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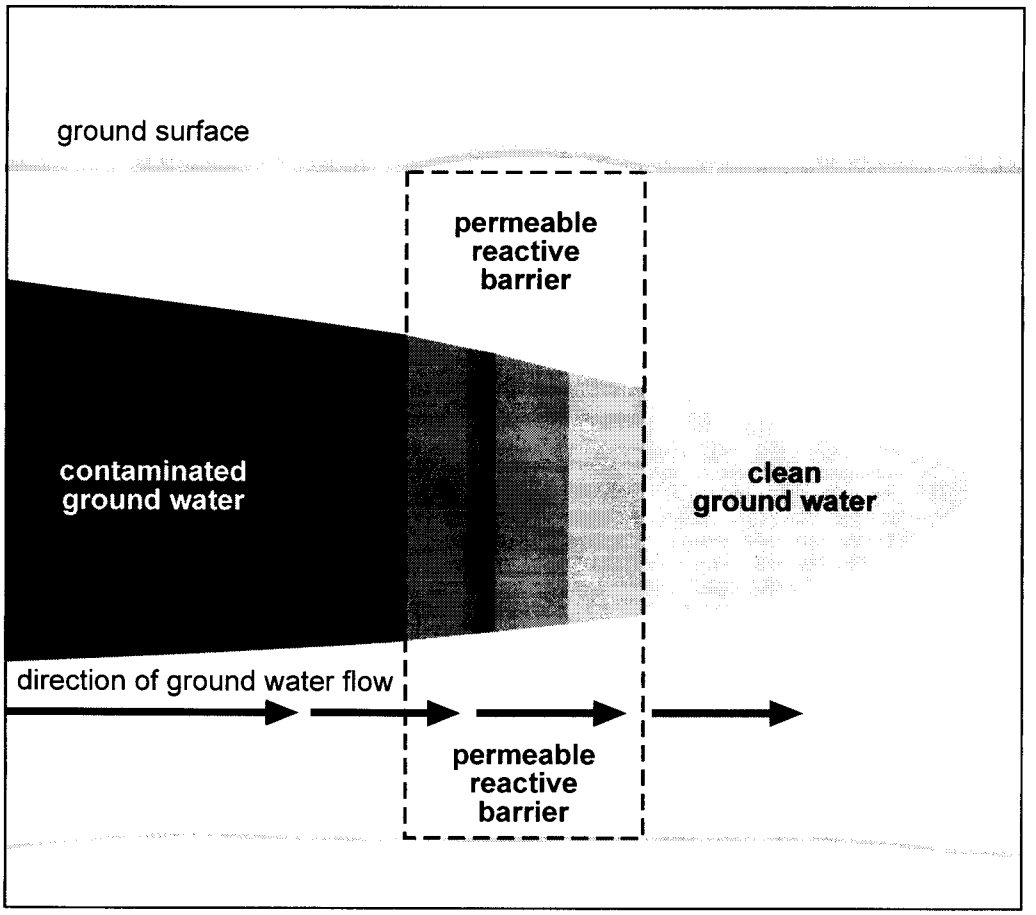
Field Applications of *In Situ* Remediation Technologies:

Permeable Reactive Barriers



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Field Applications of *In Situ* Remediation Technologies:

Permeable Reactive Barriers

U.S. Environmental Protection Agency
Office of Solid Waste and Emergency Response
Technology Innovation Office
Washington, DC 20460
Walter W. Kovalick, Jr., Ph.D., Director

Notice

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Foreword

Approximately 76% of the Superfund hazardous waste sites in the United States have contaminated ground water. The conventional approach for remediating contaminated ground water has been to extract the contaminated water, treat it above ground, and reinject or discharge the clean water in a process known as "pump-and-treat." The recovered contaminants must be disposed of separately. Pump-and-treat technologies require considerable investment over an extended period of time, and it has been shown that these technologies often do not actually remove the source of the contamination. Current policies and laws stress "permanent" remedies over simple containment methods. Consequently, there is considerable interest in and effort being expended on alternative, innovative treatment technologies for contaminated ground water.

This report is one in a series that documents recent pilot demonstrations and full-scale applications of technologies that either treat soil and ground water in place or increase the solubility and mobility of contaminants to improve their removal by other remediation technologies. It is hoped that this information will allow more regular consideration of new, less costly, and more effective technologies to address the problems associated with hazardous waste sites and petroleum contamination. This and the other reports listed below are available from EPA's Technology Innovation Office World Wide Web site at http://www.epa.gov/tio/pubitech.html.

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Hydrofracturing/Pneumatic Fracturing
Cosolvents
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Ground-Water Circulation Wells

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Introduction

This document is a status report on the use of permeable reactive barriers (PRBs) for ground-water remediation in the United States, Canada, and selected locations abroad. Included in this report are profiles of ongoing and completed pilot- and full-scale PRB demonstrations as well as full-scale installations. The profiles are organized by the type of contaminant treated. At some sites, PRBs are being used to address more than one type of contaminant. Profiles for these site are included in all applicable sections of this document.

Sites included were identified by the members of the Permeable Reactive Barriers Action Team under the Remediation Technologies Development Forum (RTDF). The Action Team was established in March 1995. Its members include representatives from government, academia, and the private sector working as partners to achieve public and regulatory acceptance of PRBs for remediating chlorinated solvents, metals, radionuclides, and other ground-water pollutants.

The profiles included in this document have been developed based on information provided by the point of contact listed in each profile. The intent is to provide potential users of PRB technology with information for making more informed decisions and, when possible, to provide pointers to additional information.

To the extent it is available, a consistent set of information is presented in each profile. This includes site name, location, characteristics of the site, major contaminants, PRB installation date, type of construction, design and installation costs, reactive materials used, results achieved, lessons learned, and point of contact for further information. This document also includes a bibliography of PRB-related articles and documents organized alphabetically by author's name. Some, but not all, of the entries in the bibliography pertain to the sites profiled in the body of the document.

An Internet version of this report is maintained in the Permeable Reactive Barriers Action Team section of the RTDF World Wide Web site at www.rtdf.org. Those who have information about additional PRB sites are encouraged to submit it for inclusion in the Web-based version. Additional profiles will be developed as sites are identified, and existing profiles will be updated periodically as new information is received. A copy of a "Permeable Reactive Barriers Profile Information Request" can be downloaded from the Web site for use in providing appropriate information.

Technology Description

A PRB is a passive *in situ* treatment zone of reactive material that degrades or immobilizes contaminants as ground water flows through it. PRBs are installed as permanent, semi-permanent, or replaceable units across the flow path of a contaminant plume. Natural gradients transport contaminants through strategically placed treatment media. The media degrade, sorb, precipitate, or remove chlorinated solvents, metals, radionuclides, and other pollutants. These barriers may contain reactants for degrading volatile organics, chelators for immobilizing metals, nutrients and oxygen to enhance bioremediation, or other agents.

Choice of reactive media for PRBs is based on the specific organic or inorganic contaminant to be remediated. Most PRBs installed to date use zero-valent iron (Fe^0) as the reactive media for converting contaminants to non-toxic or immobile species. For example, Fe^0 can reductively dehalogenate hydrocarbons, such as converting trichloroethylene (TCE) to ethylene, and reductively precipitate anions and oxyanions, such as converting soluble Cr^{+6} oxides to insoluble Cr^3 hydroxides. The reactions that take place in the barriers are dependent on parameters such as pH, oxidation/reduction potential, concentrations, and kinetics. The hydrogeologic setting at the site is also critical—geologic materials must be relatively conductive and a relatively shallow aquitard must be present to contain the system.

Most PRBs are installed in one of two basic configurations: funnel-and-gate or continuous trench, although other techniques using hydrofracturing and driving mandrels are also used. The funnel-and-gate system employs impermeable walls to direct the contaminant plume through a gate, or treatment zone, containing the reactive media. A continuous trench is installed across the entire path of the plume and is filled with reactive media.

Chlorinated Solvents

Aircraft Maintenance Facility, OR

Installation Date:
March 1998

Contaminants:
TCE

Reactive Media:
Fe^0

Installation Cost:
$600,000

Construction:
Funnel and Gate

Point of Contact:
James Romer
EMCON Associates
1150 Knutson Road
Suite 5
Medford, OR 97504
Tel: 541-770-6977
Fax: 541-770-7019
E-mail:
jromer@emconinc.com

A full-scale demonstration of a permeable reactive barrier (PRB) to remediate ground water contaminated with trichloroethylene (TCE) was installed in March 1998 at an aircraft maintenance facility in southern Oregon.

Site Background

Historical use of chlorinated solvents for degreasing purposes resulted in the ground-water contamination by TCE and other degradation compounds. Total volatile organic compound (VOC) concentration in the upper aquifer encountered at the site was approximately 500 μg/L.

The site is underlain by heterogeneous alluvial deposits ranging from sandy silts to silty gravels. At a depth of 24-34 ft below ground surface (bgs) is a fine-grained aquitard. The depth to the water table varies seasonally between 4 and 8 ft bgs. Average hydraulic conductivity for the alluvial deposits is 3 ft/day.

Technology Application

The funnel-and-gate system consists of two gates, each 50 ft wide, and a 650-ft-long funnel. The funnel walls are composed of a 2-ft-thick soil-bentonite slurry installed to the top of the aquitard with a hydraulic conductivity of 3×10^{-4} ft/day. The first gate is composed of two layers, each 50 ft wide and 9 in thick, consisting of 100% zero-valent iron filings (Fe^0). Both layers were installed using a continuous trencher, then connected to the funnel by driven sheet piles. The second gate, upgradient from the first, is 3 ft wide, 60 ft long, and composed of mixed sand and iron filings. It was installed with a trackhoe and drag box.

Results

Four monitoring wells, two upgradient and two downgradient, have been installed for each gate. Sampling began in April 1998. Current plans call for sampling every two months for four periods and then quarterly for the foreseeable future.

Caldwell Trucking, NJ

Installation Date:
April 1998

Contaminants:
TCE

Reactive Media:
Fe^0

Installation Cost:
$1,120,000

Construction:
Hydraulic Fracturing

Point of Contact:
John Vidumsky
DuPont Specialty Chemicals
Barley Mill Plaza 27/2226
Lancaster Pike and Route 141
Wilmington, DE 19805
Tel: 302-892-1378
Fax: 302-892-7641
E-mail: john.e.vidumsky@usa.dupont.com

A full-scale permeable reactive barrier (PRB) system was installed at Operating Unit (OU) 2 of the Caldwell Trucking Superfund Site in northern New Jersey in April 1998. The PRB system is being considered as an alternative to the pump-and-treat system specified in the site's Record of Decision (ROD). U.S. EPA agreed to negotiate an amendment to the ROD if, after one year of operation, performance data on the PRB system showed success in terms of achieving remediation objectives.

The system is expected to achieve the same mass removal (500 kg/yr) as the originally proposed pump-and-treat system. The barrier is designed to reduce initial trichloroethylene (TCE) concentrations of 6,000-8,000 μg/L in the ground water to below 50 μg/L.

Site Background

The Caldwell Trucking site encompasses 11 acres near the Passaic River that were used for disposal of septic wastes in unlined ponds from the 1950s to 1984 and industrial waste containing lead and TCE. The site contains areas of glacial deposition overlying basalt flows with an average conductivity of approximately 0.1 in/sec. The majority of ground-water flow occurs in a 25 ft-deep sand and gravel aquifer confined below an impermeable clay layer at an average elevation of 160 ft above mean sea level. The water table is located approximately 5-15 ft below ground surface. A fractured basalt zone is located below the sand/gravel aquifer at 100-125 ft above mean sea level. The TCE plume extends 4,000 ft off-site. Studies indicated that the rate of natural attenuation occurring at this site is 3,000 kg/yr.

Technology Application

The PRB system was installed in unconsolidated sands and a fractured basalt zone using a combination of hydraulic fracturing and permeation infilling. The barrier system is 50 ft deep, beginning about 15 ft below ground. The system consists of two 3-in walls, 150 ft and 90 ft in length and uses 250 tons of zero-valent iron (Fe^0) as the reactive material. Construction of the PRB system involved hydraulic fracturing of the upper sand/gravel zone, using 15 hydrofrac/infilling wells at 15-ft intervals, and permeation infilling of the lower sedimentary zone (pumping a gel containing the Fe^0 down a well into the fractured bedrock through an open borehole).

Cost

The total installation cost of the PRB system (both walls) at this site is estimated at $1,120,000—$670,000 for the 90-ft (hydrofracing) wall and $450,000 for the 150-ft (permeation infilling) wall. This includes the cost of design, construction, materials, and the reactive material.

Results

Monitoring wells and surface waters have been sampled at least monthly for volatiles and metals, and other parameters have been measured. To date, the barrier has achieved 95% degradation of TCE in the ground water, from an upgradient concentration of 7,000 μg/L to a downgradient concentration of less than 400 μg/L. TCE ground-water concentrations, affected by variable ground-water flow velocities and desorption of TCE from the site soils, are expected to reach pseudo steady-state conditions in early 1999.

Lessons Learned

The low temperature and high pH at which the guar gum gel used for installation was formulated slowed its enzymatic degradation after it was in place. As a solution, a pH buffer and additional enzyme were injected. Guar breakdown then occurred and TCE reductions were observed. Otherwise, the gel has not interfered with the barrier's permeability nor impacted the iron's reactivity.

Federal Highway Administration (FHA) Facility, Lakewood, CO

Installation Date:
October 1996

Contaminants:
TCA; 1,1-DCE; TCE; cDCE

Reactive Media:
Fe^0

Installation Cost:
$1,000,000

Construction:
Funnel and Multiple Gate

Point of Contact:
Peter McMahon
U.S. Geological Survey
Denver Federal Center
(MS-415)
Denver, CO 80225
Tel: 303-236-4882, x286
FAX: 303-236-4912
E-mail:
pmcmahon@usgs.gov

A permeable reactive barrier (PRB) system was installed in October 1996 at a site in Lakewood, Colorado.

Site Background

Contaminants at the site included 1,1,1-trichloroethane (TCA), 1,1-dichloroethylene (1,1-DCE), trichloroethylene (TCE), and cis-dichloroethylene (cDCE). The contaminated area is an unconfined aquifer that is 15-25 ft thick and consists of unconsolidated gravelly sand overlying weathered (fractured) claystone. These units are in hydraulic connection and act as one aquifer. The geometry of the aquifer is irregular, with a local presence of clay lenses in the unconsolidated sand and sandstone lenses in the claystone. The aquifer is confined from below by unweathered (unfractured) claystone.

Technology Application

The PRB system is comprised of a 1,040-ft funnel section and four reactive gate sections, each 40 ft wide. This was the first funnel and multiple gate PRB system using granular zero-valent iron (Fe^0). A high degree of lateral geologic heterogeneity and variation in volatile organic compound (VOC) concentrations led to varying iron thicknesses in each gate. The gates were constructed using a sheet pile "box." Native material was excavated from the box and the reactive material installed, separated from the aquifer materials by a layer of pea gravel.

Cost

Installation cost of the PRB system was about $1,000,000. This includes the cost of design, construction, materials, and the zero-valent iron.

Results

Ground-water velocities through the gates were expected to range from 1 ft/day to 10 ft/day, depending upon the hydrogeologic conditions in the vicinity of the respective gates. Measurements in the cells using a heat-pulse flowmeter have ranged from < 0.1 ft/day to about 1.5 ft/day. Design concentrations include up to 700 μg/L of TCE and 700 μg/L of 1,1-DCE. Half-lives of about 1 hour or less were measured for these compounds in bench-scale design studies. The only VOC exiting the cells above the 5 μg/L reporting level is 1,1-dichloroethane, which has been measured up to 8 μg/L on the downgradient side of the cells. There is some evidence of

the precipitation of calcite and siderite in the cells based on decreases in calcium and inorganic carbon in the treated ground water. This is estimated to result in a potential porosity loss of 0.5% of the porosity per year of operation.

Hydraulic head has increased upgradient of the barrier, with up to 10 ft of head difference measured across the barrier. This increases the possibility for contaminated water to move around the barrier. Indeed, VOC concentrations are increasing in ground water moving around the south end of the barrier and there is some evidence of VOCs moving under the barrier in one location.

Former Drycleaning Site, Rheine, Westphalia, Germany

Installation Date:
June 1998

Contaminants:
PCE, 1,2-DCE

Reactive Media:
Fe^0, iron sponge

Design Cost:
$30,000

Installation Cost:
$93,000

Construction:
Continuous Wall

Point of Contact:
Dr. Martin Wegner
Dr. Wilfried Moeller
Mull & Partner
Ingenieurgessellschaft
mbH
Osteriede 5, 30827
Garbsen, Germany
Tel: 49-5131-4694-55 or
49-5131-4694-55
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E-mail: Wegner_Mull
@compuserve.com

A full-scale permeable reactive barrier (PRB) was installed at a former drycleaning site in an urban area in Rheine, Westphalia in Germany.

Site Background

Tetrachloroethylene (PCE) and 1,2-dichloroethylene (1,2-DCE) are the primary contaminants of concern at the site. Initial maximum concentrations in the plume were 20 mg/L for PCE and 0.5 mg/L for 1,2-DCE. The 1,640-ft-long, 820-ft-wide plume is present in a loamy sand aquifer that extends 16-33 ft below grade. The water table is about 10 ft below the ground surface. The hydraulic conductivity varies between about 0.3 and 2.8 ft/day. The distance from the center of contamination to the treatment wall is about 1,300 ft.

Technology Application

The PRB is a continuous reactive wall that varies between 2 and 3 ft wide and is 74 ft long. The PRB was constructed by drilling a line of overlapping 3-ft diameter boreholes which were filled with reactive material to ground-water level, and with clean soil to ground surface level. The PRB uses two reactive media: 69 tons of granular iron (Fe^0) mixed with gravel at a 1:2 volume ratio (34.5 tons each of Fe^0 and gravel) in 33 ft of the wall and 85 tons of iron sponge in 41 ft of the wall. A concrete-filled borehole separates the two segments. (Iron sponge consists of wood shavings or wood chips impregnated with hydrated iron oxide. It is used for removal of H_2S in oil and gas processing operations.)

Cost

The mandrel construction method was chosen because it was determined to be easier and less expensive than continuous sheet piling construction. Design costs were $30,000. Installation costs including construction and reactive material totaled $93,000. An additional $13,000 was spent on monitoring and $24,000 on the installation of gas measurement devices.

Results

This is the first continuous treatment wall in Germany and was built as a research project with no specific target cleanup concentrations. However, the PRB has resulted in significant reduction in the concentration of contaminants—especially PCE. The effluent concentration of PCE from both sections of the wall is

less than 100 μg/L. There has been only a low level of metabolite production. No vinyl chloride was observed in the affluent or effluent of the PRB. There was measurable production of hydrogen only at the very beginning of the remediation process—simultaneous with a complete reduction of nitrogen to ammonia. Ground-water samples are being collected monthly.

Lessons Learned

Due to increasing microbial activity at the site of the PRB, hydrogen emission is decreasing. Nitrate now is reduced to nitrogen or N_2O. The sulfate effluent concentration is decreasing due to the sulfate reduction to sulphured hydrogen.

Former Manufacturing Site, Fairfield, NJ

Installation Date:
September 1998

Contaminants:
1,1,1-TCA, PCE, TCE, DNAPL

Reactive Media:
Fe^0

Design Cost:
$150,000

Installation Cost:
$725,000

Construction:
Continuous Trench

Point of Contact:
Stephen Tappert
VECTRE Corporation
15 Route 15 South
Lafayette, NJ
07848-0930
Tel: 973-383-2500
Fax: 973-579-0025
E-mail: set@vectre.com

A full-scale permeable reactive barrier (PRB) was installed at a site in Fairfield, NJ, to treat chlorinated solvent contamination.

Site Background

The site, a former electromechanical product manufacturing, assembly, and testing facility is currently in operation as a school. It consists of a single one-story slab foundation brick building and paved parking lot covering 60% of a 2.8-acre plot of land. The site is underlain by 15-20 ft of silty sand with some gravel, overlying a lacustrine clay 10-15 ft thick. The clay unit varies in depth from 15-23 ft below grade. Ground water at the site occurs under water-table conditions within the glacial sediments above bedrock, and under confined conditions in the deeper sand aquifer. Shallow ground-water flow is moving toward a nearby creek at an average hydraulic gradient of 0.005 ft/ft. Depth-to-water in the shallow zone has been as high as 4 ft below grade. An upward vertical ground-water gradient exists between the shallow aquifer and the silty sand unit underlying the clay, with a head difference of almost 6 ft in some areas.

Environmental investigations at the site identified a plume of chlorinated solvents, with an apparent source in the vicinity of a former dry well and septic system. Contamination was limited to the shallow sandy aquifer. The total VOC concentration at the plume front was approximately 4,500 μg/L. Key contaminants included 1,200 μg/L trichloroethane (1,1,1-TCA), 19 μg/L tetrachloroethylene (PCE), and 110 μg/L trichloroethylene (TCE). A pool of dense nonaqueous-phase liquid (DNAPL) was also identified with significant concentrations of solvents in saturated soils below 15 ft. Underground utilities in place at the site included two storm drains and a sewer line at 13 ft below grade.

Technology Application

Prior to installation of the PRB, the DNAPL pool was excavated. As a remedial measure, the excavation was partially backfilled with a 1:1 mix of zero-valent iron (Fe^0) and sand. For the PRB, conventional sheet piling construction was selected as the most reliable approach with the most predictable timeframe for completion. The PRB was constructed as a continuous barrier located ahead of the highest plume concentrations to prevent offsite migration. The bottom portion of the barrier used a 4:1 iron/sand mixture and the upper portion of the barrier used a 3:2

iron/sand mixture. A total of 720 tons of iron were used. The final barrier was 127 ft wide, 25 ft deep, and 5 ft thick. After the barrier was installed, the site was graded and seeded, and the parking lot was repaved. Construction was generally straightforward with the only major problem being the below-grade sewer line that permitted a large volume of water to enter the excavation. Construction ultimately required subaqueous excavation to complete that section of the wall.

