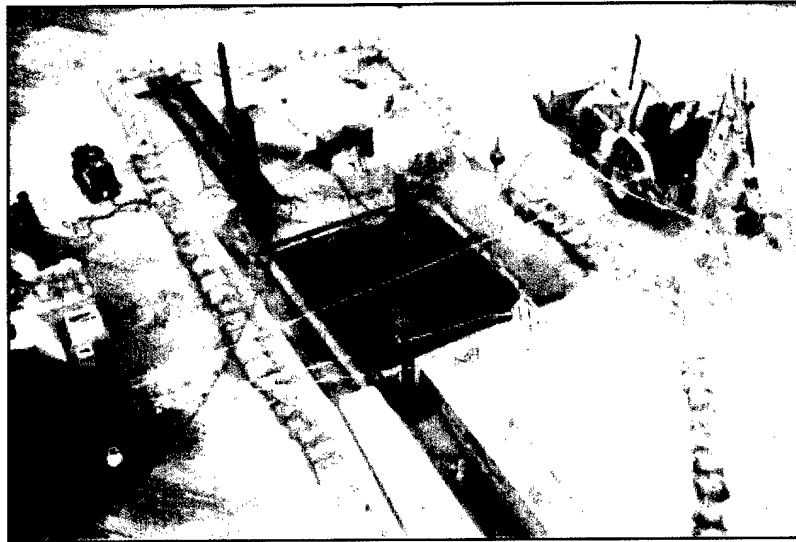




NAVAL FACILITIES ENGINEERING SERVICE CENTER
Port Hueneme, California 93043-4370

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COST AND PERFORMANCE REPORT FOR THE PERFORMANCE EVALUATION OF A PILOT-SCALE PERMEABLE BARRIER AT FORMER NAVAL AIR STATION MOFFETT FIELD, MOUNTAIN VIEW, CALIFORNIA



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**Cost and Performance Report
for the
Performance Evaluation of a Pilot-Scale Permeable Barrier
at Former Naval Air Station Moffett Field,
Mountain View, California**

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Abbreviations and 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
<i>cis</i> -1,2-DCE	<i>cis</i> -1,2-dichloroethene
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
HAZWOPER	hazardous waste operations
IRP	Installation Restoration Program
ITRC	Interstate Technology & Regulatory Cooperation
K	Hydraulic conductivity
LNAPL	light, nonaqueous-phase liquid
MCL	maximum contaminant level
mg/L	milligrams per liter
MS	matrix spike
msl	mean sea level
NFESC	Naval Facilities Engineering Service Center
NPL	National Priorities List
O&M	operations and maintenance
PCE	perchloroethene
PPE	personal protective equipment

RI/FS	Remedial Investigation/Feasibility Study
SEM	scanning electron microscopy
$t_{1/2}$	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

Section 1: 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-dichloroethylene (*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 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, *cis*-1,2-DCE, and vinyl chloride to well below their respective maximum contaminant levels (MCLs). 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. The dimensions of the barrier itself are 10 feet wide by 10 feet long, and it extends from approximately 5 to 22 feet below ground surface. The combined width of the funnel-and-gate section is 50 feet. 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 appear to be precipitating out in 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. There were no indications, at the end of 16 months, of any impending decline in the reactivity or hydraulic performance of the barrier.

The barrier operated unattended and without maintenance after construction. The only recurring cost would be for compliance monitoring. If the barrier retains its performance over approximately 8 years, indications are that it will be more cost-effective than a groundwater pump-and-treat system.

Section 2: 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, 1997; 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.

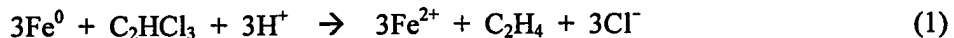
2.1 Technology Background

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.



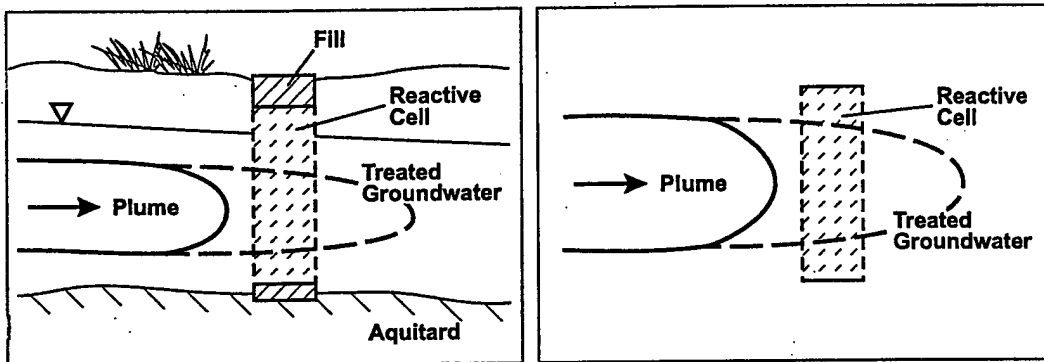
Ethene and ethane are the main products of TCE degradation. However, indications are that these final reaction products are generated through multiple pathways. By the hydrogenolysis pathway, TCE degrades to *cis*-1,2-DCE, which in turn degrades to vinyl chloride. Both *cis*-1,2-DCE and vinyl chloride 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.

