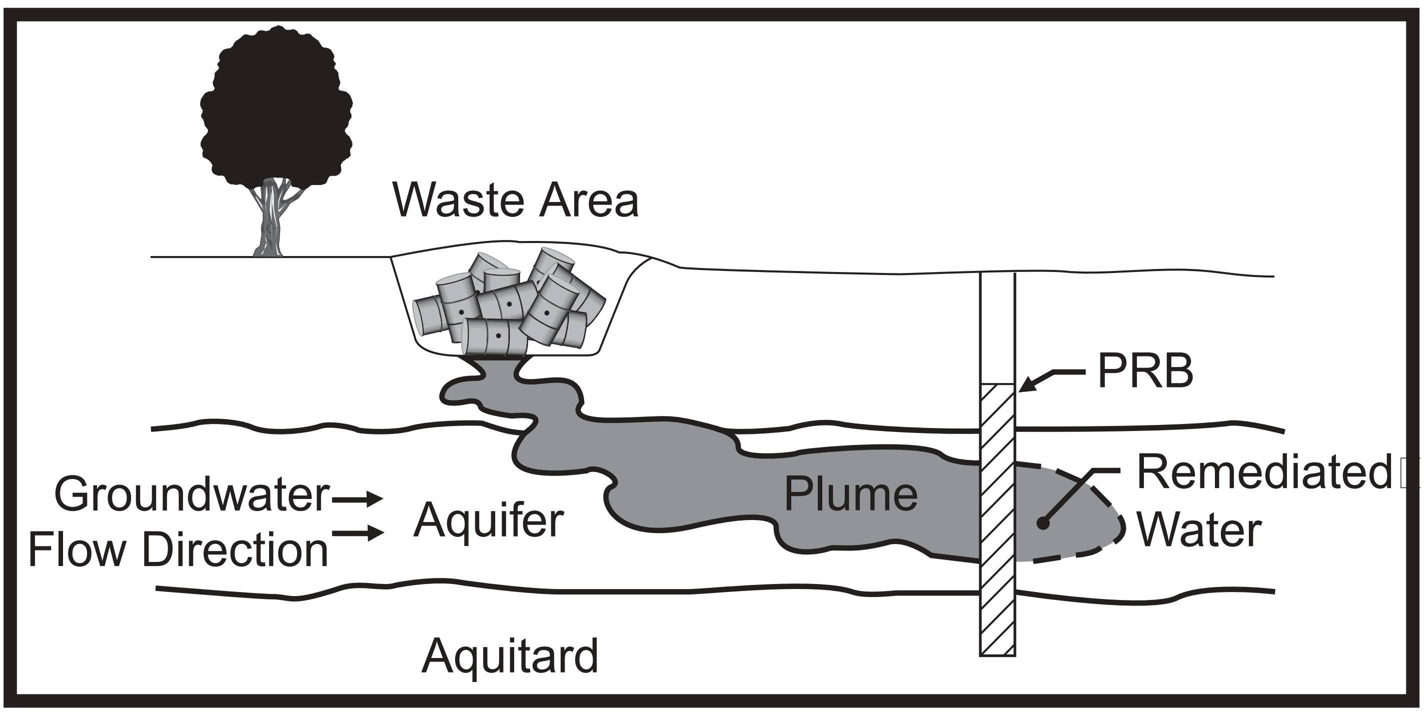
Field Applications of *In Situ* Remediation Technologies: Permeable Reactive Barriers



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

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Notice

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Introduction

A permeable reactive barrier (PRB) contains or creates a reactive treatment zone oriented to intercept and remediate a contaminant plume. It removes contaminants from the groundwater flow system in a passive manner by physical, chemical or biological processes. Some PRBs are installed as permanent or semi-permanent units across the flow path of a contaminant plume. Some PRBs are installed as *in situ* reactors that are readily accessible to facilitate the removal and replacement of reactive media. Most have the reactive media installed or created in intimate contact with the surrounding aquifer material.

This report summarizes information about the use of PRBs for groundwater remediation at 47 sites in the United States, Canada, and selected locations abroad. PRB sites included were identified by the Remediation Technologies Development Forum (RTDF) Permeable Reactive Barriers Action Team members, and information was provided by the points-of-contact listed. The U.S. Environmental Protection Agency's (EPA) Technology Innovation Office has prepared this document to assist potential PRB users in making more informed decisions related to their respective sites.

Complete profiles of these sites are available on the Remediation Technologies Development Forum/Permeable Reactive Barriers Action Team's Internet site (*www.rtdf.org/public/permbarr/prbsumms/default.cfm*).

In addition to the site-by-site information included (pages 9-23), charts and graphs at the end of this section of the report summarize overall statistics concerning the sites profiled. For example, Figure 1 (page 4) shows that PRBs were used for full-scale cleanup at most of the sites profiled and provides a breakdown of these sites by the category of contaminants treated. Figure 2 (page 4) shows the breakdown of U.S., Canadian, and European sites profiled by contaminant groups. Figure 3 (page 5) illustrates that the profiles are almost evenly divided between Federal and private-sector sites, and Figure 4 (page 5) shows the types of barriers used at these sites. Figure 5 (page 6) illustrates that, while zero-valent iron (Fe^0) was the most frequently used reactive medium, a variety of other media or media mixtures are available and have been used in PRBs.

Internet versions of the PRB profiles are updated periodically as new information is received. Profile information for PRB sites that are currently not in the database may be submitted on-line at *www.rtdf.org/public/permbarr/prbsumms/default.cfm* by clicking on the "Submit New Profile" button at the top of the page.

The RTDF/PRB Action Team was established in 1995. Its members include representatives from government, academia, and the private sector working as partners to further public and regulatory acceptance of PRBs for remediating chlorinated solvents, metals, radionuclides, and other groundwater pollutants.

