ESTCP
Cost and Performance Report

(CU-9604)

Permeable Reactive Wall Remediation of Chlorinated Hydrocarbons in Groundwater

July 1999

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

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LIST OF ACRONYMS

2-D	two-dimensional
3-D	three-dimensional
AFB	Air Force Base
Battelle	Battelle Memorial Institute
Br	bromine
BRAC	Base Realignment and Closure
BTEX	benzene, toluene, ethylbenzene, and xylenes
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFC	chlorofluorocarbon
cis-1,2-DCE	*cis*-1,2-dichloroethene
CRB	continuous reactive barrier
CVOC	chlorinated volatile organic compound
DCA	dichloroethane
DCE	dichloroethene
DNAPL	dense, nonaqueous-phase liquid
DO	dissolved oxygen
DOC	dissolved organic carbon
DoD	Department of Defense
EDS	energy dispersive spectroscopy
EFA	Engineering Field Activity
Eh	redox potential relative to standard hydrogen electrode
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
ETI	EnviroMetals Technology, Inc.
F&G	funnel & gate
gpm	gallons per minute
HAZWOPER	hazardous waste operations
IRP	Installation Restoration Program
ITRC	Interstate Technology & Regulatory Cooperation
K	hydraulic conductivity
k	reaction rate constant

LIST OF ACRONYMS (continued)

LNAPL	light, nonaqueous-phase liquid
MCL	maximum contaminant level
mg/L	milligrams per liter
MS	matrix spike
msl	mean sea level
n	total porosity
NFESC	Naval Facilities Engineering Service Center
NPL	National Priorities List
O&M	operations and maintenance
OVA	organic vapor analyzer
PCE	perchloroethene
PPE	personal protective equipment
PV	present value
RI/FS	Remedial Investigation/Feasibility Study
SEM	scanning electron microscopy
t1/2	half-life
TCE	trichloroethene
TDS	total dissolved solids
TOC	total organic carbon
TSS	total suspended solids
U.S. EPA	United States Environmental Protection Agency
VOA	volatile organic analysis
VOC	volatile organic compound
XRD	x-ray diffraction

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Technical material contained in this report has been approved for public release.

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1.0 EXECUTIVE SUMMARY

A pilot-scale permeable reactive barrier was installed at Moffett Field in April 1996 and its performance was monitored over the following 16 months on a quarterly basis. The details of this study are described in a technology evaluation report (Battelle, 1998). This document provides a brief account of the technology evaluation. The objective was to capture and treat a small portion of the West Side Plume that contains chlorinated volatile organic compound (CVOC) contaminants, primarily trichloroethene (TCE), *cis*-1,2-dichloroethene (*cis*-1,2-DCE), and perchloroethene (PCE). The reactive cell in the funnel-and-gate type barrier is composed of granular zero-valent iron, a strong reducing agent. The flowthrough thickness of the reactive cell is 6 ft and it is lined on either side by 2 ft of pea gravel. The reactive cell and pea gravel comprise the gate, which is 10 ft-long and is flanked on each side by 20-foot long funnel walls.

The lowering of groundwater redox potential (Eh) and dissolved oxygen (DO), and the presence of nonchlorinated hydrocarbon products in the reactive cell, indicated conditions conducive to abiotic reductive dechlorination. Over the 16-month period after construction, the barrier consistently reduced groundwater concentrations of TCE, PCE, *cis*-1,2-DCE, and vinyl chloride to well below their respective maximum contaminant levels (MCLs) or to non-detect levels, which were the design criteria or performance goals for the barrier. The range of degradation half-lives of these compounds observed in the field system conformed well with the half-lives predicted during bench-scale column tests. The reactive cell did not contribute any significant levels of dissolved iron to the groundwater and the water exiting the cell contained below 0.3 mg/L of iron, the secondary drinking water standard.

Water levels, a down-hole groundwater velocity meter, and tracer tests were used to evaluate the hydraulic flow characteristics of the barrier. The hydraulic capture zone of the barrier appears to be about 30 feet wide and extends about midway along each funnel wing. This capture zone estimate was based on the estimated groundwater velocity, porosities, and dimensions of the reactive cell and aquifer. The estimated groundwater velocity in the reactive cell ranges between 0.2 to 2 feet/day, providing a minimum residence time of 3 days in the reactive medium; the design requirement for contaminant degradation to desired levels was 2 days. The flow through the aquifer and the gate is heterogeneous and there appears to be more flow through the deeper portions of the reactive cell than in the shallower portions.

The geochemical evaluation included analysis of inorganic parameters in the barrier and its vicinity, as well as analysis of core samples of the iron collected at the end of 16 months of operation. Calcium and iron compounds precipitated out of solution during flow through the reactive cell. However, the actual calcium precipitate mass found on the iron cores was much lower than the loss of dissolved calcium in the groundwater flowing through the reactive cell. This may indicate that not all the precipitates formed stay in the gate; colloidal-sized precipitates could be flowing out with the groundwater. The hydraulic gradient across the flowthrough thickness of the gate remained relatively consistent through the 16 months of operation. There were no indications during the 16 months of operation of any decline in the reactivity or hydraulic performance of the barrier. Future reactive and hydraulic performance of the barrier is difficult to predict.

The barrier operated unattended and without maintenance after construction. As long as the reactive and hydraulic performance of the barrier holds, the only recurring cost expected is for compliance monitoring. If the barrier retains its performance over approximately 6 years, the cost evaluation indicates that it will be more cost-effective than a groundwater pump-and-treat system.

2.0 TECHNOLOGY DESCRIPTION

A permeable reactive barrier in its simplest form can be visualized as a trench filled with porous reactive material, placed in the path of a groundwater plume (Figure 2.1 a and b) (Gavaskar et al., 1998; Gillham, 1996). As the plume passes through the reactive material, the target contaminants are degraded to potentially nontoxic compounds. Several variations of this simple configuration are possible depending on individual site characteristics (Figure 2.1 a through d). One common variation shown in Figure 2.1c is the funnel-and-gate system, which combines permeable (gate) and impermeable (funnel) sections of the barrier to capture increased flow and better distribute the contaminant loading on the reactive medium. Multiple gates can be used for wider plumes. A simple gate could consist of a reactive cell or trench filled with the reactive medium (e.g., granular iron). The gate also could be divided into a reactive cell and other components. For example, pea gravel sections could be installed along the upgradient and downgradient edges of the reactive cell to improve porosity and mixing of the influent and effluent through the gate.

2.1 TECHNOLOGY BACKGROUND

Permeable reactive barriers have emerged over the last 5 years as a promising alternative to pump-and-treat systems for treating dissolved groundwater contamination. The main advantage of a reactive barrier is the passive nature of the treatment. That is, for the most part, its operation does not depend on any external labor or energy input. Once installed, the barrier takes advantage of the in-situ groundwater flow to bring the contaminants in contact with the reactive material. A passive treatment system is especially desirable for contaminants such as chlorinated solvents, where the plume is likely to persist for several decades or hundreds of years. Considerable research (15 field pilot tests and 5 full-scale applications) has been conducted over the last 5 years to demonstrate variations of this technology.

The reactive material used in the barrier may vary depending on the type of contaminants being treated. The most common reactive medium used so far has been granular zero-valent iron, the use of which was patented by the University of Waterloo, Ontario (Gillham, 1993). Other reactive materials, such as bimetals and magnesium dioxide, are also being researched by the scientific community.

2.2 THEORY OF OPERATION AND LIMITATIONS

Zero-valent iron is a strong reducing agent that can abiotically reduce dissolved contaminants, such as PCE, TCE, and other chlorinated solvents.

$$3Fe^{0} \% C_2HCI_3 \% 3H^{\%} \ddot{y} 3Fe^{2\%} \% C_2H_4 \% 3CI^{\&} \qquad \textbf{(1)}$$

Ethene and ethane are the main products of TCE degradation. However, indications are that these final reaction products are generated through multiple pathways. By the hydrogenolysis pathway, TCE degrades to *cis*-1,2-DCE, which in turn degrades to vinyl chloride. Both *cis*-1,2-DCE and vinyl chloride are fairly persistent under the reducing conditions of the iron medium and degrade to ethene and ethane more slowly than TCE or PCE. Fortunately, only 5% or less of TCE appears to take this pathway. Most

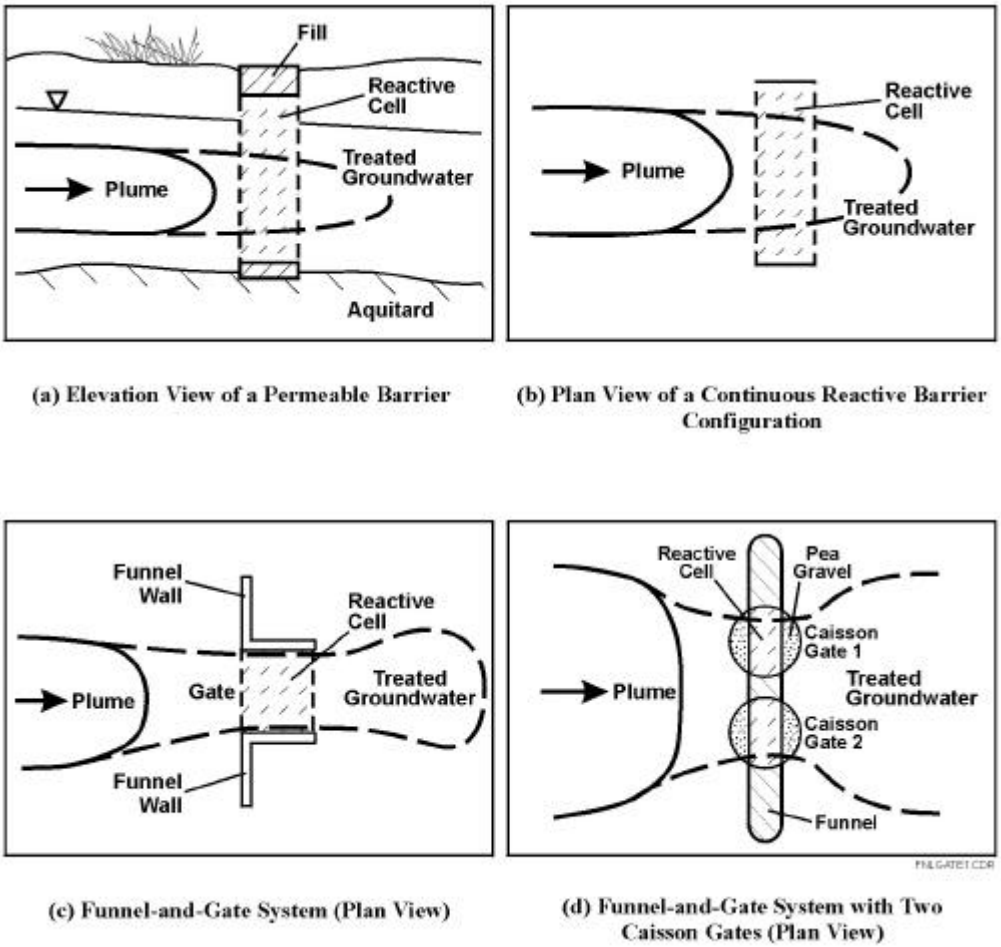
of the TCE appears to degrade to ethene and ethane by the beta-elimination pathway (Roberts et al., 1996) through the formation of intermediates such as acetylene. These intermediates are short-lived and quickly degrade to ethene and ethane. Other contaminants such as dissolved chromium and uranium, which are amenable to reduction by iron, also can be treated by precipitating them out of the groundwater. Some CVOCs, such as 1,1-dichloroethane (DCA), may be relatively recalcitrant to degradation by iron.

2.3 TECHNOLOGY SPECIFICATIONS

The technology performance specifications for the permeable reactive barrier technology usually involve the following:

- Treating the contaminants in the captured groundwater to below their respective maximum contaminant levels (MCLs), drinking water standards, or to a risk-based alternative level.
- Ensuring that the interaction between the barrier materials and the ground-water constituents does not cause environmentally deleterious materials to be released in the downgradient aquifer.
- Achieving the desired hydraulic capture efficiency.
- Ensuring that the barrier retains its reactivity and hydraulic capture efficiency in the long term.
- Ensuring that the barrier represents a cost-effective option for the treatment of the targeted contamination at the site.

Being a passive technology, ease of operation is the main advantage of the permeable barrier. Once the barrier is installed, operator involvement is limited to the relatively infrequent monitoring required to ensure that the barrier is performing as designed. Any maintenance required also is likely to be relatively infrequent, judging by the performance of the Moffett Field barrier so far.