2.3 Technology Specifications

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

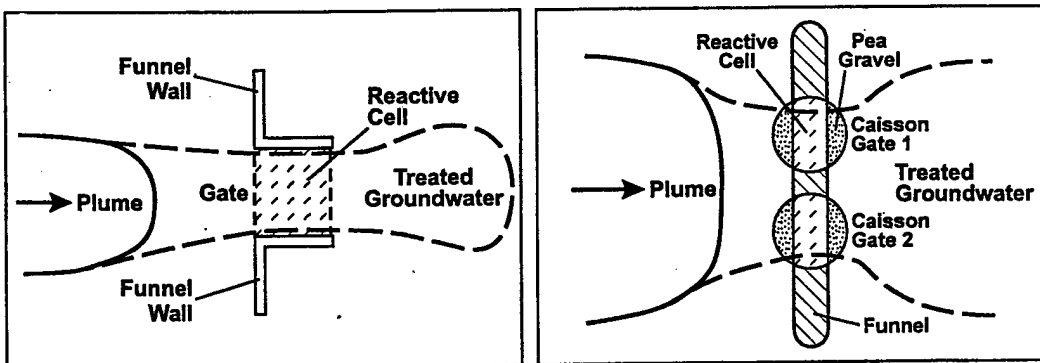
- Treating the contaminants in the captured groundwater to below their respective maximum contaminant levels (MCLs), drinking water standards, or to a risk-based alternative level.
- Ensuring that the interaction between the barrier materials and the groundwater constituents does not cause environmentally 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 are 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 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.

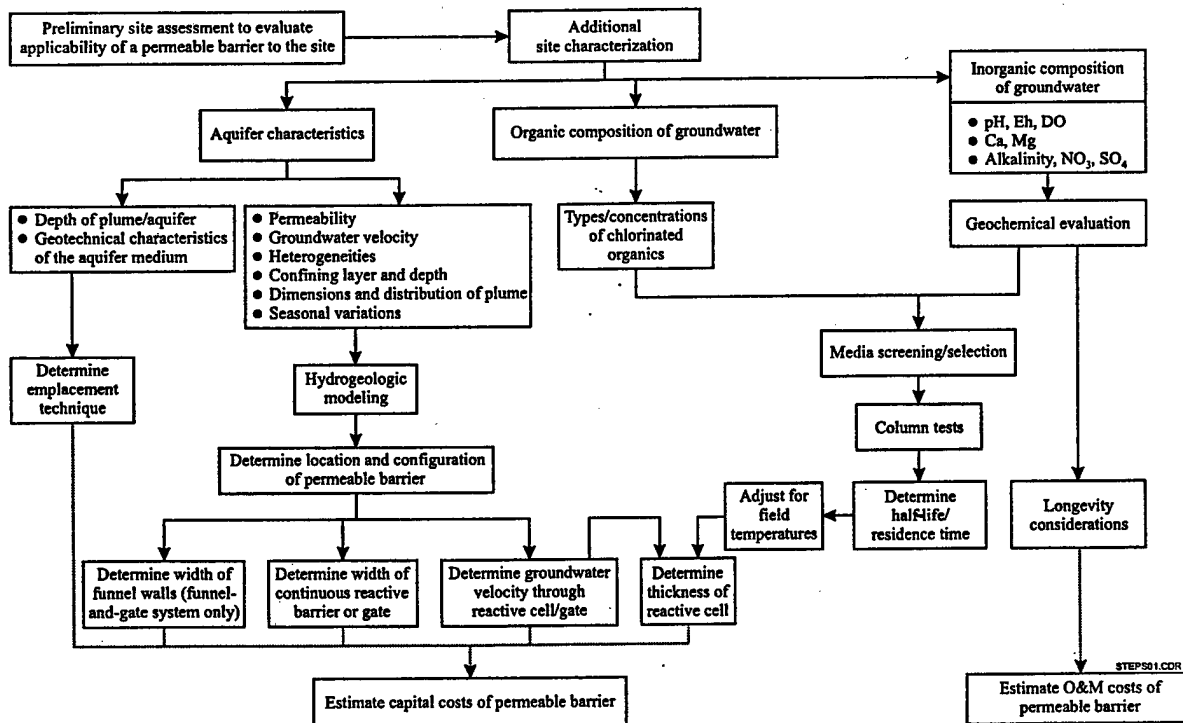


Figure 2-2. Steps in the Design of a Permeable Barrier System

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 over Conventional Technologies

