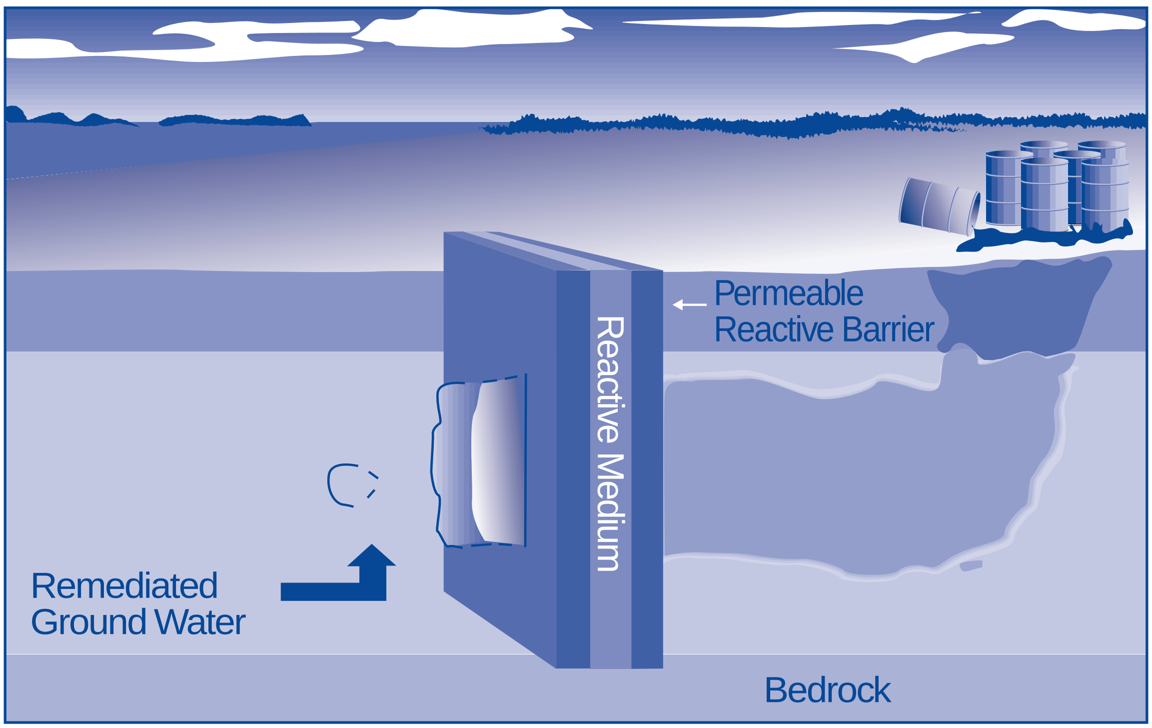
Technical/Regulatory Guidelines

Regulatory Guidance for Permeable Reactive Barriers Designed to Remediate Inorganic and Radionuclide Contamination



September 1999

Prepared by
Interstate Technology and Regulatory Cooperation Work Group
Permeable Reactive Barriers Work Team

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ABOUT ITRC

Established in 1995, the Interstate Technology & Regulatory Council (ITRC) is a state-led, national coalition of personnel from the environmental regulatory agencies of some 40 states and the District of Columbia; three federal agencies; tribes; and public and industry stakeholders. The organization is devoted to reducing barriers to, and speeding interstate deployment of, better, more cost-effective, innovative environmental techniques. ITRC operates as a committee of the Environmental Research Institute of the States (ERIS), a Section 501(c)(3) public charity that supports the Environmental Council of the States (ECOS) through its educational and research activities aimed at improving the environment in the United States and providing a forum for state environmental policy makers. More information about ITRC and its available products and services can be found on the Internet at **www.itrcweb.org.**

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The following individuals also contributed to the Examples and Current Applications Section and other sections of the document: David Blowes - Waterloo Centre for Groundwater Research; Robert Puls, PhD - USEPA National Risk Management Research Laboratory; Jonathan Fruchter - Batelle Pacific Northwest National Laboratory; David Naftz - US Geological Survey; Ed Feltcorn - USEPA; Vernon Cromwell - US DoE Grand Junction; Baohua Gu & David Watson - Oak Ridge National Laboratory; Annette Primrose - Rocky Mountain Remediation Services.

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EXECUTIVE SUMMARY

The contamination of groundwater in the United States is a challenging problem. It has been estimated that 300,000-400,000 contaminated waste sites may account for 750 billion dollars of remediation over the next three decades (National Academy of Sciences, 1994). The successful treatment of contaminated groundwater is a further challenge. Conventional treatment methods, such as pump and treat systems, have been shown to be somewhat ineffective. Selection of a groundwater treatment technology is a crucial and often costly proposition. Emerging groundwater treatment technologies may provide effective, lower-cost alternatives. It is important to fully understand all aspects of any innovative technology. This guidance document was developed to address the regulatory requirements of permeable reactive barriers (PRB) and try to achieve a consensus on requirements. It should prove useful to regulators, stakeholders and technology implementers.

The document is divided into sections dealing with site characterization, modeling, permitting, construction, monitoring, waste management, maintenance, closure, health and safety and stakeholder concerns. From a regulatory perspective, the most important sections of the document are most likely the permitting, monitoring, and closure sections. Appendix B provides examples and current applications where PRBs have been, or will be, installed. Specifics regarding the design and installation of PRBs are not covered within this document, however the reference to documents that provide this information is included within the introduction.

Site characterization is a critical step in order to deploy a PRB. A complete understanding of the site geology, hydrogeology, and geochemistry, as well as the contaminant profile, is necessary. Specifics on field and laboratory analytical parameters are provided in Table 2-3. Once a complete understanding of the site has been accomplished, it is important to develop a conceptual site model in order to relate the data in three-dimension. Numerous hydrogeological and geochemical models are available to further evaluate site conditions.

Permitting issues associated with PRBs include the state or federal programs associated with Underground Injection Control, National Pollution Discharge Elimination System, Air Quality, and RCRA. Permitting will typically not be an extensive process in PRB deployment, as permits may not be required depending on the design of the technology. Construction related issues are briefly discussed in this document. The requirements are similar to a typical construction project.

Monitoring is a critical regulatory issue and is addressed in detail within the document. Monitoring of the groundwater upgradient, within and downgradient of the PRB is essential to determine both performance and effectiveness of the remedial system. The proper placement of monitoring wells is essential. The document discusses some concerns in monitoring well placement and Figures 2 and 3 are provided for guidance purposes. The placement of monitoring wells must be a site-specific decision based on groundwater modeling. Monitoring frequency should also be determined on a site-specific basis taking into account concerns such as groundwater flow velocity and the contaminants of concern. Table 7-1 is provided as a guide in determining monitoring frequency.

Waste management issues surrounding PRBs include the proper classification and disposal of

contaminated soil, groundwater, and reactive media. Because PRBs are an emerging technology, maintenance issues are somewhat undefined. The document urges the development and revision of an operation and maintenance plan prior to construction. Closure of the PRB is also undefined due to a lack of historical perspective. A critical issue for PRBs designed to treat inorganic and radionuclide contamination, is whether to retain a wall, or remove it following remediation. These treatment systems are designed to concentrate the contaminants within the PRB and therefore may present re-contamination issues. Furthermore, PRBs tend to lose porosity with age and can affect the groundwater flow vectors. It is important not to treat closure of the PRBs lightly, to develop a closure plan before installation and refine the plan, as needed, during operation.

Health and safety issues are standard for the industry and follow Occupation Safety and Health Administration Requirements. Stakeholder concerns should be addressed in detail. This may require holding public meetings, information sessions, distributing informative bulletins, or developing a neighborhood-canvassing program. The document provides detail on the many stakeholder concerns.

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REGULATORY GUIDANCE FOR PERMEABLE REACTIVE BARRIERS DESIGNED TO REMEDIATE INORGANIC AND RADIONUCLIDE CONTAMINATION

1.0 INTRODUCTION

The Permeable Barrier Walls Work Team of the ITRC is comprised of representatives from six state regulatory agencies (New Jersey, Colorado, Florida, Massachusetts, Washington, and New York). Participation from stakeholders, federal agencies, and members of the Remediation Technology Development Forum (RTDF) has also facilitated the development of this document. The Permeable Barrier Walls Work Team has prepared this document to provide regulatory guidance for the implementation of Permeable Reactive Barrier Technologies. This document is intended to serve as a regulatory guide for stakeholders, regulators, and technology implementers when a PRB is chosen as a remedial action. The team has identified potential regulatory issues and recommended regulatory guidance for PRBs, wherever possible.