Cost

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

Results

Cleanup goals for chlorinated solvents at the site were New Jersey Ground Water Quality Criteria: 1 μg/L for PCE, 1 μg/L for TCE, and 30 μg/L for 1,1,1-TCA. Monitoring wells were installed upgradient, downgradient, and within the PRB and samples were collected one month after installation. At that time, VOC concentrations at the center of the plume decreased to 33 μg/L within the PRB. Subsequent quarterly sampling results showed an increase in pH from approximately 6.5 to 9.5, a change in Eh from -50 mv to -400 mv, and concentrations of VOCs at or near detection limits in the middle of the wall. Future sampling plans include quarterly monitoring of selected wells for two years, then continued monitoring with reduced frequency after that.

Lessons Learned

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

Industrial Site, Belfast, Northern Ireland

Installation Date:
December 1995

Contaminants:
TCE, 1,2-cDCE

Reactive Media:
Fe^0

Installation Cost:
$375,000

Construction:
Slurry Wall Funnel
In Situ Reaction Vessel

Point of Contact:
Stephanie O'Hannesin
EnviroMetal
Technologies, Inc.
42 Arrow Road
Guelph, Ontario
N1K 1S6 Canada
Tel: 519-824-0432
Fax: 519-763-2378
E-mail:
sohannesin@beak.com

A full-scale field test of a permeable reactive barrier (PRB) system was conducted at an industrial facility in Belfast, Ireland.

Site Background

A circular *in situ* reaction vessel filled with iron was installed to a depth of about 40 ft in December 1995, to treat up to 390 mg/L of trichloroethylene (TCE) and related breakdown products. Previous owners of the site had used chlorinated solvents while manufacturing electronic components. Years of spillages resulted in an intense but localized plume close to the current site boundary.

The TCE plume at this site is located in an area characterized by a thick deposit of till (up to 78 ft) underlain by Mercia mudstones. The till has silt, sand, and gravel lenses that allow contaminants to migrate from the source; however, migration is constrained by the specific orientation of the permeable lenses that contain discrete clay or clayey silt lenses. The depth of the barrier was chosen to intercept the horizon of low permeability that is present at a depth of around 33 ft. The site is characterized as having a water table approximately 20 ft below ground surface, and an underlying aquifer about 40 ft in depth.

Technology Application

Two 100-ft bentonite cement slurry walls directed water to the inlet of the steel reaction vessel, which was 4 ft in diameter and contained a 16-ft vertical thickness of zero-valent iron (Fe^0). Ground water flowed by gravity through the iron zone and discharged through a piped outlet on the downgradient side of the slurry wall. The vessel was equipped with a manhole to access the top of the iron zone, in the event that periodic scarification of the iron surface proved access was necessary. The system was designed to provide residence time of about 5 days.

Cost

The total cost of the system, including slurry walls, granular iron, reaction vessel, and engineering was about $375,000.

Results

The system was designed to meet ground-water-quality criteria of 500 μg/L for TCE, which apply to ground water beneath industrial land slated for redevelopment. Flow rates through the reactor have varied substantially since its installation, but data have shown an

overall 99.7% reduction in TCE and cis-1,2-dichloroethylene (cDCE) levels through the reaction vessel. Both increased and decreased levels of cDCE resulting from reductive dehalogenation have been identified. TCE levels in the system have been decreasing in the effluent sample ports. Only low levels (in the range of 100 μg/L) of cDCE have been detected. Vinyl chloride, a common breakdown product of this process, has not appeared in appreciable quantities.

Industrial Site, Coffeyville, KS

Installation Date:
January 1996

Contaminants:
TCE, 1,1,1-TCA

Reactive Media:
Fe^0

Installation Cost:
$400,000

Construction:
Funnel and Gate

Point of Contact:
Greg Somermeyer
SECOR International, Inc.
4700 McMurry Drive
Suite 101
Fort Collins, CO 80525
Tel: 970-226-4040
Fax: 970-226-4099

This permeable reactive barrier (PRB) system was installed at the property boundary of an industrial site in Coffeyville, KS, in January 1996.

Site Background

The site covers about 200 acres and is hydrologically and geochemically complex. Contaminants include trichloroethylene (TCE) and 1,1,1-trichloroethane (TCA). Prior releases at this site had generated a dissolved plume approximately 875 yds long contaminated with 400 μg/L of TCE and 100 μg/L of 1,1,1-TCA. Contaminant transport occurred to the greatest lateral extent in a basal sand and gravel unit just above shale bedrock, which lies about 30 ft beneath the site. There is nearby public use of shallow ground water necessitating measures to prevent additional off site migration.

Technology Application

The PRB system uses a funnel-and-gate configuration to direct ground water through a single, permeable treatment gate that is 20 ft long and 3 ft thick. The funnel section of the system consists of two 490-ft soil-bentonite slurry walls on either side of the treatment gate. Zero-valent iron (Fe^0) is used as the reactive material. The treatment wall contains 70 tons of the iron. A low ground-water flow velocity of 0.2 ft/day permitted the use of this relatively high funnel-to-gate ratio. The system is installed to a depth of 30 ft in a basal alluvial aquifer.

Cost

The installation cost for the system, including slurry walls, treatment gate, and granular iron, was approximately $400,000.

Results

No determinations of ground-water velocity through the system have been made to date. Concentrations in the iron zone are below Maximum Contaminant Levels (MCLs).

Industrial Site, NY

Installation Date:
December 1997

Contaminants:
TCE, cDCE, VC

Reactive Media:
Fe^0

Installation Cost:
$797,000

Construction:
Continuous Trench

Point of Contact:
Diane Clark
Stearns & Wheler, LLC
One Remington Park Dr.
Cazenovia, NY 13035
Tel: 315-655-8161
Fax: 315-655-4180
E-mail: diane.clark@
stearnswheler.com

A full-scale permeable reactive barrier (PRB) was installed at a former plating facility in Central New York in December 1997.

Site Background

Trichloroethylene (TCE), cis-1,2-dichloroethylene (cDCE), and vinyl chloride (VC) are the primary contaminants of concern at this facility. Initial concentrations ranged from 200-1,280 μg/L for TCE, 300-1,800 μg/L for cDCE, and 26-53 μg/L for VC. Total volatile organic compounds (VOC) concentrations ranged from 300 μg/L-900 μg/L. The goal of this project is to clean the site to New York ground-water standards, 5 μg/L for TCE, 5 μg/L for cDCE, and 2 μg/L for VC.

The 370-ft plume is present in a sand and gravel aquifer that extends from 4-21 ft below grade, and the water table is located 4-5 ft below ground surface. Based on the results of slug tests, the hydraulic conductivity of the material in the aquifer ranges from about 16 to 230 ft/day.

Technology Application

The PRB uses 742 tons of bulk granular zero-valent iron (Fe^0) for reductive dehalogenation of chlorinated aliphatic compounds. It was constructed as a continuous wall, measuring 1 ft thick and 18 ft deep, across the entire width of the plume. An additional 1-ft-thick continuous wall was placed 10 ft upgradient of the longer wall and in the portion of the plume with the highest concentrations of total VOCs to provide additional residence time in the reactive iron.

The system was installed with continuous trenching equipment that uses a large cutting chain excavator combined with a trench box and loading hopper. To construct the barrier, the cutting chain removed the native soil along the trench line. As the machine advanced along the trench line, the granular iron was lowered through the hopper and trench box into the excavated trench. During this process, the trenching equipment proved to move faster than the rate at which the iron settled into the excavated trench. As a result, the top 2 ft of the trench had to be backfilled with a backhoe to reach the 18-ft depth.

A 3-ft bench was excavated prior to the use of the trenching equipment, allowing the wall to be installed to the maximum depth

of the clay layer, which was 21 ft below normal site grade. The spoils removed from the trench were then spread on the surface of the bench on the upgradient side of the iron. Finally, the spoils were covered by backfill of the clean soil excavated for the bench, amounting to a minimum of 2 ft of clean soil as cover.

Cost

A predesign study determined that a continuous permeable reactive barrier was more cost-effective than a funnel-and-gate system at this site. Installation costs for the full-scale system were $797,000. This includes construction, materials, and the cost of the reactive material. In addition, it includes the cost of site improvements allowing access by the trenching equipment. Design cost for this system is not available. Because several issues that would not be required for other installations were included in this system's design cost, site managers indicate that it probably would not be applicable, as far as scale-up, to other sites.

Results

Recent sampling results have indicated upgradient concentrations of 2,200 μg/L TCE, 4,900 μg/L 1,2-DCE, and 260 μg/L VC. Downgradient results showed only 5 μg/L 1,2-DCE and 23 μg/L VC. Ground-water samples will be collected on a quarterly basis for a total of 5 years.

Lessons Learned

At this particular site, construction of a continuous trench system was more cost-effective than a funnel-and-gate system. This option also required the shortest construction period, minimizing disruption to the landowner. In addition, site managers were able to manage trench spoils onsite, instead of having to dispose of them offsite. Spoils were spread in the benched area and capped with a minimum 2 ft of top soil, which had been stripped off prior to construction and stockpiled.

Industrial Site, SC

Installation Date:
November 1997

Contaminants:
TCE, cDCE, VC

Reactive Media:
Fe^0

Design Cost:
$50,000

Installation Cost:
$350,000

Construction:
Continuous Trench

Point of Contact:
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Phase 1 of a full-scale permeable reactive barrier (PRB) was installed at a former industrial site in Manning, SC, in November 1997.

Site Background

Trichloroethylene (TCE), cis-1,2-dichloroethylene (cDCE), and vinyl chloride (VC) have been detected in two aquifers that underlie the site at concentrations of 25 mg/L, 3.5 mg/L, and 0.9 mg/L, respectively. TCE concentrations in the lower of the two contaminated aquifers are generally one order of magnitude less than those in the upper aquifer.

The upper aquifer is 5-15 ft below ground surface (bgs). It is composed primarily of sandy to silty fill material with a hydraulic conductivity of 2 ft/day. A clay unit forms the lower boundary of this aquifer. The intermediate aquifer (18-27 ft bgs) is composed of fine silt laminae and very fine sand layers within the clay unit and has a hydraulic conductivity of 2.6 ft/day. The lower portion of this clay unit forms a boundary between the intermediate and lower aquifers. Monitoring wells did not detect any volatile organic compounds (VOCs) in the lower aquifer.

Technology Application

The PRB was installed to the base of the intermediate aquifer. It is a 1-ft-wide continuous trench composed of 50% sand and 50% zero-valent iron (Fe^0) by volume in the form of iron filings. The 400 tons of Fe^0 was homogeneously distributed throughout the sand using cement-mixing equipment. A one-pass trenching technique was used from a surface bench 4-6 ft bgs. This surface bench allowed the trenching equipment to reach the final depth of 29 ft bgs. Phase 1 of the installation called for a 325-ft section to address the highest concentrations of VOCs and mitigate suspected off-site migration. Phase I construction—including mobilization, benching, installation, and demobilization—was completed in 4 weeks.

Cost

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

Results

Cleanup goals for the site are 0.005 mg/L for TCE, 0.070 mg/L for cDCE, and 0.002 mg/L for VC. After the initial 9 months of system operation, positive indicators for dechlorination were measured at downgradient monitoring wells for both VOC concentrations and indicator compounds (pH, eH, chloride). However, due to the slow rate of ground-water flow and the fact that VOCs were present downgradient of the wall at installation, performance evaluations continue. Construction of Phase 2 will extend the wall to a total length of 1,000 ft to treat the entire contaminant plume.

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

Modifications to the ground-water monitoring schedule were also necessary to take into account differences in ground-water flow rates. Sampling upgradient and downgradient of the wall is conducted on a quarterly basis. Semi-annual sampling is anticipated in the future.

Lessons Learned

Compared with other methods, continuous trenching provided cost-effective installation and a high degree of confidence that materials would be placed according to the design, to create a continuous treatment wall with equal distribution of the Fe^0.

Because of the reduced ground-water flow velocity at the site, more time than originally estimated will be required to complete an initial flushing of VOCs in downgradient ground water. This site may require 18-24 months to complete dechlorination sufficient to achieve cleanup levels.

Expectations and data collection efforts relative to performance will be planned to accommodate a relatively long initial period of operation and monitoring.

Intersil Semiconductor Site, Sunnyvale, CA

Installation Date:
February 1995

Contaminants:
TCE, cDCE, VC, Freon 113®

Reactive Media:
Fe^0

Installation Cost:
$1,000,000

Construction:
Funnel and Gate

Point of Contact:
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In January 1995, after being approved by the California Regional Water Quality Control Board, a permeable reactive barrier (PRB) was installed at the Intersil Semiconductor Site in Sunnyvale, CA.

Site Background

Intersil had manufactured semiconductors at the site from the early 1970s until 1983. In 1972, the company had installed a concrete, epoxy-lined, in-ground system at the facility to neutralize acid in wastewater before discharge to a sanitary sewer. Soil and ground-water contamination from halogenated volatile organic compounds (VOCs) was identified near the neutralization holding tank site after it was removed early in 1987. Initial concentrations of contaminants were 50-200 μg/L of trichloroethylene (TCE), 450-1,000 μg/L of cis-1,2,-dichloroethylene (cDCE), 100-500 μg/L of vinyl chloride (VC), and 20-60 μg/L of Freon 113®. Ground-water extraction and treatment, using an air stripper, began late in 1987. The *in situ* PRB system replaced the existing pump-and-treat system which was being maintained at a significant cost. The original system has been removed and the property has been restored to full economic use. The monitoring wells provide access to the *in situ* system for periodic monitoring compliance.

The contaminated area is in a semiconfined aquifer that is 2-4 ft thick. It is composed of interfingering zones of silty, fine-grained sand, fine- to medium-grained sand, and gravelly sand. The geometry of the aquifer is irregular, with a local presence of clay lenses. The aquifer is mostly confined by an upper silty-clay and clay layer, which ranges from 9-12 ft thick, and by a lower aquitard of clay and silty clay, which is about 65 ft thick.

Technology Application

The physical constraints of the site helped determine the geometry of the PRB and the construction technique used. To address historically changing ground-water flow directions, low permeability walls were installed upgradient and perpendicular to the PRB to contain affected ground water onsite prior to flow through the barrier. The treatment zone is sandwiched between permeable gravel layers to evenly distribute flow through the zone. The barrier itself is 4 ft wide, 36 ft long, and 20 ft deep. It is charged with 220 tons of granular iron (Fe^0) to a depth of about 11 ft. A low, permeable "wing" that extends perpendicular from the treatment wall to about 20 ft downgradient was installed to reduce

the impact on ground-water velocity through the wall due to variations in regional flow direction.

Cost

Installation cost for the *in situ* PRB system, including the slurry walls used to direct ground water toward the permeable reactive barrier, was $1,000,000. This includes the cost of construction, materials, and the iron. Design cost for this system is not available.

Results

The cleanup goal established for the site is to reduce contaminant concentrations to levels below the Maximum Contaminant Level (MCL) set by the State of California and Primary Drinking Water Standards—5 μg/L for TCE, 6 μg/L for cDCE, 0.5 μg/L for VC, and 1,200 μg/L for Freon 113®. Since installation, VOC concentrations have been reported below cleanup goals from monitoring wells located within the iron wall. While seasonal hydraulic mounding has been observed above the PRB, it is not expected to affect long-term performance of the barrier. Affected ground water is contained onsite when mounding is present. When the mounding dissipates, ground water again flows through the barrier and is treated.

Lessons Learned

In addition to helping distribute flow through the PRB, the pea gravel zone placed upgradient of the PRB has resulted in precipitation of naturally occurring minerals and partial treatment of target chemicals upgradient of the iron treatment zone. Some mixing of the iron into the pea gravel zone is likely to have occurred during construction and resulted in chemical conditions favorable for some mineral precipitation (for example, higher pH, lower redox potential than ambient ground water). This is evidenced by inorganic chemistry data from wells within the pea gravel. While site managers did not anticipate this benefit, the result is expected to extend the life of the treatment zone relative to the potential negative effects of mineral precipitation.

Kansas City Plant, Kansas City, MO

Installation Date:
April 1998

Contaminants:
1,2-DCE, VC

Reactive Media:
Fe^0

Design Cost:
$200,000

Installation Cost:
$1,300,000

Construction:
Continuous Trench

Point of Contact:
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A permeable reactive barrier (PRB) was installed in April 1998 at the U.S. Department of Energy's Kansas City Plant in Kansas City, MO.

Site Background

Contaminants of concern include 1,2-dichloroethylene (1,2-DCE) and vinyl chloride (VC). Maximum initial concentrations encountered at the site were 1,377 μg/L of 1,2-DCE and 291 μg/L of VC.

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

Technology Application

The PRB was constructed as a continuous trench measuring 130 ft long. Sheet piles were driven into bedrock to support the side walls. The resulting excavation was 6 ft wide. The first 6 ft of the trench above bedrock was filled with 100% zero-valent iron (Fe^0). The remainder of the trench was filled with 2 ft of Fe^0 and 4 ft of sand. These differing thicknesses were used to compensate for the increased flow-through thickness required for the basal gravel unit. Approximately 8,320 cubic feet of reactive iron was used in the permeable barrier.

Cost

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

Results

Cleanup goals for the site are Maximum Contaminant Levels (MCLs) as defined in 40 CFR 141.2 and listed in 40 CFR 141.61(a) and 40 CFR 264.94. (70 μg/L for 1,2-DCE and 2 μg/L for VC.) The VOC plume is predominant in the basal gravel unit.

A number of monitoring wells have been installed. Upper completion wells are screened in the saturated clay. The clay soil extends from the ground surface to a depth of approximately 25 ft. Lower completion wells are screened in the basal gravel formation which varies in thickness from about 3-5 ft and overlays the bedrock (shale). Lower completion wells were installed at the upgradient face, center, and downgradient face of the wall at three locations. Sidegradient wells were installed as well to confirm that the contamination is not going around the wall. Results of a January 16, 1999, sampling event indicate that all compliance wells are below MCLs.

Plans call for investigative fieldwork to be conducted at the PRB in February 1999. This will include subjecting a number of the wells to colloidal borescope measurements, heat-pulse flow meter measurements, and enhanced (nitrogen pressure) single well testing in order to address the following questions:

- Can flow rates and directions within an iron wall be adequately determined?
- Are there significant flow contrasts within the treatment area?
- Can the enhanced single-well testing procedure adequately determine permeability contrasts within the treatment zone?
- How do the borescope, heat-pulse meter, and enhanced single-well testing procedures compare with respect to ease-of-use and precision of measurement?

Lessons Learned

The two main advantages for choosing the continuous permeable wall design were predictability and economics.

A continuous permeable wall impacts the existing ground-water flow system less than some other designs. Modeling (predicting) "changes" in flow directions and velocities were not required for this design as would have been for a funnel-and-gate system. The upgradient horizontal extent of the plume and ground-water levels are expected to experience little change.

The cost and time required for constructing a continuous permeable reactive wall was estimated to be less than for constructing a series of impermeable wall and gate sections. The continuous wall was expected to be constructed with a one-pass deep trenching machine. However, the contractor had difficulties with the trenching machine, which may have been due to the heavy, wet clay. The problems encountered resulted in utilization

of conventional sheet pile construction of the permeable wall. This should actually benefit the long-term performance. For example, there was better opportunity during the installation process to verify intimate contact of iron placement with the bedrock surface; additional wall thickness was created by the use of "Z" piles; and uniform, continuous placement of iron was visually verified.

Lowry Air Force Base, CO

Installation Date:
December 1995

Contaminants:
TCE

Reactive Media:
Fe^0

Installation Cost:
$530,000

Construction:
Funnel and Gate

Point of Contact:
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A demonstration project of a permeable reactive barrier (PRB) to remediate ground water contaminated with chlorinated hydrocarbons was initiated at Lowry Air Force Base, CO.

Site Background

Contamination at Lowry is a result of various base activities generating contaminants that were transferred to local ground water via storm drains, septic tanks, or direct infiltration. The total chlorinated hydrocarbon concentration was approximately 1,400 μg/L, primarily consisting of trichloroethylene (TCE).

The Lowry site is underlain by unconsolidated alluvial deposits and artificial fill that is approximately 18 ft thick. These surficial deposits overlie bedrock consisting of silty claystones and sandy siltstones. The local water table aquifer is approximately 9 ft below ground surface (bgs) and saturates alluvial material as well as the upper 10 ft of underlying bedrock in places. Local ground-water flow patterns are partly controlled by paleochannels eroded into the underlying bedrock. Hydraulic conductivity for the site averages 35 ft/day, and the average ground-water velocity is 1 ft/day.

Technology Application

The funnel-and-gate system constructed consists of a 10-ft-wide and 5-ft-thick reactive wall composed of 100% granular, zero-valent iron (Fe^0) and two 14-ft sheet piling walls that were installed to a depth of 17 ft.

Cost

The total installation cost for the system was approximately $530,000. This includes design, construction, materials, and the reactive material.

Results

Thirty-four wells located within and proximate to the wall were used to monitor the system's performance. Seven sets of samples were taken from December 1995 through June 1996. Data analysis indicates that a first-order, abiotic reaction involving reductive dehalogenation is taking place within the reactive iron wall. Chlorinated hydrocarbons are being completely degraded within the first foot of the wall. After 18 hours residence time (2 ft into the wall), all analytes degrade to their respective analytical quantitation limits. In addition, intermediate breakdown products

produced during the process are also degraded. The wall was resampled in May 1997 with similar results. Since the PRB was designed and built as a short-term solution, there are no plans to continue the monitoring. A slurry wall containment area was constructed in October 1997 30-50 ft upgradient of the PRB as part of a new source-area remedial system.

U.S. Coast Guard Support Center, Elizabeth City, NC

Installation Date:
June 1996

Contaminants:
Cr^{+6}, TCE

Reactive Media:
Fe^0

Installation Cost:
$500,000

Construction:
Continuous Trench

Point of Contact:
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A full-scale demonstration of a permeable reactive barrier (PRB) to remediate ground water contaminated with chromium and chlorinated organic compounds was initiated at the U.S. Coast Guard Support Center site in Elizabeth City, NC, in 1995.

