COST AND PERFORMANCE REPORT

Permeable Reactive Barriers Interim Summary Report:
Permeable Reactive Barriers
Using Iron With a Bulking Agent
as a Reactive Media

May 2002

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

Introduction

This report provides an interim summary of information of eight projects (seven full-scale and one pilot-scale) using permeable reactive barriers (PRBs) where iron with a bulking agent was used as a reactive media for treatment of contaminated groundwater. A PRB contains or creates a reactive treatment zone oriented to intercept and remediate a contaminant plume. Contaminants are removed from the groundwater flow system by physical, biological, or chemical processes (EPA, 2002a).

Table 1 summarizes available information about the eight projects, including year of installation, specific contaminants treated, PRB configuration and wall dimensions, installation method, installation depth, reactive media used, and cost data. Each of the PRBs was installed between 1995 and 2000.

Information about seven of the eight projects was obtained from *Installation Profiles* published by the Remediation Technologies Development Forum[1] (RTDF), and which are available online at www.rtdf.org. Information on the additional project (Lake City Army Ammunition Plant) was obtained from the U.S. Environmental Protection Agency (EPA) Remediation and Characterization Innovative Technologies web site at <www.EPAReachIT.org> and follow-up communication with the EPA project manager for the site. The eight projects are:

Full-Scale Projects

- F.E. Warren Air Force Base – *Cheyenne, Wyoming*
- Lake City Army Ammunition Plant – *Independence, Missouri*
- Rocky Flats Environmental Technology, Solar Ponds Plume – *Golden, Colorado*
- Rocky Flats Environmental Technology, East Trenches Site – *Golden, Colorado*
- Seneca Army Depot – *Romulus, New York*
- Somersworth Sanitary Landfill – *Somersworth, New Hampshire*
- Watervliet Arsenal – *Watervliet, New York*

Pilot-Scale Project

- Bodo Canyon – *Durango, Colorado*

Each of the PRB projects profiled in this report used iron (zero-valent iron or Fe^0) combined with a bulking agent, such as sand, wood chips, or copper or steel wool.

Iron was one of the first reactive media used in PRBs for treating groundwater contaminated with chlorinated volatile organic compounds (VOC's), and many PRBs have reactive zones

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

containing only iron as a reactive media. Recently, PRBs have been installed using a reactive zone consisting of iron combined with a bulking agent. Bulking agents have been combined with iron for several reasons, including improving groundwater flow conditions within the reactive zone, treatment of additional contaminants not addressed by iron alone, and reducing project cost.

Summary of PRB Projects Using Iron with Bulking Agents

Contaminants Treated

Six of the eight PRB projects were used to treat groundwater contaminated primarily with chlorinated VOCs, including tetrachloroethene (PCE), trichloroethene (TCE), dichloroethene (DCE), methylene chloride, vinyl chloride (VC), carbon tetrachloride, and chloroform. One project at the Rocky Flats Environmental Technology (Rocky Flats) site (Solar Ponds Plume) and the Bodo Canyon site treated groundwater contaminated with uranium, as well as other inorganic contaminants. Nitrate was present in groundwater at the Solar Ponds Plume site, while the Bodo Canyon site also was contaminated with such metals as arsenic, molybdenum, selenium, vanadium and zinc.

PRB Configuration

All eight projects employed either a continuous reactive wall (five sites) configuration or a reaction vessel (three sites) configuration. An example configuration of the continuous wall installed at the Somersworth Landfill is included in this report as Figure 1. The continuous reactive wall configuration was intended to intercept the flow of contaminated groundwater and treat it without affecting groundwater flow. In the reaction vessel configuration, groundwater was routed via natural or engineered preferential pathways to a subsurface reaction vessel. Water flow through a reaction vessel was designed to be perpendicular to groundwater flow, rather than the parallel flow that is characteristic of the continuous reactive wall configuration. The funnel and gate PRB configuration, which is used to capture groundwater over a large area and direct it to a smaller reactive zone, was not used in these projects.

PRB Installation Method

Six of the eight PRBs were installed using supported excavation technologies such as slurries, sheet piling, shoring techniques, or trench boxes used to hold the excavation open during construction. The Lake City Army Ammunition Plant and the Somersworth Sanitary Landfill used a biodegradable slurry, Watervliet Arsenal used a shoring technique, and both Rocky Flats sites used high-density polyethylene panels to support excavation during construction. The installation method employed at the Somersworth Sanitary Landfill (excavation using a biopolymer slurry for support) was chosen for its low cost and suitability for site conditions. The Seneca Army Depot PRB was constructed using an unspecified continuous trenching technology which allowed the simultaneous excavation of the trench and installation of the reactive media. The Bodo Canyon PRB did not specify the installation method used. None of the projects employed unsupported excavation techniques or direct placement technologies, such as injection, *in situ* soil mixing, vibrated I-beam, hydraulic fracturing, jetting, and mandrel (H-beam).

PRB Installation Depth

The eight PRBs were designed to be installed to a depth where the base of the wall was keyed into an impermeable subsurface layer, such as claystone or bedrock. Seven of the eight projects were keyed into the underlying impermeable layer. The design of the PRB at the Lake City Army Ammunition Plant specified a depth ranging from 30 to 60 feet below ground surface (bgs), into the underlying weathered shale bedrock. Due to the collapse of material in the trench during construction of the wall, the project manager stated that it was unclear as to whether the wall had been keyed into the shale bedrock. For the two Rocky Flats projects (East Trenches Site and Solar Pond Plume) a clay layer was located approximately 16 to 26 feet bgs. Excavations at these sites were completed to a depth at which the wall would be situated an average of three feet into the claystone. The PRB at the Seneca Army Depot was installed into the top 1 to 2 feet of the underlying weathered shale bedrock, resulting in a wall depth ranging from 7 to 12 feet bgs.

Reactive Media Used

Iron (zero-valent iron or Fe^0) is the most common reactive media used in PRB installations (United States Air Force Research Laboratory, 2000). Iron reacts with contaminants as groundwater passes through the PRB, and increases the degradation rates of those contaminants. While iron alone has been used as a reactive media in many PRB applications, each of the PRB projects included in this case study used iron mixed with a bulking agent as the reactive media. Information from these PRB projects suggest that use of a bulking agent with iron may be beneficial for improving groundwater flow conditions within the reactive zone and for enhancing treatment of specific contaminants.

