ESTCP
Cost and Performance Report

(CU-9907)

Evaluating the Longevity and Hydraulic Performance of Permeable Reactive Barriers at Department of Defense Sites

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COST & PERFORMANCE REPORT
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LIST OF ACRONYMS

AFB	Air Force Base
AFCEE	Air Force Center for Environmental Excellence
AFRL	Air Force Research Laboratory
BEI	backscatter electron image
bgs	below ground surface
BRAC	Base Realignment and Closure
CPT	cone penetrometer testing
CRB	continuous reactive barriers
CVOC	chlorinated volatile organic compound
DCE	dichloroethylene
DNAPL	dense, nonaqueous-phase liquid
DO	dissolved oxygen
DoD	U.S. Department of Defense
EDS	energy dispersive spectrometer/spectroscopy
ESTCP	Environmental Security Technology Certification Program
gpm	gallons per minute
ITRC	Interstate Technology Regulatory Council
MCL	maximum contamination level
NA	not analyzed
NAS	Naval Air Station
NFESC	Naval Facilities Engineering Service Center
O&M	operations and maintenance
OMB	Office of Management and Budget
ORP	oxidation-reduction potential
ORNL	Oak Ridge National Laboratory
P&T	pump and treat
PCE	perchloroethylene
PLFA	phospholipid fatty acid
PRB	permeable reactive barrier
PV	present value
PVC	polyvinyl chloride

LIST OF ACRONYMS (continued)

RACER	Remedial Action Cost Engineering and Requirements (System)
RTDF	Remediation Technologies Development Forum
SERDP	Strategic Environmental Research and Development Program
TCE	trichloroethylene
TDS	total dissolved solids
U.S. EPA	U.S. Environmental Protection Agency
USACE	U.S. Army Corps of Engineers

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- Steve White, U.S. Army Corps of Engineers, provided significant field guidance and support, especially at the Seneca Army Depot site, where he personally conducted several of the field measurements.

- Matt Turner, New Jersey Department of Environmental Protection, coordinated the Interstate Technologies Regulatory Cooperation (ITRC) participation in this project. The ITRC was instrumental in reviewing critical work plans and reports. Several ITRC members also participated in an important survey that was conducted to determine regulatory concerns and monitoring approach for this technology. The results of this survey helped to refocus the efforts of the project team during the project.

- Timothy McHale, Air Force Research Laboratory, and Robert Edwards (the designated Air Force Center for Environmental Excellence representative) provided guidance and review support.

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

1.0 EXECUTIVE SUMMARY

The goal of this project was to evaluate short- and long-term performance issues associated with permeable reactive barriers (PRBs) installed at several U.S. Department of Defense (DoD) sites. A PRB is a passive, in situ technology, in which natural groundwater flow brings contaminants into contact with a reactive or adsorptive material that removes the dissolved contaminants and protects downgradient receptors. Therefore, PRBs have potentially lower life cycle costs compared to an equivalent pump-and-treat system. The key regulatory driver for the technology is the proven ability of common barrier materials, such as elemental iron, to meet groundwater cleanup standards for many common contaminants, including chlorinated solvents and certain heavy metals. Regulatory interest in this project was driven by the two challenges involved in implementing PRBs, namely, their longevity and hydraulic performance.

The Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP) sponsored this project. The Naval Facilities Engineering Service Center (NFESC) was the lead agency for the DoD project. Battelle, under contract to NFESC, planned and implemented the technical scope and has prepared this report to summarize the results. The Remediation Technologies Development Forum (RTDF) Permeable Barriers Work Group and the Interstate Technology Regulatory Council (ITRC) Permeable Reactive Barriers Team provided document review support for the project.

The two primary technical objectives of the project were:

- Assessing the longevity of PRBs made from iron, the most common reactive medium used to date. Longevity refers to the ability of a PRB to maintain its reactivity and hydraulic performance over long-term operation.

- Assessing the hydraulic performance of various PRBs in terms of their ability to meet the desired groundwater capture zone and residence time requirements.

Longevity

The longevity evaluation focused primarily on the PRBs at former Naval Air Station (NAS) Moffett Field and former Lowry Air Force Base (AFB). These two sites were selected because the PRBs at these sites had sufficient history of field operation and because the groundwater at these sites had moderate to high levels of total dissolved solids (TDS), an important factor in precipitation processes that affect longevity.

The longevity evaluation consisted of the following elements.

- Groundwater geochemistry monitoring
- Iron core collection and analysis
- Geochemical modeling
- Accelerated column tests

For the longevity evaluation, the accelerated column tests provided the best quantitative estimate of the useful life of a PRB; the other tools provided mostly qualitative results. The column tests showed that the reactivity of the iron declines with long-term exposure to groundwater. The rate of decline in reactivity was higher for the Lowry AFB columns, because the groundwater at Lowery AFB contains a higher level of dissolved solids than the NAS Moffett Field groundwater. Declines in reactivity occurred in both columns even though the pH and ORP distributions in the columns remained constant. Based on the rate of loss of reactivity in the columns and on the estimated groundwater velocity at these two sites, the projected life of the PRBs at former NAS Moffett Field and Lowry AFB is approximately 30 years. The "life" of these PRBs was defined as the time period over which the reactivity of the iron declines by a factor of two. The slower groundwater flow at Lowry AFB leads to approximately the same mass flux of dissolved solids through the PRBs at both sites, even though the absolute level of dissolved solids is higher in the groundwater at Lowry AFB. The precipitation causing this loss of reactivity appears to be forming thin films over the iron surfaces, and tracer tests in the columns did not indicate any significant porosity loss or clogging.

Hydraulic Performance

The hydraulic performance evaluation focused primarily on the PRBs at former NAS Moffett Field (funnel and gate), former Lowry AFB (funnel and gate), Seneca Army Depot (continuous reactive barrier), and Dover AFB (funnel with two gates).

The hydraulic performance evaluation made use of the following tools.

- Water level measurements and slug tests
- HydroTechnics™ flow sensors and colloidal borescope
- Groundwater flow and solute transport modeling

For the hydraulic evaluation, careful water level measurements coupled with groundwater modeling gave the best results at the evaluated sites and may be the most useful of the available tools. The direct flow measurements with flow sensors and the borescope sometimes provided groundwater flow velocities and directions that contrasted sharply with the results of water level measurements. The direct flow measurements are point estimates. Bulk flow estimates provided by water levels are probably more indicative of the flow regimes around the PRBs. The sensors or borescope may be useful for further delineation of flow at highly heterogeneous sites, or at sites where groundwater chemistry or water levels have indicated sub-optimal hydraulic performance.

A present value comparison of the costs of a PRB and an equivalent pump-and-treat system at various sites has shown that it takes approximately 7 to 10 years to obtain a payback on the initial capital investment in a PRB. The longevity evaluation provides some reassurance that, at many sites, the useful life of zero-valent iron PRBs will exceed the projected payback period. At many sites, PRBs are installed within the boundaries of the plume; therefore, it may take several years for a noticeable improvement in water quality to appear downgradient of the PRB. Regulatory agencies currently are addressing this issue in the short term by monitoring groundwater quality inside the PRB and ensuring that it meets target cleanup goals. In the long term, as treated water exiting the PRB continues to flush the aquifer, it is expected that the compliance point will be shifted to a suitable location (such as a property boundary) downgradient of the PRB.

2.0 TECHNOLOGY DESCRIPTION

2.1 DEVELOPMENT AND APPLICATION OF THE TECHNOLOGY

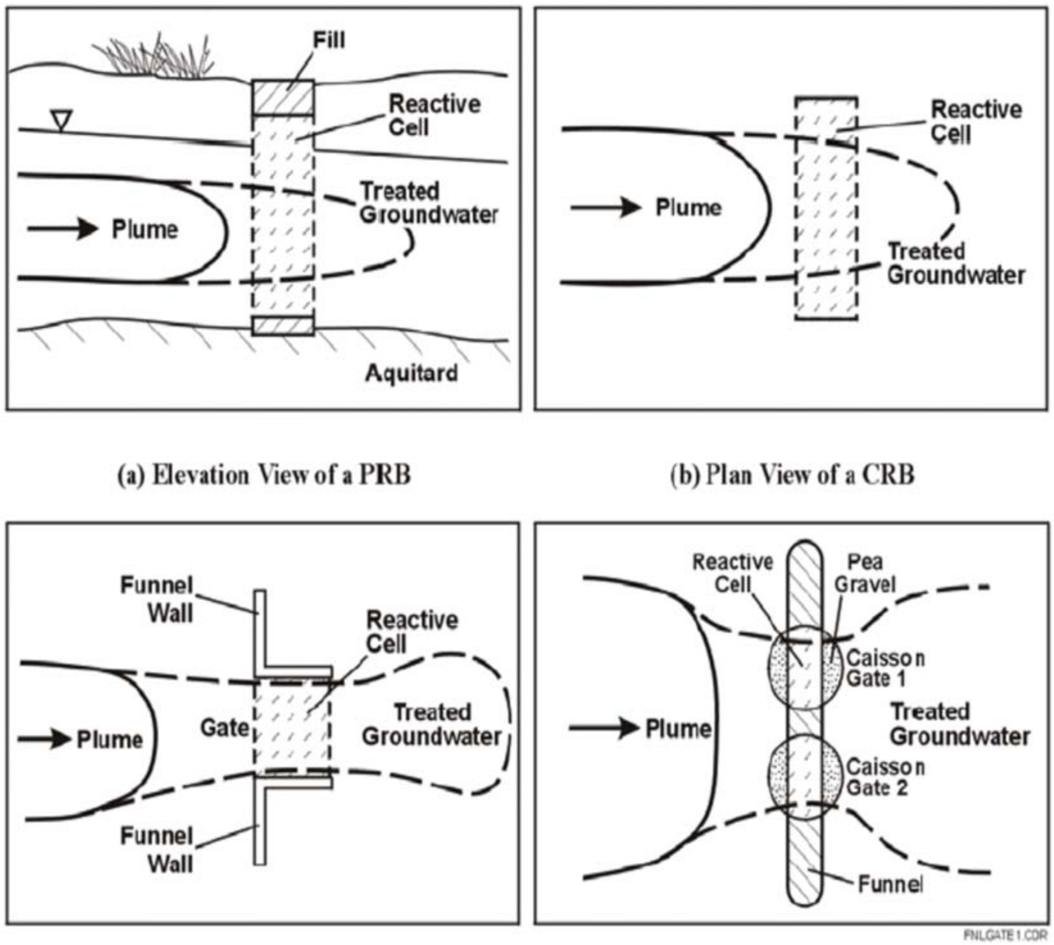
The PRB concept was developed by the University of Waterloo, which recognized the potential for using granular elemental iron for in situ treatment of groundwater contaminants (Reynolds et al., 1990; Gillham and O'Hannesin, 1992; Gillham, 1993). From the mid-1990s to the present, this technology has proven to be attractive to a number of site owners who have implemented pilot-scale or full-scale barriers, primarily for groundwater contaminated with chlorinated solvents. Many chlorinated solvents, such as trichloroethylene (TCE) or perchloroethylene (PCE), form dense, nonaqueous-phase liquid (DNAPL) source zones in aquifers. Because these sources are persistent in the environment, the dissolved solvent plumes emanating from these sources also are very long lived. PRBs, because of their passive operation, provide a potentially cost-effective means of containing these plumes and protecting downgradient receptors.

Because of these advantages, many site owners have been quick to apply this technology. However, both site owners and regulators perceive two challenges related to its application. One is the issue of longevity, or the time period over which a PRB will retain acceptable reactive and hydraulic performance. The other is the issue of hydraulic performance, or the ability of the PRB to meet its groundwater capture zone and residence time requirements. Despite field investigations conducted at several sites prior to this study, these two issues continued to pose a challenge. The current study, as summarized in this report, led to considerable progress in addressing the issue of longevity. The hydraulic performance of PRBs proved more difficult to address, although considerable strides were made in understanding the flow regimes at several PRB sites and the applicability and limitations of several flow measurement tools at PRB sites.

2.2 DESCRIPTION OF THE PERMEABLE BARRIER TECHNOLOGY

In its simplest form, a PRB is a trench in the path of a contaminant plume (see Figure 1). The trench is filled with a medium that treats the contamination through processes such as chemical reduction, aerobic or anaerobic degradation, or adsorption. The primary advantage of the PRB technology is its passive nature; the plume is carried to the treatment zone by the natural groundwater flow.

Also, the passive nature of its operation makes this technology potentially cost-effective for environmentally persistent contaminants, such as chlorinated solvents, in groundwater. Elemental iron has been the most common reactive medium used in PRBs. Elemental or zero-valent iron is a strong reducing agent that can degrade or remove several common groundwater contaminants, such as TCE, PCE, and chromium. The reasons for the popularity of granular iron as a reactive medium are easy availability, reasonable cost, and demonstrated ability to treat a variety of organic and inorganic dissolved contaminants. In several laboratory and field studies, the ability of the iron to reduce these contaminants to target contaminant levels, which in many cases were federally-mandated maximum contaminant levels (MCLs), has been proven (Gillham, 1996; Gavaskar et al., 2002). Examples of other groundwater contaminants amenable to treatment by various barrier media are hexavalent chromium, radionuclides, and nitrates.



(a) Elevation View of a PRB

(b) Plan View of a CRB

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

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

Figure 1. Schematic Illustrations of Some PRB Configurations.

The two main PRB configurations are the continuous reactive barrier (CRB) and the funnel-and-gate system. A continuous reactive barrier has only a permeable section (filled with reactive medium), whereas a funnel-and-gate system has both permeable (gate) and impermeable (funnel) sections. The funnel directs more groundwater towards the gate and was devised early on as a means of capturing more of the target plume. However, because the price of granular iron has dropped from \$650/ton to about \$350/ton in recent years, many sites have been using the less complex CRB configuration. Funnel-and-gate systems may still be considered at some sites with special needs (for or example, sites with underground utilities or sites that need to retrieve and replace the reactive medium frequently).

Trench-type barriers are common because they are relatively easy to install, quality control issues (e.g., continuity of the reactive medium in the treatment zone) are easier to address, and commonly available equipment can be used for their construction. In addition, with improvements in trenching techniques, relatively long (1,100 ft long at the Tonolli Superfund Site) and deep (60 ft bgs at Lake City Army Ammunitions Plant) PRBs have become feasible with trenching. Other construction methods, such as jetting, hydraulic fracturing, and vibratory beam, have been demonstrated at some sites, as they offer some cost advantages at deep sites; however, their application is relatively more difficult and their performance has so far been difficult to evaluate.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

Several landmark studies have tested various aspects of the PRB technology. The first field pilot test was conducted by the University of Waterloo at a controlled site in Borden, Ontario (Gillham and O'Hannesin, 1994). A laboratory study conducted by Johns Hopkins University (Roberts et al., 1996) was instrumental in generating a better understanding of the reaction mechanisms involved in the degradation of chlorinated solvents by iron. Subsequently, SERDP funded a detailed study of PRB design, construction, and monitoring methods that resulted in the field pilot application of a PRB at Dover AFB and culminated in the preparation of two editions of a comprehensive design guidance document (Gavaskar et al., 1997; Gavaskar et al., 2000). A field demonstration funded by ESTCP at former NAS Moffett Field provided important insights into several technology-related issues, such as the applicability of PRBs at highly heterogeneous sites, the flow regime inside a PRB, use of groundwater modeling for improved design and monitoring of PRBs, and impacts on downgradient water quality (Battelle, 1998). Another detailed performance evaluation of a PRB was conducted by the U.S. Environmental Protection Agency (U.S. EPA) at the Coast Guard Site in Elizabeth City, North Carolina (Puls et al., 1995). The current study, summarized in this report, augments the previous studies by focusing on two issues that persisted for this technology, namely, longevity and hydraulic performance.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The PRB technology offers the following potential advantages, especially in comparison to the conventional plume control remedy of pump and treat.

- The passive nature of PRB operation can lead to lower labor and energy requirements and costs in the long term.
- The absence of aboveground structures facilitates property transfers, and the land surface is available for more diverse uses.
- A variety of dissolved contaminants can be treated with a variety of commonly available reactive and adsorptive media to meet most applicable groundwater cleanup targets, as long as adequate capture and residence time can be achieved.

Potential limitations of the PRB technology include the following.

- PRB design and construction generally involve a greater capital investment than for an equivalent pump-and-treat system. Also, at many sites, pump-and-treat systems may already exist as part of an interim remedy.
- Post-construction modifications and changes, if required, may be more difficult and expensive than for a pump-and-treat system. Therefore, it is important to understand the groundwater flow regime and get the PRB installation and operation right the first time.

- The plume possibly may outlive the useful life of the PRB. The results of this current project show that granular iron PRBs, when designed with appropriate safety factors, probably can retain sufficient performance for many years, but may have to be regenerated or replaced at some point.

3.0 DEMONSTRATION DESIGN

3.1 PROJECT OBJECTIVES

There are two primary objectives of the current project.

- Assess the longevity of PRBs made from iron, the most common reactive medium used so far. Longevity refers to the ability of a PRB to maintain its reactivity and hydraulic performance (residence time and capture zone) in the years following its field.

- Assess the hydraulic performance of various PRBs, in terms of the ability of the PRB to provide the influent groundwater with the desired residence time in the reactive medium and to capture the desired portion of the upgradient plume.

Despite field investigations conducted at several sites prior to this study, these two issues had remained somewhat difficult to resolve. The uncertainty over the longevity of a field PRB has led to regulatory agencies requesting that site owners develop a contingency plan (such as implementation of a pump-and-treat system) in case of PRB failure. Regulatory agencies have tried to address uncertainties in hydraulic performance by requesting monitoring for plume breakthrough (insufficient residence time) and bypass (inadequate capture). The current study, as summarized in this report, led to considerable progress in resolving the issue of longevity. The hydraulic performance of PRBs proved more difficult to resolve, although considerable strides were made in understanding the flow regimes at several PRB sites and the applicability and limitations of several flow measurement tools.

3.2 SELECTION OF TEST SITES

Although field data from PRBs at several DoD sites initially were examined, the project subsequently focused on those sites that afforded the necessary range of site characteristics and PRB designs. The longevity evaluation focused primarily on the following two sites.

- Former Naval Air Station (NAS) Moffett Field
- Former Lowry AFB

These two sites were selected because PRBs were installed at those sites at least three years before the current project started (that is, they had sufficient history of field operation) and because the groundwater at these sites was relatively high in TDS, an important factor in accelerating the determination of precipitation potential and longevity. The hydraulic performance evaluation focused primarily on the following four sites.

- Former NAS Moffett Field (funnel-and-gate)
- Former Lowry AFB (funnel-and-gate)
- Seneca Army Depot (continuous reactive barrier)
- Dover AFB (funnel with two gates)

These sites provided a range of PRB designs and hydrogeologic characteristics that could be studied so that appropriate guidance could be provided for future applications. In addition to these primary focus sites, PRBs at other sites, such as Cape Canaveral Air Station (Hangar K) and former NAS Alameda, initially were examined, but were de-emphasized as resources were focused on field investigations at sites that appeared to offer the most features of interest for the current project. Also, a separate detailed study at former NAS Alameda (Einarson et al., 2000) provided sufficient information for this evaluation.

3.3 CHARACTERISTICS OF SITES SELECTED FOR DETAILED EVALUATION

The characteristics of the sites selected for detailed evaluation under the current project are described in this section.