Site Background

The primary contaminants of concern are hexavalent chromium (Cr^{+6}) and trichloroethylene (TCE). Initial maximum concentrations were more than 4,320 μg/L for TCE and more than 3,430 μg/L for Cr^{+6}. The contaminant plume was estimated to cover a 34,000-ft^2 area. The plume is adjacent to a former electroplating shop that operated for more than 30 years prior to 1984 when operations ceased. Ground water begins approximately 6 ft below ground surface, and a highly conductive zone is located 16-20 ft below the surface. This layer coincides with the highest aqueous concentrations of chromium and chlorinated organic compounds found on the site. A low-conductivity layer—clayey, fine sand to silty clay—is located at a depth of about 22 ft. This layer acts as an aquitard to the contaminants located immediately above.

Technology Application

A continuous wall composed of 100% zero-valent iron (Fe^0) was installed in June 1996 using a trencher that was capable of installing the granular iron to a depth of 24 ft. The continuous trenching equipment used for the installation has a large cutting chain excavator system to remove native soil combined with a trench box and loading hopper to emplace the iron.

The trenched wall is approximately 2 ft thick and about 150 ft long. The wall begins about 3 ft below ground surface and consists of about 450 tons of granular iron.

Cost

The total installation cost was $500,000. This includes the cost of design, construction, materials, and the iron, which cost about $175,000.

Results

The wall was designed to meet cleanup goal concentrations of 0.05 mg/L of Cr^{+6} and 5 μg/L of TCE. Performance monitoring has been conducted on a quarterly basis since November 1996. In addition to 2-in PVC compliance wells, the wall is monitored using a series of multilevel sampling (MLS) ports to monitor the geochemical mechanisms occurring in the barrier and in the downgradient aquifer. Sampling results for chromium indicate that all chromium has been removed from the ground water within the

first 6 inches of the wall as expected. No chromium has been detected downgradient of the wall either in the MLS ports or in the compliance wells located immediately behind the wall. Results thus far indicate that the barrier is successfully reducing TCE, c-DCE, and vinyl chloride concentrations to less than MCL levels for the vast majority of the monitored portions of the wall. Of 29 downgradient MLS ports, MCLs for TCE and vinyl chloride are exceeded in 1 and 3 ports, respectively. TCE concentrations are generally below 5 μg/L within the wall, but exceed 50 μg/L at the lowest depth. There are some indications that the TCE plume may have dipped lower in this part of the aquifer following wall installation. The slight elevation beyond target levels for vinyl chloride seen in the MLS ports are not reflected in adjoining compliance wells. Downgradient vinyl chloride concentrations in the MLS ports have declined with time. Nowhere do c-DCE concentrations exceed regulatory limits.

Numerous vertical and angle cores also have been collected at the site to examine changes to the iron surface and to evaluate the formation of secondary precipitates which may affect wall performance over time. These cores continue to be studied.

Lessons Learned

Researchers are investigating the possibility that the TCE plume has dipped lower in the aquifer after the wall was installed and is now moving under the wall. A significant amount of recharge occurred into the reaction zone following installation due to removal of the concrete parking lot covering the site. This recharge may have driven the plume deeper than had previously been observed allowing some of the plume to move under the wall. Interestingly, there is still significant treatment below the wall where no iron resides.

Based on limited preliminary electrical conductivity profiles, the wall is approximately 19-21 in thick, compared to the design thickness of 23 in. Some minor vertical discontinuities were observed in the conductivity data and have been confirmed with coring. These small gaps are probably due to bridging within the trencher hopper during iron emplacement.

Area 5, Dover Air Force Base (AFB), DE

Installation Date:
January 1998

Contaminants:
PCE, TCE, DCE

Reactive Media:
Fe^0

Installation Cost:
$800,000

Construction:
Funnel and Gate

Point of Contact:
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A pilot-scale field demonstration of a permeable reactive barrier (PRB) is being conducted at the Area 5 site at Dover AFB, DE. The demonstration is funded by the Strategic Environmental Research and Development Program (SERDP).

Site Background

The Dover site is contaminated with perchloroethylene (PCE), trichloroethylene (TCE), and dichloroethylene (DCE). The maximum concentrations encountered during site characterization were 5,617 μg/L of PCE, 549 μg/L of TCE, and 529 μg/L of DCE. Area 5 lies within the Atlantic Coastal Plain Physiographic Province, consisting of Cretaceous to Recent sedimentary deposits of gravel, sand, silt, clay, limestone, marl, and chalk dipping to the southeast. Ground water is located 5-15 ft below ground surface. The clay aquitard is located 40-45 ft below the surface. The hydraulic conductivity values used for design of the permeable barrier were based on an aquifer conductivity range of 10-50 ft/day.

Technology Application

Major objectives of the demonstration include comparing two reactive media schemes and examining innovative emplacement techniques designed to reduce the cost of construction for PRB systems. The funnel-and-gate system, installed in January 1998, consists of two gates that are 8 ft wide and 45 ft deep. One gate is filled with pure, zero-valent iron (Fe^0) filings with a 10% iron/sand pretreatment zone to stabilize flow and remove dissolved oxygen. The second gate also is filled with iron, but it is preceded by a 10% pyrite/sand mixture. The mixture serves to moderate the pH of the reactive bed, thereby decreasing the precipitates formed.

The gates were constructed with 8-ft-diameter caissons that were removed after reactive media emplacement. The funnel sections were built using Waterloo interlocking sheet piling driven to the 45-ft depth and keyed into the underlying clay aquitard.

Cost

The total installation cost for the system was $800,000. This includes the cost of design, construction, materials, and the reactive material.

Results

Results of the demonstration are unknown at this time. Two comprehensive monitoring events are planned for July and December 1998. The demonstration is being used to validate the document "Design Guidance for Application of Permeable Barriers to Remediate Dissolved Chlorinated Solvents," developed with input from state and federal regulators and published in February 1997. At the completion of the project (approximately December 1998), the guidance document will be updated to reflect lessons learned.

Borden Aquifer, Ontario, Canada

Installation Date:
1991

Contaminants:
TCE, PCE

Reactive Media:
Fe^0

Installation Cost:
$30,000 (not including Fe^0 and labor)

Construction:
Continuous Trench

Point of Contact:
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University of Waterloo
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A pilot-scale demonstration of a permeable reactive barrier (PRB) to remediate ground water contaminated with trichloroethylene (TCE) and perchloroethylene (PCE) was conducted at the Canadian Forces Base in Borden, Ontario, Canada. The PRB was installed in 1991.

Site Background

Contamination was the result of a previous site study to determine the dissolution characteristics of a mixed non-aqueous fluid. The contaminant plume was about 6.5 ft wide and 3.3 ft thick. Initial concentrations were 250,000 μg/L TCE and 43,000 μg/L PCE. The plume source was located about 13 ft below ground surface (bgs) and 3.3 ft below the water table.

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

Technology Application

Reactive material was installed using sealable joint sheet piling 18 ft downgradient from the source. Individual piles were interlocked to create a rectangular cell normal to ground-water flow direction that was 18 ft long, 5 ft wide, and 32 ft high. The pilings were then driven as a unit to a depth of 32 ft using a hydraulic vibratory driver suspended by a crane. The joints were sealed with a bentonite-based sealant, and the water table was lowered below the depth of excavation. The cell was then excavated and the native material was replaced with a mix of 22% (by weight) zero-valent granular iron (Fe^0) and 78% coarse sand from 12.4-20 ft bgs. This mixture had a hydraulic conductivity of 124 ft/day. After emplacement of the mixture, the sheet pilings were removed.

Cost

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

Results

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

Cape Canaveral Air Station, FL

Installation Date:
October-November 1997

Contaminants:
TCE, DCE, VC

Reactive Media:
Fe^0

Design Cost:
$292,000 (for two barriers)

Installation Cost:
$279,000 (Mandrel)
$238,000 (Jet-Assisted Grout)

Construction:
Continuous Walls with Overlapping Panels

Point of Contact:
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Side-by-side, pilot-scale demonstrations of two emplacement techniques for permeable reactive barriers (PRBs) are being conducted at the industrial area of Cape Canaveral Air Station, FL.

Site Background

The site is contaminated with 90 mg/L of trichloroethylene (TCE), 7 mg/L of vinyl chloride (VC), and 170 mg/L of dichloroethylene (DCE). The water table at the site is about 5 ft below ground surface. Ground-water flow is in the range of 0.1-0.5 ft/day and changes with depth.

Technology Application

A major objective of the demonstration was to compare the two emplacement methods. Both wall systems included a 50-ft main wall followed by 10-ft wall placed 4 ft downgradient from it and a third 10-ft wall placed 4 ft downgradient of the second. This provided a total target length of 70 linear ft for each technique. In the first installation, a hollow mandrel, or vibrated beam, created a void that is 4 in thick, about 45 ft deep, and 32 in long for each panel of the wall. A vibratory hammer drove the beam to the required depth. The void was filled with the reactive material through a chute at the top of the mandrel. About 98 tons of 100% zero-valent iron (Fe^0) was used to construct the wall, and adjacent panels were overlapped to provide continuity in the wall. In the second installation, high-pressure water jets, guided by a 36-in I-beam, were used in addition to the water to create the void for each wall panel. A vibratory hammer was used to drive the beam to depth. The void was filled with a slurry made by mixing Fe^0 with guar gum and a binder. About 107 tons of Fe^0 was used for this emplacement. As in the first installation, adjacent wall panels were overlapped to provide continuity.

Cost

Total installation cost for the two barriers at this site was $809,000. This includes design, construction, materials, and the reactive media. The design cost for both walls totaled $292,000. Mobilization and demobilization, construction, materials, and the reactive material for the mandrel system was $279,000. Mobilization and demobilization, construction, materials, and the reactive material for the jet-assisted grout system was $238,000.

Results

Results of the demonstration are unknown at this time. Dedicated *in situ* flow sensors and ground-water monitoring wells were installed after construction of the walls to track performance.

Quarterly monitoring is scheduled to continue until November 1998, and a report of demonstration results is expected to be issued in 1999.

Industrial Site, NY

Installation Date:
May 1995

Contaminants:
TCE, cDCE, VC

Reactive Media:
Fe^0

Installation Cost:
$250,000

Construction:
Funnel and Gate

Point of Contact:
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Stearns & Wheler
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A pilot-scale, *in situ* funnel-and-gate system using metal-enhanced reductive dehalogenation was installed at an industrial facility in New York in May 1995 and operated for 2.5 years.

Site Background

A 370-ft-wide plume of trichloroethylene (TCE) with concentrations of 300 μg/L existed at this former plating facility. As a result of reductive dehalogenation of TCE, 100-500 μg/L of cis-1,2-dichloroethylene (cDCE) and 80 μg/L of vinyl chloride (VC) also were present. These contaminants were present in a 15-ft shallow sand and gravel aquifer that overlays a dense clay confining layer about 20 ft below ground surface (bgs). The water table was located approximately 4-5 ft bgs. Hydraulic conductivity of materials in this area was approximately 1.6 in/sec.

Technology Application

The reactive section (gate) of the system contained zero-valent iron (Fe^0). It was 12 ft long, 3.5 ft thick, and extended from 3-18 ft below grade. The gate was flanked by 15-ft sections of sealable joint sheet piling extending laterally on either side to form the funnel. Monitoring wells were installed upgradient, within, and downgradient from the reactive zone.

Cost

Installation costs for the system were approximately $250,000. This includes the cost of design, construction, materials, and 45 tons of reactive material, which cost $30,000 (or about $0.12/gal treated).

Results

Data on volatile organic compounds (VOCs) indicated that chlorinated VOC concentrations were reduced to Maximum Contaminant Levels (MCLs), or approximately 5 μg/L for TCE and cDCE and 2 μg/L for VC, within 1.5 ft of travel through the reactive zone. Consistent performance was maintained over the 2.5-year monitoring period. Based on water-level data, the ground-water flow velocity through the zone was about 1 ft/day, and a 24-ft wide portion of the plume was captured and treated. Microbial analyses on ground-water samples indicated no significant increase in microbial populations in the Fe^0 relative to the population present in the aquifer.

Approximately 2,098,800 gal of ground water were treated during operation of the pilot-scale system.

The PRB system was destroyed following completion of the pilot-scale demonstration to make way for a full-scale installation in 1997.

LEAP Permeable Barrier Demonstration Facility, Portland, OR

Installation Date:
October 1997

Contaminants:
Cr^{+6}, PCE

Reactive Media:
SMZ

Design Cost:
$75,000

Installation Cost:
$25,000

Construction:
Hanging Barrier in Perforated Metal Frame

Point of Contact:
Robert Bowman
Dept. of Earth & Environmental Science
New Mexico Tech
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Socorro, NM 87801
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A pilot-scale demonstration was conducted at the Large Experimental Aquifer Program (LEAP) site at the Oregon Graduate Institute of Science and Technology near Portland, OR.

Site Background

The main purpose of the demonstration was to quantify the ability of a surfactant-modified zeolite (SMZ) permeable reactive barrier (PRB) to intercept and retard the migration of a mixed plume containing 22 mg/L of chromate (Cr^{+6}) and 2 mg/L of perchloroethylene (PCE). The goal was to test laboratory-based predictions of behavior of the SMZ, using Cr^{+6} and PCE as "type" contaminants (anionic metal and chlorinated hydrocarbon). The pilot-test was conducted in a contained, simulated aquifer. The aquifer was filled with sand and had a hydraulic conductivity of 56.7 ft/day.

Technology Application

The barrier of SMZ was hung in the center of the simulated aquifer about 3 ft above the base in order to simulate emplacement in front of an advancing plume in a shallow, unconfined aquifer. The barrier had three modules, each about 6.5 ft long. Overall, the barrier was about 20 ft long, 3 ft thick, and 6.5 ft deep, and used 12 tons of the reactive medium. Since this was a pilot-scale test under controlled conditions, the reactive medium was contained in a frame to facilitate removal and replacement with other test media in the future.

Cost

Total design cost for the barrier system was about $75,000. Total installation cost was about $25,000. This includes the cost of construction, materials, and the reactive material.

Results

The contaminant plume was injected into the simulated aquifer for 2 months, and performance was monitored. Samples were collected approximately weekly from a network of 63 sample nests (315 sample points) in the aquifer and 18 sample nests (90 sample points) within the barrier. Analysis of preliminary data indicates that the barrier performed according to design specifications, with retardation factors for Cr^{+6} and PCE both on the order of 50. Final interpretation of data from the sampling and chemical analyses is

in progress. Pending the results of this of the pilot-scale effort, a full-scale implementation is anticipated.

Lessons Learned

Barrier performance is very sensitive to the interface between aquifer material and reactive barrier materials. Sufficient permeability contrast must be established and maintained to avoid plume deflection. The causes for poor permeability contrast, whether due to inherent media property differences or barrier installation, can be difficult to isolate. Long-term compaction of the material with resultant loss in hydraulic conductivity needs further evaluation. Low-conductivity zones in an earlier phase of the project were difficult to detect and locate.

Massachusetts Military Reservation CS-10 Plume, Falmouth, MA

Installation Date:
June 1998

Contaminants:
PCE, TCE

Reactive Media:
Fe^0

Installation Cost:
$160,000

Construction:
Hydraulic Fracturing

Point of Contact:
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Installation of a permeable reactive barrier (PRB) system to remediate ground water contaminated with chlorinated solvents was completed by University of Waterloo researchers at the Massachusetts Military Reservation (MMR) near Falmouth, MA, in 1998.

Site Background

The uniqueness of the project was the great depth of the site—the Chemical Spill 10 (CS-10) plume extends to about 120 ft below ground surface (bgs) near its source area. The demonstration program was pilot-scale in width, but full-scale in depth. The primary contaminants of concern at this site are perchloroethylene (PCE) and trichloroethylene (TCE), for which initial maximum concentrations of 300 μg/L and 15 μg/L, respectively, were identified. A 600 ft-wide contamination plume resulting from the maintenance of BOMARC missiles and related equipment during the 1960s exists in the area of MMR's Buildings 4642 and 4601, now known as the UTES site. The CS-10 demonstration site is located in an area of glacial outwash sand and gravel, where the water table is located approximately 80 ft bgs. Ground-water flow velocity in the area is approximately 1 ft/day, and the horizontal hydraulic conductivity is approximately 200 ft/day. Maximum contaminant concentrations were identified at about 100 ft bgs.

Technology Application

Two iron walls approximately 20 ft apart were installed perpendicular to the contaminant plume using vertical hydrofracturing with a guar-based slurry. In the preliminary design for this project, installation methods were selected for their ability to emplace granular iron to the required depth. This installation technique required the drilling of 1-ft-diameter boreholes at 15-ft intervals along the wall. The "frac wells" were installed from ground surface to below the base of the contamination zone, and a specially-designed frac tool was used to cut a vertical notch for initiation of the fracture. A fracture was then induced and filled with granular iron suspended in a hydrated and cross-linked guar slurry. The propagating fracture from one frac well coalesced with the emplaced material from the adjacent well, thus forming a continuous vertical wall. The upgradient wall contains 44 tons of fine- to medium-granular iron (Fe^0) (Master Builders GX-027), averages 3.3 inches in thickness and 48 ft in width, and extends from approximately 78 ft to more than 120 ft in depth.

A second wall, of similar dimensions, but consisting of a mixture of 5 tons of sand and 5 tons of granular iron, was emplaced to demonstrate the possible use of sand as a filler and permeability-increasing amendment for more highly reactive enhanced-iron materials. The upgradient, 100%-iron wall was verified by active resistivity and borehole radar tomography, hydraulic pulse interference testing, and borehole deviation measurements. More than 30 monitoring wells have been installed to monitor performance of the demonstration project.

Installation cost for this demonstration is estimated to be $160,000. This includes design, construction, materials, and the reactive media.

Results

Although cleanup goals were not specified for this demonstration, cleanup to levels below maximum contaminant levels (MCLs) served as the target. Sampling of the ground water upgradient and downgradient of the PRB system is conducted every 2-3 months. Results of the demonstration will be available upon its completion in mid-2000.

Lessons Learned

It was recognized early in the demonstration process that, depending upon the initial contaminant concentrations and flow velocity, this type of PRB system may require multiple walls to achieve a sufficient thickness. For the MMR CS-10 source area plume, three 3-in thick commercial Fe^0 walls were expected to be needed for full treatment with an adequate factor of safety.

The 100% iron wall was installed successfully. During the installation of the second wall, however, fracturing control was lost when the propagating fracture came close to two screened monitoring wells deviating as much as 7 ft horizontally over their 150-ft length. Use of the system to remediate deep plumes such as this requires that the proximity (3-dimensional coordinates) of screened monitoring wells to the wall installation be carefully planned and checked with borehole deviation testing. As a result of an unanticipated delayed break of the cross-linked guar during construction of the system, more time was required for reestablishment of ground water flow through the wall. Accordingly, it was determined that an improved guar-iron mix design was needed to establish flow through reactive zones soon after installation of the walls.

Moffett Federal Airfield, Mountain View, CA

Installation Date:
April 1996

Contaminants:
TCE, 1,2-DCE, PCE

Reactive Media:
Fe^0

Design Cost:
$100,000

Installation Cost:
$365,000

Construction:
Funnel and Gate

Point of Contact:
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Naval Facilities
Engineering
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A pilot-scale permeable reactive barrier (PRB) was constructed in April 1996 at the former NAS Moffett Field in Mountain View, CA, by the U.S. Navy Engineering Field Activity-West.

Site Background

Previous investigations identified extensive ground-water contamination on the site from dissolved chlorinated hydrocarbons—trichloroethylene (TCE), dichloroethylene (1,2-DCE), and perchloroethylene (PCE)—much of which originated offsite. Initial concentrations were 2,990 μg/L (TCE), 280 μg/L (1,2-DCE), and 26 μg/L (PCE) upgradient of the iron gate. The overall Moffett Field solvent plume is more than 10,000 ft long and about 5,000 ft wide.

Subsurface sediments at the Moffett Field PRB site are a mixture of alluvial-fluvial clay, silt, sand, and gravel. Sands and gravels are present as lens-shaped, interbraided channel deposits that are presumed to have incised into the clay and silt layers. Contamination is present in two aquifer zones that extend from 5-60 ft below ground surface (bgs). These aquifer zones are separated by a discontinuous, semiconfining clay layer (aquitard) at approximately 25 ft bgs, ranging from 1-15 ft in thickness. Average linear flow velocities from onsite pumping tests were calculated to be about 1-4 ft/day. Hydraulic conductivity values for the separating aquitard layer range from 10^{-5}-10^{-3} ft/min. Soil porosity values in the silts and sands ranged from 30-45%.

Technology Application

A funnel-and-gate system was installed in the upper aquifer zone to just above the aquitard using a trenching method. The system includes a reactive iron gate that is 10 ft wide by 6 ft long and contains about 75 tons of granular zero-valent iron (Fe^0). The iron cell is bounded by 2-ft sections of pea gravel at upgradient and downgradient locations. Two 20-ft-long steel sheet pile funnels or wing walls are positioned on either side of the reactive iron gate.

Costs

The costs of planning and design of the system was $100,000. Installation cost, including construction, materials, and the reactive material, was approximately $365,000. Bench-scale testing required another $75,000.

Results

The U.S. Department of Defense Environmental Security Technology Certification Program (ESTCP) has sponsored the demonstration project at Moffett Field for the past three years. The Naval Facilities Engineering Service Center has collected performance monitoring and cost data to validate the PRB technology for potential use at DoD sites worldwide. Water quality sampling from 1996 (June and September) and 1997 (January, April, July, and October) from about 70 monitoring wells in or near the reactive barrier consistently have indicated significant degradation of chlorinated compounds. All principal contaminant concentrations had been reduced to below Maximum Contaminant Levels (MCLs) or non-detectable levels within the first 2-3 ft of the gate (iron cell). Bromide tracer testing at the PRB site revealed that flow velocities through the cell are about 0.5-2 ft/day. The final PRB technology evaluation report for the Moffett Field pilot demonstration project was published in November 1998. A summary version was published in December 1998.