Sand is the most common bulking agent used in the PRBs described in this report. It had been employed to improve the hydraulic conductivity or other flow characteristics within the reactive zones of the PRB. The increased hydraulic conductivity may increase the flow in the system by allowing more water access to the iron at a faster rate (*Battelle, 2000*). At the Rocky Flats East Trenches Site, horizontal layers of iron mixed with pea gravel, iron alone, and granular material alone, were used to achieve the desired groundwater flow through the reactive zone (configured as a reaction vessel). For the Watervliet Arsenal PRB, iron was mixed with sand for the reactive zone. The hydraulic conductivity within the reactive zone was measured to be 8.9 feet per day, which is significantly higher than the hydraulic conductivity of the surrounding geology (0.45 feet per day).

At the Rocky Flats Solar Ponds Plume, bulking agents were used to enhance treatment of certain contaminants that were not addressed adequately by iron alone. The PRB employed a reactive zone comprised of 10% iron combined with sawdust and leaf mold. The organic material in the reactive zone was used to induce denitrification to enhance the removal of nitrate, which, in addition to the chlorinated VOCs, was present in the groundwater.

Project Performance

Table 2 summarizes the performance data provided for the eight projects. At the eight sites, the PRBs reduced individual contaminant concentrations that had ranged from 38 micrograms per liter (µg/L) to 170,000 to below site-specific cleanup goals ranging from non-detect to 70 µg/L (for chlorinated solvents). Because seven of the eight projects included in this report were installed after 1999, information on the longevity of the eight PRBs included in the report was not available.

One PRB that had not met its performance goal is the Seneca Army Depot site, where the contaminants were TCE and cis-1,2-DCE. The cleanup goals at this site were based on the New York State cleanup standards of 5 µg/L for both contaminants. The PRB reduced the TCE concentration from 9,100 µg/L to non-detectable concentrations. The DCE in the effluent from the PRB ranged from 20 to 40 µg/L, which was higher than the cleanup goal of 5 µg/L. The higher concentration was attributed to greater than expected influent concentrations of TCE (the source of the DCE via degradation pathway), and greater than expected groundwater velocity. The Seneca Project profile reported that TCE had been reduced by 98%.

Although performance goals were not provided for the Bodo Canyon PRB, data show that individual metal concentrations were reduced from as high 8,800 µg/L to less than 360 µg/L. The decrease in concentrations of individual contaminants was more than 99% for all contaminants with the exception of molybdenum, which decreased by 70%. Performance data for the Lake City Army Ammunition Plant are not yet available.

Table 2

Permeable Reactive Barriers Using Iron with a Bulking Agent for Reactive Media Summary of Project Performance

Project	Contaminant	Influent Concentration (μg/L)	Effluent Concentration (μg/L)	Cleanup Goal (μg/L)	Reported % Reduction	Calculated % Reduction
Full-Scale Projects						
F.E. Warren Air Force Base	TCE	21,000	ND	NP	NP	NP
	cis-DCE	5,600	ND	NP	NP	NP
	VC	120	ND	NP	NP	NP
Lake City Army Ammunition Plant	1,1-DCE	NP	NP	NP	NP	NP
	TCE	NP	NP	NP	NP	NP
	VC	NP	NP	NP	NP	NP
Seneca Army Depot	TCE	9,100	NP	5	>99%	NP
	cis-1,2-DCE	1,100	40	5	NP	>96%
Somersworth Sanitary Landfill	PCE	410	NP	5	NP	NP
	TCE	370	NP	5	NP	NP
	1,2-DCE	530	NP	70	NP	NP
	VC	1,900	NP	2	NP	NP
Watervliet Arsenal	VOCs	4,700	NP	NP	NP	NP
Rocky Flats Environmental Technology, Solar Ponds Plume	NO_3	170,000	5,000	100,000	NP	97%
	U	28 pCi/L	1pCi/L	10pCi/L	NP	>96%
Rocky Flats Environmental Technology, East Trenches Plume	TCE	4,500	ND	5	NP	NP
	PCE	490	ND	5	NP	NP
	CCl_4	240	ND	5	NP	NP
	Chloroform	140	ND	10	NP	NP
	cis-1,2-DCE	38	ND	70	NP	NP
	Methylene chloride	470	NP	5	NP	NP
Pilot-Scale Project						
Bodo Canyon	As	186	2.2	NP	NP	99%
	Mo	1,180	359	NP	NP	70%
	Se	337	5.9	NP	NP	>98%
	U	5,540	1.2	NP	NP	>99%
	V	8,800	<6	NP	NP	>99%
	Zn	1,600	<4	NP	NP	>99%

NP- Not Provided
Note: All projects were on-going; data provided based on information in Installation Profiles

Project Cost

Cost information was available for seven of the eight projects. Total project installation costs ranged from $255,000 for the small pilot-scale project at Bodo Canyon to $2.4 million for the large, full-scale application at F.E. Warren Air Force Base. Information was provided about costs associated with project installation and design (for some projects) but not operation and maintenance. Design costs ranged from $100,000 to $217,000 for five of the sites (F.E. Warren Air Force Base, Seneca Army Depot, Somersworth Sanitary Landfill, Watervliet Arsenal, and Bodo Canyon).

Table 3 summarizes unit costs calculated for four full-scale PRB applications using iron with a bulking agent. The following table summarizes unit costs calculated using total project costs based on the length of wall constructed ($ per linear foot) and the area (length times maximum depth when average depth is not available) of wall constructed ($ per square foot). No cost adjustments were made to normalize the project costs in relation to the date when the costs were incurred or the geographic location of the project.

Table 3

Permeable Reactive Barriers Using Iron with a Bulking Agent as Reactive Media
Summary of Unit Costs

Unit Costs					
Project	**PRB Length (Feet)**	**PRB Maximum Depth (Feet)**	**Installation Cost (Excluding Design Cost When Provided)**	**Cost per Linear Foot ($)**	**Cost per Square Foot ($)**
F.E. Warren Air Force Base	568	24	$ 2,400,000	$ 4,225	$ 176
Seneca Army Depot	650	12	$ 350,000	$ 538	$ 45
Somersworth Sanitary Landfill	915	47	$ 2,000,000	$ 2,186	$ 47
Watervliet Arsenal	270	12	$ 278,000	$ 1,030	$ 86

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

Table 4

Permeable Reactive Barriers Using Iron with a Bulking Agent for Reactive Media Operating Parameters

Operating Parameters	
Parameter	**Range of Values**
Soil Classification:	Varied (provided for three projects)
Clay Content and/or Particle Size Distribution:	Not provided
PH:	Not provided
Porosity:	Not provided
Depth Below Ground Surface or Thickness of Zone of Interest:	12 to 60 feet bgs
Total Organic Carbon:	Not provided
Presence of Nonaqueous-Phase Liquids:	Not provided
Groundwater Flow Rate:	0.3 to 2 gallons per minute (gpm) (provided for two projects)
Type of Reactive Media:	Iron with bulking agents

Lessons Learned Related to PRBs Using Iron with Bulking Agents

The following is a summary of lessons learned from the eight projects included in this case study according to the RTDF.