(a) Elevation View of a Permeable Barrier

(b) Plan View of a Continuous Reactive Barrier Configuration

(c) Funnel-and-Gate System (Plan View)

(d) Funnel-and-Gate System with Two Caisson Gates (Plan View)

Figure 2.1. Schematic Illustrations of Some Permeable Barrier Configurations (Gavaskar et al., 1998)

2.4 KEY DESIGN STEPS

Figure 2.2 shows the steps in the design of a permeable reactive barrier. These steps involve the determination of the following:

- Site characteristics affecting barrier design
- Reaction rates or half-lives (through column testing)
- Location, configuration, and dimensions of the barrier (through hydrogeologic modeling)
- Longevity (through a geochemical evaluation)
- Emplacement options
- Cost

Some of the design steps are interrelated. Adequate site characterization provides the contaminant distribution and hydrogeologic parameters required for designing the location, configuration, and dimensions

of the barrier. Column tests may be used to determine the reaction rates of the contaminants, which are then used to determine the residence time or contact time required, which in turn is used (along with the groundwater velocity determined during site characterization) to determine the thickness of the reactive cell. The width of the reactive cell or gate depends upon the relative permeabilities of the aquifer and reactive medium, as well as the width of the plume targeted for capture. The depth of the barrier is determined by the depth of the aquitard. In most cases, especially for chlorinated solvent contamination, the barrier is

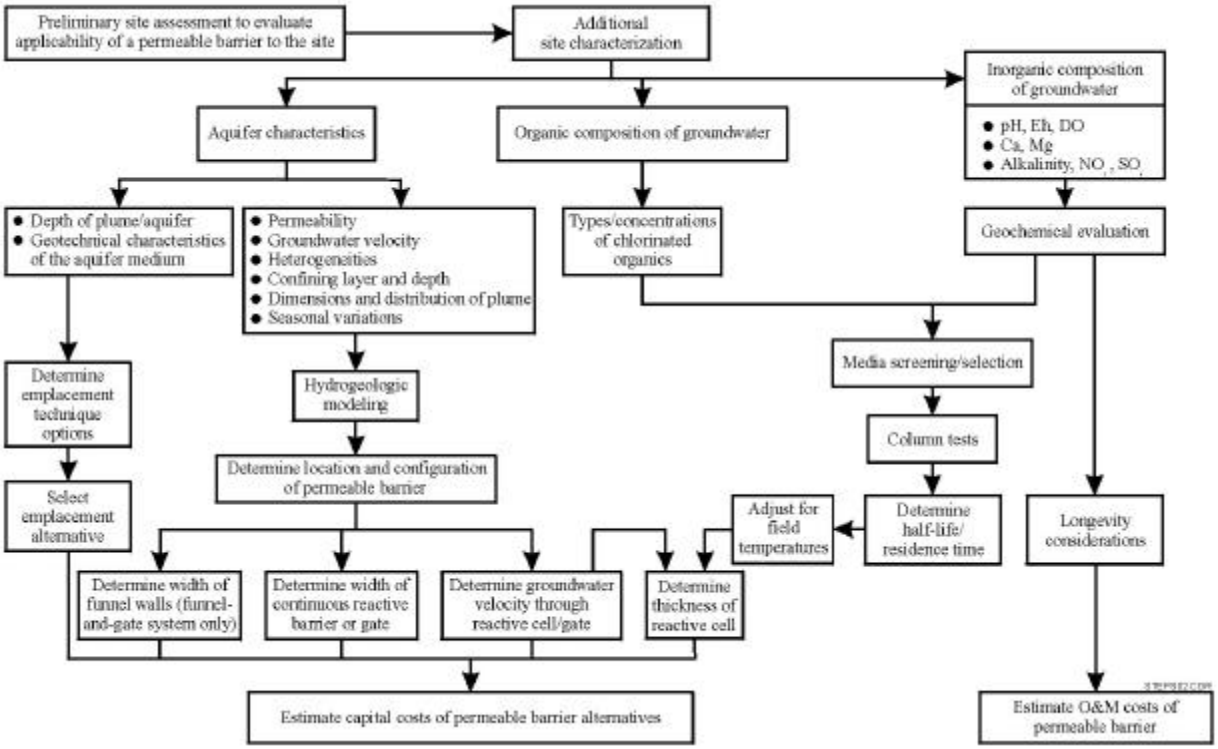


Figure 2.2. Steps in the Design of a Permeable Barrier System

expected to be keyed into the aquitard. Hanging barriers (those completed to a depth above the aquitard) have been proposed but they may be more suitable for plumes emanating from light, nonaqueous-phase liquid (LNAPL), rather than dense, nonaqueous-phase liquid (DNAPL) sources.

Evaluation of the inorganic constituents of the site groundwater provides an indication of the barrier's expected longevity and of the safety factors that may be required in the barrier dimensions to account for eventual decline in performance.

2.5 MOBILIZATION, CONSTRUCTION, AND OPERATION

Once the location, configuration, and dimensions of the barrier have been designed, a qualified geotechnical contractor is hired to construct the barrier. Most qualified geotechnical contractors have standard construction equipment (such as a backhoe, crane, vibratory hammer, front-end loader, etc.) that can be used for the job. Generally, at least 6 weeks are required for mobilization, including 4 to 5 weeks for

readying the equipment and transporting it to the site. Once at the site, the equipment can be set up relatively quickly and construction usually starts within a week. Most of the equipment can be set up in a 50- by 50-foot area that has no overhead utilities. The iron or other reactive medium has to be purchased and transported to the site as well. The iron is generally sold in 3,000-pound waterproof bags and is in a form ready to be installed. Monitoring wells within the barrier are installed during barrier construction. Monitoring wells in the surrounding aquifer can be installed at any time with standard well drilling equipment. Once the barrier is installed and the ground surface has been restored, the barrier operates on its own using the natural groundwater flow to bring the contaminants in contact with the reactive medium.

2.6 ADVANTAGES AND LIMITATIONS OF PERMEABLE BARRIERS

The permeable barrier technology has five main advantages over conventional pump-and-treat systems:

- It is passive in nature (no external energy is consumed).
- It has the potential for treating dissolved chlorinated solvents in a groundwater plume to very low levels.
- No aboveground structures are required, making the property suitable for reuse.
- No hazardous waste byproducts requiring disposal are generated, and discharge of treated effluent is not needed. At many sites, soil excavated during barrier construction contains low concentrations of contaminants and is handled in the same fashion as construction debris. However, this should be verified at each site.
- It has potential for long-term unattended operation.

Permeable barrier application may be limited by the following considerations:

- Presence of aboveground or underground building structures at the desired barrier location could present difficulties in construction.
- Deeper plumes may be inaccessible or expensive to remediate with permeable barriers based on currently available commercial emplacement techniques.
- Presence and properties of an aquitard into which the barrier can be keyed.
- Extremely low or high groundwater velocities may lead to difficulties in groundwater capture or barrier sizing and cost.

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3.0 DEMONSTRATION DESIGN

This section describes the strategy and planning leading to the construction of the pilot barrier at Moffett Field and the subsequent performance evaluation.

3.1 DEMONSTRATION SITE/FACILITY BACKGROUND

As part of the Installation Restoration Program (IRP), the U.S. Navy has been identifying and evaluating past hazardous waste sites at the former Naval Air Station, Moffett Field (now referred to as Moffett Federal Airfield) in an effort to control the spread of contamination from these sites. Moffett Field, as it is still commonly called, is located in Mountain View, California. Moffett Field appeared on the Superfund's National Priorities List (NPL) in June 1987. As a result, the RI/FS process was initiated as required by the Comprehensive Environ-mental Response, Compensation, and Liability Act (CERCLA).

Several investigations at Moffett Field have identified extensive groundwater contamination by chlorinated solvents. The contaminants of concern are TCE; *cis*-1,2-DCE; PCE; 1,1-DCE; and 1,1-DCA. Remediation of groundwater contaminated with chlorinated volatile organic compounds (CVOCs) by pump-and-treat systems is difficult, costly, and generally ineffective. NFESC and the U.S. Navy's EFA West are therefore investigating alternative technologies that have potential technical and cost advantages over conventional pump-and-treat systems. The permeable barrier technology has been identified by the U.S. Environmental Protection Agency (U.S. EPA, 1995) as an emerging technology for cleanup of groundwater contaminated with chlorinated solvents, and was the technology of choice for this pilot demonstration in the West Side Plume (a large regional chlorinated solvent plume on the west side of Moffett Field).

3.2 PHYSICAL SETUP AND OPERATION

Table 3.1 shows the schedule of events leading to the completion of the demonstration. The pilot barrier was constructed at Moffett Field in April 1996. Preliminary monitoring of groundwater conditions in and around the Moffett Field permeable barrier was conducted in June 1996, about 6 weeks after installation, to establish that the barrier was functioning as designed. The results of this preliminary monitoring event showed that the TCE and PCE concentrations in the groundwater flowing through the barrier were being significantly reduced.

Subsequent quarterly monitoring (five quarters) has enabled the evaluation of barrier performance under seasonal changes in contaminant and flow characteristics. Quarterly monitoring also allowed an estimation of the length of time it takes the barrier to reach steady-state performance. In addition, two tracer tests and down-hole groundwater velocity measurements were conducted. At the end of approximately 1.5 years, core samples of the reactive medium from the barrier and a core sample of the downgradient aquifer were collected and analyzed to evaluate potential precipitation and biofouling effects on the barrier and aquifer media, respectively.

Table 3.2 shows the various participants involved in the demonstration. Battelle, under contract to NFESC, prepared the performance monitoring plan for the demonstration, coordinated its implementation,

conducted the hydrogeologic and geochemical modeling, evaluated the monitoring and modeling results, and prepared this demonstration report. TetraTech EMI (formerly PRC

Table 3.1. Demonstration Activities Schedule

Activity	Date Completed
Site characterization Bench-scale tests Groundwater modeling reports Performance Monitoring Plan (draft) Updated groundwater modeling report Performance Monitoring Plan (final)	December 1995 October 1995 December 1995/June 1996 September 1996 November 1996 July 1997
Pilot barrier construction	April 1996
First quarterly monitoring event Second quarterly monitoring event Third quarterly monitoring event Fourth quarterly monitoring event Fifth quarterly monitoring event	June 1996 September 1996 January 1997 April 1997 October 1997
First tracer test Second tracer test Iron cores collection	April 1997 August 1997 December 1997
Draft Performance Evaluation Report Final Performance Evaluation Report	June 1998 November 1998

Table 3.2. List of Project Participants

Funding for Demonstration	
ESTCP	**BRAC**
NFESC Evaluation of barrier performance	**EFA West** Design and construction
Battelle Performance evaluation plan Field monitoring Data evaluation, modeling Report preparation **Tetra Tech EMI** Field monitoring **Subcontract laboratories** Analysis of iron cores **Precision Sampling Inc.** Drilling for iron cores	**Tetra Tech EMI** Bench-scale tests Barrier design Oversee construction **EnviroMetal Technologies, Inc.** Design guidance **Slurry Systems Inc.** Construction subcontractor **Subcontract laboratories** Groundwater analysis

Environmental Management, Inc.), under contract to EFA West, conducted the bench-scale tests, coordinated the design, supervised the construction of the pilot barrier, and conducted the sampling and analysis for the field effort outlined in the performance monitoring plan.

3.3 DEMONSTRATION SITE/FACILITY CHARACTERISTICS

This section describes the results of the site characterization conducted to determine the physical characteristics of the aquifer underlying the pilot barrier site.

3.3.1 Description of Contaminant Plume

The permeable reactive barrier lies within a regional groundwater plume of CVOCs. Cleanup and contaminant identification activities have been underway at Moffett Field since 1987. Contaminants at Moffett Field include waste oils, solvents, cleaners, and jet fuels. Among many possible sources of contamination on the site are several underground storage tanks, aboveground storage tanks, a dry cleaning facility, and sumps. CVOCs found in the vicinity of the barrier include TCE; PCE; *cis*-1,2-DCE; 1,1-DCE; 1,1-DCA; and other chlorinated hydrocarbons. TCE is the most prevalent contaminant on the site. Nonchlorinated volatile organic compounds (VOCs), such as benzene, toluene, ethyl-benzene, and xylene (BTEX) compounds, are mostly absent in the vicinity of the current barrier demonstration project.

The CVOC plume exists mainly in the A aquifer (IT Corp., 1993). The plume is more than 10,000 feet long, about 5,000 feet wide, oriented north/northeast, and tapers to the north. TCE levels reported by IT Corp. (1992) exceeded 20 mg/L, and PCE levels were about 0.5 mg/L in the A aquifer. The distribution of TCE in the West Side Plume is shown in Figure 3.1.