Lessons Learned

Coring results have suggested that conditions exist for potential long-term formation of chemical precipitates in the iron cell. This may lead to an eventual reduction in the longevity and efficiency (permeability and reactivity) of the reactive barrier. The DoD ESTCP, U.S. Environmental Protection Agency (EPA), and U.S. Department of Energy (DOE), in partnership with the RTDF Permeable Reactive Barriers Action Team, are sponsoring additional performance and longevity evaluations to support widespread regulatory acceptance and encourage use of PRB technology. As part of these efforts to further investigate the potential concerns for biological fouling and chemical precipitation, annual water-quality sampling and iron-cell coring are planned at several PRB sites across the country, including Moffett Field, over the next three years.

Savannah River Site TNX Area, Aiken, SC

Installation Date:
July 1997

Contaminants:
TCE, cDCE, CT, NO_3

Reactive Media:
Fe^0

Installation Cost:
$120,000

Construction:
GeoSiphon Cell

Point of Contact
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Westinghouse SRC/SRS
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The GeoSiphon Cell (patent pending) was installed in the TNX flood plain at the Savannah River Site (SRS) by auger and caisson methods in July 1997. The cell was installed to demonstrate treatment of ground water contaminated with chlorinated volatile organic compounds (CVOCs).

Site Background

Ground-water contamination has been detected in the TNX water table aquifer, but not in the semi-confined or deep aquifers underlying the site. Predominant contaminants, and average concentrations of each, detected in the TNX flood plain are trichloroethylene (TCE) at 200-250 μg/L, cis-1,2-dichloroethylene (cDCE) at 20-50 μg/L, carbon tetrachloride (CT) at 15-45 μg/L, and nitrate (NO_3) at 10-70 mg/L.

The TNX Area is a semi-works facility for the Savannah River Technology Center, which is located 0.25 mile from the Savannah River near Aiken, SC. The facility was used for pilot-scale testing and evaluation of various chemical processes associated with SRS. The water table elevation averages 100 ft above mean sea level under the TNX site, while the Savannah River elevation averages 85 ft. In the flood plain where contamination was detected, the water table aquifer is approximately 35-40 ft thick. It consists of interbedded sand, silty sand, and relatively thin clay layers. Based on testing and modeling analysis, the aquifer may be characterized as having a horizontal hydraulic conductivity of 65 ft/day, vertical hydraulic conductivity of 30 ft/day, effective porosity of 0.15, pore velocity of 3 ft/day, and a horizontal gradient of 0.007.

Technology Application

The TNX GeoSiphon Cell is a large-diameter (8-ft) well containing granular zero-valent iron (Fe^0) as a treatment media (in place of gravel pack). The cell passively induces flow by use of a siphon from the cell to the Savannah River. The flow is induced by the natural hydraulic head difference between the cell and the river. The passively-induced flow draws contaminated ground water through the treatment cell, where the Fe^0 reduces the CVOCs to ethane, ethene, methane, and chloride ions. Treated water is discharged to the Savannah River.

During Phase I testing of this technology, which was completed in December 1997, flow through the TNX GeoSiphon Cell was

induced by pumping and the treated water was discharged to the existing TNX National Pollutant Discharge Elimination System outfall. Testing indicated that TCE degradation is the limiting compound to treatment below the Primary Drinking Water Standard Maximum Contaminant Levels within the TNX GeoSiphon Cell. Data indicated that approximately 8 gal/hr of ground water contaminated with 200-250 μg/L of TCE could be treated, while maintaining the average discharge TCE concentration below 5 μg/L. Field first-order rate constants produced from the steady state TCE data increased with flow rate from 0.347 to 0.917/hr.

During Phase II, flow through the TNX GeoSiphon Cell was induced by siphon and the treated water was discharged to an existing outfall ditch that flows into the Savannah River. To allow continuous operation, the siphon line configuration was optimized to include an upward rise from the cell to the outfall ditch, an air chamber at the crest adjacent to the outfall ditch, and a steep drop into the outfall ditch with line termination in a sump. The head differential available to drive the system (approximately 1.4 ft) produced a continuous flow rate of 2.5-2.7 gal/min. Approximately 1.2 ft of head was utilized to drive flow through the cell itself, and approximately 0.2 ft of head was utilized to drive flow through the siphon line. Based on these results, a new siphon line will be installed between the cell and a target location, thus producing a 5-ft head differential capable of inducing an estimated 9.5 gal/min through the GeoSiphon Cell.

Phase III of this demonstration project will involve installation and operation of a full-scale GeoSiphon Cell system for treatment of the entire TNX contaminated ground-water plume.

Cost

Phase I system costs are estimated at $119,155, including $26,400 for iron; $27,411 for other construction materials; and $65,344 for mobilization, labor, rentals, and related installation expenses. Approximately 49.7 tons of 0.25-2.0 mm (particle size) granular cast iron was used in the installation of the first TNX GeoSiphon Cell (TGSC-1).

Lessons Learned

The GeoSiphon Cell was selected for use at the TNX Area because it offers passive (no power requirements), *in situ* treatment at lower operating and maintenance costs than pump-and-treat technology. In contrast to funnel-and-gate or continuous permeable wall

technologies, the GeoSiphon Cell could be constructed using an existing foundation and well drilling techniques. In addition, there is potential for accelerating cleanup through the use of induced flow rates greater than natural flow. With a maximum siphon lift of 25 ft, application of the GeoSiphon Cell technology was found to be limited to areas of shallow ground water such as that existing at the TNX Area.

SGL Printed Circuits, Wayne, NJ

Installation Date:
November 1994

Contaminants:
TCE, PCE, cDCE

Reactive Media:
Fe

Installation Cost:
$48,000

Construction:
Reaction Vessel

Point of Contact:
John Vogan
EnviroMetal
Technologies, Inc.
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N1K 1S6 Canada
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Demonstration of a metal-enhanced dechlorination process for destroying chlorinated volatile organic compounds (CVOCs) in aqueous media took place from November 1994 to February 1995. The process was demonstrated under EPA's SITE Program at the SGL Printed Circuits site in Wayne, Passaic County, New Jersey, using a pilot-scale, above-ground treatment reactor containing a reactive iron medium.

Site Background

Influent ground water was contaminated with trichloroethylene (TCE) at concentrations ranging from 54-590 μg/L, perchloroethylene (PCE) at concentrations ranging from 4,100-13,000 μg/L, and cis-1,2-dichloroethylene (cDCE) at concentrations ranging from 35-1,600 μg/L.

Technology Application

In this technology, ground water pumped from extraction wells and the sump passes through a check valve, a 5-micron water filter, a flow meter, and an air eliminator before entering the treatment reactor. The water filter removes suspended solids from influent water, eliminating the need for a layer of well sand or pea gravel above the reactive iron medium.

After entering the treatment reactor, water flows by gravity through the reactive medium. At the SGL site, an 8-ft-diameter fiberglass reactor containing a 5.5-ft-thick layer of the reactive medium was employed. Approximately 20 tons of granular iron were used in the reactor. The porosity of the iron medium, after placement and settling in the reactor, was estimated to be about 0.4. The iron rested on a 6-in layer of coarse silica sand, referred to as "well sand," which acted as a strainer and prevented the granular iron from washing out into the effluent line. The reactor drained through a collector line located in the well sand at the bottom of the reactor, and the collector line directed the treated water to the effluent line. Treated effluent was returned to the shallow, unconsolidated aquifer through several monitoring wells modified to serve as reinjection wells. The process provided a reactor contact time of about 1 day.

Cost

Costs for this metal-enhanced dechlorination process were estimated to be about $91 per 1,000 gal treated. Capital costs for

installing an above-ground treatment reactor such as this were about $48,000, including equipment and construction but excluding hydrogeologic characterization, bench-scale studies, permitting, and installation of ground water extraction/reinjection systems. Minimum annual operation and maintenance costs were approximately $10,000.

Results

Results indicated that the process achieved the demonstration effluent target level of 1 μg/L for TCE and PCE, and that PCE removal efficiencies consistently were greater than 99.9%. Sedimentation on the reactive iron surface, variations in reactor temperature, and other factors potentially affected the technology's performance. Approximately 61,000 gal of ground water containing PCE, TCE, and cDCE were treated during the demonstration.

Somersworth Sanitary Landfill, NH

Installation Date:
1994

Contaminants:
TCE, VC

Reactive Media:
Fe^0

Installation Cost:
To be determined

Construction:
Funnel and Gate

Point of Contact:
Roger Duwart
U.S. Environmental Protection Agency
Region 1
John F. Kennedy Federal Building
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Site Background

The Somersworth Sanitary Landfill Superfund 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.

In 1981, the City of Somersworth implemented a closure plan for the landfill that involved the covering of a portion of the landfill with clean fill. Volatile organic compounds (VOCs), principally trichloroethylene (TCE) and vinyl chloride (VC), are present in the ground water. TCE and VC levels have been detected as high as 370 μg/L and 1,900 μg/L, respectively.

The site is characterized by sands and gravels having a hydraulic conductivity ranging from 28-14 ft/day. The hydraulic gradient varies from 0.01-0.004 ft/ft near the edge of the waste. The top of the water table ranges from less than 2 ft to about 20 ft below ground surface. As much as 10% of the waste is in the ground water. The aquifer is about 40 ft thick.

Technology Application

The clean-up plan selected by EPA uses zero-valent iron (Fe^0) to treat the ground water through reductive dechlorination. Since the technology has not been implemented at this scale or in a landfill setting, a pilot-scale wall was installed in 1994 and is currently under evaluation. The pilot-scale PRB system consists of an 8-ft-diameter "gate" of iron between layers of gravel. Slurry walls measuring 4.5 ft funnel ground water through the gate.

Results for the pilot-scale wall currently under evaluation include:

- VOCs have been reduced 50% between upgradient aquifer and wall, providing a strong case for biodegradation that occurs via sequential anaerobic and aerobic processes.
- VOCs have been reduced to non-detectable levels at the first monitoring point in the wall.
- Ground water velocity has been slower than the design rate due to reduced hydraulic conductivity (possibly due to soil densification).

- Reduction in bicarbonate, Ca, Mg, Fe, Mn, and sulfate has been shown within the first 14 inches of iron zone.
- Within the iron zone, ground water became strongly reducing (reduced DO, ORP) and alkaline (pH 10).

The objective of the pilot-scale study has been to provide data to enable design of a full-scale system to be completed by February 1999. Of particular interest is whether unacceptable precipitation and/or biofouling is occurring within or on the iron media.

The cleanup goals of the full-scale project will be:

Contaminants	Interim Cleanup Level (µg/L)
Benzene*	5
1,1-Dichloroethylene	7
Methylene chloride*	5
Tetrachloroethylene	5
Trichloroethylene	5
Vinyl chloride	2
cis-1,2-Dichloroethylene	70
trans-1,2-Dichloroethylene	100

(* These contaminants are not affected by the permeable reactive barrier.)

Lessons Learned

During the installation of the pilot-scale wall, contractors attempted to drive an 8-ft diameter, 48-ft-long steel caisson into the aquifer with a vibratory hammer. Due to unexpected cobbles which presumably caused the bottom of the caisson to flare, the caisson became stuck. In order to remove it (to allow for the placement of pea gravel and iron filings) the lower 13 ft of the caisson were cut off and plugged. This allowed the remainder of the caisson to be removed as the gravel and iron were placed.

The pilot-scale PRB was installed very close to a wetland on the downgradient side of the landfill. As a result of a nearly snowless winter, little precipitation infiltrated the landfill; it went into the wetland instead. This caused a reverse flow (the wetland ground-water level being somewhat higher than the landfill ground-water level near the pilot) through the PRB, which made assessment of its effectiveness difficult. The flow reversal, however, should not negatively affect long-term performance.

When a "normal" flow regime was established, less flow than expected went through the PRB. A "skin effect," due probably to the installation technique, was theorized as the cause. Alternate

installation techniques are being investigated to avoid the skin effect and installation problems. A continuous trench of reactive material should allow for flow through the PRB which more closely emulates flow through the aquifer.

U.S. Naval Air Station, Alameda, CA

Installation Date:
December 1996

Contaminants:
cDCE, VC, TCE, BTEX

Reactive Media:
Fe^0, O

Installation Cost:
$400,000

Construction:
Funnel and Sequenced Treatment Gate

Point of Contact:
Michaye McMaster
Beak International Inc.
42 Arrow Rd.
Guelph, Ontario
N1K 1S6 Canada
Tel: 519-763-2325
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E-mail:
mmcmaster@beak.com

The second part of a pilot-scale demonstration of an *in situ* sequenced permeable reactive barrier (SPRB) for the remediation of chlorinated solvents and petroleum hydrocarbons was conducted at Alameda Point (formerly U.S. Naval Air Station Alameda) in Alameda, California.

Site Background

The initial phase of this demonstration, which had been conducted at Canadian Forces Base Borden, Ontario, Canada, evaluated three technologies for their ability to treat perchloroethylene (PCE), carbon tetrachloride (CCl_4) and toluene. The technologies were: (1) abiotic reductive dechlorination using zero-valent iron (Fe^0), followed by oxygen releasing compound (ORC™) to promote aerobic biodegradation; (2) natural attenuation; and (3) a permeable nutrient injection wall, using benzoate to promote anaerobic biodegradation, followed by an aerobic (oxygen) biosparge gate for aerobic biodegradation.

The Alameda demonstration used Fe^0 followed by oxygen biosparging in a funnel-and-gate system to remediate trichloroethylene (TCE); cis-1,2-dichloroethylene (cDCE); vinyl chloride (VC); and toluene, benzene, ethyl benzene, and xylene (BTEX). Total initial (upgradient) concentrations of chlorinated VOCs exceeded 100 mg/L, and toluene was found at levels of up to 10 mg/L.

Historical air photos of the site indicate open disposal pits upgradient of the SPRB. The shallow aquifer is composed of 22-24 ft of sandy artificial fill material that was hydraulically placed on bay silts and clays. The hydraulic conductivity of the overlying sandy fill material is 0.057 ft/day (~21 ft/year). The underlying bay silts and clays are 15-20 ft thick and act as a confining unit. Depth to ground water ranges from 4 to 7 ft below ground surface.

Technology Application

During construction of the funnel-and-gate system, the artificial fill sand was excavated to the top of the confining bay mud unit. To prevent settling, a concrete pad (nominally 2 ft thick) was placed at the bottom of the excavation; the gate was then constructed on this base. The gate is 10 ft wide and 15 ft long. As ground water passes through the gate it contacts the following media: about 18 in of coarse sand mixed with 5% Fe^0, 5 ft of Fe^0, a 3-ft pea gravel

transition zone, a 3-ft biosparge zone, and a 2-ft pea gravel zone. The 10-ft funnels were placed on either side of the gate, perpendicular to the direction of water flow.

Between February 1997 and May 1998, two pumping wells were used to operate the system under controlled conditions. For a period of about 70 days, the system operated at a flux rate of approximately 45 ft^3/day to determine the maximum velocity it could process. At this velocity, breakthrough was observed in several down-gradient monitoring points. Then, the system operated for about one year at a flux rate of approximately 12 ft^3/day, more representative of conditions that would exist as a result of the funnel sections. Finally, the system was allowed to operate under natural gradient conditions.

Results

The remedial objectives of the project generally were met, except with respect to cDCE and VC, with typical effluent concentrations of about 136 μg/L and 217 μg/L respectively. Retardation of the toluene or other hydrocarbons as a result of sorption to the granular iron precluded an assessment of petroleum hydrocarbon degradation. Breakthrough of cDCE and VC indicated that biodegradation (likely via aerobic oxidation) of these compounds was occurring in the biosparge zone. An estimated 66% of the VC and 30% of the cDCE was volatilized. Assessment of multilevel data showed excellent degradation (>91%) of the chlorinated organics using the granular iron at high influent concentrations (>100 mg/L total VOCs). At lower influent concentrations, almost complete degradation (>99%) was observed. The biosparge zone supported aerobic biodegradation of VC and cDCE, and by January 1998 remedial objectives were being met at the last set of sampling wells in the gate.

Results obtained to date suggest sparging rates in the biosparge zone should be minimized to reduce volatilization of contaminants from the water column. In addition, monitoring should continue so that long-term performance of the SPRB can be assessed.

The U.S. Navy has begun to operate the site; current plans call for a hydraulic study to examine ground-water flow in the funnel-and-gate area and for monitoring to continue on a quarterly basis.

Watervliet Arsenal, Watervliet, NY

Installation Date:
October 1998

Contaminants:
PCE, TCE, cDCE, trans-DCE, VC

Reactive Media:
Concrete, sand, and iron

Design Cost:
$113,000

Installation Cost:
$257,000

Construction:
Excavate and Fill

Point of Contact:
Russell Marsh
U.S. Army Corps of Engineers, Baltimore District
P.O. Box 1715
Baltimore, MD 21203
Tel: 410-962-2227
Fax: 404-962-2318
E-mail: russell.e.marsh@usace.army.mil

A permeable reactive barrier (PRB) pilot system was installed at the Watervliet Arsenal near Albany, NY, in October 1998 to remediate ground water contaminated with chlorinated volatile organic compounds (CVOCs).

Site Background

The contaminated area, known as the Siberia Area, has been used for the interim storage of raw and hazardous materials involved in cannon manufacturing. Contaminants and the initial concentrations found in the area were: perchloroethylene (PCE), 1,100 μg/L; trichloroethylene (TCE), 1,500 μg/L; cis-dichloroethylene (cDCE), 4,200 μg/L, trans-dichloroethylene (trans-DCE), 11 μg/L; and vinyl chloride (VC), 1,700 μg/L. Two unconsolidated deposits are encountered in the area. The upper deposit is a fill material approximately 2-4 ft thick, and the second is a clayey-silt typically 12-15 ft below grade and extending to the weathered bedrock. Hydraulic conductivities in the fill material range from 0.4-2.0 ft/day, and from 0.2-1.4 ft/day in the clayey silt. A relatively conservative ground-water velocity of 0.15 ft/day was used in the design of the reactive wall. The water table is generally 3-5 ft below grade.

Technology Application

The PRB system at Watervliet Arsenal consists of two separate walls. The upgradient wall, which is 205 ft long, is positioned to capture the majority of the plume source area. The downgradient wall, which is 83 ft long, was installed to capture a portion of the plume that is downgradient of the longer wall and to serve as a polishing wall for the upgradient wall. An excavator with temporary sheeting and concrete mixing equipment were used to construct the walls, which contain 163 tons of sand and 165.5 tons of iron. Excavation was required to remove large debris such as concrete, rebar, and wood at the site. Use of a nearby concrete plant and truck provided the ability to obtain a relatively consistent mixture of sand and iron.

Design costs for the Watervliet Arsenal PRB system were $113,000, and installation costs (including construction, materials, and reactive material) are estimated at $257,000. An additional $17,000 was incurred for licensing fees.

Results

Cleanup goals for the contaminants of concern are: PCE, 5 μg/L; TCE, 5 μg/L; cis-DCE, 5 μg/L; trans-DCE, 5 μg/L; and vinyl chloride, 2 μg/L. Monthly ground water sampling will be performed for six months to monitor remediation progress; semi-annual sampling will follow. Based on the analytical results of ground water tests, it is anticipated that concentrations will reach the target cleanup goals.

Lessons Learned

Use of this type of PRB system required a thorough understanding of geohydrologic conditions at the site. It was found that the color of the sand used in the wall can affect quality-control efforts. Sand used at the Watervliet Arsenal met the technical requirements such as gradation and density, but its dark color was similar to that of iron. As a result, visual differentiation of the material was more difficult than if a light color of sand had been used.

X-625 Groundwater Treatment Facility, Portsmouth Gaseous Diffusion Plant, Piketon, OH

Installation Date:
March 1996

Contaminants:
TCE

Reactive Media:
Fe^0

Installation Cost:
$4,000,000

Construction:
Horizontal Well

Point of Contact:
Thomas C. Houk
Portsmouth Gaseous Diffusion Plant
3930 US Route 23S
Piketon, OH 45661
Tel: 614-897-6502
Fax: 614-897-3800
E-mail: uk9@ornl.gov

A pilot-scale field test of reactive media (zero valent iron) for degrading trichloroethylene (TCE) in ground water is currently in place at the X-625 Groundwater Treatment Facility at the U.S. Department of Energy's (DOE) Portsmouth Gaseous Diffusion Plant in Piketon, Ohio.

Site Background

Influent concentrations of TCE for the treatment facility range from 70 to 150 μg/L. Contamination resulted from past waste disposal practices at the plant.

The uppermost layer underlying the site is composed of approximately 30 ft of silt. The contaminated aquifer resides below this layer within a 2 to 10-ft layer of silty gravel and has a hydraulic conductivity of approximately 20 ft/day. Bedrock is 32-40 ft below ground surface (bgs).

Technology Application

The X-625 facility consists of a 500-ft horizontal well that collects TCE-contaminated ground water from within the silty-gravel aquifer underlying the treatment area at a depth of 30 ft. This ground water is fed into a building constructed at an elevation that is 3-5 ft below bedrock. The ground water then is distributed through a series of canisters filled with zero-valent iron (Fe^0). The flow rate into the facility has been less than 1 gallon per minute (gpm). The facility is currently being converted to accommodate a higher ground-water flow rate (5 gpm). After conversion, treatment will be through Fe^0 in the form of foamed pellets. Electrochemical enhancement by passing a current through the iron media also is being considered.

Results

Testing of Fe^0 filings was conducted from March 1996 through March 1998. Results indicated a reduction of TCE concentrations to less than 5 μg/L after passage through the treatment system. Reductions in the hydraulic conductivity of the iron media due to mineral precipitation (e.g., iron oxides and iron sulfides) were observed. The life of the reactive media will be dependent on high Fe^0 corrosion rates influenced by the high sulfate levels in the ground water.