PRB Configuration

- At the Somersworth Sanitary Landfill, a continuous wall configuration was used rather than a funnel and gate configuration which may have altered the natural groundwater flow in the area and caused mounding conditions. In addition, the configuration design and the bio-polymer construction method were effective and economical for a large Fe^0 PRB. However, difficulties during construction identified a need to monitor the stability of the bio-polymer slurry during construction.

- For the Watervliet Arsenal PRB, groundwater modeling was used to design the PRB. The results showed that flow barriers (funnels) at the site would have created underflow and reduced wall efficiency. Also, modeling showed that walls not constructed perpendicular to groundwater flow could have created “piping,” leading to underflow or mounding, that would reduce wall efficiency.

PRB Installation Method

- For the Rocky Flats sites, it was reported that the length of open trench must be minimized to reduce slope failure, during construction equipment operations and stockpiling adjacent to open trenches must be minimized, maintenance operations must be considered in the design of the PRB, backfill specifications must be rigidly followed, and gravity flow would be most effective when the natural contours of a hillside can be used.

Reactive Media Used

- Bulking agents have been combined with iron for use in PRBs to improve groundwater flow conditions within the reactive zone, treat additional contaminants not addressed by iron alone, and reduce project costs.

- During installation of the Watervliet Arsenal PRB, it was not always possible to visually determine whether the sand and iron mixture was mixed well because the iron and sand were the same color. Consequently, samples were collected and the iron separated from the sand using a magnet.

Project Performance

- At the Seneca Army Depot, the PRB did not reduce the concentration of DCE to below its cleanup goal of 5 µg/L. The PRB would need to be thicker and comprised completely of reactive material to remove DCE to meet the cleanup goal.

- The Bodo Canyon PRB reduced concentrations of a wide variety of constituents. However, the hydraulic head was limited by the elevation between the PRBs and the holding tank. In addition, gasses (H_2 and CH_4) that built up in the PRB required venting, and may have contributed to flow stoppage.

- For the Lake City Army Ammunition Plant, the project manager stated that several questions have been raised about whether the PRB is performing properly. Some current theories are that because the viscosity and pH of the biodegradable slurry were not maintained during installation, the trench collapsed during installation. The failure may have led to a reduction in the permeability of the PRB, resulting in the mounding or groundwater behind the barrier. It is unclear whether the PRB was effectively installed at a depth sufficient to be keyed into the underlying bedrock.

Project Cost

- Reduction of project cost was not reported as a factor for choosing iron with a bulking agent for any of the PRBs included in this report. However, the *Installation Profiles* for the Rocky Flats sites reported that the estimated cost for a PRB employing iron with a bulking agent as a reactive media was approximately one-quarter of the estimated cost for a baseline pump and treat system.

- Unit costs for the four continuous wall PRB applications with cost information at which chlorinated VOCs were treated ranged from $538 to $4,225 per linear foot and from $45 to $176 per square foot. It is likely that matrix characteristics and operating parameters such as soil classification; clay content and particle size distribution; pH; porosity; depth bgs or thickness of zone of interest; total organic carbon; presence of NAPLs; groundwater flow rate; and type of reactive media, also may be direct or indirect factors in project cost. However, because of the dissimilarity between sites profiled in the case study, more significant conclusions regarding PRB cost could not be made.

References

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Analysis Preparation

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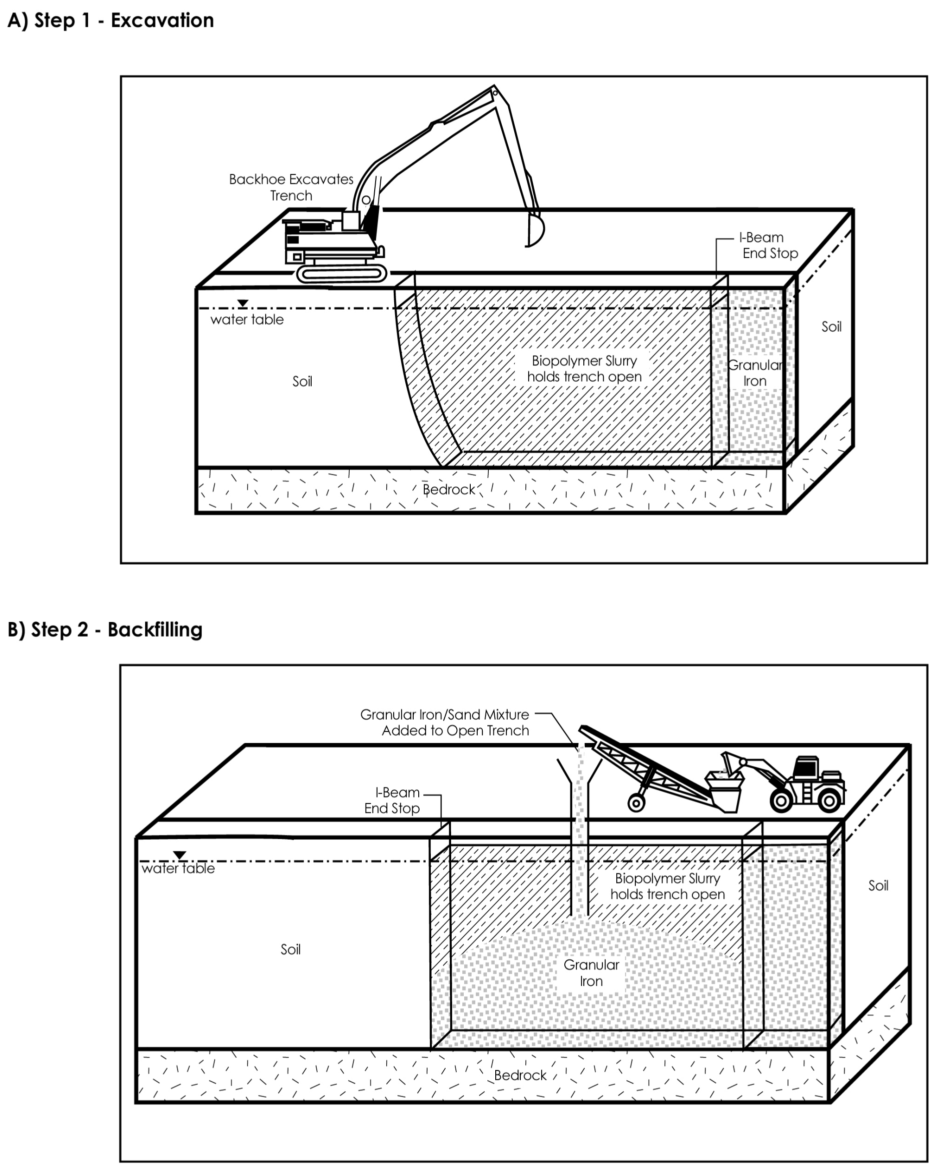
Table 1