3.3.1 Former NAS Moffett Field

The funnel-and-gate PRB at the former NAS Moffett Field PRB site has been monitored and evaluated in significant details as part of a previous ESTCP project (Battelle, 1998). The surficial aquifer at this site is divided into two aquifer zones–a shallow zone (A1) and a deep zone (A2). The barrier is installed in the A1 zone of the surficial semiconfined aquifer at the site. The A1 aquifer zone is approximately 25 ft deep. Borings at the site suggest that several sand channels exist in the otherwise silty sand aquifer. The barrier was installed in a funnel-and-gate configuration through a major sand channel (Figure 2) within the lower conductivity silty and clayey layers. In general, the site reflects channeled groundwater flow in a multilayered aquifer system. The granular iron used in the PRB was supplied by Peerless Metal Powders, Inc., Detroit, MI.

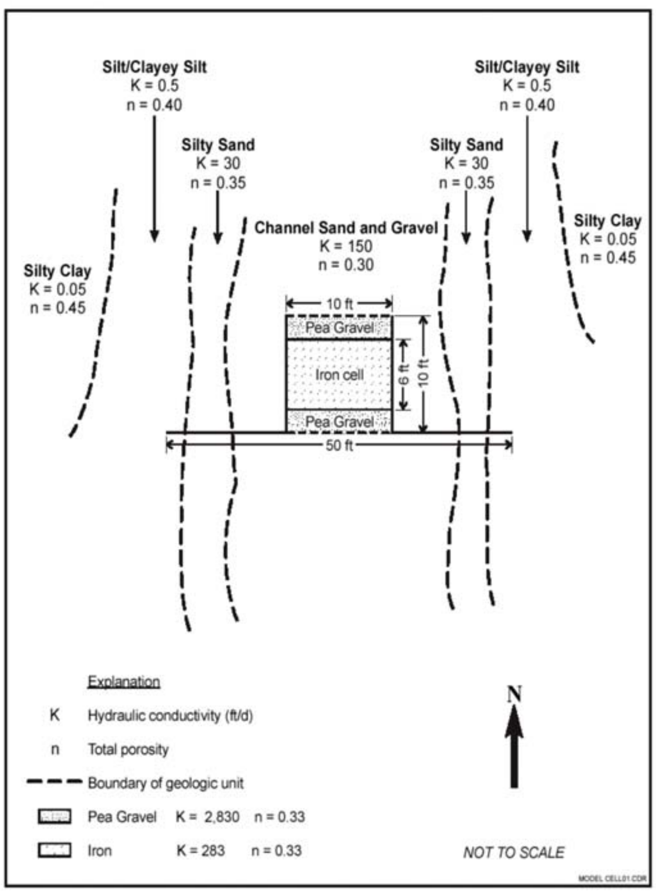


Figure 2. PRB at Former NAS Moffett Field Relative to Lithologic Variations in the Surrounding Aquifer.

3.3.2 Former Lowry AFB

The aquifer at former Lowry AFB is comprised of 11 ft of silty-sand to sand and gravel in an unconfined aquifer which overlies weathered claystone bedrock 23-30 ft below ground surface (bgs) (Versar, Inc., 1997). Some degree of heterogeneity is present in the form of sand and clay lenses. The barrier was set up in a funnel-and-gate arrangement with funnel walls at an angle to the reactive cell (Figure 3). The iron for the barrier was supplied by Master Builders Supply, Streetsboro, OH.

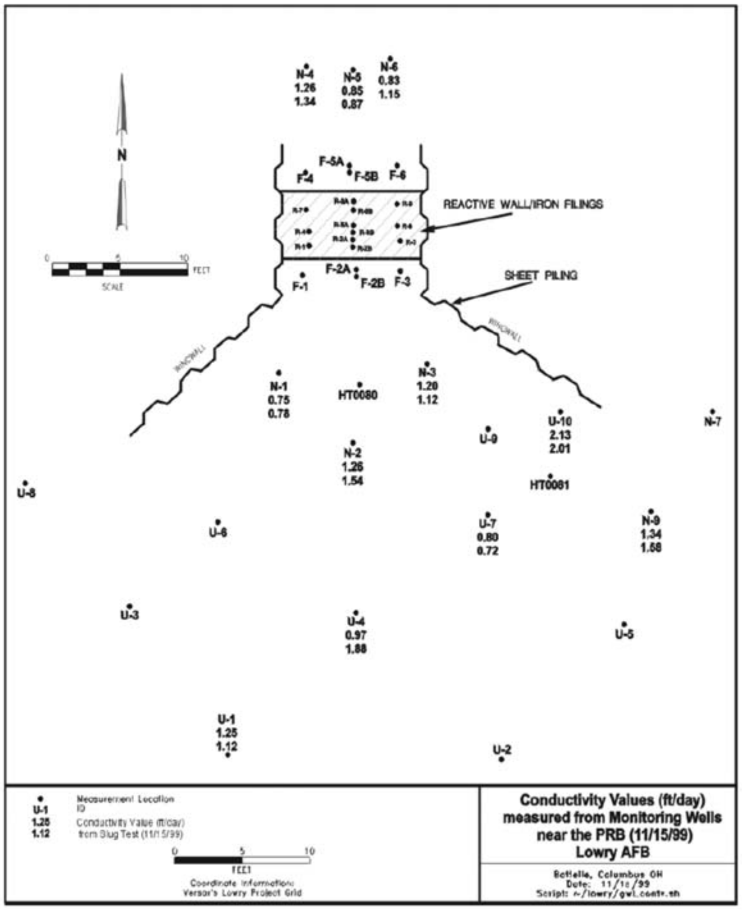


Figure 3. Design and Hydraulic Conductivity Values (ft/day) of PRB at Former Lowry AFB.

3.3.3 Seneca Army Depot

Groundwater flows through fractured shale and overlying glacial till at Seneca Army Depot (Parsons Engineering Services, Inc., 2000). The aquifer is unconfined. The PRB at Seneca is a 600-ft-long continuous trench, approximately 1 ft wide and keyed into competent shale bedrock 5-10 ft bgs (Figure 4). The barrier consists of a 50/50 mixture of sand and iron. Overall, the Seneca Army Depot site reflects a shallow glacial till aquifer with a long, thin PRB designed to treat a diffuse plume spread over a large area. During the current project, 14 new 2-inch monitoring wells were installed (two inside the PRB and 12 in the surrounding aquifer, near the northern end of the PRB) to determine the flow divide and the capture zone.

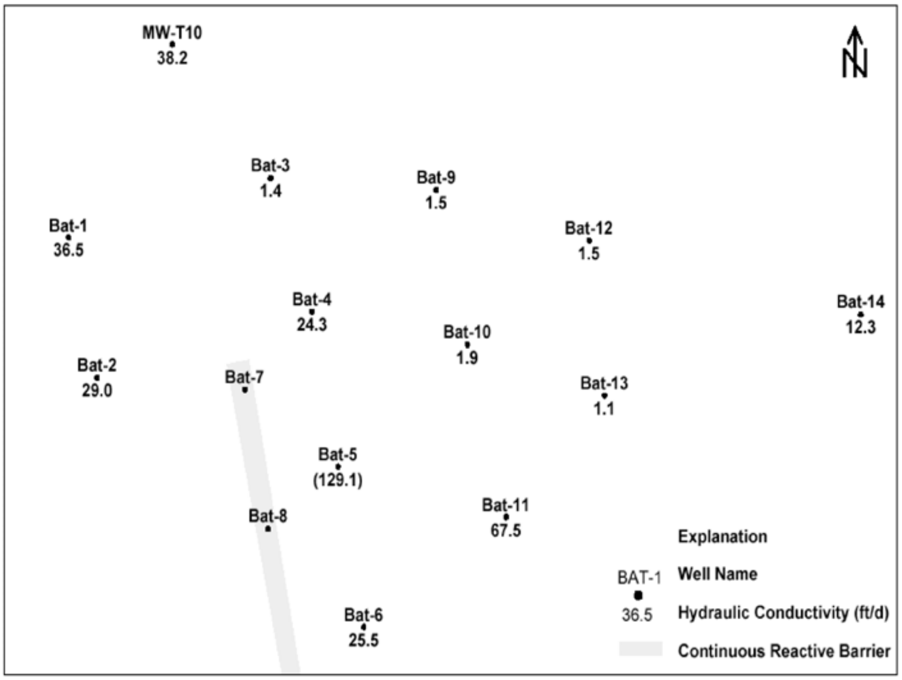


Figure 4. Hydraulic Conductivity Values (ft/d) from Slug Tests at the Seneca Army Depot CRB Showing Variations in Hydraulic Conductivity at the Site.

3.3.4 Dover AFB

The funnel-and-gate PRB at Dover AFB was designed, installed, and monitored as part of a SERDP-funded project by Battelle (Battelle, 1997; 2000a). The aquifer at the Dover AFB site consists of unconfined silty sand deposits overlying a thick clayey confining layer. The aquifer is approximately 20-25 ft thick and fairly homogenous, except for several silty-clay lenses in the upper portion of the aquifer. The hydraulic gradient in the area is fairly low (0.002) and variable, with noticeable seasonal fluctuations. The PRB consists of a funnel-and-gate system with two gates (Figure 5). Interlocking sheet piles (Waterloo Barrier™) constitute the funnel and caisson excavations filled with reactive media (iron) constitute the two gates. The Dover AFB site represents a low-flow velocity setting in a thick, homogenous aquifer. As part of the current project, water level measurements and colloidal borescope measurements were performed at this site.

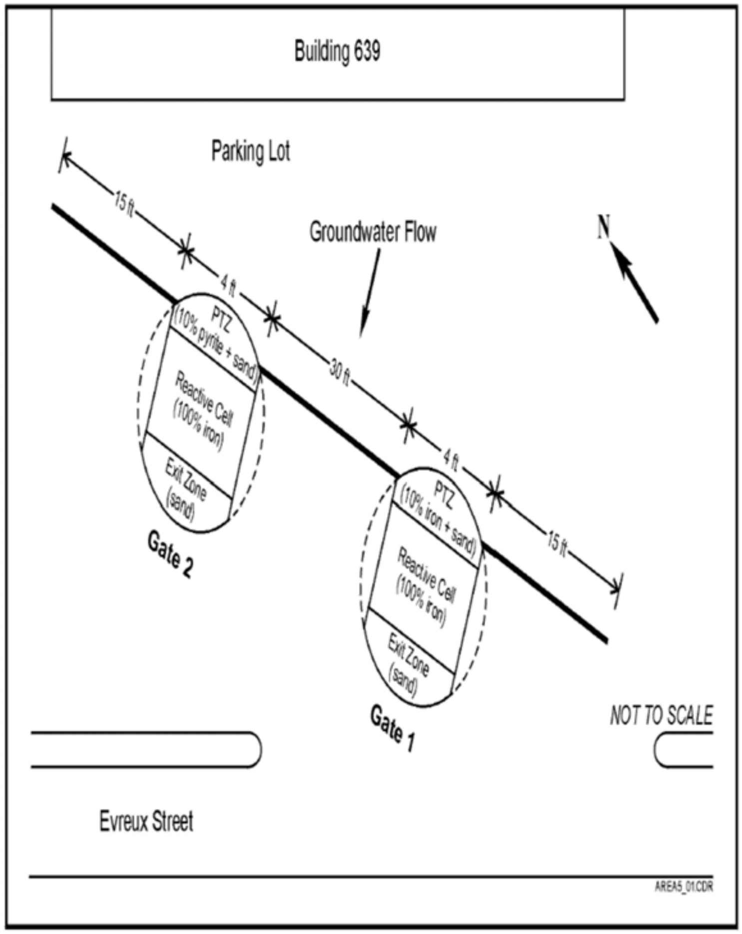


Figure 5. Plan View of PRB at Dover AFB.

3.4 PERFORMANCE ASSESSMENT STRATEGY

The performance assessment objectives were achieved by using a select variety of tools that allowed the project to fill in the data gaps identified in the existing information from the PRB sites. Both performance objectives, longevity and hydraulic performance, presented significant challenges for the project. The strategy that evolved used a combination of tools to address each objective and overcome the limitations of each individual tool.

3.4.1 Longevity Evaluation Strategy

From the beginning of the project, it was clear that developing predictions about the life of a granular iron barrier would be difficult, given the short history of the technology in the field, the lack of information on kinetic rates of precipitation and reactivity loss that could be used in predictive models, and the difficulty of conducting any kind of laboratory simulations that would mimic the exposure of the iron to many pore volumes (i.e., long periods) of groundwater. Tools that initially were used in the current project to evaluate longevity include the following.

- Analysis of inorganic constituents in groundwater influent and effluent.
- Analysis of iron cores collected from field PRBs.
- Geochemical modeling.

Tools that have become fairly conventional for evaluating precipitation in field PRBs include groundwater monitoring (influent and effluent) and iron core collection and analysis. By analyzing the groundwater influent and effluent (or upgradient and downgradient) to the PRB, the loss of inorganic constituents (e.g., calcium, magnesium, alkalinity, sulfate, silicate, etc.) sustained by the groundwater can be measured as it moves through the reactive cell of the PRB. The differences in or loss of groundwater constituents represents the potential precipitation that has occurred in the PRB. However, there are two challenges to using these tools.

- First, the losses in inorganic constituents measured in the groundwater often do not match the amount of precipitate observed on core samples of iron collected from the PRB. This mismatch can partly be explained by the fact that there is considerable uncertainty in the spatial extrapolation of the amount of precipitate observed on small core samples of iron to the rest of the reactive cell, as precipitates may be unevenly deposited in different parts of the iron.

- Second, even if the amount of precipitate formed could be accurately determined, it is unclear how these precipitates distribute on the iron surfaces (whether in mono-layers that use up maximum surface area or in multiple layers that conserve the available reactive sites). Also, because the mechanism through which the precipitates may be bound to the iron and the process by which electrons are transferred between the iron and the contaminants is unclear, it is difficult to correlate loss of surface area with loss of reactivity. In other words, it is unclear to what extent iron can continue to react with the contaminants through a layer of precipitates on its surface.

Geochemical modeling previously has been used to elucidate the precipitation process (Battelle, 1998; Gavaskar et al., 2000; Sass et al., 2001). Two types of models are available – equilibrium models (models that assume an infinitely long contact time between the iron and the groundwater constituents) and kinetic models (models that can be can be calibrated to contact time, if the various reaction kinetics or rate constants involved are known). Because the kinetics of iron-groundwater reactions have not yet been documented, although attempts have been made by some researchers (Yabusaki et al., 2001) to do that, kinetic models have limited applicability. However, equilibrium models are useful for identifying the *types*, if not the quantity, of precipitates; these models were used in the current project to understand the kinds of precipitation reactions occurring in the iron and to provide some indication of what to look for when analyzing the iron cores.

Given the limitations of the indicative tools described above, there was a need for direct empirical evidence of any decline in reactivity of the iron due to exposure to groundwater. Therefore, in the current project, accelerated column tests were conducted to simulate the field performance of PRBs at former NAS Moffett Field and former Lowry AFB. The objective of the accelerated column tests was to examine if and to what extent the reaction rates (or half lives) of the contaminants would deteriorate when the iron was exposed to many pore volumes (i.e., long periods) of contaminated groundwater flow. Unlike tests conducted by John Hopkins University (Arnold and Roberts, 2000; Totten et al., 2001), which currently is studying the effect of individual inorganic and organic constituents in groundwater on the iron, the accelerated column tests in the current project were conducted with actual groundwater from the two study sites (former NAS Moffett Field and former NAS Lowry AFB). The same iron used in those PRBs (Peerless Metal Products, Inc., iron at for NAS Moffett Field, and Master Builder, Inc., iron at former Lowry AFB) was used to pack the two columns. A small amount of oxygen scavenger was added to the groundwater influent to the columns to restore the low dissolved oxygen (DO) levels of the native groundwater, because the groundwater is relatively anaerobic at both sites. In this manner, the interplay of factors occurring in the two field PRBs were simulated as closely as possible.

Higher groundwater flowrates were maintained in the columns than were present in the field PRBs, in order to accelerate the exposure of the iron to the groundwater. Previous studies (O'Hannesin, 1993) have shown that contaminant half-lives are independent of the flowrate; this was confirmed through half-life measurements conducted at different flowrates during the current project. Accelerating the flow through the column permits an examination of the changes in reactivity of the iron when exposed to many pore volumes (or several years) of groundwater flow. Given the short history of field PRBs (6 years maximum), this simulation provided valuable insights into the future behavior of the iron-groundwater systems at these sites.

3.4.2 Hydraulic Performance Evaluation Strategy

The PRB technology relies upon the use of hydraulic characteristics of the site for successful performance over the short and long term. Therefore, a careful consideration of the hydrogeologic issues must be incorporated at all stages of the project: site screening, characterization, design, construction, and performance assessment. Most reports about sub-optimum performance at some PRB sites may be attributed to hydraulic factors. The issues of concern include insufficient residence time resulting in contaminant breakthrough; inability to verify flow through the reactive cell; plume bypass around, under, or over the barrier; seasonal fluctuations in groundwater flow that result in variation in performance; and the effect of nearby site features such as drains, surface water, operating pump-and-treat systems, etc. Almost all of these issues can be related to the two primary objectives involved in designing a PRB and monitoring its hydraulic performance.

- Ensure that the PRB will capture the desired portion of the plume.
- Ensure that the desired residence time in the reactive cell will be met.

Capture zone width refers to the width of the zone of groundwater that will pass through the reactive cell or gate (in the case of funnel-and-gate configurations) rather than pass around the ends of the barrier or beneath it. Capture zone width can be maximized by maximizing the discharge (groundwater flow volume) through the reactive cell or gate. Residence time refers to the amount of time contaminated groundwater is in contact with the reactive medium within the gate. Residence times can be maximized either by minimizing the discharge through the reactive cell or by increasing the flowthrough thickness of the reactive cell. Thus, the design of PRBs must balance the need to
maximize capture zone width (and discharge) against the desire to increase the residence time. Contamination occurring outside the capture zone will not pass through the reactive cell. On the other hand, if the residence time in the reactive cell is too short, contaminant levels may not be reduced sufficiently to meet regulatory requirements.

The basic tools and methods that can be used at various stages of a PRB project for improving the probability of successful implementation have been discussed in details in the design guidance (Gavaskar et al., 2000). The two classes of design used in the current study are site characterization and groundwater flow modeling.

- Site Characterization – this includes developing a detailed understanding of the site geology, hydrogeology, contaminant distribution, and seasonal fluctuations and incorporating the ranges in these aspects into the PRB design to maximize successful implementation.

- Groundwater Flow Modeling – this includes incorporating the site parameters into the computer simulation tools so that the spatial and temporal variations in these parameters can be evaluated and the appropriate safety factors can be determined for PRB design and monitoring system configuration.

The hydraulic performance evaluation strategy consisted of two major elements. One, an effort was made to conduct more detailed characterization of the flow regime around existing field barriers. Two, groundwater modeling was used to obtain a better understanding of the various factors that determine flow at these PRB sites. The objective was to get a better understanding of the groundwater capture zone and residence time at these sites. Therefore, most of the evaluation was conducted on the upgradient side of the PRBs. Groundwater flow direction and velocity ultimately are the two key parameters that need to be estimated to make this determination. The evaluation included the following tools.

- Water level measurements.
- Slug tests.
- In situ flow sensors.
- Colloidal borescope.
- Groundwater flow and solute transport modeling.

Former NAS Moffett Field, former Lowry AFB, Seneca Army Depot, and Dover AFB were the sites subjected to a more detailed evaluation. These sites provided a wide range of site and PRB design characteristics.

4.0 PERFORMANCE ASSESSMENT

4.1 LONGEVITY ASSESSMENT

The results of the longevity evaluation indicate that the reactivity of the iron deteriorates progressively over time or over exposure to groundwater. The results of the longevity evaluation are summarized in the following subsections.