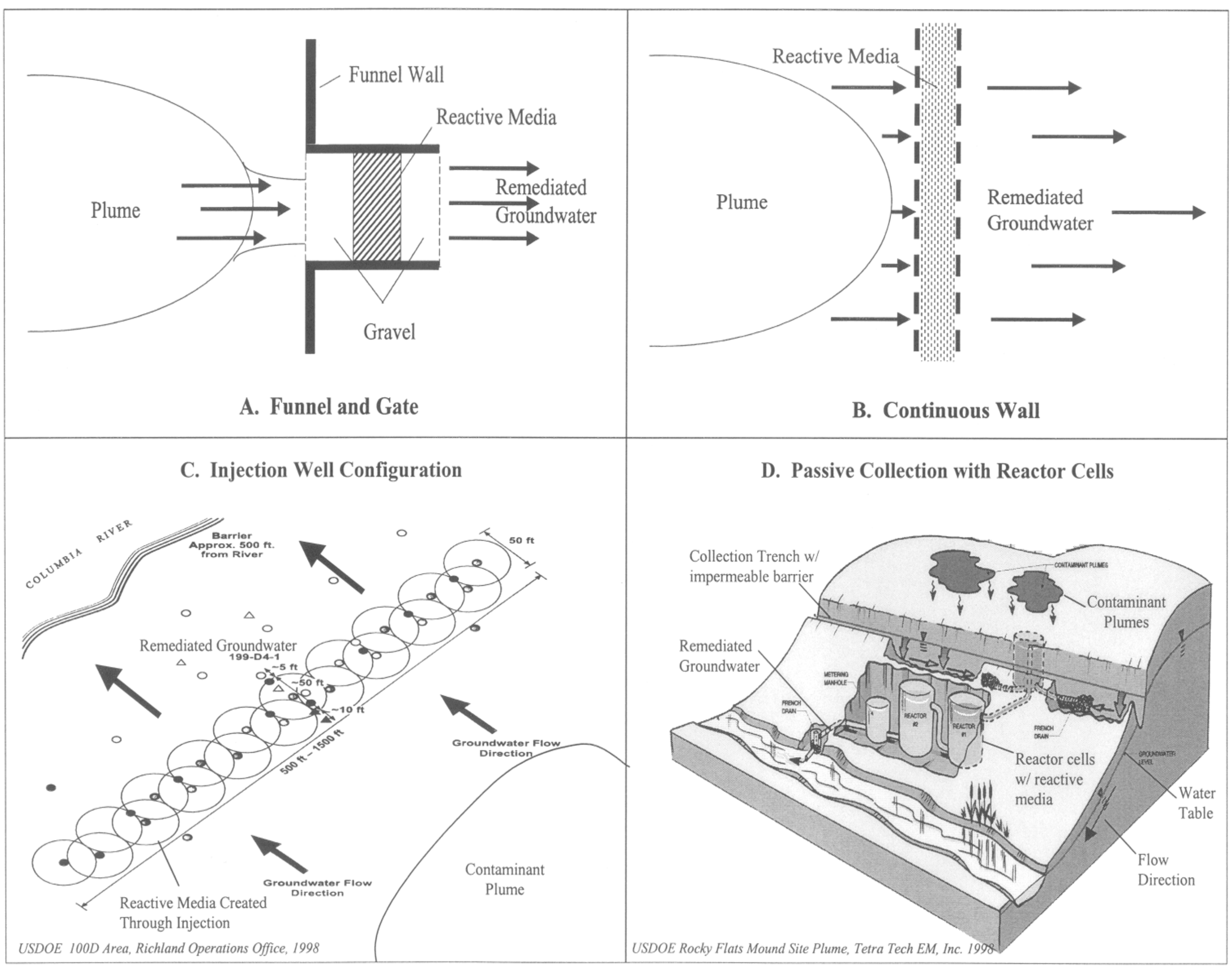
In general, the mechanism through which PRBs remediate contaminated groundwater consists of contaminated water passing through the reactive zone of the PRB where the contaminants are either immobilized or chemically transformed to a more desirable state. Therefore, a PRB is a barrier to contaminants, but not to groundwater flow. The use of PRBs for remediation of inorganic and radionuclide contamination is continuously evolving. Because this is an emerging technology, the overall full-scale installation experience with this technology is limited relative to the research, laboratory testing, and field testing that has been performed indicating PRB potential for successful contaminant remediation. Examples of potential inorganic and radionuclide contaminants amenable to PRB treatment include chromium, sulfate, and uranium. For further technical information on additional inorganic and radionuclide contaminants amenable to PRB treatment, descriptions of the treatment mechanisms and other information on the maturity of this technology, refer to the Remediation Technologies Development Forum (RTDF) Guidance Document, EPA/600/R-98/125 *Permeable Reactive Barrier Technologies for Contaminant Remediation* (1998). This document along with other reference and supporting information can be obtained from the RTDF website at http://www.rtdf.org.

PRBs offer advantages over conventional groundwater technologies such as pump and treat. For instance, the technology operates passively once installed and therefore may provide lower operation and maintenance costs. This technology also has various limitations and should not be considered as the only remedy for a site. In many cases, PRBs may be one of a number of technologies used in the remediation of a site. PRB systems are typically implemented to protect surface water or specific groundwater uses. The time frame necessary to remediate a groundwater plume should be considered in evaluation of a PRB system as a groundwater remedy. Long-lived plumes, due to the nature of some of the contaminants discussed in this document, may require large areas of groundwater to remain under institutional controls for long periods. PRB installations, therefore, may need to be considered in conjunction with other remedial technologies.

Because this is an evolving technology, this document is intended as a guide and should be updated periodically. Suggestions concerning future revisions and comments can be sent to Brian Ellis at Coleman Federal (208-375-9896), Boise, Idaho. In addition, current research should always be reviewed when considering the guidelines outlined in this document. Users of this document are encouraged to consult the references listed in Section 13 (References) for further background and technical information on this technology. Much of the information presented in this document was based upon workplans and operational experience at seven on-going projects where PRBs are being used to remediate groundwater contaminated with inorganics and radionuclides. The team used these workplans as a reference and evaluated regulatory issues using the collective experience within the group. Where possible, the group tried to use regulatory expertise to reach a consensus. Summaries of these projects are provided in Appendix B (Examples and Current Applications).

To provide consistency, Figure 1 is provided to illustrate the terms used in this document.

Figure 1. Types of Permeable Reactive Barriers



As indicated by the title, this document focuses on providing regulatory guidance for PRBs designed to remediate inorganic and radionuclide contamination. The object is to provide regulatory guidance for state and federal regulators, consultants and project managers. This document points out important regulatory considerations to take into account during site characterization, modeling and design, monitoring, and closure of a PRB. Case studies from around the country have also been included to show various designs, contaminants, reactive media, and cost data for implementing PRB technologies.

Users of this document are encouraged to refer to the ITRC's website or Appendix C to order copies of the Permeable Barrier Walls Work Team's previous document *Regulatory Guidance for Permeable Barrier Walls Designed to Remediate Chlorinated Solvents*, dated September, 1997, and the Armstrong Laboratory/Environics Directorate, U.S. Air Force document *Design Guidance for Application of Permeable Barriers to Remediate Dissolved Chlorinated Solvents*, dated February, 1997, for additional background and technical information on the PRB technology.

2.0 SITE CHARACTERIZATION

A site must be thoroughly characterized in order to design and install a PRB. The physical setting and the site's regulatory constraints must be accounted for before this technology can be considered feasible. Important features of the physical setting include topography, structures at the surface, underground utilities and structures, surface water features, and ecological resources. All sources of existing information should be researched including permits and radiation licenses, operating records, waste disposal records, interviews, site reconnaissance maps and aerial photographs, and previous reports. This existing information may need to be enhanced by acquiring and properly analyzing additional site-specific data needed to develop an appropriate design. Sampling should be supported by a Sampling and Analysis Plan which is based on specific Data Quality Objectives (USEPA, 1994).

2.1 Data Requirements

Since the emphasis of this guidance is on requirements for PRBs and the determination of their success as a remedial alternative, a detailed description of data needs before, during, and after emplacement is presented in Tables 2-1 and 2-2. Section 7 provides more detail regarding monitoring data requirements. Chemical and biological parameters involved with reaction mechanisms affecting inorganic contaminants are discussed in detail in Chapter 3 of the RTDF's *Permeable Reactive Barrier Technologies for Contaminant Remediation* (1998).

Baseline conditions prior to PRB installation may be measured in order to determine the effects that installation has on contaminant concentrations and distributions, and on aquifer levels. This should include, but is not limited to, information about the site's hydrogeology, contaminant plume(s), and geochemistry. In addition, microbiological parameters may need to be considered, however, these criteria are still under investigation.

2.1.1 Hydrogeologic Data

All relevant hydrogeologic and aquifer characteristics should be identified so that the PRB can be designed to capture the entire targeted portion of the contaminant plume. These characteristics should include stratigraphy, vertical and horizontal lithologic continuity, fracturing, groundwater levels and gradient, flow velocity, hydraulic conductivity, temperatures, pH, porosity, aquifer heterogeneity, preferential pathway, depth to aquitard, and aquitard continuity, thickness and competence. All major controlling influences on groundwater flow should be defined (e.g. bedrock, production wells, tidal and seasonal influences, surface features, and infiltration). Remedial investigation activities such as soil borings and aquifer testing may be necessary to enhance existing site information. Hydrogeologic data will typically include maps and cross-sections in order to present three dimensional aspects of the hydrogeology.

2.1.2 Contaminant Plumes(s)

Information regarding the contaminant plume(s), the existence of non-aqueous phase liquid (NAPL), and contaminant source(s) should be provided. The nature and concentration of all contaminants and their vertical and lateral distributions should be included. The concentration of contaminants within soil should also be assessed to determine the effect on groundwater concentrations. The contaminant flux should be sufficiently characterized so that the typically higher upgradient concentrations can be accommodated by the PRB design. Aquifer level measurements are particularly important in areas where low flows or seasonally fluctuating water tables must be accounted for in the PRB design. These fluctuations impact both the performance of the media and hydraulic capture.

2.1.3 Geochemical Data

The groundwater chemistry of all dissolved constituents should be evaluated for its potential to affect the performance of the PRB. For instance the existence of NAPL could influence the performance of a PRB. Groundwater chemistry may be modified considerably as it passes through a zero-valent iron PRB (e.g. increase in pH, Eh reduction with elimination of oxygen, and reduction of carbonate alkalinity). These changes may cause dissolved iron and the reactant surfaces to become coated with precipitates such as calcite or siderite. The organic and inorganic composition of the aquifer will have an impact on the fate and transport of compounds upgradient and downgradient from the wall through reaction with sorbed organic materials, clays, reactions with carbonates, etc. The concentrations of inorganics and radionuclides, as well as any associated organics, should be determined to aid in selecting the amount and type of reactive media to be used.

2.1.4 Microbiologic Data

Microbial data may be needed on a site-specific basis. The role of microbes relative to PRBs may be either beneficial or detrimental. Beneficial effects could result in degradation or immobilization of contaminants while biofouling of the PRB would be detrimental. More information on microbiological data requirements will be determined through ongoing research.

2.2 Analytical Methods

Inorganic analytes (e.g. nitrites, sulfates, and metals) should be measured by USEPA-approved methods. Besides being contaminants at some sites, these inorganic analytes can provide valuable information on the chemistry of the local groundwater and its effects on the performance of the reactive media.At sites where radiological contamination is suspected, radiological analysis such as isotopic analysis should be performed to determine the concentrations of site-specific radionuclides, gross alpha and gross beta. Laboratory methods may include alpha or gamma spectroscopy or various mass spectroscopy methods. Standardized methods for characterizing radiologically-contaminated sites are described in the *Multi-Agency Radiation Survey and Site Investigation Manual* (USEPA et al, 1997).