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 more uses.
- No hazardous waste byproducts requiring disposal are generated, and discharge of treated effluent is not needed.
- It has potential for long-term unattended operation.

Section 3: 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 Environmental Response, Compensation, and Liability Act (CERCLA).

Several investigations at Moffett Field have identified extensive groundwater contamination by chlorinated solvents. The primary contaminants of concern are TCE; *cis*-1,2-DCE; 1,1-DCE; 1,1-DCA; and PCE. 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 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.

Table 3-1. Demonstration Activities Schedule

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

Table 3-2. List of Project Participants

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

3.3.1 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. 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.

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 interconnected 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.

3.3.2 Site Hydrology. Water levels and pumping tests indicate that the A1 aquifer zone behaves as a semi-confined 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.

3.3.3 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, ethylbenzene, 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.

3.3.4 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 by personnel inside the trench. 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.

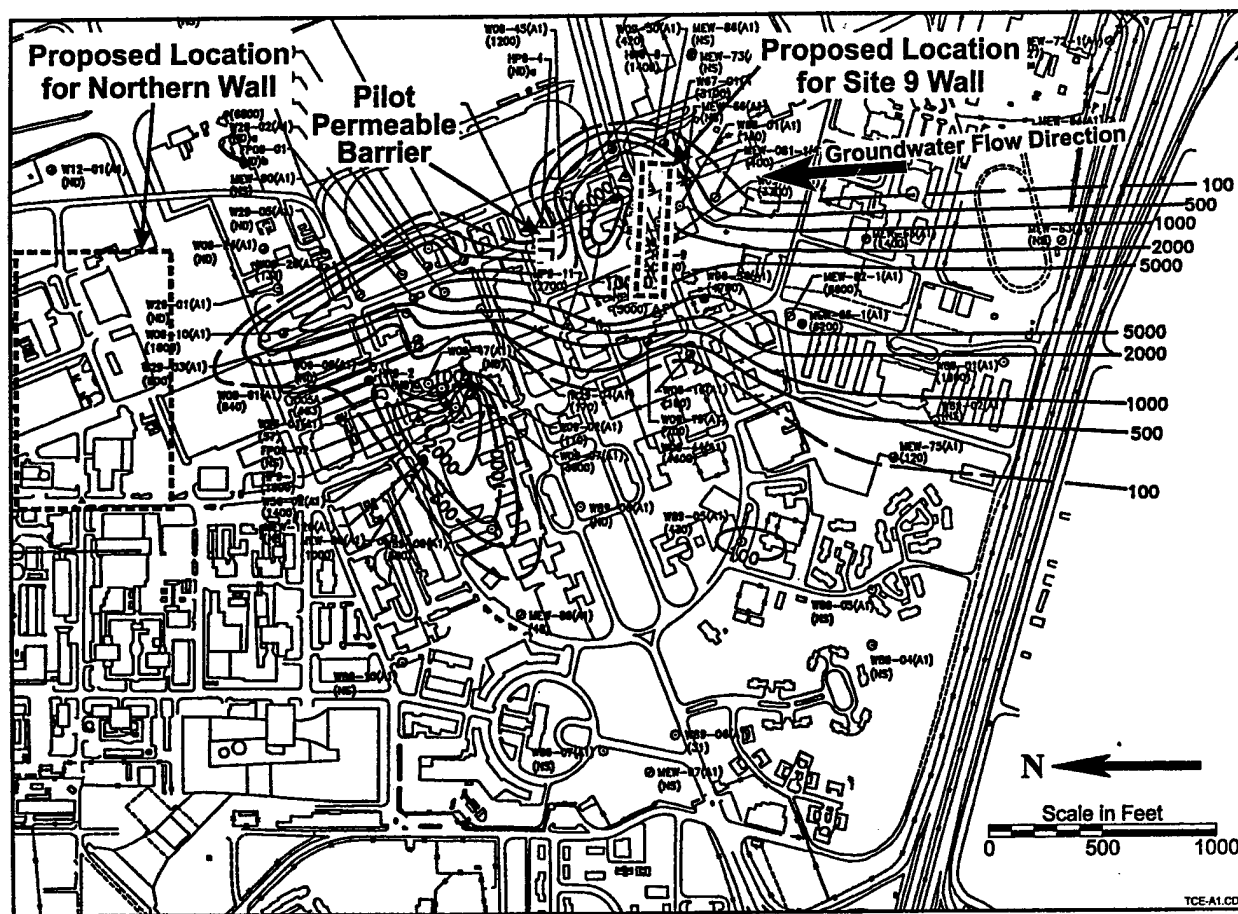


Figure 3-1. TCE Concentration Contour Map for A1 Aquifer Zone, 2nd Quarter 1991 (Source: IT Corp., 1991)

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 environmentally 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 downgradient aquifer by water flowing through the strongly reducing iron cell.
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 through 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 six 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.

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.

Table 3-3. Monitoring Frequency

Parameter Type	Analytes	Sampling Schedule				
		Jun-96	Sep-96	Jan-97	Apr-97	Oct-97
Field parameters	Water level, pH, groundwater temperature, Eh, DO	✓	✓	✓	✓	✓