Permeable Reactive Barriers Using Iron With a Bulking Agent as a Reactive Media
Project Summary Information

Site Name and Location	Year Installed	Construction Method	Wall Dimensions (Length and Maximum Depth)	Reactive Media	Contaminant	Install Cost (Design Cost)
Full Scale Walls						
F.E. Warren Air Force Base, Cheyenne, WY	1999	Supported excavation	568 ft long, 24 ft deep	Iron and sand	TCE;, cis-DCE; VC	$2,400,000 ($217,000)
Lake City Army Ammunition Plant, Independence MO	2000	Supported excavation	400 ft long, 60 ft bgs	Iron and sand	TCE; 1,1-DCE; VC	Not provided
Seneca Army Depot, Romulus NY	1999	Continuous trenching	650 ft long, 12 ft bgs	Iron and sand	TCE; cis 1,2-DCE	$350,000 ($100,000)
Somersworth Sanitary Landfill, Somersworth, NH	2000	Supported excavation	915 ft long, 47 ft bgs (8 sections, 100 ft each)	Iron and sand	PCE; TCE; cis 1,2-DCE; VC	$2,000,000 ($200,000)
Watervliet Arsenal, Watervliet, NY	1999	Supported excavation	270 ft long, 12 ft bgs (2 sections, 180 ft and 90 ft)	Iron and sand	Chlorinated VOCs – specific contaminants not specified	$278,000 ($113,000)
Full Scale Reaction Vessels						
Rocky Flats Environmental Technology Solar Ponds Plume, Golden, CO	1999	Supported Excavation	Trench-1,100 ft by 30 ft bgs (2 vessels)	Iron and wood chips	Nitrate; U	$1,300,000
Rocky Flats Environmental Technology East Trenches Site, Golden CO	1999	Supported excavation	Trench-1,200 ft by 26 ft bgs (2 vessels)	Iron and pea gravel	TCE; PCE; Carbon tetrachloride; Chloroform; cis 1,2-DCE; Methylene chloride	$1,300,000
Pilot Scale Reaction Vessel						
Bodo Canyon, Durango, CO	1995	Not provided	Not provided	Iron, copper wool, and steel wool	As; Mo; Se; U; V; Zn	$255,000 ($125,000)

Figure 1

Schematic Diagram of Continuous Reactive Wall at the Somersworth Sanitary Landfill



Construction Sequence for Chemical Treatment Wall

GEOSYNTEC CONSULTANTS

Source: RTDF

Permeable Reactive Barrier Project Profile:
F.E. Warren Air Force Base, Cheyenne, WY

Installation Year:	1999
Contaminants:	cis-Dichloroethene, Trichloroethene, Vinyl Chloride
Reactive Media:	Iron and sand
Cost:	$2,617,000
Construction:	Trench Box
Point of Contact:	Ernesto J. Perez HQ AFCEE/ERD-FEW F.E. Warren AFB 300 Vesle Drive, Suite 600 Cheyenne, WY 82005-2778 Telephone: 307-773-4356 Facsimile: 307-773-4153 Email: Ernesto.Perez@warren.af.mil

A full-scale permeable reactive barrier (PRB) was installed as an Interim Remedial Action (IRA) at F.E. Warren Air Force Base Spill Site 7 in Cheyenne, WY in 1999. The construction contractor chose a trench box system because of subsurface conditions and requirements for tracking iron usage. Trichloroethylene (TCE), cis-dichloroethylene (cis-DCE), and vinyl chloride (VC) are the contaminants of concern at the site. Initial concentrations encountered at the site were 21,000 µg/L for TCE, 5,600 µg/L for cis-DCE, and 120 µg/L for VC.

Spill Site 7 is an area where waste solvents associated with liquid oxygen production were discharged to a surface drainage ditch and infiltrated to groundwater at depths of 8-20 ft. The heterogeneous aquifer and geotechnical properties complicated the placement and composition of the PRB. The existing infrastructure on the site and the rare and endangered species area down gradient of the site added further limitations to the placement of the PRB. There is a 4-ft ground-water elevation fluctuation and no well-defined confining layer. Hydraulic conductivity varies from 0.01-4 ft/day.

The PRB consists of 3 segments, each 4 ft wide and ranging in length from 155-251 ft, a total of 568 ft long. Each segment contains a different mix and thickness of reactive media depending on the ground-water velocity and level of contaminants. One segment consists of pure iron filings, another a 25%/75% mix of iron and sand, and the third a 37.5%/62.5% mix of iron and sand. The vertical depth of the PRB is 15 ft, while the depth below ground surface ranges from 6-24 ft. Installation costs including materials, construction, oversight, and the technology licensing fee, totaled approximately $2.4 million. Design costs were approximately $217,000.

Samples taken down gradient of the PRB indicate that concentrations of TCE and its degradation products (cis-DCE and VC), were reduced to non-detectable levels. Sampling was conducted quarterly for the first year and semi-annually thereafter.

Lessons Learned

Successful PRB designs often require extensive site characterization in the pre-design phase. Successful installations require effective site layout, construction sequence, and heavy equipment selection. Construction methods must be flexible enough to be modified to accommodate unforseen conditions. A complete understanding of the characteristics and behavior of backfill material is important.

Note: This is the complete installation profile provided by the Remediation Technology Development Forum (www. rtdf.org) for this project. Included in this project profile are photographs of the installation of the PRB.