4.1.1 Groundwater Chemistry Evaluation

At former NAS Moffett Field, concentrations of TCE, PCE, and *cis*-1,2-dichloroethylene (*cis*-1,2-DCE) in the effluent from the reactive cell iron continues to be below their respective MCLs and below detection (see Table 1). The well locations are shown in Figure 6. Figure 7 shows how TCE and cis-1,2-DCE levels vary along the flowpath through the PRB at Moffett Field. Most of the treatment occurs in the upgradient half of the iron. Table 2 shows the field parameter measurements along the flowpath through the PRB. A noticeable clean groundwater front is not clearly identifiable in the downgradient aquifer, although some preliminary signs indicate that it could occur in the future. After five years of PRB operation in the sand channel enclosed by silty clay sides, it was expected that introduction of chlorinated volatile organic compound (CVOC)-free groundwater effluent would lead to a noticeable improvement in downgradient groundwater quality, despite some contrary site conditions. One or more of the following site conditions could be acting to delay or prevent an improvement in downgradient groundwater quality.

Table 1. Target CVOC Concentration after Five Years of PRB Operation at Former NAS Moffett Field (May 2001).

Wells (Ordered Progressively Along Flowpath)	PCE (µg/L)	TCE (µg/L)	*cis*-DCE (µg/L)	Vinyl Chloride (µg/L)
Upgradient A1 Aquifer Well				
WIC-1	21 J	1,700	270	<10
Upgradient Pea Gravel Well				
WW-11	13 J	960	230	<5
Reactive Cell Wells				
WW-12	<3	2.4 J	100	1.3
WW-14	<3	0.70 J	0.65 J	<1
Downgradient Pea Gravel Well				
WW-15	<3	21	3.9 J	<1
WW-15-Dup	<3	22	4.3 J	<1
Downgradient A1 Aquifer Well				
PIC-31	<6	160	17	<2.0
WIC-12	24 J	1,500	260	<10
WIC-9	<15	480	60	<5
WIC-3	<30	1,400	240	<10

Note: The qualifier 'J' indicates that the compound was detected, but at a level below the practical quantitation limit.

- Less groundwater may be flowing through the more conductive reactive cell or gate than is predicted or than is flowing around or below the PRB. In some wells screened at shallower depths, a proportionate relative decline in CVOC and inorganic constituents (e.g., calcium) is noticeable over time, which would support this scenario. CVOC levels have declined somewhat over time in the upgradient aquifer too, making the determination more difficult.

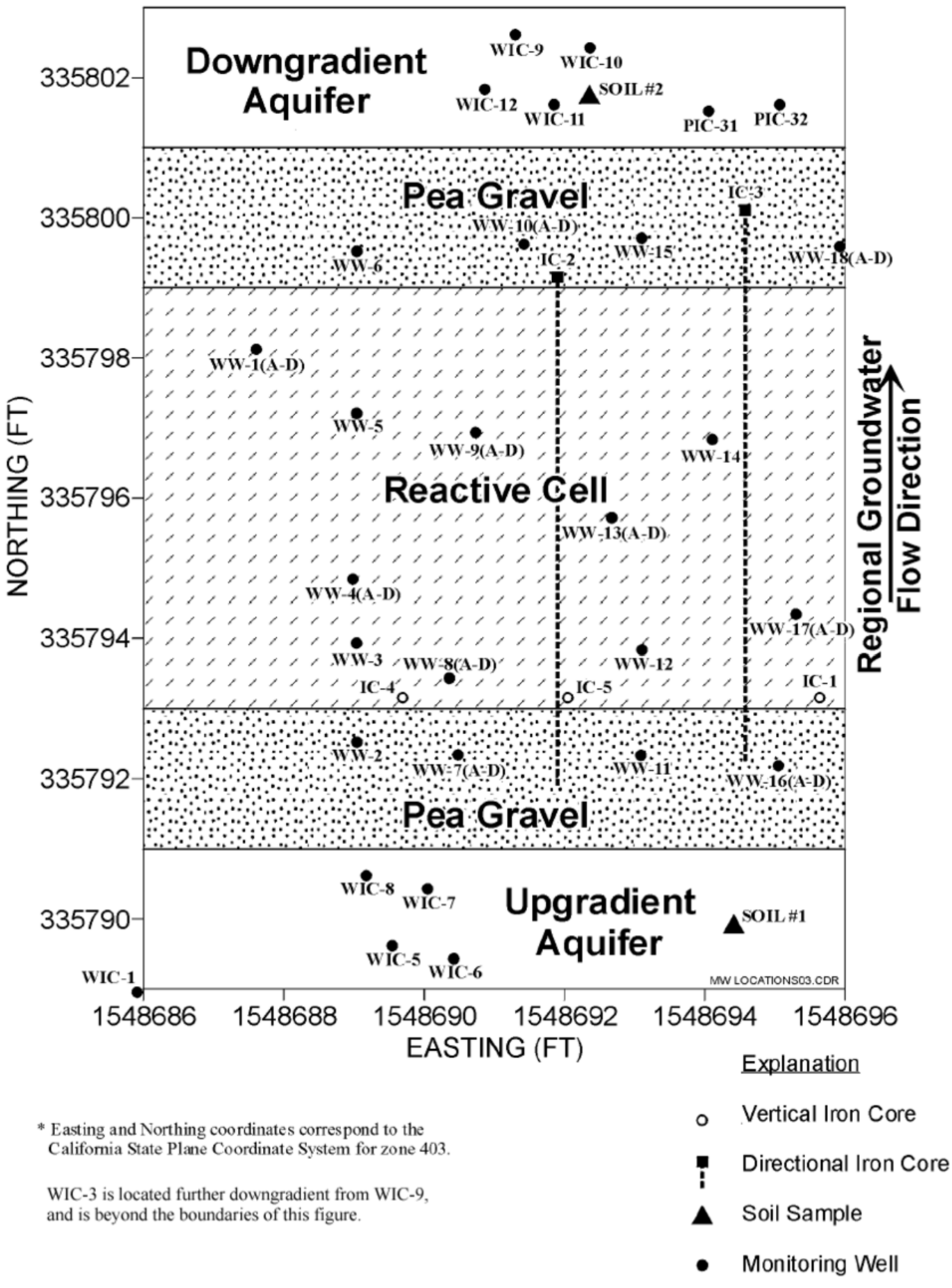
- Recontamination of cleaner groundwater effluent from the PRB may be occurring from contaminated groundwater flowing under the PRB (the pilot-scale PRB intentionally was not keyed into the clay layer for fearing of breaching a thin aquitard) or from the lower aquifer zone. The downgradient monitoring wells that are screened at a depth near the base of the PRB continue to be the most contaminated, indicating that underflow is occurring. However, vertical gradients that were upward in the vicinity of the PRB before PRB installation have consistently turned downward after the installation; this would tend to reduce the mixing of groundwater flowing under and through the PRB.

- Contaminated groundwater may be flowing around the funnel walls of the pilot-scale PRB that was designed to capture only a small part of a regional plume. This is a less likely scenario because the sand channel, which probably accounts for most of the groundwater flow in the local region of the PRB, directs flow mostly through the gate. The funnel walls encounter minimal additional groundwater flowing through the silty-clay deposits around the channel.

- CVOCs trapped in the silty clay layers surrounding the sand channel may be diffusing. This type of contaminant persistence has been observed at other sites, even with pump-and-treat systems. However, diffusion is a slow process and water quality improvement immediately downgradient of the PRB would still be expected.

- Groundwater may be channeling through preferential pathways in the iron. I n the PRB at Moffett Field, several monitoring wells are distributed spatially in the iron. None of the wells in the downgradient half of the iron has shown any significantly elevated levels of CVOCs, indicating that channeling is not likely to be causing breakthrough, given the overdesign of the barrier. Although channeling is an unlikely cause for breakthrough of CVOCs in PRBs that have sufficient safety factors, the fact that as much as 70% void space was estimated in the PRB at Dover AFB indicates that channeling may be a possibility at some closely designed PRB sites. However, at former NAS Moffett Field, where a tracer test was conducted in the field PRB (Battelle, 1998), the high porosity of the iron in the PRB seemed to slow down the progress of the tracer along the flowpath, rather than speed up flow through preferential channels.

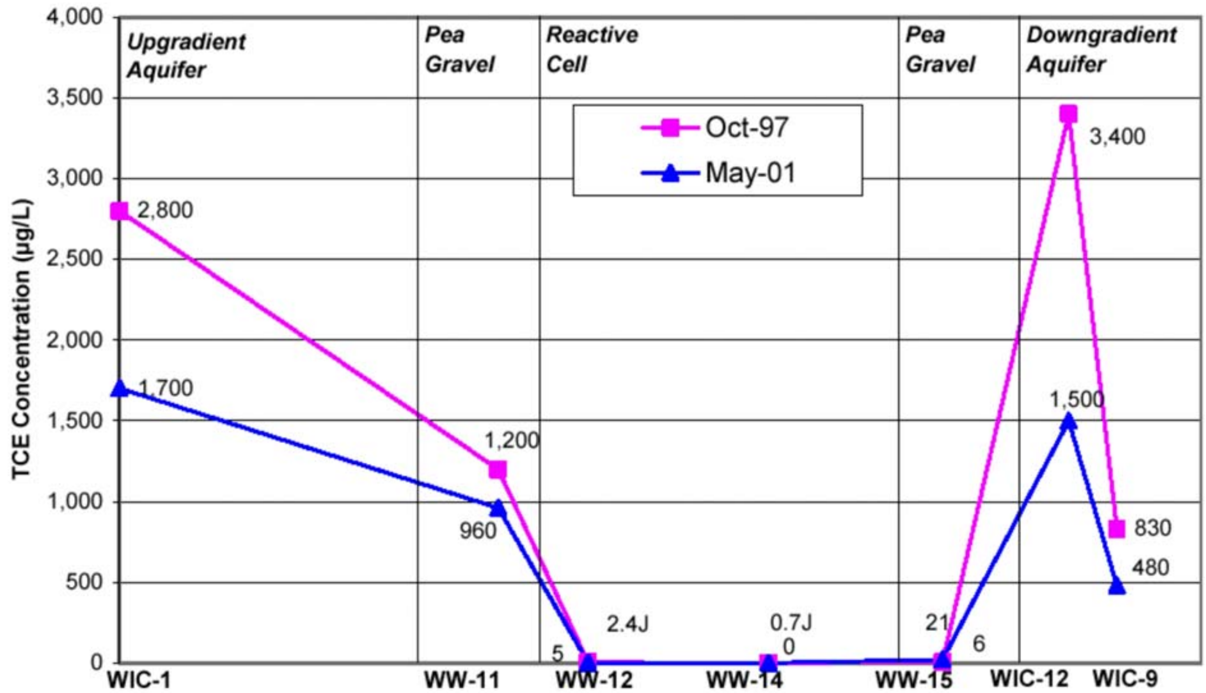
Most of the dissolved calcium, iron, magnesium, sulfate, nitrate, and silica in the groundwater flowing through the PRB at former NAS Moffett Field were removed. Levels of alkalinity and TDS were considerably reduced. These constituents are likely to have precipitated out in the PRB. The groundwater pH rose from 7.0 to 10.9 and the ORP dropped from 134 to -821 mV in the iron. These trends are consistent with previous monitoring events conducted after the PRB was installed. There is no sign that the pH or ORP conditions in the reactive cell are being carried over into the downgradient aquifer. However, some of the shallower downgradient wells located just 2 ft from the downgradient edge of the PRB are showing some signs of decline in levels of inorganic constituents (such as calcium and alkalinity), indicating the effects of treated groundwater emerging from the reactive cell.



* Easting and Northing coordinates correspond to the California State Plane Coordinate System for zone 403.

WIC-3 is located further downgradient from WIC-9, and is beyond the boundaries of this figure.

Figure 6. Monitoring Well Network in the PRB at Former NAS Moffett Field.



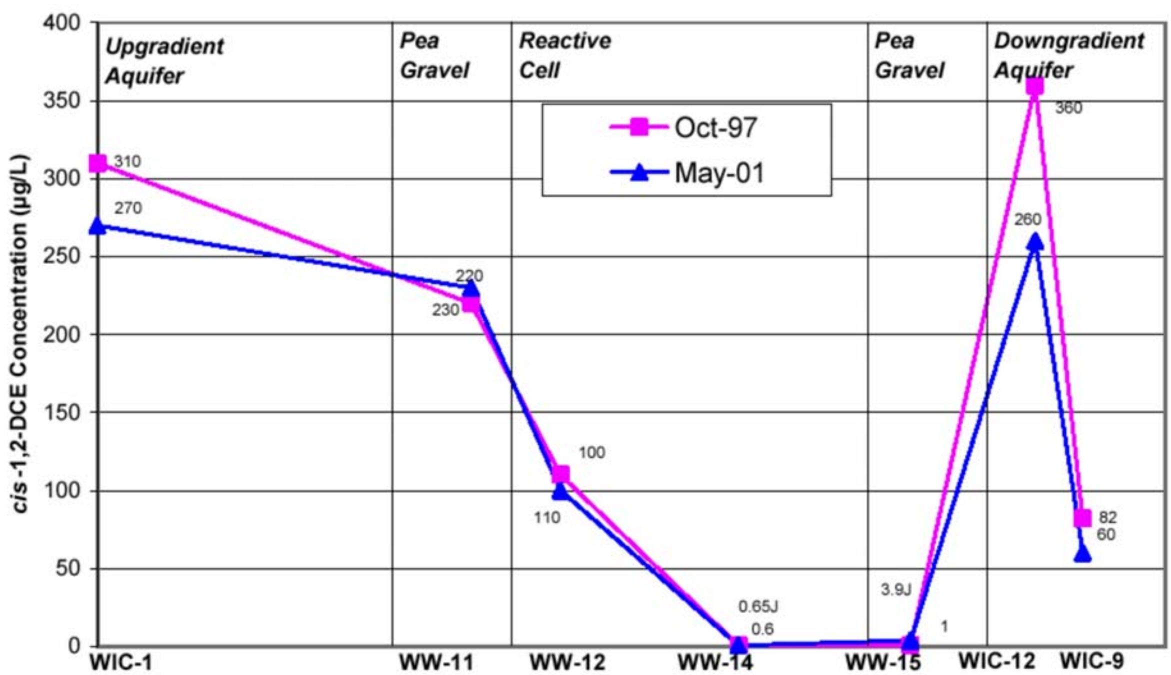


Figure 7. Changes in TCE and *cis*-1,2-DCE along the Flowpath through the PRB at Former NAS Moffett Field.

Table 2. Selected Results of Field and Inorganic Parameter Measurements for PRB at Former NAS Moffett Field (May 2001).

Wells (Ordered Progressively Along Flowpath)	Temperature (°C)	pH	ORP (mV)	DO (mg/L)	TDS (mg/L)
Upgradient A1 Aquifer Well					
WIC-1	19.8	7.0	133.9	0.6	820
Upgradient Pea Gravel Well					
WW-11	20.6	7.0	229	0.7	810
Reactive Cell Wells					
WW-12	20.4	10.0	-40.2	1.0	130
WW-14	20.5	10.9	-820.8	0.4	110
Downgradient Pea Gravel Well					
WW-15	20.6	9.7	-8	0.4	92
Downgradient A1 Aquifer Well					
WIC-3	20.7	7.0	121.9	0.6	820
WIC-9	21.0	7.3	141.1	3.2[(a)]	270
WIC-12	20.6	7.0	-13.2	0.7	830
PIC-31	20.2	9.3	-137.3	0.4	150

(a) The DO value of 3.2 mg/L from WIC-9 is unusually high and is inconsistent with the ORP reading from the same well and other aquifer wells. This value is considered to be an outlier.

At former Lowry AFB, TCE, *cis*-1,2-DCE, and *trans*-1,2-DCE were treated to below MCLs and below detection in the upgradient half of the reactive cell iron. These results indicate that, given sufficient residence time, not only the primary contaminants but also the reduction byproducts can be treated by iron to below detection. At this site too, there were no signs of a clean groundwater front on the downgradient side of the PRB during sampling conducted in September 1999, four years after installation of the barrier. Possible reasons include:

- mixing of the PRB effluent with contaminated groundwater flowing around the pilot-scale PRB installed inside the plume to capture only part of the plume, and
- less groundwater flowing through the more conductive reactive cell or gate than predicted or than may be flowing around the PRB.

At former Lowry AFB, most of the dissolved calcium, iron, magnesium, manganese, nitrate, and dissolved silica were removed from the groundwater flowing through the reactive cell. Levels of alkalinity, sulfate, and dissolved solids were considerably reduced. The groundwater pH rose from 6.9 to 11.5 and ORP dropped from -13 to -725 mV in the iron. These trends are consistent with trends seen in previous monitoring events. There were no signs that any of the geochemical changes in the reactive cell were being transmitted to the downgradient aquifer; a downgradient well, about 5 ft away from the PRB, had the same geochemical constitution as the upgradient groundwater, indicating that any contribution of the treated water emerging from the PRB was overwhelmed by groundwater flowing around the PRB.

4.1.2 Evaluation of Iron Cores and Silt Deposits

At former NAS Moffett Field, geochemical analysis of iron cores from the PRB showed the following.

- Calcium, silicon, and small amounts of sulfur were the elements identified on the iron particles.
- Aragonite, calcite (both forms of calcium carbonate), and iron carbonate hydroxide (similar to siderite) were the mineral species identified on the iron particles.
- Most of these minerals were concentrated in the iron samples collected from the upgradient edge of the reactive cell, indicating that the rest of the iron had not encountered much precipitation.

Calcite, iron oxyhydroxide (FeOOH) or goethite, ettringite (calcium-aluminum sulfate), and katoite (calcium-aluminum silicate) were the mineral species identified in the silt from the silt traps in the monitoring wells in the PRB at former NAS Moffett Field (see Figure 8). The elements iron and magnesium were identified in the silt, but could not be associated with any particular mineral species. Some mineral species (such as feldspar, muscovite, mica and clay minerals) that probably originated from the pea gravel (granite) also were identified. The presence of minerals in the silt traps that are traceable to the groundwater indicates that not all the precipitates formed deposit on the iron medium. Finer, colloidal particles can be transported by the flow to other locations within the PRB, some of which become trapped in the monitoring wells.

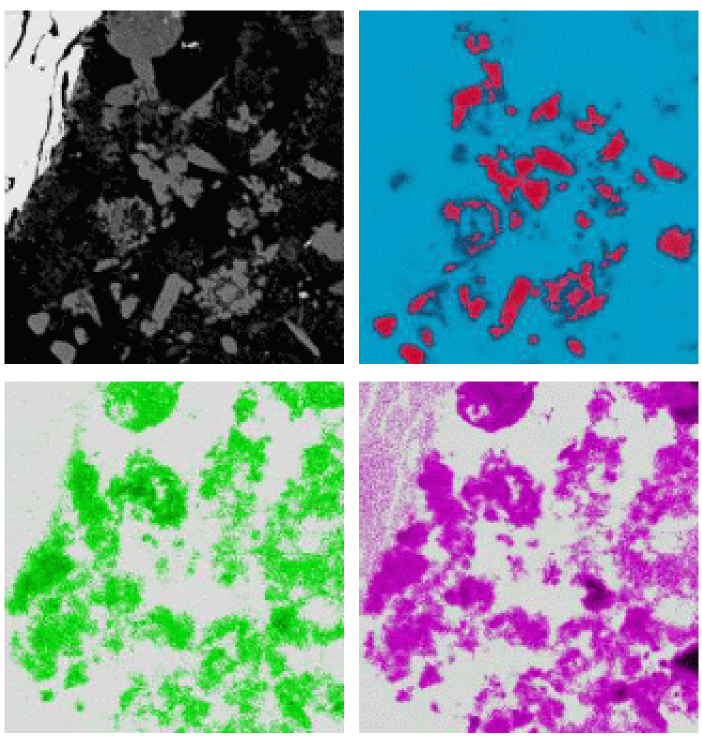


Figure 8. Silt Sample from WW-12 at Former NAS Moffett Field. [Clockwise from top left are BEI Showing Iron and Calcium; and EDS Maps Showing Calcium (Red), Magnesium (Green), Silicon (Violet).]

