or compact rather than permeate the soil.
- Microfine cement-based grouts produce strong, durable, low permeability barriers.
- Crosswell seismic tomography is effective for identifying cement-grout invaded soils, but cannot verify barrier continuity.
- Borehole measurement of electromagnetic resistivity, moisture content, and temperature changes can identify grout invasion, but not continuity.

### 3.4.2.1 Viscous Liquid Barrier

Viscous liquid barrier (VLB) technology uses injectable, environmentally benign materials to form a containment barrier. Low viscosity liquids are injected using permeation grouting through multiple boreholes in the subsurface. After injection, the liquids gel, forming an impermeable barrier that is biologically and chemically inert, unaffected by filtration, and environmentally safe. See Figure 6 for a diagram of a VLB. VLBs have multiple applications including encapsulation (permanent immobilization of contamination) and creation of an impermeable container that surrounds and isolates the contaminants. They also have the ability to seal off permeable aquifer zones to provide containment in coordination with treatment (Moridis et al., August 1996). The field tests have had mixed success in being able to attain the desired hydraulic conductivities (see state of the technology section).

In collaboration with the manufacturers, special formulations of Colloidal Silica (CS) and PolySiloXane (PSX) were designed specifically for the VLB (Moridis et al., August 1996). See Section 3.4.3.1 for more information on CS and PSX. The new formula CS was designed to resist soil chemistry effects, and the new PSX has a lower initial viscosity (Moridis et al., September 1998). Both of these materials can be injected using standard/available equipment.

It is necessary to match the injection fluid to the waste and to soil characteristics. The geologic matrix appears to be critical to the application and success of this technology (Van Price, personal communication). Soil permeability affects the gel time (Moridis et al., September 1996). In high permeability soils, it is advantageous for the grout to gel quickly so it remains in the desired

region. In contrast, in low permeability soils, it is beneficial for the grout to gel slowly so it will have time to invade the desired region prior to setting. Permeability is also important for determining injection well spacing.

Figure 6: Viscous Liquid Barrier Installation
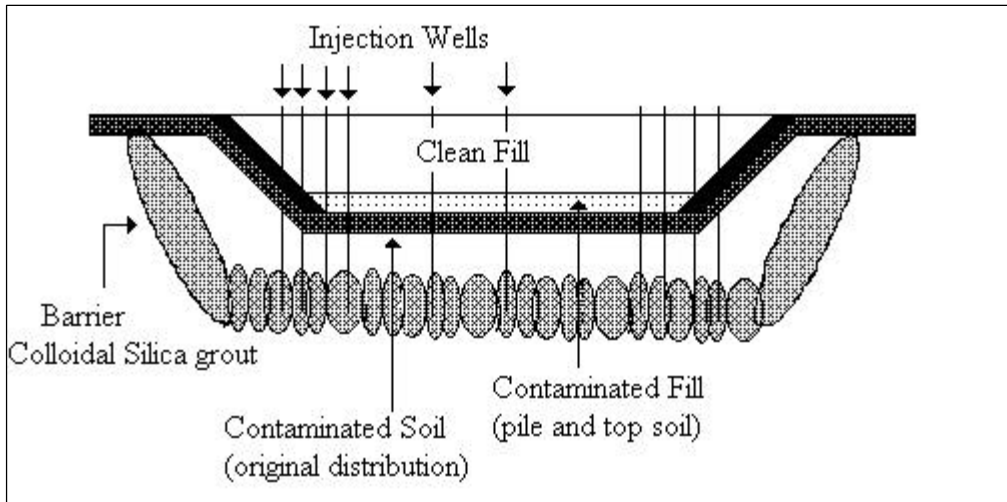
Source: Adapted from Moridis et al., 1996

Advantages

- Applicable to sandy, porous soils with permeabilities greater than 10^{-2} cm/s
  – Permeability depends on grout permeability and saturation in the pore space
- Emplacement with minimal or no destruction of soil matrix
- In situ technique
  – Contamination is not disturbed
  – Cost is reduced because there are no spoils to treat
  – Minimum risk of human exposure
- CS and PSX are biologically and chemically inert (Moridis et al., September. 1996)
- CS and PSX are Food and Drug Administration (FDA) approved for food contact because they pose no health hazard
- Horizontal (bottom) or vertical barriers can be constructed
- Applicable to a range of hazardous contaminants including radionucleotides, heavy metals, organics, and mixed waste (Moridis et al., August 1996)
- Can be used alone or in coordination with treatment technologies

Disadvantages

- Not effective in clay soils
- The material might desiccate over time (Scott McMullin, personal communication)
- Limited to the unsaturated zone

Cost

At Brookhaven National Laboratory (BNL), the cost for the VLB demonstration was $593,000 (MSE-TA, 1998), whereas, the model predicted the cost would be $550,000, a value that is within 10% of the actual demonstration costs. The VLB proved to be a cost-effective alternative compared to excavation and disposal. Based on identical site size and conditions, it was estimated

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that excavation and disposal would cost $2,122,000. Construction of a slurry wall under the same conditions would cost approximately $91,000 (MSE-TA, 1998).

The cost data for the BNL project included equipment, grout materials, labor, and emplacement. Site-specific characteristics, such as project management, permitting, engineering support, engineering design, and site characterization were not incorporated into the analysis (MSE-TA, 1998). Cost will vary depending on the grouting method, drilling method, depth of drilling, and grouting materials. The verification cost is $3/ft^2 of barrier and monitoring is $2/ft^2 (MSE-TA, 1998).

State of the Technology

The VLB technology was developed at the Lawrence Berkeley National Laboratory (LBNL). Over the last eight years, DOE has invested $12 million in the design, testing, and implementation of this technology (Scott McMullin, personal communication). The work was supported originally by a CERCLA action at the Savannah River Site (SRS) Retention Basin 281-3. A different technology was chosen for the SRS, but the potential exists for using VLB at other DOE sites (Wes Germany, personal communication).

1. In 1995, a demonstration occurred at the Los Banos Gravel Company, which has a subsurface similar to Hanford. The demonstration site was excavated to a depth of 21 ft. Both CS and PSX gelled and cross linked in the subsurface (Moridis et al., September 1996). In spite of soil heterogeneity, both materials produced fairly uniform injections. The injection bulbs achieved hydraulic conductivities of 10^{-5} cm/s (Scott McMullin, personal communication). The investigators concluded that multiple injections were required to obtain the desired permeability (Moridis et al., September 1996), but grouted soil was two orders of magnitude less permeable than the ungrouted sand fractions. The gel time for CS and cross linkage time for PSX was 2 – 2.5 hours (Moridis et al., September 1996).

CS Performance Characteristics:
- Grouted and sealed fractures and large pores occurred in the clay.
- In open areas, CS did not appear to saturate the voids, but "appeared to seal access to them."
- CS provided some structural strength to the soil matrix (Moridis et al., September 1996).
- The initial viscosity was 5 cP, which is easy to inject.
- Sand with an initial hydraulic conductivity of 10^{-4} m/s achieved hydraulic conductivities of 10^{-10} m/s after grouting (Moridis et al., August 1996).
- CS is much cheaper than PSX, but it is possible to use a combination of the two.

PSX Performance Characteristics:
- PSX creates a grout bulb that is almost symmetric.
- It grouted and sealed gravels, cobbles, sands, silts, and clays.
- It filled large and small voids
- The initial viscosity is 10 cP, which is easy to inject.
- It imparted structural strength and elasticity to the soil (unlike the CS) allowing the formation of vertical segments.
- PSX has lower hydraulic conductivity than CS.

