COST AND PERFORMANCE REPORT

Permeable Reactive Barriers Interim Summary Report:
Permeable Reactive Barriers
Using Continuous Walls to Treat
Chlorinated Solvents

May 2002

U.S. Environmental Protection Agency
Office of Solid Waste and Emergency Response
Technology Innovation Office

Introduction

The report provides an interim summary of six projects (five full-scale and one pilot-scale) using permeable reactive barriers (PRBs) with continuous subsurface walls composed of various reactive media to treat groundwater contaminated primarily with chlorinated solvents. A PRB contains or creates a reactive treatment zone oriented to intercept and remediate a contaminant plume. Contaminants are removed from the groundwater flow system by physical, biological, or chemical processes (EPA, 2002a).

Table 1 summarizes available information about the six projects, including year of installation, specific contaminants treated, PRB configuration and wall dimensions, installation method, installation depth, reactive media used, and cost data. Each of the PRBs was installed between 1991 and 1998.

Information on all six projects was obtained from *Installation Profiles* published by the Remediation Technologies Development Forum[1] (RTDF) and which are available online at <www.rtdf.org>. The six projects are:

Full-Scale Projects.

- Copenhagen Freight Yard – *Copenhagen, Denmark*
- Former Manufacturing Site – *Fairfield, New Jersey*
- Industrial Site – *Manning, South Carolina*
- Kansas City Plant – *Kansas City, Missouri*
- Shaw Air Force Base (AFB) – *Sumter, South Carolina*

Pilot-Scale Project

- Borden Aquifer – *Ontario, Canada*

Summary of PRB Projects Using Continuous Reactive Walls to Treat Chlorinated Solvents

Contaminants Treated

For each of the six projects, the PRB was used to treat groundwater contaminated primarily with chlorinated solvents, including cis- and trans-1,2-dichloroethene (DCE); trichloroethene (TCE); vinyl chloride (VC); 1,1,1-trichloroethane (TCA); tetrachloroethene (PCE); carbon tetrachloride (CCl_4); chloroform (CCl_3); and dichloroethane (DCA). At each of the sites, those contaminants were present in the dissolved phase; however, at the Former Manufacturing site in Fairfield, New

[1] The RTDF has an ongoing effort to track PRB projects in the field and to periodically update information about those projects. When the case study was prepared, RTDF had published *Installation Profiles* for 47 PRB projects. The RTDF selects PRB projects for its web site based on availability of information, and includes mostly sites that have been in the field for relatively longer periods of time, as well as sites with relatively greater amounts of information. While not a representative sample of sites, the projects tracked by the RTDF provide a cross-section of the general types of projects in which PRBs had been installed. In addition, the RTDF is performing a longer-term review of project performance, and the data available for the case study is a snapshot of data available to date.

Jersey, PCE, 1,1,1-TCA, and TCE were present in the form of separate-phase dense nonaqueous-phase liquids (DNAPL).

PRB Configuration

All six projects employed a continuous wall configuration. An example of the continuous wall configuration from the Copenhagen site was included in this case study as Figure 1. The continuous reactive wall configuration was intended to intercept the flow of contaminated groundwater and treat the groundwater without significantly affecting flow. The two other typical configurations for PRBs, the reaction vessel, which routes groundwater via natural or engineered preferential pathways to a subsurface reaction vessel, and funnel-and-gate, which is used to capture groundwater over a larger area and direct it to a reactive zone, were not used in these projects.

PRB Installation Method

Two of the six PRBs were installed using continuous trenching techniques, including chain trenching at Shaw AFB and one-pass trenching at the Industrial Site in Manning, South Carolina. For example, at the Industrial Site, a one-pass trenching technique was used to excavate the trench. A surface bench was installed between four feet and six feet below ground surface (bgs) because although the wall was designed to reach a depth of 29 feet, the trenching equipment only extended to approximately 24 feet bgs. In addition, minor caving problems were encountered during installation, which were alleviated by relocating equipment that had put too much weight on the sidewalls of the trench.

The remaining four PRBs were installed using supported excavation techniques incorporating sheet piles. For example, the PRB at the Copenhagen Freight Yard was installed using sheet piling as a form of supported excavation. The sheet piling was installed along the perimeter of the planned excavation area for the PRB. The area inside the sheet piling was excavated and then backfilled with iron. Another example of a PRB employing sheet piling construction is the Former Manufacturing Site, where first the area of known DNAPL contaminant was excavated from the subsurface and the excavation was backfilled with a 1 to 1 mixture of iron and sand. The PRB at the site was installed downgradient of the excavation using a sheet piling technique. During construction of the PRB, a below-grade sewer line was encountered which allowed a large amount of water to flow into the trench and thus complicated construction. Ultimately, subaqueous excavation (excavation below the water table) was required to complete the section of the wall located in the area around the sewer line.

Other installation methods for PRBs that are available are unsupported excavation techniques and direct placement technologies, such as *in situ* soil mixing, vibrated I-beam, hydraulic fracturing, jetting, and mandrel (H-Beam).

PRB Installation Depth

The six PRBs were installed to maximum depths ranging from 8 feet to 32 feet bgs. Of the six sites, four (the Former Manufacturing Site, the Industrial Site, the Kansas City Plant, and the Borden Aquifer) were keyed into an impermeable layer. Two sites (the Copenhagen Freight Yard and Shaw AFB) did not provide information about whether the PRBs had been keyed into an impermeable layer.