Permeable Reactive Barrier Project Profile:
Lake City Army Ammunition Plant, Independence, MO

Installation Year: 2000
Contaminants: 1,1-Dichloroethene, Trichloroethene, Vinyl Chloride
Reactive Media: Iron and sand
Cost: Information not provided
Construction: Continuous wall
Point of Contact:
Scott Marquess
Remedial Project Manager
U.S. EPA, Region 7
901 North Fifth Street
Kansas City, KS 66101
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Email: marquess.scott@epa.gov

In 2000, a full-scale permeable reactive barrier (PRB) continuous wall was installed at the Lake City Army Ammunition Plant (LCAAP) Superfund Site in Independence, Missouri to treat groundwater contaminated with 1,1-dichloroethene (DCE), trichloroethene (TCE), and vinyl chloride (VC). This site is a Superfund remedial site that is a cooperative effort by the U.S. Department of Defense and U.S. EPA Region 7.

The area at the LCAAP that is the focus of the PRB is referred to as Area 18, which is located in the northern central portion of the site. This area was used as a disposal area for industrial wastewater, oil and grease, solvents, plant trash, and demolition waste and contained solvent disposal pits, which are the primary sources of contamination in Area 18. DCE, TCE, and VC are present in the groundwater and lead and other metals are present in the surface soil.

The PRB system at the site was installed using a trench excavator and biodegradable slurry. The wall is approximately 400 feet in length. It was installed to a maximum depth of 60 feet below ground surface (bgs) and was intended to be keyed into the underlying shale bedrock. A mixture of 26% iron and 74% sand was used in the PRB as a reactive media.

There were several issues identified by the Remedial Project Manager (RPM) during the PRB installation phase. The trench failed during construction apparently because the viscosity and pH of the biopolymer slurry was not maintained. Once the wall was installed, artesian conditions were observed on the upgradient side of the wall. Groundwater was mounding behind the wall, apparently due to insufficient flow through the wall caused by the trench failure during construction. Also, it was unclear as to whether the wall had actually been keyed into the shale bedrock.

No cost or performance results are available at this time and the project is awaiting more funding before further action is taken.

Note: This project was identified in the EPA REACHIT database <www.EPAReachIt.org>. The EPA RPM provided additional information on the current status of the project.

Permeable Reactive Barrier Project Profile:
Seneca Army Depot Activity, Romulus, New York

Installation Year:	1999
Contaminants:	Trichloroethene and cis-1,2-Dichloroethene
Reactive Media:	Iron and sand
Cost:	$450,000
Construction:	Continuous wall
Point of Contact:	Michael Duchesneau Parsons Engineering Science, Inc. 30 Dan Road Canton, MA 02021-2809 Telephone: (781) 401-2492 Facsimile: (781) 401-2492 Email: michael.duchesneau@parsons.com

A full-scale demonstration permeable reactive barrier (PRB) system was installed at Seneca Army Depot Activity in Romulus, New York in 1999. Continuous wall trenches were chosen based on the system's lower cost, ease of installation, expectation of less disruption in groundwater flow, and ability to treat the upper surface of the bedrock aquifer. Trichloroethene (TCE) and cis-1,2-dichloroethene (DCE) are the contaminants of concern at the site. Following a removal action using low temperature thermal desorption (LTTD) in 1996, the concentrations dropped from 51,000 to 9,100 µg/L for TCE and from 130,000 to 1,100 µg/L for cis-DCE.

The site is an ash landfill area for a former trash incinerator used for the disposal of chlorinated solvents. A TCE/DCE groundwater plume (1,200 ft long by 600 ft wide) emanated from the ash landfill source area. The geological matrix is comprised of 6 by 8 ft of glacial till with fractured shale to 20 ft. The depth of the water varies over the year from ground surface to 6 to 8 ft below ground surface (bgs). The average hydraulic conductivity of the glacial till is 1.8×10^{-4} in/sec and that of the fractured shale is 1.4×10^{-5} in/sec. The shale conductivity decreased with increasing depth. There is poor connection between the overburden and the bedrock.

The PRB is 650 ft long, 14 in wide, and 7 to 12 ft deep with a cover of approximately 1 ft of natural soil. It is installed from the ground surface into the top 1 to 2 ft of the weathered shale bedrock. The 5,525 ft^3 of reactive material used is a 50/50 mixture of zero valent iron (Fe^0) and sand. The total installation cost including construction and materials was $350,000. Design costs, including a 3-D groundwater model, were $100,000.

The cleanup goal was based on the New York State standard of 5 µg/L. Samples taken after 4 quarters of monitoring revealed 100% removal of TCE. Removal of cis-DCE was less than expected. Concentrations downgradient and within the wall were measured at 20-40 µg/L. Removal of DCE will require additional reactive iron. Future walls are pending if DCE removal can be achieved. Sampling continues intermittently as funding allows.

Lessons Learned

Monitoring results indicate that walls will need to be thicker and comprised of 100% reactive material. Incomplete treatment of cis-DCE was attributed to greater than expected PRB influent concentrations of TCE (500 as opposed to 100 µg/L) and greater than expected variability of groundwater velocities. These variations necessitate the installation of additional monitoring wells to determine concentrations and velocities. Column study tests of the reactive iron may also be needed to determine if the reactivity of the iron may have contributed to the DCE breakthrough.

Note: This is the complete installation profile provided by the Remediation Technology Development Forum <www.rtdf.org> for this project. Included in this project profile are photographs of the installation of the PRB at this site.

Permeable Reactive Barrier Project Profile:
Somersworth Sanitary Landfill Superfund Site, Somersworth, New Hampshire

Installation Year: 2000
Contaminants: Tetrachloroethene; Trichloroethene; 1,2-Dichloroethene; and Vinyl Chloride
Reactive Media: Iron and sand
Cost: $2,200,000
Construction: Continuous wall
Point of Contact: Tom Krug
GeoSyntec Consultants
160 Research Lane, Suite 206
Guelph, Ontario, Canada
Telephone: (519) 822-2230
Facsimile: Not provided
Email: tkrug@geosyntec.com

A full-scale permeable reactive barrier (PRB) system was installed in 2000 at the Somersworth Sanitary Landfill Superfund Site in Somersworth, New Hampshire. The site is a 26-acre landfill that was constructed in the early 1930s on the site of a former sand and gravel quarry. The landfill was used to dispose of household trash, business refuse, and industrial wastes. Waste was burned at the landfill until 1958. From 1958 to 1981, the waste material was placed in excavated areas, compacted, and covered with soil. In 1981, use of the landfill stopped when the City of Somersworth began disposing of its municipal waste at a regional incinerator. Also in 1981, the City implemented a closure plan for the landfill that involved the covering of a portion of the landfill with clean fill. Volatile organic compounds (VOCs), including tetrachloroethene (PCE) trichloroethene (TCE), 1,2-dichloroethene (DCE), and vinyl chloride (VC) were found to be present in the groundwater. Initial concentrations encountered were up to 410 µg/L for PCE, up to 370 µg/L for TCE, up to 530 µg/L for 1,2-DCE, and up to 1,900 µg/L for VC.