Iron oxyhydroxide (goethite) and silica were the main minerals traceable to the groundwater that were found on the iron cores from the upgradient edge of the reactive cell at former Lowry AFB.

Surprisingly, no calcium or carbonate was detected on the iron core samples analyzed. This finding is in marked contrast to the results of the column test simulation using Lowry site groundwater and Master Builder iron, where two forms of calcium carbonate were detected throughout most of the column. The disparity in these results could be due to extremely slow groundwater movement in the Lowry field barrier, which would have caused most of the precipitation to occur in the most upgradient portion of the iron that may not have been represented in any of the cores samples taken.

In terms of mass and vertical thickness of deposits in the wells, less silt was found in the monitoring wells at former Lowry AFB than at former NAS Moffett Field, even though the silt traps at Moffett Field had been flushed periodically. A minor amount of rankinite (calcium silicate), though tentatively identified, was the only mineral traceable to a precipitation reaction within the barrier. The groundwater at Lowry AFB is particularly high in dissolved solids, especially sulfate, alkalinity, and calcium. It is surprising that no signs of precipitates associated with these constituents were found on the iron medium or in the monitoring well silt. Once again, the column test results differed from the field measurements in that sulfur was detected on the iron medium used in the column test. Similarly, one possible explanation for this is that the groundwater flow through the PRB is much less than predicted.

4.1.3 Microbiological Evaluation

Microbiology results, based on phospholipid fatty acid (PLFA) profiles, from the former NAS Moffett Field reactive cell and adjacent aquifer showed a predominance of Gram-negative bacteria, indicating that highly adaptable bacterial communities were present. These results also showed that the aquifer soil downgradient of the Moffett Field PRB had a less diverse microbiological community than the soil upgradient of the PRB. Furthermore, the upgradient soil contained a high proportion of biomarkers indicative of metal-reducing bacteria, whereas no such markers were detected in the downgradient soil. Total cell mass was highest in the upgradient soil and lowest in the downgradient soil; the cell mass in the iron cell was between these extremes. PLFA analysis of the iron samples indicates that different bacteria contributed to the anaerobic Gram-negative populations in these samples. The iron samples contained proportionally five times less the amount of a biomarker for sulfate reducing bacteria than the upgradient soil. Altogether, these results may be indicating that the microbial community is still becoming acclimated to conditions inside the PRB. No significant buildup of microbial populations was visible on the iron itself.

Samples of iron from the Lowry PRB also contained highly diverse microbial communities composed primarily of Gram-negative bacteria. However, some iron samples were composed mainly
of eukaryote PLFA or had equal distributions of eukaryotes and normal saturated PLFA. The Gram-negative communities were in a stationary phase of growth and did not show signs of environmental stress.

4.1.4 Evaluation with Geochemical Models

Geochemical modeling was used to predict a likely sequence of mineral precipitation events in the field PRB at former NAS Moffett Field, based on groundwater responses to changes in pH and oxidation-reduction potential (ORP) in the presence of zero-valent iron. Four separate scenarios were run with the following possible phases common to each run: calcite, magnesite, brucite, ferrous hydroxide, and tobermorite. In each of the four scenarios, one or more of the following minerals were allowed to form: siderite, mackinawite, marcasite, and magnetite. All four scenarios predicted changes in pH and ORP that were similar to those observed in the field or laboratory column tests. Also, all four scenarios predicted declines in inorganic species in the groundwater, but at somewhat different proportions. When iron corrosion rate data from available literature were used to predict precipitation rates, the model predictions matched the trends in groundwater chemistry in the Moffett Field barrier for all major species except dissolved silica. The reason for failing to predict silica loss in the barrier was that the likely silica-controlling phase is not known, although thermodynamic data for such a phase may not be available anyway. However, published iron corrosion rates are much too slow to model the changes occurring during short residence times inside the columns. Despite providing ample indication of the types and quantities of precipitates formed in the PRB, groundwater monitoring, iron core analysis, and geochemical modeling provided no links between time and reactivity of the iron, as it was unclear how these precipitates affected the reactivity of the iron in the long term. To establish some preliminary links between period of exposure to groundwater and potential loss of reactivity of the iron, long-term accelerated column tests were conducted to simulate long-term operation at the field PRBs.

4.1.5 Evaluation with Accelerated Column Tests

Long-term accelerated column tests were conducted with groundwater from the field PRBs at former NAS Moffett Field and former Lowry AFB. The columns were packed with fresh iron obtained from the same sources that were used at these two sites. The two columns were adjusted to a flowrate at which pH and ORP reached a plateau (indicating that majority of the reactions between the iron and groundwater had occurred in the column), but which was fast enough that many pore volumes of groundwater could be passed through the column (or many years of PRB operation could be simulated). After some trial-and-error, a flowrate of 12.5 ft/day was eventually established as optimum for the column test. At this flowrate, all the precipitates generated stayed in the column (at higher flowrates, there was a tendency for finer precipitates to be transported out with the flow. If a representative normal flowrate of 0.5 ft/day is assumed at both sites, than the flow in the columns is accelerated 25 times. The 1,300 pore volumes of groundwater passed through each column and the 1.5 years of column testing simulate 30 years or more of operation of the field PRBs. A related test conducted with the same columns showed that the TCE half-life was independent of the flowrate over a wide range of flowrates.

The column tests show that over the 1,300 pore volumes of flow that the iron was exposed to, the half-life of TCE increased approximately by a factor of 2 in the Moffett Field column (see Figure 9) and by a factor of 4 in the Lowry AFB column (see Figure 10). Although some effects of aging may be intrinsic to the iron itself, or to the manufacturing process, other differences may be due to the inorganic content of the water and the subsequent precipitation of dissolved solids. Former NAS Moffett Field has groundwater with a moderate level of dissolved solids and former Lowry AFB has groundwater with relatively high levels of dissolved solids; consequently, the Lowry column showed a greater decline in reactivity over the same period of exposure to groundwater than did the Moffett Field column.

The mechanism for the loss of iron reactivity with TCE is not known with certainty. However, it does appear from column testing that iron in both column tests lost reactivity fairly uniformly, rather than developing a front of inactivated iron that progressively migrates along the length of the

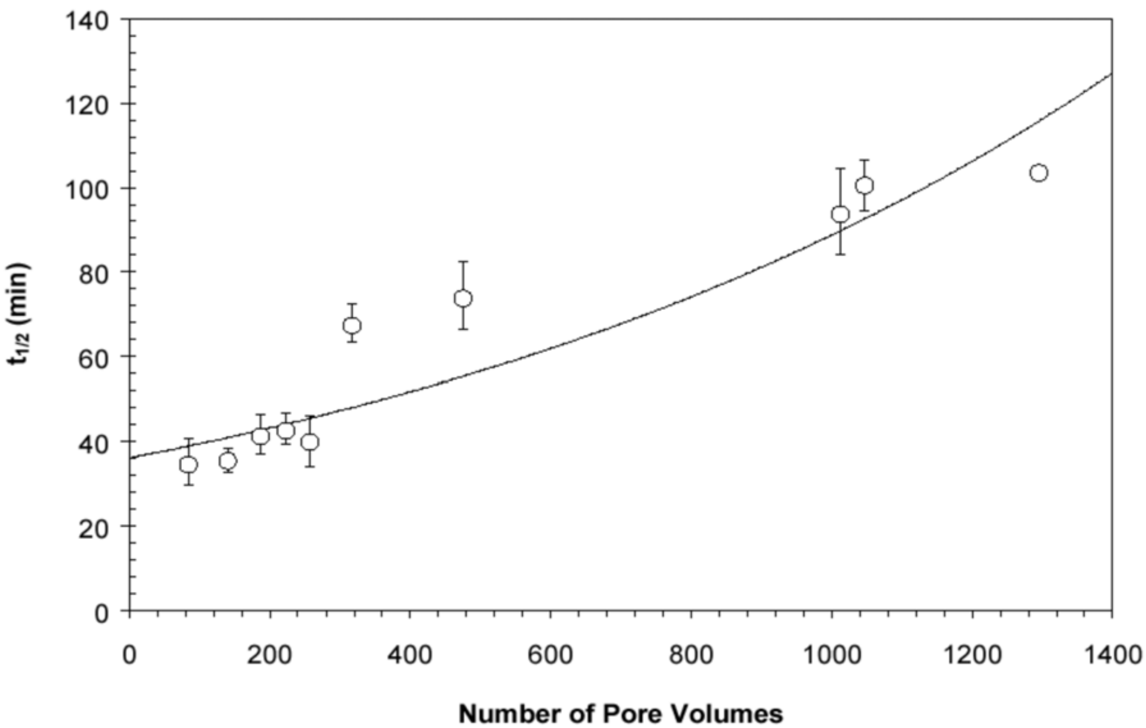


Figure 9. Plot of TCE Half-Lives for Moffett Field Column at Different Cumulative Pore Volumes.

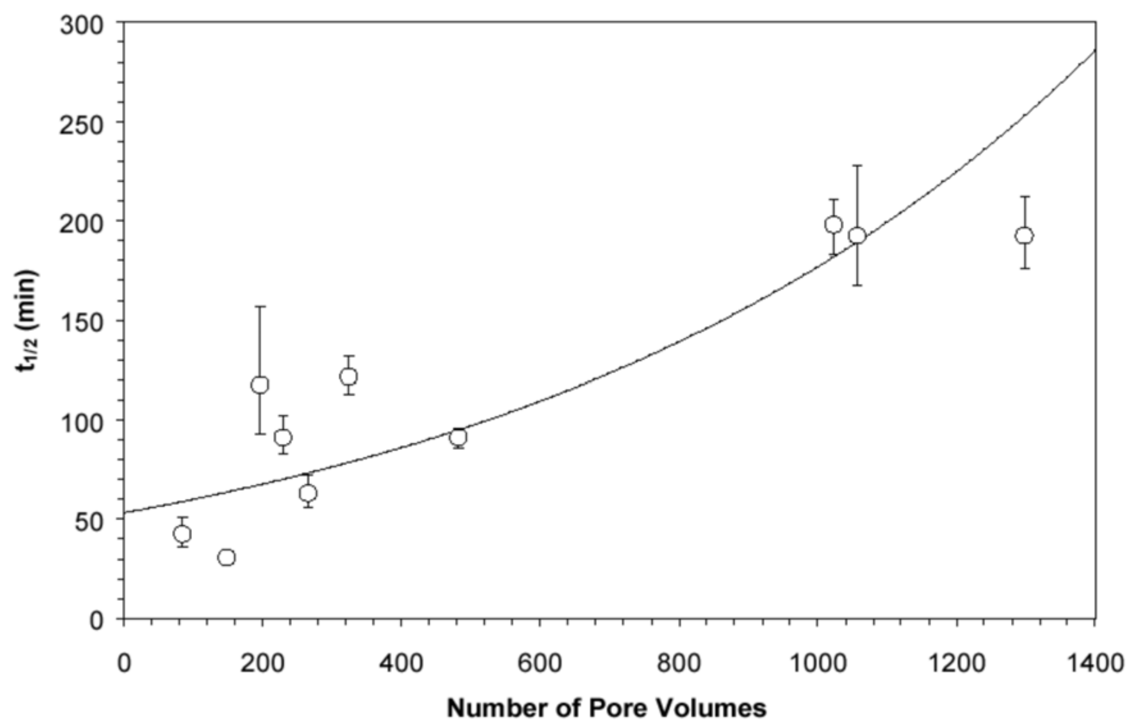


Figure 10. Plot of TCE Half-Lives for Lowry Column at Different Cumulative Pore Volumes.

column. One reason for the uniform change in reactivity may be deposition of non-electrically conductive coatings on the iron grains, such as calcium carbonate, amorphous silicates, sulfide and sulfate minerals, and ferrous hydroxide. Because of the accelerated flowrate in the columns, these precipitates were distributed along a longer distance than would normally occur in a field barrier. However, it is important to note that ferrous hydroxide can form by reaction of water with iron, even if the water has no ionic content. So, for example, if a barrier is very thick or if water moves through very slowly, most of the ionic content of the water will be scrubbed out near the influent end, leaving water with low ionic content in the downgradient portion of the barrier.

The pH and ORP distribution in the two columns remained relatively constant once the test flowrate of 12.5 ft/day was established in the columns, even though the reactivity of the iron declined. One practical consequence for long-term monitoring may be that pH and ORP may not be good early indicators of declining PRB performance. Although these simple measurements are good indicators of iron performance in the short term (to evaluate the quality of the PRB construction and flow stabilization through the iron), they may not be useful tools for tracking the long-term decline in the performance of a barrier. Instead, a time series of measurements of the ratio (C/C_0) of contaminant concentrations at two fixed points, one in the upgradient aquifer (C0) and one in the reactive cell (C), may provide a better indication of an impending decline in reactivity. The advantage of using this ratio is that seasonal and long-term variations in influent plume concentrations are normalized out.

The column test results indicate the following.

- The geochemical constituents of the groundwater do affect the reactivity of the iron upon long-term exposure to groundwater.

- The rate of decline in iron reactivity over time is dependent on the native level of certain dissolved solids (e.g., alkalinity, sulfate, calcium, magnesium, and silica) in the groundwater.

- The PRB is likely to be passivated before the entire mass of zero-valent iron is used, unless some way of regenerating or replacing the reactive medium is developed and implemented.

The porosity and permeability of the iron (and hence the residence time) was not considerably affected over the duration of the test, as indicated by a tracer test conducted in the column after 1,300 pore volumes of flow. Therefore, the reactive performance of the iron is likely to decline much faster than any potential decline in long-term hydraulic performance.

The progressive decline in iron reactivity over time indicates that the residence time required to meet groundwater cleanup targets also will be progressively higher in the long term. One way of ensuring that sufficient residence time is available in the future is to incorporate a higher safety factor in the currently designed flowthrough thickness of the reactive medium in the PRB. Therefore, there is a tradeoff between current cost and future PRB performance.

A longevity prediction (in number of years) for each site depends on the groundwater flowrate through the PRB. The best understanding of groundwater flow through the two PRBs indicates that 1,300 pore volumes of groundwater would flow through the PRB at former NAS Moffett Field in approximately 30 years. At former Lowry AFB, where the groundwater flowrate is much slower, the best estimate equates 1,300 pore volumes to approximately 80 years of operation. Therefore, it is not just the absolute level of dissolved solids, but also the mass flux of certain dissolved constituents that determines how long a PRB will last. Despite the higher precipitation potential of the groundwater at former Lowry AFB, the time rate of loss of reactivity at the two sites may turn out to be approximately the same (factor of 2 decline over 30 years at Moffett Field versus factor of 4 decline over 80 years at Lowry AFB).

A rough interpolation indicates that the PRBs at both sites would have a nominal life of approximately 30 years, if the influent TCE concentrations and groundwater flowrates remain relatively constant over this period. As a safety factor of 2 has been fairly common in the design of several existing PRBs, the definition of longevity as a reduction in reactivity by a factor of 2 seems
appropriate. If a safety factor of 2 was used in the design thickness of the PRB, then a factor of 2 decline in the reactivity of the PRB would imply the possibility that target cleanup levels may not be met at that point in time. This does not mean that the PRB has stopped functioning at this point in time. It implies that some other means would be required to extend the life of the PRB, if the plume and DNAPL source still persist. Greater reliance on natural attenuation on the downgradient side and/or regeneration of the iron medium through in situ or ex situ methods may be desirable, especially because the loss of reactivity appears to be a surface phenomenon and the bulk of the zero-valent iron mass is intact.

Economic calculations (see Section 5) using present value (PV) analyses conducted by the investigators at the Moffett Field and Dover AFB sites indicates that the payback period for a PRB is generally about 10 years. Therefore, a 30-year life expectancy for a PRB appears to ensure that the initial capital invested in the PRB will be more than recovered through annual savings realized through reduced operation and maintenance (O&M) costs, as compared to an equivalent pump-and-treat system.

To a large extent, the accuracy of the longevity prediction will depend on the accuracy of the groundwater flow estimates. At many sites, groundwater flowrates (and residence times) can be estimated only in a range of half or one order of magnitude. The same uncertainty gets translated to the longevity estimates. Typical values of groundwater flow parameters obtained by examining several different modes of measurements (water levels, slug tests, flow sensors, and tracer test) were used to estimate the longevity at the Moffett Field and Lowry AFB sites. It is interesting to note that if the groundwater flow velocity at Lowry AFB had been comparable to that at Moffett Field, the life expectancy of the Lowry AFB barrier probably would have been 15 years.

The decline in reactivity in the columns occurred even though the pH and ORP distributions in the iron remained constant. Therefore, simple field measurements, such as pH and ORP, may not be indicative of loss of reactivity of the iron in field PRBs, in the long term. The DoD report recommends that a time series of measurements of the ratio (C/C_0) of contaminant concentrations at two points, one located in the reactive medium (C) and the other located in the upgradient aquifer (C_0) be used to determine changes in reactivity in the field PRB over time.

Examining the ratio, rather than the absolute concentrations, allows native and seasonal fluctuations in influent contaminant concentrations to be normalized out. In the short-term, pH is a relatively good indicator of the establishment of steady flow conditions and residence time distribution in the iron medium, both in column tests and in field PRB installations.

4.2 HYDRAULIC PERFORMANCE ASSESSMENT

The purpose of hydrogeologic investigations conducted under the current project was to evaluate the major issues related to capture zone and residence time. These two hydraulic issues were investigated by conducting a field evaluation of PRBs at various DoD sites and conducting computer simulations to evaluate the effects of hydraulic variations and characterization uncertainties.

The following sections provide a brief discussion of the monitoring and modeling efforts, followed by a discussion of key findings and their implications for design and performance assessment at future PRB sites.

PRBs have been installed at DoD sites with a variety of site characteristics. Table 3 summarizes the hydraulic parameters measured during the field evaluation at four different DoD sites that were the particular focus of this project. Overall, PRBs have been fairly effective over a wide range of site conditions.

Table 3. Representative Hydraulic Parameters Measured for Aquifers at the DoD PRB Sites Evaluated.

Site	Former NAS Moffett Field	Former Lowry AFB	Seneca Army Depot	Dover AFB
Aquifer type	Semiconfined	Unconfined	Unconfined	Unconfined
Aquifer material	Sand Channel	Silty Sand to Sand and Gravel	Glacial Till	Silty Sand
Depth of aquitard (ft)	25	17	8-10	35-40
Aquifer vertical thickness (ft)	20	11	8	15-25
Aquifer porosity	0.30	0.30	0.18	0.31
Aquifer hydraulic conductivity (ft/d)	0.1-633	1.1-3.1	0.4-126	1.8-101
Typical hydraulic conductivity (ft/d)[(a)]	30	1.7	25	7.4
Hydraulic gradient (ft/ft)	0.005-0.009	0.035	0.005-0.01	0.0015-0.002
Typical hydraulic gradient	0.007	0.035	0.006	0.0018
Range of groundwater velocity (ft/day)	0.0017-19.0	0.013-0.36	0.011-7.0	0.0087-0.65
Approximate groundwater velocity (ft/day)	0.7	0.2	0.8	0.04
Reactive cell thickness (ft)	6	5	1	4
Calculated range of residence times [(b)] (days)	0.3-3,529	14-385	01.-91	6-456
Typical resident time (days)	9	25	1	100

(a) The typical hydraulic conductivity is the most prevalent value from the range of values measured.
(b) This range is calculated to encompass the entire range of measured hydraulic conductivities. The extreme values in this range of residence times may not be realistic, but are provided to illustrate the uncertainties inherent in the estimation.
(c) Hydraulic conductivity used in modeling (Einarson et al., 2000).