3.3.2 Site Geology

Sediments in the Moffett Field area are a complex mixture of fluvial-alluvial clay, silt, sand, and gravel that slopes toward San Francisco Bay in the northeast (PRC, 1993, 1995; IT Corp. 1993). The deposits are Holocene/Pleistocene in age and generally are associated with flood events. Sands and gravels form interbraided channel structures that are incised into silt and clay deposits. These channels are divided into layered aquifers designated as A, B, and C aquifers. These aquifers extend more than 200 feet below land surface. Multiple channels of sand and gravel have been delineated at various elevation intervals within the aquifer zones (PRC, 1995).

The major region of interest for this study is the near-surface A aquifer. This zone is not laterally homogeneous due to the interbraided channel nature of the sediments. In the immediate vicinity of the permeable barrier, well logs, cone penetrometer tests, and geophysical logs were used to characterize sand channels and surrounding interchannel deposits. Several individual channels were mapped in the A aquifer and the permeable barrier was located in one of these sand channels, roughly perpendicular to the length of the channel (see Figures 3.2 and 3.3). The reactive gate and the funnel walls cover the whole width of the channel and are keyed into low-permeability sediments east and west of the target channel. These heterogeneities are likely to have a significant impact on groundwater flow through and around the barrier wall.

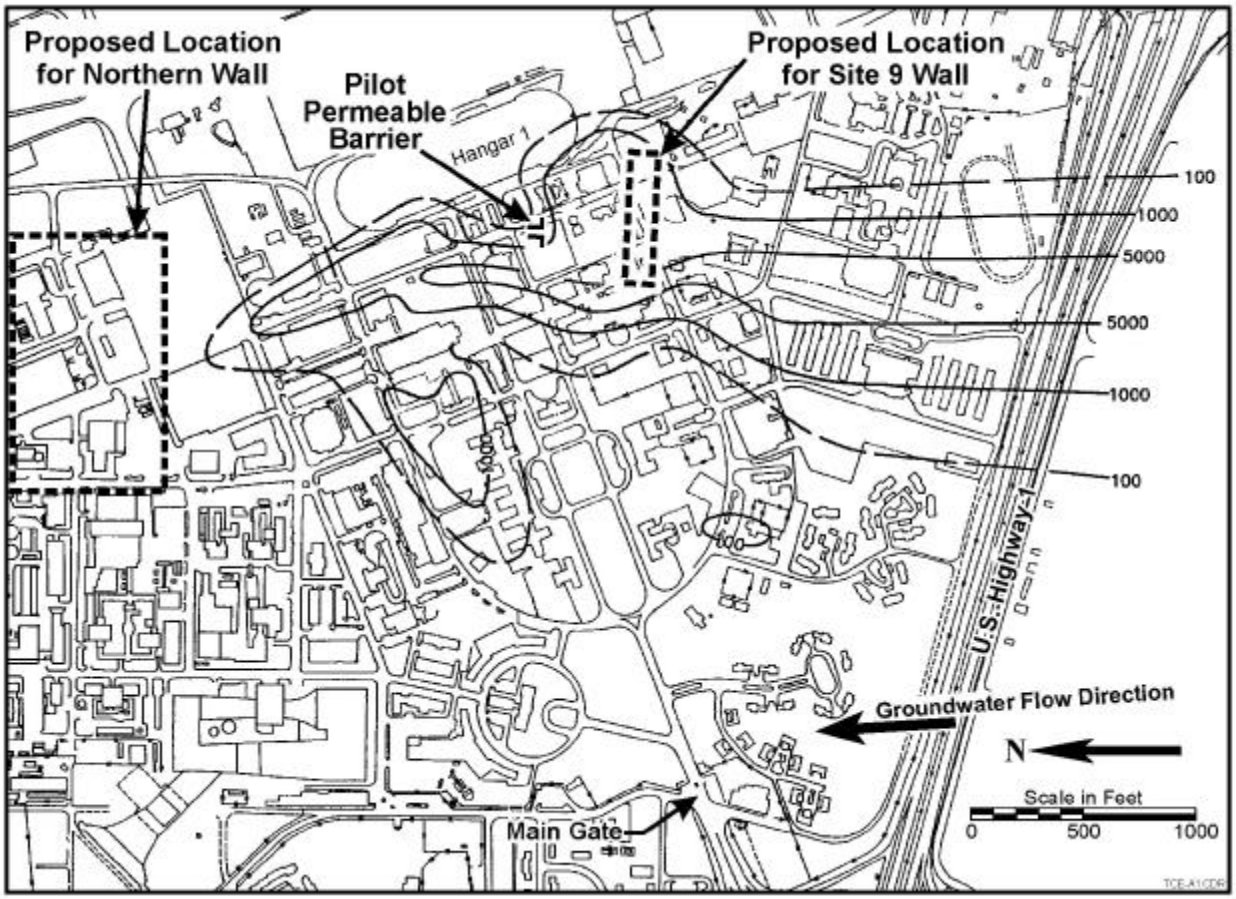

Figure 3.1. TCE Concentration (in µg/L) Contour Map for A1 Aquifer Zone, Second Quarter 1991 (Source: IT Corp., 1991)

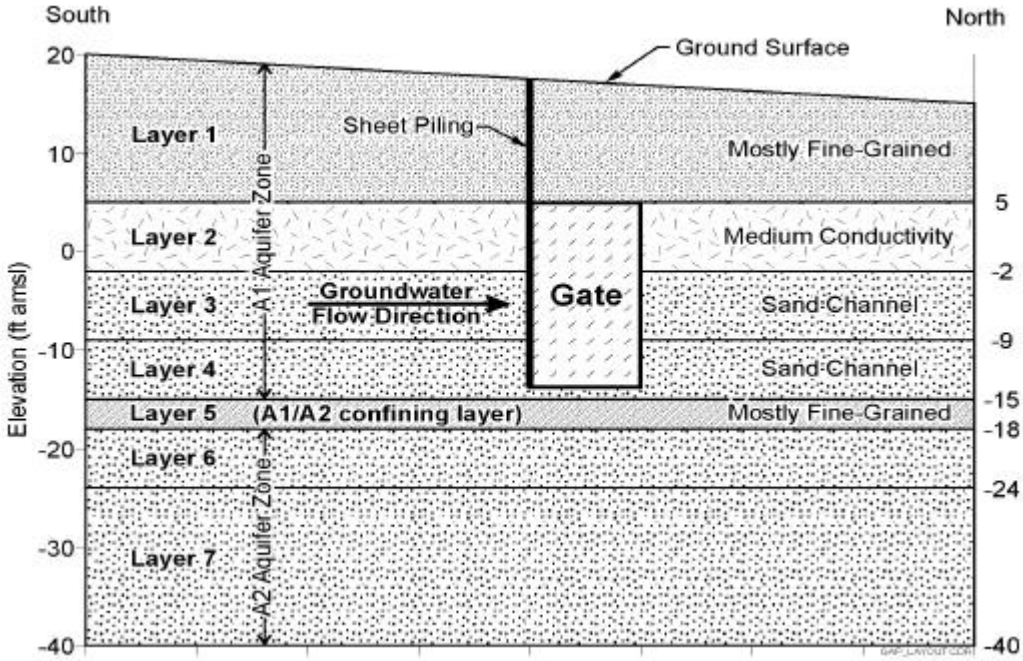

Figure 3.2. Schematic Depiction of the Geology in the Vicinity of the Permeable Barrier Along a North-South Vertical Section

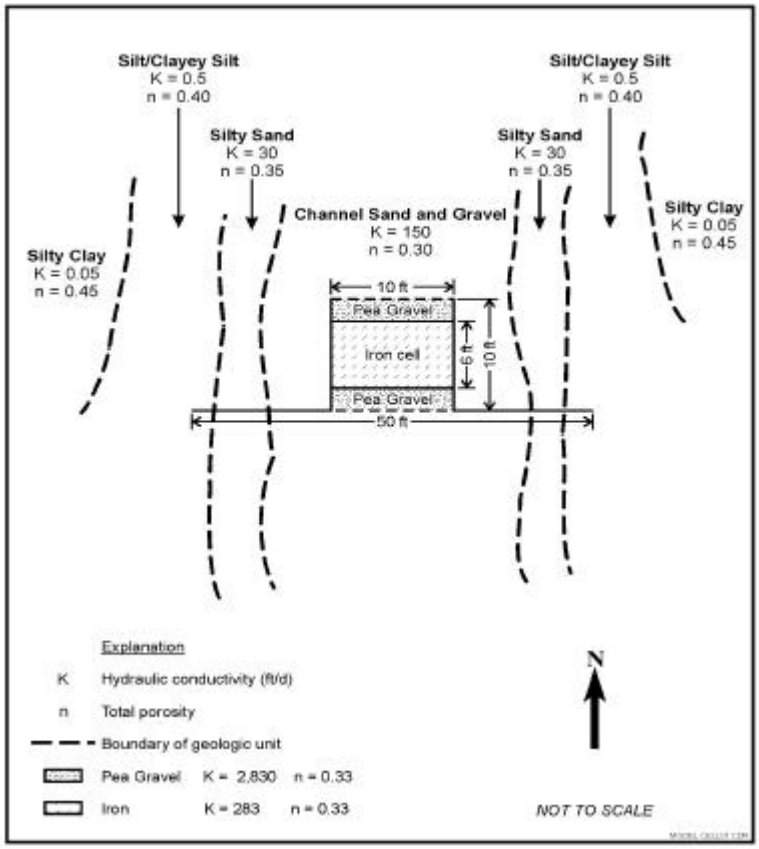

Figure 3.3. Permeable Barrier Location and Horizontal Dimensions Relative to Lithologic Variations in Surrounding A1 Aquifer Zone at Moffett Field

In the vertical direction, the A aquifer can be further divided into two zones, A1 and A2, separated by a silty-clay zone called the A1/A2 confining layer (aquitard). The A1 aquifer zone is up to 20 feet thick and is overlain by a clayey surface layer of varying thicknesses. Well logs and paleochannel maps suggest that the confining layer underlying the A1 aquifer zone is relatively thin in some areas and discontinuous. The A1 and A2 aquifer zones are inter-connected in some areas. The A2 aquifer zone is 0 to 20 feet thick and extends to 40 feet below mean sea level (msl). Although both A1 and A2 aquifer zones are contaminated, the pilot-scale reactive barrier penetrates only the A1 zone.

3.3.3 Site Hydrology

Water levels and pumping tests indicate that the A1 aquifer zone behaves as a semiconfined aquifer at this site. In the vicinity of the permeable barrier location, the observed hydraulic gradient varies from 0.005 to 0.009. This is also a representative range for historic hydraulic gradient at the site. Although there are

some small-scale local variations due to heterogeneities, the overall flow direction is roughly from south to north toward the San Francisco Bay. An IT Corp. (1993) report notes a slight upward gradient from A2 to A1 in the area, suggesting that the A2 aquifer zone is not fully confined. The connection between the two aquifers is also suggested by the presence of groundwater contamination in both the aquifers. Historic water level information from the site indicates that there is a strong correlation between the water levels in shallow aquifers and the rainfall. Thus, the groundwater levels are usually the highest during winter months when most of the rainfall occurs and lowest during late summer.

Four pumping tests were conducted by IT to determine the hydraulic properties of sediments in the area (IT Corp., 1993). Hydraulic conductivity (K) estimates from well tests range from 13 to 461 feet/day in the A1 aquifer zone and from 9 to 576 feet/day in the A2 aquifer zone. These tests show that there is a strong variability in the hydraulic conductivity at the site. Porosity values from 23 samples (PRC, 1993) ranged from 0.30 for sand and gravel to 0.45 for silty clay. Slug tests and pumping tests in the A1/A2 confining layer showed K of 0.1 to 0.3 foot/day.

As part of this demonstration, an attempt was made to improve the K determination at the site. Slug tests were conducted in February 1997 within the reactive cell and in the aquifer wells (Battelle, 1997). The tests within the reactive cell were inconclusive because recoveries were rapid and good time series profiles of water levels were unachievable due to the high K of the granular iron. Better results were obtained in the slug tests conducted in the aquifer. K values ranged from 0.04 foot/day to 633 feet/day and were related to lithologic variations as expected from previous site characterizations. The higher K values were observed in wells that are located in the sand channel that runs through the deeper regions of the A1 aquifer zone containing the pilot gate. The lower K values were observed in wells located in the interchannel silty and clayey deposits that run through the location of the funnel walls.

A representative range of groundwater velocity in the A1 aquifer zone was calculated to be 0.2 to 5.0 feet/day. However, the true range of velocities is probably at the lower end of the representative range when considered on a site-wide scale. Based on the site characterization information, the groundwater flow velocity in the A1 aquifer zone varies depending on the hydraulic properties of the sediments in very localized settings.