- Sand with an initial hydraulic conductivity of 10^{-4} m/s achieved hydraulic conductivities of 10^{-12} m/s after grouting (Moridis et al., August, 1996).

2. In 1997, MSE-TA was funded to install a VLB on a clean site at Brookhaven National Laboratory (BNL). CS was used to construct a full three-dimensional containment barrier (wedge shaped). DOE chose CS because of its commercial availability. Perfluorocarbon tracers (PFCs/PFTs), SF6 tracers, ground penetrating radar (GPR), and electron resistance tomography (ERT) were used for verification and monitoring. PFTs and SEAtrace[TM] were used to detect gaps, and GPR and ERT were used to assess the physical characteristics of the wall (emplacement, size, and position). After installation, the barrier was excavated. There were some "good segments," but the barrier as a whole did not achieve the minimum hydraulic conductivity of 10^{-7} cm/s required by EPA (Scott McMullin, personal communication). Hydraulic conductivities on the order of 10^{-5} to 10^{-6} cm/s were obtained. A piece of the wall was left in place to be developed as a verification test site. The following is a chronology of events for this installation:

   - DOE, in coordination with MSE, is trying to determine why the barrier installed at BNL did not achieve the minimum hydraulic conductivity. MSE conducted in situ permeability testing and analysis in the laboratory. The main question is whether the problem is due to the barrier design, the grout material (CS), or the emplacement (Scott McMullin, personal communication). There are still a lot of unresolved issues associated with this technology.
   - In September 1998 an internal review took place.
   - In November 1998, a peer review process began to determine whether or not to proceed with the use of this technology on a contaminated site.
   - In 1999, a full-scale demonstration is planned at a contaminated site, contingent on the decision of the peer reviewers.

Points of Contact

Andrea Hart, Project Manager
MSE-TA, Inc.
P.O. Box 4078
Butte, MT 59702
Phone: 406/494-7410
e-mail: ahart@in-tch.com

George Moridis, Principal Investigator
Lawrence Berkeley National Laboratory
Phone: 510/486-4746
Fax: 510/486-5686
e-mail: GJMoridis@lbl.gov

John Apps, Principal Investigator
Lawrence Berkeley National Laboratory
Phone: 510/486-5193
Fax: 510/486-5686
e-mail: JAApps@lbl.gov

Skip Chamberlain, DOE EM-50 Program Manager
19901 Germantown Road
MS 1135CL, Cloverleaf Building
Germantown, MD 20874
Phone: 301/903-7248
Fax: 301/903-1530
e-mail: grover.chamberlain@em.doe.gov

3.4.3 Particulate and Chemical Grouting (Flowable)
Grout barriers are constructed using particulate or chemical grouts or a combination of both. The most common grouts are particulate grouts including slurry mixtures of cement, bentonite, and

water. Particulate grouts tend to be more viscous and better adapted to large pore spaces where they can spread through the pores. Chemical grouts typically contain a chemical base, a catalyst, and a solvent such as water (EPA, 1998). Examples of chemical grouts include montan wax, sodium silicate, acrylate, urethane, or Ludox. Ludox is a colloidal silica gel developed by DuPont. The density and viscosity of Ludox are similar to water and the gel time can be controlled from a few hours to thousands of hours. Laboratory results show a decrease in permeability of four orders of magnitude (Mutch et al., 1997).

3.4.3.1 Montan Wax

The concept of using montan wax for containment was developed in Germany in 1985 by a company called Vereinigte Mitteldeutsche Braunkohlenwerke AG (MIBRAG). The injected material is a combination of melted wax, surfactant, bentonite, and water. Melted wax is injected into water at a temperature of $95° – 98°$ C, and then a small amount of surfactant is added to the emulsion (Voss et al., 1993). Additions of sodium bentonite clay break the emulsion, causing the particles of wax to aggregate. In the subsurface, the particles continue to bind to one another, thus, filling voids and forming an impermeable barrier. The temperature of the wax and water, as well as the amount of bentonite, can be altered depending on the permeability of the soil.

Montan wax was first mined in 1921. The largest know deposits of montan wax are in the coal fields of former East Germany. The mining process involves extraction of the wax from coal. Montan wax, used to form subsurface barriers, is typically mixed with bentonite. The addition of sodium bentonite serves to bind the surfactant causing the wax particles to aggregate.

Properties of Montan Wax (Voss et al., 1994):
- It is a fossil plant wax with properties similar to natural plant waxes. Plants produce it to prevent desiccation.
- The wax is hard.
- It has a high melting point.
- It consists of mixture of waxes, resins, and asphaltene-like materials.
- It contains C-24 to C-32 carbon chain esters of long-chain acids and alcohols.
- It is typically used for carbon inks, emulsions, polishes, and lubricants.
- Permeability is stable and does not change over time (Kretzschmar et al., 1997).

- Laboratory tests show significant reductions in soil permeability from $6.5 \times 10^{-4} – 3.6 \times 10^{-2}$ cm/s to $3.7 \times 10^{-8} – 1.6 \times 10^{-4}$ cm/s (Mutch et al., 1997).
  – It is not effective on soils with permeabilities less the 5×10^{-4} cm/s.
- It is non-toxic to fish (Kretzschmar et al., 1997).

Advantages
- In situ technique, fewer health risks, no need to extract or treat contaminated soil
- Able to reduce the hydraulic conductivity by as much as five orders of magnitude in the laboratory (Caldonazzi et al., 1993 in Voss et al., 1994)
- Compatible with most types of hazardous waste (Voss et al., 1994)
- Naturally produced, environmentally friendly
- Chemically, radiologically, and biologically resistant (Wilson, 1995)
- Flexible

- Does not contract
- Very viscous and capable of traveling long distances (Roberds, personal communication)
- Does not degrade with time (Wilson, 1995)

Disadvantages
- Rapidly degrades in the presence of inorganic bases and glycols (Voss et al., 1994)
- Problems with emplacement in the United States
- Limited supply because there are only two mines in the world
  – Montan wax, mined in Germany, is imported and soil in the United States by Strohmeyer and Arpe, Inc.
  – Northern California
- Expensive, however, the cost is due to installation, not the wax itself (Golder Federal Associates)
- Hard to install because requires high injection pressures to overcome geologic formations
- Difficult to control the breakdown of the montan wax emulsion, thereby increasing the viscosity and making injection virtually impossible (Wilson, 1995)
- Limited by how much the rock can be fractured to inject the wax
- Limited to sandy, porous soils

The following are some potential applications (Kretzschmer, 1997):
- Montan wax may be injected through wells, using high-pressure jet grouting, to create vertical and/or horizontal barriers at depths up to 300 m (Kretzschmer, 1997).
- Slit walls with montan wax mud cakes (impermeable) on the walls and slit filled with mud and montan wax can be made and used at a maximum depth of 100 m (Kretzschmer, 1997).
- Montan wax can be applied onto surfaces as a sealant to prevent infiltration.
- Montan wax can be applied in a well filled with coiled tubing.