The alluvial material underlying the Kansas City Plant was underlain by shale bedrock. The PRB was installed by driving the sheet piles into the subsurface to the depth of the shale bedrock. At Shaw AFB, the PRB was excavated to a depth of 24 feet bgs. The original design called for the PRB to be installed at a depth of 30 feet bgs, however the saturated sands and the hydrostatic pressure prevented the chain trenching machinery from reaching that depth.

Reactive Media Used

Iron (zero-valent iron or Fe^0) is the most common reactive media used in PRB installations (U.S. Air Force Research Laboratory, 2000). Iron reacts with chlorinated solvents as groundwater passes through the PRB, and increase the rate of degradation for those contaminants. All six projects used iron as the reactive media. At three PRBs (Former Manufacturing Site, Kansas City Plant, and Borden Aquifer), sand was incorporated into the reactive zone along with the iron.

Project Performance

Table 2 summarizes the performance data provided for the six projects. At the six sites, the PRBs reduced individual contaminant concentrations that had ranged from 19 micrograms per liter (µg/L) to 250,000 µg/L to as low as non-detect levels and 340 µg/L. Information on the projected longevity of the six PRBs included in the report was not available.

The PRB at the Kansas City Plant site degraded approximately 97% of 1,2-DCE and VC in influent groundwater during the first 17 months of operation. However, sampling conducted at a well south of the wall indicated that the PRB configuration was causing contaminated groundwater to migrate around the PRB. A downgradient pump-and-treat system was operated to address this migrating contamination. At the Borden Aquifer in Ontario, initial contaminant concentrations were 250,000 µg/L for TCE and 43,000 µg/L for PCE. The TCE concentration was reduced by 90% and the PCE concentration by 86%. Five years after installation of the PRB, low amounts of calcium carbonate were detected in the wall, however, the wall was projected to maintain its effectiveness for at least five additional years. At the Copenhagen site, the total concentration of chlorinated solvents was reduced 95%, from greater than 1,000 µg/L to less than 50 µg/L.

Table 2

Permeable Reactive Barriers Using Continuous Walls to Treat Chlorinated Solvents Summary of Project Performance

Project	Contaminant	Influent Concentration (µg/L)	Effluent Concentration (µg/L)	Cleanup Goal (µg/L)	Reported % Reduction	Calculated % Reduction
Full-Scale Projects						
Copenhagen Freight Yard	cis-DCE	3,000	NP	NP	NP	NP
	trans-DCE	700	NP	NP	NP	NP
	TCE	NP	NP	NP	NP	NP
	PCE	NP	NP	NP	NP	NP
	VC	NP	NP	NP	NP	NP
Former Manufacturing Site	1,1,1-TCA	1,200	ND*	30	NP	NP
	PCE	19	ND*	1	NP	NP
	TCE	110	ND*	1	NP	NP
Industrial Site	TCE	25,000	NP	5	NP	NP

Project	Contaminant	Influent Concentration (µg/L)	Effluent Concentration (µg/L)	Cleanup Goal (µg/L)	Reported % Reduction	Calculated % Reduction
	cis-DCE	3,500	NP	70	NP	NP
	VC	900	NP	2	NP	NP
Kansas City Plant	1,2-DCE	1,377	NP	70	97	NP
	VC	291	NP	2	97	NP
Shaw AFB	TCA	18,100	1	NP	NP	>99%
	DCA	4,554	340	NP	NP	93%
	DCE	2,500	40	NP	NP	98%
	VC	180	290	NP	NP	Increase
Pilot Scale Study						
Borden Aquifer	TCE	250,000	NP	NP	90%	NP
	PCE	43,000	NP	NP	86%	NP

ND Reported concentrations at or near detection limit*

NP Not Provided

Note: All projects were on-going; data provided based on information in Installation Profiles

Project Cost

Cost information was available for the six projects. Total project installation costs ranged from $30,000 for the Borden Aquifer PRB to $1.3 million for the PRB at the Kansas City Plant. The Borden PRB was a pilot-scale project and the installation cost excluded the cost for labor and reactive media, which had been donated. The Kansas City PRB was a full-scale project and was 130 feet long. Design costs ranging from $50,000 for the Industrial Site PRB to $200,000 for the Kansas City PRB were provided for four of the sites.

Table 3 summarizes unit costs calculated for the five full-scale continuous wall PRB applications that treated chlorinated solvents. The following table summarizes unit costs calculated using total project costs based on the length of wall constructed ($ per linear foot) and based on the area (length times maximum depth) of wall constructed ($ per square foot). No cost adjustments were made to normalize project costs in relation to the date when the costs were incurred or the geographic location of the project.

Table 3

Permeable Reactive Barriers Using Continuous Walls to Treat Chlorinated Solvents Summary of Unit Costs

Project	PRB Length (Feet)	PRB Maximum Depth (Feet)	Installation Cost (Excluding Design Cost When Provided)	Cost per Linear Foot ($)	Cost per Square Foot ($)
Copenhagen Freight Yard	50	28	$ 235,000	$ 4,700	$ 168
Former Manufacturing Site	127	25	$ 725,000	$ 5,700	$ 228
Industrial Site	325	29	$ 300,000	$ 920	$ 32
Kansas City Plant	130	12	$ 1,300,000	$ 10,000	$ 833
Shaw AFB	270	24	$ 942,000	$ 3,500	$ 145

Based on the available cost data, no clear trends in unit costs based on length or depth of the PRBs are evident. Table 4 summarizes the matrix characteristics and operating parameters for the six projects that may have affected cost and performance for the PRB applications.