Several different types of aquifer materials were encountered at the sites, with soil ranging from alluvial silty sands to artificial fill to glacial till. Aquifer thickness ranged from 8 to 20 ft. The deepest DoD site where a PRB was installed was Dover AFB, where the aquifer was 35 ft bgs. Aquifer porosity at the DoD sites was generally around 0.30, except at Seneca Army Depot, where it was more variable due to aquifer heterogeneity. Representative aquifer permeability varied from 6 to 221 ft/day. However, when all of the slug and pump test data from various sites were examined, the permeability of the aquifer materials showed a much greater range, spanning several orders of magnitude from less than 0.001 ft/day to more than 633 ft/day. This exemplifies the wide variability in aquifer characteristics at sites, and the importance of capturing this variability in designing and monitoring PRBs. Groundwater gradients ranged from 0.001 to 0.01 ft/ft. This parameter may have a considerable effect on PRB performance, because it affects residence times in the reactive cell. Several sites exhibited seasonal variations in gradient due to seasonal trends and/or precipitation events. Based on reported hydraulic parameters, linear groundwater flow velocities at the investigated PRB sites ranged from 0.04 to 0.83 ft/day.

4.2.1 Water Level and Slug Test Measurements

Water level surveys provide information on groundwater gradients and capture zones for PRBs to demonstrate that groundwater is flowing through the barrier at a rate that will ensure adequate destruction of the contamination. Several rounds of water level surveys were performed at the selected DoD PRB sites during the current project. In general, the groundwater surveys demonstrated a positive gradient in the expected flow direction through the PRBs at all four DoD sites; that is, when gradients were measured from upgradient to downgradient aquifer.

Within the PRBs themselves, hydraulic gradients were extremely flat, which is expected of highly permeable and porous media. A few transient flow reversals were reported at the Moffett Field site, but these occurrences appear to have been temporary and generally within the measurement error (Battelle, 1998). At former NAS Moffett Field, monitoring conducted during a previous project showed that some mounding appeared to be occurring at the downgradient end of the PRB, which may indicate that groundwater discharge from the highly permeable PRB media to the generally less permeable aquifer meets with some resistance. The results of water levels measured in May 2001 as part of the current project are shown in Figure 11. Among all the PRB sites evaluated under the current project, the PRB at former NAS Moffett Field provided the most certainty in terms of verifying a groundwater capture zone and occurrence of flow through the PRB, probably because the sand channel surrounded by silty-clay deposits constrained flow from diverging to the sides. Close examination of the water level map in Figure 11 shows flow divides occurring about half way across the length of each funnel wall. Based on these water levels, an approximate estimate of capture zone is 30 ft. The capture zone includes the flow directly upgradient of the 10-ft-wide gate and halfway across 20-ft-wide funnel wall. Water-level surveys are a key monitoring activity for confirming gradients at PRB sites.

Based on a typical hydraulic gradient of 0.007, observed during water level mapping events, and a typical hydraulic conductivity of 30 ft/day, representative of slug test results in the sand channel, a typical groundwater velocity of 0.7 ft/day and a residence time of 9 days are estimated as shown in Table 3. This residence time estimate matches the results of a tracer test (Battelle, 1998) conducted during a previous project. The wide variability in the hydraulic conductivities measured at different locations in the aquifer and the likelihood of preferential pathways in the iron medium itself, as seen in the tracer test, create substantial uncertainty in the groundwater velocity and residence time estimates.

Although the water level information at the DoD sites usually showed capture by the PRBs, at some sites the groundwater gradient was often so low that water level surveys were less conclusive than expected. Because there is a limit to the accuracy of a groundwater survey (usually 0.01 ft or 1/10 inch), careful design of a monitoring well network is required to obtain useful water level information. A general rule for water levels is to space the monitoring wells at distances equivalent

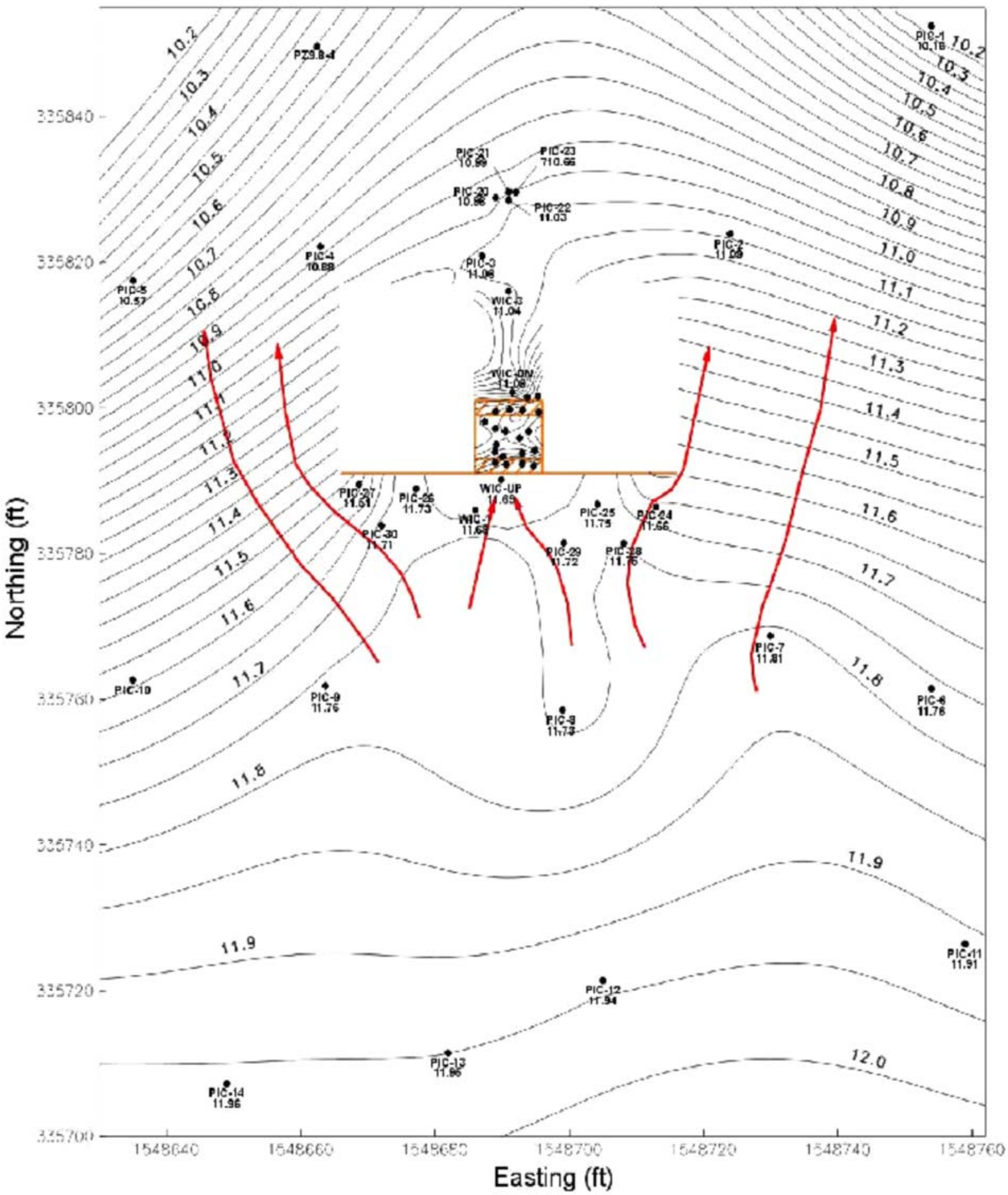


Figure 11. May 2001 Water Levels and Flow Patterns in the Vicinity of Former NAS Moffett Field PRB.

to at least the measurement accuracy divided by the gradient. For example, wells in an aquifer with a gradient of 0.001 would require spacing of at least 10 ft to acquire a measurable 0.01 ft or higher difference in water levels. In practice, PRB dimensions along the groundwater flow directions are often smaller (generally less than 10 ft) than the monitoring well spacing required for sufficient resolution in water level measurements. Therefore, at most sites, water level surveys are likely to be challenging.

One way of improving the accuracy of water level measurements for evaluating horizontal gradients is to ensure that the screened intervals of all the wells in the monitoring network are at a uniform depth throughout the network. This approach has improved the feasibility of water level surveys at sites, such as Dover AFB, with very low hydraulic gradients.

Seasonal fluctuations in the gradient must be accounted for in the analysis of water level data. For example, at Dover AFB, historical measurements indicated that groundwater flow direction changed by about 30° on a seasonal basis (Battelle, 2000a). This had a considerable effect in determining an optimum design and orientation of the PRB so that the PRB was perpendicular to the flow during most times of the year. Before designing a PRB, at least four quarters of water level data should be obtained to account for seasonal fluctuations in groundwater velocity and direction. In addition, information on long-term extremes in water levels and flow directions obtained from historical records, where available, should be considered in the designing PRBs.

The capture zone produced by a PRB in the upgradient aquifer may be determined by contouring the water levels for wells in and around the PRB. However, these maps are not always conclusive, due to a limited number of data points, limitations in obtaining accurate water level differences over short distances, and low magnitude of the gradient itself. For this project, although most maps of observed water levels demonstrate flow through the PRB, a well-defined capture zone was rarely apparent from the field data. For example, at Lowry AFB (see Figure 12), gradients were relatively strong in the upgradient aquifer and indicated not only flow progressing in the expected direction toward the reactive cell, but also the asymmetric nature of the capture zone due to the effect of an adjacent stream on the east side. The capture zone at Lowry AFB appears to be approximately 20 ft wide, with 10 ft of capture directly upgradient of the gate and 10 ft along the western funnel wall. Most of the flow upgradient of the eastern funnel wall appears to be directed towards the flowing stream on the east. Based on the hydraulic conductivities measured during slug tests and the hydraulic gradient obtained from water level measurements, a typical groundwater velocity of 0.2 ft/day and a typical residence time of 25 days are estimated, as shown in Table 3. A moderate variability in the hydraulic conductivity estimates in the sandy aquifer creates some uncertainty in these estimates.

On the other hand, at Seneca Army Depot and Dover AFB, the flow divide and therefore the capture zone were difficult to determine. At Dover AFB, the native gradient itself is low. At Seneca Army Depot (Figures 13 and 14), the difficulty was that the PRB was relatively thin (1 ft flowthrough thickness) and generated a very minor disturbance in the natural flow patterns.

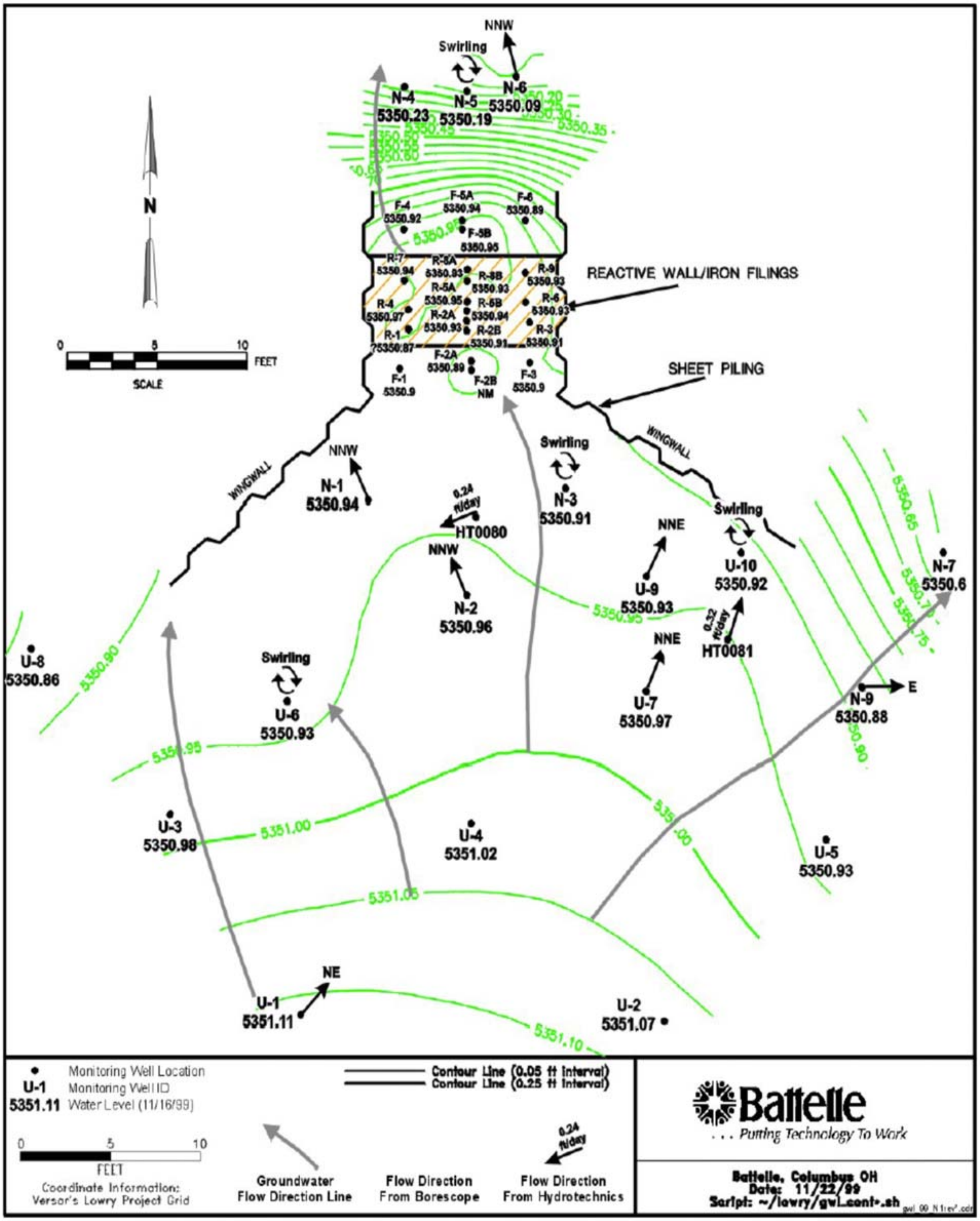


Figure 12. November 1999 Water Levels and Other Hydraulic Measurements at Lowry AFB PRB.

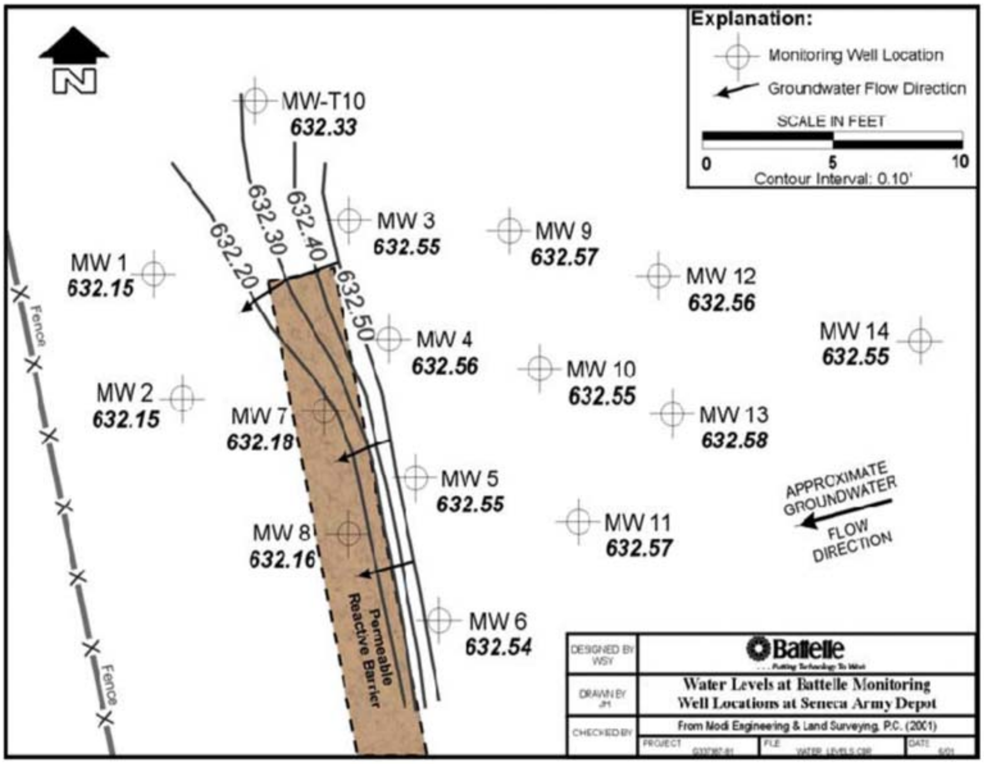


Figure 13. July 2001 Water Levels at Seneca Army Depot PRB.

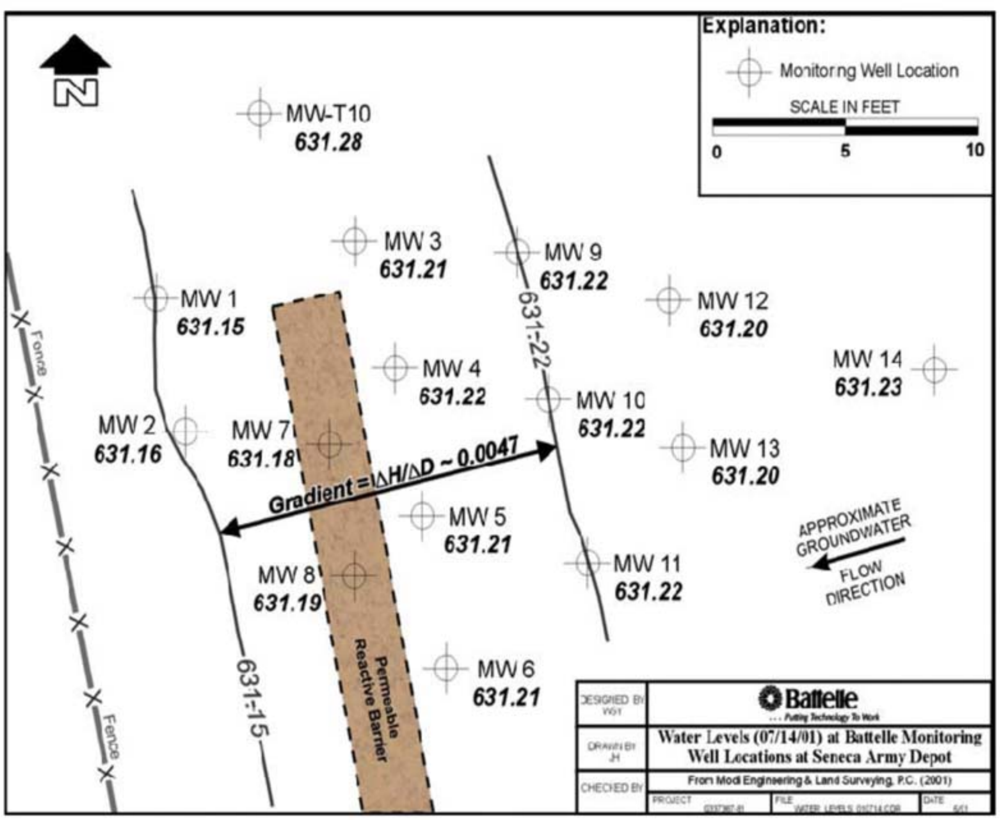


Figure 14. July 2001 Water Levels at Seneca Army Depot PRB.