Figure 1

PRB Sites by Scale and Contaminant

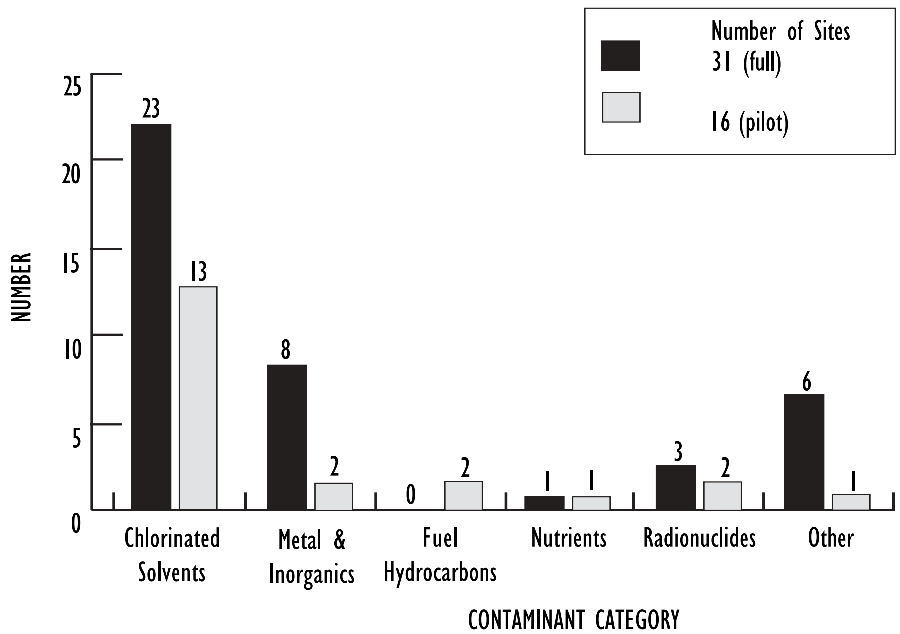


Figure 2

Profiled PRB Sites by Location and Contaminant

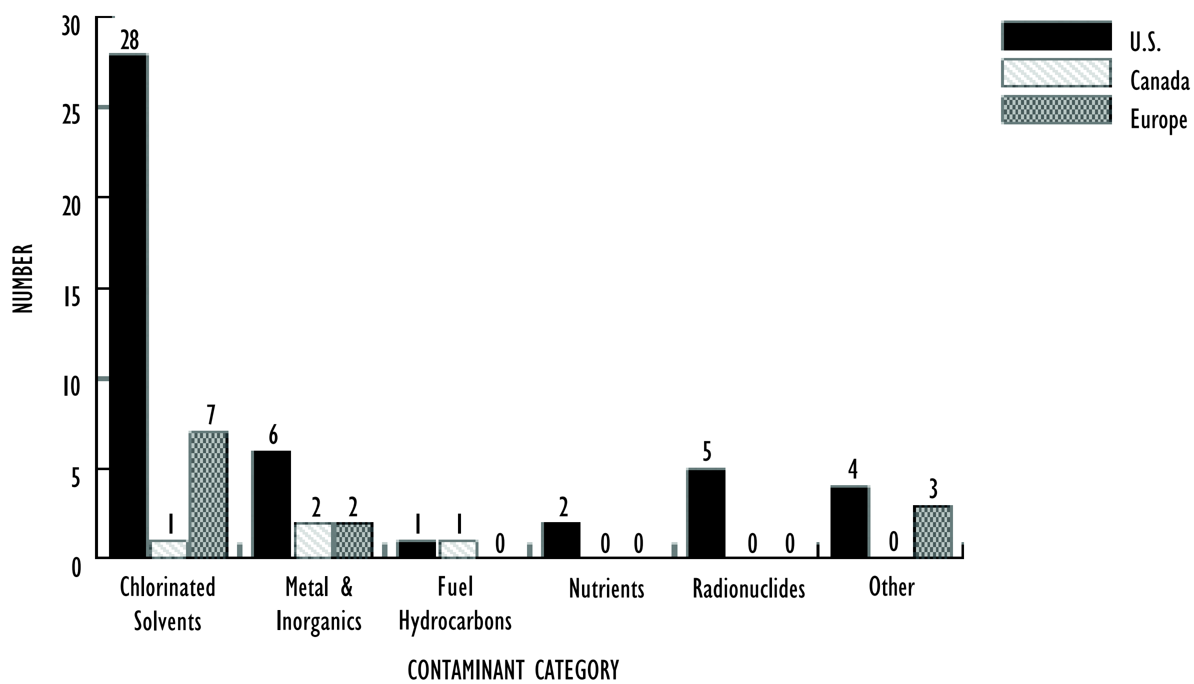


Figure 3