3.3.4 Moffett Field Barrier Design

A bench-scale study (PRC, 1995) was conducted to determine the most suitable iron source (batch tests) and to determine the CVOC degradation rate (column tests). Five batch tests indicated that the iron from Peerless Metal Powders, Inc. had the greatest sustained efficiency for PCE and TCE degradation. Consequently, iron from this source was used in the two column tests and field installation. A 50% by weight iron-sand mixture was used in both columns. The column tests provided data on half-lives of TCE (0.87 to 1.0 hr), PCE (0.29 to 0.81 hr), *cis*-1,2-DCE (3.1 hr), vinyl chloride (4.7 hr), and 1,1-DCA (9.9 hr). However, as an additional safety measure to ensure that the required degradation was obtained, 100% iron was used as the reactive medium in the field barrier.

In the design phase, based on factors such as the half-lives from the column tests, the estimated groundwater velocity, and the expected influent CVOC concentrations, a flowthrough thickness of 6 ft was

determined for the reactive cell in the permeable barrier at the Moffett Field site. The design objective was to reduce the CVOC concentrations in the reactive cell effluent to below their respective MCLs or below detection. The MCLs for the CVOCs of interest are 5 mg/L (PCE and TCE), 70 mg/L (*cis*-1,2-DCE), and 2 mg/L (vinyl chloride). 1,1-DCA is not of regulatory concern at this site and does not have a MCL.

Figures 3.3 and 3.4 show the design dimensions of the pilot funnel-and-gate system installed in April 1996. As seen in Figure 3.3, the design attempted to locate the gate in the sand channel to capture the bulk of the contaminant flow and the funnel in the interchannel deposits to intercept more (but not all) of the plume. The design did not require that the barrier be keyed in the relatively thin A1/A2 aquitard to avoid breaching

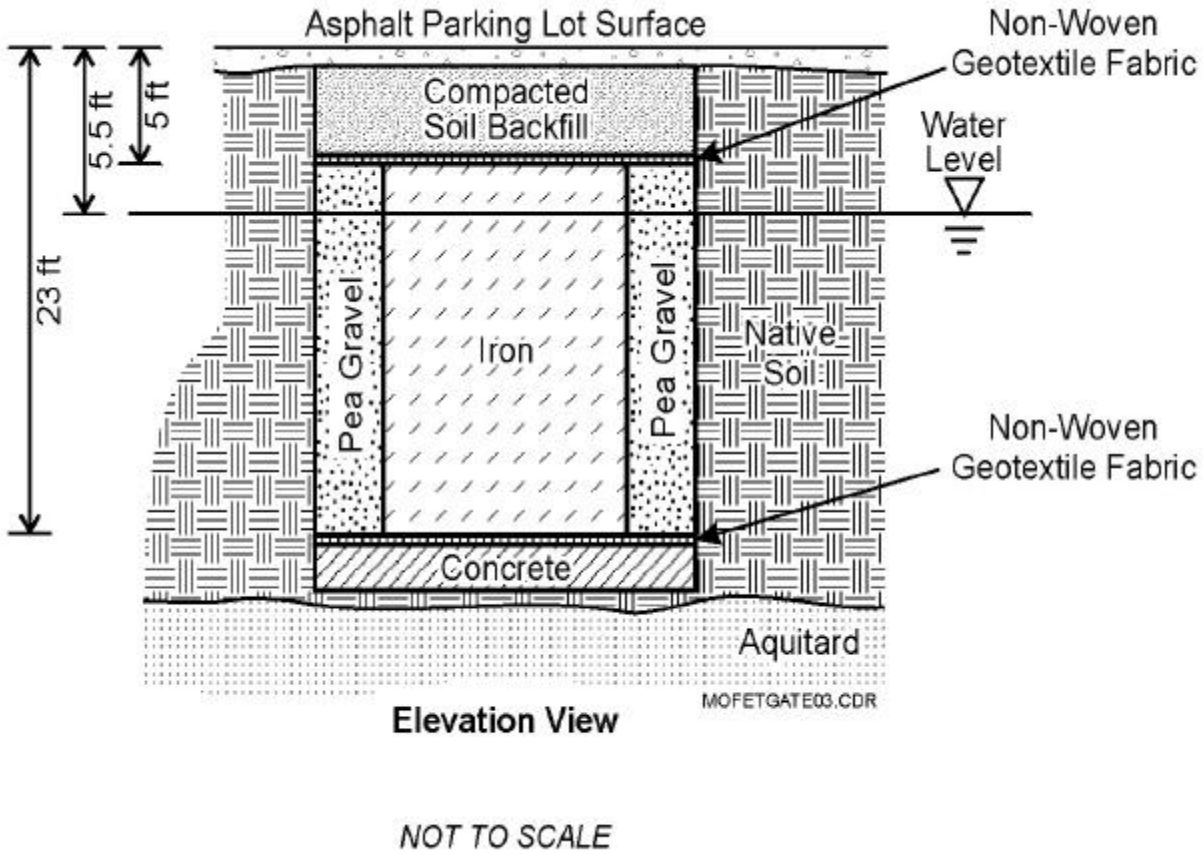

Figure 3.4. Permeable Reactive Barrier at Moffett Field (Elevation View)

it. Pea gravel sections were added to the gate to better distribute the influent to and effluent from the reactive cell. Figures 3.5 and 3.6 show the locations and construction of the monitoring wells within the gate and in the surrounding aquifer.

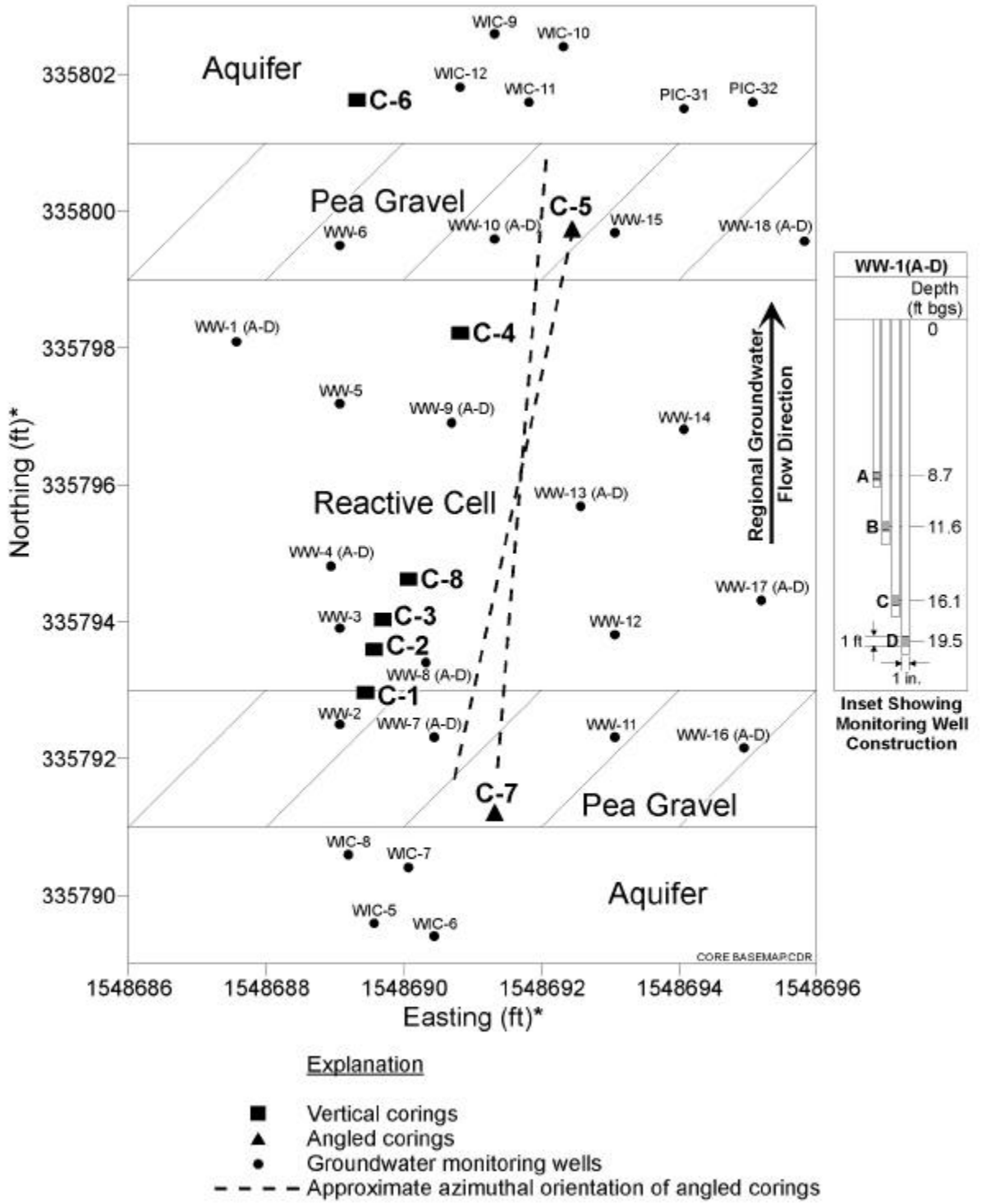

Figure 3.5. Planar View of Coring Locations and Groundwater Monitoring Wells

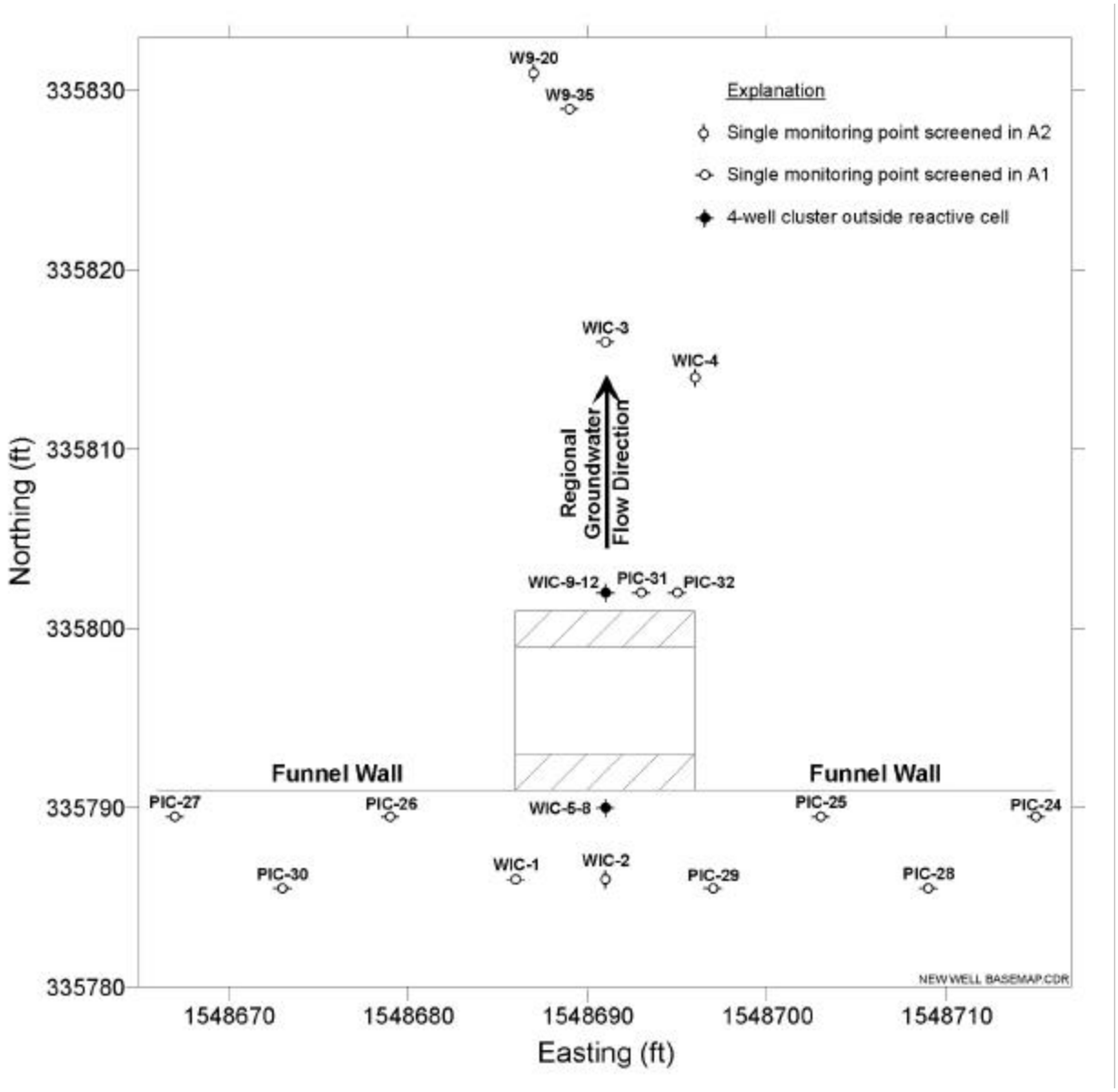

Figure 3.6. Location Map for Monitoring Wells

3.3.5 Construction and Operation of the Moffett Field Barrier

Slurry Systems, Inc. was contracted by EFA West to construct the pilot barrier (see cover photo). A backhoe was used to excavate the trench. Sheet piles with sealable joints were used to form the funnel and to hold the sides of the excavation. Sheet piles were temporarily installed in the gate as dividers to separate the pea gravel and iron sections. The iron was obtained from Peerless Metal Products, Inc. and was in the -8 to +40 mesh particle-size range. After the excavated trench box was completed and the dividers had been installed, the monitoring wells in the gate were suspended with a frame. The iron and pea gravel were poured in their respective sections through a bag suspended on top of the gate. The iron and pea gravel were poured around the standing wells and packed into place. A geosynthetic liner was placed on top and backfill was added to make up the grade. The ground surface was then repaved for continued use as a parking lot. The aquifer wells were drilled with standard drilling equipment and completed with flush mounts to maintain the parking lot grade. After construction was completed, the asphalt surface was restored.