Future sampling plans will be developed during conversion to the higher flow rate, which is expected to be completed by October 1998.

Metals and Inorganics

Nickel Rim Mine Site, Sudbury, Ontario, Canada

Installation Date:
August 1995

Contaminants:
Ni, Fe, Sulfate

Reactive Media:
Organic Carbon

Installation Cost:
$30,000

Construction:
Cut and Fill

Point of Contact:
David W. Blowes
Waterloo Centre for
Groundwater Research
University of Waterloo
Waterloo, Ontario,
Canada
Tel: 519-888-4878
Fax: 519-746-5644

A full-scale continuous permeable reactive barrier (PRB) was installed in August 1995 downgradient from an inactive mine tailings impoundment at the Nickel Rim Mine site in Sudbury, Ontario, Canada.

Site Background

Nickel Rim was an active mine from 1953 to 1958. Primary metals extracted were copper (Cu) and nickel (Ni). Tailings have been undergoing oxidation for approximately 40 years. The ground-water plume emanating from the tailings is discharging to a nearby lake. The primary contaminants on site are Ni, iron (Fe), and sulfate. Initial concentrations were 2400-3800 mg/L sulfate, 740-1000 mg/L Fe, and up to 10 mg/L Ni.

The contaminated aquifer is 10-26 ft thick and composed of glacio-fluvial sand. The aquifer is confined to a narrow valley, bounded on both sides and below by bedrock. Ground-water velocity within the aquifer is estimated to be 49 ft/yr.

Technology Application

The PRB was installed across the valley using a cut-and-fill technique. The barrier spans the valley and is 50 ft long, 14 ft deep, and 12 ft wide. It is composed of a reactive mixture containing municipal compost, leaf compost, and wood chips. Pea gravel was added to the mixture to increase hydraulic conductivity. Coarse sand buffer zones were installed on both the upgradient and downgradient sides of the reactive material. A 12-in clay cap was placed on top of the PRB to minimize entry of surface water and oxygen into the PRB. Remediation at the Nickel Rim Mine Site was accomplished by sulfate reduction and metal sulfide precipitation resulting from the presence of the organic material.

Cost

The installation cost was approximately $30,000. This includes design, construction, materials, and the reactive mixture.

Results

Monitoring wells were installed along a transect parallel to ground-water flow. Samples were collected one month after installation and again nine months after installation. Passing through the PRB resulted in a decrease in sulfate concentrations to 110-1,900 mg/L. Iron concentrations decreased to <1-91 mg/L.

Dissolved Ni decreased to <0.1 mg/L within and downgradient of the PRB. In addition, pH increased from 5.8 to 7.0 across the barrier. As a whole, the PRB converted the aquifer from acid-producing to acid-consuming. Monitoring is planned to continue for a minimum of three years with sampling occurring biannually.

Tonolli Superfund Site, Nesquehoning, PA

Installation Date:
August 1998

Contaminants:
Pb, Cd, As, Zn, Cu

Reactive Media:
Limestone

Installation Cost:
To be determined

Construction:
Continuous Trench

Point of Contact:
Steven J. Donohue
U.S. Environmental Protection Agency, Region 3
Hazardous Site Control Division, 3HS22
1650 Arch Street
Philadelphia, PA 19103-2029
Tel: 215-814-3215
Fax: 215-814-3002
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Construction of a full-scale permeable reactive barrier (PRB) was completed in August 1998 at the Tonolli Superfund Site near Nesquehoning, PA.

Site Background

The PRB is being used to remediate ground water contaminated with heavy metals, including lead (Pb), cadmium (Cd), arsenic (As), zinc (Zn), and copper (Cu). Maximum concentrations of these contaminants encountered were 328 μg/L of Pb, 77 μg/L of Cd, 313 μg/L of As, 1,130 μg/L of Zn, and 140 μg/L of Cu.

The Tonolli Corporation operated a battery recycling and secondary lead smelting plant at the site from 1974 until 1986, and currently is responsible for cleanup activities. The presence of elevated dissolved metals in the ground water is attributed to both waste sources and anthropogenic sources from the dumping of battery acid during past site operations, and the acid mine drainage effect of the mine spoils.

Remedial investigations indicated that contamination is confined to the underlying overburden aquifer located in coal mine spoil at 0-19 ft below ground surface, and alluvium at 74-113 ft. Ground water in the area flows horizontally southeast toward Nesquehoning Creek. Vertical ground-water flow is downward in the northern portion of the site, and upward in the southern portion of the site, where it discharges to the creek. The goal of ground-water remediation is to achieve background levels for contaminants in the overburden aquifer.

Technology Application

To construct the PRB, a ground-water trench, approximately 3 ft wide, 20 ft deep, and 1,100 ft long, was dug using a trackhoe. Trench boxes were installed parallel to the creek along the southern site property boundary.

Cost

Design and installation cost for this PRB system are not currently available.

Results

PRB performance results will be available upon completion of remedial activities in 1999.

Lessons Learned

One-pass trenching equipment was evaluated and determined to be impractical. Problems arose during construction as a result of the presence of rubble and concrete foundations, sloughing of mine spoil, and the close proximity of a railroad spur and an onsite landfill embankment. In addition, the wall was designed to be 1 ft in width but required expansion to 3 ft.

U.S. Coast Guard Support Center, Elizabeth City, NC

Installation Date:
June 1996

Contaminants:
Cr^{+6}, TCE

Reactive Media:
Fe^0

Installation Cost:
$500,000

Construction:
Continuous Trench

Point of Contact:
Robert W. Puls
U.S. EPA/National Risk Management Research Laboratory
P.O. Box 1198
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Tel: 580-436-8543
Fax: 580-436-8706
E-mail:
puls.robert@epa.gov

A full-scale demonstration of a permeable reactive barrier (PRB) to remediate ground water contaminated with chromium and chlorinated organic compounds was initiated at the U.S. Coast Guard Support Center site in Elizabeth City, NC, in 1995.

Site Background

The primary contaminants of concern are hexavalent chromium (Cr^{+6}) and trichloroethylene (TCE). Initial maximum concentrations were more than 4,320 µg/L for TCE and more than 3,430 µg/L for Cr^{+6}. The contaminant plume was estimated to cover a 34,000-ft^2 area. The plume is adjacent to a former electroplating shop that operated for more than 30 years prior to 1984 when operations ceased. Ground water begins approximately 6 ft below ground surface, and a highly conductive zone is located 16-20 ft below the surface. This layer coincides with the highest aqueous concentrations of chromium and chlorinated organic compounds found on the site. A low-conductivity layer—clayey, fine sand to silty clay—is located at a depth of about 22 ft. This layer acts as an aquitard to the contaminants located immediately above.

Technology Application

A continuous wall composed of 100% zero-valent iron (Fe^0) was installed in June 1996 using a trencher that was capable of installing the granular iron to a depth of 24 ft. The continuous trenching equipment used for the installation has a large cutting chain excavator system to remove native soil combined with a trench box and loading hopper to emplace the iron.

The trenched wall is approximately 2 ft thick and about 150 ft long. The wall begins about 3 ft below ground surface and consists of about 450 tons of granular iron.

Cost

The total installation cost was $500,000. This includes the cost of design, construction, materials, and the iron, which cost about $175,000.

Results

The wall was designed to meet cleanup goal concentrations of 0.05 mg/L of Cr^{+6} and 5 µg/L of TCE. Performance monitoring has been conducted on a quarterly basis since November 1996. In addition to 2-in PVC compliance wells, the wall is monitored using a series of multilevel sampling (MLS) ports to monitor the geochemical mechanisms occurring in the barrier and in the downgradient aquifer. Sampling results for chromium indicate that all chromium has been removed from the ground water within the

first 6 inches of the wall as expected. No chromium has been detected downgradient of the wall either in the MLS ports or in the compliance wells located immediately behind the wall. Results thus far indicate that the barrier is successfully reducing TCE, c-DCE, and vinyl chloride concentrations to less than MCL levels for the vast majority of the monitored portions of the wall. Of 29 downgradient MLS ports, MCLs for TCE and vinyl chloride are exceeded in 1 and 3 ports, respectively. TCE concentrations are generally below 5 μg/L within the wall, but exceed 50 μg/L at the lowest depth. There are some indications that the TCE plume may have dipped lower in this part of the aquifer following wall installation. The slight elevation beyond target levels for vinyl chloride seen in the MLS ports are not reflected in adjoining compliance wells. Downgradient vinyl chloride concentrations in the MLS ports have declined with time. Nowhere do c-DCE concentrations exceed regulatory limits.

Numerous vertical and angle cores also have been collected at the site to examine changes to the iron surface and to evaluate the formation of secondary precipitates which may affect wall performance over time. These cores continue to be studied.

Lessons Learned

Researchers are investigating the possibility that the TCE plume has dipped lower in the aquifer after the wall was installed and is now moving under the wall. A significant amount of recharge occurred into the reaction zone following installation due to removal of the concrete parking lot covering the site. This recharge may have driven the plume deeper than had previously been observed allowing some of the plume to move under the wall. Interestingly, there is still significant treatment below the wall where no iron resides.

Based on limited preliminary electrical conductivity profiles, the wall is approximately 19-21 in thick, compared to the design thickness of 23 in. Some minor vertical discontinuities were observed in the conductivity data and have been confirmed with coring. These small gaps are probably due to bridging within the trencher hopper during iron emplacement.

100 D Area, Hanford Site, WA

Installation Date:
September 1997

Contaminants:
Cr^{+6}

Reactive Media:
Sodium dithionite

Installation Cost:
$480,000

Construction:
Injection

Point of Contact:
Jonathan S. Fruchter
Batelle Pacific
Northwest
National Laboratory
P.O. Box 999 (K6-96)
Richland, WA 99352
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A large-scale treatability test of an *In Situ* Redox Manipulation (ISRM) method is being conducted at the 100D Area of the U.S. Department of Energy (DOE) Hanford Site in Washington.

Site Background
Chromate (Cr^{+6}) concentrations of up to 2 mg/L have been detected within the 100D Area. Contamination resulted from the use of chromium-bearing anti-corrosion agents in onsite reactors.

The 100D Area is underlain by both glacial and fluvial sediments, predominantly sands and gravels. Hydraulic conductivity is approximately 100 ft/day. The upper surface of the contaminated aquifer is approximately 85 ft below ground surface and is approximately 15 ft thick, constrained at its lower boundary by an aquitard.

Technology Application
ISRM involves injection of a chemical reducing agent in the contaminant plume downgradient from the source area. This agent alters the chemical redox potential of aquifer fluids and sediments. Redox-sensitive metals migrating through the treatment zone are immobilized. The treatability test at Hanford's 100D Area began in September 1997 and consists of injecting sodium dithionite into a series of five existing wells to a depth of 100 ft below ground surface. Treated zones for each well overlap, creating a 150-ft-long barrier that is approximately 50 ft wide.

Cost
The installation cost is estimated to be $480,000. This includes the cost of design, construction, materials, and the reactive material.

Results
Sodium dithionite was injected into the first of the five wells in 1997. As a result, aqueous chromate concentrations have been reduced below 8 μg/L. After the completion of a gas tracer test studying rates of reoxygenation in the treated plume, plans called for sodium dithionite to be injected into the remaining four wells in mid-1998, followed by a bromide tracer test to determine the effect of the treatability test on ground-water flow within the aquifer. Performance monitoring is expected to continue through the end of 1999.

LEAP Permeable Barrier Demonstration Facility, Portland, OR

Installation Date:
October 1997

Contaminants:
Cr^{+6}, PCE

Reactive Media:
SMZ

Design Cost:
$75,000

Installation Cost:
$25,000

Construction:
Hanging Barrier in Perforated Metal Frame

Point of Contact:
Robert Bowman
Dept. of Earth & Environmental Science
New Mexico Tech
801 LeRoy Place
Socorro, NM 87801
Tel.: 505-835-5992
Fax: 505-835-6436
E-mail:
bowman@nmt.edu

A pilot-scale demonstration was conducted at the Large Experimental Aquifer Program (LEAP) site at the Oregon Graduate Institute of Science and Technology near Portland, OR.

Site Background

The main purpose of the demonstration was to quantify the ability of a surfactant-modified zeolite (SMZ) permeable reactive barrier (PRB) to intercept and retard the migration of a mixed plume containing 22 mg/L of chromate (Cr^{+6}) and 2 mg/L of perchloroethylene (PCE). The goal was to test laboratory-based predictions of behavior of the SMZ, using Cr^{+6} and PCE as "type" contaminants (anionic metal and chlorinated hydrocarbon). The pilot-test was conducted in a contained, simulated aquifer. The aquifer was filled with sand and had a hydraulic conductivity of 56.7 ft/day.

Technology Application

The barrier of SMZ was hung in the center of the simulated aquifer about 3 ft above the base in order to simulate emplacement in front of an advancing plume in a shallow, unconfined aquifer. The barrier had three modules, each about 6.5 ft long. Overall, the barrier was about 20 ft long, 3 ft thick, and 6.5 ft deep, and used 12 tons of the reactive medium. Since this was a pilot-scale test under controlled conditions, the reactive medium was contained in a frame to facilitate removal and replacement with other test media in the future.

Cost

Total design cost for the barrier system was about $75,000. Total installation cost was about $25,000. This includes the cost of construction, materials, and the reactive material.

Results

The contaminant plume was injected into the simulated aquifer for 2 months, and performance was monitored. Samples were collected approximately weekly from a network of 63 sample nests (315 sample points) in the aquifer and 18 sample nests (90 sample points) within the barrier. Analysis of preliminary data indicates that the barrier performed according to design specifications, with retardation factors for Cr^{+6} and PCE both on the order of 50. Final interpretation of data from the sampling and chemical analyses is

in progress. Pending the results of this of the pilot-scale effort, a full-scale implementation is anticipated.

Lessons Learned

Barrier performance is very sensitive to the interface between aquifer material and reactive barrier materials. Sufficient permeability contrast must be established and maintained to avoid plume deflection. The causes for poor permeability contrast, whether due to inherent media property differences or barrier installation, can be difficult to isolate. Long-term compaction of the material with resultant loss in hydraulic conductivity needs further evaluation. Low-conductivity zones in an earlier phase of the project were difficult to detect and locate.

Fuel Hydrocarbons

East Garrington, (Near Olds), Alberta, Canada

Installation Date:
September 1995

Contaminants:
BTEX

Reactive Media:
O_2

Design/Installation Cost:
$67,200

Construction:
Trench and Gate

Point of Contact:
Marc Bowles
Komex International Ltd.
16th Avenue, NW
Suite 100
Calgary, Alberta
Canada T3B 0M6
Tel: 403-247-0200
Fax: 403-247-4811
Email: mbowles@
calgary.komex.com

A pilot-scale permeable reactive barrier (PRB) was installed at the East Garrington gas plant in Alberta, Canada in September 1995.

Site Background

Initial concentrations of up to 12 mg/L of BTEX (benzene, toluene, ethylbenzene, and xylene) were detected. The gas processing plant was contaminated by condensate, lube oil, flare pit wastes, and other materials. The goal of the pilot-scale demonstration was to contain the BTEX onsite and ensure that only treated ground water migrated offsite.

The site is underlain by 10-16 ft of low-conductivity glacial till composed of silty clay and cobble-rich deposits that grade into a clay-rich sandy to silty basal unit. This is underlain by a silty shale with occasional interbedded sandstone units. The contaminated aquifer extends from the near the surface to 10 ft below ground surface (bgs).

Technology Application

Two 145-ft-long cut-off tenches were excavated at right angles to each other through the fine-grained glacial sediments down to the relatively impermeable bedrock. The bottom, and the downgradient sides of the trenches were then sealed with an impermeable, synthetic liner before being filled with highly permeable aggregate. The PRB systems consists of three 6-foot wide modular treatment gates in series. They were constructed of vertical culverts that inject air into the contaminated ground water, which promotes hydrocarbon degradation. The residence time inside the treatment gate is approximately 24 hours. The treated ground water then passes through an infiltration gallery composed of thin vertical trenches filled with highly permeable gravel.

A passive permeable reactive barrier was chosen as a remedy for the site because of its low maintenance costs, despite the longer timeframe required for remediation. More specifically, a trench-and-gate system was selected over a funnel-and-gate system because of its advantages in low permeability sediments such as glacial tills. Compared with traditional stand-alone barriers, the combination of a cut-off wall and adjacent drainage trench (1) improves drainage of the contaminated zone; (2) increases the size of the capture zone both horizontally and vertically; and (3)

prevents damming effects such as mounding which force contaminants around or under funnel walls.

Cost

Design and installation costs for the system were approximately $67,200. This includes design, construction, and materials.

Results

Results of the pilot-scale project show that the contaminant plume has been captured and treated by the trench-and-gate system. Recent sampling yielded BTEX concentrations below 10 μg/L at the treatment gate, and no contaminants have been detected offsite. Monitoring equipment includes soil moisture sensors, tensiometers, and pressure transducers installed upgradient, downgradient, and along the trench. Experiments conducted in the system using artificially contaminated water suggest that total BTEX concentrations up to 2.5 mg/L can be effectively treated. Sampling will continue on a biannual basis.

Lessons Learned

During installation, an unusually high water table led to trenching problems. The high water table increased installation costs, but had no effect on maintenance costs.

Air sparging was found to be an effective method for enhancing biodegradation through the addition of oxygen to the treatment cell. Experiments using Oxygen Releasing Compound were not effective. However, the addition of phosphorus increased degradation rates.

U.S. Naval Air Station, Alameda, CA

Installation Date:
December 1996

Contaminants:
cDCE, VC, TCE, BTEX

Reactive Media:
Fe^0, O

Installation Cost:
$400,000

Construction:
Funnel and Sequenced Treatment Gate

Point of Contact:
Michaye McMaster
Beak International Inc.
42 Arrow Rd.
Guelph, Ontario
N1K 1S6 Canada
Tel: 519-763-2325
Fax: 519-763-2378
E-mail:
mmcmaster@beak.com

The second part of a pilot-scale demonstration of an *in situ* sequenced permeable reactive barrier (SPRB) for the remediation of chlorinated solvents and petroleum hydrocarbons was conducted at Alameda Point (formerly U.S. Naval Air Station Alameda) in Alameda, California.

Site Background

The initial phase of this demonstration, which had been conducted at Canadian Forces Base Borden, Ontario, Canada, evaluated three technologies for their ability to treat perchloroethylene (PCE), carbon tetrachloride (CCl_4) and toluene. The technologies were: (1) abiotic reductive dechlorination using zero-valent iron (Fe^0), followed by oxygen releasing compound (ORC™) to promote aerobic biodegradation; (2) natural attenuation; and (3) a permeable nutrient injection wall, using benzoate to promote anaerobic biodegradation, followed by an aerobic (oxygen) biosparge gate for aerobic biodegradation.

The Alameda demonstration used Fe^0 followed by oxygen biosparging in a funnel-and-gate system to remediate trichloroethylene (TCE); cis-1,2-dichloroethylene (cDCE); vinyl chloride (VC); and toluene, benzene, ethyl benzene, and xylene (BTEX). Total initial (upgradient) concentrations of chlorinated VOCs exceeded 100 mg/L, and toluene was found at levels of up to 10 mg/L.

Historical air photos of the site indicate open disposal pits upgradient of the SPRB. The shallow aquifer is composed of 22-24 ft of sandy artificial fill material that was hydraulically placed on bay silts and clays. The hydraulic conductivity of the overlying sandy fill material is 0.057 ft/day (~21 ft/year). The underlying bay silts and clays are 15-20 ft thick and act as a confining unit. Depth to ground water ranges from 4 to 7 ft below ground surface.

Technology Application

During construction of the funnel-and-gate system, the artificial fill sand was excavated to the top of the confining bay mud unit. To prevent settling, a concrete pad (nominally 2 ft thick) was placed at the bottom of the excavation; the gate was then constructed on this base. The gate is 10 ft wide and 15 ft long. As ground water passes through the gate it contacts the following media: about 18 in of coarse sand mixed with 5% Fe^0, 5 ft of Fe^0, a 3-ft pea gravel

transition zone, a 3-ft biosparge zone, and a 2-ft pea gravel zone. The 10-ft funnels were placed on either side of the gate, perpendicular to the direction of water flow.

Between February 1997 and May 1998, two pumping wells were used to operate the system under controlled conditions. For a period of about 70 days, the system operated at a flux rate of approximately 45 ft^3/day to determine the maximum velocity it could process. At this velocity, breakthrough was observed in several down-gradient monitoring points. Then, the system operated for about one year at a flux rate of approximately 12 ft^3/day, more representative of conditions that would exist as a result of the funnel sections. Finally, the system was allowed to operate under natural gradient conditions.

Results

The remedial objectives of the project generally were met, except with respect to cDCE and VC, with typical effluent concentrations of about 136 µg/L and 217 µg/L respectively. Retardation of the toluene or other hydrocarbons as a result of sorption to the granular iron precluded an assessment of petroleum hydrocarbon degradation. Breakthrough of cDCE and VC indicated that biodegradation (likely via aerobic oxidation) of these compounds was occurring in the biosparge zone. An estimated 66% of the VC and 30% of the cDCE was volatilized. Assessment of multilevel data showed excellent degradation (>91%) of the chlorinated organics using the granular iron at high influent concentrations (>100 mg/L total VOCs). At lower influent concentrations, almost complete degradation (>99%) was observed. The biosparge zone supported aerobic biodegradation of VC and cDCE, and by January 1998 remedial objectives were being met at the last set of sampling wells in the gate.

Results obtained to date suggest sparging rates in the biosparge zone should be minimized to reduce volatilization of contaminants from the water column. In addition, monitoring should continue so that long-term performance of the SPRB can be assessed.

The U.S. Navy has begun to operate the site; current plans call for a hydraulic study to examine ground-water flow in the funnel-and-gate area and for monitoring to continue on a quarterly basis.