State of the Technology
1. In 1992 – 1994, a three-year testing program took place to determine the suitability of montan wax emulsion for containment barriers at DOE sites (Voss et al., 1993). Phase I consisted of laboratory tests that focused on compatibility and permeability. The results demonstrated that montan wax is compatible with methanol, xylene, aniline, cupric sulfate, hydrochloric acid, and sodium hydroxide, but shows rapid destruction in the presence of glycols. The most successful permeability test was on the Hanford soil where the hydraulic conductivity was reduced by five orders of magnitude to 4×10^{-8} cm/s. Phase II involved a single-borehole injection test, using permeation grouting and performance monitoring. The test was done at an uncontaminated site near SBLs Chemical Waste Landfill. Three montan wax formulations were tested and the results were promising for sandy, gravelly soils. The final phase was a multiple-borehole injection test used to construct a horizontal barrier. Phase III, in 1994, involved field trials at a site near the municipal landfill in Richland, WA. Placement of the montan wax using standard permeation grouting methods was not successful (Burgess, 1994).
2. In 1990 – 1997, FlowWaste conducted 24 applications of montan wax in Germany (FlowTex® and Romanta, 1997). These applications involved soil stabilization, surface

sealing, construction of water reservoirs, sowing of a mining strip, and immobilization of soil contamination.

3. Currently, several groups in Germany are researching this technology using jet grouting and soil mixing to emplace montan wax (Montan, September/October 1995). For instance, the German company FlowTex® is currently studying the use of montan wax to form subsurface horizontal barriers below existing waste sites. After trying traditional injection technology, FlowTex® developed a new installation method called Flowmonta, specifically for horizontal barrier installation. Emplacement with Flowmonta involves a combination of horizontal directional drilling followed by jet grouting. The grout is injected in only two directions forming a bowl of overlapping panels.

Points of Contact

FlowWaste GMBH	FlowTex®
Ingo Sass	Burkard Lenze
Entsorgungsmanagement	Chausseestraße 1
Am Hardtwald 1	D-06317 Amsdorf
76275 Ettlingen, Germany	Post Röblingen
Phone: +49-7243/549744 or	Germany
+49-7243/549700	Phone: +49-3460/140163
Fax: +49-7243/549799	Fax: +49-3460/140159

3.4.3.2 Glyoxal-Modified Sodium Silicate Grout

The Societe Francaise Hoechst in France developed glyoxal-modified sodium silicate (sold under the trade name of Klebogel™). Sodium silicate is a grout consisting of water, Klebolink™ S, Klebolink H1, and Klebolink K (Voss et al., 1994). Changing the proportions of these compounds can alter the hardening time and viscosity. The set/gel time is controlled by the purity of the material. Sodium silicate has been used extensively in the United States and Europe as a soil strengthener in unconsolidated soils (Voss et al., 1994).

Advantages
- Compatible with most types of hazardous waste except solutions of sodium hydroxide (Voss et al., 1994)
- Low permeability, less than 10^{-9} m/s (Roberds et al., unpublished)
- Flexible
- Minimal shrinkage
- Viscosity increases rapidly as it sets

Disadvantages
- Limited to sand and gravel
- Rapidly degraded by inorganic bases and glycols (Voss et al., 1994)
- Soil chemistry can considerably alter gel time (Voss et al., 1994)
- Longevity questioned (Golder Federal Associates (Roberds), personal communication)
- Expensive relative to other grouts
- Difficult to achieve uniform penetration

Cost

The cost of the grout material is a function of the desired set time. A fast setting mix (up to 2 hours) does not include silica sol and costs about \$1/gallon. A slow setting mix (up to 2 days) includes silica sol and costs about \$2/gallon (Roberds et al., unpublished).

State of the Technology
1. In 1993 – 1994, DOE tested sodium silicate. No work seems to have been done since that time.

3.4.3.3 Colloidal Silica
PQ Corporation, Valley Forge, PA, developed a Colloidal Silica (CS) formulation called Nyacol DP5110. The CS contains an isomorphic substitution of silicon by aluminum on the surface. For applications of CS, see Section 3.4.2.1 Viscous Liquid Barrier.

Advantages
- Very durable
- Poses no health hazard
- Practically unaffected by filtration
- Chemically and biologically benign
- Gel time can be controlled by a neutralizing agent or a concentrated salt solution added before injection
  – At Los Banos, $CaCl_2$ electrolyte solution used
  – Gel time is temperature dependent
- Hydraulic conductivities of 10^{-8} cm/s obtained in the laboratory after two injections
- Preliminary studies showed CS to be compatible with a range of wastes contained in the buried tanks at the Hanford site (Moridis et al., August 1996)
- Heavy metals incorporated (immobilized) into the gel (Moridis et al., September 1996)

Disadvantages
- Tends to interact with the soil matrix

3.4.3.4 PolySiloXane
The PolySiloXane (PSX) tested was called 2-7154-PSX-10 and was developed by Dow Corning in Midland, MI. For applications of PSX, see Section 3.4.2.1 Viscous Liquid Barrier.

Advantages
- Addition of catalyst increases viscosity
- Gel time controlled by the amount of catalyst
- Poses no health hazard
- Practically unaffected by filtration
- Chemically and biologically benign
- Less sensitive to soil chemistry than CS gelation
- Hydraulic conductivities of 10^{-10} cm/s obtained in the laboratory after a single injection
- Preliminary studies showed compatibility with a range of wastes contained in the buried tanks at Hanford (Moridis et al., August 1996)
- Can "coat and isolate soil grains covered with organic contaminants" (Moridis et al., September 1996)

3.5 VIBRATING BEAM CUTOFF BARRIER

The vibrating beam is a grouting method suitable for shallow soils. A vibratory pile driver is used to drive a modified H-beam into the subsurface. The pile has injection nozzles at the tip. As the beam is withdrawn, grout is injected through the nozzles into the void (Rumer et al., 1995). Cement-bentonite grouts are used most often. A continuous barrier can be formed by successively overlapping beam penetrations.

Advantages
- In situ technique
- Can be installed in small areas

Disadvantages
- Walls are thin (several inches) and subject to hydrofracture
- Difficult to penetrate dense soils
- Limited to shallow walls
- Difficult to know exact location of the tip of the beam

3.6 VITRIFICATION: GEOMELT

In 1980, Batelle Memorial Institute developed the process of in situ vitrification for DOE, and in 1983, Geosafe Corporation sublicensed the technology. In situ vitrification technology applies electricity between four graphite electrodes to generate temperatures (1,600° – 2,000° C), high enough to melt the soil and contaminants in the soil. Contaminants may be destroyed, removed, or immobilized (Campbell et al., 1996). This process incorporates inorganic contaminants (e.g., heavy metals and radionucleotides) into the vitrified glass and destroys most organic pollutants through pyrolysis (heat affected chemical bond breaking) (EPA ORD website, in situ vitrification). The resulting product is glass, which is nonhazardous, chemically stable, and immobile. The organic by-products escape from the soil as gases. The temperature necessary to melt the soil depends on the alkali metal oxide content of the soil (EPA ORD website). In order for this technology to work, the soil matrix must contain at least 1.4% sodium and potassium oxides by weight. Most soils contain this quantity (EPA ORD website).

GeoMelt is one type of vitrification, developed within the last year by Geosafe Corporation (Jim Hanson, personal communication). Planar melting is a type of vitrification involving vertical melting and the formation of vertical planes.

The vitrified product is five to ten times stronger than regular concrete (GeoMelt fact sheet) and is not affected by wet/dry or freeze/thaw cycles. Additionally, organics are removed and the expected geologic lifespan is thousands to millions of years.

Advantages*
- In situ technique
- Can be applied to a variety of site and waste conditions
- Able to treat multiple contaminants simultaneously
- Pre-treatment is not required

- Cost-effective technology because extensive site and waste characterization is not necessary. Proven cost effective for difficult sites and wastes
- Successfully demonstrated (U.S. EPA SITE Program)
- Organics converted to nonhazardous gaseous products like carbon dioxide and water
- Has successfully treated volatiles (benzene), semivolatiles (pesticides), and low volatility compounds (PCBs, dioxins/furans) (Campbell et al., 1996)
- Inorganics, including heavy metals and most radionucleotides, are chemically destroyed or physically incorporated into the vitrification product
- Ability to control volume melted by altering the amount of electric power added
- Capable of treating both organics and inorganic
- Commercially available

*These are advantages of vitrification in general and are not specific to containment barriers.