Standard precautions for building construction (hard hat and safety shoes) were used during construction (modified Level D Site). An organic vapor analyzer (OVA) was kept on hand to screen excavated soil and well development water, but it did not show any hazards that would require special personal protective equipment.

3.4 PERFORMANCE EVALUATION OBJECTIVES AND THE ASSOCIATED MONITORING STRATEGY

The performance objectives (in order of priority) for the technology demonstration were as follows:

1. Ensuring reactivity of the barrier. This objective seeks to ensure that the portion of the CVOC plume flowing through the barrier is being remediated. Remediation at this site implies reduction of PCE, TCE, *cis*-1,2-DCE, and vinyl chloride concentrations to below their respective MCLs. The presence of byproducts of abiotic reduction, such as *cis*-1,2-DCE, vinyl chloride, ethene, ethane, and methane in the reactive cell were evaluated as evidence of degradation. Half-lives (or reaction rates) in the field barrier were estimated for the target contaminants and compared to the half-lives obtained during bench-scale tests.

2. Assessing downgradient aquifer quality. This objective seeks to ensure that no environ-mentally deleterious materials are being introduced through the barrier into the downgradient aquifer. Potential materials of concern are dissolved iron (emanating from the reactive cell) and biological growth. Iron is subject to a secondary drinking water limit of 0.3 mg/L. Biological growth could be stimulated by the anaerobic conditions created in the down-gradient aquifer by water flowing through the strongly reducing iron cell. Chloride and pH were also measured in the reactive cell effluent and downgradient aquifer.

3. Assessing hydraulic capture efficiency of the barrier. This objective seeks to assess the efficiency of groundwater capture. Is the field barrier capturing the targeted portion of the groundwater in the design? This includes ensuring that the volume of water flowing through the barrier is equivalent

to that estimated in the design, as well as ensuring that this volume of water is coming from the targeted portion of the aquifer.

4. Evaluating longevity of the barrier. Precipitates formed though the interaction between the iron medium and the native inorganic constituents (e.g., calcium, dissolved oxygen, and alkalinity) of the groundwater may, over a period of time, deposit on the iron surfaces in the reactive cell. Such deposits could potentially affect both the reactivity and hydraulic performance of the barrier. This objective seeks to evaluate the type and degree of such precipitation and its impact on the long-term performance of the barrier.

5. Estimating cost of the barrier application. The capital costs for the pilot barrier were noted during construction. The capital and O&M costs for a proposed full-scale application were estimated and compared to the costs of an equivalent pump-and-treat system.

3.5 SAMPLING AND ANALYSIS PROCEDURES

The performance monitoring plan was designed such that sampling activities would correspond with each of the study's objectives. The following sections summarize the sampling and analysis activities.

3.5.1 Monitoring Frequency

Table 3.3 summarizes the sampling schedule for all of the analytes. Water samples were collected on approximately a quarterly basis (over five quarters) for chemical analysis. During each sampling event, the existing wells in the reactive cell, pea gravel, and in the immediate vicinity of the aquifer were sampled. Measurements of field parameters were usually performed within 1 week of sample collection so that the various kinds of measurements could be gathered within a short period of time.

Table 3.3. Monitoring Frequency

Parameter Type	Analytes	Sampling Schedule[a]				
		Jun-96	Sep-96	Jan-97	Apr-97	Oct-97
Field parameters	Water level, pH, groundwater temperature, Eh, DO	U	U	U	U	U
Volatile organic compounds	CVOCs	U	U	U	U	U
	Dissolved gases (H2 CO2, methane, ethane, ethene, acetylene, and propane)			U		U
Inorganics and neutrals	Metals (K, Na, Ca, Mg, and Fe) Anions (NO3, SO4, Cl, Br, F, sulfide, alkalinity) Neutrals (TDS, TSS, TOC, DOC)	U	U	U	U	U
Water elevations	Water level measurements (13 total events)	U	U	U	U	U

Parameter Type	Analytes	Sampling Schedule[a]				
Continuous monitoring	Water level, pH, temperature, Eh			U	U	
Reactive cell core samples	XRD, SEM, EDS, Raman spectroscopy, microbial analysis(b)					U

(a) Groundwater sampling for CVOC analysis conducted in April 1997 was repeated in July 1997 to enable the subcontract analytical laboratory to achieve better detection limits. Iron core samples were collected in December 1997.
(b) In addition to the cores collected from the reactive cell, one core was collected from the downgradient aquifer for microbial analysis.
TDS = total dissolved solids DOC = dissolved organic carbon EDS = energy dispersive spectroscopy
TSS = total suspended solids XRD = x-ray diffraction
TOC = total organic carbon SEM = scanning electron microscopy

After the fifth quarter of water sampling, core samples of the iron in the reactive cell were collected. A core sample of soil from the downgradient aquifer was also collected to evaluate possible biological activity resulting from the anaerobic conditions created by the barrier.

3.5.2 Groundwater Sampling and Analysis

Groundwater sampling provides essential information on water movement, organic contaminant levels, and inorganic chemistry needed to understand and model the performance of the permeable barrier. Groundwater samples were collected and prepared for laboratory chemical analysis; field parameters were analyzed on site. Table 3.3 lists the parameters that were measured in the wells in and around the permeable barrier. Samples for determination of CVOCs, inorganic analytes, and field parameters were obtained from all wells in the permeable barrier and vicinity. Samples for determination of dissolved gases and certain additional analytes were obtained primarily from longer screened wells to reduce the total volume of water removed from the short-screen wells.

3.5.2.1 Groundwater Sampling Procedures

The main challenge in collecting groundwater samples was to minimize the impact of sampling on flow through the permeable barrier. Water withdrawal during sampling can lead to faster flow and reduced residence time of groundwater in the reactive medium. To prevent artificial gradients, water samples were extracted at low flowrates using an aboveground peristaltic pump. Also, to minimize disruption of normal flow through the barrier, successive samples were collected in different parts of the barrier, rather than from neighboring wells.

3.5.2.2 Groundwater Analysis Methods

Table 3.4 lists the standard analytical methods used for the groundwater samples collected during the quarterly sampling events. Individual parameters are grouped according to field measurements, organic analytes, and inorganic analytes. The primary purpose of taking field parameter measurements is to monitor chemical conditions within the reactive cell that can affect its performance. Therefore, water temperature, pH, Eh, and DO were measured at every well location. To obtain accurate readings, the field parameters were measured using suitable down-hole probes.

The CVOCs of primary interest are the chlorinated hydrocarbons (EPA Method 8260) and light hydrocarbons (EPA Method 3810), including hydrogen gas, carbon dioxide, methane, ethane, ethene, acetylene, and propane. These CVOC analyses were performed to help identify the distribution of contaminants in and around the permeable barrier, as well as potential byproducts of degradation.

Table 3.4. Analytical Requirements for Groundwater Samples

Parameter	Critical	Analysis Method	Sample Volume	Storage Container	Preservation	Sample Holding Time
Field Parameters						
Water Level	Yes	Down-hole	None	None	None	None
pH	Yes	probe	None	None	None	None
Water Temperature	Yes	Down-hole	None	None	None	None
Eh	Yes	probe	None	None	None	None
DO	No	Down-hole	None	None	None	None
		probe				
		Down-hole				
		probe				
		Down-hole				
		probe				
Organic Analytes						
CVOCs	Yes	EPA 8260	2 x 40 mL	VOA Vial	4EC, pH<2 (HCI)	14 d
Dissolved Gases	No	EPA 3810	2 x 40 mL	VOA Vial	4EC, pH<2 (HCI)	14 d
Inorganic Analytes						
Cations	Yes	EPA 200.7	100 mL	Polyethylen	Filter, 4EC, pH<2	180 d
K, Na, Ca, Mg, Fe				e	(HNO_3)	
Anions	Yes	EPA 300.0	100 mL		4EC	7 d
NO3, SO4, Cl, Br, F	Yes	EPA 310.1	100 mL	Polyethylen	4EC	14 d
Alkalinity	Yes	EPA 9030	100 mL	e	4EC	14 d
Sulfide				Polyethylen		
Neutrals	No	EPA 160.2	100 mL	e	4EC	7 d
TDS	No	EPA 160.1	100 mL	Polyethylen	4EC	7 d
TSS	No	EPA 415.1	40 mL	e	4EC, pH<2 (H_2SO_4)	7 d
TOC	No	EPA 415.1	40 mL		4EC, pH<2 (H_2SO_4)	7 d
DOC				Polyethylen		
				e		
				Polyethylen		
				e		
				Polyethylen		
				e		
				Polyethylen		
				e		

3.5.3 Core Sample Collection Methods

As outlined in the performance monitoring plan, at the end of the monitoring period (approximately 20 months after installation of the barrier), a few core samples were collected from within the reactive cell to look for signs of iron encrustation, precipitate formation, and microbial growth. These conditions have the potential to reduce the efficiency of the permeable barrier by restricting flow through the gate and reducing residence time in the reactive cell. They also affect the longevity of the barrier and hence the operating costs. As shown in Figure 3.5, core samples were taken at several locations within the reactive cell to

obtain adequate spatial information about possible changes in the granular iron medium. A single core was taken from the downgradient aquifer to evaluate microbial growth in the portion of the aquifer influenced by the reactive cell. All cores were maintained at low temperatures (4°C) under anaerobic conditions until they were subsectioned (by depth) for analysis. Each subsection of the iron was homogenized and split into smaller samples in an anaerobic chamber to prepare for analysis.

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4.0 PERFORMANCE ASSESSMENT

The design/performance objectives of the pilot-scale barrier installation at Moffett Field were (a) to verify that the groundwater effluent from the reactive cell met MCLs (or was below detection levels) for the target CVOC contaminants, and (b) to verify that the funnel-and-gate system was capturing groundwater flowing across the entire width of the sand channel and part of the width of the inter-channel deposits on either side of the sand channel.

4.1 DEGRADATION OF CONTAMINANTS IN THE GATE

4.1.1 Degradation of TCE, *cis*-1,2 DCE, PCE, and Vinyl Chloride

Concentrations of CVOCs for the five monitoring events are presented in the full report (Battelle, 1998d). Time trends in the concentrations of TCE, and *cis*-1,2-DCE in the permeable barrier and nearby wells over five quarters are shown graphically for four representative wells in Figures 4.1 and 4.2. These selected wells lie along the centerline through the gate in the general direction of groundwater flow.

Figure 4.1 shows that TCE concentration increased steadily in the WIC-1 aquifer well from 1,180 mg/L in June 1996 to 2,800 mg/L in October 1997. Consequently, TCE concentrations in the upgradient pea gravel well (WW-7C) showed an increasing trend from 570 to 1,000 mg/L. Concentrations of TCE are somewhat lower in the pea gravel than in the upgradient aquifer, which is thought to be due in part to horizontal and vertical mixing of the heterogeneously distributed contamination entering through the influent groundwater. Another possible explanation is that a small amount of iron may have become mixed into the pea gravel during construction, resulting in limited degradation of the contaminants there.

In both the reactive cell wells (WW-4C and WW-9C) in Figure 4.1, TCE is below its MCL (5 mg/L) in every quarter, except June 1996. WW-4C is located approximately 2 feet into the reactive cell and WW-9C is located approximately 4 feet into the reactive cell. The relatively higher TCE concentrations in June 1996 are probably due to unsteady-state conditions within the reactive cell, which had just been constructed 2 months earlier. Factors leading to unsteady-state operation include adsorption-desorption on the iron surfaces, residual contamination in the reactive cell from construction activities, and contamination entering from the downgradient aquifer. It should be noted that the barrier was constructed within the plume boundaries. After the initial sampling event in June 1996, there were no other occurrences of such elevated TCE concentrations in the iron zone. Furthermore, the fact that TCE is reduced below detection in WW-4C indicates that more than sufficient residence time is available within the reactive cell to degrade TCE well below its MCL.