The site is characterized by sands and gravels having a hydraulic conductivity in the range of 0.02 cm/second. The hydraulic gradient varies from 0.01 to 0.004 ft/ft near the edge of the waste. The top of the water table ranges from less than 2 to 20 ft below ground surface. As much as 10% of the waste is located below the water table. The aquifer is 30-40 ft thick.

The PRB is a continuous wall 915 ft long and extending to a depth of 26 to 47 ft below the ground surface. The PRB was designed with 8 sections, each approximately 100 ft long, with differing amounts of zero-valent iron (Fe^0) corresponding to the Fe^0 required to treat the specific concentration of VOCs entering each section of the PRB. The vertical interval of the PRB (interval containing Fe^0) ranges from 20 to 40 ft. A continuous wall was used for the PRB as opposed to a funnel-and-gate system to reduce the impacts on the existing groundwater flow conditions at the site and to reduce the potential for mounding of groundwater on the upgradient side of the PRB. The cleanup goals for VOC contaminants are: 5 µg/L for PCE; 5 µg/L for TCE; 70 µg/L for cis-1,2-DCE; and 2 µg/L for VC.

The PRB was installed using an open trench supported by a biodegradable bio-polymer slurry. This installation method was used because of its low cost and suitability for site conditions.

The construction method dictated that the PRB have a minimum thickness of 30 in, corresponding to the width of the excavator bucket. Inert, coarse washed sand was mixed with the Fe^0 before being placed in the trench. The different sections of the PRB contained Fe^0-sand mixtures with between 40% and 100% Fe^0 by weight. Total design cost for the system amounted to $200,000; construction/installation cost, including the cost of Fe^0, totaled $2,000,000.

Some difficulties were encountered during installation. The PRB was divided into 23 separate panels, each typically 30 to 50 ft long. The contractor initially installed alternating panels (primary panels) along the length of the PRB, then installed secondary panels between the primary panels. Typically, primary panels were excavated in one day. During the installation of the primary panels, the bio-polymer remained stable (i.e., maintained sufficient viscosity to support the trench) overnight or in some cases for several days. During the installation of the first two secondary panels, the contractor had difficulties maintaining the stability of the bio-polymer and some sand and silt settled out into the bottom of the trench before the Fe^0 was placed in the trench. Following these difficulties, the contractor excavated and backfilled secondary panels in a single day and difficulties with subsequent panels were averted. The area affected by the silt and sand represents approximately 1% of the PRB. The difficulties during construction have not had any measurable effect on the performance of the PRB. Sampling is being conducted three times per year to monitor PRB performance.

Groundwater monitoring conducted during the first year following installation shows that the PRB is operating as designed. Ongoing groundwater monitoring required by the Consent Decree for the Site is being conducted three times per year.

Lessons Learned

The approach to the design and the bio-polymer construction method were demonstrated to be effective and economical for a large Fe^0 PRB. Difficulties during construction highlighted the need to monitor the stability of the bio-polymer slurry during construction.

Note: This is the complete installation profile provided by the Remediation Technology Development Forum <www.rtdf.org> for this project. Included in this project profile are photographs, and a schematic diagram of the PRB at this site.

Permeable Reactive Barrier Project Profile

Watervliet Arsenal, Watervliet, New York

Installation Year: 1999
Contaminants: Volatile Organic Compounds
Reactive Media: Iron and concrete sand
Cost: $391,000
Construction: Continuous wall
Point of Contact: Grant A. Anderson
U.S. Army Corps of Engineers
10 South Howard St.
Baltimore, MD 21201
Telephone: (410) 962-6645
Facsimile: (410) 962-7731
Email: Grant.A.Anderson@nab02.usace.army.mil

Two continuous walls have been installed for full-scale cleanup of groundwater at the Watervliet Arsenal, the oldest cannon manufacturing facility in the United States. Years of land disposal of wastes from the manufacturing of cannons and the operation of a burn pit contaminated groundwater with up to 4,700 µg/L of volatile organic compounds (VOCs).

The site is underlain by a layer of fill extending 10 to 12 ft below ground surface (bgs) and consisting of mixed sands, clay, rubble, and wood. The hydraulic conductivity of this layer is approximately 8.9 ft/day, and the hydraulic gradient is 0.16 ft/ft. Underlying the fill is a tight (hydraulic conductivity of 0.45 ft/day) layer of lacustrine silt, clay, and peat atop weathered bedrock. The water table is situated within the fill at 2 to 5 ft bgs. The seasonal fluctuation of the water table is 2 to 3 ft.

Two 3-ft-wide and 8- to 12-ft-deep continuous walls were constructed with the goal of reducing levels of chlorinated VOCs to non-detect immediately downgradient of the walls. The southern wall, constructed perpendicular to groundwater flow, is 180 ft long; the northern wall, located further downgradient, is 90 ft long. The walls were constructed using a conventional track-mounted excavator, and the trenches held open with shoring plates with “speed shores”. A mixture of granular iron and concrete sand were placed manually from transit trucks using chutes. The total amount of reactive materials used was 165 tons of iron and 163 tons of sand.

During installation, it was not always possible to visually determine whether or not the sand/iron mixture was well mixed because the iron and sand were the same color. As a result, samples had to be collected and the iron separated from the sand using a magnet. Each component was weighed and the results were compared to the concrete plant’s weight slips to ensure proper mixing.

The installation cost of the walls, which includes construction and materials only, was $278,000; the design cost was $113,000. These costs are estimated to be about one-third the cost of designing and building a pump and treat system, and the O&M costs over a 30-year period are expected to be approximately $3 million lower.

One advantage of the constructing the treatment walls rather than a pump-and-treatment system is that the remediation area can be used largely without restriction since there are no plumbing systems or treatment plants to interfere with traffic or storage at the site. However, the presence of the walls may limit other remedial measures and construction. For example, a pump-and-treat system could not be installed in the deeper bedrock aquifer to address possible contamination near the wall. Any dewatering of the surficial aquifer would defeat the operation of the walls.