Disadvantages**
- Heat may cause contaminant migration
- Treatment of soil at depths greater than 20 ft "requires special provisions" (GeoMelt website). Heterogeneous soils may limit depth
- Rate of melting may be altered if organic content by weight is greater than 10%
- Soil must be "acceptable for joule heated melting" (GeoMelt website)
- Vitrified walls estimated to be more costly than many traditional barrier technologies

*These are disadvantages of vitrification in general and are not specific to containment barriers.

State of the Technology
1. In 1998, the ability of the technology to make vertical planes was demonstrated.
2. In 1998, a field-test showed it was possible to construct single walls up to 24 ft long and 12 ft deep (Jim Hanson, personal communication). The technology can be used to install multiple planes. The thickness is variable and can be altered based on the contaminant present and the role of the containment system.

Points of Contact
Geosafe Corporation
2952 George Washington Way
Richland, WA 99352
Phone: 509/375-0710

3.7 HORIZONTAL BARRIERS

3.7.1 Horizontal Subsurface Barrier (HSSB) Technology (patent pending)
The horizontal subsurface barrier (HSSB) technology involves fracturing the soil matrix by "creating stress points" over a broad area (Muhlbaier et al., 1997). The soil tends to preferentially fracture along the horizontal plane. HSSB uses air injected into the boreholes at increasing air pressures to cause the soil to fracture. After soil fracture formation, fluid is injected along the fracture. At the Savannah River Site, Bingham fluid was injected along the plane of the fracture. See Figure 7 for schematic diagram of HSSB.

Figure 7: Typical HSSB Barrier
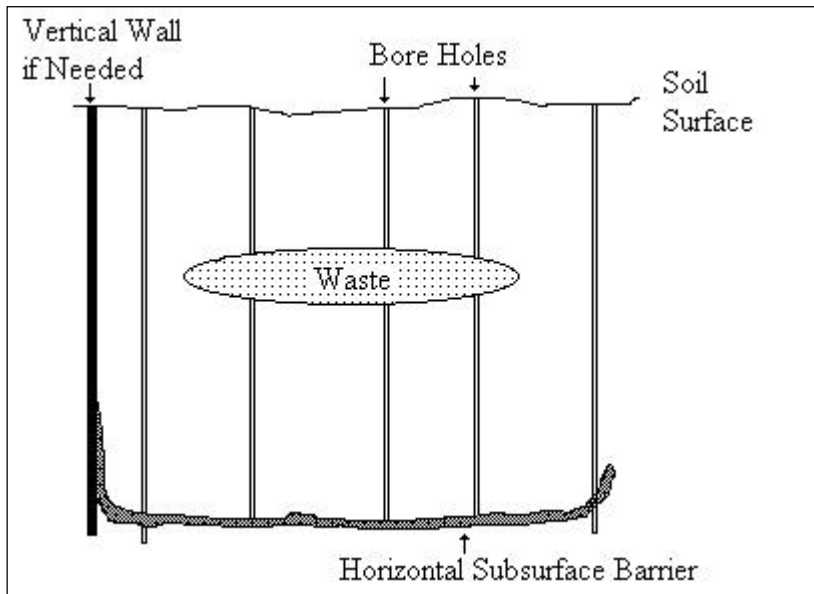
Source: Adapted from RCS

Advantages
- In situ technique
- Can be used to stop, collect, or destroy subsurface contaminants (Soil Remediation Barriers Company Information)
- Impervious barrier (containment) or porous reactive barrier (treatment)
- Placement horizontally or vertically (in conjunction with current technology)
- Minimal disruption of soil and contaminant
- Can be installed at various depths
- Applicable to a variety of contaminants
- Barrier may be flexible or rigid
- Thin (for example, the barrier installed at SRS was 1/16 – 1/4 inches thick)

Disadvantages
- Hard to ensure barrier continuity
- Current method of installation too expensive for large-scale commercial use (Muhlbaier et al., 1997)

The following additional factors should be considered when applying this technology:
- How to control the angle of the fracture
- Placement of injection ports
- Barrier thickness
- Sealing techniques for injection points
- Effectiveness in a variety of soil types

State of Technology

1. In 1996, INEEL conducted a pilot study at the Savannah River Site, Aiken, SC. Excavation of the test site, which involved multiple slices through the barrier, showed the barrier to be continuous (SERDP, 1997). The barrier had a total diameter of 16 ft and curved upwards 3 – 4 ft. The bottom portion of the bowl was relatively flat and measured 8 ft in diameter and 8 ft in depth.
2. In 1998, INEEL did not receive funding to continue this work.

Points of Contact
Dave Muhlbaier
Soil Remediation Barriers Company
5 Whitemarsh Drive
Aiken, SC 29803
Phone: 803/648-8246
e-mail: drmuhlbaier@csranet.com

3.7.2 Buried Waste Containment System

RAHCO International, Inc. developed a horizontal buried waste containment system for Idaho National Engineering and Environmental Laboratory (INEEL). The technology involves constructing a horizontal slot beneath the existing waste, injecting cementitious material into the opening, and monitoring to ensure successful emplacement of the barrier. Tests performed in 1997 proved the technology to be feasible and very successful (Ann Marie Smith, personal communication). Lockheed Martin Idaho Technologies Company (LMITCO) performed the initial site surveys, barrier studies, and sensor evaluations for the test.

The construction of the buried waste containment system utilizes specialized cast-in-place barrier placement machines (BPM) and conventional trenching equipment. The BPM excavates a trench on the sides and underneath the waste. As the trenches are being excavated, the machine injects grout into the trenches (Molony et al., 1998). The soil is excavated by minidiscs and used to backfill the trench after the grout has been injected. The BPM installs both the impermeable horizontal barrier and long-term monitoring equipment. A grid of fiber optic sensors and sensor tubes are installed with the grout. The sensors are embedded in the barrier trenches for long-term monitoring. In addition, the BPM contains a barrier void detection system consisting of a series of pressure sensors along the injection head (Molony et al., 1998). The sensors are capable of detecting a drop in pressure caused by a void in the barrier. When a void is detected, the system will automatically alter the flow of grout.

Advantages
- In situ technique
- Excavated soil is replaced (near the point of excavation) after barrier installation
- Barrier emplacement system
- Long-term monitoring system

Disadvantages
- Soils with a high moisture content can plug the cutterhead
- Minidiscs less effective in wet soils and in areas with boulders than other soils
- Soil matrix affects the "flatness" of the slot

- Difficult to move excavated soil saturated with water and/or boulders

State of the Technology
1. In 1997, proof-of-principle testing of the buried waste containment system occurred at the RAHCO facility. A barrier was placed beneath waste pits without disturbing the pits, and field-tests were conducted of full-scale sections of the barrier placement system. The barrier material was a latex-modified grout mix containing Rapid Set® cement. The grout had a quick set time, low permeability, high adhesion, resistance to chemical attack, and resilience to cracking (Molony, 1998).
2. In 1998, INEEL did not receive funding to continue this work

Points of Contact
RAHCO International, Inc.
P.O. Box 7400
Spokane, WA 99207
Phone: 509/467-0770
Fax: 509/466-0212

3.8 BARRIER MATERIALS THAT IMPROVE PERFORMANCE

3.8.1 Tires
Scrap tire chips were first added to slurry walls as a method of decreasing the mobility of VOCs through engineered containment systems. Shredded tires were found to significantly improve the ability of slurry walls to contain VOCs. Park et al. (1996) has shown that adding ground tires to the soil-bentonite slurry backfill can reduce the hydraulic conductivity of the cutoff wall. The shredded tires adsorb (sorb) VOCs, such as toluene, methylene chloride, trichloroethylene (TCE), and m-xylene from the solution. Park et al. (1996) chose to test these organics because they are commonly present at waste disposal sites.