Table 2-3 identifies suggested field and laboratory parameters that should be monitored within the groundwater. The table lists analyte/parameter, analysis method, sample volume, storage container, preservation method and sample holding time. This table should be used as a guide to select site-specific parameters of concern and is not all-inclusive. Other parameters may apply. State-specific protocols should be reviewed to determine whether filtered or unfiltered samples should be collected.

2.3 Data Management

During site characterization activities, careful field notes and field data forms should be kept and maintained for the project. Upon completion of these activities, all data should be recorded including appropriate visual presentations such as maps, graphs, diagrams, etc.

During site characterization and monitoring, site-specific groundwater quality objectives should be identified and used to determine the appropriate analytical methods based upon the goals and clean-up standards/criteria applicable to the site. In addition, Quality Assurance/Quality Control (QA/QC) requirements and reporting requirements should be determined by project-specific data quality objectives. All QA/QC measures required by the analytical method used should be completed. At a minimum, the lab should provide QA/QC summary documentation (including non-conformance summary report and chain of custody) with the analytical results. QA/QC deliverables, as specified by the analytical method, should be maintained and made available upon request for at least three years. Ultimate responsibility for QA/QC documentation belongs with the responsible party of a site or the contractor installing the PRB for a site. In addition, all state-specific reporting requirements should be adhered to, as they tend to vary from state to state.

3.0 BENCH SCALE TESTING

Following site characterization, bench scale treatability testing is usually performed to aid in PRB design. The objectives of bench scale testing include:

- Screening and selecting suitable reactive media,
- Optimizing contaminant residence times in the reactive media,
- Predicting ultimate contaminant removal capacity,
- Determining byproduct and water quality issues (including speciation characteristics for metals and other inorganic contaminants),
- Estimating costs,
- Determining potential for precipitation/plugging of reactive media,
- Evaluating potential for leaching of the reactive media.

Bench scale tests can be conducted in batch or column (continuous) mode. Batch testing can be useful as an initial screening tool to evaluate reaction rates or adsorptive capacity, different reactive media, and degradation of recalcitrant contaminants.

Column testing provides more reliable reaction rate or absorptive capacity of different parameters than batch testing. This data can also provide information concerning the lifetime and effectiveness of the reactive media, and act as a predictive model to optimize timing to replenish the reactive media. Column testing provides information from dynamic flow conditions. Sampling ports placed along the column provide more information on changing contaminant and inorganic concentration over distance than can be determined by batch sampling. High groundwater velocities may require use of longer columns or multiple columns in series. Sampling frequency may be increased if contaminant breakthrough becomes evident.

Contaminated groundwater from the site should be used during bench scale tests so that physical, chemical, and biological effects on the treatment media can be evaluated. If circumstances prohibit the use of actual contaminated groundwater from the site, the alternatives are: deionized water spiked with contaminant(s) of concern, or, preferably, clean groundwater from the site spiked with contaminant(s) of concern.

4.0 MODELING

4.1 Conceptual Site Model

A conceptual site model is a three-dimensional representation that conveys what is known or suspected about contamination sources, release mechanisms, and the transport and fate of those contaminants. The conceptual model provides the basis for assessing potential remedial technologies at the site. "Conceptual site model" is not synonymous with "computer model"; however, a computer model may be helpful for understanding and visualizing current site conditions or for predictive simulations of potential future conditions. Computer models, which simulate site processes mathematically, should in turn be based upon sound conceptual site models to provide meaningful information. Computer models typically require a lot of data, and the quality of the output from computer models is directly related to the quality of the input data. Because of the complexity of natural systems, models necessarily rely on simplifying assumptions that may or may not accurately represent the dynamics of the natural system. Calibration and sensitivity analyses are important steps in appropriate use of models. Even so, the results of computer models should be carefully interpreted and continuously verified with adequate field data.[1]

[1] Paragraph taken from *Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action, Underground Storage Tank Sites,* USEPA OSWER Directive 9200.4-17, November 1997, p. 11. ***http://www.epa.gov/swerust1/directiv/9200417z.htm.***

Table 2-1. Activities Suggested to Achieve Objectives

Primary Objective	**Detailed Sub-objective**	**Data Analysis Method**	**Timing of Activity**
Determine applicability of PRB at site	Characterize hydrogeologic conditions and contaminant profile to determine whether the PRB installation is applicable at the site	Analysis of borings, push technology, monitor wells, and modeling	During alternative alalysis
Evaluate performance of reactive media	Evaluate reactivity of media. Determine reaction rate, residence time, and compliance with state-specific clean-up standards. Identify the potential need for alternative clean-up standards or technologies if compounds cannot be treated to compliance levels.	Batch and column experiments.	During design and during system operation
Define hydrogeologic characteristics	Evaluate impact of PRB on aquifer and ensure capture of contaminants.	Compare pre and post emplacement aquifer hydrologic tests and water quality data across PRB	During design, emplacement and system operation
	Hydrologic performance evaluation including contaminant degradation capability, system longevity (i.e., compaction, plugging, precipitate formation and migration, by-product formation, etc.) and subsurface characteristics.	Compare post emplacement and final aquifer hydrologic tests across the reactive media using site investigation techniques. Evaluate precipitate formation from geochemical data and modeling.	During bench scale longevity testing, feasibility study, design, and system operation
	Determine groundwater gradient.	Measure water levels.	Before construction and during system operation
Determine Constructability of the PRB	Evaluate the ability to achieve design depth and width.	Install boreholes test pits, and/or conduct cone penetrometer testing.	Before construction
	Evaluate ability to emplace reactive media without abrading, crushing or mixing with fines from excavated and surrounding materials.	Observe. Review proposed construction method.	Before and during construction
	Evaluate the ability of the method to control and provide QA of design parameters.	Review design package	Before and during construction
	Identify operational issues in the following categories: environmental impacts, public acceptance, health and safety.	Review proposed design package/ construction method. Solicit public comment.	During feasibility study, design and construction
	Identify any other construction issues and ideas for improvement	Observe	During construction
Evaluate costs	Determination of design and installation costs.	Obtain quotes and cost estimates.	During procurement process, feasibility study and design
	Determine any operation/maintenance and monitoring costs.	Obtain quotes and cost estimation tools.	Feasibility study and design
	Develop information for cost comparisons with other remedies.	Obtain quotes and cost estimation tools, perform Benefit/Cost Analysis, if necessary.	Feasibility study and design
	Obtain information to document final Cost & Performance	Federal Remediation Technology Roundtable	Throughout project

Table 2-2. Data Gathering Activities to Support Objectives

	Activity	Main Purpose	Data Provided
A	Up and Down gradient monitoring well installation	Hydrologic testing and characterization. Water quality monitoring.	Contaminant delineation, lithology, water level monitoring to determine groundwater flow vectors.
		Determine flow rate and direction in and around PRB.	Water level measurements for sampling and tracer tests.
B	Contaminants and water quality baseline	Establish trends and baseline dissolved phase contaminant concentrations in monitoring wells.	Groundwater concentration of contaminants of concern, pH, conductivity, Eh, DO, and other ions in solution (see Table 2-3).
C	Pre-emplacement hydrologic tests, water levels, hydraulic conductivity, transmissivity monitoring and geologic conceptual site model	Determine geologic properties of site prior to PRB installation.	Hydrologic conductivity, storativity, vertical anisotropy, transmissivity, location and geologic nature of confining unit(s).
D	Batch and column experiments	Determine characteristics of reactive media.	Reactions and rates of reactions, absorptive capacity, by-products, effects on water quality, reactive media thickness, hydraulic performance, stability, cost analysis.
E	Modeling and measurement of the aquifer	Determine optimal PRB configuration & placement.	Prediction of plume capture and effect of system on aquifer characteristics. Transmissivity and flow determinations and predictions.

Table 2-3. Field and Laboratory Parameters

Analyte or Parameter	Analytical Method	Sample Volume [b]	Sample Container	Preservation	Sample Holding Time
Field Parameters					
Water Level	In-hole Probe	None	None	None	None
pH	In-hole Probe or Flow-thru Cell	None	None	None	None
Groundwater temperature	In-hole Probe	None	None	None	None
Redox Potential	Flow-thru Cell	None	None	None	None
Dissolved Oxygen	Flow-thru Cell [a]	None	None	None	None
Specific Conductance	Field Instrument	None	None	None	None
Turbidity	Field Instrument	None	None	None	None
Salinity	Field Instrument	None	None	None	None
Organic Analytes					
Volatile Organic Compounds (VOCs) [c]	USEPA SW846, Method 8240	40 mL	Glass VOA vial	4ºC, pH<2	14 Days
				No pH adjustment	7 Days
	USEPA SW846, Method 8260a or b	40 mL	Glass VOA vial	4ºC, pH<2	14 Days
				No pH adjustment	7 Days
	40 CFR, Part 136, Method 624	40 mL	Glass VOA vial	4ºC, pH<2	14 Days
				No pH adjustment	7 Days
Inorganic Analytes					
Metals [d]: K, Na, Ca, Mg, Fe, Al, Mn, Ba, V, Cr^{+3}, Ni	40 CFR, Part 136, Method 200.7	100mL	Polyethylene	4ºC, pH<2, (HNO_3)	180 days
Metals: Cr^{+6}	40 CFR, Part 136, or HACH method	200ml	Glass, Plastic	4ºC	24 hours
Anions: SO_4, Cl, Br, F	40 CFR, Part 136, Method 300.0	100mL	Polyethylene	4ºC	28 days
NO_3	40 CFR, Part 136, Method 300.0	100mL	Polyethylene	4ºC	48 hours
Alkalinity	40 CFR. Part 136, Method 310.1	100mL	Polyethylene	4ºC	14 days
Other					
TDS	40 CFR, Part 136, Method 160.2	100 mL	Glass, Plastic	4ºC	7 days
TSS	40 CFR, Part 136, Method 160.1	100 mL	Glass, Plastic	4ºC	7 days
TOC	40 CFR, Part 136, Method 415.1	40 mL	Glass	4ºC, pH <2 (H_2SO_4)	28 days
DOC	40 CFR, Part 136, Method 415.1	40 mL	Glass	4ºC, pH <2 (H_2SO_4)	28 days
Radionuclides					
Field Screening	HPGe gamma spectroscopy	None	None	None	None
	FIDLER				
Gross α / Gross β activities (screening)	Gas Proportional Counting	[e] 125 ml	[e] polyethylene	[e] pH<2, (HNO_3)	[e] N/A
Specific Isotopes (Am, Cs, Pu, Tc, U)	Alpha Spectroscopy	[e] 4 L	[e] polyethylene	[e] pH<2, (HNO_3)	[e] 6 months
	Gamma Spectroscopy				