Table 4

Permeable Reactive Barriers Using Continuous Walls to Treat Chlorinated Solvents Operating Parameters

Parameter	Range of Values
Soil Classification:	Varied (provided for six projects)
Clay Content and/or Particle Size Distribution:	Not provided
pH:	Not provided
Porosity:	Not provided
Depth Below Ground Surface or Thickness of Zone of Interest:	8 feet to 32 feet bgs
Total Organic Carbon:	Not provided
Presence of Nonaqueous-Phase Liquids:	DNAPL (Former Manufacturing Site)
Groundwater Flow Rate:	0.3 gpm to 2 gpm (provided for two projects)
Type of Reactive Media:	Iron (alone or mixed with sand)

Lessons Learned Related to PRBs Using Continuous Reactive Walls to Treat Chlorinated Solvents

The following is a summary of lessons learned from the six projects included in the report.

PRB Configuration

- For Shaw AFB, treatment of daughter products within the PRB zone should be considered in specifying the width and retention time required to meet cleanup goals.

- At the Kansas City Plant, the cost and time required for constructing a continuous permeable reactive wall was estimated to be less than that needed to construct a series of impermeable wall and gate sections.

PRB Installation Method

- At the Industrial Site, continuous trenching provided cost-effective installation and a high degree of confidence that materials would be placed according to the design to create a continuous treatment wall with equal distribution of the zero-valent iron, compared to other methods.

- At the Kansas City Plant, the installation of the PRB caused a redistribution of hydraulic head and a partial change in the plume direction; as a result, some of the groundwater flowed around the wall, bypassing the treatment.

Project Performance

- For the Kansas City Plant, pre-characterization for one PRB system may not be sufficient for another because differing subsurface conditions may require special installation considerations.
- At the Industrial Site, the groundwater flow velocity was reduced because the PRB was installed through two aquifers, which required more time than originally had been estimated to complete an initial flushing of the VOCs in the downgradient groundwater.
- Site managers for the Industrial Site PRB indicated that the presence of chloride at the site was not a good indicator of the effectiveness of the dechlorination process.

Project Cost

- Unit costs for the five full-scale PRB applications ranged from $920 to $10,000 per linear foot and from $32 to $833 per square foot. It is likely that additional matrix characteristics and operating parameters, such as soil classification; clay content and/or particle size distribution; pH; porosity; depth below ground surface or thickness of zone of interest; total organic carbon; presence of NAPLs; groundwater flow rate; and type of reactive media also may directly or indirectly factor in to project cost.
- The cost of one-pass trenching was underestimated at the Kansas City Plant due to difficulties in characterizing subsurface materials. The trenching equipment was not able to penetrate all of the wet clays underlying the site, and the installation method was changed to sheet piles. That change increased the total cost of the project.

References

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Analysis Preparation

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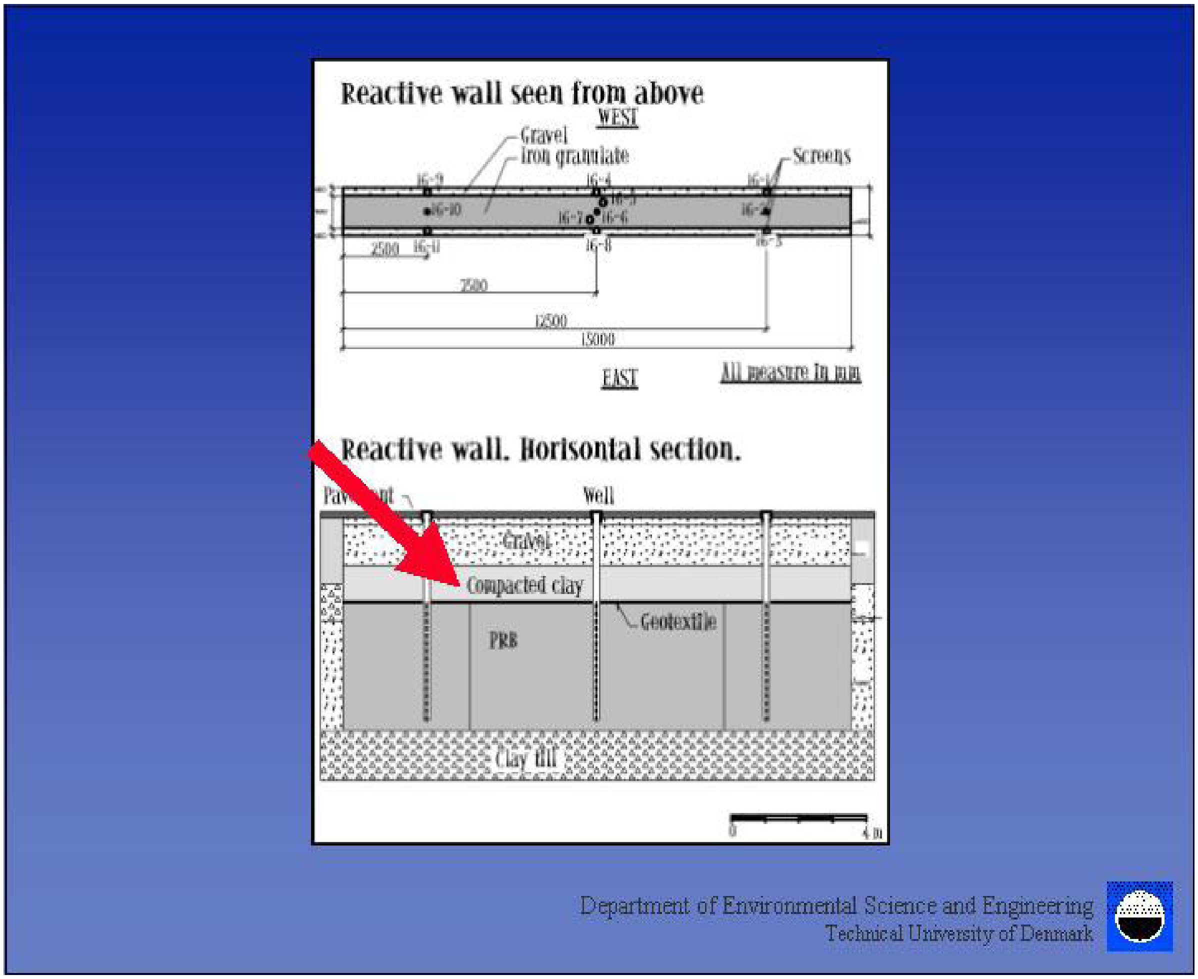
Table 1