Tire pieces ranging from 1.3 – 2.5 cm effectively sorbed the VOCs. The necessary thickness of shredded tires depends on the amount of organic compounds to be removed. Park et al. (1996) found that compounds requiring larger quantities of tires for sorption were also more biodegradable, so a thickness greater than 30 cm would rarely be necessary. Differences in sorbance capacity of the ground tires depended on the characteristics of the polymers in the tires (Kim et al., 1997), and sorption was not temperature or pH dependent.

Advantages
- Inexpensive
- Potentially applicable to barrier walls other than slurry walls (Jim Park, personal communication)
- Method of disposal for scrap tires
- Removes some organics from contaminated sites
- Retains some organics while they are naturally degraded
- No negative effect on wall performance
- Cut-off wall effectively becomes a reactive barrier (Park et al., 1997)
- Tire chips can sorb a wide variety of organic compounds (Kim et al., 1997)

- Ground tires have a sorption capacity of 1.4% – 5.6% greater than activated granular carbon (Park et al., 1996)

Disadvantages
- Limited to sorption of organics
- 3.5% – 7.9% of the organics sorbed and then desorbed (Park et al., 1996)
- Possible leaching of organic compounds from the scrap tire chips (Park et al., 1996)
- In the laboratory phase and not yet field tested

Cost
The cost of adding tires to a slurry wall is minimal and should not significantly increase the price of the wall.

State of the Technology
1. Although the laboratory-scale results are very promising, funding for a field-scale demonstration are lacking.

Points of Contact
Jae (Jim) Park, Associate Professor of Environmental Engineering
Department of Civil and Environmental Engineering
University of Wisconsin-Madison
3230 Engineering Hall
1415 Engineering Drive
Madison, WI 53706
Phone: 608/262-7247
Fax: 608/262-5199
e-mail: park@engr.wisc.edu

3.8.2 Microfibers
Cement barriers risk cracking, thereby diminishing the strength of the containment system and increasing the potential for leakage. Cracks pose a special problem when the barrier is exposed to repeated wet-dry cycles (Allan et al., 1995). Polypropylene fibers have been found to "improve toughness, reduce cracking from plastic shrinkage, and decrease crack width and transfer stress across cracks" (Bentur, 1989 in Allan et al., 1995). The potential benefit gained by adding fibrillated polypropylene fibers is that the fibers can reduce microcrack width in shrink-swell soils. While fibers do not stop the formation of cracks, they can reduce the extent of cracking by decreasing crack width and growth, thereby improving the overall performance of the grout (Allan et al., 1995). The addition of fibers increases the strength of the barrier, but it does not change the permeability (Rumer and Mitchell, 1996). The addition of fibers is not always beneficial (Allan et al., 1995).

State of the Technology
1. Brookhaven National Laboratory was working on the addition of microfilaments until several years ago, but currently, there appears to be no research in this area, even though Rumer and Mitchell (1996) have mentioned that microfibers provide added strength.

4.0 MONITORING WALL INTEGRITY

4.1 GAS TRACERS

4.1.1 Perfluorocarbon Gas Tracers
Perfluorocarbon Gas Tracers (PFTs/PFCs) are involved in a geophysical technique that can be used in the vadose zone to determine the physical properties of a barrier. However, existing subsurface geophysical techniques are unable to detect small defects (less than an inch) in a barrier at depths greater than 100 ft. PFT technology requires the following equipment: tracer gases, injection equipment, samplers, and analyzers. Tracer technology is based on the rate of migration of a tracer from the point of injection to a collection well (Sullivan et al., 1998). Gas tracers are injected on the inside of the barrier, and concentrations of the gas are measured in geoprobe monitoring wells outside of the barrier. A capillary adsorbent tracer sampler (CATS) is usually used to measure the monitoring well concentrations of PFTs.

The concentration of PFTs in the external monitoring wells is used to determine if there is a breach in the barrier. If concentrations of PFTs in the wells are approximately the same, the barrier is considered intact. On the other hand, if a breach occurs, the concentration of tracer measured in the monitoring wells will be orders of magnitude greater, even for a small hole. The quantity, type, and location of tracer detected on the monitoring side of the barrier indicates the size and location of the breach (i.e., the larger the opening, the greater the amount of tracer detected) (Heiser et al., 1997). The spectra of the tracers passing through the wall is used to identify the location of the breach relative to the tracer injection points. PFTs can be used to detect small holes in the wall as well as slight imperfections. PFTs can "definitely detect a problem, but there is a question of how precisely they can locate the problem in the field" (Terry Sullivan, personal communication). Theoretically, PFTs should be very precise, but realistically, field detection is much less precise than in the laboratory. The thrust of the current work is to determine how precisely PFTs can locate a defect in the barrier.

Advantages
  - Negligible background concentrations so only small amounts are needed for verification
  - Nontoxic, nonreactive, nonflammable
  - Commercially available
  - Most sensitive nonradioactive tracer (can be detected in concentrations as low as 10 parts per quadrillion (ppq) of air)
  - Multi-tracer technology (six PFTs can be simultaneously deployed, sampled, and analyzed with the same instrumentation)
  - Improved spatial resolution
  - PFT concentrations can be analyzed in several minutes in the field or in the laboratory using gas chromatography (Dietz 1986 in Sullivan et al., 1998)
  - Non-intrusive
  - Potentially able to locate fractures only a few centimeters in size (Sullivan et al., 1998)
  - PFTs have regulatory acceptance for other applications
  - Multiple applications (e.g., verify emplacement, check repairs, long-term monitoring)

<u>Disadvantages</u>
- Only tested in sandy, very porous soils
- Must have about one order of magnitude difference in diffusion between soil and barrier
- Limited to vadose zone
- Depth of application is site specific and depends on geology and hydrogeology

<u>Cost</u>
The cost of using PFTs depends on the size of the subsurface barrier because the size will dictate the number of samples that need to be collected. An estimated unit cost per sample is about $20. However, this number may be higher or lower depending on the scale of the problem (Terry Sullivan, personal communication).

<u>State of the Technology</u>
1. In 1996, three barriers were tested at two different sites at Brookhaven National Laboratory. In all three cases, PFTs were very promising.
2. In 1997, proof-of-concept testing occurred at the Hanford geotechnical test facility. After completion, the close-coupled barrier was excavated and visually inspected. The PFT results were consistent with the visual inspection (Sullivan et al., 1998).
3. In August 1998, testing is planned for PFTs on a wall with known holes at a site at BNL.
4. By the summer 1999, the technology is expected to be commercially available.