Volatile organic compounds	CVOCs	✓	✓	✓	✓	✓
	Dissolved hydrocarbon gases			✓		✓
Inorganics and neutrals	Metals (K, Na, Ca, Mg, and Fe)					
	Anions (NO ₃ , SO ₄ , Cl, Br, F, sulfide, alkalinity)	✓	✓	✓	✓	✓
	Neutrals (TDS, TSS, TOC, DOC)					
Water elevations	Water level measurements (13 total events)	✓	✓	✓	✓	✓
Continuous monitoring	Water level, pH, temperature, Eh			✓	✓	
Reactive cell core samples	XRD, SEM, EDS, Raman spectroscopy, microbial analysis					✓

TDS = total dissolved solids
 TSS = total suspended solids
 TOC = total organic carbon
 DOC = dissolved organic carbon
 XRD = x-ray diffraction
 SEM = scanning electron microscopy
 EDS = energy dispersive spectroscopy

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.

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. Cores samples were taken at several locations within the reactive cell to obtain adequate spatial information about possible changes in the granular iron medium.

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 probe	None	None	None	None
pH	Yes	Down-hole probe	None	None	None	None
Water Temperature	Yes	Down-hole probe	None	None	None	None
Eh	Yes	Down-hole probe	None	None	None	None
DO	No	Down-hole probe	None	None	None	None
Organic Analytes						
CVOCs	Yes	EPA 8260	2 x 40 mL	VOA Vial	4°C, pH<2 (HCl)	14 d
Dissolved Gases	No	EPA 3810	2 x 40 mL	VOA Vial	4°C, pH<2 (HCl)	14 d
Inorganic Analytes						
<i>Cations</i>						
K, Na, Ca, Mg, Fe	Yes	200.7	100 mL	Polyethylene	Filter, 4°C, pH<2 (HNO ₃)	180 d
<i>Anions</i>						
NO ₃ , SO ₄ , Cl, Br, F	Yes	300.0	100 mL	Polyethylene	4°C	7 d
Alkalinity	Yes	310.1	100 mL	Polyethylene	4°C	14 d
Sulfide	Yes	9030	100 mL	Polyethylene	4°C	14 d
<i>Neutrals</i>						
TDS	No	160.2	100 mL	Polyethylene	4°C	7 d
TSS	No	160.1	100 mL	Polyethylene	4°C	7 d
TOC	No	415.1	40 mL	Polyethylene	4°C, pH <2 (H ₂ SO ₄)	7 d
DOC	No	415.1	40 mL	Polyethylene	4°C, pH <2 (H ₂ SO ₄)	7 d

Section 4: PERFORMANCE ASSESSMENT

4.1 Degradation of Contaminants in the Gate

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 $\mu\text{g/L}$ in June 1996 to 2,800 $\mu\text{g/L}$ in October 1997. Consequently, TCE concentrations in the upgradient pea gravel well (WW-7C) showed an increasing trend from 570 to 1,000 $\mu\text{g/L}$. 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.