At both these sites, uniformly screened monitoring wells and multiple monitoring events led to at least some events that afforded discernible groundwater flow trends. To conserve limited resources, the monitoring well network at Seneca Army Depot was limited to one end of the relatively long PRB. The water level map for this site for April 2001 (Figure 13) shows a steep gradient immediately upgradient of the PRB and flat water levels farther away. It also shows that the flow lines point towards the PRB at the northern end of the site indicating capture of the plume from that area. However, during July 2001 (Figure 14) the water levels are flat upgradient of the PRB, showing the seasonal effects on the flow patterns and residence times. In both cases, there is a downward gradient from upgradient to downgradient wells, indicating the flow is occurring through the PRB.

At the former NAS Moffett Field where a large number of monitoring wells installed at similar depth are available and the flow is constrained through a sand channel, it was possible to draw a capture zone upgradient of the funnel-and-gate PRB (Figure 11). In this case, the capture zone appears to be the soft-wide zone directly upgradient of the reactive cell and extending to about half the width of the funnel wall on each side.

Vertical gradients were analyzed previously at the Moffett Field site, where upgradient wells were installed at four different depth intervals. Analysis of these water levels (Battelle, 1998) suggests that a slight downward gradient was induced by the installation of the PRB. A moderate, but progressively downward, gradient was observed from the shallower wells to the deeper wells. In addition, the previously upward (pre-construction) gradient between the lower aquifer to the upper aquifer in which the PRB was placed was reversed to a downward gradient after installation. The effect of such changes in flow patterns on plume capture should be considered in designing and monitoring PRBs at sites with layered aquifers or PRBs that are not keyed into the underlying confining layers.

Within the aquifer media, the tests at Moffett Field (Figure 3) and Seneca (Figure 4) revealed aquifer heterogeneity. The Moffett site contains a relatively specific sand channel within silty sand, while the Seneca site suggested more widespread variations in permeability associated with the glacial till aquifer and presence of anthropogenic preferential pathways. These differences were reflected in the barrier designs: the Moffett PRB was a 30 ft wide funnel which intercepted the sand channel, while the Seneca design was a 600 ft long trench. At Lowry AFB, all the slug tests showed an exceptionally narrow conductivity range, indicating a relatively homogeneous aquifer (see Table 4).

Table 4. Results of Slug Tests at DoD Sites.

Site	Hydraulic Conductivity (ft/day)	
	Aquifer	**PRB**
Dover AFB	1.8 to 101	234 to 812
Former Lowry AFB	1.1 to 3.1	NA
Former NAS Moffett Field	0.1 to 633	NA
Seneca Army Depot	0.4 to 126	NA

NA = not analyzed

4.2.2 Measurement of Velocity with HydroTechnics™ Sensors and Colloidal Borescope

The velocity of the groundwater in aquifers and PRBs also can be measured directly using in situ sensors such as the HydroTechnics™ sensor or borehole probes such as the colloidal borescope. During the current project, the HydroTechnics™ sensors were deployed at the former Lowry AFB site, and the colloidal borescope was used at the Dover AFB and former Lowry AFB sites. Two HydroTechnics™ sensors were installed at the Lowry PRB site in October 1999. One sensor was installed about 5 ft directly upgradient of the PRB and the other was installed towards the end of the eastern funnel wall to assess the flow divide (Figure 12). As shown below, all of these probes have encountered mixed success.

The second velocity sensor used in the current project, the colloidal borescope, was developed at Oak Ridge National Laboratory (ORNL) for the measurement of flow conditions in monitoring wells (Kearl et al., 1992). The instrument relies on the use of a specialized downhole camera for observation of colloidal particle movement across the well screen. The moving particles are recorded on a computer screen for calculation of flow direction and velocity. The borescope is limited to observations in the preferential flow zones within the well and therefore the results may be biased towards the faster flow zones in the aquifer (Kearl, 1997).

The borescope was employed at the Lowry site in a total of eleven wells both upgradient and downgradient of the barrier (Figure 12). No measurements could be made inside the reactive cell the diameter of the monitoring wells in the cell was too small. Although three of the wells showed swirling flow directions, the other wells generally indicated flow to the north into the PRB. Groundwater flow velocities in preferential flow zones were much higher (2.2 to11.3 ft/day) than the 0.2 ft/day flow velocity other observations suggest for the site. This reveals that the borescope may be limited to measure velocities in high flow zones rather than flow throughout the aquifer thickness (bulk flow). The flow directions in most wells show a reasonable match with the flow vectors determined from water-level vectors. However, there is not a good match between flow vectors from the HydroTechnics™ probe upgradient of the reactive cells.

The borescope was used at the Dover PRB site in fourteen wells at the site. The results at Dover were generally mixed, with many of the wells showing a swirling pattern or flow directions not matching the conceptual model of flow through the barrier. The mixed flow direction results using the borescope appear to match the extremely flat water levels at the site.

Overall, it appears that the borescope has limited applicability in the low flow settings such as Dover AFB, where few preferential pathways exist. At sites with a reasonably high flow velocity or presence of preferential pathways, the borescope appears to be more useful. If the objective of monitoring is to find preferential flow zones at a site, then this instrument can be used at a reasonable cost.

4.2.3 Groundwater Modeling for Performance Assessment

Groundwater modeling has been performed at most PRB sites, although to varying degrees of detail, to evaluate capture of the contaminant plumes. The major advantage of constructing a detailed groundwater flow model is that several design configurations, site parameters, and performance and longevity scenarios can be readily evaluated once the initial model has been set up. Thus, the combined effect of several critical parameters can be incorporated simultaneously into one model.

The hydraulic performance of PRBs is affected by many variables, including barrier dimensions, hydraulic properties of the reactive media, and variations in aquifer conditions. To assess the impact of these parameters, groundwater flow modeling was performed to illustrate various scenarios. Such factors as groundwater flow velocity, residence times within the PRB, capture zones, and gradients were evaluated as indicators of PRB effectiveness. Issues related to field observations in operational PRBs were addressed with respect to how hydraulic conditions affect PRB performance. A general discussion on the use of computer simulations to design and evaluate PRBs is presented in Gupta and Fox (1999). More detailed discussion of the modeled scenarios is presented in Battelle (2000b) modeling report. The rest of this section provides general examples of modeling capture zones and residence times in PRBs, a example of a CRB modeling for Seneca Army Depot PRB, and illustrations of some unique hydrogeologic scenarios related to PRBs. The modeling of other DoD sites, especially the former NAS Moffett Field and Dover AFB PRBs, has been presented in previous Battelle reports (Battelle, 1998; Battelle, 2000a).

In general, modeling involves two parts: groundwater-flow modeling and transport modeling. Groundwater flow modeling involves simulating the flow volumes and velocities in and around the PRB. The finite difference computer program MODFLOW (McDonald and Harbaugh, 1988) is the accepted industry standard for groundwater flow modeling and capable of simulating PRB scenarios. Depending on the site, modeling of the flow conditions before and after the installation of the PRB may be performed to assess the overall impact of the PRB on the flow system.

Flow output may be coupled with a groundwater transport model, which simulates the movements of particles or plumes in the flow field. Typical transport models include MODPATH (Pollack, 1989), MT3D (Zheng, 1990), and RWALK3D (Battelle, 1995).

In the field, it is difficult to measure water level differences within the small area of the PRB. This is further complicated by the fact that gradients in highly permeable PRB media are low. For instance, if modeling indicates a gradient of 0.001 ft/ft in a PRB 20 ft long, then water levels would vary by only 0.02 ft from the entrance of the PRB to the exit of the PRB. These differences in water levels approach the limits of the accepted accuracy of water level measurements (0.01 ft). Consequently, transport modeling is valuable to simulate groundwater movement to determine potential range of residence times where traditional monitoring methods are limited.

Aquifer gradients may vary in direction with precipitation events, pumping, and various other processes. One strategy to ensure that a PRB will capture the desired contamination plume is to incorporate a safety factor into the design of the system, based on seasonal variations in gradient direction (Figure 15). The following safety factor accounts for seasonal variations in gradient direction when designing or evaluating a PRB system:

$$(\mathrm{TAN}\ (45^\circ + \alpha/2))$$

where α = seasonal fluctuation in gradient direction (°).

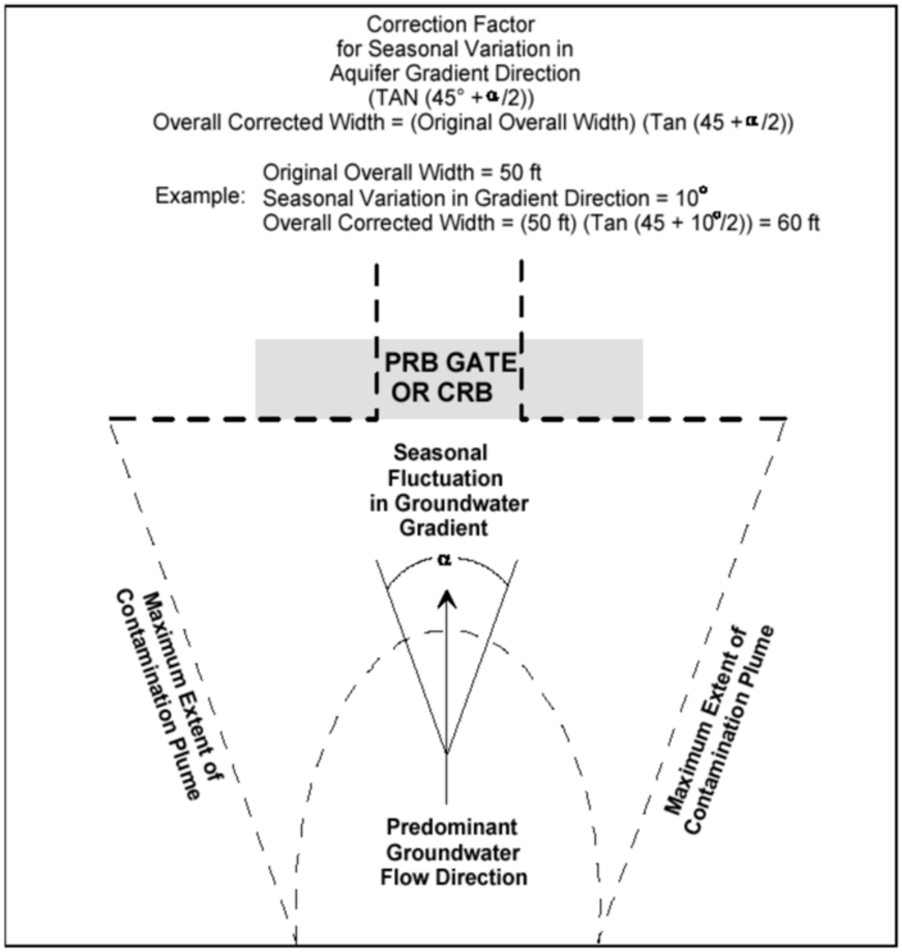


Figure 15. Diagram Illustrating Correction Factor for Seasonal Fluctuations in the Direction of Gradient.

The correction factor may be used to modify the width of the PRB. For example, an aquifer where the gradient varies by 5° seasonally would require only a 9% increase in width (Tan(45+(5°/2) = 1.09), whereas an aquifer where the gradient varies by 15° seasonally would require a 30% increase in width (Tan(45+(15°/2) = 1.30). The safety factor may be applied to either continuous reactive barriers or funnel-and-gate systems. With a continuous reactive barrier, the overall width may be adjusted. With a funnel-and- gate PRB, the entire width of the system may need to be adjusted or the barrier wings may be lengthened to increase the capture zone width. However, the efficiency of the system is reduced once the barrier wings become much wider than the gate portion of the PRB, so this should be considered when increasing the width of the PRB.

Another option to rectify an existing PRB that encounters angled flow into the barrier is to conduct engineering modifications. To investigate the effect of different modifications on a barrier that is not capturing the desired part of the plume, several scenarios (Table 5) were modeled. In the model, the aquifer was assigned a conductivity of 15 ft/d, an 8-ft by 2-ft barrier was assigned a conductivity of 1,000 ft/d, and a gradient of 0.01 was assigned at a 30° angle to the barrier. In this setup, it is assumed that barrier is not capturing the desired part of the plume because it was improperly installed or the groundwater flow direction changed. Figure 16 shows forward particle tracking through a PRB for the base scenario. Some of the plume is captured by the barrier due to the conductivity contrast, but more than half of the plume flows around the barrier.

Table 5. Summary of Modeling to Increase Capture for Groundwater Flow at an Angle to the PRB.

Scenario	Figure	Plume Capture (Approximate)	Comments
Base scenario	16	40%	Plume flows at an angle past the PRB.
Upgradient trench	17	100%	Some of the plume initially flows around the PRB.
Flanking sheet-pile barrier	18	95%	Groundwater flow concentrated through a small portion of the PRB.
Additional reactive barrier	19	100%	New PRB positioned perpendicular to groundwater flow direction.

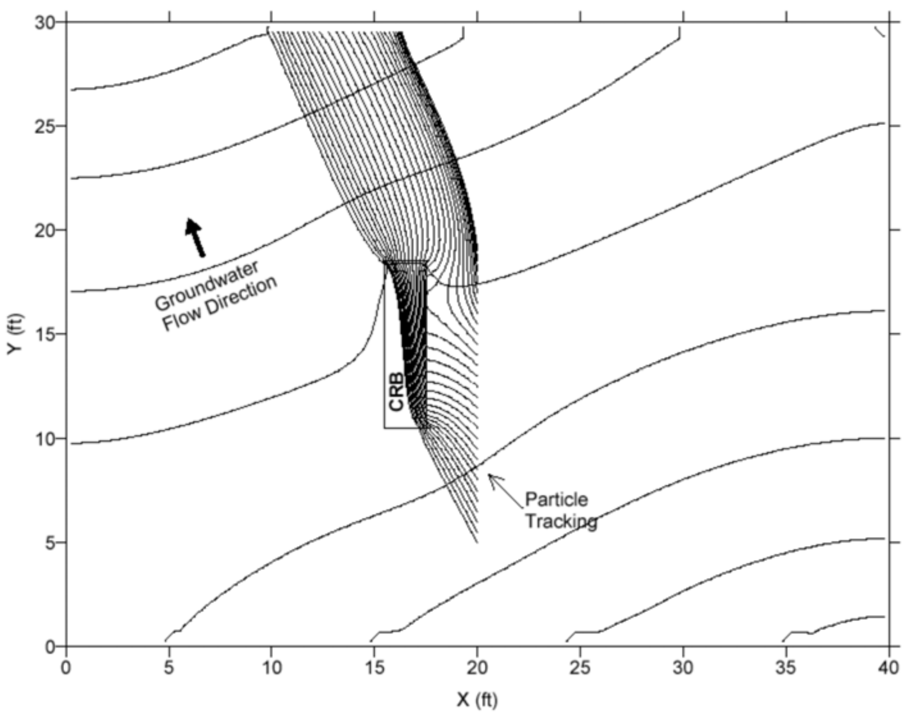


Figure 16. Base Case Model and Groundwater Flow at an Angle to the PRB.

To resolve this situation, several remedies were considered. First, installing a cutoff sheetpile barrier at the upgradient area of the barrier was modeled (Figure 17). This solution redirects the plume through the barrier, but flow is concentrated in a small portion of the barrier. However, this scenario is fairly cost-effective, as installing a sheet pile is relatively low cost compared to many of the other remedies, such as modifying the reactive cell dimensions. Adding a high conductivity trench upgradient of the barrier increased the capture zone dramatically (Figure 18); this setup appears to distribute groundwater throughout the reactive barrier as well. A final scenario examined was that of installing another reactive barrier section perpendicular to the direction of groundwater flow (Figure 19). As would be expected, this scenario captures the plume. However, it effectively doubles the price of the applied remedy.

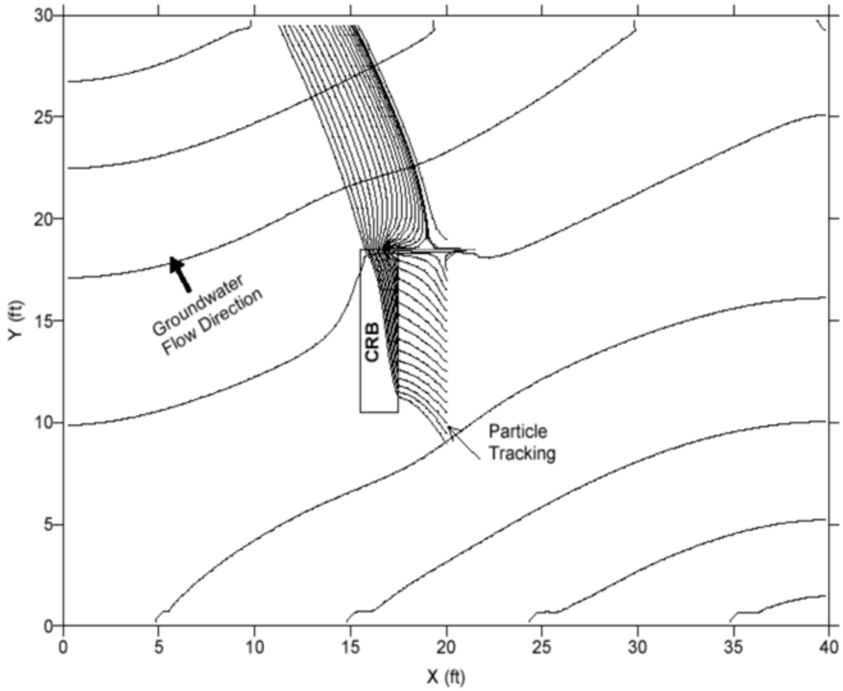


Figure 17. Model with Downgradient Barrier and Groundwater Flow at an Angle to the PRB.

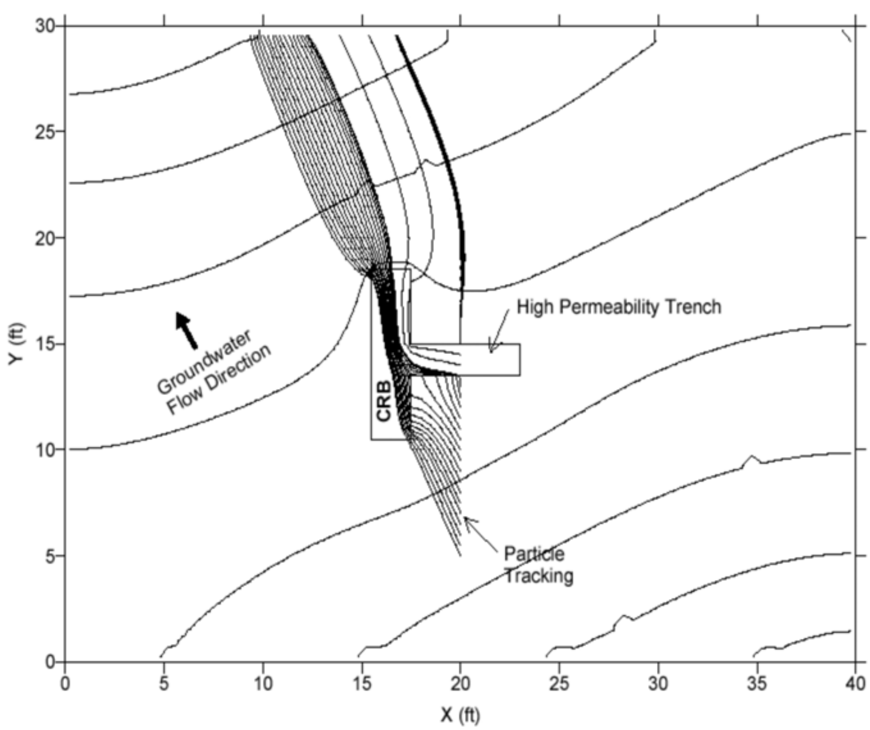


Figure 18. Model with Upgradient Trench and Groundwater Flow at Angle to the PRB.