<u>Points of Contact</u>
Terry Sullivan
Building 830
Brookhaven National Laboratory
Upton, NY 11973
Phone: 516/344-2840
Fax: 516/344-4486
e-mail: sulliva1@bnl.gov

4.1.2 Science and Engineering Associates, Inc. (SEA)
SEAtrace™ is a subsurface gaseous tracer system developed by Sandia National Laboratories and SEA, Inc. for the detection of leaks in subsurface barriers and liners. The tracer gas sulfur hexafluoride (SF_6) is injected into the contained area. As it diffuses through the barrier into the surrounding area, it is detected by a multi-point vapor sampling system (Sandia website). See Figure 8 for a simple diagram of the SEAtrace™ gas tracer monitoring system. The soil analysis is done by a system called MultiScan™, which automatically samples and analyzes gas and contamination. The tracer concentrations are converted into an inverse optimization code that identifies the size and location of the defect in the wall. Within 30 minutes, the inversion analysis is complete. Although it is more difficult to determine the size of the leak than the location of the breach, the SEAtrace™ system is capable of locating the leak to within 0.5 m and identifying the size of the leak to within 0.15 m (Sandia website).

Figure 8: SEAtrace^TM Gas Tracer Monitoring System
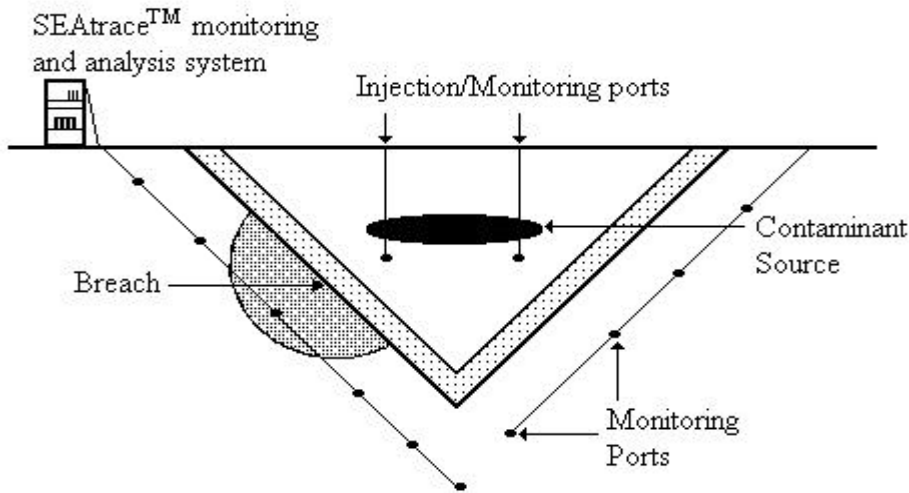
The SEAtrace^TM system uses a photoacoustic gas analyzer manufactured by Innova Instruments. The system can measure essentially any gas compound with an infrared absorption spectrum and can be configured to simultaneously analyze five compounds (Bill Lowry, personal communication). This includes all volatile organic compounds, freons, tracer gases such as sulfur hexafluoride, carbon dioxide, and many others. At a particular site, the system can be set to analyze the five dominant contaminants.

Advantages
- Nondestructive
- Can be used to monitor emplacement and long-term integrity of the wall
- Inexpensive and cost-effective
- Non-toxic
- Applicable to any impermeable barrier in the vadose zone
- Easy to install sample ports using direct push techniques
- MultiScan^TM can operate autonomously for weeks to months at a time
- Results available within 30 minutes of sampling
- Capable of detecting multiple leaks
- Remote data access

Disadvantages
- Accuracy of results is dependent on the leakage model and the unknown input parameters (SEAtrace^TM)
- Limited to unsaturated media

Cost
Based on a typical large barrier with a wall area of 42,000 ft^2 (SEAtrace^TM), the total verification and monitoring cost would be $355,000 (30% for installation and materials, 37% for design and analysis, and 33% for a monitoring system). The unit cost/barrier wall area is $8.45/ft^2. However, the cost drops to $7/ft^2 if the system is reused at other sites.

State of the Technology
1. In 1996, Sandia National Laboratories in Albuquerque, NM, conducted proof-of-concept-tests.
2. In 1997 – 1998, at Brookhaven National Laboratory in Upton, NY, SEAtrace[TM] successfully detected flaws in the viscous liquid barrier.
3. In 1997 – 1998, at Dover Air Force Base, Dover, DE, SEAtrace[TM] successfully detected two flaws engineered in the thin diaphragm wall to within 0.3 m of the actual location (SEAtrace[TM]).
4. The technology is ready for field application.

Points of Contact
Bill Lowry
Science and Engineering Associates, Inc.
3205 Richards Lane, Suite A
Santa Fe, NM 87505
Phone: 505/424-6955
Fax: 505/424-6956
e-mail: blowry@seabase.com
http://www.seabase.com

4.1.3 Comparison of PFTs and SEAtrace[TM]
The following is a comparison of the gas tracers, PFTs and SEAtrace[TM]:

- SEAtrace[TM] typically uses Sulfur hexafluoride (SF_6) as the gas tracer. SF_6 occurs naturally in the environment at higher concentrations then perfluorocarbons.
- SF_6 gas tracers must be injected at concentrations of parts per billion (ppb). PFTs only need to be injected at concentrations of ppq (quadrillion). Because much less PFT is needed, it is possible to inject multiple times and thus gain more information about the location and size of the breach (Sullivan et al., 1998).
- SF_6 is available commercially (SEAtrace[TM]).
- Both tracer gases detected known defects in the wall of a colloidal silica barrier at Brookhaven National Laboratory in 1997.
- A comparison of the two technologies is planned for the summer or fall of 1998 at the SEA facility in New Mexico (sandy soil) where the subsurface colloidal silica barrier has known defects.
- SEAtrace[TM] is able to operate autonomously for long time periods.

4.2 ELECTRICAL RESISTANCE TOMOGRAPHY (ERT)
Electrical resistance tomography was first identified as a geophysical imaging tool in 1978 and has evolved into a system able to detect leaks from underground storage tanks, monitor subsurface air sparging, and map the movement of contaminant plumes (Daily et al., 1998). ERT uses conduction currents to measure resistivity and produce cross sectional subsurface maps based on images before and after barrier emplacement. To measure the resistivity, a current is passed between two electrodes. The barrier materials are more electrically conductive than the surrounding soils and appear as anomalies on the tomographs (Daily et al., 1998). The barrier wall thickness determines the borehole separation and depth. Thinner walls require the electrodes to be

closer together to form the image. ERT can also be used to evaluate the hydraulic conductivity of the barrier.

Advantages
- Applicable to a variety of soil types and demonstrated in clay rich and sandy soils (MSE-TA)
- Can be used in surface, cross borehole, or surface to borehole configurations
- Nondestructive
- Successful in monitoring wall emplacement (Daily et al., 1998)
- Applicable above and below the water table
- Can detect small (1 m) and large (100 m) structures
- Effective at depths of 10 to 500 ft (LLNL website)
- Two- and three-dimensional imaging is possible
- 50% to 75% Fewer boreholes needed vs. conventional drilling (LLNL website)
- Automated collection of data
- Images available in 1 – 6 hours
- Stainless steel electrodes are durable, inexpensive, and easy to replace
- Relatively quick and easy to install electrodes
- Can be used to monitor emplacement or leak detection (MSE, 1996)

Disadvantages
- Insufficient resolution to detect small defects in the wall
- Spatial resolution is site specific
- Highly trained professionals required to operate the complex data inversion algorithms
- Structure of interest must have electrical properties in contrast to the surrounding soil

Cost
The cost of the hardware is approximately $50,000. The cost range for the engineering workstation required for data inversion is $10,000 – $20,000. The cost of licensing the data inversion is project specific (Pacific Northwest National Laboratory website).