[a] - If <1.0 mg/L use photometric field kit for analysis.
[b] - See Section 7.4 (Sampling) of this report for variances in sample volumes.
[c] - GC methods may be substituted once identity of compounds and breakdown products are verified.
[d] - Other metals analytes which are characteristic of the media should be included.
[e] - General guidelines, the parameter is a laboratory specific parameter.
**For a list of applicable abbreviations, see Appendix A

Information useful in developing the conceptual site model includes:

- Sketches, cross sections, and block diagrams,
- Flow nets in map view and cross-section,
- Geometry, geochemistry, and distribution of geologic materials both laterally and vertically for both the aquifer and underlying aquatard,
- Mineralogy and geochemical characteristics of the aquifer,
- Description of lateral aquifer boundaries,
- Discussion of major withdrawals or recharge to the aquifer,
- Leakage from overlying bodies of water, wetlands or underlying aquifers,
- The nature of any confining units that might be present,
- The gaining or losing nature of any surface water bodies within or adjacent to the aquifer,
- Horizontal and vertical hydraulic gradients,
- Hydraulic conductivity and storativity of the different geologic materials in the aquifer,
- Distribution of natural recharge across the aquifer,
- Data presentation and analysis of geochemical parameters that could affect performance,
- Distribution/extent of solid-phase, non-dissolved metals and/or radionuclides.

The more complex the site, the greater the level of effort required to evaluate the hydrogeology, and the more detailed the conceptual model becomes.

4.2 Hydrogeologic Models

Depending on the complexity of the groundwater flow and the contaminant plume(s) at the site, hydrogeological modeling should be considered in designing the PRB, and in refinement of the conceptual site model. Hydrogeologic models may include groundwater flow, contaminant transport and geochemistry models.

Modeling requires an in-depth understanding of groundwater flow and begins with the collection of comprehensive data on the aquifer being studied. If aquifer data is limited and does not contain significant information with which to compare and verify the response of a model, erroneous conclusions may be made. The model should be periodically updated as new field data is obtained. The primary objective of hydrogeologic modeling is to simulate site-specific processes with a high degree of confidence using an adequate number of representative data points.

Hydrogeologic modeling is necessary for the following reasons:

- To estimate an approximate location and configuration of the PRB with respect to groundwater flow, plume movement and flow velocity through the reactive media,
- To optimize the dimensions of the PRB and reactive media,
- To estimate hydraulic capture zone,
- To determine the optimal location and sample frequency of monitoring wells,
- To evaluate the hydraulic effects of potential losses in porosity, flow bypass,

underflow, overflow or flow across aquifers.

A number of hydrogeologic computer models are available commercially. Some states may have specific requirements to use a particular model. Flow and transport models range from simple two-dimensional models to more complex three-dimensional models. Model selection should be based on site-specific information and established project objectives. At some sites, the processes may be relatively simple and a basic model will provide adequate results. Complex sites may require a more complex model.

Qualitative geochemical calculations and geochemical modeling can be used to evaluate the performance of the reactive media, as well as contaminant fate and transport models. Geochemical modeling attempts to interpret and predict groundwater chemistry based on assumed chemical reactions. Geochemical methods can be used to evaluate pH and alkalinity changes from installation of the reactive media that could lead to chemical and physical (mass transfer) phenomena. For treatment of metals, the geochemical model should account for various oxidation states of metal complexes and their respective solubilities as a function of pH, redox potential and/or dissolved oxygen as appropriate.

State-specific requirements should be reviewed to determine what information should be submitted for regulatory review or maintained by the responsible party.

5.0 PERMITTING

Programs under which permitting issues may arise during the installation or application of this technology include the Underground Injection Control (UIC) program, state or federal water discharge programs (National Pollution Discharge Elimination System (NPDES) or state equivalent), state or federal air quality programs, and state and federal RCRA programs, all of which are addressed below. It should be noted that a number of states do not require permits for remedial activities when performed under State Superfund or corrective action programs (e.g. RCRA). In lieu of permits, these remedial activities are required to meet the technically substantive requirements (e.g. discharge limitations, monitoring requirements, design specifications, performance criteria, etc.) of the applicable regulations. In these cases the person performing the remediation would be required to submit a work plan/remedial design for state review and approval. The issue of the need for permits versus meeting the technical substantive requirements should be clarified with the state agency overseeing the project. In addition to these major considerations, state-specific regulations, as well as local municipal requirements, should be reviewed to ensure compliance. For instance, many states require a permit for the installation of a well. In some cases, the location of the site may trigger the need for permits. An example would be an installation close to or within a wetlands area.

UIC requirements will typically not be applicable for the installation of a PRB. However, monitoring for leachability of the reactive media (Fe, etc.) in downgradient groundwater should be a requirement of the site-specific monitoring plan in most instances. The only consideration in determining the applicability of UIC requirements is the installation technique. When the installation involves excavation and the construction of a wall, or similar techniques of emplacement (caisson, mandrel, continuous trencher, etc.), UIC requirements would not apply. An installation of this type will not necessarily meet the definition of a well under UIC regulations. Furthermore, when the reactive media is emplaced in the ground in solid form, UIC requirements would not be applicable. However, if the reactive media is installed by a high pressure jetting technique, injection of reactive chemical solutions, or by vertical hydraulic fracturing, UIC requirements, in some circumstances, would be applicable. The applicability of the UIC requirements under these conditions will be a state-by-state determination. If states are not authorized from USEPA to enforce the UIC program, the regional USEPA office will need to be contacted in order to make the determination. A review of the pertinent regulations should be conducted during initial design stages of the project.

Water discharge requirements may be applicable for the disposal of excess water generated during installation. The need to address water discharge requirements is discussed in Section 8.0, Waste Management.

Air quality requirements will not typically apply if modeling indicates that radionuclides are not released at levels above regulatory limits during installation of a PRB. PRBs are usually installed downgradient of the contamination source in an area where aqueous contamination is the major concern. The concentrations of radionuclides released under these conditions are typically below regulatory levels and would not trigger air discharge requirements. However, an evaluation is usually required to determine the need for health and safety monitoring and to ensure that there are no off-site excursions of fugitive emissions.

In some cases PRBs will be treating groundwater contaminated by listed hazardous wastes, which by applying the contained in rule are considered hazardous waste. Since the PRB is considered an in-situ treatment technology, its deployment would not trigger RCRA management requirements for the treatment of the groundwater. Contaminated material removed during the construction or closure of the PRB would have to be managed in accordance with the applicable regulations as discussed in section 8.0 Waste Management. Closure plans, similar to the closure plan requirements for RCRA facilities, should be developed to consider and address issues discussed in Section 10.

6.0 CONSTRUCTION RELATED ISSUES

QA/QC should also be applied to the construction of PRB systems. Construction activities may consist of the following items:

- Funnel wall/impermeable barrier placement (see Figure 1),
- Placement and sealing of sheet pilings,
- Trenching and reactive media placement,
- Mixture of reactive media and backfill,
- Submittal of as built diagrams.

Additional design QA/QC considerations and guidance for various types of PRBs can be found in Battelle's *Design Guidance for Application of Permeable Barriers to Remediate Dissolved Chlorinated Solvents* (Battelle, 1997).

7.0 MONITORING

The major objective of groundwater monitoring is to ascertain compliance with applicable state standards and to ensure treatment effectiveness. Concerns with PRBs which treat inorganics and radionuclides that can impact decisions on monitoring include: 1) precipitation within the reactive media can be more prevalent than with the treatment of organic contaminants, depending upon the reactive media, the need to monitor flow rate and patterns becomes more important over the operational life of the PRB; 2) leaching or desorption of contaminants of concern can occur with changes in geochemistry over its operational life and the post closure period, which could affect the duration of monitoring and decisions on the closure of the PRB (see section 10.0 Closure). It may be necessary to identify alternative concentration limits (ACLs) or to incorporate supplemental technologies to address contaminants that may be above criteria at a particular site.

7.1 Monitoring Well Construction

7.1.1 Aquifer Wells

State-specific requirements should be followed for the installation of monitoring wells that are intended to monitor groundwater quality and/or levels. Many states have well installation standards or guidelines, or require a permit for the installation of a well. The permit process may require an application and a fee.

7.1.2 Wells Within the Permeable Reactive Barrier

The design of monitoring wells installed within the reactive media will differ significantly from the typical well construction criteria. These wells will not incorporate a sand pack or grouting into the design, as is typically required in state well installation requirements. Reactive media wells will be surrounded by the backfilled reactive media and can be finished at the surface similar to aquifer wells. The monitoring wells are usually constructed using smaller diameter (1 or 2 inch) PVC casing. Smaller diameters are preferred to limit the purge volume. The diameter must be sufficient to accommodate sampling equipment. In the case of a funnel and gate configuration, reactive media wells can be suspended in the excavation prior to backfilling. These wells can be supported by a metal framework which is removed during backfilling of the reactive media. For other configurations, wells may be pushed into the reactive media. The wells may have a long screen or may be positioned in clusters with small screen intervals for sampling discrete areas and various depths.

Individual state requirements for monitoring wells will vary and may limit alternatives for well design and construction. Therefore, proponents should discuss the state-specific monitoring well requirements to determine design and construction options for monitoring wells within the reactive barrier.