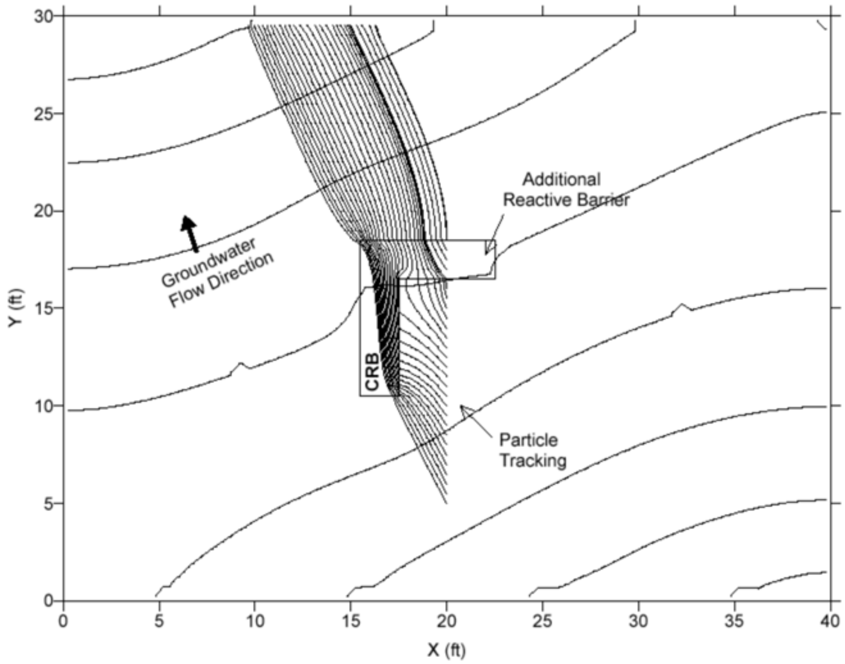


Figure 19. Model with Additional Reactive Barrier and Groundwater Flow at an Angle to the PRB.

Overall, it appears that installing a high conductivity upgradient trench leading to the barrier or a sheet pile barrier at the downgradient end of the barrier are most effective in directing flow into the barrier. Of these two options, the upgradient trench results in better flow throughout the barrier. A final option would be to add an additional reactive barrier along the downgradient end of the pre-existing reactive barrier.

In summary, the challenge in validating the hydraulic performance of PRBs is not that any of the monitoring shows that the PRBs are not working as desired, but that it is difficult to conclusively show how well the hydraulic objectives of the PRB, capture zone and residence time, are being achieved. The main reason for this is the lack of monitoring tools that can override the uncertainties in geologic media and provide high resolution over short distances at a reasonable cost.

5.0 COST ASSESSMENT

The cost assessment for this study focused on the PRBs at former NAS Moffett Field and Dover AFB. Costs were estimated for field demonstration-scale and full-scale PRBs at these two sites (Battelle, 1998; Battelle 2000a), as well as for equivalent pump-and-treat systems. PRBs and pump-and-treat systems are the two most common remedies applied for plume containment at chlorinated solvent sites.

5.1 COST REPORTING

An effective way of examining the cost of a PRB is as a life cycle cost (or present value for long-term application). The present value of a PRB then can be compared to the present value of an equivalent pump-and-treat system for economic analysis of the technology choice at a site. Present value is a method of discounting future costs to the present, a method that is widely used for estimating costs of long-term projects. The design guidance (Gavaskar et al., 2000) contains a detailed description of the present value method as applied to PRBs.

In this section, for each site (Moffett Field and Dover AFB), the cost of the field demonstration scale PRB was first estimated. These demonstration-scale costs were used as the basis for estimating the cost of a full-scale PRB at each of these two sites. Then, the costs of the full-scale PRBs were compared with equivalent pump-and-treat systems. (An equivalent pump-and-treat system would be one that captures and treats the same amount of water flowing through the PRB.)

5.1.1 PRB and Pump-and-Treat System Costs at Former NAS Moffett Field

Table 6 shows the capital investment incurred and the O&M cost projected for the size of PRB installed at former NAS Moffett Field (Battelle, 1998). The field demonstration-scale PRB consists of a 10-ft wide and 10-ft thick trench-type gate with a 40-ft wide sheet pile funnel. The PRB is completed to a depth of 25 ft bgs, just above a thin clay layer that demarcates the shallow A1 aquifer zone. The largest single component of the $652,000 capital investment is the barrier construction cost. As with any successful implementation of a remediation technology, site characterization and engineering design are major components of capital investment. The bench-scale treatability tests and iron medium itself are the other important components. If this were a remediation project, instead of a demonstration project, the capital investment items that probably would have been lower are the monitoring wells ($30,000 instead of the $45,000 in Table 6) and the post-construction monitoring ($80,000 instead of $150,000 in Table 6). The only recurring annual cost anticipated for the next few years is monitoring.

Table 6. Cost of Field Demonstration PRB at Former NAS Moffett Field.

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

For a full-scale application, the design assumed that the PRB would be extended both horizontally (to cover more of the plume) and vertically (to cover the A2 aquifer zone that lies below the A1 aquifer zone to a depth of 65 ft bgs). Site representatives envisioned building the PRB in two sections: a smaller (600-ft wide) barrier called the Site 9 Wall in the core of the plume to capture the more concentrated portion, and a larger (1,100-ft wide) barrier called the Northern Wall at the edge of the plume to prevent its progress. The projected costs of these two sections of the full-scale PRB are listed in Table 7. The total capital investment required would be $4.9 million. As with the demonstration-scale PRB, the largest component of the full-scale PRB is the construction cost. The projected annual O&M costs are approximately $72,000, primarily for monitoring. In addition to the annual O&M, it was assumed that the iron in the PRB would have to be replaced periodically (every 10 years) at a cost of approximately $267,000. This is listed in Table 7 as an extraordinary maintenance that is not part of the annual O&M cost.

Table 7. Estimated Cost of a Full-Scale PRB at Former NAS Moffett Field.

Item	Sub-Total ($)	Total Cost ($)
Capital Investment		
Bench-scale tests		75,000[(a)]
Site characterization - Site characterization (hydrogeologic/chemical) - Other testing and welding	 100,000 17,820	 117,820
Engineering Design, Modeling		100,000
Site Preparation		115,258
Construction of Barrier - Mobilization - Trench installation - Gates completion (including iron medium) - Funnel completion - 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
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 and safety)		271,047
Capital Investment Total		**4,910,942**
O&M		
Annual operations (monitoring cost incurred every year)		72,278
Maintenance (incurred every 10 years)		267,538
PV over 30 years at 2.9% real rate of return		**$14,382,000**

(a) 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.

Because the PRB is a long-term technology application, the capital investment and annual O&M costs cannot simply be added up to obtain a total cost, as would be done for a short-term technology application. This is because the capital investment is a cost that is incurred immediately, whereas O&M costs for a long-term PRB (just as with a pump-and-treat system) are spread over several years or decades. Therefore, a present value (PV) calculation is used to obtain the overall or life cycle cost of a PRB. In Table 7 (and all the calculations in the rest of the tables in this report), a real rate of return of 2.9%, as was recommended by the Office of Management and Budget (OMB) in 2000 for long-term (30-year) projects was used to estimate PV. The PV of the PRB at Moffett Field is estimated at $14 million over 30 years, assuming (conservatively) that iron replacement may be required every 10 years.

For comparison purposes, the PV cost of an equivalent pump-and-treat system (20 gpm) operating over 30 years was estimated at $17 million, as shown in Table 8. These costs are based on the design of a pump-and-treat that was initially planned at Moffett Field for this regional plume (PRC, 1996). Therefore, there is a potential savings of $3 million over 30 years from installing a PRB instead of a pump-and-treat system at this site.

Table 8. Estimated Cost of A Full-Scale Pump-and-Treat System at Former NAS Moffett Field.

Item	Cost
Capital Investment	
Site characterization	$117,820
Engineering Design and Modeling	$100,000
Site Preparation	$219,080
Groundwater extraction wells, piping, and pumps	$783,150
Aboveground treatment systems (carbon for water polishing and catalytic oxidizer for air polishing treatments)	$85,771
Distributive costs	$107,085
Capital Investment Total	**$1,412,086**
Annual O&M	
System operation and routine maintenance	$460,000
Groundwater and air discharge monitoring, plume monitoring	$170,000
Carbon replacement (annualized)	$34,746
Catalyst replacement (annualized)	$30,000
Annual O&M Total	**$694,746**
Present value over 30 years at 2.9% real rate of return	**$17,081,000**

The savings grow if the plume, as expected, last for 50 years or 100 years. The savings would be much higher if, as now expected from the results of this study, the iron lasts for more than 10 years without being replaced.

5.1.2 PRB and Pump-and-Treat System Costs at Dover AFB

Table 9 shows the costs incurred for installing and operating the field demonstration-scale PRB at Dover AFB. This PRB has two 4-ft wide gates with a 60-ft wide sheet pile funnel, and each gate is 4 ft thick. Just as with the Moffett Field PRB, the main component of capital investment of the PRB is the construction cost, followed by the site characterization and design costs. If this were a remediation project, instead of a demonstration project, the treatability column test and monitoring system construction costs would be lower (potentially, $50,000 for less extensive column tests and $25,000 for a smaller monitoring well network). For both Moffett Field and Dover AFB PRBs, it is difficult to envision requiring much less capital investment than was incurred at these two sites, even if it were a remediation project of the same scale.

Table 9. Cost of Groundwater Treatment and Monitoring for PRB Demonstration at Dover AFB.

Item	Description	Basis	Cost[a]
Phase 1: Preconstruction Activities			
Preliminary site assessment	Historical site data evaluation	Remedial Investigation/Feasibility Study, other reports procurement and evaluation; site meeting	\$15,000
Site characterization	Characterization plan, fieldwork, laboratory analysis	CPT pushes for geologic mapping and temporary wells; analysis of water samples for CVOCs; select samples for geotechnical analysis; slug tests; ground-penetrating radar survey[a,b]	\$150,000
Column tests	Two columns for two reactive media combinations; Area 5 groundwater	Three-month on-site test and laboratory analysis of water samples[b]; report	\$100,000[b]
Design; procurement; regulatory review	Data evaluation, modeling, engineering design, Design/Test Plan; construction subcontractor procurement; regulatory interactions	Characterization, column test data evaluation; hydrogeologic modeling; geochemical evaluation; engineering design; report; procurement process; regulatory approvals; preconstruction meeting	\$100,000
		Subtotal	**\$365,000**
Phase 2: PRB Construction			
Site preparation	Utilities clearances; arrangement for equipment/media storage and debris disposal	Coordination with Base facilities staff	\$10,000
Reactive media procurement	Connelly iron, shipping; pyrite source identification, procurement; pyrite chunks, crushing, sizing, shipping	Iron: 54 tons @ \$360/ton Pyrite: 5 tons @ \$1,400/ton Pyrite preparation: \$12,000 Shipping: \$9,000	\$47,000
PRB construction	Mobilization/demobilization; installation of two 8-ft-diameter caisson gates to 40-ft depth; and one 60-ft long sheet pile funnel; asphalt parking lot restoration	Mob./demob.: \$38,000 Gates: \$133,000 Monitoring wells: \$25,000 Funnel: \$51,000 Surface restoration: \$17,000	\$264,000
Monitoring system construction	Thirty-four PVC aquifer wells installed for monitoring the pilot-scale PRB (fewer wells would be required for a full-scale system); four in situ groundwater velocity sensors	Aquifer wells: \$37,000 Velocity sensors: \$16,000	\$53,000
		Subtotal	**\$374,000**
		Capital Investment Total	**\$739,000**

(a) Includes costs incurred for labor and materials by Battelle and its construction subcontractor C^3 Environmental, as well as broad estimates of relevant costs incurred by Dover AFB staff for site arrangements and by U.S. EPA-NERL for the on-site column tests. Some cost items in this table may not be applicable at other sites.

(b) This level of testing was done for demonstration purposes and may be excessive for full-scale application.

Table 10 shows the projected costs of a full-scale PRB at Dover AFB. The full-scale PRB is expected to include four 8-ft diameter caisson gates and one 120-ft long sheet pile funnel. The O&M costs are separated into annual costs (primarily for monitoring) and periodic maintenance costs for replacing the spent iron medium. If the iron were to be replaced every 10 years (a conservative assumption), then the PV of the PRB over 30 years of operation would be $4.6 million.

Table 10. Estimated Cost of a Full-Scale PRB at Dover AFB.

Item	Description	Basis	Cost
Phase 1: Preconstruction Activities			
Preliminary site assessment	Historical site data evaluation	Remedial Investigation/Feasibility Study, other reports procurement and evaluation; site meeting	$15,000
Site characterization	Characterization plan, fieldwork, laboratory analysis	CPT pushes for geologic mapping and temporary wells; analysis of water samples for CVOCs and inorganics; slug tests in existing wells	$200,000
Column Tests	Two column tests; Area 5 groundwater	Column tests and laboratory analysis of water samples; report	$50,000
Design; procurement of subcontractors; regulatory review	Data evaluation, modeling, engineering design, interactions with regulators	Hydrogeologic modeling; engineering design; report; regulatory interactions	$100,000
		Subtotal	**$365,000**
Phase 2: PRB Construction			
Site preparation	Utilities clearances; arrangements for equipment/media storage and debris disposal	Coordination with regulators and Base facilities staff	$10,000
Reactive media procurement	Connelly iron, shipping	Iron: 108 tons @ $360/ton Shipping: $9,000	$48,000
PRB construction	Mobilization/demobilization; installation of four 8-ft-diameter caisson gates to 40-ft depth, and one 120-ft-long sheet pile funnel; asphalt parking lot restoration	Mob./demob.: $60,000 Gates: $266,000 Monitoring wells: $25,000 Funnel: $102,000 Surface restoration: $34,000	$487,000
Monitoring system construction	Thirty-four PVC aquifer wells installed for monitoring the PRB	Aquifer wells: $37,000	$37,000
		Subtotal **Capital Investment Total**	**$582,000** **$947,000**
Annual Monitoring Activities			
Groundwater sampling	Quarterly, labor, materials, travel	40 wells	$80,000
CVOC analysis	Quarterly, 40 wells	44 per quarter @ $120/sample	$20,000
Inorganic analysis	Annual, 20 wells	22 @ $150/sample	$4,000
Water-level survey	Quarterly, labor	40 wells per quarter	$4,000
Data analysis; report; regulatory review	Quarterly, labor	Four times per year	$40,000
		Annual Operating Cost	**$148,000**
Periodic Maintenance (once every 10) years			
Site preparation	Permitting, clearances	Labor	$10,000
Reactive media procurement	Connelly iron, shipping	Iron: 108 tons @ $360/ton Shipping: $9,000	$48,000
Removal/replacement of gates	Mobilization/demobilization; installation of four 8-ft-diameter caisson gates to 39-ft depth; asphalt parking lot restoration	Mob./demob.:$38,000 Gates: $266,000 Monitoring wells: $25,000 Surface restoration: $34,000	$363,000
		Periodic Maintenance Total	**$421,000**
		Present value over 30 years at 2.9% real rate of return	**$4,618,000**

Table 11 shows the estimated PV cost of an equivalent pump-and-treat system (10 gpm) operating over 30 years to be $4.9 million at this site. These costs are based on the costs of a pilot-scale pump-and-treat system that was built and operated at Dover AFB (different site) in the same aquifer. The savings would grow if the plume lasts longer than 30 years (as expected) and/or if the iron in the PRB needs replacement at a lower frequency than every 10 years (very likely, based on the results of the longevity evaluation in this study).

Table 11. Estimated Cost of a Full-Scale Pump-and-Treat at Dover AFB.

Item	Description	Basis	Cost[(a)]
		Phase 1: Preconstruction Activities	
Preliminary site assessment	Historical site data evaluation	Remedial Investigation/Feasibility Study, other reports procurement and evaluation; site meeting	$15,000
Site characterization	Characterization plan, fieldwork, laboratory analysis	CPT pushes for geologic mapping and temporary wells; analysis of water samples for CVOCs and inorganics; slug tests in existing wells	$200,000
Design; procurement; regulatory review	Data evaluation, modeling, engineering design, Design Plan; procurement; regulatory interactions	Characterization data analysis; hydrogeologic modeling; engineering design; report; procurement; regulatory review	$100,000
		Subtotal	**$315,000**
		Phase 2: P&T System Construction	
Site preparation	Utilities clearances; arrangement for equipment storage	Coordination with Base facilities staff	$10,000
P&T system construction	Installation of three 4-inch- diameter extraction wells; pumps; air stripper; catalytic oxidizer; polishing carbon; shed; piping	20-gpm groundwater extraction and treatment system	$145,000
Monitoring system construction	Thirty PVC aquifer wells installed for monitoring plume movement	Aquifer wells: $32,000	$32,000
		Subtotal **Capital Investment Total**	**$187,000** **$502,000**
		Annual P&T System O&M (includes routine maintenance)	
System operation	Keeping P&T system operational	Labor, energy consumption, materials replacement, waste handling, routine maintenance, replacement of pumps, etc.	$66,000
Groundwater monitoring	Quarterly, 40 wells; CVOC, inorganics, water levels	Labor, materials, analytical	$148,000
		Annual Operating Cost	**$214,000**
		Periodic Maintenance (once every 10) years	
Carbon replacement	Polishing carbon for liquid	Used carbon disposal, new carbon installation	$7,000
		Periodic Maintenance (once every 5) years	
Catalyst replacement	Oxidizer catalysts for effluent air treatment	Used catalyst disposal, new catalyst installation	$21,000
		Present value over 30 years at 2.9% real rate of return	**$4,857,000**

(a) Includes costs incurred for labor and materials by Battelle and its construction subcontractor C^3 Environmental, as well as broad estimates of relevant costs incurred by Dover AFB staff for site arrangements and by U.S. EPA-NERL for the on-site column tests. Some cost items in this table may not be applicable at other sites.

5.2 COST ANALYSIS

The costs of PRBs vary widely depending on a variety of site and PRB characteristics. In general, the depth and the length of a PRB continue to drive the costs of a PRB application. The deeper the aquifer and the longer the PRB, the greater is the cost. Depth is single biggest cost consideration with PRBs. Down to 25 to 30 ft bgs, a backhoe excavator or continuous trencher may be used. In this depth range, for relatively short barriers (e.g., 50 ft or less), backhoes, with their lower fixed (mobilization) costs, may be less expensive than continuous trenchers. For longer barriers, a continuous trencher may be more cost-effective, as long as there are no geotechnical impediments (such as cobbles or utility lines). A continuous trencher requires a higher mobilization cost, but is swift and the entire operation can be done in days.

Recent advances in construction (e.g., the biodegradable slurry method) have allowed site owners to install barriers as deep as 65 ft bgs (e.g., Pease AFB) using a backhoe-type excavator and a trench-type barrier. For sites where the affected aquifer is deeper, innovative methods, such as jetting and hydraulic fracturing, are available, but there is not as much widespread experience yet with these techniques for PRBs. Also, these innovative methods may involve higher cost, although the higher cost and some uncertainty involved may be worthwhile at deeper, less accessible sites.

The Remedial Action Cost Engineering and Requirements System (RACER) model developed by the DoD is a good way of obtaining preliminary cost estimates of a PRB application during the preliminary site assessment or conceptual model stage, when the detailed design of the PRB has not yet been developed. Site owners then can take advantage of RACER's database of costs for various activities, such as trenching or drilling, for which RACER provides costs based on the state in which the PRB will be installed. However, once the detailed design of a PRB has been completed, site-specific costs based on actual bids from suppliers and contractors should be obtained.