Permeable Reactive Barriers Using Continuous Walls to Treat Chlorinated Solvents Project Summary Information

Site Name and Location	Year Installed	Construction Method	Wall Dimensions (Length and Maximum Depth)	Reactive Media	Contaminant	Install Cost (Design Cost)
Full-Scale Projects						
Copenhagen Freight Yard, Copenhagen, Denmark	1998	Supported excavation	50 ft long; 28 ft bgs	Fe^0	cis-DCE, trans-DCE, TCE, PCE, VC	$235,000
Former Manufacturing Site, Fairfield, New Jersey	N/A	Supported excavation	127 ft long; 25 ft bgs	Fe^0 and sand	1,1,1-TCA; PCE; TCE	$725,000 ($150,000)
Industrial Site, Manning, South Carolina	1997	Continuous trench	325 ft long; 29 ft bgs	Fe^0	TCE; cis-1,2-DCE; VC	$300,000 ($50,000)
Kansas City Plant, Kansas City, Missouri	1996	Supported excavation	130 ft long; 8 ft bgs	Fe^0 and sand	cis-1,2-DCE; VC	$1,300,000 ($200,000)
Shaw AFB, Sumter, South Carolina	1998	Continuous trench	4 walls, 270 feet long each; 24 ft bgs	Fe^0	TCA, DCA, DCE, VC	$942,000 ($123,000)
Pilot-Scale Study						
Borden Aquifer, Ontario, Canada	1991	Supported excavation	18 ft long; 32 ft bgs	Fe^0 and sand	TCE, PCE	$30,000 (excluding labor and reactive medial costs)

Figure 1

Schematic Diagram of Continuous Reactive Wall at the Copenhagen Site



Note: Best Available Quality

Source: RTDF

Permeable Reactive Barrier Project Profile:
Copenhagen Freight Yard, Copenhagen, Denmark

Installation Year: 1998
Contaminants: cis-Dichloroethylene, trans-Dichloroethylene, Trichloroethylene, Tetrachloroethene, and Vinyl Chloride
Reactive Media: Fe^0
Cost: $235,000
Construction: Continuous Trench
Point of Contact:
Peter Kjeldsen
Technical University of Denmark
Environmental & Resources DTU
Building 115
DTU, DK-2800
Kgs. Lyngby Denmark
Telephone: +45 45251561
Facsimile: +45 45932850
Email: pk@er.dtu.dk

A full-scale permeable reactive barrier (PRB) system was installed in 1998 to remediate chlorinated aliphatics in a shallow aquifer at the Copenhagen Freight Yard in Copenhagen, Denmark. Degreasing agents, including trichloroethylene (TCE) and possibly perchloroethylene (PCE), were used in train repair operations on the site. The upper aquifer contains chlorinated aliphatics in concentrations up to 4,000 µg/L. Although cis- and trans-1,2-dichloroethylene (DCE) are the dominant contaminants due to dehalogenation in the aquifer, PCE, TCE, and vinyl chloride (VC) also are found. Up to 3,000 µg/L of cis-1,2-DCE and up to 700 µg/L of trans-1,2-DCE are present.

The local geology consists of a top layer of 6.5 ft of sandy fill underlain by 3.3-6.6 ft of clayey fill mixed with peat. Below that is 6.5-10 ft of marine coastal sand, which acts as a local upper groundwater aquifer with a piezometric head about 8 ft below ground level. The sand is underlain by 3.3-6.6 ft of clayey till followed by 20 ft of silty, fluvial sand in hydraulic contact with Danien limestone, which acts as a regional groundwater aquifer. The permeability of the upper aquifer is 0.00019 ft/s, and the average linear velocity of the groundwater is about 0.36 feet per day (ft/day).

The PRB system is about 50 ft long, 20 ft deep, and 3 ft thick. During construction of the PRB, sheet pilings were installed first, and the area inside was excavated to form a continuous trench that was backfilled with 83 short tons of Fe^0. The top of the PRB is 8.2 ft below ground and is covered with a layer of geotextile, compacted clay, gravel, and pavement on top. The PRB was installed to cut off that part of the plume where the total concentration of chlorinated aliphatics exceeds 100 µg/L.

Sampling has been completed. To date, the PRB has effectively treated upgradient concentrations of chlorinated aliphatics above 650 µg/L, bringing them below 10 µg/L downstream. Total chlorinated solvents reduced in the PRB from greater than 1,000 µg/L to less than 50 µg/L, which represents about a 95% reduction.