7.2 Monitoring Well Placement

Groundwater modeling should be used as a tool for the determination of monitoring well locations. Groundwater monitoring wells should be installed both upgradient and downgradient (on both sides) of the PRB. At a minimum, selection of monitoring well screen intervals and lengths should consider:

- Site geology,
- Aquifer thickness,
- Aquifer flow (horizontal and vertical) characteristics,
- Presence of multiple aquifers,
- Nature of contamination,
- Construction details of the PRB,
- Conformance with State guidance and regulations.

Installation of multi-level monitoring wells may be appropriate. The number and location of wells must be sufficient to quantify reductions in contaminant levels, as well as changes in flow rates and direction over time, so as to provide a measure of performance of the PRB. If a funnel and gate design is used, a monitoring well should be placed at the ends of the funnel wall to ensure that contaminants are not migrating through or around the PRB (refer to Section 7.8 of this report). While an aquifer may be homogeneous, the installation of multi-level or cluster wells are recommended within the reactive media since it has the potential for developing heterogeneities due to possible compaction of the reactive media, and the development of corrosion products or precipitates within the reactive media pore space. It is important that some wells be screened at the bottom of the excavation of the reactive media to monitor for potential contaminant migration beneath the wall. In addition, when employing a funnel and gate system or variation thereof, monitoring wells should be installed near the walls of the reactive media, as the groundwater velocity tends to be greater at these points. Note that when assessing optimum well locations, contaminant breakthrough may very well occur along the reactive media walls, and not necessarily within the middle of the reactive media. (Refer to Section 7.8 and Figures 2 and 3 which graphically depict the monitoring well placement concepts outlined in this section) The appropriate location and number of monitoring wells will be determined by the size and geometry of contaminant plume, the size of the PRB, groundwater flow rate, the heterogeneity of the geologic formation and reactive media, and the potential for other site activities to impact groundwater flow in the vicinity of the PRB. It is important, when considering the number and location of wells, that all aspects of the contaminant plume are characterized and conceptually understood.

7.3 Analytical Parameters and Methods

USEPA methodologies should be employed for analysis. Table 2.3 lists analyte or parameter, analysis method, sample volume, sample container, preservation and sample holding time.

7.4 Sampling

Sampling of wells close to the reactive media or within the reactive media requires special considerations in order to obtain a representative sample. Typical well purging methods and volumes will not apply to these wells. In order to obtain a representative groundwater sample, the residence time of the groundwater within the reactive media must not change. The volume of groundwater removed and the rate at which it is removed must not change the residence time within the reactive media. A very low flow purge rate and a small volume of groundwater should be purged to ensure that the groundwater being sampled has had sufficient time to react with the reactive media. Alternatives for sampling include use of a low flow sampling procedure (see Puls and Barcelona, 1996), dedicated submersible pumps, packers or other specialized sampling devices which reduce the purge and sample volume. There are currently no guidelines on the amount or rate at which groundwater should be purged. This is an issue which must be determined on a case-by-case basis. Keep in mind, however, that a slower and smaller purge will have the least effect on residence time, thus providing a more representative sample of the reactive media performance.

Conventional purging and sampling can be used on monitoring wells positioned away from the reactive media, provided the purging and sampling will not influence groundwater flow through the reactive media.

In areas where the groundwater elevation (hence flow) is tidally influenced, the timing of the sampling event should consider the impacts of the tidal fluctuations.

7.5 Monitoring Frequency

The design and establishment of a monitoring schedule is sensitive to groundwater flow velocity. If a PRB is built downgradient of a plume, it may take weeks or months for the plume to reach the barrier, especially when groundwater flow velocities are low. Measuring inorganic parameters and radionuclides before the plume reaches the PRB may be unnecessary, however, measuring field parameters is still important. Table 7-1 provides monitoring frequency guidance for PRBs; as always, site-specific considerations and professional judgement should be used to determine frequencies and parameters.

Several issues to consider when determining monitoring frequency include:

- Groundwater flow velocity,
- Reactive media residence time,
- Contaminants of concern,
- Fluctuation in contaminant concentration,
- Location and placement of PRB next to plume,
- Seasonal fluctuations in groundwater elevation.

Table 7-1. Suggested Permeable Reactive Barrier Monitoring Frequency

Parameter	Frequency
A - First Quarter After Installation	
Field Parameters	Monthly
Inorganic Analytes***	
Inorganic Contaminants	
Radionuclides	
Groundwater Levels	Weekly (until equilibrium is reached)
B - Initial Monitoring Program (1 - 2 years)	
Field Parameters	Quarterly
Inorganic Analytes***	
Inorganic Contaminants	
Radionuclides	
Groundwater Levels	Monthly, then to be determined
C - Long Term Monitoring	
Field Parameters	Quarterly (may be modified based on performance)
Inorganic Analytes***	
Inorganic Contaminants	
Radionuclides	
Groundwater Levels	
D - Post-Closure Monitoring	
Inorganic Contaminants of Concern	To be determined based upon the closure method and data collected during operation of the PRB
Leachable Constituents from Reactive Media	
Radionuclides of Concern	

* Refer to Table 2-3 for analysis method.
** Groundwater levels should be measured to 0.01 feet.
*** See Table 2-3 for parameters

In general, during the first quarter after the plume reaches the PRB, monthly sampling of field parameters, inorganic constituents and/or radionuclides should be performed on wells within and close to the reactive media. These data will help evaluate the effect of the PRB installation on the surrounding aquifer. It should be noted that monitoring during the first quarter will not be representative of the performance of the PRB after equilibrium is reached. Disturbances caused by the installation process have been known to create changes in the concentration of groundwater contaminants. These changes should be monitored and recorded until this process is better understood. Initial placement of a PRB has been reported to temporarily increase the levels of groundwater contaminants in some instances. The increase may be due to the desorption of contaminants from the installation technique, changes in groundwater flow velocity or some unknown phenomenon. The potential exists for the placement of a PRB to create a vector of groundwater contamination which may affect non-contaminated wells. These phenomena result from transitory effects from the installation process. The overall performance of the PRB system should not be affected over a longer time period. In some instances, enhanced performance of the PRB has been reported during the first few months following system start-up, after which performance tends to reach an equilibrium. As more experience with PRBs is accumulated, the initial monitoring program may be subject to modification. After the first quarter, samples for chemical analyses should be collected on a quarterly basis from the wells within the reactive media and selected upgradient and downgradient wells. Wells along and at the ends of the funnel wall(s) should also be sampled quarterly to evaluate movement under and around the wall. In establishing monitoring requirements for the first year, evaluation of modeling data should be performed to identify the most useful data points. Monitoring should be designed to evaluate the sensitivities of a variety of parameters over the first year of operation at a site. A strategy may then be developed to re-evaluate the monitoring parameters and locations, and analytical data on a continuing basis to ensure that the sampling locations and parameters are appropriate. This may result in the elimination of redundant monitoring points or certain parameters at specific sampling locations from the quarterly monitoring plan.

Continual adjustments based upon an increased understanding of the performance of the system and recalibration of the model should drive decisions on establishing the frequency and locations of monitoring. Based on the long-term performance of the wall and a re-evaluation of the monitoring plan and operational data, a modification from the quarterly sampling schedule may be instituted after the first or second year of operation.

Gathering groundwater level data is a relatively inexpensive analysis which can provide a great deal of information regarding the performance of the system. During the first quarter, groundwater level data should be collected on a weekly basis for all wells associated with the PRB to determine and observe any changes in the components of groundwater flow after PRB installation. Measurement of groundwater levels during the first and second year of operation should be conducted on a monthly basis, during which evaluation of the data will indicate where the frequency can be reduced or where monitoring wells can be eliminated from the monitoring program. Groundwater level data should be collected, even if the plume has not yet reached the wall to ensure that equilibrium is being reached and that no damming of the aquifer is occurring. This schedule of groundwater monitoring takes into account seasonal variations in groundwater levels.

7.6 Hydraulic Evaluation

Evaluation of hydraulic flow parameters is a primary concern for PRBs. Precipitation within and near the PRB can lead to clogging and channeling which, in turn, impact the PRBs effectiveness, making monitoring changes in flow patterns and decreased permeability within the reactive media a primary concern. The site characterization should evaluate flow heterogeneities of the natural subsurface system to be used as a base line for post-barrier installation.

In addition to routine groundwater level elevations (discussed above) there are several techniques to evaluate hydraulic characteristics on a non-routine basis. These include in-situ flow meters, groundwater velocity probes, or pressure transducers available for the determination of flow rates and directions. These field instruments can provide real-time data on the PRB without affecting residence time. Tracer tests may also be utilized to provide information on flow rate and channeling through the reactive media. Whether or not a permit is required for the injection of the tracer material will be a state-specific determination. Slug tests or pump tests may be used to determine media flow characteristics within and around the PRB. These tests can provide information on hydraulic conductivity within various media. However, caution should be employed in and around the reactive media, where the test could change the media residence time. In some instances, cores of material from the PRB and/or adjacent aquifer may be collected. These cores can provide valuable information of solid phase transformations that may affect PRB performance (e.g. pptn.→clogging as mechanism of metal removal). Care must be taken that core collection does not compromise reactive barrier performance by altering flow field.

7.7 Long-Term Monitoring

Long term monitoring is necessary to verify continued performance of the PRB. Evaluation should occur on a yearly basis to determine the adequacy of monitoring frequencies and locations. The monitoring frequency is suggested to occur on a quarterly basis for field parameters, inorganic parameters, radionuclide parameters, and ground water levels. However, the nature of treatment of inorganics and radionuclides (e.g. precipitation) and the potential for clogging and channeling of the reactive media as well as desorption and leaching of contaminants of concern should be taken into consideration when decisions are made with regard to modifying the monitoring frequency.

7.8 Examples of Monitoring Scenarios

Figures 2 and 3 depict the monitoring issues discussed in this document. The figures show expected groundwater flow lines, provide hypothetical examples of monitoring well placement, and the types of information which may be gathered from that placement. Site-specific conditions should always dictate the placement of monitoring wells.

A Determine downgradient groundwater quality.

B Ensure treatment effectiveness and determine groundwater flow rate.

C Determine treatment effectiveness, groundwater flow rate and reactive media fouling.