Figure 4.2 illustrates the trend in *cis*-1,2-DCE over the performance monitoring period. This figure shows that *cis*-1,2-DCE concentrations have remained fairly constant at each of the well locations during the 16-month period. It also indicates that *cis*-1,2-DCE degrades more slowly than TCE, as there is a much wider difference between concentrations in the two reactive cell wells (WW-4C and WW-9C) in Figure 4.2 then is seen in Figure 4.1. However, *cis*-1,2-DCE concentrations are always below the MCL (70 mg/L) in WW-9C, which is further along the groundwater flow direction.

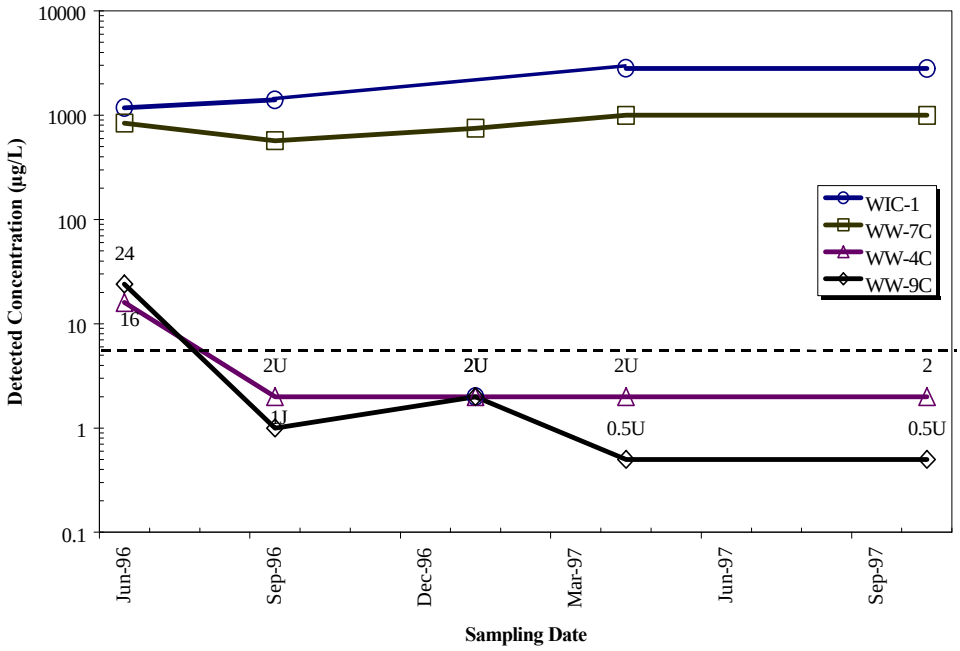

Figure 4.1. Concentrations of TCE in Four Monitoring Wells During the Performance Monitoring Period. (Concentrations qualified with a "U" indicate that the analyte was undetected at the detection limit stated.)

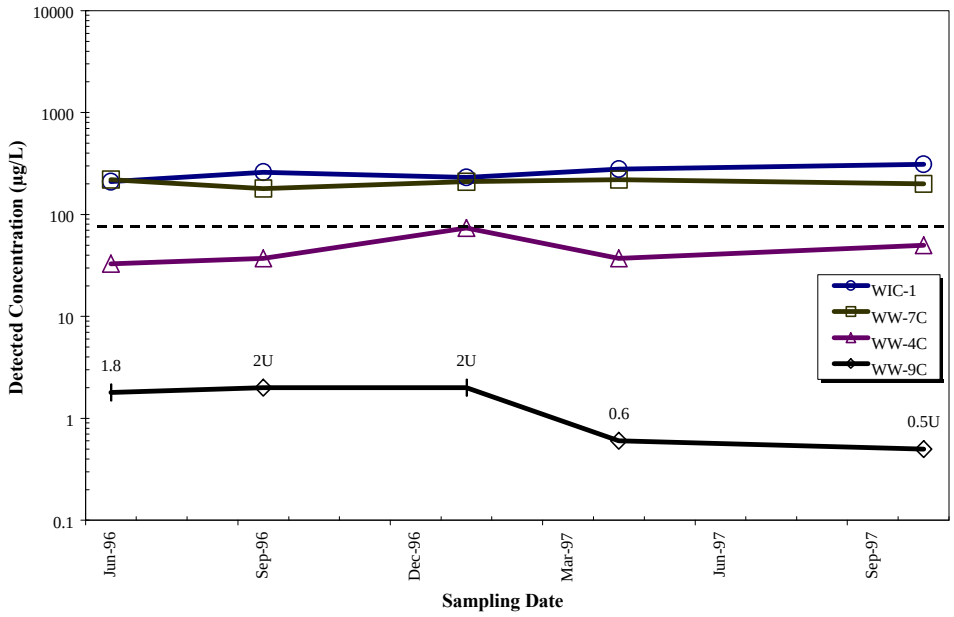

Figure 4.2. Concentrations of *cis*-1,2-DCE in Four Monitoring Wells During the Performance Monitoring Period. (Concentrations qualified with a "U" indicate that the analyte was undetected at the detection limit stated.)

As with TCE and *cis*-1,2-DCE, PCE was reduced to well below its MCL (and below detection) in the reactive cell effluent. Low levels (1 mg/L) of vinyl chloride were only detected in the first row of wells (WW-8) inside the reactive cell, indicating that it is generated during the degradation of PCE, TCE, and *cis*-1,2-DCE, but is itself reduced to below detection in the reactive cell effluent.

4.1.2 Degradation of Other CVOCs

The concentration of CFC-113 ranges from nondetectable to around 50 mg/L in most of the upgradient A1 aquifer zone and pea gravel wells, and is below detection (2 mg/L) in the reactive cell wells. This result indicates complete destruction of CFC-113 in the reactive barrier. Similarly, 1,1-DCE is approximately 30 to 40 mg/L in the upgradient aquifer and pea gravel wells and is below detection (0.5 mg/L) in the reactive cell. However, 1,1-DCA concentrations are 20 to 30 mg/L in the upgradient aquifer and pea gravel wells and remain detectable (1 to 10 mg/L) in the downgradient portion of the reactive cell. 1,1-DCA is possibly the most resistant compound to reductive dechlorination in the treatment zone. However, 1,1-DCA has no regulatory MCL and is not perceived as an environmental concern at the site.

4.1.3 Degradation Rate Constants and Half-Lives

The dechlorination efficiency of the barrier can be characterized by estimating the reaction rate constants and half-lives of the contaminants in the field system. Degradation rate constants were calculated for the TCE, *cis*-1,2-DCE, and 1,1-DCA as described below. Other compounds degraded too fast and rates could not be estimated for them.

Rather than relying on concentration data from individual wells, which may be subject to local flow anomalies and other uncertainties, average concentrations were estimated for five volume slices perpendicular to the groundwater flow through the gate. The volume slices were created by dividing the gate into five 2-foot-thick sections. Volumes 1 and 5 are the upgradient and downgradient pea gravel, respectively. Volumes 2 through 4 are in the reactive cell. Each volume section is 10 feet wide (same as the gate width) and extends from 11 feet above msl to 2 feet below msl. Masses of contaminants were calculated using EarthVision™ software by summing (integrating) isopleths (concentration ranges) over each volume section. Isopleths were chosen to provide a broad distribution of concentration contours. Average concentrations in each section were then calculated by dividing the integrated mass by the volume.

Table 4.1 shows the calculated average concentration within each volume section. As expected, concentrations declined from volume 1 to volume 5 in the direction of groundwater flow through the reactive cell. Volume 5 data were ignored in the calculations because CVOC concentrations start to rebound in the downgradient pea gravel, where water from the downgradient (contaminated) aquifer is drawn in due to the sharp permeability contrast and mixed with the treated effluent from the reactive cell. The downgradient aquifer is contaminated because of pre-existing contamination (the barrier was placed inside the boundary of the plume) and due to contamination flowing around or, possibly, under the barrier. The elevated CVOC concentrations in the downgradient pea gravel are not caused by breakthrough as evidenced by the fact that CVOCs were below detection in the wells that are more than 2 ft along the flow direction in the iron.

Table 4.1. Calculation of Average Contaminant Concentrations in Volumes

Monitoring Event	Contaminant	Average Concentration (µg/L) in Volume Number[a]				
		1	2	3	4	5
January 1997	TCE	688	25.8	1.51(b)	1.51(b)	15.1(b)
	cis-1,2-DCE	257	35.1	1.88	1.50(b)	2.63(b)
	1,1-DCA	33	14.0	4.48	1.73	1.73(b)
October 1997	TCE	506	16.3	1.13(b)	1.19(b)	11.2(b)
	cis-1,2-DCE	177	43.8	2.61	1.05(b)	1.49(b)
	1,1-DCA	15.8	12.5	6.81	2.51	1.40(b)

(a) Volume 1 is at the influent end of the gate.
(b) Ignored in calculation of reaction rate constant (k), either because this average includes values below the detection limit or because it includes contamination from the downgradient aquifer.

Results of the rate constant and half-life calculations are tabulated in Table 4.2. It can be seen that higher estimates of groundwater flow velocity in the reactive cell leads to higher estimates of k and lower estimates of t½. Table 4.2 also shows the half-lives estimated during bench-scale testing (PRC, 1995); the bench-scale results were adjusted for 100% granular iron used in the field barrier as opposed to the 50:50 iron-sand mixture used in the bench tests (see footnote (b) in the table). It can be seen that for a flow velocity between 0.2 and 0.5 foot/day, there is generally good agreement between the field and bench-scale half-lives.

4.2 DOWNGRADIENT WATER QUALITY

Dissolved iron concentrations in the reactive cell and downgradient pea gravel were generally less than 0.02 mg/L, which is far below the secondary drinking water standard of 0.3 mg/L. The pH of the groundwater rises to 10, DO concentration declines to less than 1 mg/L, and the Eh declines to -600 mV in the reactive cell. However, these parameters (pH, DO, and Eh) rapidly regress to their original values as soon as the water leaves the reactive cell. In fact, the regression starts in the downgradient pea gravel itself, indicating that there is mixing of treated water and untreated water from the aquifer in the downgradient pea gravel.

Table 4.2. Results of Degradation Rate Calculations[a]

Monitoring Event	Estimated Flow Velocity (feet/day)	TCE		*cis*-1,2-DCE		1,1-DCA	
		k (hr^{-1})	$t_{½}$ (hr)	k (hr^{-1})	$t_{½}$ (hr)	k (hr^{-1})	$t_{½}$ (hr)
January 1997	**0.2**	**0.66**	**1.1**	**0.32**	**2.1**	**0.12**	**6.0**
	0.5	**1.6**	**0.42**	**0.81**	**0.86**	**0.29**	**2.4**
	1	3.3	0.21	1.6	0.43	0.58	1.2
	2	6.6	0.11	3.2	0.21	1.2	0.60
October 1997	**0.2**	**0.69**	**1.0**	**0.28**	**2.5**	**0.07**	**9.4**
	0.5	**1.7**	**0.4**	**0.70**	**0.99**	**0.20**	**3.8**
	1	3.4	0.2	1.4	0.49	0.37	1.9
	2	6.9	0.1	2.8	0.25	0.73	0.94
Bench-scale test results[b]		1.7	0.40	0.34	1.4	0.16	4.3

(a) Determination of rate constants (k) depends on groundwater flow velocity. Velocities and rate calculations for the bolded amounts are consistent with bench-scale results in the last row of the table.

(b) Rate constants (k) and half-lives (t2) were calculated from bench-scale data (PRC, 1995). The rate constants shown in this table were adjusted by a factor of 2.3 to account for the higher expected reactive surface area of 100% iron (as used in the pilot barrier) compared to the reactive surface area in the 50:50 mass mixture of iron and sand used in the bench-scale column tests.

4.3 HYDRAULIC PERFORMANCE

The hydraulic evaluation of the Moffett Field permeable barrier consisted of a variety of measurements using water levels, down-hole groundwater velocity probes, slug tests, and tracer tests. Based on these measurements, the following conclusions can be made:

The estimated capture zone is about 30 ft wide, and encompasses the entire width of the sand channel and part of the interchannel deposits on either side along the funnel walls. This estimate was based on the estimated groundwater velocities, porosities, and dimensions of the barrier and aquifer.

- The estimated groundwater velocity range through the reactive cell is between 0.2 to 2 ft/day. This provides a residence time of at least 3 days in the reactive cell, versus the design requirement of 2 days.