Detailed hydraulic studies of groundwater levels and contaminant concentration distributions revealed that as much as one-fifth of the plume is migrating around the barrier and escaping the PRB's capture zone. The reason why water is flowing around the barrier may be due to a combination of factors. The PRB may not be in an ideal location to capture the plume that is flowing more to the northeast than the initial site investigation indicated. Also, hydraulic conductivity of the Fe^0 in the PRB has decreased with time. The loss of conductivity is probably due to precipitation of iron hydroxides, carbonates, and calcium carbonates. Slug tests in the PRB revealed conductivity of 0.00004-0.00021 ft/sec, compared to the value of 0.0016 ft/sec that the manufacturer provided. An estimated 2,200 lb of iron hydroxide ($Fe[OH]_2$), 440 lbs of calcium carbonate ($CaCO_3$), 440 lbs of iron carbonate ($FeCO_3$), and 130 lbs of iron sulfide (FeS) precipitate in the PRB each year.

Lessons Learned

Precipitation leading to decreased permeability of the PRB may occur in groundwater containing high concentrations of inorganic compounds. In the Freight Yard PRB, the total dissolved solids decreased with about 600 mg/L passing though the wall. If the permeability of the Freight Yard PRB continues to decrease, the efficiency of the PRB also may decrease with time.

Note: This is the complete installation profile provided by the Remediation Technology Development Forum <www.rtdf.org> for this project. Presentation slides containing a schematic diagram of the PRB and analytical graphs are available through a link in the online installation profile.

Permeable Reactive Barrier Project Profile:
Former Manufacturing Site, Fairfield, NJ

Installation Year: Not provided
Contaminants: 1,1,1-Trichloroethane; Tetrachloroethylene; and Trichloroethylene
Reactive Media: Fe^0
Construction: Continuous Trench
Point of Contact: Stephen Tappert
RTC VECTRE Corporation
15 Route 15 South
Lafayette, NJ 07848-0930
Telephone: (973) 383-2500
Facsimile: (973) 579-0025
Email: stappert@trccos.com

A full-scale permeable reactive barrier (PRB) was installed at a site in Fairfield, NJ, to treat chlorinated solvent contamination. The site, a former electromechanical product manufacturing, assembly, and testing facility, is currently in operation as a school. It consists of a single one-story slab foundation brick building and paved parking lot covering 60% of a 2.8-acre plot of land. Environmental investigations at the site identified a plume of chlorinated solvents, with an apparent source in the vicinity of a former dry well and septic system. Contamination was limited to the shallow sandy aquifer. The total VOC concentration at the plume front was approximately 4,500 µg/L. Key contaminants included 1,200 µg/L trichloroethane (1,1,1-TCA), 19 µg/L tetrachloroethylene (PCE), and 110 µg/L trichloroethylene (TCE). A pool of dense nonaqueous-phase liquid (DNAPL) was also identified with significant concentrations of solvents in saturated soils below 15 ft. Underground utilities in place at the site included two storm drains and a sewer line at 13 ft below grade.

The site is underlain by 15-20 ft of silty sand with some gravel, overlying a lacustrine clay 10^{-15} ft thick. The clay unit varies in depth from 15-23 ft below grade. Groundwater at the site occurs under water-table conditions within the glacial sediments above bedrock, and under confined conditions in the deeper sand aquifer. Shallow groundwater flow is moving toward a nearby creek at an average hydraulic gradient of 0.005 ft/ft. Depth-to-water in the shallow zone has been as high as 4 ft below grade. An upward vertical groundwater gradient exists between the shallow aquifer and the silty sand unit underlying the clay, with a head difference of almost 6 ft in some areas.

Prior to installation of the PRB, the DNAPL pool was excavated. As a remedial measure, the excavation was partially backfilled with a 1:1 mix of zero-valent iron and sand. For the PRB, conventional sheet piling construction was selected as the most reliable approach with the most predictable timeframe for completion. The PRB was constructed as a continuous barrier located ahead of the highest plume concentrations to prevent offsite migration. The bottom portion of the barrier used a 4:1 iron/sand mixture and the upper portion of the barrier used a 3:2 iron/sand mixture. A total of 720 tons of iron were used. The final barrier was 127 ft wide, 25 ft deep, and 5 ft thick. After the barrier was installed, the site was graded and seeded, and the parking lot was repaved. Construction was generally straightforward with the only major problem being the below-grade sewer line that permitted a large volume of water to enter the excavation. Construction ultimately required subaqueous excavation to complete that section of the wall.

Design costs for the barrier, including a licensing fee, were $150,000. Installation costs (which include construction, materials, and reactive media) totaled $725,000.

Cleanup goals for chlorinated solvents at the site were New Jersey Groundwater Quality Criteria: 1 µg/L for PCE, 1 µg/L for TCE, and 30 µg/L for 1,1,1-TCA. Monitoring wells were installed upgradient, downgradient, and within the PRB and samples have been collected on a quarterly basis since system installation. VOC concentrations at the center of the plume have decreased to near detection limits within the PRB. Quarterly sampling results have also reported an increase in pH from approximately 6.5 to 9.5, a decrease in Eh from -50 mv to -400 mv, and concentrations of VOCs at or near detection limits in the central portion of the wall. Quarterly monitoring of selected wells will continue for one more year, then with reduced frequency after that.