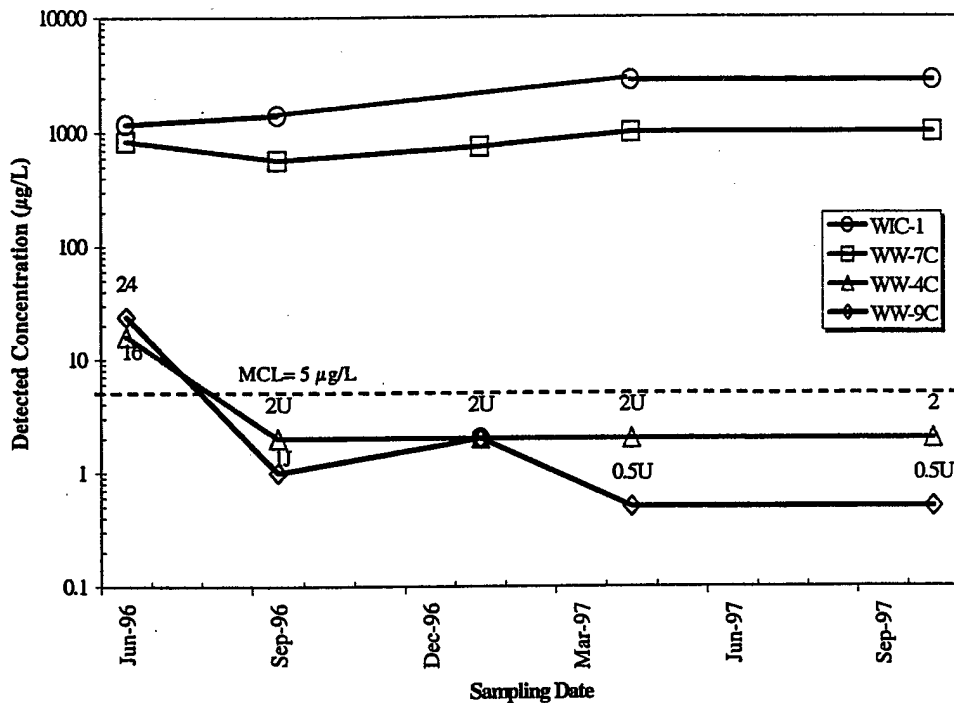


Figure 4-1. Concentrations of TCE in Four Water Samples over the Performance Monitoring Period

In both the reactive cell wells (WW-4C and WW-9C) in Figure 4-1, TCE is below its MCL (5 µg/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). However, *cis*-1,2-DCE concentrations are always below the MCL (70 µg/L) in WW-9C, which is further along the groundwater flow direction.