PRB Sites by Private and Government Sectors

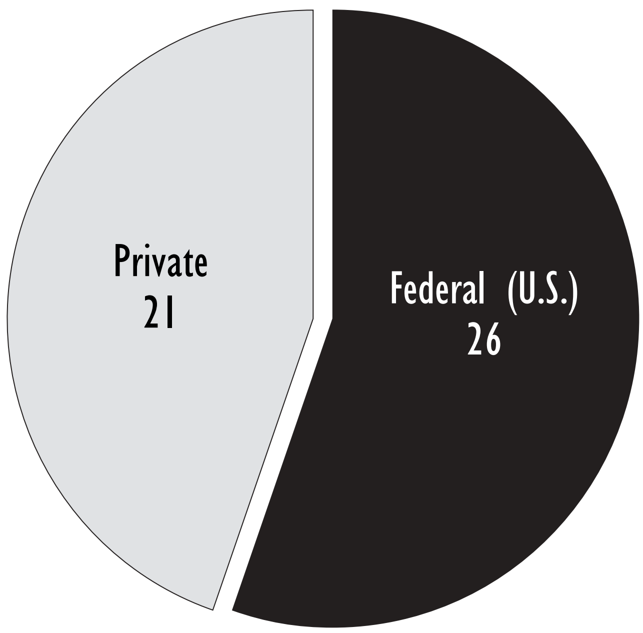


Figure 4

PRB Sites by Type of Barrier

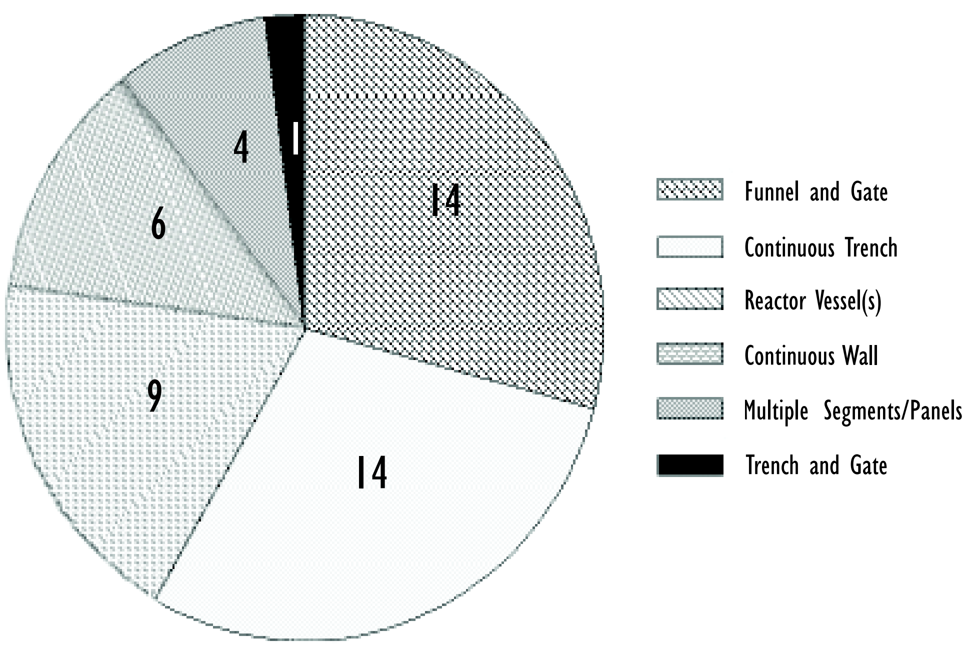
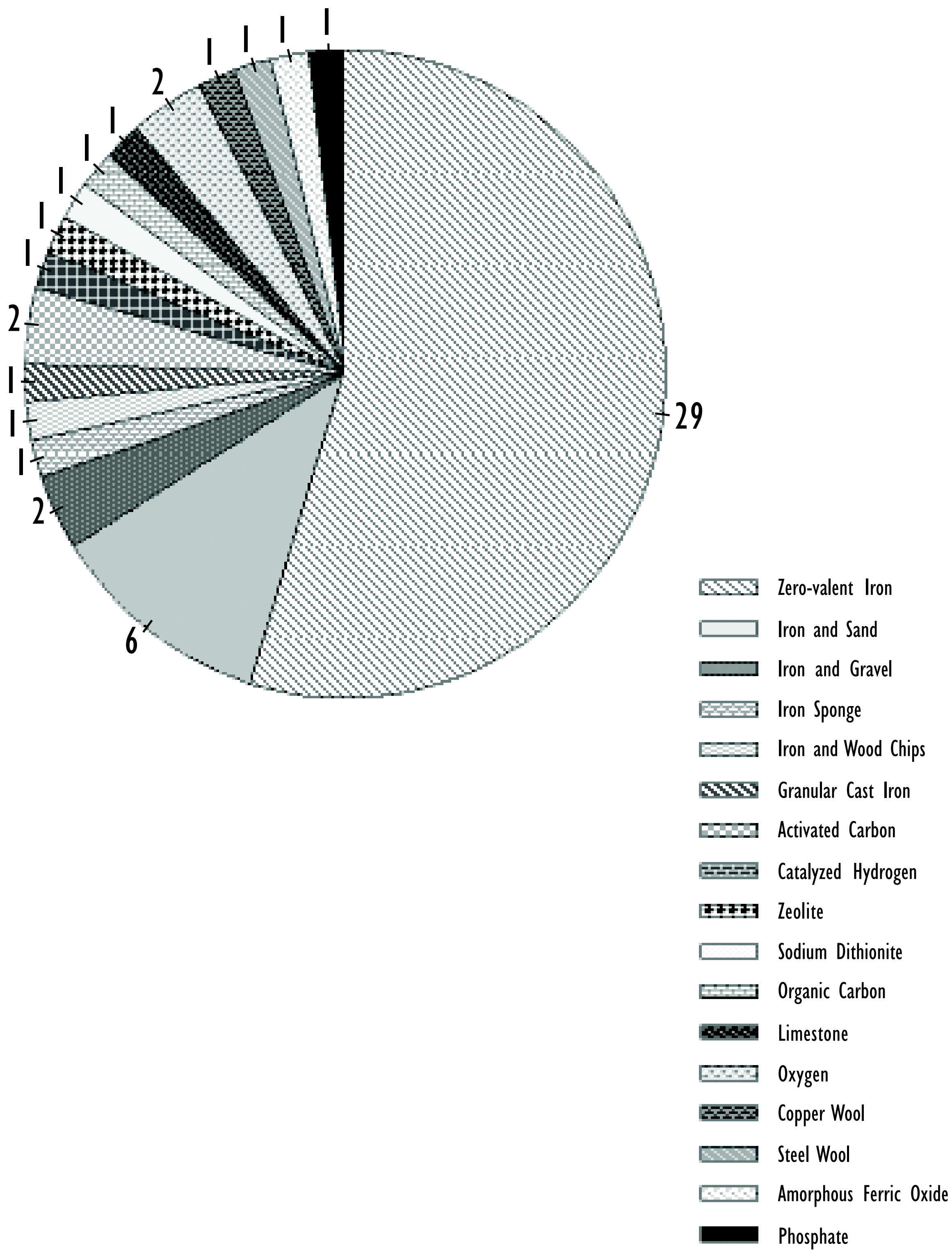