Lessons Learned

Detailed knowledge of the site and detailed planning were critical to making this technology work. Also, it was important to get the state agency on the team early to expedite the project.

Note: This is the complete installation profile provided by the Remediation Technology Development Forum <www.rtdf.org> for this project.

Permeable Reactive Barrier Project Profile:
Industrial Site, Manning, SC

Installation Year: 1997
Contaminants: Trichloroethylene, cis-1,2-Dichloroethylene, and Vinyl Chloride
Reactive Media: Fe^0
Construction: Continuous trench
Point of Contact: Steven Schroeder
RMT, Inc.
100 Verdae Blvd.
P.O. Box 16778
Greensville, SC 29606-6778
Telephone: (864) 281-0030
Facsimile: (864) 287-0288
Email: steve.schroeder@rmtinc.com

Phase 1 of a full-scale permeable reactive barrier (PRB) was installed at a former industrial site in Manning, SC, in November 1997. Trichloroethylene (TCE), cis-1,2-dichloroethylene (cDCE), and vinyl chloride (VC) have been detected in two aquifers that underlie the site at concentrations of 25 mg/L, 3.5 mg/L, and 0.9 mg/L, respectively. TCE concentrations in the lower of the two contaminated aquifers are generally one order of magnitude less than those in the upper aquifer.

The upper aquifer is 5-15 ft below ground surface (bgs). It is composed primarily of sandy to silty fill material with a hydraulic conductivity of 2 ft/day. A clay unit forms the lower boundary of this aquifer. The intermediate aquifer (18-27 ft bgs) is composed of fine silt laminae and very fine sand layers within the clay unit and has a hydraulic conductivity of 2.6 ft/day. The lower portion of this clay unit forms a boundary between the intermediate and lower aquifers. Monitoring wells did not detect any volatile organic compounds (VOCs) in the lower aquifer. The hydraulic conductivity of the upper aquifer is reported to be 2 ft/day while the intermediate aquifer's hydraulic conductivity is 2.6 ft/day. No information is provided on the lower aquifer.

The PRB was installed to the base of the intermediate aquifer. It is a 1-ft-wide continuous trench composed of 50% sand and 50% zero-valent iron by volume in the form of iron filings. The 400 tons of zero-valent iron was homogeneously distributed throughout the sand using cement-mixing equipment. A one-pass trenching technique was used from a surface bench 4-6 ft bgs. This surface bench allowed the trenching equipment to reach the final depth of 29 ft bgs. Phase 1 of the installation called for a 325-ft section to address the highest concentrations of VOCs and mitigate suspected offsite migration. Phase I construction—including mobilization, benching, installation, and demobilization—was completed in 4 weeks.

Design for this PRB system was $50,000. The total installation cost for both phases will be approximately $350,000. This includes construction, materials, and the cost of the reactive media.

Cleanup goals for the site are 0.005 mg/L for TCE, 0.070 mg/L for cDCE, and 0.002 mg/L for VC. Quarterly groundwater sampling and analysis from wells both upgradient and downgradient of the wall is continuing. While VOC concentrations in the upgradient monitoring wells remain highly variable, wells installed on the downgradient side of the wall have shown generally consistent downward trends and lower VOC concentrations than the upgradient wells.

Minor problems were encountered at the start of Phase 1 installation, with some material cave-in occurring at the top 3-4 ft of the trench sidewalls. This problem was alleviated by reconfiguring the location of the feed hopper on top of the boot and by adding steel plates to the top portion of the boot, to improve material flow. Installation through the two aquifers has affected groundwater flow in the vicinity of the treatment wall. By providing a greater connection between the two aquifers, groundwater velocities have been reduced and groundwater flowpaths modified slightly. The reduction in groundwater velocities and modified flowpaths should not affect the capability of the treatment wall to intercept and adequately treat VOCs at the site. Increased residence time for treatment will improve the long-term treatment efficacy.

Modifications to the groundwater monitoring schedule were also necessary to take into account differences in groundwater flow rates.

Lessons Learned

Compared with other methods, continuous trenching provided cost-effective installation and a high degree of confidence that materials would be placed according to the design, to create a continuous treatment wall with equal distribution of the zero-valent iron.

Because of the reduced groundwater flow velocity at the site, more time than originally estimated will be required to complete an initial flushing of VOCs in downgradient groundwater.

Site managers have found that the presence of chloride is not a good indicator of the effectiveness of the dechlorination process for this site.

Note: This is the complete installation profile provided by the Remediation Technology Development Forum <www.rtdf.org> for this project. Plots of analytical data are available through a link in the online installation profile.

Permeable Reactive Barrier Project Profile:
Kansas City Plant, Kansas City, MO

Installation Year: 1998
Contaminants: 1,2-Dichloroethylene and Vinyl Chloride
Reactive Media: Fe^0
Cost: $1,500,000
Construction: Continuous trench
Point of Contact: Paul Dieckmann
Allied Signal FM&T
2000 East 95th Street
P.O. Box 419159
Kansas City, MO 64141-6159
Telephone: (816) 997-2335
Fax: (816) 997-7361
Email: pdieckmann@KCP.com

A permeable reactive barrier (PRB) was installed in April 1998 at the U.S. Department of Energy's (DOE) Kansas City Plant in Kansas City, MO. Contaminants of concern include 1,2-dichloroethylene (1,2-DCE) and vinyl chloride (VC). Maximum initial concentrations encountered at the site were 1,377 µg/L of 1,2-DCE and 291 µg/L of VC.