Nutrients

Y-12 Site, Oak Ridge National Laboratory, TN

Installation Date:
December 1997
November 1997

Contaminants:
U, Tc, HNO_3

Reactive Media:
Fe^0

Installation Cost:
$1,000,000

Construction:
Funnel and Gate
Continuous Trench

Point of Contact:
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Environmental Sciences Division
Oak Ridge, TN 37831-6036
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Permeable reactive barrier (PRB) systems have been constructed in two different ground-water pathways through the Y-12 site at the U.S. Department of Energy's (DOE) Oak Ridge National Laboratory, TN.

Site Background

Liquid wastes, including nitric acid (HNO_3) with uranium (U), and technetium (Tc), were placed in disposal ponds on the site from 1952 to 1981. The site was capped in 1983. Leached wastes have contaminated both ground and surface water.

The site is underlain by unconsolidated clay and regolith overlying fractured shales. The permeability of the clay is very low (approximately 4×10^{-7} in/sec), but the weathered bedrock above the shales generally has a higher permeability (locally as high as 4×10^{-4} in/sec). The depth to ground water is 10-15 ft, and the shallow unconsolidated unit aquifer is 10-20 ft thick. The PRBs are focused on capturing ground water in this shallow unconsolidated zone.

Technology Application

Pathway 1 PRB

A funnel-and-gate system was installed in the area designated Pathway 1 in December 1997. The system is approximately 220 ft long and consists of two wing walls designed to funnel ground water to a concrete vault containing treatment canisters for evaluating different treatment media. The treatment vault consists of five vertically stacked reactors. An advantage of vertical reactors is the ease of cleaning and replacing used or clogged iron. The wing walls were installed to a depth of approximately 25 ft. The natural ground-water gradient and permeability contrast between the gravel backfill in the trench and surrounding native silt and clay is designed to generate flow through the treatment zone. Barriers were installed using a guar gum slurry for support to reduce slumping in the trench. An enzyme breaker was used to digest the guar which was recycled down the trench as construction progressed.

Pathway 2 PRB

A continuous trench system was installed in the area designated Pathway 2 in November 1997. It is 225 ft long, 2 ft wide, 22-30 ft deep, and filled with gravel except for a 26-ft section in the middle

that is filled with 80 tons of zero-valent iron (Fe^0). Guar gum was added during excavation to keep the trench walls from collapsing. The trench was installed parallel to the direction of ground-water flow.

Although total iron and ferrous iron concentrations were initially high after installation, concentrations have decreased as the pH within the iron has increased over time (to as high as 9 or 10). This initial spike is likely a result of enhanced microbial activity from the guar used in the barrier installation. Due to the effect of the guar on ground-water chemistry, nitrate concentrations increased in the upgradient wells over time. Sulfate levels in the ground water have decreased as sulfate is reduced to sulfide. Additionally, a decreased concentration of calcium in ground water was observed and may be attributed to the precipitation of calcium carbonate within the iron barrier. Continued monitoring and performance evaluation is in progress to better understand the flow paths through the PRB, the potential for clogging due to mineral precipitation, and the long-term effectiveness for uranium removal.

The total installation cost for the two walls was approximately $1,000,000. This includes the cost of design, construction, materials, and the reactive material.

Results

The goals of the project were to investigate the feasibility and effectiveness of passive *in situ* treatment systems to remove the contaminants in the ground water that are migrating to Bear Creek from the disposal ponds. Early results indicate that Fe^0 is an efficient and cost-effective method of simultaneously removing certain radionuclides, such as U and Tc, as well as HNO_3. Sampling to monitor performance is occurring on a monthly basis.

Lessons Learned

Pathway 1 PRB

The use of guar increased biological activity in the system.

Pathway 2 PRB

Preliminary evaluation of hydraulic and chemical data suggests that, under wet-season hydraulic conditions, contaminated ground water may migrate across the trench instead of down the trench as designed. Vertical gradients at the site appear to have a significant impact on ground-water flow and capture. The data suggest that to effectively operate passively in all hydraulic conditions, the trench needs to be longer and discharge at a lower hydraulic head

downgradient. The following modifications are planned for the Pathway 2 PRB in fiscal year 1999 to enhance treatment efficiency:

- The trench will be extended an additional 100 ft to increase the ground-water capture zone.
- Guar will not be used to excavate the trench extension because of potential geochemical impacts on the iron media, native soil, and ground water observed during initial trench construction.
- Ground water from the trench extension will be siphoned approximately 800 ft to a second Fe^0 treatment zone deployed in subsurface concrete boxes.
- The treated water will flow into an infiltration trench downgradient of the second treatment zone.

Public School, Langton, Ontario, Canada

Installation Date:
August 1993

Contaminants:
PO_4^{3-}, NO_3^-

Reactive Media:
Fe/Ca oxides,
high-Ca limestone,
organic carbon

Installation Cost:
$5,000

Construction:
Funnel and Gate

Points of Contact:
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A pilot-scale demonstration of a funnel-and-gate system designed to remediate phosphate (PO_4^{3-}) and nitrate (NO_3^-) was installed on the grounds of a public school in Langton, Ontario, Canada in August 1993.

Site Background

The system was emplaced to remove PO_4^{3-} and NO_3^- from a large-capacity conventional septic system located on the school property that had operated over a 45-year period. The site is underlain by a thick body of medium sand with a hydraulic conductivity of 72 ft/day. The water table is located at a depth of 10 ft and the ground-water velocity is 330 ft/yr. The contaminated aquifer is unconfined.

Technology Application

Ground water was funneled between two walls constructed from sealable joint sheet pilings that extend 16 ft from the central gate area. The funnel walls extended 5 ft below the water table. The central gate was 6 ft wide, 6 ft long, and extended 6 ft below the water table. The gate contained two distinct treatment zones. The PO_4^{3-} treatment zone, which was 2 ft thick, contained a reactive mixture of 6% iron and calcium oxides (Fe/Ca oxides), 9% high-Ca limestone, and 85% local aquifer sand. The phosphate was removed by adsorption onto Fe oxides and precipitation of Ca-PO_4 phases. The 2-ft-thick NO_3^- treatment zone contained wood chips that removed nitrate by bacterial denitrification.

Cost

The installation cost was $5,000.

Results

Monitoring over one year for NO_3 and two years for PO_4 indicated significant drops in concentrations of both. PO_4^{3-} concentrations decreased from 1.0-1.3 mg/L on the influent side of the barrier to 0.3 mg/L on the effluent side. NO_3^- concentrations decreased from 23-82 mg/L upgradient of the gate to <2 mg/L within the gate. There are no plans to continue monitoring.

Lessons Learned

One lesson learned from this demonstration is that if walls are not keyed into a underlying impermeable material, underflow must be carefully considered.

Savannah River Site TNX Area, Aiken, SC

Installation Date:
July 1997

Contaminants:
TCE, cDCE, CT, NO_3

Reactive Media:
Fe^0

Installation Cost:
$120,000

Construction:
GeoSiphon Cell

Point of Contact
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The GeoSiphon Cell (patent pending) was installed in the TNX flood plain at the Savannah River Site (SRS) by auger and caisson methods in July 1997. The cell was installed to demonstrate treatment of ground water contaminated with chlorinated volatile organic compounds (CVOCs).

Site Background

Ground-water contamination has been detected in the TNX water table aquifer, but not in the semi-confined or deep aquifers underlying the site. Predominant contaminants, and average concentrations of each, detected in the TNX flood plain are trichloroethylene (TCE) at 200-250 μg/L, cis-1,2-dichloroethylene (cDCE) at 20-50 μg/L, carbon tetrachloride (CT) at 15-45 μg/L, and nitrate (NO_3) at 10-70 mg/L.

The TNX Area is a semi-works facility for the Savannah River Technology Center, which is located 0.25 mile from the Savannah River near Aiken, SC. The facility was used for pilot-scale testing and evaluation of various chemical processes associated with SRS. The water table elevation averages 100 ft above mean sea level under the TNX site, while the Savannah River elevation averages 85 ft. In the flood plain where contamination was detected, the water table aquifer is approximately 35-40 ft thick. It consists of interbedded sand, silty sand, and relatively thin clay layers. Based on testing and modeling analysis, the aquifer may be characterized as having a horizontal hydraulic conductivity of 65 ft/day, vertical hydraulic conductivity of 30 ft/day, effective porosity of 0.15, pore velocity of 3 ft/day, and a horizontal gradient of 0.007.

Technology Application

The TNX GeoSiphon Cell is a large-diameter (8-ft) well containing granular zero-valent iron (Fe^0) as a treatment media (in place of gravel pack). The cell passively induces flow by use of a siphon from the cell to the Savannah River. The flow is induced by the natural hydraulic head difference between the cell and the river. The passively-induced flow draws contaminated ground water through the treatment cell, where the Fe^0 reduces the CVOCs to ethane, ethene, methane, and chloride ions. Treated water is discharged to the Savannah River.

During Phase I testing of this technology, which was completed in December 1997, flow through the TNX GeoSiphon Cell was

induced by pumping and the treated water was discharged to the existing TNX National Pollutant Discharge Elimination System outfall. Testing indicated that TCE degradation is the limiting compound to treatment below the Primary Drinking Water Standard Maximum Contaminant Levels within the TNX GeoSiphon Cell. Data indicated that approximately 8 gal/hr of ground water contaminated with 200-250 μg/L of TCE could be treated, while maintaining the average discharge TCE concentration below 5 μg/L. Field first-order rate constants produced from the steady state TCE data increased with flow rate from 0.347 to 0.917/hr.

During Phase II, flow through the TNX GeoSiphon Cell was induced by siphon and the treated water was discharged to an existing outfall ditch that flows into the Savannah River. To allow continuous operation, the siphon line configuration was optimized to include an upward rise from the cell to the outfall ditch, an air chamber at the crest adjacent to the outfall ditch, and a steep drop into the outfall ditch with line termination in a sump. The head differential available to drive the system (approximately 1.4 ft) produced a continuous flow rate of 2.5-2.7 gal/min. Approximately 1.2 ft of head was utilized to drive flow through the cell itself, and approximately 0.2 ft of head was utilized to drive flow through the siphon line. Based on these results, a new siphon line will be installed between the cell and a target location, thus producing a 5-ft head differential capable of inducing an estimated 9.5 gal/min through the GeoSiphon Cell.

Phase III of this demonstration project will involve installation and operation of a full-scale GeoSiphon Cell system for treatment of the entire TNX contaminated ground-water plume.

Cost

Phase I system costs are estimated at $119,155, including $26,400 for iron; $27,411 for other construction materials; and $65,344 for mobilization, labor, rentals, and related installation expenses. Approximately 49.7 tons of 0.25-2.0 mm (particle size) granular cast iron was used in the installation of the first TNX GeoSiphon Cell (TGSC-1).

Lessons Learned

The GeoSiphon Cell was selected for use at the TNX Area because it offers passive (no power requirements), *in situ* treatment at lower operating and maintenance costs than pump-and-treat technology. In contrast to funnel-and-gate or continuous permeable wall

technologies, the GeoSiphon Cell could be constructed using an existing foundation and well drilling techniques. In addition, there is potential for accelerating cleanup through the use of induced flow rates greater than natural flow. With a maximum siphon lift of 25 ft, application of the GeoSiphon Cell technology was found to be limited to areas of shallow ground water such as that existing at the TNX Area.

Radionuclides

Fry Canyon Site, UT

Installation Date:
August 1997

Contaminants:
U

Reactive Media:
Fe^0, AFO, PO_4

Design Cost:
$30,000

Installation Cost:
$140,000

Construction:
Funnel and Gate

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A field-scale demonstration of a permeable reactive barrier (PRB) system is underway at an abandoned uranium upgrader site in Fry Canyon, UT. The U.S. Environmental Protection Agency (EPA) is the lead agency on the site.

Site Background

The ultimate goal of the demonstration is to determine the technological and economic feasibility of using permeable chemical or biological obstacles, placed in the flow path, for removing dissolved metals and radionuclides from contaminated ground water. This project is testing the performance of three permeable reactive barriers at the Fry Canyon site. Anticipated results of the research for each of the PRBs tested will include long-term removal efficiencies for uranium and an evaluation of the commercialization potential for each. Specific objectives of the field demonstration project include: (1) hydrologic and geochemical characterization of the site prior to emplacement of barriers; (2) design, installation, and operation of three PRBs; and (3) evaluation of barrier performance and commercialization potential.

At the Fry Canyon site, the water table is approximately 8-9 ft below ground surface, and the underlying aquifer ranges from 1-6 ft deep. Estimated hydrologic properties and measured hydraulic gradients indicate that ground water in the alluvial aquifer moves at a rate of about 1.5 ft/day nearly parallel to the direction of stream flow. The uranium (U) concentration in the shallow colluvial aquifer ranges from 60 μg/L in water from a background well to 20,700 μg/L in water beneath the tailings. The hydraulic conductivity of the barriers is approximately 1,500 ft/day, while that of the surrounding native material is 1 to 2 orders of magnitude smaller. Native material consists of poorly sorted fine- and medium-grained sand.

Technology Application

The funnel-and-gate system, installed in August 1997, is comprised of three barriers, each constructed of different reactive materials. One is bone char phosphate (PO_4), another is foamed zero-valent iron (Fe^0) pellets, and the third is amorphous ferric oxide (AFO). Each barrier is approximately 7 ft wide, 3 ft thick, and 4 ft deep. Approximately 110 ft^3 of material was used in each barrier. Each contains 22 monitoring points, a water-quality

mini-monitor, four pressure transducers, and a flow-sensor port. According to steady-state modeling results, ground-water velocities in the reactive walls are about 4.5 ft/day.

Cost

The EPA and U.S. Geological Survey have estimated that the design cost (engineering design and planning for the funnel-and-gate construction) for this system totals $30,000. The installation cost, including construction, materials, and the reactive materials, totals $140,000. These estimates do not include bench-scale testing of the candidate barrier materials.

Results

Overall, results to date show that the system is controlling uranium migration in Fry Canyon. One year of uranium-concentration data have been collected from the three PRBs installed using funnel-and-gate designs. The input uranium concentrations are significantly different for each PRB, ranging from less than 1,000 mg/L in the PO_4 PRB to higher than 20,000 mg/L in the AFO ZVI. The input uranium concentrations to each of the PRBs also vary seasonally by approximately 4,000 to 7,000 mg/L. During the first year of operation, the PRBs are removing the majority of incoming uranium; however, the percentage of uranium removal varies with time and barrier material. The ZVI PRB has consistently removed greater than 99.9 percent of the input uranium concentration in flow-path 1. The percentage of uranium removed in the PO_4 and AFO PRBs is slightly less than the ZVI PRB. Except for two monitoring periods, over 90 percent of the input uranium concentration was removed in the PO_4 barrier. The AFO PRB removed over 90 percent of the input uranium concentration through November 1997. From January 1998 through September 1998 the uranium removal percentage was reduced to less than 90 percent. Studies will continue to evaluate the barriers under varying hydrologic and geochemical conditions. Final results will be presented after peer review in the report to be issued by end of fiscal year 1999.

Lessons Learned

The Fry Canyon project has shown continued promise for use of PRB technology at appropriate sites (as determined by characterization). Uranium reduction ratios were calculated for all water samples collected from each reactive wall from September 1997 through January 1998. These calculations indicate that the Fe^0 reactive chemical wall has been most efficient in removing uranium from ground water; however, uranium removal

efficiencies in the PO_4 and AFO walls also have been high. Other lessons learned to date include the following:

- Project results thus far indicate that the PO_4 binder system can be used to customize reactive materials effectively.
- Data also suggest, however, that the dissolution of Fe^0 and its associated clogging could present problems, while the AFO is less subject to clogging and iron release. Although the possibility exists for elevated iron concentrations downgradient of the PRB (which could cause degradation in water quality not present before barrier installation); to date, iron concentrations in downgradient wells do not seem to present a large water-quality problem.

Numerous geochemical, hydrological, and other factors that affect uranium removal efficiencies and processes in each of the PRBs are currently being evaluated. These factors include:

- Changes in the amount and velocity of water flowing through the PRBs
- Type and quantities of minerals forming within the PRBs
- Leakage between underlying "no-flow" paths through the PRBs

The following potential problems also are being assessed:

- In a low-gradient system like Fry Canyon, it is difficult to estimate mass of treated water and, at times, whether there is even flow through some of the gate structures. This presents an unknown to regulators in estimating total mass of contaminant that will be cleaned up per unit of time since PRB deployment.
- Seasonal changes are apparent in the PRBs' efficiency in removing uranium. The processes causing these changes need to be identified in order to effectively determine long-term clean-up goals.
- PRBs that are placed adjacent to ephemeral channels could be destroyed or have their long-term function significantly compromised during intense thunderstorm events in the Fry Creek drainage basin without proper erosion control measures.
- Ground settling could compromise the lack of visual impact that PRBs have in future remediation applications and could impact monitoring wells.

Y-12 Site, Oak Ridge National Laboratory, TN

Installation Date:
December 1997
November 1997

Contaminants:
U, Tc, HNO_3

Reactive Media:
Fe^0

Installation Cost:
$1,000,000

Construction:
Funnel and Gate
Continuous Trench

Point of Contact:
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Permeable reactive barrier (PRB) systems have been constructed in two different ground-water pathways through the Y-12 site at the U.S. Department of Energy's (DOE) Oak Ridge National Laboratory, TN.

Site Background

Liquid wastes, including nitric acid (HNO_3) with uranium (U), and technetium (Tc), were placed in disposal ponds on the site from 1952 to 1981. The site was capped in 1983. Leached wastes have contaminated both ground and surface water.

The site is underlain by unconsolidated clay and regolith overlying fractured shales. The permeability of the clay is very low (approximately 4 x 10^{-7} in/sec), but the weathered bedrock above the shales generally has a higher permeability (locally as high as 4 x 10^{-4} in/sec). The depth to ground water is 10-15 ft, and the shallow unconsolidated unit aquifer is 10-20 ft thick. The PRBs are focused on capturing ground water in this shallow unconsolidated zone.

Technology Application

Pathway 1 PRB

A funnel-and-gate system was installed in the area designated Pathway 1 in December 1997. The system is approximately 220 ft long and consists of two wing walls designed to funnel ground water to a concrete vault containing treatment canisters for evaluating different treatment media. The treatment vault consists of five vertically stacked reactors. An advantage of vertical reactors is the ease of cleaning and replacing used or clogged iron. The wing walls were installed to a depth of approximately 25 ft. The natural ground-water gradient and permeability contrast between the gravel backfill in the trench and surrounding native silt and clay is designed to generate flow through the treatment zone. Barriers were installed using a guar gum slurry for support to reduce slumping in the trench. An enzyme breaker was used to digest the guar which was recycled down the trench as construction progressed.

Pathway 2 PRB

A continuous trench system was installed in the area designated Pathway 2 in November 1997. It is 225 ft long, 2 ft wide, 22-30 ft deep, and filled with gravel except for a 26-ft section in the middle

that is filled with 80 tons of zero-valent iron (Fe^0). Guar gum was added during excavation to keep the trench walls from collapsing. The trench was installed parallel to the direction of ground-water flow.

Although total iron and ferrous iron concentrations were initially high after installation, concentrations have decreased as the pH within the iron has increased over time (to as high as 9 or 10). This initial spike is likely a result of enhanced microbial activity from the guar used in the barrier installation. Due to the effect of the guar on ground-water chemistry, nitrate concentrations increased in the upgradient wells over time. Sulfate levels in the ground water have decreased as sulfate is reduced to sulfide. Additionally, a decreased concentration of calcium in ground water was observed and may be attributed to the precipitation of calcium carbonate within the iron barrier. Continued monitoring and performance evaluation is in progress to better understand the flow paths through the PRB, the potential for clogging due to mineral precipitation, and the long-term effectiveness for uranium removal.

The total installation cost for the two walls was approximately $1,000,000. This includes the cost of design, construction, materials, and the reactive material.

Results

The goals of the project were to investigate the feasibility and effectiveness of passive *in situ* treatment systems to remove the contaminants in the ground water that are migrating to Bear Creek from the disposal ponds. Early results indicate that Fe^0 is an efficient and cost-effective method of simultaneously removing certain radionuclides, such as U and Tc, as well as HNO_3. Sampling to monitor performance is occurring on a monthly basis.

Lessons Learned

Pathway 1 PRB

The use of guar increased biological activity in the system.

Pathway 2 PRB

Preliminary evaluation of hydraulic and chemical data suggests that, under wet-season hydraulic conditions, contaminated ground water may migrate across the trench instead of down the trench as designed. Vertical gradients at the site appear to have a significant impact on ground-water flow and capture. The data suggest that to effectively operate passively in all hydraulic conditions, the trench needs to be longer and discharge at a lower hydraulic head

downgradient. The following modifications are planned for the Pathway 2 PRB in fiscal year 1999 to enhance treatment efficiency:

- The trench will be extended an additional 100 ft to increase the ground-water capture zone.
- Guar will not be used to excavate the trench extension because of potential geochemical impacts on the iron media, native soil, and ground water observed during initial trench construction.
- Ground water from the trench extension will be siphoned approximately 800 ft to a second Fe^0 treatment zone deployed in subsurface concrete boxes.
- The treated water will flow into an infiltration trench downgradient of the second treatment zone.

Other Organic Contaminants

Marzone Inc./Chevron Chemical Company, Tifton, GA

Installation Date:
August 1998

Contaminants:
BHC, beta-BHC, DDD, DDT, xylene, ethylbenzene, lindane, and methyl parathion

Reactive Media:
Activated carbon

Design Cost:
$230,000

Installation Cost:
$520,000

Construction:
Funnel and Gate

Point of Contact:
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A permeable reactive barrier (PRB) was installed in August 1998 at Operable Unit 1 of the Marzone site in Tifton, GA, to remediate ground water contaminated with pesticides and volatile organic compounds (VOCs).