- The hydraulic performance of the barrier is within the design expectations.

4.4 GEOCHEMISTRY AND EVALUATION OF LONGEVITY

Table 4.3 summarizes the geochemical parameters measured in the vicinity of the permeable barrier. Reductions in the concentrations of calcium, magnesium, alkalinity, and sulfate as the groundwater passes through the reactive cell indicate the formation of precipitates. It is unclear however, how much of the precipitate stays in the reactive cell and how much moves out by colloidal transport. Iron core samples were collected after 18 months of operation and subjected to acid digestion and chemical analysis, x-ray diffraction, Raman spectroscopy, and scanning electron microscopy. These tests showed the presence of carbonate and sulfide deposits on the surfaces of the iron. Amorphous ferric hydroxide and lepidocrocite (FeOOH) were also noticed on some of the iron samples and indicate oxidation of the iron itself. Formation of these deposits indicate that at some point in time, the reactivity and/or the hydraulic performance of the iron will be adversely affected. When that will occur is still unclear, and further empirical evidence from laboratory and field studies is required on this issue.

4.5 COMPARISON TO TECHNOLOGY CLAIMS

In general, the performance of the pilot barrier at Moffett Field was able to meet the claims made for the technology.

4.6 OVERALL CONCLUSIONS

In general, the barrier performance was within the expectations of the technology and the design for this site. Although the precipitation caused by inorganic reactions in the reactive cell is a long-term concern,

there was no evidence that the hydraulic performance of the barrier would be affected in the next several years. It is unclear when the precipitation may cause the reactivity of the iron medium to decline, but there were no signs during the 20-month period of the demonstration that such a decline had begun.

Table 4.3. Moffett Field Inorganic Chemical Data (April 1997 Monitoring Event)[a]

Monitoring Location	Calcium	Magnesium	Sodium	Iron	Alkalinity	Chloride	Nitrate	Sulfate
Upgradient A1 Aquifer Zone	134-158	50-64	30-38	< 0.02	250-314	40-45	2-3	322-362
Upgradient Pea Gravel	163-177	64-73	32-35	< 0.02-0.12	215-310	31-46	2-3	264-342
Reactive Cell	0.5-8	0.3-33	33-42	< 0.02-0.04	14-90	38-43	< 0.05	1-111
Downgradient Pea Gravel	1-13	0.3-2	26-32	< 0.02-0.3	12-19	37-42	< 0.05	1-29
Downgradient A1 Aquifer Zone	13-162	1-58	25-41	< 0.02-0.03	18-270	40-45	2-3	19-347

(a) All concentrations are in mg/L; alkalinity expressed as $CaCO_3$.

5.0 COST ASSESSMENT

This section discusses the cost considerations involved in the application of the permeable barrier technology.

5.1 SUMMARY OF TREATMENT COSTS FOR THE DEMONSTRATION

The groundwater treatment and monitoring costs incurred during the demonstration are shown in Table 5.1. Only the costs associated with the treatment of the groundwater are included; costs associated with the entire validation effort are not included. The cost of purchasing the iron medium ($39,375) and the construction cost ($323,000) were based on actual vendor bids. The other costs were based on the best available estimates. Spoils generated during trenching were reused at another site at Moffett Field because they were found to be mostly uncontaminated.

Table 5.1. Groundwater Treatment and Monitoring Costs for the Demonstration

Items	Sub-Total ($)	Total Cost ($)
Capital Investment		
Site characterization		100,000
Bench-scale tests (4 batch tests, 2 column tests)		75,000
Engineering design, modeling, and planning		100,000
Iron medium		39,375
–75 tons @ $450/ton	33,750	
–Transportation to site (75 tons @ $75/ton)	5,625	
Construction of barrier (includes labor and materials)		323,000
–Site preparation/restoration	133,000	
–Sheet pile funnel	60,000	
–Trench gate (with backhoe)	100,000	
–Monitoring wells within gate	30,000	
Monitoring wells in the aquifer vicinity (10 wells @ $1,500/well)		15,000
Disposal of trench spoils (as nonhazardous waste)		0
Total Capital Investment		**652,375**
O&M Cost		
Maintenance (over the 20 months of operation)		0
Monitoring (five full events @ $30K each)		150,000
Total O&M Cost		**150,000**
Total Demonstration Cost		**802,375**

The primary advantage of the permeable barrier is immediately apparent. Once installed, there are no

O&M costs involved (other than monitoring), at least in the first few (or several) years of operation. At some point in time, it is anticipated that there will be maintenance costs for regenerating or replacing the iron reactive medium.

5.2 SCALE-UP RECOMMENDATIONS

The conclusions from the Moffett Field demonstration (Section 4.3) and the performance observations and lessons learned (Section 6.2) were used as the basis for examining the viability of a full-scale barrier for the West Side Plume at Moffett Field. Unlike an aboveground treatment system, where scaling up involves increasing the size of the equipment to handle larger volumes of feed, an in-situ treatment system has to be scaled up by taking into account the subsurface characteristics of the aquifer region that will be affected. This is especially true if, as has been proposed at Moffett Field by site representatives, the probable full-scale system will be installed at locations different from the location of the pilot barrier. The need for a different location for the full-scale system derives from differences in the objectives of the pilot- and full-scale reactive barriers. For the pilot system, it was important to be within the plume so that the barrier would have immediate access to the contaminants. Aside from that consideration, the location of the pilot barrier was determined primarily by considerations of ease of access and maximization of benefits from limited resources. If, on the other hand, the objective of the full-scale system is to prevent the plume from migrating any further, the barrier will have to be placed downgradient of the leading edge of the plume.

The Navy currently is negotiating the areas of responsibility for cleanup of the regional plume. This will have a major effect on the actual placement of the permeable wall. The wall locations chosen for this exercise are for costing purposes only. One possible scenario is schematically depicted in Figure 5.1 and is discussed further in the following subsections. Considerable study of the aboveground features of the site (buildings, roads, etc,), subsurface features (utilities, exact location of sand channels, etc.), contaminant distribution, and groundwater movement is required to select an optimal scenario.

5.2.1 Design of a Full-Scale Barrier at Moffett Field

The design methodology recommended for permeable barriers was illustrated in Figure 2.2. The bench-scale column testing and geochemical evaluation conducted during the pilot barrier design should be sufficient, and these two steps need not be repeated. But the remaining steps will have to be implemented to design the full-scale application.

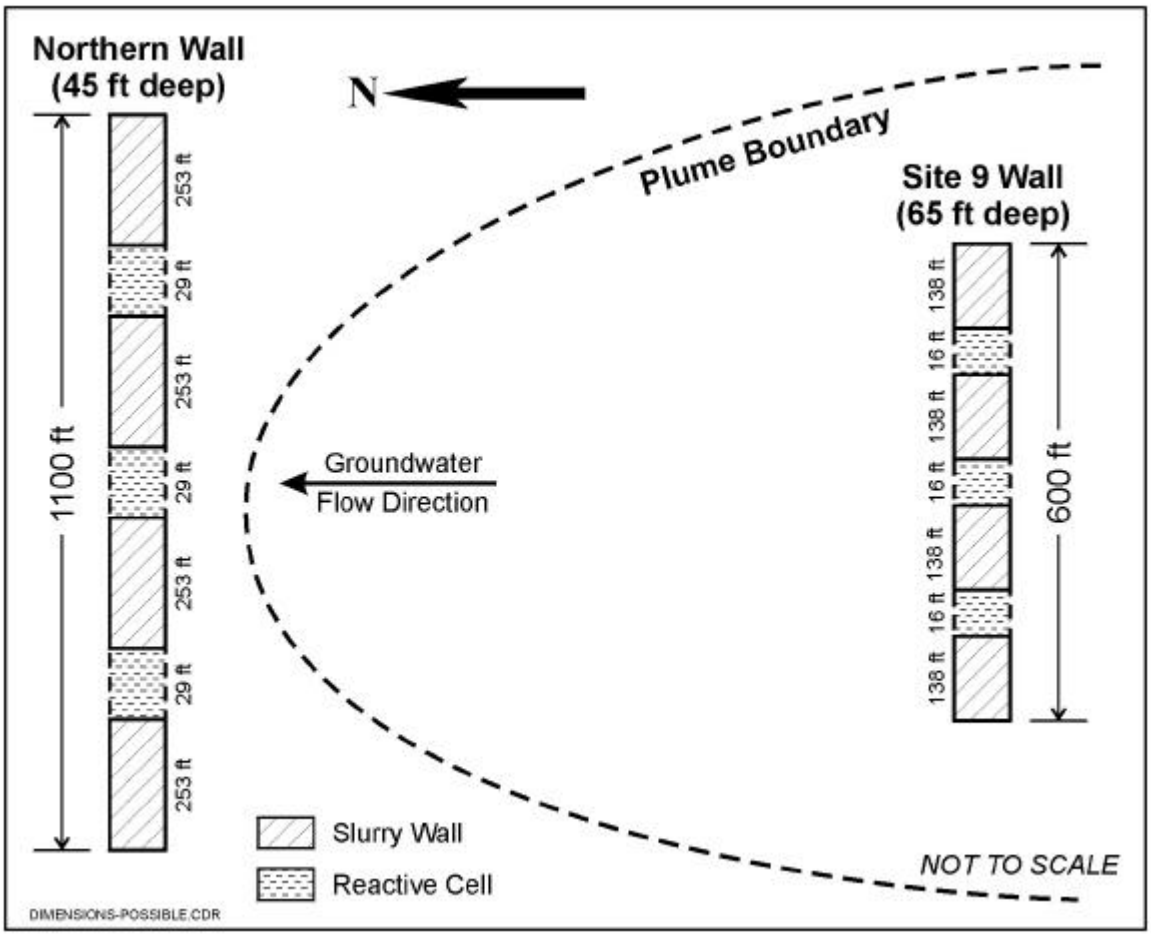

Figure 5.1. Configuration and Dimensions of Possible Full-Scale Barrier at Moffett Field

5.2.2 Cost Projections for Full-Scale Barrier at Moffett Field

One of the scenarios proposed by site representatives is used here, with some modifications, for presenting the scale-up guidance. In this scenario (Figure 5.1), the full-scale permeable barrier for the West Side plume at Moffett Field would be constructed in two sections. One section, called the Site 9 Wall, would be constructed just south of Building 88, and would capture and treat the highly concentrated portion of the contamination moving through a key sand channel. The other section, called the Northern Wall, would be constructed downgradient from the leading edge of the plume, and would control further migration of the plume. In all the scenarios, a barrier that extends down to the base of the A2 aquifer zone is envisioned. The aquitard in some locations can be up to 65 feet deep, making this barrier deeper than any full-scale barrier installed so far. This depth consideration increases the construction cost compared to other sites. For example, a clamshell would probably be used instead of a backhoe to key the barrier into the

65-foot-deep aquitard, thus increasing the time and cost of construction. Conventional trench gates and slurry wall funnels have been assumed for this application in the absence of other commercially available "true-and-tested" techniques. At this time, most innovative methods (e.g., jetting) are still under development.

Table 5.2 summarizes the costs of this full-scale barrier illustration. Details for individual cost items and were developed by NFESC based on preliminary projections by site representatives for the application (TetraTech EMI, personal communication). Technology licensing issues are being negotiated with ETI.

To obtain some perspective on the economic benefits of the permeable barrier, the total cost of the permeable barrier was compared with the total cost of the pump-and-treat option. The cost of the pump-and-treat system for the West Side plume was estimated by NFESC, based on projections made in a long-term action plan by site representatives (PRC, 1996). The pump-and-treat system is expected to consist of 27 extraction wells that withdraw 166 gallons per minute (gpm) of water from near the edge of the plume. The extracted water would be treated with an air stripper and advanced oxidation system. Table 5.3 summarizes the comparison of permeable barrier and pump-and-treat options based on the present values (PV) of the estimated costs (that is, the estimated costs in today's dollars). A real rate of return of 5% was used in the calculations as the discount rate. As seen in Table 5.3, the permeable barrier requires a higher initial capital investment. However, over time, the O&M savings keep accruing and the permeable barrier breaks even in approximately the sixth year, based on these calculations. O&M costs are factored in annually and barrier maintenance cost is factored in every 10 years; calculations of cost savings (or additional costs) for the permeable barrier are shown in the last column. In the sixth year, the PV cost of the pump-and-treat system exceeds that of the permeable barrier, indicating that the permeable barrier is more cost-effective over the long term.

For a broader perspective on permeable barrier cost, Table 5.4 provides a summary of the barrier construction costs reported at various sites where this technology has been implemented. Both pilot- and full-scale systems are represented in the table. The barrier configuration, continuous reactive barrier (CRB) or funnel and gate (F&G), is also provided in the table. The 1,700-foot-long, full-scale Moffett Field barrier, if built, would be the longest one so far. At a depth of 65 feet, it would also be the deepest barrier built with commercially available, conventional excavation techniques.