The Kansas City Plant site is underlain by alluvial sediments that range from 20-33 ft in thickness. Lower alluvial sediments are characterized by low plasticity clays that overlie basal gravels. The alluvial sediments are underlain by bedrock shale. The basal gravel is the most permeable unit and acts as a semi-confined aquifer. The hydraulic conductivity of the basal gravel is 34 ft/day, while the hydraulic conductivity of the overlying clay unit is 0.75 ft/day.

The PRB was constructed as a continuous trench measuring 130 ft long. Sheet piles were driven into bedrock to support the sidewalls. The resulting excavation was 6 ft wide. The first 6 ft of the trench above bedrock was filled with 100% zero-valent iron. The remainder of the trench was filled with 2 ft of zero-valent iron and 4 ft of sand. These differing thicknesses were used to compensate for the increased flow-through thickness required for the basal gravel unit. Approximately 8,320 ft3 of reactive iron was used in the permeable barrier.

Design costs were approximately $200,000. Design costs included pre-design site characterization done to obtain additional chemical, hydrological, and geotechnical data. Installation costs were $1,300,000. This includes construction, materials, the reactive material, and hazardous waste transportation and disposal.

Cleanup goals for the site are Maximum Contaminant Levels (MCLs)—70 µg/L for 1,2-DCE and 2 µg/L for VC. The VOC plume is predominant in the basal gravel unit.

Early in the project (1999), results of a sampling event indicated that all compliance wells were below MCLs but that concentrations were slowly rising in a sidegradient well. By April 1999, the contaminant concentration exceeded the MCLs. Based on further monitoring, it was estimated that the PRB captured and destroyed 97% of the contaminant mass that passed through or around the barrier during the initial 17 months of the demonstration.

Sampling conducted in 1999 detected vinyl chloride and 1,2-DCE in a well about 4 ft south of the wall at levels exceeding site clean up standards. Contamination in this well continued to increase throughout the remainder of the year. New wells installed 40 ft south of the wall detected contamination by the same compounds but at levels below site clean up standards. Wells further south were free of contamination.

A pump test was conducted approximately 60 ft from the northern end of the wall in 1999 to determine the hydraulic conductivity of a former buried channel. It was thought that this channel may act as a conductive zone channeling contamination around (north) of the wall. Results of the pump test and data from newly installed wells in this area showed that the buried channel exhibited a conductivity very similar to that calculated from the original pre-design pump test (38 ft/day vs. 34 ft/day). The buried channel was also found to be free of contamination and that upgradient (contaminated) groundwater at the walls northern portion flowed into the wall with no bypass.

A detailed hydrogeologic investigation consisting of the installation and sampling of new wells, a pump test, and slug tests was conducted at the south end of the PRB in the Spring 2000. The pump test occurred in a well approximately 40 ft south of the wall. Results of this study identified a zone of high hydraulic conductivity (K>100 ft/day). Water levels also suggested a smear layer at the leading edge of the wall possibly created during construction.

Sampling of the barrier was discontinued in May of 2000. A new well, installed about 180 ft downgradient of the wall in April 2000 exhibited contamination over site cleanup standards. Regulatory authorities, however, required that an existing pumping well 140 ft downgradient of the wall resume pumping by June 1, 2000. The pumping well was restarted June 1, effectively rendering the PRB ineffective. Sampling of existing monitoring wells for VOC's in and around the wall occurs once a year for regulatory permitting purposes.

An additional assessment of the wall is currently being conducted exploring approaches to enhance performance.

Lessons Learned

The following are among lessons learned in this PRB installation:

Detailed hydrogeologic characterization is required when designing PRBs. Sufficient pre-characterization for one type of containment system may not be sufficient for another.

For sites where pump and treat had already been occurring, sufficient time must be allowed for the groundwater flow system and more importantly the contaminant plume to return to ambient non-pumping conditions.

Installation of the continuous PRB did cause a redistribution of heads and a partial change in plume direction. The wall acted somewhat like an equalization tank redistributing heads. Flow gradient into the north end of the wall was about four times higher than at the south end. As a result, some of the groundwater flow at the south end was redistributed around the wall.

- The cost and time required for constructing a continuous permeable reactive wall was estimated to be less than that for constructing a series of impermeable wall and gate sections. The continuous wall was expected to be constructed with a one-pass deep trenching machine. However, the contractor had difficulties with the machine, which may have been due to the heavy, wet clay. The problems encountered resulted in utilization of conventional sheet pile construction of the permeable wall. This should actually benefit the long-term performance. For example, there was better opportunity during the installation process to verify intimate contact of iron placement with the bedrock surface; additional wall was created by the use of "Z" piles; and uniform, continuous placement of iron was visually verified.

Note: This is the complete installation profile provided by the Remediation Technology Development Forum <www.rtdf.org> for this project. Photographs of the installation are available through a link in the online installation profile.

Permeable Reactive Barrier Project Profile:

Shaw Air Force Base, Sumter, SC

Installation Year: 1998
Contaminants: Trichloroethane, Dichloroethane, Dichloroethylene, and Vinyl Chloride
Reactive Media: Fe^0, iron filings
Cost: $1,065,000
Construction: Continuous Wall Trenches
Point of Contact: Richard Roller
Shaw Air Force Base
Environmental Flight
345 Cullen Street
Shaw Air Force Base
Sumter, SC
Telephone: (803) 895-9991
Facsimile: (803) 895-5103
Email: richard.roller@shaw.af.mil

A full-scale permeable reactive barrier (PRB) system was installed at Shaw Air Force Base in Sumter, SC, in 1998. Parallel continuous wall trenches were chosen based on favorable site conditions for chain trenching, the relatively shallow depth of contaminants, timely installations (within five days), and the immediate effectiveness of the system. Tricholoethane (TCA), Dichloroethane (DCA), dichloroethylene (DCE), and vinyl chloride (VC) are the contaminants of concern at the site. Initial concentrations of these analytes were 18,100 µg/L for TCA; 4,554 µg/L for DCA; 2,500 µg/L for DCE; and 180 µg/L for VC.