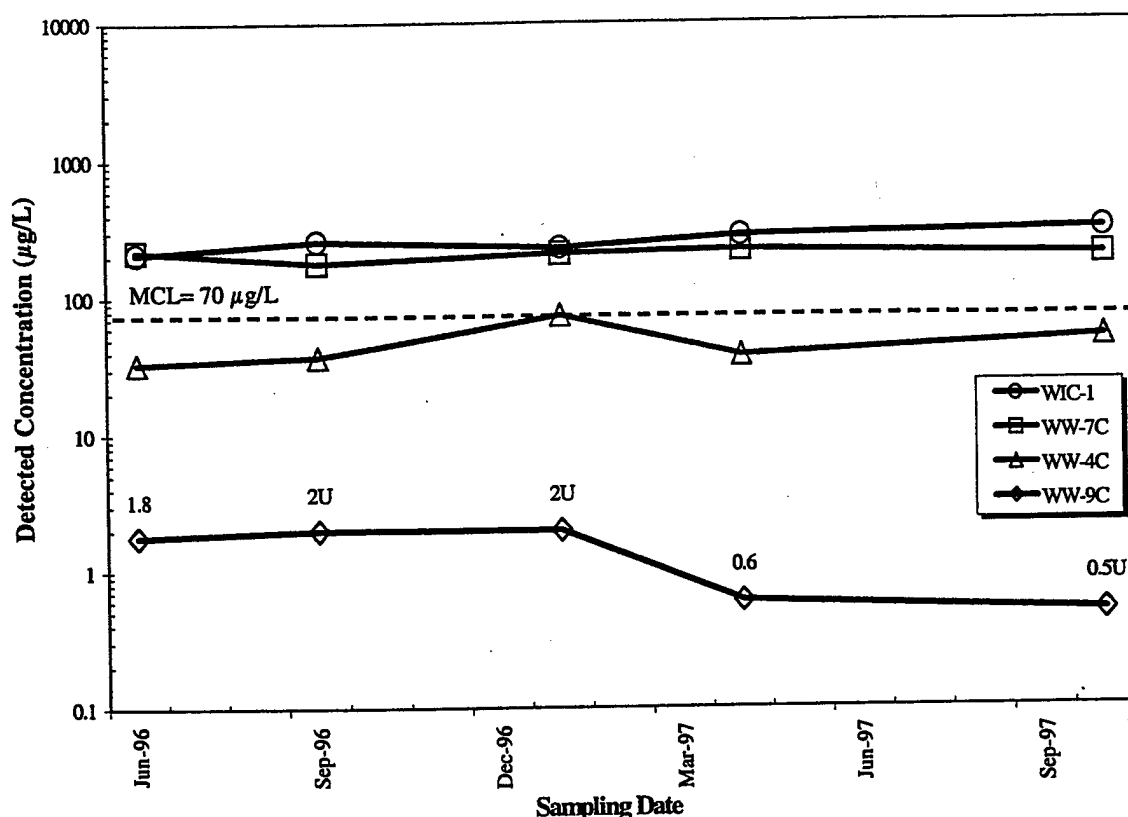


Figure 4-2. Concentrations of *cis*-1,2-DCE in Four Water Samples over the Performance Monitoring Period

4.1.1 Other CVOCs. The concentration of CFC-113 ranges from nondetectable to around 50 µg/L in most of the upgradient A1 aquifer zone and pea gravel wells, and is below detection (2 µg/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 µg/L in the upgradient aquifer and pea gravel wells and is below detection (0.5 µg/L) in the reactive cell. However, 1,1-DCA concentrations are 20 to 30 µg/L in the upgradient aquifer and pea gravel wells and remain detectable (1 to 10 µg/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.

4.1.2 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*TM 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.

Results of the rate constant and half-life calculations are tabulated in Table 4-2. It can be seen that as the expected flow velocity in the reactive cell increases, the estimated *k* increases and estimated *t*_{1/2} decreases. 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.

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)
	<i>cis</i> -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)
	<i>cis</i> -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.

4.2 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.

4.3 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 4-2. Results of Degradation Rate Calculations^(a)

Monitoring Event	Flow Velocity (feet/day)	TCE		<i>cis</i> -1,2-DCE		1,1-DCA	
		<i>k</i> (hr ⁻¹)	<i>t</i> _{1/2} (hr)	<i>k</i> (hr ⁻¹)	<i>t</i> _{1/2} (hr)	<i>k</i> (hr ⁻¹)	<i>t</i> _{1/2} (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 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 and half-lives were calculated from bench-scale data (PRC, 1995). The rate constants shown in this table are 2.3 times those obtained in the column tests, where a 50:50 (by mass) mixture of iron:sand was used.

Section 5: 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

Item	Sub-Total (\$)	Total Cost (\$)
Capital Cost Items		
Site characterization		100,000
Bench-scale 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		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 Cost		652,375
Annual O&M Cost Items		
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 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.), contaminants 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.