Monitoring of groundwater quality at Watervliet Arsenal shows that the walls are meeting project goals. Long-term monitoring will continue twice per year.

Lessons Learned

Thus far in this project, constructing the continuous walls has shown that groundwater modeling can be a powerful tool for design. Studies showed that flow barriers (funnels) would have created underflow and reduced wall efficiency. Also, modeling showed that walls not constructed perpendicular to groundwater flow could have created “piping”, which causes underflow or mounding. This would change the hydrodynamics of the system and could affect the residence time of groundwater in the walls. It was difficult to estimate the amount of water that would enter a trench during installation. The estimate, made by excavating a test pit, resulted in the selection of a holding tank that was many orders of magnitude too large.

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

Permeable Reactive Barrier Project Profile:
Rocky Flats Environmental Technology Site (Solar Ponds Plume), Golden, Colorado

Installation Year: 1999
Contaminants: Nitrate and Uranium
Reactive Media: Iron and wood chips
Cost: $1,300,000
Construction: Reaction vessels
Point of Contact: Annette Primrose
Kaiser-Hill Co, LLC
Rocky Flats Environmental Technology Site
10808 Highway 93, Unit B, Building 116
Golden, CO 80403-8200
Telephone: (303) 966-4385
Facsimile: (303) 966-5180
Email: Annette.Primrose@rfets.gov

Full-scale permeable reactive barrier (PRB) systems have been installed to treat contaminated ground water at three sites at the U.S. Department of Energy's Rocky Flats Environmental Technology Site (RFETS) in Golden, Colorado. These projects were a cooperative effort between RFETS and the Department of Energy (DOE) Subsurface Contaminant Focus Area, with support from U.S. EPA's National Risk Management Research Laboratory.

Another of these PRB systems was installed in 1999 to treat contaminated groundwater at the Solar Ponds Plume where, as a result of past waste storage practices, nitrate (NO_3) and uranium (U) are present in excess of the Action Level Framework Tier I level groundwater concentrations defined in the RFCA. The Solar Ponds were drained and the sludges removed by 1995, but contaminated groundwater migrated away from the source area to a nearby creek. Contaminant concentrations at the Solar Ponds Plume are: NO_3 at 140 to 170 mg/L and U at 20 to 28 pCi/L. The treatment goal is to meet surface water standards of 100 mg/L of nitrate and 10 pCi/L of uranium in the adjacent creek. These goals are currently being achieved.

The groundwater collection system at the Solar Ponds Plume extends approximately 1,100 ft. To install the collection system, an excavation was dug at a variable depth of approximately 20 to 30 ft bgs and approximately 10 ft into claystone. The barrier consists of the same HDPE panels as the barrier at the East Trenches Plume; it was installed and operates in the same way.

The below grade, concrete treatment cell is divided into two sections. Treatment media occupies the lower 10 ft of each section. The first cell is about 32 ft long and 17 ft wide and is filled with a mixture of sawdust and leaf mold with 10% zero-valent iron (Fe^0) by weight to induce denitrification and to remove the uranium by chemical reduction. The media was selected on the basis of bench scale tests conducted at the University of Waterloo. The second cell is about 11 ft long and 17 ft wide and is filled with Fe^0 to act as a final polisher. The two treatment cells can be run in series or in parallel.

Water exiting the treatment cell typically contains less than 5 mg/L NO_3 and less than 1 pCi/L U. While the PRB system does not collect and treat all the groundwater in this plume, the surface water standards are consistently met in the nearby creek.

Lessons Learned

Lessons learned to date from these installations include the following: (1) during construction, the length of trench open must be minimized to reduce slope failure, (2) equipment operations and stockpiling adjacent to open trenches must be minimized, (3) maintenance must be considered in a PRB's design, (4) backfill specifications must be rigidly followed, (5) gravity flow is most effective when the natural contours of a hillside can be utilized; and (6) cost estimated for this system are about one-fourth of the estimated baseline “pump-and-treat” costs.

Note: This is the complete installation profile provided by the Remediation Technology Development Forum <www.rtdf.org> for this project. Included in this project profile is a link to a website that contains additional information about this site: <www.envnet.org>

Permeable Reactive Barrier Project Profile:
Rocky Flats Environmental Technology Site (East Trenches Site), Golden, Colorado

Installation Year:	1999
Contaminants:	Trichloroethene, Tetrechloroethene, Carbon Tetrachloride, Chloroform, cis-1,2-Dichlororethene, Methylene Chloride
Reactive Media:	Iron and pea gravel
Cost:	$1,300,000
Construction:	Reaction vessels
Point of Contact:	Annette Primrose Kaiser-Hill Co, LLC Rocky Flats Environmental Technology Site 10808 Highway 93, Unit B, Building 116 Golden, CO 80403-8200 Telephone: (303) 966-4385 Facsimile: (303) 966-5180 Email: Annette.Primrose@rfets.gov

Full-scale permeable reactive barrier (PRB) systems have been installed to treat contaminated ground water at three sites at the U.S. Department of Energy's Rocky Flats Environmental Technology Site (RFETS) in Golden, Colorado. These projects were a cooperative effort between RFETS and the Department of Energy (DOE) Subsurface Contaminant Focus Area, with support from U.S. EPA's National Risk Management Research Laboratory.

The same type of PRB system was installed in 1999 to treat contaminated ground water at the East Trenches Plume. As a result of past waste storage practices, VOCs are present in excess of the Action Level Framework Tier I level ground-water concentrations defined in the Rocky Flats Cleanup Agreement. Sources were removed in 1996, but the contaminated groundwater migrated away from source areas towards a nearby creek. Contaminant concentrations at the East Trenches plume are primarily: trichloroethene (TCE), 2,700 to 4,500 µg/L; tetrachloroethene (PCE), 250 to 490 µg/L; carbon tetrachloride (CCl_4), 130 to 240 µg/L; chloroform, 82 to 140 µg/L; cis-1,2-dichloroethene (DCE), 23 to 38 µg/L; and methylene chloride, 6 to 470 µg/L. The treatment goal at the site is to remove contaminants of concern (COCs) to below Action Levels specified in the Rocky Flats Cleanup Agreement. This involves removal of the volatile organic compounds (VOCs) as follows—TCE to 5 µg/L; PCE to 5 µg/L; CCl_4 to 5 µg/L; chloroform to 100 µg/L; cis-1,2-DCE to 70 µg/L; and methylene chloride 5 µg/L.