State of the Technology
1. In 1991 – 1992, the technology was successfully demonstrated in Lawrence Livermore National Laboratory's (LLNL) Dynamic Underground Stripping Project. In 1994, the Savannah River Integrated Demonstration Project used ERT to monitor the cleanup of VOCs from saturated and unsaturated zones.
2. In 1997 – 1998, a full-scale demonstration of a thin diaphragm wall occurred at Dover Air Force Base, Dover, DE. ERT detected most of the barrier, but for unknown reasons, the technology did not detect the upper or lower parts of the barrier (Daily et al., 1998). One explanation is that low electrical contrast of the clays inhibited imaging of the upper and lower regions. In addition, ERT was unable to identify individual panels due to insufficient resolution. The technology successfully identified a breach in the wall that was confirmed during excavation.
3. In 1997 – 1998, a full-scale demonstration of a viscous liquid barrier occurred at Brookhaven National Laboratory, NY. It was possible to image the subsurface without

baseline data because of large differences in electrical conductivity between the subsurface and grout. Cross boreholes were used for imaging.

Points of Contact

William Daily
Lawrence Livermore National Laboratory
Livermore, CA 94550
Phone: 925/422-8623
Fax: 925/422-2495
e-mail: daily1@llnl.gov

Abelardo Ramirez
Lawrence Livermore National Laboratory
Livermore, CA
Phone: 925/422-6909
Fax: 925/422-3925
e-mail: ramirez3@llnl.gov

4.3 GROUND PENETRATING RADAR (GPR)

GPR is a geophysical tool that has been in use since the late 1940s and has been of interest in the environmental field since the 1970s. The first applications of GPR occurred in the early 1970s to locate subsurface structures such as mining tunnels and buried waste (Heiser et al., 1997). GPR uses electromagnetic waves to penetrate the surface. A radar antennae is passed along a set of grid lines across a site, and when the waves come into contact with materials in the subsurface, part of the wave energy is reflected back to a receiving station. The changes in radar signal (reflection or absorption) can be used to map the subsurface. The quantity of energy reflected depends on the electrical conductivity encountered along the path (MSE, 1996). The amount of energy reflected, in addition to the travel time, can be used to determine the depth of the obstruction. GPR can potentially be used to verify the emplacement, location, and continuity of a subsurface barrier, as well as track a contaminant plume around a containment facility (Rumer and Mitchell, 1996).

Advantages
- Non-intrusive
- Potentially able to identify breach and discontinuity and determine size of both
- Provides a three-dimensional image of the structure
- Typically works better than seismic technology above the water table

Disadvantages
- Susceptible to interference from metallic objects
- Penetration depth is determined by frequency and soil type
  – Much harder to penetrate clay
  – Lower frequencies can penetrate to a greater depth, but lose resolution
- The electrical conductivity of the containment material must contrast "sufficiently" for GPR to be effective (MSE, 1996)

Cost
For specific cost and vendor information see EPA's Vendor Field Analytical and Characterization Technologies System (VendorFACTS). The database contains information provided by vendors on the application, performance, and use of their products. VendorFACTS is available at http://www.epareachit.org.

1. In 1994, Sandia National Laboratory (SNL) used GPR to verify grout placement. A soil matrix containing caliche (brittle, limestone-like material) indicated limited usefulness of GPR because of the difficulty involved in penetration (MSE, 1996).
2. In 1994, GPR was used in Richland, WA, to verify grout placement. It successfully located the sodium silicate grout but was unable to locate the montan wax grout.
3. In 1995, SNL successfully used GPR to show the near-surface extent of the grout injections in addition to locating voids larger than 1 m (MSE, 1996).
4. In 1995, GPR used the Hanford Site to verify the emplacement of a close-coupled barrier wall. A report concluded that GPR was successful in monitoring the installation of the subsurface barrier. However, Heiser et al. (1997) found that "the data do not appear useful for verification" at this site. This site was complicated because the barrier wall surrounded a large metal storage tank, which may have altered the radar signals. GPR may be a useful tool in other situations.
5. In 1995, the Oak Ridge National Laboratory used GPR to map the thickness and continuity of a frozen barrier. The technology was considered successful because of the large difference in electrical properties of ice and water.
6. In 1997 – 1998, the viscous liquid wall was tested at Brookhaven National Laboratory, NY, but no data are available.
7. In 1997 – 1998, a thin diaphragm wall was tested at Dover, DE, but no data are available.

4.4 SEISMIC/ACOUSTIC METHODS

Seismic methods rely on measuring the speed of waves traveling through a specific medium. Reflection and/or refraction of the wave depends on the physical and chemical properties of the media. The waves can be detected and measured by special sensors. A specific type of seismic technology called crosswell seismic tomography or crosshole seismic imaging places transmitters in one borehole and receivers in another borehole. The time it takes the seismic waves to travel between the transmitter and a receiver is inverted into a two-dimensional map of velocity and structure (Rumer et al., 1996). Seismic wave velocity is proportional to the density of the media. Seismic methods use velocity to evaluate the integrity of a subsurface barrier by comparing time measurements before and after grouting. Resolution varies with frequency such that higher frequency waves provide better resolution. The technology is similar to GPR except that it uses different energy frequencies and a different energy source (MSE-TA, unpublished).

Advantages
- Non-intrusive or semi-invasive (boreholes)
- Applicable to vertical or horizontal barriers
- Can potentially be used for leak detection
- Applicable to surface, borehole, or surface to borehole configurations
- Usually works better below the water table in consolidated sediments

Disadvantages
- Penetration distance should be less than 5 m (MSE-TA, unpublished)

State of the Technology

1. In 1987, at Hill Air Force Base, UT, seismic/acoustic methods were used for the detection of a mud slurry trench. The technology successfully identified the presence and shape of the barrier but was unable to identify the location (MSE, 1996).
2. In 1995, Oak Ridge National Laboratory and the Massachusetts Institute of Technology used seismic/acoustic methods to identify the presence of three cement monoliths.
3. Sandia National Laboratory (SNL) successfully identified the existence and location of grout materials.
4. In 1997– 1998, the Savannah River Site used seismic technology to monitor the emplacement of a viscous liquid barrier, and Dover Air Force Base, DE, used a seismic technology to monitor the emplacement of a thin diaphragm wall.

4.5 ELECTRO-ACOUSTICS (OR SEISMO-ELECTRICS)

Electro-acoustics is a subsurface imaging technology combining electrical and acoustical methods. The detection capabilities are better than either electric or acoustic methods alone (MSE, 1996). This imaging technique emits an acoustic pulse that is detected as an electrical signal. The acoustic waves interact with the electrical structure of the medium (MSE, 1996).

State of the Technology
1. In 1995, Oak Ridge National Laboratory conducted a technology demonstration.
2. ISOTRON® is developing this technology.

4.6 SLURRY WALL MONITORING (GERMANY)

In Germany, a new geoelectrical technology is being tested for locating heterogeneities and/or leakage zones in slurry walls. This technology involves the placement of vertical chains within the slurry wall during construction to identify regions of high permeability within the wall. Deciding where to position individual electrodes (vertically and horizontally) is based on site-specific considerations. Each electrode can measure electrical potential and introduce electrical current.

Advantages
* High spatial resolution
* Applicable to all kinds of waste
* No system of this kind currently exists

Disadvantages
* Must be installed during construction of slurry wall

State of the Technology
1. In November 1996, electrodes were installed successfully in a slurry wall near Mannheim-Sandhofen, Germany. The monitoring system was installed to a depth of 22 m.
2. In July 1998, a hole was drilled in a slurry wall and investigators are in the process of using tracer tests and geoelectrical measurements to locate the hole (Heike Bradl, personal communication). An offer is being prepared to encapsulate a waste site in Vienna, Austria.