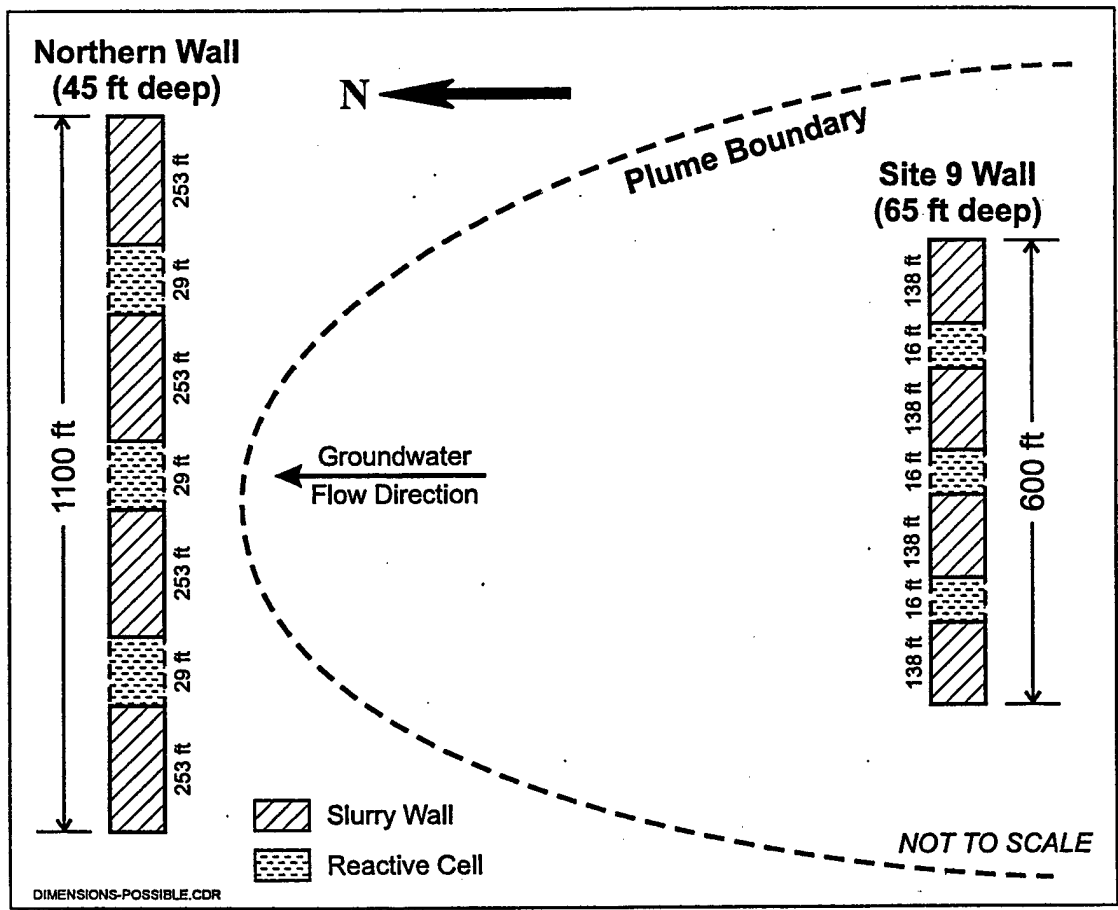


Figure 5-1. Configuration and Dimensions of Possible Full-Scale Barrier at Moffett Field

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.

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.

Table 5-2. Projected Cost of a Full-Scale Permeable Barrier at Moffett Field

Item	Sub-Total (\$)	Total (\$)
Capital Costs:		
Bench-scale tests		75,000 ^(b)
Site characterization		
—Site characterization (hydrogeologic/chemical)	100,000	117,820
—Other testing and welding	17,820	
Engineering Design, Modeling		100,000
Site Preparation		115,258
Construction		
—Mobilization	39,693	
—Trench installation	557,812	
—Gates completion (including iron medium)	1,847,910	3,659,405
—Funnel completion	1,156,164	
—Demobilization	39,693	
—Surface restoration	18,133	
Monitoring wells installation		46,000
Spoils disposal on-site (trench soils)		16,370
Spoils disposal off-site (removed asphalt)		387,989
Site Restoration and Post-Construction Reports		
—Site cleanup	6,032	122,053
—Removal of temporary utilities/facilities	81,021	
—Post-construction submittals	35,000	
Distributive costs (administrative, health & safety)		271,047 ^(c)
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 ^(d)

- (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) Distributive cost estimate does not include overhead costs and profit.
- (d) Rule-of-thumb estimate of 25% of iron medium cost every 10 years.

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). Table 5-3 summarizes the comparison of permeable barrier and pump-and-treat options. As seen in this table, 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.

Table 5-3. Total Cost Comparison of 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 Cost	\$4.9 M	\$1.4 M	-\$3.5 M
Today's estimate	Annual O&M cost	\$72 K	\$695 K	Not applicable
Today's estimate	Barrier maintenance cost every 10 years	\$268 K	Not applicable	Not applicable
6	Capital and O&M cost	\$5.3 M	\$5.6 M	\$0.2 M
10	Capital and O&M cost	\$5.9 M	\$8.4 M	\$2.5 M
20	Capital and O&M cost	\$6.9 M	\$15 M	\$8.4 M
30	Capital and O&M cost	\$7.9 M	\$22 M	\$14 M
40	Capital and O&M cost	\$8.9 M	\$29 M	\$20 M
50	Capital and O&M cost	\$9.8 M	\$36 M	\$26 M

Section 6: 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 barrier versus a funnel-and-gate system should be evaluated at every site based on site characteristics and geotechnical considerations. 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.
- ❑ Different construction methods may be cost-effective for different sites. All these techniques should be considered for the construction. 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 contaminants 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).

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 may have limitations too, and are likely to cost more in the long term at many sites.