The site was formerly a fire training area where combustible wastes (jet fuel, spent solvents, waste oils, and hydraulic fluids) were burned in an unlined and bermed pit. Fluids that were not ignited during the fire training exercises drained through the fine- to medium-grained sandy soil impacting groundwater. Contaminants migrated eastward with the groundwater flow, toward the lower-lying plain of Long Branch Creek. Depending on the season, depth to groundwater ranges from 8-14 ft below ground surface (bgs) in the area of the pit and 3-6 ft bgs in the flood plain. Total depth of the shallow aquifer is approximately 60-70 ft bgs. Groundwater flow velocity is 1.5 ft/day, and porosity is 10-20%.

The PRB consists of four parallel continuous wall trenches, each measuring 8 in wide, 270 ft long, and 24 ft deep. The trenches are approximately 10 ft apart. The saturated sands and hydrostatic pressure prevented the chain trenchers from attaining the originally planned 30 ft depth and 14-in width. This fact was realized at the time of installation. Design costs were $123,000. Installations costs, including site preparation, construction, materials, and patent royalties, totaled $942,000.

Samples taken from the same location at which pre-design concentrations were observed and at the down gradient edge of the PRB show reductions from 18,100 to <1 µg/L for TCA; from 4,554 to 340 µg/L for DCA; and from 2,500 to 40 µg/L for DCE. VC increased from 180 µg/L to 290 µg/L. VC is a daughter product of the dechlorination processes and is produced at higher concentration than the PRB was originally designed to destroy. However, monitored natural attenuation processes at the down gradient edge of the PRB have indicated sufficient biodegradation rates to reduce the VC levels at a proposed compliance boundary prior to entering a creek. Long-term sampling is conducted quarterly.

Lessons Learned

The production of daughter products within the PRB zone should be considered in specifying the width and retention time required to treat contaminated groundwater to remedial levels.

Note: This is the complete installation profile provided by the Remediation Technology Development Forum <www.rtdf.org> for this project.

Permeable Reactive Barrier Project Profile:
Borden Aquifer, Ontario, Canada

Installation Year: 1991
Contaminants: Trichloroethylene and Tetrachloroethene
Reactive Media: Fe^0
Cost: $30,000
Construction: Continuous trench
Point of Contact: Stephanie F. O'Hannesin
Environmental Technologies, Inc.
745 Bridge Street West
Suite 7
Waterloo, Ontario N2V2G6 Canada
Telephone: (519) 746-2204 Ext: 235
Facsimile: (519) 764-2209
Email: sohannesin@eti.ca

A pilot-scale demonstration of a permeable reactive barrier (PRB) to remediate groundwater contaminated with trichloroethylene (TCE) and perchloroethylene (PCE) was conducted at the Canadian Forces Base in Borden, Ontario, Canada. The PRB was installed in 1991. Contamination was the result of a previous site study to determine the dissolution characteristics of a mixed non-aqueous fluid. The contaminant plume was about 6.5 ft wide and 3.3 ft thick. Initial concentrations were 250,000 µg/L TCE and 43,000 µg/L PCE. The plume source was located about 13 ft below ground surface (bgs) and 3.3 ft below the water table.

The contaminated surficial aquifer is composed of medium-fine sand. Its lower boundary is a thick clay deposit located 30 ft below the surface. The upper boundary of the aquifer varies between 6.5 ft and 10 ft bgs. Hydraulic conductivity for the surficial sand aquifer is 20.5 ft/day.

Reactive material was installed using sealable joint sheet piling 18 ft downgradient from the source. Individual piles were interlocked to create a rectangular cell normal to groundwater flow direction that was 18 ft long, 5 ft wide, and 32 ft high. The pilings were then driven as a unit to a depth of 32 ft using a hydraulic vibratory driver suspended by a crane. The joints were sealed with a bentonite-based sealant, and the water table was lowered below the depth of excavation. The cell was then excavated and the native material was replaced with a mix of 22% (by weight) zero-valent granular iron and 78% coarse sand from 12.4-20 ft bgs. This mixture had a hydraulic conductivity of 124 ft/day. After emplacement of the mixture, the sheet pilings were removed.

The cost for installation, exclusive of the cost of reactive iron and labor, was $30,000. The reactive material and the labor were donated.

A total of 348 monitoring wells were installed upgradient and downgradient from the wall, as well as within the reactive material. Concentration distributions were monitored over a period of five years. The PRB reduced TCE concentrations by 90% and PCE concentrations by 86%. No vinyl chloride was detected in the samples. The low amounts of calcium carbonate precipitate detected in the wall after five years suggests that the wall's performance should persist for at least another five years. Since the residual source was remediated using permanganate flushing, there are no plans for additional sampling.

Note: This is the complete installation profile provided by the Remediation Technology Development Forum <www.rtdf.org> for this project. A website with additional information on this PRB is available through a link in the online installation profile.