Note: Wells B, C, D are located along lines through the reactive media to monitor flow paths. Monitoring wells are placed at both the sides and the middle of the reactive media to monitor differences in flow.

D Determine upgradient concentration of contaminants, the potential for reactive media fouling and groundwater flow rate.

E Determine leakage, underflow or overflow across the funnel wall.

F Ensure plume capture and determine if contaminant is migrating around the funnel wall.

NOTE: *The above letters (A-F) pertain to monitoring well placement in Figures 2 and 3.*

Figure 2 Funnel and Gate

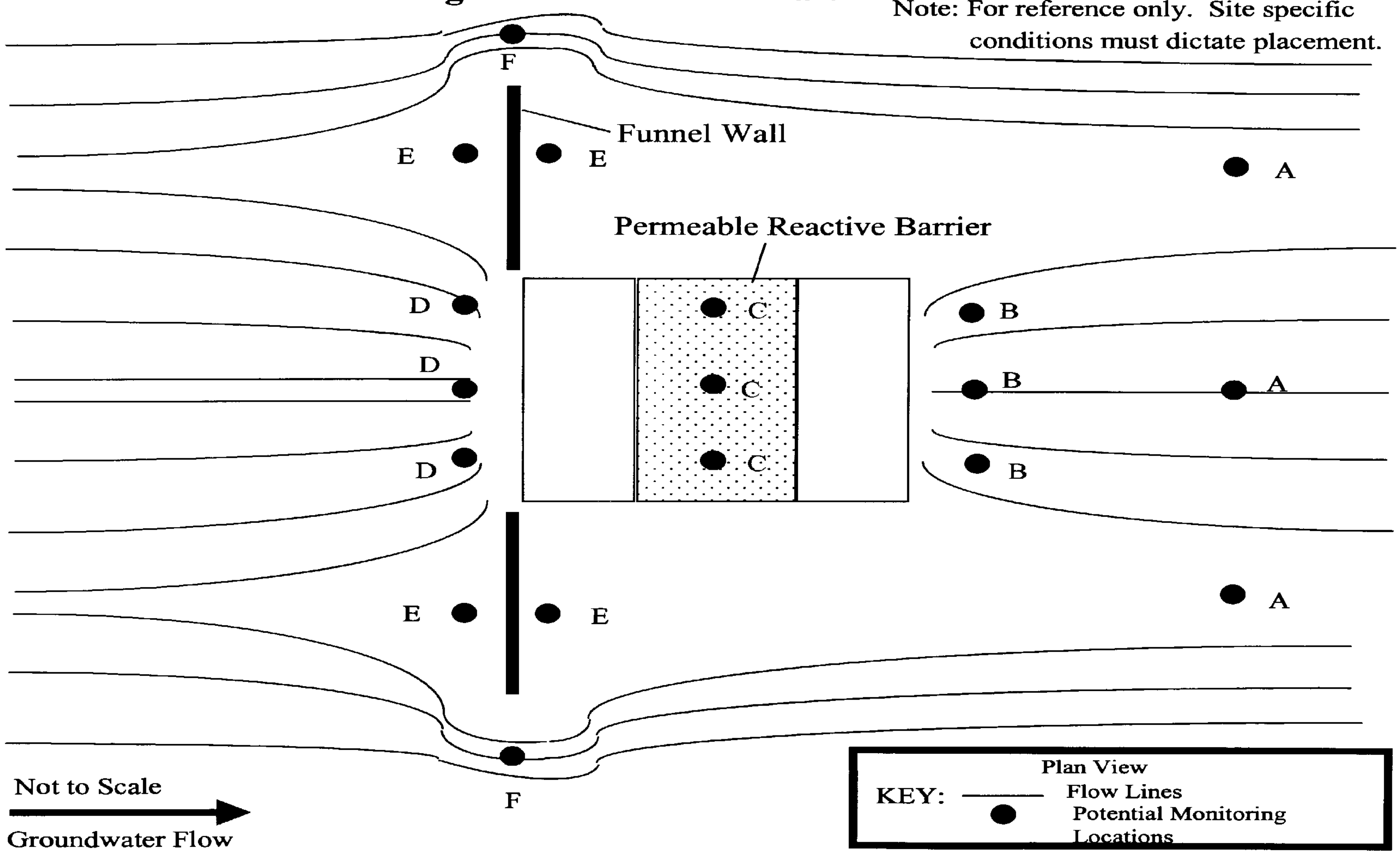
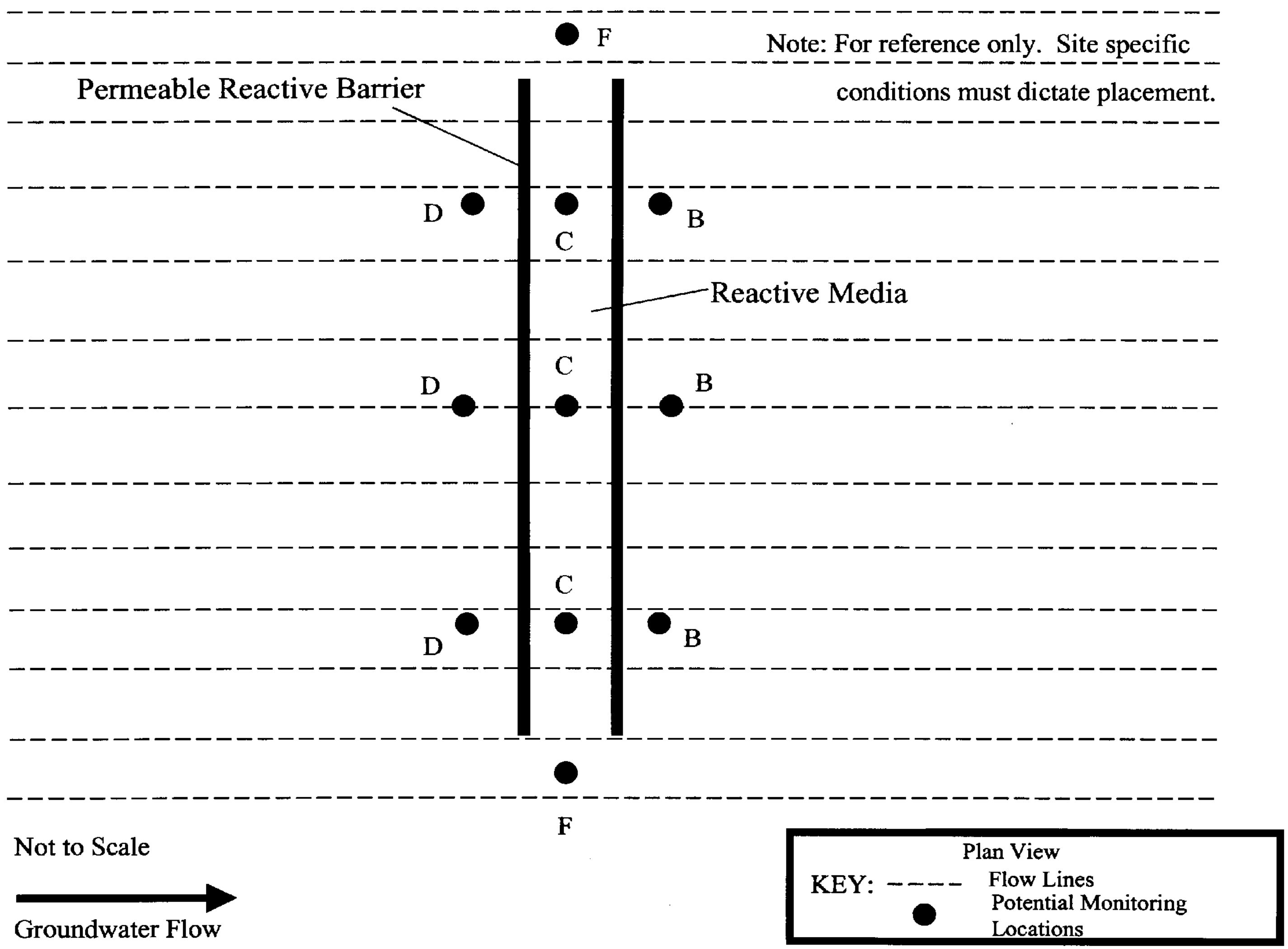


Figure 3 Continuous Wall



7.9 Alternative Methods

As this technology develops, innovation in sampling and analytical methods may result in proposals to utilize alternative methods. Sampling, analysis, and monitoring methods other than those outlined in this guidance may be proposed as a variance. State regulatory agencies should evaluate the applicability of a variance based upon the following criteria:

- The method has previously been used successfully under similar site conditions, as documented by a regulatory agency,
- The method has been tested successfully by an independent, non-regulatory verification entity,
- The method is approved by the agency, based upon site-specific conditions or technology modifications.

8.0 WASTE MANAGEMENT

Potential wastes from a PRB system include contaminated soil, groundwater, and contaminated reactive media from change-out or closure of the system. Substantive requirements and criteria which dictate waste classifications need to be clearly identified for each waste type. Classification of wastes will determine disposal options.

Contaminated soils may be generated during site investigation or PRB installation. Any soil contaminated with inorganics or radionuclides should be classified in accordance with applicable state and federal hazardous waste or radiological waste regulations prior to disposal. Classification can occur in-situ through the use of soil borings or from soil stockpiled during installation. In either situation, state-specific requirements should be followed for sample parameters and frequency to ensure the soil is properly classified prior to disposal. If the generated soil is classified as hazardous, state and/or federal regulations will dictate the disposal method. Land Disposal Restrictions and listed hazardous waste requirements should be adhered to where applicable. State-specific requirements may also regulate the management or disposal of non-hazardous waste if the material is contaminated. Disposal options for inorganic-contaminated soils include on-site, if permitted, or at an off-site hazardous waste disposal facility. If the disposal site is off-site, the accepting disposal facility will provide waste acceptance criteria. If radiologically-contaminated soils are below state-specified radiological levels, the soil may be classified as naturally occurring radioactive material and can often be disposed of on-site or at solid waste landfills. Above these specific levels, the soil is classified as low-level waste (or mixed waste if the soil includes hazardous waste). Disposal sites accepting low-level or mixed waste are limited. Depending on the soil volume, it may be cost-effective to treat soils classified as mixed waste to remove the hazardous component(s) and allow their disposal more economically as low-level waste. Additional U.S. Department of Transportation requirements may also apply to the shipping of these wastes. Wastes shipped from a federal facility may require an Offsite Rule Determination by the appropriate USEPA regional office.