Site Background

A 1994 Record of Decision originally selected a pump-and-treat system to remediate the ground water. During remedial design activities, however, it was determined that an *in situ* treatment system such as a funnel-and-gate system may be a more appropriate technology for the specific site conditions. The Marzone facility was used as a pesticide formulation facility from 1950 until the 1980s. Ground-water contaminants of concern and their initial maximum concentrations are: alpha-hexachlorobenzene (BHC) (60 mg/L), beta-BHC (98.5 mg/L), DDD (7.6 mg/L), DDT (9.3 mg/L), xylene (94,000 mg/L), ethylbenzene (6,100 mg/L), lindane (54.6 mg/L) and methyl parathion (47 mg/L). A shallow aquifer is located at a depth of 7 ft and a deeper aquifer exists at approximately 25 ft. Hydraulic conductivity is estimated at 2.9-4.6 ft/day. Soils in this area consist of a mixture of sand, sandy clay, and clay.

Technology Application

The modified funnel-and-gate system comprises a 400-ft barrier wall that was installed using a vibrating beam technology. A collection trench lined with geotextile and filled with granular drain material was constructed upgradient of and parallel to the barrier wall. Ground water collected in this trench moves by way of a slotted well screen and associated piping into treatment vaults containing approximately 1,800 pounds of activated carbon located between the collection trench and barrier wall. From the treatment vaults, ground water moves slowly (1-2 gal/min) by way of piping through the barrier wall and into a distribution trench of similar construction as the collection trench but running perpendicular to the barrier wall.

Cost

Design costs for the Marzone PRB system were $230,000. Installation costs, including construction, materials, and reactive material, are estimated at $520,000.

Results

Cleanup goals for the contaminants of concern are: 0.00003 mg/L for alpha-BHC, 0.0001 mg/L for beta-BHC, 0.00077 mg/L for DDD, 0.00054 mg/L for DDT, 10 mg/L for xylene, 0.7 mg/L for ethylbenzene, 0.0002 mg/L for lindane, and 0.0039 mg/L for methyl parathion. Sampling of the treatment vault effluent is conducted on a monthly basis. Preliminary sampling indicates contaminant concentrations that are below detection levels.

Lessons Learned

The funnel-and-gate system was selected for use because if offered less impact to the surrounding community than other treatment technologies, while being partially self-operational. Flushing of the system is required every 3-4 weeks in order to reinitiate flow; as a result, costs for operation and maintenance are higher that anticipated.

Bibliography

Bibliography of Field Applications of Permeable Reactive Barrier Technology

Appleton, E.L. 1996. "A Nickel-Iron Wall Against Contaminated Groundwater." *Environmental Science & Technology,* 30:12, 536A-539A.

Bain, J.G.; D.W. Blowes; S.G. Benner. 1998. "Treatment of Acidic, Mine-Associated Discharge to a Lake Using a Permeable Reactive Barrier." *1998 American Geophysical Union Spring Meeting, 26-29 May, Boston, MA.*

Baker, M.J.; D.W. Blowes; C.J. Ptacek. 1997. "Phosphorous Adsorption and Precipitation in a Permeable Reactive Wall: Applications for Wastewater Disposal Systems." *1997 International Containment Technology Conference and Exhibition, 9-12 February, St. Petersburg, FL.* 697-703. CONF-970208-Proc. DE98001967.

Barton, W.D.; P.M. Craig; W.C. Stone. 1997. "Two Passive Groundwater Treatment Installations at DOE Facilities." *1997 International Containment Technology Conference and Exhibition, 9-12 February, St. Petersburg, FL.* 827-834. CONF-970208-Proc. DE98001967.

Benner, S.G.; D.W. Blowes; C.J. Ptacek. 1997. "A Full-Scale Porous Reactive Wall for Prevention of Acid Mine Drainage." *Ground Water Monitoring and Remediation.* 17:4 (Fall): 99-107.

Benner, S.G.; D.W. Blowes; C.J. Ptacek. 1997. "Porous Reactive Wall for Prevention of Acid Mine Drainage: Results of a Full-Scale Field Demonstration." *1997 International Containment Technology Conference and Exhibition, 9-12 February, St. Petersburg, FL.* 835-843. CONF-970208-Proc. DE98001967.

Benner, S.G.; D.W. Blowes; C.J. Ptacek. 1997. "Sulfate Reduction in a Permeable Reactive Wall for Prevention of Acid Mine Drainage." *The 213th National Meeting of the American Chemical Society, San Francisco, CA. Preprint Extended Abstracts, Division of Environmental Chemistry.* 37:1, 140-141.

Bennett, T.A.; D.W. Blowes; R.W. Puls; R.W. Gillham; C.J. Hanton-Fong; C.J. Ptacek; S.F. O'Hannesin; J.L. Vogan. 1997. "Design and Installation of an In Situ Porous Reactive Wall for Treatment of Cr(VI) and Trichloroethylene in Groundwater." *The 213th National Meeting of the American Chemical Society, San Francisco, CA. Preprint Extended Abstracts, Division of Environmental Chemistry.* 37:1, 243-245.

Bennett, T.A.; D.W. Blowes; R.W. Puls; R.W. Gillham; C.J. Hanton-Fong; C.J. Ptacek; S.F. O'Hannesin; J.L. Vogan. 1998. "An In-Situ Permeable Iron-Filings Wall to Remediate Cr(VI) and TCE Contaminated Groundwater." *Subsurface Barrier Technologies Conference: Engineering Advancements and Application Considerations for Innovative Barrier Technologies, 26-27 January 1998, Tucson, AZ.* International Business Communications, Southborough, MA.

Betts, K.S. 1998. "Novel Barrier Remediates Chlorinated Solvents." *Environmental Science & Technology,* 1 November 1998, 495A.

Blowes, D.W.; C.J. Ptacek; K.R. Waybrant; J.D. Bain; W.D. Robertson. 1994. "In Situ Treatment of Mine Drainage Water Using Porous Reactive Walls." *The "New Economy": Green Needs and Opportunities. Environment and Energy Conference of Ontario, November 15 & 16, 1994, Toronto, Ontario.*

Blowes, D.W.; C.J. Ptacek; J.A. Cherry; R.W. Gillham; W.D. Robertson. 1995. "Passive Remediation of Groundwater Using In Situ Treatment Curtains." *Geoenvironment 2000: Characterization, Containment, Remediation, and Performance in Environmental Geotechnics.* American Society of Civil Engineers, Reston, VA. Geotechnical special publication 46 (v.2), 1588-1607.

Blowes, D.W.; C.J. Ptacek; C.J. Hanton-Fong; J.L. Jambor. 1995. "In Situ Remediation of Chromium Contaminated Groundwater Using Zero-Valent Iron." *The 209th American Chemical Society National Meeting, Division of Environmental Chemistry, 2-7 April 1995, Anaheim, CA. Preprint Extended Abstracts.* 35:1, 780-783.

Blowes, D.W.; C.J. Ptacek; K.R. Waybrant; J.G. Bain. 1995. "In Situ Treatment of Mine Drainage Water Using Porous Reactive Walls." *Proceedings, Biominet Annual General Meeting on Biotechnology and the Mining Environment, 26 January 1995, Ottawa, Ontario.* 119-128.

Blowes, D.W.; C.J. Ptacek; J.G. Bain; K.R. Waybrant; W.D. Robertson. 1995. "Treatment of Mine Drainage Water Using In Situ Permeable Reactive Walls." *Proceedings, Sudbury '95 Symposium on Mining and the Environment, 28 May-1 June 1995, Sudbury, Ontario.* V.3, 979-987.

Blowes, D.W.; R.W. Puls; T.A. Bennett; R.W. Gillam; C.J. Hanton-Fong; C.J. Ptacek. 1997. "In-Situ Porous Reactive Wall for Treatment of Cr(VI) and Trichloroethylene in Groundwater." *1997 International Containment Technology Conference, 9-12 February 1997, St. Petersburg, FL.* 851-857. CONF-970208-Proc. DE98001967.

Blowes, D.W.; R.W. Puls; C. Ptacek; T.A. Bennett; K.U. Mayer; A.R. Pratt. 1998. "Permeable Reactive Barrier for Cr(VI) Treatment: from Concept to Implementation." *1998 American Geophysical Union Fall Meeting, 6-10 December, San Francisco, CA.*

Borden, R.C. ; R.T. Goin; C.M. Kao; C.G. Rosal. 1996. *Enhanced Bioremediation of BTEX Using Immobilized Nutrients: Field Demonstration and Monitoring.* 68 pp. EPA/600/R-96/145. PB97-186290.

Borden, Robert C.; Russell Todd Goin; Chih-Ming Kao. 1997. "Control of BTEX Migration Using a Biologically Enhanced Permeable Barrier." *Ground Water Monitoring & Remediation.* 17:1, 70-80.

Bowles, M.; L.R. Bentley; J. Barker; D. Thomas; D. Granger; H. Jacobs; S. Rimbey; B. Hoyne. 1997. "The East Garrington Trench and Gate System: It Works," *The 6th Annual Conference on Groundwater and Soil Remediation, Montreal, 18-21 June 1997.*

Bowman, Robert. 1999. "Pilot-Scale Testing of a Surfactant-Modified Zeolite PRB." *Ground Water Currents.* EPA/542/N-99/002. (Available through http://clu-in.org.)

Byerly, B.T.; W.D. Robertson. 1996. "Remediation of Landfill Leachate Using Infiltration and Reactive Barrier Technology: a Field Study." *Environmental Biotechnology: Principles and Applications*. Kluwer Academic Pub. ISBN: 0792338774. 417-430.

Caruana, Alex. 1998. "1,200-Foot Permeable Reactive Barrier in Use at the Denver Federal Center." *Ground Water Currents*. March, No. 27. (Available through http://clu-in.org.)

Chapman, S.W.; B.T. Byerly; D.J. Smyth; R.D. Wilson; D.M. Mackay. 1997. "Semi-Passive Oxygen Release Barrier for Enhancement of Intrinsic Bioremediation." *In Situ and On-Site Bioremediation: Volume 4.* Battelle Press, Columbus, OH. 209-214.

Clark, D.K.; T.L. Hineline. 1996. "Evaluation of Funnel and Gate System for In Situ Treatment of TCE Plume." *Proceedings of the 28th Mid-Atlantic Industrial and Hazardous Waste Conference, 14-17 July 1996, Buffalo, NY.* Technomic Publishing Co., Lancaster, PA. 337-341.

Clark, D.K.; T.L. Hineline; J. Vogan; S.F. O'Hannesin. 1996. "In Situ Treatment of a TCE Plume Using a Funnel and Gate System: a Case Study." *Petroleum Hydrocarbons and Organic Chemicals in Groundwater: Prevention, Detection, and Restoration. National NWWA/API Conference, November 1996, Houston, TX.* National Water Well Association. 165-174.

Clark, D.K.; J. Vogan; S. O'Hannesin. 1996. "Application of Passive Remediation for Groundwater Impacted with Chlorinated Solvents." *Remediation Management,* 4th quarter 1996.

Cole, Jason D.; Sandra Woods; Kenneth Williamson; David Roberts. 1998. "Demonstration of a Permeable Barrier Technology for Pentachlorophenol-Contaminated Groundwater." *Designing and Applying Treatment Technologies: Remediation of Chlorinated and Recalcitrant Compounds*. Battelle Press, Columbus, OH. 121-126.

Cumming, Lydia; Bruce Sass; Arun Gavaskar; Eric Drescher; Travis Williamson; Melody Drescher. 1998. "Bench-Scale Tracer Tests for Evaluating Hydraulic Performance of Permeable Barrier Media." *Designing and Applying Treatment Technologies: Remediation of Chlorinated and Recalcitrant Compounds*. Battelle Press, Columbus, OH. 97-102.

Curtis, G.P.; P.B. McMahon. 1998. "Numerical Simulation of Geochemical Reactions at a Zero Valent Iron Wall Remediation Site." *1998 American Geophysical Union Spring Meeting, 26-29 May, Boston, MA.*

Dwyer, B.P.; D.C. Marozas; K. Cantrell; W. Stewart. 1996. *Laboratory and Field Scale Demonstration of Reactive Barrier Systems.* 13 pp. SAND–96-2500. DE97001355.

Dwyer, B.P.; D.C. Marozas. 1997. "In-Situ Remediation of Uranium Contaminated Groundwater." *1997 International Containment Technology Conference and Exhibition, 9-12 February, St. Petersburg, FL.* 844-850. CONF-970208-Proc. DE98001967.

Fairweather, V. 1996. "When Toxics Meet Metal." *Civil Engineering—ASCE,* 66:5, 44-48.

Federal Remediation Technologies Roundtable. 1998. *Remediation Case Studies: Innovative Groundwater Treatment Technologies, Volume 11.* EPA/542/R-98/015. PB99-106775.

Feltcorn, Ed; Randy Breeden. 1997. "Reactive Barriers for Uranium Removal." *Ground Water Currents.* December, No. 26. (Available through http://clu-in.org.)

Focht, R.M.; R.W. Gillham. 1995. "Dechlorination of 1,2,3-Trichloropropane by Zero-Valent Iron." *The 209th American Chemical Society National Meeting, Division of Environmental Chemistry, 2-7 April 1995, Anaheim, CA. Preprint Extended Abstracts.* 35:1, 741-743.

Focht, R.; J. Vogan; S. O'Hannesin. 1996. "Field Application of Reactive Iron Walls for In-Situ Degradation of Volatile Organic Compounds in Groundwater." *Remediation,* 6:3, 81-94.

Focht, R.M.; J.L. Vogan; S.F. O'Hannesin. 1997. "Hydraulic Studies of In-Situ Permeable Reactive Barriers." *1997 International Containment Technology Conference and Exhibition, 9-12 February, St. Petersburg, FL.* 975-981. CONF-970208-Proc. DE98001967.

Fruchter, J.S.; C.R. Cole; M.D. Williams; V.R. Vermeul; S.S. Teel; J.E. Amonette; J.E. Szecsody; S.B. Yabusaki. 1997. "Creation of a Subsurface Permeable Treatment Barrier Using In-Situ Redox Manipulation." *1997 International Containment Technology Conference and Exhibition, 9-12 February, St. Petersburg, FL.* 704-710. CONF-970208-Proc. DE98001967.

Gallant, William A.; Brian Myller. 1997. "The Results of a Zero Valence Metal Reactive Wall Demonstration at Lowry AFB, Colorado." *Air & Waste Management Association's 90th Annual Meeting & Exhibition, 8-13 June 1997, Toronto, Ontario, Canada.*

Gallinati, J.D.; S.D. Warner. 1994. "Hydraulic Design Considerations for Permeable In-Situ Groundwater Treatment Walls." *Association of Groundwater Scientists and Engineers, NGWA, October 1994, Las Vegas, NV.*

Gallinati, J.D.; S.D. Warner; C.L. Yamane; F.S. Szerdy; D.A. Hankins; D.W. Major. 1995. "Design and Evaluation of an In-Situ Ground Water Treatment Wall Composed of Zero-Valent Iron." *Ground Water,* 33:5, 834-835.

Gavaskar, Arun; Neeraj Gupta; Bruce Sass; Tad Fox; Robert Jonosy. 1997. *Design Guidance for Application of Permeable Barriers to Remediate Dissolved Chlorinated Solvents.* 202 pp. NTIS. AL/EQ-TR-1997-0014. AD-A327159.

Gillham, R.W.; D.R. Burris. 1992. "Recent Developments in Permeable In Situ Treatment Walls for Remediation of Contaminated Groundwater." *Third International Conference on Ground Water Quality Research: Subsurface Restoration Conference, 21-24 June 1992, Dallas, TX.* 66-68.

Gillham, R.W.; D.W. Blowes; C.J. Ptacek; S.F. O'Hannesin. 1994. "Use of Zero-Valent Metals in In-Situ Remediation of Contaminated Ground Water." *In-Situ Remediation: Scientific Basis for Current and Future Technologies—33rd Hanford Symposium on Health and the Environment.* Battelle Press, Columbus, OH. Part 2, 913-930.

Gillham, R.W.; S.O. O'Hannesin; S. Orth; J. Vogan. 1996. "Field Applications of Metal Enhanced Dehalogenation of Chlorinated Organic Contaminants." *WEFTEC '95: 68th Annual Conference & Exposition of the Water Environment Federation, 21-25 Oct 1995, Miami Beach, FL.* Water Environment Federation, Alexandria, VA. p 224. CONF-951023.

Gillham, R. W.; S. F. O'Hannesin; M. S. Odziemkowski; R. A. Garcia-Delgado; R. M. Focht; W. H. Matulewicz; J. E. Rhodes. 1997. "Enhanced Degradation of VOCs: Laboratory and Pilot-Scale Field Demonstration." *1997 International Containment Technology Conference, 9-12 February, St. Petersburg, FL.* 858-863.

Gillham, R.W.; D.R. Burris. 1997. "Recent Developments in Permeable in Situ Treatment Walls for Remediation of Contaminated Groundwater." *Subsurface Restoration,* Ann Arbor Press, Chelsea, MI. 343-356.

Gillham, R. 1998. "In Situ Remediation of Groundwater Using Granular Iron: Case Studies." *Subsurface Barrier Technologies Conference: Engineering Advancements and Application Considerations for Innovative Barrier Technologies, 26-27 January 1998, Tucson, AZ.* International Business Communications, Southborough, MA.

Gravelding, D. 1998. "Design and Construction of a 1200 Foot Funnel & Gate System." *Subsurface Barrier Technologies Conference: Engineering Advancements and Application Considerations for Innovative Barrier Technologies, 26-27 January 1998, Tucson, AZ.* International Business Communications, Southborough, MA.

Gupta, N.; B.M. Sass; A.R. Gavaskar; J.R. Sminchak; T.C. Fox; F.A. Snyder; D. O'Dwyer; C. Reeter. 1998. "Hydraulic Evaluation of a Permeable Barrier Using Tracer Tests, Velocity Measurements, and Modeling." *Designing and Applying Treatment Technologies: Remediation of Chlorinated and Recalcitrant Compounds.* Battelle Press, Columbus, OH. 157-162.

Haigh, Dale. 1997. "Reactive Barrier System Reduces TCE in Northern Ireland Installation." *Water Online,* 08/05/97. (Available at http://news.wateronline.com/case-studies/CS707292.html.)

Hayes, Joseph J.; Donald L. Marcus. 1997. "Design of a Permeable Reactive Barrier In Situ Remediation System, Vermont Site." *In Situ Remediation of the Geoenvironment.* American Society of Civil Engineers, Reston, VA. Geotechnical Special Publication No. 71, 56-67.

Hubble, D.W.; R.W. Gillham; J.A. Cherry. 1997. "Emplacement of Zero-Valent Iron for Remediation of Deep Containment Plumes." *1997 International Containment Technology Conference, 9-12 February, St. Petersburg.* 872-878. CONF-970208-Proc. DE98001967.

Janosy, R. J.; J. E. Hicks; D. O`Sullivan. 1998. "Site Characterization to Aid in the Design of a Permeable Barrier at Dover AFB." *Designing and Applying Treatment Technologies: Remediation of Chlorinated and Recalcitrant Compounds.* Battelle Press, Columbus, OH. 127-132.

Jefferis, S.A.; G.H. Norris; A.O. Thomas. 1997. "Developments in Permeable and Low Permeability Barriers." *1997 International Containment Technology Conference and Exhibition, 9-12 February, St. Petersburg, FL.* 817-826. CONF-970208-Proc. DE98001967.

Jefferis, Stephan A.; Graham H. Norris. 1998. "Reactive Treatment Zones: Concepts and a Case History." *NATO/CCMS Pilot Study: Evaluation of Demonstrated and Emerging Technologies for the Treatment of Contaminated Land and Groundwater—Phase III. Session on Treatment Walls and Permeable Reactive Barriers, No. 229.* 66-76. EPA/542/R-98/003.

Korte, Nic; Olivia R. West; Liyuan Liang; Mark J. Pelfrey; Thomas C. Houk. 1997. "A Field-Scale Test Facility for Permeable Reactive Barriers at the Portsmouth Gaseous Diffusion Plant." *Federal Facilities Environmental Journal.* 8:3, 105-104.

Lee, David R.; David J.A. Smyth; Steve G. Shikaze; Robin Jowett; Dale S. Hartwig; Claire Milloy. 1998. "Wall-and-Curtain for Passive Collection/Treatment of Contaminant Plumes." *Designing and Applying Treatment Technologies: Remediation of Chlorinated and Recalcitrant Compounds.* Battelle Press, Columbus, OH. 77-84.

Liang, L.; O.R. West; N.E. Korte; et al. 1997. *The X-625 Groundwater Treatment Facility: A Field-Scale Test of Trichloroethylene Dechlorination Using Iron Filings for the X-120/X-749 Groundwater Plume.* 71 pp. ORNL/TM--13410. DE98007047.

Mackenzie, P. D.; S. S. Baghel; G. R. Eykholt; D. P. Horney; J. J. Salvo; T. M. Sivavec. 1995. "Pilot-Scale Demonstration of Reductive Dechlorination of Chlorinated Ethenes by Iron Metal." *The 209th National Meeting of the American Chemical Society, Anaheim, CA. Preprint Extended Abstracts, Division of Environmental Chemistry.* 35:1, 796-799.

Manz, C.; K. Quinn. 1997. "Permeable Treatment Wall Design and Cost Analysis." *1997 International Containment Technology Conference and Exhibition, 9-12 February, St. Petersburg, FL.* 788-794. CONF-970208-Proc. DE98001967.

Marcus, Donald L.; James Farrell. 1998. "Reactant Sand-Fracking Pilot Test Results." *Designing and Applying Treatment Technologies: Remediation of Chlorinated and Recalcitrant Compounds*. Battelle Press, Columbus, OH. 85-90.

Mayer, K.U.; D.W. Blowes; E.O. Frind. 1998. "Formulation of the Model MIN3P and Its Application to an In-Situ Reactive Barrier." *1998 American Geophysical Union Spring Meeting, 26-29 May, Boston, MA.*

Morkin, Mary; J. Barker; R. Devlin; Michaye McMaster. 1998. "In Situ Sequential Treatment of a Mixed Organic Plume Using Granular Iron, O_2 and CO_2 Sparging." *Designing and Applying Treatment Technologies: Remediation of Chlorinated and Recalcitrant Compounds*. Battelle Press, Columbus, OH. 289-294.