Table 5.2. Project Cost of a Full-Scale Permeable Barrier at Moffett Field

Items	Sub-Total ($)	Total Cost ($)
Capital Costs:		
Bench-scale tests (4 batch tests, 2 column tests)		75,000[b]
Site characterization –Site characterization (hydrogeologic/chemical) –Other testing and welding	 100,000 17,820	 117,820
Engineering Design, Modeling		100,000
Site Preparation (Permitting, traffic control, storage, and administration)		115,258
Construction (labor and materials) –Mobilization –Trench installation –Gates completion (six trench gates with 2,518 tones of iron medium at $350/ton) –Funnel completion (slurry wall) –Demobilization -Surface restoration	 39,693 557,812 1,847,910 1,156,164 39,693 18,133	 3,659,405
Monitoring wells installation		46,000
Spoils disposal on-site (trench soils)		16,370[c]
Spoils disposal off-site (removed asphalt)		387,989
Site Restoration and Post-Construction Reports –Site cleanup –Removal of temporary utilities/facilities –Post-construction submittals	 6,032 81,021 35,000	 122,053
Distributive costs (administrative, health & safety)		271,047[d]
Total Capital Cost		**4,910,942**
O&M Costs:		
Annual operations (monitoring cost incurred every year)		72,278
Maintenance (incurred every 10 years)		267,538[e]

(a) Details of individual cost items are provided in Appendix G of the Technology Evaluation Report (Battelle, 1998d, Table G-1).

(b) Bench-scale testing for the pilot permeable barrier should be sufficient for implementing the full-scale barrier. However, the costs of additional bench-scale tests are included in this cost estimate, in the event they are needed.

(c) Assuming spoils will be disposed as non-hazardous material. At some sites with very high contamination, the spoils could be considered hazardous, and their disposal would cost more.

(d) Distributive costs include the administrative costs that are not included in site preparation. These include items

such as health and safety during construction and project supervision.

(e) Maintenance costs are difficult to estimate because none of the barriers installed so far have required maintenance. The estimates in this table are based on a rule of thumb suggested by ETI that maintenance required will be equivalent to spending 25% of the iron medium cost every 10 years.

Table 5.3. Total Cost Comparison of the Present Value (PV) Costs of the Permeable Barrier and Pump-and-Treat Options at Moffett Field[(a)]

Years of Operation	Item	Permeable Barrier	Pump & Treat System	Cost Savings for Permeable Barrier
0	Capital Investment	$4.9 M	$1.4 M	-$3.5 M
Annual	Annual O&M cost	$72 K	$695 K	$623 K
—	Barrier maintenance cost every 10 years	$268 K	Not applicable	-$268 K
6	PV of Capital and O&M costs	$5.3 M	$5.6 M	$0.2 M
10	PV of Capital and O&M costs	$5.9 M	$8.4 M	$2.5 M
20	PV of Capital and O&M costs	$6.9 M	$15 M	$8.4 M
30	PV of Capital and O&M costs	$7.9 M	$22 M	$14 M
40	PV of Capital and O&M costs	$8.9 M	$29 M	$20 M
50	PV of Capital and O&M costs	$9.8 M	$36 M	$26 M

Table 5.4. Cost of Permeable Reactive Barriers

PRB Site	Type of Barrier	Dimensions of each reactive section*	Length of Funnel* (ft)	Amount of Iron Used (tons)	Source of Iron	Unit Cost of Iron ($/ton)	Total Cost of Iron ($)	Total Construction Cost ($)	Notes
Moffett Field	F&G	10 ft long 6 ft thick 22 ft deep	20	75	Peerless	450	33,750	323,000	Includes monitoring wells
Alameda	F&G	10 ft long 5 ft thick 20 ft deep	40	70	Peerless	385	27,000	400,000	Construction cost includes biosparge system
Dover AFB	F&G (2 gates)	4 ft long 4 ft thick 40 ft deep	60	40	Peerless	350	14,000	400,000	Includes monitoring wells
Lowry AFB	F&G	10.75 ft long 5 ft thick 17.5 ft bgs	30	45	Master Builder	700	31,500	75,000	—
Cape Canaveral Air Station	CRB	51.5 ft long (mandrel section) 49 ft long (JAG section) 0.3 ft thick 45 ft deep	N/A	Mandrel (98) JAG (83)	Peerless	Mandrel (571) JAG (892)	Mandrel (56K) JAG (74K)	809K [Mandrel (252K) JAG (233K)]	Includes monitoring wells
Watervliet Arsenal	CRB (2 sections)	205 & 83 ft long 2.5 ft thick 9-11 & 7-10 ft deep	N/A	120 and 30	Connelly-GPM	N/A	N/A	257,000	Design–$113,000 License–$17,000
Seneca Army Depot	CRB	645 ft long 1 ft thick 8-10 ft deep	N/A	222	N/A	N/A	N/A	N/A	—
Denver Federal Center	F&G (4 gates)	40 ft long 6,4,2, and 2 ft thick 23-32 ft deep	1,040	241, 207, 77, and 58	Peerless	N/A	400,000	1,000,000	Includes pea gravel
Elizabeth City	CRB	150 ft long 2 ft thick 24 ft deep	N/A	450	N/A	N/A	175,000	500,000	—
Kansas City Plant	CRB	30 ft long variable thickness, 6 ft max. 30 ft deep	N/A	N/A	Peerless	N/A	N/A	N/A	—

PRB Site	Type of Barrier	Dimensions of each reactive section*	Length of Funnel* (ft)	Amount of Iron Used (tons)	Source of Iron	Unit Cost of Iron ($/ton)	Total Cost of Iron ($)	Total Constructio n Cost ($)	Notes
Rocky Flats	F&G	Special cells	230	50	Connelly	400	20,000	610,000	—

N/A = not available; F&G = funnel & gate; CRB = continuous reactive barrier; JAG = jet assisted grouting

* Thickness is measured along flow direction; depth of reactive section is listed as total depth below ground surface (bgs)

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6.0 IMPLEMENTATION ISSUES

This section examines the lessons learned from this demonstration and their implications for full-scale application at Moffett Field and other sites.

6.1 COST OBSERVATIONS

The demonstration results indicate that the cost of a permeable barrier is closely linked to the selected design and construction method. The following issues should be considered to optimize barrier application costs:

- Conducting adequate site characterization and modeling to improve the design and lower capital cost. The greater the certainty in the hydrogeologic parameter estimates, the better the capability of reducing the dimensions and applying smaller safety factors in the barrier design.

- The relative cost of using a continuous reactive barrier versus a funnel-and-gate system should be evaluated at every site based on site characteristics and geotechnical considerations. More iron is generally required in continuous reactive barriers, in which iron is distributed along the entire width of the plume and is therefore used somewhat inefficiently compared to a funnel and gate. However, with the cost of iron falling to $350/ton over the last few years, the cost differential between installing a continuous reactive barrier versus installing an intervening slurry wall or sheet pile funnel walls may be favorable for the continuous reactive barriers at some sites. Continuous reactive barriers may in many cases be a simpler and more cost-efficient design, with fewer hydraulic performance concerns than a funnel-and-gate system.

- Different construction methods may be cost-effective for different sites. A variety of construction techniques should be considered. Innovative techniques, such as caisson installations and continuous trenchers, offer potential for monetary savings. The choice of slurry wall versus sheet pile for funnel walls should also be evaluated at every site.

- The monitoring network for the barrier should be discussed with regulators as early as possible in the process. Indications from Moffett Field and other sites are that both the number of monitoring points and the monitoring frequency requirements of the barrier are relatively low, and can be reduced further over the years.

- Research is underway for investigating acids or chelating agents as flushing agents to regenerate the reactivity and hydraulic properties of barriers after long-term exposure to groundwater. If successful, this research holds the promise of lower maintenance costs in the future. Otherwise, there is some uncertainty about eventual maintenance costs.

- The comparison of the barrier cost with the cost of other options, such as pump-and-treat systems, should be carefully evaluated. Intangible benefits, such as the absence of aboveground structures with the permeable barrier option, should be considered.

6.2 PERFORMANCE OBSERVATIONS AND LESSONS LEARNED

The Moffett Field demonstration provided several key indications of the site and technology factors driving barrier performance. It is important to take these factors into account when planning a full-scale permeable barrier at Moffett Field or other sites.

The following factors drive the performance of the barrier and should be taken into consideration during design and implementation at this and other sites:

- **Nature of the Aquitard.** A competent aquitard is required so that the barrier can be properly keyed in.

- **Target Contaminants.** Bench-scale testing was a good predictor of field performance for this demonstration.

- **Aquifer Heterogeneities.** Heterogeneities may impact the flow system, which can be modeled during design on the basis of site characterization data and 2-D or 3-D flow model. At some sites, such as Moffett Field, heterogeneities play a key role in groundwater movement and contaminant transport.

- **Geotechnical Considerations.** The presence of aboveground buildings and subsurface utilities overlying the plume limits the possible locations of the barrier. In the absence of subsurface utilities, a continuous reactive barrier may prove to be more cost-effective compared to a funnel-and-gate system, although the reactive medium may not be optimally used. A funnel-and-gate system may be more suitable if there are intervening utilities at the desired location.

- **Groundwater Velocity Estimation.** Due to the heterogeneous nature of the site and because of the limitations of the measurement methods, the groundwater velocity for the Moffett Field demonstration was estimated within a relatively wide range. This may continue to be a challenge at Moffett Field because of the nature of the site.

- **Projections of Contaminant Concentrations Reaching the Barrier.** The pilot barrier design at Moffett Field was based on maximum concentrations of up to 3,000 µg/L of TCE and 600 µg/L of *cis*-1,2-DCE that were present in the vicinity of the barrier at the time of the site characterization. However, if the barrier is expected to be operational over a period of 15 or 30 years, and the plume continues to develop during this period, the concentrations encountered at the barrier could be much higher. It is important to ensure that there is a sufficient safety factor incorporated in the design thickness of the reactive cell to account for the increased concentrations.

- **Role of the Pea Gravel.** In the pilot barrier, the pea gravel was helpful in homogenizing the flow and the influent contamination, providing a well-mixed location for monitoring influent and effluent concentrations, and increasing the porosity and hydraulic conductivity of the gate. However, the presence of the pea gravel does tend to make the flow system more complex by introducing several sharp conductivity and porosity contrasts.

- **Monitoring Network.** The monitoring network need not be as extensive as the one used for the demonstration. Based on the lessons learned from this demonstration and the guidance in other references (Gavaskar et al., 1998; ITRC, 1997), the monitoring network needs to include sufficient wells to be able to evaluate possible breakthrough and plume bypass.

- **Monitoring Frequency.** Monitoring once a year seems adequate based on the trends observed during this demonstration. Water levels and target contaminants may be monitored more frequently in the first quarter or first year until the performance of the barrier is established.

- **Geochemical Characteristics of the Site Groundwater.** In general, sites with high DO or high TDS in the groundwater are likely to exhibit a higher potential for precipitate formation.

6.3 REGULATORY ISSUES

The predominance of groundwater contamination and the lack of methods to treat the contamination in an effective and economical manner is a problem of great concern to the U.S. EPA and the regulated community. The regulators are especially concerned about the issue of chlorinated solvent contamination in groundwater and its potential for persisting for hundreds of years despite efforts to pump and treat it. The U.S. EPA has identified six abiotic technologies that are emerging as possible cleanup remedies for recalcitrant sites (U.S. EPA, 1995). Treatment walls or permeable barrier technology is one of them.

The Interstate Technology and Regulatory Cooperation (ITRC) Working Group, a group that includes regulators from various states interested in certifying innovative technologies, has formed a subgroup to review permeable barrier applications. This subgroup held its first meeting in Philadelphia in September 1996. The ITRC subgroup recently published a regulatory guidance for permeable barriers designed to remediate chlorinated solvents (ITRC, 1997). The ITRC updates can be obtained from their web site at http://www.sso.org/ecos/itrc.

In general, most regulators and site managers are convinced about the contaminant degradation capabilities of permeable reactive barriers. Given sufficient residence time, the reactive medium does degrade target contaminants to desired levels. This can be backed up with bench-scale column tests. Hydraulic performance and longevity are the two issues that continue to generate some uncertainty. Flow (plume) bypass around and above the barrier has been experienced at some sites (Denver Federal Center and Somersworth sites), at least under transient conditions. Although adequate site characterization and a good design can minimize the potential for such occurrences, some uncertainty remains. There are also limitations based on the amount sites are willing to spend to characterize subsurface complexities. On the other hand, there is a growing realization that pump-and-treat systems have limitations too, and are likely to cost more in the long term at many sites.

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APPENDIX A

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