Contaminated groundwater may be generated from the dewatering of the excavation during the installation process and during subsequent testing and monitoring. Equipment decontamination may also generate waste waters. Several disposal options that meet state requirements may be available. Water can be disposed at a permitted off-site commercial facility, a publicly owned treatment works or on-site in accordance with a NPDES permit or permit waiver, by land application, or by other approved means. The use of continuous trencher or jetting installation techniques can often reduce the total volume of contaminated soil and groundwater requiring treatment or disposal.

Reactive media may eventually become contaminated with enough metals or radionuclides that they must be disposed of as hazardous, low-level, or mixed waste. Even if levels of metals or radionuclides in the groundwater or source area are not above waste determination levels for these constituents, the media may qualify as a waste by concentrating these elements. The design of PRB systems needs to consider the ease of removal of the reactive media for this eventuality.

9.0 MAINTENANCE

An operation and maintenance plan should be developed for PRB installation. This should include a contingency plan to address alternative sampling and investigative corrective action procedures in the event the PRB fails to meet performance criteria. It has been estimated that the service life of the PRB is 5 to 10 years and is greatly affected by groundwater flow rates, the contaminant concentrations and pH, and biological or chemical fouling within the reactive media. Knowledge of the reactions which govern contaminant transformation is a key in determining a maintenance schedule. Reactions occurring within the PRB may cause chemical and biological fouling.

It has been estimated that some degree of maintenance could be required every 5 years to manage precipitate formation, especially in highly mineralized and/or oxygenated groundwater, and in less mineralized groundwater, every 10-15 years (RTDF document, *Permeable Reactive Barrier Technologies for Contaminant Remediation*). Removal of precipitates may significantly increase operation and maintenance costs associated with PRB use. While there hasn’t appeared to be any need for rejuvenation to date, some methods, including organic and inorganic chemical acid treatment, and chemical derusters are presently being laboratory-tested (telephone conversation, Puls, 1999). Some techniques such as hydraulic mixing with jetting equipment would provide the potential for adding chemical descalents, yet there is still uncertainty as to whether or not maintenance is needed to control the effects of precipitate formation.

10.0 CLOSURE

Currently, there is no history of PRB closure. Due to this lack of history it is difficult to specify an appropriate closure option for PRBs that treat groundwater contaminated with metals and/or radionuclides. The PRB treatment mechanism for metals and/or radionuclides differs significantly from a PRB installed to treat chlorinated solvents (See ITRC, December 1997). In contrast to a PRBs treatment mechanism for chlorinated solvents, PRBs do not degrade metals and radionuclides;

the contaminants remain in a modified chemical/physical state (e.g. alteration of oxidation state, formation of insoluble precipitates, absorption of contaminants or precipitates, etc.). Treatment mechanisms involve a change in the oxidation state of the metals and/or radionuclides under specific groundwater re-dox conditions and the contaminants form precipitates. A change in re-dox conditions over a period of time has the potential to alter the contaminants' oxidation state, causing it to re-mobilize. Another long-term consideration is the formation of precipitates and its impact on the permeability of the PRB. As the PRB becomes less permeable, thereby affecting groundwater flow, the reactive media should be removed and disposed at an appropriate disposal facility. Finally, PRBs will have limited absorptive capacity directly impacting its long-term effectiveness and closure options. If the absorptive capacity of the reactive media is reached or contaminants are found to be leaching from the barrier into groundwater, then the reactive media should be removed from the aquifer and disposed at an appropriate disposal facility. Since contaminants remain in some form, it is difficult to predict the long-term implications of allowing the reactive barrier to remain in place after remediation is complete. If the PRB remains in place, monitoring should be determined based upon the closure method and data collected during operation of the PRB.

Site-specific factors which will influence removal of reactive media include:

- Loss of permeability through the reactive media,
- Contaminant desorption from reactive media,
- Potential for spent reactive material to provide a future contaminant source,
- Concentrations of contaminants in reactive media affect disposal options,
- Reaching capacity of the reactive media,
- Future use of property,
- Cost of removal vs. long-term operation and maintenance,
- State requirements for closure,
- Non-contaminant changes in downgradient water quality,
- The potential need for institutional controls.

Upon completion of treatment, all monitoring wells, if not needed for follow-up or future groundwater monitoring, should be plugged and abandoned in accordance with state-specific regulations and requirements. If the reactive barriers are removed they should be transported to an appropriate disposal facility, which may depend on the contaminants involved. Concentration of contaminants in the reactive barrier might influence appropriate disposal. Dewatering may be necessary prior to backfilling the PRB area with clean soil. Once backfilled, the area should be brought to elevation and revegetated in a manner similar to its surrounding area.

11.0 HEALTH AND SAFETY

A Site-Specific Health and Safety Plan should be developed and implemented in accordance with the Occupation Safety and Health Administration (OSHA) regulations 20CFR 1910.120, the Hazardous Waste Operations and Emergency Response Rule. The requirements include:

a. Site Specific Health and Safety Plan
b. Contaminant Specific Exposure Symptoms and Warnings, and
c. Training Requirements and Decontamination Procedures

12.0 STAKEHOLDER CONCERNS

A stakeholder is any non-regulatory affiliated party with interest in a particular site or technology. Stakeholders within the community in which the PRB will be deployed should be properly informed, educated, and involved in the decision making process and consulted regarding the utilization of the technology. This may require holding public meetings or information sessions, distributing informative bulletins or developing a neighborhood canvassing program. The document entitled *A Guide to Tribal and Community Involvement in Innovative Technology Assessment* explains the need for community involvement during site planning and implementation and should be used as a reference tool in forming a community outreach program. The USEPA has developed a citizen's guide as a reference for PRBs. The document is entitled *A Citizen's Guide to Treatment Walls*, and can be ordered directly from the USEPA.

Stakeholders have previously expressed the following concerns about proposed PRBs:

- There has been concern that the PRB treats the entire plume. In areas where there are preferential groundwater flow paths, ensuring total treatment must be demonstrated.
- Because this technology is passive (that is, it depends on the natural flow of the contaminant plume to pass through the wall), complete breakdown or immobilization will only occur after the entire plume has passed through the wall. This may take many years. A groundwater monitoring system should be put in place to monitor the performance. Local authorities should be informed of potential disruptions to landscaping and other activities during replacement of the media.
- When the PRB is used for precipitation of metals, it is not certain how long the wall will be effective. Wall permeability may decrease due to precipitation of metals, salts and biological activity. Passive treatment walls may lose their reactive capacity over time, and the reactive media may have to be replaced periodically. As above, a groundwater monitoring system should be put in place to monitor performance. Local authorities should be informed of disruption in landscaping, and other activities on site during replacement.
- There is insufficient information about what environmental conditions may influence remobilization of contaminants. For example, changes in pH, groundwater flow, or

rainfall may create conditions that contribute to remobilization of contaminants. These factors should be identified prior to installation of this remedy and should be monitored over the long term.

- Potential leaching of reactive media or contaminates should be evaluated.
- When the PRB is used for precipitation of metals, the media may have to be removed and disposed of as a hazardous waste, or contained in some other fashion. A plan, similar to a closure and post-closure plan mandated by RCRA should be completed prior to installation. If it is known that the reactive media will have to be contained or disposed of due to its hazardous properties, RCRA-type financial assurances should also be made part of the closure and post-closure plans.
- A contingency plan should be incorporated into proposals for this remedy. This should address alternative remedies in case the PRB fails to meet agreed upon goals, and actions that would be taken if potable water becomes contaminated.
- The remedial action work plan should address access restrictions during operations and deed restrictions if the PRB is left in place. Local authorities should be informed and be able to provide input at the time a decision is being made to keep a PRB in place.
- Special attention should be paid when the PRB is used for radionuclides. Communities are concerned about concentrating radionuclides in underground walls if they are long-lived, or are gamma emitters. Periodic information sessions should be offered to the community and local government. Institutional controls (deed and access restrictions) may be considered. Communities may oppose leaving radionuclide-contaminated walls in the ground once remediation of groundwater has been completed.

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APPENDIX A

ACRONYMS

APPENDIX A

Acronyms

ACL	alternative concentration limit
AFO	amorphous ferric oxide
Al	aluminum
α	alpha
Am	americium
Ba	barium
β	beta
^{o}C	degrees Celsius
Ca	calcium
Cl	chlorine
CFR	Code of Federal Regulations
Cr^{+3}	trivalent chromium
Cr^{+6}	hexavalent chromium
$Cr(OH)_3$	chromium hydroxide
Cs	cesium
DO	dissolved oxygen
2-D	2 dimensional
3-D	3 dimensional
DOC	dissolved organic carbon
DOD	Department of Defense
DoE	Department of Energy
Eh	redox potential
F	flourine
Fe	iron
Fe^{+3}	ferric iron
Fe^{+2}	ferrous iron
FIDLER	Field Instrument for Detection of Low-Energy Radiation
GC	gas chromatograph
HPGe	High Purity Germanium
HNO_3	nitric acid
H_2SO_4	sulfuric acid
ITRC	Interstate Technology & Regulatory Cooperation
K	potassium
Mg	magnesium
mg/L	milligrams/liter
mL	milliliter
Mn	manganese
MS	mass spectrometry
Na	sodium
NAPL	non-aqueous phase liquid
Ni	nickel

Acronyms (continued)