Figure 5

PRB Sites by Reactive Medium Used



Abbreviations Used in This Document

AFO	amorphous ferric oxide
As	arsenic
bgs	below ground surface
BHC	alpha-hexachlorobenzene
Bq	Becquerel
BTEX	benzene, toluene, ethylbenzene, xylene
CaCO3	calcium carbonate
CB	cement bentonite
Cd	cadmium
Cr^{+6}	chromium, chromate
Cu	copper
DCA	dichloroethane
DCB	dichlorobenzene
DCE	dichloroethylene
DCM	dichloromethane
DDD	$(ClC_6H_4)_2CHCHCl_2$; an insecticide with properties similar to DDT
DDT	$C_{14}H_9C_{15}$; a water-insoluble crystalline insecticide
DNAPL	dense nonaqueous-phase liquid
DSM	Deep Soil Mixing
Eh	Electrochemical Potential
Fe^0, ZVI	zero-valent iron
FeCO3	iron carbonate
Fe[OH]2	iron hydroxide
FeS	iron sulfide
Freon 11	trichlorofluoromethane
Freon 13	trichlorotrifluoroethane
Freon 113®	1,1,2-Trichloro-1,2,2-trifluorethane
ft	foot, feet
g	gram, grams
gpm	gallons per minute
HC	hydrocarbon
HDPE	high-density polyethylene
in	inch, inches
K	Kelvin
kg	kilograms
L	litre
MCB	chlorobenzene
MCL	Maximum Contaminant Level
mg	milligram, milligrams
Mn	manganese
mv	millivolts
Mo	molybdenum
Ni	nickel
O_2	oxygen
OU	operable unit
PAH	polynuclear aromatic hydrocarbon
Pb	lead
PCE	perchloroethylene, tetrachloroethylene
pCi	picoCuries
PO_4	bone char phosphate
PRB	permeable reactive barrier
s, sec	second, seconds

Se	selenium
Sr-90	strontium
Tc	technetium
TCA	trichloroethane
TCE	trichloroethylene
U	uranium
V	vanadium
VC	vinyl chloride
VOC	volatile organic compound
yd	yard, yards
Zn	zinc
µg	microgram, micrograms

Site Profile Summary

NOTE: Sites with more than 1 type of contaminant are listed under each appropriate contaminant category.

Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Chlorinated Solvents - Full Scale								
Aircraft Maintenance Facility	Southern OR	1998	TCE	Funnel and Gate	$600 K	Fe^0		Dave Weymann Tel: 503-624-7200 Fax: 503-620-7658 Email: dweymann@ emconinc.com
Caldwell Trucking	Northern NJ	1998	TCE	Hydraulic Fracturing, Permeation Infilling	$1.12 M	Fe^0	Only 60% degradation rate in groundwater; pursuing other measures	John Vidumsky Tel: 302-892-1738 Fax: 302-892-7641 Email: john.e.vidumsky@ usa.dupont.com
Copenhagen Freight Yard	Copenhagen, Denmark	1998	*cis* 1,2-DCE, *trans*-DCE, TCE, PCE, VC	Continuous Trench	$235 K	Fe^0	effective treatment of upgradient concentration; part of plume migrated around barrier; conductivity decreased with time	Peter Kjeldsen Tel: +45 45251561 Fax: +45 45932850 Email: pk@er.dtu.dk
F.E. Warren Air Force Base	Cheyenne, WY	1999	TCE, *cis* 1,2-DCE, VC	Trench Box	$2.617 M	Fe^0 and Sand	concentrations of contaminants reduced to non-detectable level	Ernesto J. Perez Tel: 307-773-4356 Fax: 307-773-4153 Email: Ernesto.Perez@ ren.af.mil
Federal Highway Administration Facility	Lakewood, CO	1996	TCA, 1,1-DCE, TCE, *cis* 1,2-DCE	Funnel and Multiple Gate	$1 M	Fe^0	VOC concentrations increased in groundwater moving around south end of PRB and in area under PRB	J.H. Woll Tel: 303-716-2106 Fax: 303-969-5903 Email: jhwoll@road.cflhd.gov

Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Chlorinated Solvents - Full Scale								
Former Dry-Cleaning Site	Rheine, Westphalia, Germany		PCE, *cis* 1,2-DCE	Continuous Wall	$160 K	Fe^0 Iron Sponge	significant reduction in concentration of contaminants	Dr. Martin Wegner Tel: 49-5131-4694-55 Fax: 49-5131-4694-90 Email: wegner@ mullundpartner.de
Former Industrial Site	Brunn am Gebirge, Austria	1999	PAH, Phenols, BTEX, HC, TCE, *cis* 1,2-DCE	Adsorptive Reactors with Hydraulic Barrier	$750 K	Activated Carbon	effective in forcing groundwater to enter PRB; level of contamination varies with groundwater level	Peter Niederbacher Tel: 43-2243-22844 Fax: 43-2243-22843 Email: niederbacher@ geol.at
Former Manufacturing Site	Seattle, WA	1999	PCE, TCE, *cis* 1,2-DCE, VC	Funnel and Gate	$350 K	Fe^0 Iron Filings	treatment efficiencies ranged from 65-99%; natural attenuation reducing concentrations before water reaches canal	Barry Kellems Tel: 206-324-9530 Fax: 206-328-5581 Email: barry.kellems@ hartcrowser.com
Former Manufacturing Site	Fairfield, NJ		1,1,1-TCA, PCE, TCE	Continuous Trench	$875 K	Fe^0	concentrations at center of plume decreased to near detection levels; pH increased, Eh decreased	Stephen Tappert Tel: 973-383-2500 Fax: 973-579-0025 Email: stappert@trccos.com

Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Chlorinated Solvents - Full Scale								
Haardkrom Site	Kolding, Denmark	1999	TCE, CR^{+6}	Continuous Trench	$358 K	Fe^0	design not effective in controlling contaminants along PRB; working on resolving problems	Peter Kjeldsen Tel: +45 45251561 Fax: +45 45932850 Email: pk@er.dtu.dk
Industrial Site	SC	1997	TCE, *cis* 1,2-DCE, VC	Continuous Trench	$400 K	Fe^0	consistent decrease in concentration levels downgradient; upgradient levels remain variable	Steven Schroeder Tel: 864-281-0030 Fax: 864-287-0288 Email: steve.schroeder@ rmtinc.com
Industrial Site	Coffeyville, KS	1996	TCE, 1,1,1-TCA	Funnel and Gate	$400 K	Fe^0	concentration in iron zone below MCLs; no determination made of groundwater velocity through system	Greg Somermeyer Tel: 970-493-3700 Fax: 970-493-2328 Email: gsomermeyer@ thermoretec.com
Industrial Site	Belfast, Northern Ireland	1995	TCE, *cis* 1,2-DCE	Slurry Wall Funnel *in situ* reaction vessel	$375 K	Fe^0	overall 99.7% reduction in contaminant levels through reaction vessel	Dale Haig Tel: 44-115-9456544 Fax: 44-115-9456540 Email: Dhaigh@ GOLDER.com
Intersil Semiconductor Site	Sunnyvale, CA	1995	TCE, *cis* 1,2-DCE, VC, Freon113®	Funnel and Gate	$1 M	Fe^0	concentrations below cleanup goals in wells within wall; groundwater contained on site until mounding dissipates	Carol Yamane Tel: 415-434-9400 Fax: 415-434-1365 Email: cyamane@ geomatrix.com

Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Chlorinated Solvents - Full Scale								
Kansas City Plant	Kansas City, MO	1998	*cis* 1,2-DCE, VC	Continuous Trench	$1.5 M	Fe^0	samples from wells north and south of PRB indicate inconsistencies in levels; high zone of conductivity; PRB rendered ineffective upon ordered resumption of pumping well	Steve Cline Tel: 423-241-3957 Fax: 423-576-8646 Email: qc2@ornl.gov
Lowry Air Force Base	CO	1995	TCE	Funnel and Gate	$530 K	Fe^0	chlorinated hydrocarbons degraded within first ft of wall; all analytes degraded 2 ft into wall	William A. Gallant Tel: 303-452-5700 Fax: 303-452-2336 Email: gallabil@versar.com
Rocky Flats Environmental Technology Site (East Trenches Plume)	Golden, CO	1999	TCE, PCE, Carbon tetrachloride, Chloroform, *cis* 1,2-DCE, Methylene chloride	Reaction Vessels	$1.3 M	Fe^0 and Pea Gravel	except for methylene chloride, concentrations routinely non-detectable	Annette Primrose Tel: 303-966-4385 Fax: 303-966-5180 Email: Annette.Primrose@ rfets.gov
Rocky Flats Environmental Technology Site (Mound Site)	Golden, CO	1998	VC, 1,1-DCE, *cis* 1,2-DCE, TCE, PCE, U, Chloroform Carbon tetrachloride,	Reaction Vessels	$590 K	Fe^0	concentrations non-detectable in effluent samples; U concentration below stream standards; low cost, effective technology	Annette Primrose Tel: 303-966-4385 Fax: 303-966-5180 Email: Annette.Primrose@ rfets.gov

Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Chlorinated Solvents - Full Scale								
Seneca Army Depot Activity	Romulus, NY	1999	TCE, *cis* 1,2-DCE	Continuous Trench	$450 K	Fe^0 and Sand	100% removal of TCE; removal of *cis* 1,2-DCE less than expected - will require added iron	Michael Duchesneau Tel: 781-401-2492 Fax: 781-401-2492 Email: michael.duchesneau@ parsons.com
Shaw Air Force Base	Sumter, SC	1998	TCA, DCA, DCE, VC	Continuous Wall Trenches	$1.065 M	Fe^0, Iron Filings	significant reductions in TCA, DCA and DCE; VC increases at PRB, but biodegrades sufficiently	Richard Roller Tel: 803-895-9991 Fax: 803-895-5103 Email: richard.roller@ shaw.af.mil
Somersworth Sanitary Landfill Superfund Site	Somersworth, NH	2000	PCE, TCE, *cis* 1,2-DCE, VC	Continuous Wall	$2.2 M	Fe^0 and Sand	groundwater monitoring indicates PRB working as designed	Tom Krug Tel: 519-822-2230 Fax: Email: tkrug@geosyntec.com
Vapokon Petrochemical Works	Sonderso, Denmark	1999	PCE, TCE, TCA, DCA, DCE, DCM, BTEX	Funnel and Gate	$940 K	Fe^0	most compounds degraded at expected rates; daughter products degraded in anoxic plume; upgradient concentrations increased possibly due to low velocities	Peter Kjeldsen Tel: +45 45251561 Fax: +45 45932850 Email: pk@er.dtu.dk
Watervliet Arsenal	Watervliet, NY	1999	VOCs	Continuous Trench	$391 K	Fe^0 and Concrete Sand	monitoring indicates walls meeting projected goals	Grant A. Anderson Tel: 410-962-6645 Fax: 410-962-7731 Email: grant.a.anderson@ nab02.usace.army.mil

Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Chlorinated Solvents - Pilot Scale								
Alameda Point	Alameda, CA	1997	*cis* 1,2-DCE, VC, TCE, BTEX	Funnel and Sequenced Gate		Fe^0, O	excellent results for VOCs at high concentrations; almost complete degradation at low concentrations; biosparge zone supported aerobic degradation of VC & *cis* 1,2-DCE	Mary Morkin Tel: 925-943-3034 ext. 203 Fax: 925-943-2366 Email: mmorkin@ geosyntec.com
Area 5, Dover Air Force Base	Dover, DE	1998	PCE, TCE, DCE	Funnel and Gate	$800 K	Fe^0	PRB functioned as designed, capturing plume and reducing contaminants below target levels; iron zone more efficient than pyrite zone in removing DO	Alison Lightner Tel: 850-283-6306 Fax: 850-283-6064 Email: alison.lightner@ tyndall.af.mil
Borden Aquifer	Ontario, Canada	1991	TCE, PCE	Continuous Trench	$30 K (reactive material and labor donated)	Fe^0	PRB reduced TCE by 90% and PCE by 86%; low calcium carbonate after 5 years indicates at least another 5 yrs of operation	Stephanie F. O'Hannesin Tel: 519-746-2204 Ext. 235 Fax: 519-764-2209 Email: sohannesin@eti.com
Cape Canaveral Air Station	Cape Canaveral, FL	1998	TCE, DCE, VC	Continuous Walls with Overlapping Panels	$809 K	Fe^0		Jerry Hansen Tel: 210-536-4353 Fax: 210-536-4330 Email: jerry.hansen@ hqafcee.brooks.af.mil

Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Chlorinated Solvents - Pilot Scale								
DuPont	Oakley, CA		Carbon tetrachloride, Chloroform, Freon 11, Freon 113	Vertically Oriented Hydraulic Fracturing	$1.15 M	Granular cast iron	No problems except at recovering an intact core of emplaced PRB at 120 ft.; alternative methods being explored	Stephen H. Shoemaker Tel: 704-362-6638 Fax: 704-362-6636 Email: Stephen.H. Sheomaker@ USA.DuPont.com
DuPont	Kinston, NC	1999	TCE	Continuous Jetted Wall with Overlapping Panels	$200 K	Granular Fe^0	TCE mass reduced by 95%; 13 of 16 geoprobe locations indicate non-detectable levels of TCE; negotiating with state to shut down pump & treat system affecting velocity through PRB	Richard C. Landis Tel: 302-892-7452 Fax: 302-892-7641 Email: Richard.C.Landis@ USA.DuPont.com
Launch Complex 34, Cape Canaveral Air Force Station	Cape Canaveral, FL	1999	TCE, *trans* DCE, *cis* 1,2-DCE	Vibrating Caissons filled with Fe^0, followed by Deep Soil Mixing	$220 K	Fe^0	TCE and daughter products non-detectable within wall and declining in downstream wells, except for VC	Debra R. Reinhart Tel: 407-823-2156 Fax: 407-823-5483 Email: reinhart@ mail.ucf.edu
Massachusetts Military Reservation CS-10 Plume	Falmouth, MA	1998	PCE, TCE	Hydraulic Fracturing	$160 K	Fe^0		Robert W. Gillham Tel: 519-888-4658 Fax: 519-746-1829 Email: rwgillha@ sciborg.uwaterloo.ca

Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Chlorinated Solvents - Pilot Scale								
Moffet Federal Airfield	Mountain View, CA	1996	TCE, *cis* 1,2-DCE, PCE	Funnel and Gate	$540 K	Fe^0	principal contaminants reduced to below maximum levels within 2-3 ft of gate	Chuck Reeter Tel: 805-982-0469 Fax: 805-982-4304 Email: creeter@fesc.navy.mil
SAFIRA Test Site	Bitterfeld, Germany	1999	Benzene, MCB, o-DCB, p-DCB, TCE, *cis* 1,2-DCE, *trans* 1,2-DCE	Vertical Well Shafts and Horizontal Wells	11 M Deutsh Mark	Hydrogen-activation Systems with and without Paladium Catalyst	pilot tests indicate promising results; project ends 6/02, expected to be extended	Dr. Holger Weiss Tel: +49-341-235-2060 Fax: +49-341-235-2126 Email: weiss@pro.ufz.de
Savannah River Site TNX Area	Aiken, SC	1997	TCE, *cis* 1,2-DCE, CT, Nitrate	GeoSiphon Cell	$119 K (phase I)	Fe^0	Phases I & II indicate that changing siphon line accelerates flow rates inducing accelerated cleanup; use limited to areas of shallow ground water	Mark Phifer Tel: 803-725-5222 Fax: 803-725-7673 Email: mark.phifer@srs.gov
U.S. Coast Guard Support Center	Elizabeth City, NC	1996	Cr^{+6}, TCE	Continuous Trench	$675 K	Fe^0	Cr continues to be removed as expected; TCE, *cis* 1, 2-DCE, and VC below MCL for most wells; plume seems to have dipped after wall installation	Robert W. Puls Tel: 580-436-8543 Fax: 580-436-8706 Email: puls.robert@epa.gov

Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Chlorinated Solvents - Pilot Scale								
X-625 Groundwater Treatment Facility, Portsmouth Gaseous Diffusion Plant	Piketon, OH	1996	TCE	Horizontal Well		Fe^0	TCE reduced to below 5µg/L; hydraulic conductivity of iron media reduced due to mineral precipitation	Thomas C. Houk Tel: 614-897-6502 Fax: 614-897-3800 Email: uk9@ornl.gov
Metals & Inorganics - Full Scale								
100D Area, Hanford Site	Hanford, WA	1997	Cr^{+6}	Injection	$480 K (wall- $5 M)	Sodium dithionite	aqueous chromate reduced below 8µg/L; plan calls for remaining cells to be treated	Jonathan S. Fruchter Tel: 509-376-3937 Fax: 509-372-1704 Email: john.fruchter@pnl.gov
Chalk River Laboratories	Ontario, Canada	1998	Sr-90	Wall and Curtain	$300 K	Clinoptilolite (zeolite)	PRB retained 100% of contaminant since installed; leakage beneath steel cut-off wall compensated for by controlling flow	David R. Lee Tel: 613-584-8811 Ext. 4710 Fax: 613-584-1221 Email: leed@aecl.ca
Former Mill Site	Monticello, UT	1999	U, As, Mn, Se, V	Funnel and Gate	$800 K	Fe^0	PRB effective in reducing contaminants; concentration of iron increases as groundwater passes through the PRB	Don Metzler Tel: 970 248-7612 Fax: 970-248-6040 Email: d.metzler@gjo.doe.com

Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Metals & Inorganics - Full Scale								
Haardkrom	Kolding, Denmark	1999	TCE, CR^{+6}	Continuous Trench	$358 K	Fe^0	design not effective in controlling contaminants along PRB; working on resolving problems	Peter Kjeldsen Tel: +45 45251561 Fax: +45 45932850 Email: pk@er.dtu.dk
Nickel Rim Mine Site	Sudbury, Ontario, Canada	1995	Ni, Fe, Sulfate	Cut and Fill	$30 K	Organic Curtain	decrease in concentration of all contaminants; PRB converted aquifer from acid-producing to acid-consuming	David W. Blowes Tel: 519-888-4878 Fax: 519-746-5644 Email:
Rocky Flats Environmental Technology Site (Solar Ponds Plume)	Golden, CO	1999	Nitrate, U	Reaction Vessels	$1.3 M	Fe^0 and Wood Chips	although system does not collect and treat all groundwater in plume, surface water standards are met in nearby creek	Annette Primrose Tel: 303-966-4385 Fax: 303-966-5180 Email: Annette.Primrose@ rfets.gov
Tonolli Superfund Site	Nesquehoning, PA	1998	Pb, Cd, As, Zn, Cu	Continuous Trench		Limestone		John Banks Tel: 215-814-3214 Fax: 215-814-3002 Email: banks.john-d@epa.gov
Vapokon Petrochemical Works	Sonderso, Denmark	1999	PCE, TCE, TCA, DCA, DCE, DCM, BTEX	Funnel and Gate	$940 K	Fe^0	most compounds degraded at expected rates; daughter products degraded in anoxic plume; upgradient concentrations increased possibly due to low velocities	Peter Kjeldsen Tel: +45 45251561 Fax: +45 45932850 Email: pk@er.dtu.dk

Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Metals & Inorganics - Pilot Scale								
Bodo Canyon	Durango, CO	1995	As, Mo, Se, U, V, Zn	Collection Drain Piped to Underground Treatment System	$380 K	Fe^0, Copper Wool, Steel Wool	only 1 of 4 PRBs ran for 3 years reducing concentrations of wide variety of contaminants	Don Metzler Tel: 970-248-7612 Fax: 970-248-6040 Email: d.metzler@gjo.doe.com
U.S. Coast Guard Support Center	Elizabeth City, NC	1996	Cr^{+6}, TCE	Continuous Trench	$675 K	Fe^0	Cr continues to be removed as expected; TCE, *cis* 1,2-DCE, and VC below MCL for most wells; plume seems to have dipped after wall installation	Robert W. Puls Tel: 580-436-8543 Fax: 580-436-8706 Email: puls.robert@epa.gov
Fuel Hydrocarbons - Pilot Scale								
Alameda Point	Alameda, CA	1997	*cis* 1,2-DCE, VC, TCE, BTEX	Funnel and Sequenced Gate		Fe^0, O	excellent results for VOCs at high concentrations; almost complete degradation at low concentrations; biosparge zone supported aerobic degradation of VC & *cis* 1,2-DCE	Mary Morkin Tel: 925-943-3034 ext. 203 Fax: 925-943-2366 Email: mmorkin@geosyntec.com

Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Fuel Hydrocarbons - Pilot Scale								
East Garrington	Alberta, Canada	1995	BTEX	Trench and Gate	\$67.2 K	O_2	plume captured and treated; no contaminants detected off-site	Marc Bowles Tel: 403-247-0200 Fax: 403-247-4811 Email: mbowles@ calgary.komex.com
Nutrients - Full Scale								
Y-12 Site, Oak Ridge National Laboratory	Oak Ridge, TN	1997	U, Tc, Nitric acid	Funnel and Gate, Continuous Trench	\$1 M	Fe^0	efficient and cost-effective method of removing this combination of contaminants	Baohua Gu Tel: 423-574-7286 Fax: 423-576-8543 Email: b26@ornl.gov
Nutrients - Pilot Scale								
Savannah River Site TNX Area	Aiken, SC	1997	TCE, *cis* 1,2-DCE, Nitric acid, Carbon tetrachloride	GeoSiphon Cell	\$119 K (phase I)	Fe^0	Phases I & II indicate that changing siphon line accelerates flow rates inducing accelerated cleanup; use limited to areas of shallow ground water	Mark Phifer Tel: 803-725-5222 Fax: 803-725-7673 Email: mark.phifer@srs.gov
Radionuclides - Full Scale								
Former Mill Site	Monticello, UT	1999	U, As, Mn, Se, V	Funnel and Gate	\$800 K	Fe^0	PRB effective in reducing contaminants; concentration of iron increases as groundwater passes through the PRB	Don Metzler Tel: 970 248-7612 Fax: 970-248-6040 Email: d.metzler@ gjo.doe.com

Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Radionuclides - Full Scale								
Rocky Flats Environmental Technology Site (Solar Ponds Plume)	Golden, CO	1999	Nitrate, U	Reaction Vessels	$1.3 M	Fe^0 and Wood Chips	although system does not collect and treat all groundwater in plume, surface water standards are met in nearby creek	Annette Primrose Tel: 303-966-4385 Fax: 303-966-5180 Email: Annette.Primrose@rfets.gov
Y-12 Site, Oak Ridge National Laboratory	Oak Ridge, TN	1997	U, Tc, Nitric acid	Funnel and Gate, Continuous Trench	$1 M	Fe^0	efficient and cost-effective method of removing this combination of contaminants	Baohua Gu Tel: 423-574-7286 Fax: 423-576-8543 Email: b26@ornl.gov
Radionuclides - Pilot Scale								
Bodo Canyon	Durango, CO	1995	As, Mo, Se, U, V, Zn	Collection Drain Piped to Underground Treatment System	$380 K	Fe^0, Copper Wool, Steel Wool	only 1 of 4 PRBs ran for 3 years reducing concentrations of wide variety of contaminants	Don Metzler Tel: 970-248-7612 Fax: 970-248-6040 Email: d.metzler@gjo.doe.com
Fry Canyon Site	Fry Canyon, UT	1997	U	Funnel and Gate	$170 K	Fe^0, AFO, PO_4	3 barriers each using different media - Fe^0 and PO_4 remove >99% of incoming U; AFO PRB reached chemical break-through	David N. Naftz, PhD Tel: 801-975-3389 Fax: 801-975-3424 Email: dlnaftz@usgs.gov

Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Other Organic Contaminants - Full Scale								
Former Industrial Site	Brunn am Gebirge, Austria	1999	PAH, Phenols, BTEX, HC, TCE, *cis* 1,2-DCE	Adsorptive Reactors with Hydraulic Barrier	$750 K	Activated Carbon	effective in forcing groundwater to enter PRB; level of contamination varies with groundwater level	Peter Niederbacher Tel: 43-2243-22844 Fax: 43-2243-22843 Email: niederbacher@geol.at
Marzone Inc./ Chevron Chemical Co.	Tifton, GA	1998	BHC, *beta*-BHC, DDD, DDT, xylene, ethylbenzene, lindane, methyl parathion	Funnel and Gate	$750 K	Activated carbon	concentrations for effluent have been below detection levels	Annie Godfrey Tel: 404-562-8919 Fax: 404-562-8896 Email: godfrey.annie@ epa.gov
Rocky Flats Environmental Technology Site (East Trenches Plume)	Golden, CO	1999	TCE, PCE, Carbon tetrachloride, Chloroform, *cis* 1,2-DCE, Methylene chloride	Reaction Vessels	$1.3 M	Fe^0 and Pea Gravel	except for methylene chloride, concentrations routinely non-detectable	Annette Primrose Tel: 303-966-4385 Fax: 303-966-5180 Email: Annette.Primrose@ rfets.gov
Rocky Flats Environmental Technology Site (Mound Site)	Golden, CO	1998	VC, 1,1-DCE, *cis*-1,2-DCE, TCE, PCE, Chloroform, U Carbon tetrachloride	Reaction Vessels	$590 K	Fe^0	concentrations non-detectable in effluent samples; U concentration below stream standards; low cost, effective technology	Annette Primrose Tel: 303-966-4385 Fax: 303-966-5180 Email: Annette.Primrose@ rfets.gov

Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Other Organic Contaminants - Full Scale								
Vapokon Petrochemical Works	Sonderso, Denmark	1999	PCE, TCE, TCA, DCA, DCE, DCM, BTEX	Funnel and Gate	$940 K	Fe^0	most compounds degraded at expected rates; daughter products degraded in anoxic plume; upgradient concentrations increased possibly due to low velocities	Peter Kjeldsen Tel: +45 45251561 Fax: +45 45932850 Email: pk@er.dtu.dk
Watervliet Arsenal	Watervliet, NY	1999	VOCs	Continuous Trench	$391 K	Fe^0 and Concrete Sand	monitoring indicates walls meeting projected goals	Grant A. Anderson Tel: 410-962-6645 Fax: 410-962-7731 Email: grant.a.anderson@nab02.usace.army.mil
Other Organic Contaminants - Pilot Scale								
SAFIRA Test Site	Bitterfeld, Germany	1999	Benzene, MCB, o-DCB, p-DCB, TCE, *cis* 1,2-DCE, *trans* 1,2-DCE	Vertical Well Shafts and Horizontal Wells	11 M Deutsch Mark	Hydrogen-activation Systems with and without Paladium Catalyst	pilot tests indicate promising results; project ends 6/02, expected to be extended	Dr. Holger Weiss Tel: +49-341-235-2060 Fax: +49-341-235-2126 Email: weiss@pro.ufz.de

The following lessons learned are based on a review of all of the site profiles. They are organized according to the major phases of the remediation process. Visit ***www.rtdf.org/public/permbarr/prbsumms/default.cfm*** and check the profiles indicated in parentheses for more detailed information.

Site Characterization

At least 5 sites reported that it is important to conduct extensive characterization in the preplanning phase. Specifically, it is important to detail the hydrogeology (Kansas City, Fry Canyon), topography (Fry Canyon), seasonal conditions (Oak Ridge), and presence of or proximity to potential obstacles (Tonolli, Chalk River).

Planning and Coordination

Several sites reported that careful planning (F.E. Warren) and coordination are critical to the success of a PRB project. Planning factors that were addressed include site layout, sequencing of the work, and selection and placement of equipment and materials (Brunn am Gebirge, Fry Canyon). Three sites addressed the issue of structuring the project so that the methods and design are flexible enough to respond to changing conditions (Chalk River, Bodo Canyon, Tonolli).

At this stage, it is also important to coordinate plans with state agencies (Fairfield, NJ) and subcontractors (Chalk River). This ensures a better understanding of the project by all interested parties.

Design and Construction

Groundwater Geochemistry and Flow

Groundwater geochemistry (FHWA) and velocity/flow are common concerns during the design and construction phases.

- Groundwater modeling is recommended as a design tool during this stage in order to avoid potential flaws (Watervliet).
- Awareness of the geochemistry can include the impact of high concentrations of inorganic compounds (Copenhagen) or affect of O_2 on microbial activity (Brunn am Gebirge).
- Groundwater velocity/flow can impact the time required to complete flushing (Industrial Site, SC) or the wall design and efficiency (Watervliet).
- The variability of velocities can affect monitoring and incomplete treatment (Seneca).
- When hydraulic conditions change seasonally, groundwater migration patterns may change (Oak Ridge).
- Reduced hydraulic conductivity of bedrock fractures coupled with shallow gradients in the vicinity of a PRB may result in a diversion of groundwater flow (Caldwell).
- Gravity flow may be considered the most effective when the natural contours of a hillside can be utilized (Rocky Flats), but groundwater at one site was reported to have moved laterally through reactive media before it moved downgradient (Monticello).

Reactive Media

Some sites performed tests comparing a variety of reactive media (Bodo Canyon, Fry Canyon) to the most commonly used media, Fe^0. A number of sites had problems with hydraulic conductivity and incomplete treatment of contaminants attributed to the concentration (Seneca) and amount or distribution of reactive media (Chalk River, Caldwell).

Other Media or Materials

Other media or materials in or around the PRB have been found to affect PRBs.

- A pea gravel zone upgradient of a PRB can result in precipitation of minerals and partial treatment of target contaminants (Intersil).
- The addition of phosphorous can increase the degradation rate (East Garrington).
- The presence of guar can increase biological activity (Oak Ridge). Guar gum gel introduced at low temperature and high pH may slow enzymatic degradation after placement in PRB (Caldwell).
- The use of bentonite slurry may make it difficult to control movement of slurry (Fry Canyon).
- The presence of chloride is not a good indication of effectiveness of dechlorination for all sites (Industrial Site, SC).

Tools and Construction Methods

The following observations were made regarding tools and construction methods:

- The use of appropriate tools and construction methods allow for better surfaces and flow patterns for groundwater (Fry Canyon).
- The system should be constructed to allow for gas venting (Bodo Canyon, Marzone).
- The length of trench box should be minimized to reduce slope failure (Rocky Flats).
- Backfill specifications should be rigorously followed (Rocky Flats).

Other Considerations

Other design and construction considerations might include:

- The impact of other remediation technologies. For example, groundwater flow and plumes at a site that has been subjected to pump and treat need time to return to non-pumping conditions (Kansas City).
- Daughter products may affect the width and retention time required to treat groundwater (Shaw).
- A funnel and gate system was selected at one site because it offered less impact on the surrounding community (Marzone).
- In placing monitoring wells, consideration should be given to no-flow areas (Fry Canyon) and the need for additional wells in areas with unanticipated variability in contaminant concentrations and groundwater velocity (Seneca).

Operations and Maintenance

Monitoring and testing of groundwater conditions, contaminants, reactive media, and materials during and after construction help ensure that the systems operate effectively. Therefore, it is important that operations and maintenance be carefully considered during site characterization, planning and design (Rocky Flats).

Cost

Observations on PRB costs include:

- Reaction vessels cost about 1/4 of a baseline pump and treat system (Rocky Flats).
- A continuous trench system is a cost effective installation with a high degree of confidence (Industrial Site, SC).
- The bio-polymer construction method is effective and economical for a large PRB (Somersworth).
- A wall and curtain construction performs well and involves relatively low cost for routine monitoring and adjustment (Chalk River).

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