Present value estimates have been calculated during previous projects (Battelle, 1998; Battelle, 2000a) for two of the PRB sites in the current project – former NAS Moffett Field and Dover AFB. Table 12 presents a sensitivity analysis that examines the costs of full-scale PRBs at these two sites in relation to the longevity expectations of the PRBs. The different scenarios examine how the PV of a PRB would change if more frequent replacements (every 5, 10, 15, 20, or 30 years) of the iron media were required.

The accelerated long-term column tests provide some measure of the longevity of the granular iron PRBs. The issue of longevity of the PRB translates into an issue of economics: Will the PRB retain it reactivity and hydraulic performance long enough for the capital invested in the PRB to be worthwhile? For example, in Table 12, the present value of a PRB at the Dover AFB site is calculated for different life expectancies of a PRB. If the PRB loses its reactivity and/or hydraulic performance in 5 years, and has to be regenerated or replaced in some fashion (with the associated extraordinary maintenance costs), then the present value over 30 years of operation is higher for a PRB than it is for an equivalent pump-and-treat system. If the PRB can function without needing regeneration or replacement for 10 years or more, the present value of the PRB becomes less than that of an equivalent pump-and-treat system. (The same is true for the PRB at Moffett Field.). In other words, the savings realized from the lower operating costs of a PRB more than offset the higher capital investment required; at many sites, PRBs require a higher capital investment than a pump- and-treat system. The bar may be set higher at sites that already have a functioning pump-and-treat

Table 12. Present Value Estimates Comparing PRBs Against Pump-and-Treat Systems at Dover AFB and Former NAS Moffett Field.

Cost/Longevity Scenario	Dover AFB[(a)]	Former NAS Moffett Field[(b)]
Pump-and-Treat System		
Capital investment cost	$502,000	$1,412,000
Annual O&M cost[(c)]	$214,000	$695,000
Present value for 30 years of operation (discount rate is 2.9%)	**$4,857,000**	**$17,081,000**
PRB		
Capital investment cost	$947,000	$4,911,000
Annual O&M cost	$148,000	$72,000
Present value over 30 years, if the PRB life is 5 years	$5,463,000	$23,653,000
Present value over 30 years, if the PRB life is 10 years	**$4,618,000**	**$14,382,000**
Present value over 30 years, if the PRB life is 15 years	$4,338,000	$11,313,000
Present value over 30 years, if the PRB life is 20 years	$4,123,000	$9,119,000
Present value over 30 years, if the PRB life is 30 years	$4,064,000	$8,429,000

(a) Costs based on Battelle, 2000a.
(b) Costs based on Battelle, 1998.
(c) In addition to the recurring annual O&M cost, a periodic maintenance cost that allows various components of the pump-and-treat system to be replaced at regular intervals is included in the present value calculation.

system, perhaps installed as an interim remedy; in this case, capital invested in the pump-and-treat system is treated as a sunk cost and is not included in the present value analysis. The reduction in operating costs resulting from a PRB would have to be sufficiently high to offset the entire capital invested in the PRB.

Although the breakeven point (year in which the present value of a PRB becomes lower than the present value of the pump-and-treat system) may vary from site to site, depending on various site and PRB characteristics, the range of breakeven points is probably between 7 to 15 years. The accelerated column tests show that even at sites with relatively high levels of dissolved solids (e.g., Lowry AFB) the PRB is likely to continue performing acceptably beyond the breakeven point (7 to 15 years after installation). One caveat is that the thickness of the reactive cell has to incorporate enough of a safety factor to handle a possible decline in reactivity of about 3 to 4 times its original value over this time period. A greater thickness would mean higher materials (iron) and construction (trenching) costs; however, the cost of a PRB is not particularly sensitive to its thickness, as it is to the depth and length of a PRB. Once the construction equipment has been mobilized to the site, a PRB with 6-foot thickness is not likely to cost proportionately more than a PRB with 3-foot thickness. However, the tradeoff between a higher safety factor (and the concomitantly higher capital investment) in the present versus the risk of future potentially expensive contingency measures (see Section 4.3.2), in case of PRB failure, has to be weighed carefully at each site.

The economic scenarios discussed above – comparing present values of PRBs and pump-and-treat systems at different life expectancies of a PRB – are probably the best approach. Given the short history of the PRB technology, the accelerated column tests provide some comfort that the rate of loss of reactivity observed in the columns makes it possible for PRBs to be worthwhile at sites where the breakeven point for the PRB is less than 25 or 30 years, a not-too-difficult target to meet at most sites. At the same time, it is recognized that the life of the PRB is finite, that at some point in the future the contingency measures described in Section 4.3.2 may be required.

5.3 SUMMARY OF COST COMPARISON

In summary, a PRB has several potential cost advantages over an equivalent pump-and-treat system. The main cost advantage accrues from the passive operation of the PRB. Although most PRBs require a somewhat higher capital investment, as compared to a pump-and-treat system, the long-term O&M costs of a PRB are much lower, consisting primarily of monitoring. In addition, the following intangible benefits tilt the balance towards PRBs in a cost-benefit analysis.

- Absence of aboveground structures that allow many more potential uses of the site and may facilitate property transfer, especially at Base Realignment and Closure (BRAC) sites.

- Avoidance of the frequent breakdown and maintenance associated with many pump-and-treat systems.

- Avoidance of the annual waste disposal management (for spent carbon or spent catalyst) required for pump-and-treat systems.

No other innovative remedy, such as air sparging or bioremediation, offers the simplicity and passive operation of a PRB for long-term remediation of persistent contaminants, such as chlorinated solvents. Air sparging requires constant energy input and frequent labor involvement. Bioremediation requires periodic electron donor injection to maintain microbial activity at levels conducive to anaerobic degradation of the CVOC contaminants. Therefore, the cost comparison has focused on PRBs and pump-and-treat systems. Some sites already have pump-and-treat systems installed as interim remedies, so the cost comparison becomes more relevant.

The assumption made about the longevity of the PRB affects the cost analysis significantly. When the replacement rate of the reactive medium (i.e., iron) is less frequent, the PV of the PRB is lower, and the savings are higher (as compared to a P&T system). The longevity evaluation described in Section 4 of this report indicates that, at many sites, PRBs are likely to last long enough for site owners to realize considerable savings.

6.0 IMPLEMENTATION ISSUES

Many of the pilot-scale PRBs that have been demonstrated at various sites, such as former NAS Moffett Field and Dover AFB, have been relatively large-sized field applications. Therefore, the issues involved with the implementation of the full-scale PRBs are not very different from those involved at these demonstration sites. In addition, full-scale PRBs have been installed now at several sites, so the experience with implementing the PRB technology is considerable. However, site owners and regulators need to be aware of several specific design, cost, and performance issues; these issues are described in this section.

6.1 COST OBSERVATIONS

The primary cost advantage of a PRB is its low O&M cost, compared to a conventional remedy, such as pump-and-treat system. For contaminants and sites where the plume is likely to persist for several years or decades, the savings that accrue from the much lower O&M cost can be considerable. Because of its passive operation, the only recurring O&M costs for a PRB are monitoring costs. As the long-term tests described in Section 4 indicate, changes occur in a PRB relatively slowly. Also, at many sites groundwater was found to be flowing at a relatively low velocity between 0.5 to 1 ft/day. Therefore, at many sites, monitoring costs themselves can be reduced by lowering the frequency of monitoring. Although the ITRC has general guidelines on sampling frequency, the actual monitoring schedule often is negotiated on a site-by-site basis, depending on factors such as level of contamination, velocity of the groundwater, and the associated risk to receptors.

Depth and length of a PRB are the two driving factors that determine the cost of implementation. The depth of the affected aquifer probably is the more crucial one, because the deeper the affected aquifer, the greater the cost. Certain depth thresholds may drive the construction method selected and the implementation cost, as mentioned in Section 5. Relatively shallow applications (down to 25 or 30 ft bgs) are the least expensive. At these depths, it is likely that a PRB will be very cost-effective. Advances in construction methods (e.g., the use of a biodegradable slurry) have enabled these same trenching techniques to be applied to aquifers as deep as 65 to 80 ft bgs (e.g., Pease AFB), while still keeping the implementation cost relatively low. Beyond these depths, innovative methods (such as jetting and hydraulic fracturing) can be used at relatively higher cost.

The cost comparison of a PRB versus an active remedy, such as a pump-and-treat system, often shows that the PRB has a lower PV, as shown in Section 5 for former NAS Moffett Field and Dover AFB. Despite the effect of discounting, whereby costs incurred in the future (much of the cost of a pump-and-treat system is incurred in future years) have a lower impact today, the PRB has a lower PV. The longer the period of operation, or longer the plume is expected to persist, the higher are the savings that accrue. Implicit in these calculations is the assumption that site owners make about the longevity of the PRB. The longer a PRB can be operated without having to change the reactive medium (iron), the more the long-term savings and lower the PV of a PRB. Given the short history of the PRB technology, the longevity tests (accelerated column tests) described in Section 4 and the cost analysis described in Section 5 provide some guidance on how to calibrate the expectations about a PRB's life expectancy. By conducting a sensitivity analysis or scenario development, the effect of different life expectancies on the life cycle cost of a PRB can be evaluated. The longevity tests described in Section 4 indicate that at many sites, the life of a PRB is likely to exceed the approximately 10 years required at many sites to achieve breakeven.

6.2 PERFORMANCE OBSERVATIONS

Two short-term issues and one long-term performance issue emerged over the course of this study. The two short-term issues were (a) hydraulic performance (plume capture and residence time) and (b) downgradient water quality.

The first issue was identified during a survey of DoD sites conducted in the first year of the project. This issue was addressed though field investigations conducted at sites, such as former NAS Moffett Field, Seneca Army Depot, and Dover AFB. Hydraulic performance remains the most difficult challenge for PRB implementation and, as shown in this study, can be addressed through adequate site characterization, groundwater modeling, and the use of safety factors in the design. The second short-term issue was identified towards the end of the project and relates to the inability to experience a noticeable improvement in downgradient water quality at PRB sites, despite the confirmed capability of the iron to degrade CVOCs that pass through the PRB with sufficient residence time. Possible causes for the lack of improvement in downgradient water quality are discussed in Section 4 and include the following.

- Impedances along the flowpath through the PRB.
- Recontamination of the water flowing through the PRB by water flowing around or below it.
- Diffusion of CVOCs trapped in silty clay lenses in the downgradient aquifer.
- Channeling of flow (along preferential pathways) through the porous iron media that would reduce the actual residence time of the CVOCs.

The long-term issue that was identified before the study began was longevity of the iron medium. This issue affects the long-term performance and cost of a PRB. Although initial efforts centered around field investigations of groundwater and iron cores, the slow groundwater flow and the (consequently) limited exposure of iron in field system to groundwater constituents necessitated an accelerated column study that provided key insights. Loss of iron reactivity, rather than loss of hydraulic performance (plugging), emerged as the main longevity issue in these tests. The loss of reactivity of the iron during exposure to almost 1,300 pore volumes of groundwater was clearly linked to the mass flux of dissolved solids in the groundwater. Precipitation of these solids under strongly reducing conditions caused a reduction in reactivity of the iron. The two factors governing the loss of reactivity were the level of dissolved solids in the groundwater and the velocity of groundwater through the iron. In general, sites with groundwater containing high levels of dissolved solids and sites with higher groundwater velocities are likely to experience a faster loss of reactivity than sites with lower levels of dissolved solids and lower flow velocities. In general, though, at most sites, PRBs are likely to retain their longevity long enough to obtain a payback on their initial capital investment.

6.3 SCALE-UP ISSUES

Because many pilot-scale PRBs have been installed to the fully required depth, the design and implementation cost estimates for full-scale applications can be done relatively accurately, as shown in Sections 4 and 5. At most relatively shallow sites (i.e., 65 ft or less), full-scale applications can be done directly, without resorting to a pilot-scale test, unless new reactive media and contaminants are involved. For application of iron for common contaminants, such as chlorinated solvents and chromium, a full-scale application can be done based on the experience generated during several pilot-scale and full-scale application. For other reactive medium contaminant combinations, a field pilot test may be helpful. Also, at sites where the hydrogeology is complex and the flow regime cannot be fully understood with a reasonable amount of site characterization, a field pilot test may be conducted to verify that the desired plume capture and residence time are being achieved.

At many sites with pilot-scale PRBs, scaling-up to a full PRB revolves around an expansion of the length or (in a few cases) the depth of the application. Where scaling up involves increasing the length of a PRB, the design is relatively straightforward, as long as the original pilot-scale PRB was oriented correctly (that is, perpendicular to the groundwater flow). If a performance evaluation has shown that the orientation or height or depth of the PRB are not optimum, scaling up will involve more detailed site characterization and groundwater modeling. When scaling up involves greater depth than the pilot-scale PRB (e.g., at former NAS Moffett Field), site owners should re-assess the construction methods used. Even a 5-ft-deeper scaled-up version may require a different construction method.

In general, a scaled-up PRB should be wide enough and deep enough to capture the desired portion of the plume or the entire plume. The captured contaminants should encounter sufficient residence time in the reactive medium. Adequate safety factors should be incorporated in the design to account for inherent uncertainties in measuring hydraulic flow parameters.

6.4 REGULATORY ISSUES

In the current project, the approach taken by several state regulatory agencies in reviewing new PRB applications was studied. This section was developed based on a survey and feedback obtained from several member States in the ITRC's Permeable Reactive Barriers Team; the New Jersey Department of Environmental Protection facilitated this survey (Turner, 2001).

Although this survey was initiated as a means of obtaining generic information about the number and types of PRBs and their monitoring systems, it provided valuable insights into valid regulatory concerns, the type of monitoring that would be required to address these concerns, and the types of contingency measures envisioned by the regulators and site owners. An encouraging theme in the survey was the amount of thought that had gone into reviewing PRB applications and the amount of attention paid by regulators to the economic impacts of their recommendations on site owners. The results of this survey are discussed below.

6.4.1 Applications Received for Installation of New PRBs

Some state regulatory agencies were directly involved in the approval process for new applications for PRBs; others left it to the site owners and their representatives to evaluate and select their own remedies, but provided input to the decision. In reviewing the information in these applications, the following regulatory concerns appeared to have been inadequately addressed by some site owners or their representatives.

- Inadequate site characterization at the proposed location of the PRB. Insufficient information was provided on plume size, location, orientation, and groundwater/plume movement.

- Possibility of flow under, over, or around the PRB.

- Possibility of reduced permeability of the PRB over time.

- Possibility of groundwater mounding.

- Inadequate reactive cell thickness.

- Constructability of the PRB with respect to deep installations, earth support, etc.

- Inadequate consideration of the effects of biocides, breaker enzymes, and their byproducts (obviously a reference to site owners implementing the bioslurry method of installation).

These responses indicate the necessity for site owners to conduct sufficient local characterization in the immediate vicinity of the proposed PRB, model different flow scenarios that incorporate the uncertainties in the site characterization, incorporate appropriate safety factors in the design, and developing a suitable monitoring scheme. These issues can be addressed appropriately during the site characterization and design stage. The PRB design guidance report (Gavaskar et al., 2000) provides a methodology for preliminary assessment of a site for the feasibility of PRB (developing a conceptual model of the site and proposed PRB), site characterization, and design.

6.4.2 Contingency Plans in Case of PRB Failure

State regulators often require that one or more of the following contingency measures be incorporated in a PRB application, to prevent contaminant migration in case of PRB failure.

- Ability to operate a pump-and-treat system, if monitoring shows contaminant breakthrough or bypass for the PRB.

- Ability to pump the PRB as an interceptor trench, a variation of the pump-and-treat measure.

- Extension of the PRB to capture more of the plume, if monitoring shows that the capture zone is inadequate.

- Blocking the end(s) of the PRB with an impermeable barrier (slurry wall or sheet piling).

- Ability to install a second PRB downgradient from or adjacent to the first one.

Regulators noted that the actual contingency measure adopted would depend on the mechanism of failure – that is, whether failure would occur because of factors such as loss of reactivity, inadequate residence time, and inadequate groundwater capture. Key issues that regulators thought would benefit from more research are developing a means of measuring hydraulic performance and identifying appropriate contingency measures to deal with any future loss of hydraulic performance.

One challenge that is foreseen, based on the results of the current project, is that determination of the functioning/malfunctioning of the PRB would take time. Many PRBs are built inside a plume, a decision often driven by the relative spacing of the plume boundary and property boundary, and the presence of aboveground features. At such sites, it may take many years for a clean groundwater front to emerge on the downgradient side of the PRB. In the meantime, it would be difficult to determine whether any observed downgradient contamination is due to diffusion of contaminants persisting in fine-grained layers in the downgradient aquifer or due to flow bypass or breakthrough. Breakthrough often can be addressed by monitoring the groundwater immediately inside the downgradient edge of the reactive cell in the PRB. On the other hand, flow bypass could be more challenging to identify. The monitoring strategies recommended by the ITRC (ITRC, 1999) often were recommended by regulators in an effort to obtain early warning of any impending failures, and are probably the best approach possible, given the limitations described above.

One contingency approach that has not been considered so far, probably because of lack of sufficient research on the subject, is regeneration of the reactive medium. Although some regeneration techniques, such as ultrasound and pressure pulsing, have been proposed, the field application of these techniques and the cost of their application needs further study.

6.4.3 Monitoring of a PRB after Installation

Some variation of the following monitoring strategies were recommended by regulators when reviewing PRB applications.

- Monitoring inside the reactive cell for potential breakthrough.
- Monitoring for bypass at the two ends of the PRB.
- Monitoring in the downgradient aquifer for breakthrough and verification that cleanup targets are met at the compliance boundary.
- A monitoring well located close to the PRB in a potential bypass route.
- Upgradient piezometers to detect short-term and/or long-term plugging of the PRB.
- Monitoring of the permeable zone beneath the aquitard to verify absence of downward migration.

Although the combination of monitoring locations selected tended to vary among sites, the overall strategy inherent in these requirements focuses on potential routes of failure. The strategy has the following three features.

- Verify that the PRB is able to meet applicable cleanup targets at a downgradient compliance boundary. Interestingly, although the hope often was that the effluent from the PRB would be below MCLs or state-mandated cleanup levels or, in some cases, below detection, the overall goal was to meet cleanup targets at a compliance boundary that could be some distance downgradient. The cleanup targets were often MCLs, but were sometimes risk based.

- Attempt to distinguish between possible failure due to breakthrough (reduced reactivity or reduced residence time) versus due to bypass (inadequate hydraulic capture). Implicit in this strategy was the desire to choose an appropriate contingency measure, that is, a contingency measure that would address the mode of failure. As an example, it would be futile to extend the ends of the PRB, if downgradient contamination was occurring due to breakthrough from the reactive medium.

- Watch for early warnings of impending failure. In the long term, the monitoring strategy seeks to identify potential loss of reactivity or potential loss of permeability before the downgradient water quality deteriorates significantly.

This is a well thought out monitoring strategy, but may be subject to the limitations of the monitoring tools available. As discussed in Section 4.2.3, for a new PRB installed inside the plume, it could be years before the cause of persistent downgradient contamination is determined. The longevity evaluation in the current project indicates that simple indicators, such as pH and ORP, may not be useful as early warning indicators; the reactivity of the iron in the long-term column tests continued to decline, even as the pH and ORP distribution in the column remained the same. Water level changes over the short distances involved when tracking flow through or around the PRB are often within the margin of error for the measurements, and therefore difficult to interpret. Direct flow measurements using sensors provide point estimates of flow velocity and direction; the point flow may not always match the bulk flow in the aquifer.

The ITRC leaves it to the site owners and the local regulators to decide, on a site-specific basis, the types and frequency of various monitoring events (e.g., quarterly monitoring of target contaminants, but less frequent monitoring of geochemical parameters). Again, the use of relatively more specialized and resource-intensive geochemical tools, such as iron coring and analysis, are left to the discretion of site owners.

7.0 REFERENCES

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