The groundwater collection system for the East Trenches Plume PRB system extends approximately 1,200 ft. To install the collection system, an excavation was dug at a variable depth of approximately 16 to 26 ft below ground surface, at least 6 in and an average of 3 ft into claystone. The barrier was installed on the downgradient side of the excavation and consists of 80-mil high-density polyethylene (HDPE) panels fitted with an interlocking strip on each side. The trench was backfilled with sand and includes a perforated HDPE groundwater collection line that was placed on the sand, and piped to a central collection sump. The collected groundwater then flows by gravity from the collection sump through a 2-in, non-perforated HDPE line to the two treatment cells.

Each treatment cell is approximately 12 ft in diameter and 13 ft tall. Groundwater enters the cells at the top and percolates through the 6.5 ft of iron. There is 1 ft of granular material on the bottom of each treatment cell to disperse the groundwater. The upper foot of each cell is a 50/50 mixture of iron and pea gravel to simplify mechanical break-up of the expected crust formation.

Results have shown that, with the exception of methylene chloride, concentrations of VOCs are routinely non-detectable in the effluent samples.

Lessons Learned

Lessons learned to date from these installations include the following: (1) during construction, the length of trench open must be minimized to reduce slope failure, (2) equipment operations and stockpiling adjacent to open trenches must be minimized, (3) maintenance must be considered in a PRB's design, (4) backfill specifications must be rigidly followed, (5) gravity flow is most effective when the natural contours of a hillside can be utilized; and (6) cost estimated for this system are about one-fourth of the estimated baseline “pump-and-treat” costs.

Note: This is the complete installation profile provided by the Remediation Technology Development Forum <www.rtdf.org> for this project. Included in this project profile is a link to a website that contains additional information about this site: <www.envnet.org>

Permeable Reactive Barrier Project Profile:
Bodo Canyon, Durango, Colorado

Installation Year: 1995
Contaminants: Arsenic, Molybdenum, Selenium, Uranium, Vanadium, Zinc
Reactive Media: Iron, copper wool, steel wool
Cost: $380,000
Construction: Collection drain piped to underground treatment system
Point of Contact: Don Metzler
U.S. Department of Energy
2597 B 3/4 Road
Grand Junction, CO 81503
Telephone: (970) 248-7612
Facsimile: (970) 248-6040
Email: d.metzler@gjo.doe.com

A pilot-scale demonstration of permeable reactive barriers (PRBs) was installed at Bodo Canyon in Durango, Colorado in 1995. The demonstration was conducted to help treat contaminated water seeping from a tailings disposal cell and test the efficiency of PRBs for remediation of uranium and metals.

Operation of PRB E began in the Spring 2000. Installation costs for the four PRBs, including construction and materials, was approximately $255,000. Design costs were about $125,000. Contaminants of concern at the site are arsenic (As), molybdenum (Mo), selenium (Se), uranium (U), vanadium (V), and zinc (Zn). Concentration of contaminants in the untreated water are 186 µg/L for As, 1180 µg/L for Mo, 337 µg/L for Se, 5540 µg/L for U, 8800 µg/L for V, and 1600 µg/L for Zn.

A total of 2.5 million yd^3 of uranium mill tailings were relocated to the Bodo Canyon disposal cell in the fall of 1990. Contaminated seeps developed along the downgradient slope of the disposal cell shortly after construction. The seep water was collected by a collection drain and piped to a retention pond, where it was regularly treated and discharged to a nearby wash.

In order to be able to compare different designs, four PRBs were installed near the retention pond. Contaminated groundwater in the collection drain (328 ft long, 4 ft wide, and 3 ft high) is diverted to a holding tank. Water from the holding tank flows to a manifold that distributes it to the PRB. Because of the limited water flow in the area, only one PRB operates at a time and the system is shut down during the winter. Flow rates vary from 0.3 to 2 gallons per minute (gpm).

Zero valent iron (Fe^0) in a variety of forms was used in each of the PRBs. Two of the PRBs were constructed similarly to septic leach fields, one containing steel wool (PRB A) and the second containing steel wool and copper wool (PRB B). Each of these systems is 20 ft wide, 3 ft long, and 7 ft high. The reactive media is about 12 in thick. The remaining two PRBs were constructed in steel tanks with baffles that forced the water to flow up and down through the PRB. One tank contained Fe^0 foam plates (PRB C) and the other contained steel wool (PRB D). The foam plates were manufactured by binding fine-grained Fe^0 with aluminosilicate. Each of these tanks is 6 ft long, 3 ft wide, and 4.2 ft deep. Approximately 70 ft^3 of reactive media was used in PRBs C and D. The baffled tanks were used because the reactive media could be easily changed.

Because of the limited flow out of the disposal cell and the fact that this was developed as a pilot demonstration project, three of the four PRBs were shut down. PRB A never ran at all; B ran for approximately one year, and D for two months. In July 1999, PRB C was excavated and 72 samples of the solid foam plates were collected. After complete removal of the plates, PRB C was refilled with granular Fe^0 (mesh size -8+20) and renamed PRB E. The change to granular Fe^0 was made in order to test the effectiveness of a more commonly used reactive media.

The baffled tank with Fe^0 foam plates (PRB C) operated the longest. Effluent concentrations in May 1999 were 2.2 µg/L for As, 359 µg/L for Mo, 5.9 µg/L for Se, 1.2 µg/L for U, <6 µg/L for V, and <4 µg/L for Zn. After 3 years, flow ceased in PRB C, probably due to mineral plugging. Water samples taken at PRB D indicated significant reductions in U concentrations from 7,430 µg/L to 738 µg/L with a flow rate of 0.66 gpm. Early in the project, samples were taken almost monthly. They are currently being taken semi-annually.

Lessons Learned

The PRB reduced concentrations of a wide variety of constituents. The hydraulic head is limited by the elevation between the PRBs and the holding tank. Additional head would be useful to keep the flow from stopping due to small decreases in hydraulic conductivity in the PRB. Gasses (H_2 and CH_4) that built up in the PRB required venting before accessing. The gasses may also have contributed to flow stoppage. The collection drain/PRB system is useful because it can easily be replaced and the flux of water is well known.

Note: This is the complete installation profile provided by the Remediation Technology Development Forum <www.rtdf.org> for this project. Included in this project profile is a link to a website with additional information on this site: <www.gjo.doe.gov>.