Morrison, Stan. 1998. *Research and Application of Permeable Reactive Barriers*. U.S. Department of Energy, Grand Junction Office. 50 pp. (Available at http://www.gwrtac.org/html/tech_status.html)

Morrison, Stan. 1998. "Fry Canyon Demonstration Project." *Subsurface Barrier Technologies Conference: Engineering Advancements and Application Considerations for Innovative Barrier Technologies, 26-27 January 1998, Tucson, AZ.* International Business Communications, Southborough, MA.

Muza, Richard. 1997. "Reactive Walls Demonstrated." *Ground Water Currents*. April, No. 24. (Available through http://clu-in.org.)

Naftz, D.L. 1997. "Field Demonstration of Reactive Chemical Barriers to Control Radionuclide and Trace-Element Contamination in Ground Water, Fry Canyon, Utah." *1997 GSA Annual Meeting, 20-23 October 1997, Salt Lake City, UT.* A-335.

Naftz, D.L.; G.W. Freethey; J.A. Davis; R. Breeden; E. Feltcorn; R. Wilhelm; R.R. Spangler; S.J. Morrison; B. Lewis; J. Brown. 1997. "Hydrologic Characterization of the Fry Canyon, Utah Site Prior to Field Demonstration of Reactive Chemical Barriers to Control Radionuclide and Trace-Element Contamination in Groundwater." *1997 International Containment Technology Conference and Exhibition, 9-12 February, St. Petersburg, FL.* 725-729. CONF-970208-Proc. DE98001967.

O'Brien, K.; G. Keyes; N. Sherman. 1997. "Implementation of a Funnel-and-Gate Remediation System." *1997 International Containment Technology Conference and Exhibition, 9-12 February, St. Petersburg, FL.* 895-901. CONF-970208-Proc. DE98001967.

O'Hannesin, S.F.; R.W. Gillham. 1992. "A Permeable Reaction Wall for In Situ Degradation of Halogenated Organic Compounds." *The 45th Canadian Geotechnical Society Conference, 25-28 October 1992, Toronto, Ontario.*

O'Hannesin, S.F.; R.W. Gillham. 1993. "In Situ Degradation of Halogenated Organics by Permeable Reaction Wall." *Ground Water Currents,* March. EPA/542/N-93/003. (Available through http://clu-in.org)

O'Hannesin, S.F.; R.W. Gillham. 1998. "Long-Term Performance of an In Situ 'Iron Wall' for Remediation of VOCs." *Ground Water.* 36:1, 164-170.

Porter, J. 1998. "Greening Process." *Ground Engineering,* 31:7, 32-33.

Powell, R.M.; R.W. Puls; D.W. Blowes; R.W. Gillham; D. Schultz. 1998. *Permeable Reactive Barrier Technologies for Contaminant Remediation.* 114 pp. EPA/600/R-98/125. (Also available at http://www.epa.gov/ada/reports.html)

Puls, R. W.; D. A. Clark; C. J. Paul; J. Vardy. 1994. "Transport and Transformation of Hexavalent Chromium Through Soils and into Ground Water." *Journal of Soil Contamination,* 3:2, 203-224. (Also available from NTIS as EPA/600/J-94/315. Order PB94-197597.)

Puls, R. W.; R. M. Powell; C. J. Paul. 1995. "In Situ Remediation of Ground Water Contaminated with Chromate and Chlorinated Solvents Using Zero-Valent Iron: a Field Study." *The 209th National Meeting of the American Chemical Society, Anaheim, CA. Preprint Extended Abstracts, Division of Environmental Chemistry.* 35:1, 788-791.

Puls, R. W.; C. J. Paul; R. M. Powell. 1996. "In Situ Immobilization and Detoxification of Chromate-Contaminated Ground Water Using Zero-Valent Iron: Field Experiments at the USCG Support Center, Elizabeth City, North Carolina." *The 4th Great Lakes Geotechnical and Geoenvironmental Conference: In-Situ Remediation of Contaminated Sites, University of Illinois, Chicago, IL.* 69-77. (Paper also available from NTIS. Order PB96-169313.)

Puls, R.W.; C.J. Paul; R.M. Powell. 1996. "Remediation of Chromate-Contaminated Ground Water Using Zero-Valent Iron: Field Test at USCG Support Center, Elizabeth City, North Carolina." *The 9th Annual Conference on Hazardous Waste Remediation: 1996 HSRC/WERC Joint Conference on the Environment.* Kansas State University, Manhattan, KS. 69-77. (Paper also available from NTIS. Order PB97-122915.)

Puls, R.W.; D.W. Blowes; R.M. Powell; D.S. Schultz; J. Vogan. 1997. *NGWA Workshop on Permeable Reactive Barriers in Ground Water.* 10 pp. EPA/600/A-97/029. PB97-192827.

Puls, R.W.; C.J. Paul; P.J. Clark. 1997. "Remediation of Chromate-Contaminated Ground Water Using an In-Situ Permeable Reactive Mixture: Field Pilot Test, Elizabeth City, North Carolina." *The 213th National Meeting of the American Chemical Society, San Francisco, CA. Preprint Extended Abstracts, Division of Environmental Chemistry*. 37:1. 241-243. (Paper also available from NTIS as EPA/600/A-97/002. Order PB97-192819)

Puls, Robert W.; Robert W. Powell. 1997. *Permeable Reactive Subsurface Barriers for the Interception and Remediation of Chlorinated Hydrocarbon and Chromium(VI) Plumes in Ground Water*. 4 pp. EPA/600/F-97/008. (Available at http://www.epa.gov/ada.)

Puls, R. W. 1998. "Remediation of Ground Water Using In-Situ Permeable Reactive Barriers: Chromate and Other Inorganic Contaminants." *Water Resources and the Urban Environment '98, Proceedings of the National Conference on Environmental Engineering*, American Society of Civil Engineers. Chicago, IL. 116-121. (Paper also available from NTIS as EPA/600/A-98/043. Order PB98-135122.)

Puls, R. W.; D.W. Blowes; R.W. Gillham. 1998. "Emplacement Verification and Long-term Performance Monitoring for Permeable Reactive Barrier at the USCG Support Center, Elizabeth City, North Carolina." *International Conference on Groundwater Quality, Tubingen, Germany.* (Paper also available From NTIS as EPA/600/A-98/085. Order PB98-151285.)

Puls, Robert W. 1998. "Permeable Reactive Barrier Research at the National Risk Management Research Laboratory, U.S. Environmental Protection Agency." *NATO/CCMS Pilot Study: Evaluation of Demonstrated and Emerging Technologies for the Treatment of Contaminated Land and Groundwater—Phase III. Special Session on Treatment Walls and Permeable Reactive Barriers, No. 229.* 3-5. EPA/542/R-98/003.

Puls, R.W.; R.M. Powell; C.J. Paul; D. Blowes. 1998. "Ground Water Remediation of Chromium Using Zero-Valent Iron in a Permeable Reactive Barrier." *Field Testing of Innovative Subsurface Remediation Technologies, American Chemical Society Symposium, 13-17 April 1997, San Francisco, CA.* (Paper also available from NTIS as EPA/600/A-98/108. Order PB98-155088.)

Reeter, Charles; Arun Gavaskar; Neeraj Gupta; Bruce Sass. 1998. "Permeable Reactive Wall Remediation of Chlorinated Hydrocarbons in Groundwater: NAS Moffett Field, Mountain View, California." *After the Rain Has Fallen: 2nd International Water Resources Engineering Conference, 3-7 August 1998, Memphis, TN.* American Society of Civil Engineers, Reston, VA. 153-158.

Robertson, W.D.; D.W. Blowes; C.J. Ptacek; J.A. Cherry. 1995. "Waterloo Denitrification Barrier: Longer Term Performance of Pilot Scale Field Trials." *Proceedings of the Waterloo Centre for Groundwater Research Annual Septic System Conference—Alternative Systems: Nutrient Removal and Pathogenic Microbes, 15 May 1995, Waterloo, Ontario.* 16-27.

Robertson, W.D.; J.A. Cherry. 1995. "In Situ Denitrification of Septic-System Nitrate Using Reactive Porous Media Barriers: Field Trials." *Ground Water*. 33:1, 99-111.

Robertson, W.D.; J.A. Cherry. 1997. "Long-Term Performance of the Waterloo Denitrification Barrier." *1997 International Containment Technology Conference and Exhibition, 9-12 February, St. Petersburg, FL*. 691-696. CONF-970208-Proc. DE98001967.

Romer, James R.; Stephanie O'Hannesin. 1998. "Use of Continuous Trenching Technique to Install Iron Permeable Barriers." *Designing and Applying Treatment Technologies: Remediation of Chlorinated and Recalcitrant Compounds*. Battelle Press, Columbus, OH. 139-143.

Rose, Alan. 1998. "An 'Underground Plan' to Capture Radioactivity." *North Renfrew Times*, May 6, 1998.

Roy, S.J.; Z. Li; K. Hildenbrand; R.S. Bowman; R.L. Johnson; T.L. Johnson; M. Perrott. 1998. "A Surfactant-Modified Zeolite Permeable Barrier for the Remediation of Chrome and PCE: Pilot Study Results." *WERC-WRHSRC-NMHWMS '98 Joint Conference on the Environment, 31 March-2 April 1998, Albuquerque, NM.*

Sabatini, David A.; Robert C. Knox; Edwin E. Tucker; Robert W. Puls. 1997. *Environmental Research Brief. Innovative Measures for Subsurface Chromium Remediation: Source Zone, Concentrated Plume, and Dilute Plume.* 16 pp. EPA/600/S-97/005. (Available at http://www.epa.gov/ada/)

Sass, Bruce M.; Arun R. Gavaskar; Neeraj Gupta; Woong-Sand Yoon; James E. Hicks; Deirdre O'Dwyer; Charles Reeter. 1998. "Evaluating the Moffett Field Permeable Barrier Using Groundwater Monitoring and Geochemical Modeling." *Designing and Applying Treatment Technologies: Remediation of Chlorinated and Recalcitrant Compounds*. Battelle Press, Columbus, OH. 169-175.

Schad, Hermann; Peter Grathwohl. 1998. "Funnel-and-Gate Systems for In Situ Treatment of Contaminated Groundwater at Former Manufactured Gas Plant Sites." *NATO/CCMS Pilot Study: Evaluation of Demonstrated and Emerging Technologies for the Treatment of Contaminated Land and Groundwater—Phase III. Special Session on Treatment Walls and Permeable Reactive Barriers, No. 229.* 56-65. EPA/542/R-98/003.

Schmithorst, W.L.; J.A. Vardy. 1997. "RCRA Corrective Measures Using a Permeable Reactive Iron Wall: U.S. Coast Guard Support Center, Elizabeth City, North Carolina." *1997 International Containment Technology Conference and Exhibition, 9-12 February, St. Petersburg, FL*. 795-800. CONF-970208-Proc. DE98001967.

Scott, M.J.; F.B. Metting; J.S. Fruchter; R.E. Wildung. 1998. "Research Investment Pays Off." *Soil and Groundwater Cleanup,* October 1998, 6-13.

Shelp, G.S.; W. Chesworth; G. Spiers. 1995. "The Amelioration of Acid Mine Drainage by an in Situ Electrochemical Method. I. Employing Scrap Iron as the Sacrificial Anode." *Applied Geochemistry.* (10): 705-713.

Shoemaker, S.H.; J.F. Greiner; R.W. Gillham. 1995. "Permeable Reactive Barriers. Assessment of Barrier Containment Technologies: a Comprehensive Treatment for Environmental Applications." *Barrier Containment Technologies for Environmental Remediation Applications.* NTIS. Chapter 11, 301-353.

Smith, M.H.; J.A. Stinson; D. O'Sullivan; R.S. Wolf. 1997. "Permeable Barrier Demonstration." *Military Engineer.* No.586, p 56.

Smyth, D.J.A.; J.A. Cherry; R.J. Jowett. 1994. "Funnel-and-Gate for In Situ Groundwater Plume Containment." *Superfund XV, 28 November-1 December 1994, WA, D.C.*

Smyth, D.J.A.; B.T. Byerley; S.W. Chapman; R.D. Wilson; D.M. Mackay. 1995. "Oxygen-Enhanced In Situ Biodegradation of Petroleum Hydrocarbons in Groundwater Using a Passive Interception System." *The 5th Annual Symposium on Groundwater and Soil Remediation, 2-6 October 1995, Toronto.* EPS Publications, Hull, PQ, Canada. ISBN: 0-660-59979-1. 23-34.

Starr, R.C.; J.A. Cherry. 1994. "In Situ Remediation of Contaminated Ground Water: the Funnel-and-Gate System." *Ground Water.* 32:3, 465-476.

Steimle, R. 1995. *In Situ Remediation Technology Status Report: Treatment Walls.* U.S. EPA, Office of Solid Waste and Emergency Response. 31 pp. EPA/542/K-94/004. (Available in PDF at http://www.epa.gov/swertio1/pubitech.html)

Szerdy, Frank S.; John D. Gallinatti; Scott D. Warner; Carol L. Yamane; Deborah A. Hankins; John L. Vogan. 1996. "In Situ Groundwater Treatment by Granular Zero-Valent Iron: Design, Construction and Operation of an In Situ Treatment Wall." *Non-Aqueous Phase Liquids (NAPLs) in Subsurface Environment: Assessment and Remediation.* American Society of Civil Engineers, Reston, VA. ISBN: 0-7844-0203-5, 245-256.

Tratnyek, Paul G. 1996. "Putting Corrosion to Use: Remediating Contaminated Groundwater with Zero-Valent Metals." *Chemistry & Industry*, 1 July 1996, No. 13, 499-503.

U.S. EPA.1996. *A Citizen's Guide to Treatment Walls.* 4 pp. EPA/542/F-96/016. (Available at http://www.clu-in.org/pub1.htm)

U.S. EPA.1997. *SITE Technology Capsule: Metal Enhanced Dechlorination of Volatile Organic Compounds Using an Aboveground Reactor, EnviroMetal Technologies, Inc.* 8 pp. EPA/540/R-96/503a.

U.S. EPA. 1997. *Innovative Technology Evaluation Report. Metal Enhanced Dechlorination of Volatile Organic Compounds Using an Aboveground Reactor, EnviroMetal Technologies, Inc.* 94 pp. EPA/540/R-96/503.

U.S. EPA. 1998. *Innovative Technology Evaluation Report. EnviroMetal Technologies, Inc.: Metal-Enhanced Dechlorination of Volatile Organic Compounds Using an In-Situ Reactive Iron Wall.* 105 pp. EPA/540/R-98/501.

U.S. EPA. 1998. *NATO/CCMS Pilot Study: Evaluation of Demonstrated and Emerging Technologies for the Treatment of Contaminated Land and Groundwater—Phase III. Special Session on Treatment Walls and Permeable Reactive Barriers, No. 229.* 114 pp. EPA/542/R-98/003. (Available in PDF at http://www.clu-in.org/partner1.htm)

U.S. EPA. 1998. "Permeable Treatment Beds." *NATO/CCMS Pilot Study: Evaluation of Demonstrated and Emerging Technologies for the Treatment of Contaminated Land and Groundwater (Phase III) 1998 Annual Report, No. 228.* 11-13. EPA 542-R-98-002. (The full document is available in PDF at http://www.clu-in.org/partner1.htm)

U.S. EPA. 1998. "Permeable Reactive Barriers for In Situ Treatment of Chlorinated Solvents." *NATO/CCMS Pilot Study: Evaluation of Demonstrated and Emerging Technologies for the Treatment of Contaminated Land and Groundwater (Phase III) 1998 Annual Report, No. 228.* 36-37. EPA 542-R-98-002. (The full document is available in PDF at http://www.clu-in.org/partner1.htm)

Vidic, Radisav D.; Frederick G. Pohland. 1996. *Treatment Walls.* Ground-Water Remediation Technologies Analysis Center (GWRTAC), Pittsburgh, PA. TE-96-01. (Available at http://www.gwrtac.org)

Vogan, J.L.; R.W. Gillham; S.F. O'Hannesin; W.H. Matulewicz; J.E. Rhodes. 1995. "Site Specific Degradation of VOCs in Groundwater Using Zero-Valent Iron." *The 209th American Chemical Society Meeting, 2-7 April 1995, Anaheim, CA. Preprint Extended Abstracts, Division of Environmental Chemistry.* 35:1, 800-804.

Vogan, J.; T.A. Krug; D. Major. 1996. "Cost Effective In Situ Remediation of Chlorinated VOCs Using Permeable Iron Reactive Walls." *HazMat International '96: 14th Annual International Environmental Management and Technology Conference, 18-20 June 1996, Atlantic City, NJ.* Advanstar Expositions. 221-227.

Vogan, J.L.; SF. O'Hannesin; A. Mace; D.K. Clark. 1996. "Evaluation of an In Situ Application of the EnviroMetal Process at a Former Industrial Facility." *The AIChe 1996 Spring National Meeting, February, New Orleans, LA.*

Vogan, J.L.; B.J. Butler; M.S. Odziemkowski; G. Friday; R.W. Gillham. 1998. "Inorganic and Biological Evaluation of Cores from Permeable Iron Reactive Barriers." *Designing and Applying Treatment Technologies: Remediation of Chlorinated and Recalcitrant Compounds.* Battelle Press, Columbus, OH. ISBN: 1-57477-061-6. 163-168.

Warner, S.D.; J.D. Gallinatti; J.H. Honniball. 1995. "The Use of Field Redox Measurements in Assessing Remediation of Ground Water Containing Petroleum Hydrocarbons and Chlorinated Organic Compounds." *Ground Water,* 33:5, 857-858.

Warner, S.D.; C.L. Yamane; J.D. Gallinati; F.S. Szerdy; D.A. Hankins. 1995. "Assessing the Feasibility of Permeable Reactive Barriers for Treating VOC-Affected Groundwater In Situ: Experience from the First Full-Scale Commercial Application in California." *International Containment Technology Workshop, Permeable Reactive Barriers Subgroup, 29-31 August 1995, Baltimore, MD.*

Warner, S.D.; C.L. Yamane; J.D. Gallinati; F.S. Szerdy; D.A. Hankins. 1997. "Permeable Reactive Barriers for Treating VOC-Affected Groundwater: Revisiting the Sunnyvale 'Iron Wall.'" *Environmental Management and Technology Conference, 5 November 1997, Long Beach, CA.* 269-282.

Warner, S.D. 1998. "The Feasibility of Permeable Reactive Barriers for in Situ Groundwater Treatment: the Sunnyvale 'Iron Wall' and Beyond." *Subsurface Barrier Technologies Conference: Engineering Advancements and Application Considerations for Innovative Barrier Technologies, 26-27 January 1998, Tucson, AZ.* International Business Communications, Southborough, MA.

Warner, Scott D.; Carol L. Yamane; John D. Gallinatti; Deborah A. Hankins. 1998. "Considerations for Monitoring Permeable Ground-Water Treatment Walls." *Journal of Environmental Engineering.* 124:6, 524-529.

Warner, Scott D.; Carol L. Yamane; N.T. Bice; F.S. Szerdy; J. Vogan; D.W. Major; D.A. Hankins. 1998. "Technical Update: the First Commercial Subsurface Permeable Reactive Treatment Zone Composed of Granular Zero-Valent Iron." *Designing and Applying Treatment Technologies: Remediation of Chlorinated and Recalcitrant Compounds.* Battelle Press, Columbus, OH. 145-150.

Watson, D.; M. Leavitt; C. Smith; T. Klasson; B. Bostick; L. Liang; D. Moss. 1997. "Bear Creek Valley Characterization Area Mixed Wastes Passive In Situ Treatment Technology Demonstration Project Status Report." *1997 International Containment Technology Conference, St. Petersburg, FL.* 730-736. CONF-970208-Proc. DE98001967.

Watson, David; Baohua Gu; Will Goldberg; Steve Dunstan; Elizabeth Rasor. 1998. "Installation and Design of Two Reactive Barriers for Treatment of Uranium and Other Contaminants at the S-3 Pond Site, Oak Ridge Y-12 Plant." *Subsurface Barrier Technologies Conference: Engineering Advancements and Application Considerations for Innovative Barrier Technologies, 26-67 January 1998, Tucson, AZ.* International Business Communications, Southborough, MA.

Weiss, H.; F.-D. Kopinke; P. Popp; L. Wunsche. 1998. "In Situ Remediation Research in a Complexly Contaminated Aquifer: the SAFIRA Test Site at Bitterfeld, Germany." *NATO/CCMS Pilot Study: Evaluation of Demonstrated and Emerging Technologies for the Treatment of Contaminated Land and Groundwater—Phase III. Special Session on Treatment Walls and Permeable Reactive Barriers, No. 229.* 84-91. EPA/542/R-98/003.

Wilson, E.K. 1995. "Zero-Valent Metals Provide Possible Solution to Groundwater Problems." *Chemical & Engineering News,* 73:27, 19-22.

Yamane, C.L.; S.D. Warner; J.D. Gallinati; F.S. Szerdy; T.A. Delfino; D.A. Hankins; J.L. Vogan. 1995. "Installation of a Subsurface Groundwater Treatment Wall Composed of Granular Zero-Valent Iron." *Proceedings of the 209th American Chemical Society National Meeting, 2-7 April 1995, Anaheim, CA. Preprints,* 35:1, 792-795.

—. 1998. "Field Testing of a Permeable Reactive Zone." *Underground Tank Technology Update,* 12:5 (Sept/Oct), 5-6.

—. 1997. "Iron Constitution: Golders Pioneers First European Use of a Reactive Barrier System for Groundwater Remediation." Ground Engineering. 30:6, 20.

—. 1997. "Nifty Iron Wall to Confront Caldwell Plume." *Superfund Week,* 11:27, July 11.

—. 1998. "Reactive Iron Walls Offer Passive Ground-Water Restoration." *Hazardous Waste Consultant,* 16:2 (Mar/Apr) 1.2-1.6.