Cost
The cost of the geoelectrical system is about 5% of the total cost of the slurry wall (Heike Bradl, personal communication).

Points of Contact
Heike Bradl
Research and Development
Bilfinger + Berger Bauaktiengesellschaft
Carl-Rei-Platz 1-5
D-68 165 Mannheim GERMANY
Phone: +49-621/459-2613
Fax: +49-621/459-2350
e-mail: fue.bilberg@t-online.de

4.7 MONITORING OF SLURRY WALLS IN THE UNITED KINGDOM

Barrier wall technology is widely accepted in the United Kingdom (UK) and Europe. Cement-bentonite walls are the most common types of containment barrier used in the UK. According to Stephan Jefferis, there is an assumption that if the wall is constructed or installed as specified, it should work. Thus, monitoring is not a primary concern to industry or the regulatory agencies in the UK (personal communication). The typical method the UK uses for long-term monitoring consists of sampling the slurry and then allowing it to set. This method is based on the assumption that the characteristics of the slurry are representative of the wall.

Probes have also been inserted into the slurry wall for long-term monitoring. This technique has been tested three times, and in each case, the technique was unsuccessful (Stephan Jefferis, personal communication). Cement-bentonite is very brittle and tends to crack when probes are inserted. Since soil bentonite is less brittle, probes containing this material might not damage the wall.

Test boxes are another type of monitoring technique used occasionally in the UK. This technology involves digging a trench the length of the wall and putting a loop in the wall. The box is then placed along the line of the wall. Three or four test boxes have been used in the UK and all tests have been satisfactory (Stephan Jefferis, personal communication). The first box installed was 2 m by 10 m and the second box was 6 m by 4 m. The slurry wall forms one side of the box. Monitoring wells are placed around and inside the box. The box traps the groundwater, which can then be tested for contaminants. Because groundwater flow is slow, it takes a long time (three months) to get enough water to run the tests. Single or multiple boxes could potentially be used for long-term monitoring. In Austria, boxes were placed between a pair of thin walls forming a continuous row of boxes. The main limitation of this technology is the expense.

The main question with slurry wall emplacement is whether the wall reached full base (fully emplaced). If problems are suspected, good construction records should help identify potentially weak areas of the wall (Stephan Jefferis, personal communication). The materials can be tested in the laboratory, but when monitoring the performance and integrity of the wall, it is important to "test" the entire wall. There is a growing interest in the UK in standardizing remedial activities.

Points of Contact
Golder Associates (UK) Ltd.
Stephan Jefferis
54-70 Moorbridge Road
Maidenhead

Berkshire SL6 8BN England UK
Phone: +44-1626/770699
e-mail: sjefferis@golder.com

APPENDIX A: MATRIX FOR EVALUATING BARRIER CQA/CQC

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, 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 20 ft	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	>	$5 \times 10^{-7} - 1 \times 10^{-7}$ cm/sec	<
Backfill Mixing/placement	Loosely Controlled	Controlled Mix/Place	Central Mix/Guided
Barrier Continuity	Interrupted	Continuous	Continuous & Confirmed
Post Construction Barrier	None	Minimal	Regular & Documented
As-Built Records	None	Construction 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 and Testing	None	Designer Specified	Independent Duplicate QA
Groundwater Chemistry Monitoring	None	Minimal	Periodic & Across Barrier

Source: EPA, 1998 *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.

APPENDIX B: GROUTABILITY

Groutability, which is the ability of soil to receive grout, depends on the permeability of the soil and the viscosity of the grout. Soils with permeabilities less then 10^{-6} cm/s are not amenable to grout, and soils with permeabilities greater than 10^{-1} cm/s require suspension grouts or chemical grouts containing filler materials (Mutch et al., 1997). Gravels and sands tend to be groutable while soils containing more than 20% silt are not usually receptive to grout (Montan Wax, 1995). Silts and clays are difficult or impossible to grout (Voss et al., 1994). There is a relationship between viscosity and soil permeability. Typically, higher viscosity grouts are better suited to high permeability soils (i.e., soils with larger void spaces), and low viscosity grouts are necessary when the soil has a low permeability (Voss et al., 1994). See Tables B-1 and B-2.

Table B-1: Relationship Between Soil Permeability and Groutability

Permeability (cm/sec)	Groutability
$\leq 10^{-6}$	Ungroutable
10^{-5} to 10^{-6}	Groutable with difficulty by grouts with viscosity < 5 cP Ungroutable with grouts having viscosity > 5 cP
10^{-3} to 10^{-6}	Groutable with low viscosity grouts, but difficult with grouts with a viscosity > 10 cP
10^{-1} to 10^{-3}	Groutable with all commonly used chemical grouts
$\geq 10^{-1}$	Requires suspension grouts or chemical grouts containing a filler material

Source: Karol 1990 in Voss et al., 1994

Table B-2: Compatibility Between Soil Matrix and Grout

Rumer et al., 1995
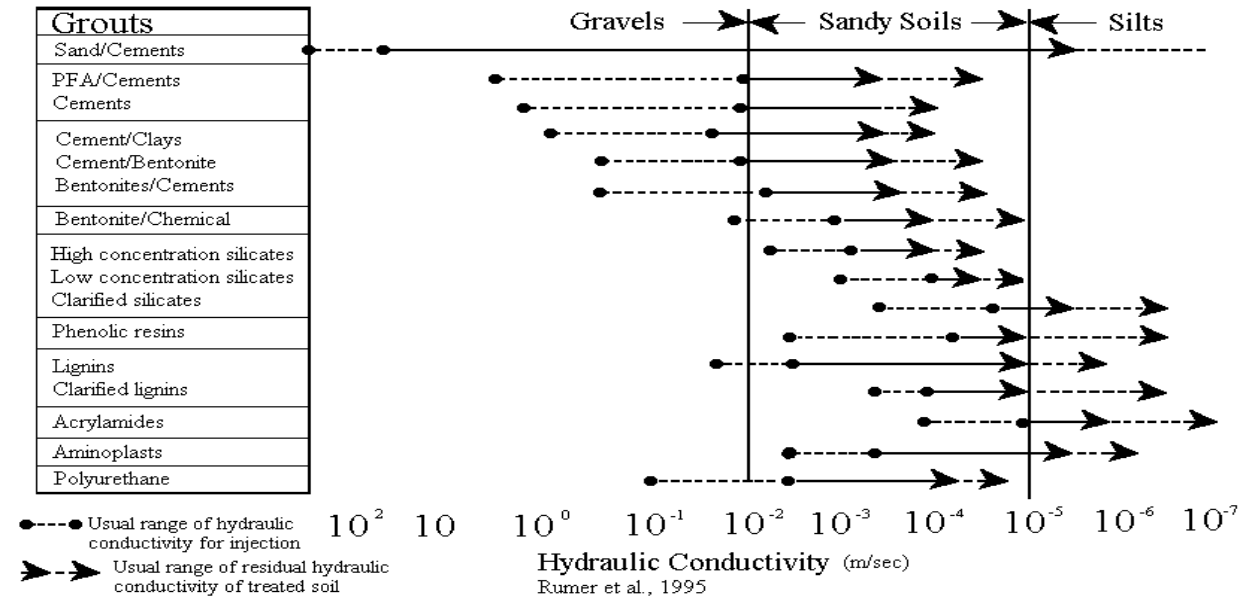
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