Section 7: REFERENCES

7.1 Key References

(Instrumental to completion of project)

- Battelle. 1997. *January 1997 Monitoring Report for the Pilot Permeable Barrier at Moffett Field*. Prepared for NFESC. May.
- Battelle. 1998a. *Field Tracer Application to Evaluate the Hydraulic Performance of the Pilot-Scale Permeable Barrier at Moffett Federal Airfield*. Prepared for NFESC, Port Hueneme, CA. February.
- Battelle. 1998b. *Core Testing Report for the Pilot Permeable Barrier at Moffett Field*. Prepared for NFESC. February.
- Battelle. 1998c. *October 1997 Monitoring Report for the Pilot Permeable Barrier at Moffett Field*. Prepared for NFESC. April.
- Battelle. 1998d. *Performance Evaluation of a Pilot-Scale Permeable Reactive Barrier at Former Naval Air Station Moffett Field, Mountain View, California*. Prepared for NFESC, Port Hueneme, CA. November.
- International Technology Corporation. 1993. *West Side Groundwater Characterization Report, NAS Moffett Field, California*. March.
- IT Corp., see International Technology Corporation.
- PRC Environmental Management, Inc. 1993. *Draft West Side Aquifers Field Investigation Technical Memorandum, Naval Air Station Moffett Field, California*. March.
- PRC Environmental Management, Inc. 1995. *Iron Curtain Bench-Scale Study Report, Moffett Federal Airfield, California*. Prepared by PRC Environmental Management, Inc. for the Department of the Navy, Contract No. N62474-88-D-5086, Task Order No. 0237. October.
- PRC Environmental Management, Inc. 1996. *Moffett Federal Airfield California West-Side Aquifers Treatment System Phase 2 Cost Opinion*. Prepared for the Department of the Navy under Comprehensive Long-Term Environmental Action Navy (CLEAN I).

7.2 Associated DoD Contracts and Records and Their Locations

- Gavaskar, A., N. Gupta, B. Sass, T. Fox, R. Janosy, K. Cantrell, and R. Olfenbittel. 1997. *Design Guidance for Application of Permeable Barriers to Remediate Dissolved Chlorinated Solvents*. Prepared for Armstrong Laboratory/Enviro-nics Directorate. Contract No. F08637-95-D-6004.
- U.S. Environmental Protection Agency. 1995. *In-situ Remediation Technology Status Report: Treatment Walls*. EPA 542-K-94-004. U.S. EPA, Office of Solid Waste and Emergency Response, Washington, DC. April.

7.3 General References

EPA, see U.S. Environmental Protection Agency.

ETI. 1998. Personal communication from John Vogan.

- Focht, R.M. 1998. "Enhanced Zero-Valent Iron Degradation of Chlorinated Solvents Using Ultrasonic Energy." In *Proceedings of the First International Conference on Remediation of Chlorinated and Recalcitrant Compounds*.
- Gavaskar, A., N. Gupta, B. Sass, R. Janosy, and D. O'Sullivan. 1998. *Permeable Barriers for Groundwater Remediation*. Battelle Press, Columbus, OH.
- Gillham, R.W. 1993. Cleaning Halogenated Contaminants from Groundwater. U.S. Patent No. 5,266,213, Nov. 30.
- Gillham, R.W. 1996. "In-situ Treatment of Groundwater: Metal-Enhanced Degradation of Chlorinated Organic Contaminants." In M.M. Aral (Ed.), *Advances in Groundwater Pollution Control and Remediation*, pp. 249-274. Kluwer Academic Publishers.
- International Technology Corporation. 1991. *Phase I Characterization Report, Naval Air Station Moffett Field, Vols. 1-5*. April.
- International Technology Corporation. 1992. *Remedial Investigation Report, Operable Unit 4, NAS Moffett Field, CA*. August.
- Interstate Technology & Regulatory Cooperation. 1997. *Regulators Guidance for Permeable Barrier Walls Designed to Remediate Chlorinated Solvents*. December.
- IT Corp., see International Technology Corporation.
- ITRC, see Interstate Technology & Regulatory Cooperation.
- Naval Facilities Engineering Service Center. 1998. Locations of sand channels at Moffett Field based on *unpublished* documents obtained from NFESC.
- NFESC, see Naval Facilities Engineering Service Center.
- Roberts, A.L., L.A. Totten, W.A. Arnold, D.R. Burris, and T.J. Campbell. 1996. "Reductive Elimination of Chlorinated Ethylenes by Zero-Valent Metals." *Environ. Sci. Technol.* 30(4):2654-2659.
- Remediation Technologies Development Forum. 1998. Web site for Permeable Reactive Barriers Action Team. Available from <http://www.rtdf.org/barriers.htm>
- RTDF, see Remediation Technologies Development Forum.
- U.S. Environmental Protection Agency. 1995. *In-situ Remediation Technology Status Report: Treatment Walls*. EPA 542-K-94-004. U.S. EPA, Office of Solid Waste and Emergency Response, Washington, DC. April.

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