NRC	Nuclear Regulatory Commission
NO_3	nitrate
NPDES	National Pollution Discharge Elimination System
OSHA	Occupational Safety Health Administration
OSWER	Office of Solid Waste and Emergency Response
PO_4	phosphate
ppb	parts per billion
ppm	parts per million
PRB	permeable reactive barrier
Pu	Plutonium
PVC	polyvinyl chloride
QA	quality assurance
QC	quality control
RCRA	Resource Conservation and Recovery Act
RTDF	Remediation Technology Development Forum
SO_4	sulfate
TCE	trichloroethene, trichloroethylene
TDS	total dissolved solids
Tc	technetium
TOC	total organic carbon
TSS	total suspended solids
VOA	volatile organic analyte
U	uranium
UIC	underground injection control
USACE	United States Army Corps of Engineers
USCG	United States Coast Guard
USEPA	United States Environmental Protection Agency
V	vanadium
VOC	Volatile Organic Compounds
ZVI	zero-valent iron

APPENDIX B

EXAMPLES AND CURRENT APPLICATIONS

APPENDIX B

Examples and Current Applications

Site descriptions attached for the following permeable reactive barrier installations:

1. Nickel Rim Mine Site, Sudbury, Ontario, Canada.
2. U.S. Coast Guard Support Center, Elizabeth City, North Carolina.
3. U.S. Department of Energy Hanford Site, Richland, Washington.
4. U.S. Environmental Protection Agency Fry Canyon Site, Utah.
5. U.S. Department of Energy Monticello Mill Tailings, Monticello, Utah
6. U.S. Department of Energy Oak Ridge National Laboratory, Oak Ridge, Tennessee.
7. U.S. Department of Energy Rocky Flats Environmental Technology Site, Golden, Colorado

1. Nickel Rim Mine Site, Sudbury, Ontario, Canada

The Nickel Rim Mine site is an inactive mine near Sudbury, Ontario. Mining operations for copper and nickel began 1953. When operations ceased in 1958 an impoundment of mine tailings was left at the site. Subsequent oxidation of the tailings and infiltration into the ground have contaminated groundwater, primarily with nickel, iron, and sulfate.

The site sits in a narrow bedrock valley. The aquifer on the valley floor consists of a glacio-fluvial sand approximately 10-26 feet thick overlying bedrock. Groundwater velocity in the aquifer is estimated to be 49 feet per year. Groundwater contaminant concentrations range from 2,400 parts per million (ppm) to 3,800 ppm sulfate; 740 to 1,000 ppm iron; and up to 10 ppm nickel.

A full-scale continuous PRB was installed by a cut-and-fill technique in August 1995. The wall extends 50 feet across the valley to a depth of 14 feet, and is 12 feet wide. The reactive material consists of a mixture of compost and wood chips, with pea gravel added to increase hydraulic conductivity of the media. Coarse sand was emplaced on the upgradient and downgradient sides of the reactive wall. To prohibit infiltration of surface water and oxygen into the reactive material, a clay cap was constructed over the wall.

A series of monitoring wells were installed in the groundwater flow path perpendicular to the wall. Initial samples were collected one month after installation, and again eight months later. Sulfate concentrations in treated groundwater have been reduced to levels of 110 to 1,900 ppm. Iron concentrations have been reduced to levels of less than 1 ppm to 91 ppm. Dissolved nickel concentrations were reduced to less than 0.1 ppm.

Semiannual sampling will take place for a minimum of three years.

Total cost of installation was $30,000, which does not include post-installation monitoring.

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Reference: http://www.rtdf.org/prbsumms/sudbury.htm

2. U.S. Coast Guard Support Center, Elizabeth City, North Carolina

The U.S. Coast Guard Support Center site is located at a USCG air support base near Elizabeth City, North Carolina, adjacent to the Pasquotank River. An electroplating shop operated in a hangar at the facility for over 30 years, ending in 1984. Release of contaminants to the subsurface from plating operations in the hangar has created an hexavalent chromium and TCE groundwater plume that extends downgradient over 125 feet toward the river. The plume is about 90 feet wide.

The contaminated aquifer is primarily a silty to clayey sand, and is underlain by sandy clay. The aquifer extends from about 6 feet to 22 feet below ground surface to the top of the low permeability sandy clay. The vertical distribution of contaminants is greatest from 16 to 20 feet below ground surface. Chromium is present at concentrations over 28 ppm near the source in the hangar. Concentrations of chromium in the plume are as high as 5 ppm, and TCE concentrations are as high as 7 ppm.

In June 1996, a full scale PRB was installed by the continuous trenching technique. The wall is located about 140 feet downgradient of the source, perpendicular to the groundwater plume flow path. It is 150 feet long, about 24 feet deep, 2 feet thick, and filled with zero-valent iron as the reactive material. The top of the wall is about 3 feet below ground surface. The barrier wall was designed to treat groundwater influent concentrations of chromium and TCE at 1.0 ppm each to meet cleanup goals of 0.05 ppm for chromium and 0.005 ppm for TCE.

A complex network of piezometers and monitoring wells were installed to monitor effectiveness of the reaction wall. Three rows of multi-port sampling piezometers were installed upgradient, within, and downgradient of the zero-valent iron. Each piezometer has seven to eleven sampling ports to monitor vertical distribution of groundwater quality from the top of the water table to the base of the wall. Additionally, ten compliance monitoring wells were installed: adjacent to the wall, and within and outside of the contaminated plume.

Quarterly sampling has taken place since November 1996. Analytical results show chromium concentrations in groundwater passing through the reaction wall decrease to non-detectable levels. TCE concentrations decrease to levels generally less than 0.005 ppm.

Total installation cost of the reaction wall was $500,000.

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References:
- http://www.rtdf.org/prbsumms/elizacty.htm
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- "USCG Support Center SCEC Interim Corrective Measures, Quarter 3 Report", prepared by Parsons Engineering Science, Inc., Section 1, Rev. 0, January, 1998.
- "USCG Support Center SCEC Interim Measures Workplan", prepared by Parsons Engineering Science, Inc., Section 5, Rev. 1, December, 1995.

3. US Department of Energy Hanford Site, Richland, Washington

The 100D Area Site of the US DOE Hanford facility is located along the Columbia River in southeastern Washington. The facility includes several deactivated nuclear reactors that were used for plutonium production from 1943 until 1987. During operations, a chromium compound was used as an anticorrosion agent in the reactor cooling water. Releases to the ground likely occurred at several locations along the waste disposal system, resulting in hexavalent chromium contamination to the groundwater beneath the site. The full areal extent of the contaminant plume is not known, however, it does reach the Columbia River.

The site is underlain primarily by sands and gravels. The top of the unconfined aquifer is 85 feet below ground surface, and is about 15 feet thick. A silty clay forms an aquitard beneath the sands and gravels. Groundwater flow is assumed to be towards the Columbia River, although it is possible that flow direction may reverse during high stages of the river. Concentrations of chromium in groundwater are as high as 2,000 ppb. Concentrations of chromium in pore waters of the Columbia River substrate are greater than 630 ppb.

A large-scale treatability test for remediation by In Situ Redox Manipulation of the chromium contaminated groundwater began at the site in 1997, and was completed in July of 1998. The treatment consists of creating a subsurface permeable treatment zone downgradient of the source area in the natural aquifer material. To create this treatment zone, sodium dithionite was injected into five, 100 feet deep wells within the contaminant plume. The sodium dithionite serves as a reducing agent for naturally occurring ferric iron (Fe^{+3}) to ferrous iron (Fe^{+2}). The ferrous iron, in turn, reduces the hexavalent chromium to trivalent chromium, which precipitates out as immobile and non-toxic $Cr(OH)_3$. Sodium dithionite reaction products (mostly sulfate) were withdrawn once the initial reducing reaction ($Fe^{+3} \rightarrow Fe^{+2}$) had occurred. This sodium dithionite residence time was approximately 18 hours. A reducing zone 50 feet in diameter was created at each injection point, resulting in a total treatment zone 150 feet long and 50 feet wide.

The point of compliance for evaluation of treatment effectiveness is the Columbia River, with a target goal of 11 ppb hexavalent chromium. Three dual-level sampling piezometers were installed into the river substrate. The target goal for compliance within the aquifer is 22 ppb hexavalent chromium. Several monitoring wells were installed on site to monitor treatment effectiveness within the groundwater plume.

Preliminary data obtained following injection of sodium dithionite into the five wells showed chromate groundwater concentrations decreased to less than 8 ppb in the aquifer.

The installation cost estimate for the entire treatability test is $ 480,000.

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References:
- "Treatability Test Plan for In Situ Redox Manipulation in the 100-HR-3 operable Unit D- Area", prepared by Pacific Northwest National Laboratory for US DOE, May 1997.
- http://www.rtdf.org/presumms/hanford.htm

4. U.S. Environmental Protection Agency Fry Canyon Site, Utah

The Fry Canyon Site is located in southeastern Utah. Abandoned and unreclaimed tailings from former uranium-upgrading activities have created a plume of uranium-contaminated groundwater. This technology demonstration is under the direction of USEPA.

The site is underlain by an colluvial aquifer: primarily fine- and medium-grained sand with some silt and gravel. The Cedar Mesa Sandstone forms the canyon walls and lies beneath the alluvium. The water table in the colluvial aquifer is about eight feet below ground surface, and ranges from one to six feet thick. Groundwater flow is to the northwest, roughly parallel to surface water flow in Fry Creek. Dissolved uranium concentrations in the aquifer range from 78 ppb in an upgradient well to 20,000 ppb in groundwater beneath the uranium tailings.

A field-scale demonstration of a funnel and gate permeable reaction wall began at the site in August 1997. The wall was constructed utilizing conventional trench and fill methods. It consists of three permeable gate sections, each containing a different reactive material. One gate is filled with bone-char phosphate (PO_4), one with foamed zero-valent iron (ZVI) pellets, and the third with amorphous ferric oxide (AFO). Each gate section is seven feet wide, three feet thick, and approximately four feet deep. A zone of pea gravel, roughly 18 inches thick, was emplaced on the upgradient side of the reactive material in all three gates. Each end of the wall (the "funnel" sections) were constructed of bentonite. The reaction wall is oriented oblique to the direction of groundwater flow.

An extensive array of monitoring points has been installed at the site. Each reactive section of the wall contains 22 sampling points: including monitoring wells, pressure transducers, a flow-sensor port, and a water quality mini-monitor.

In September of 1997, monitoring results produced dissolved uranium concentrations of over 3,000 ppb entering the PO_4 gate decreasing to levels of 2 to 580 ppb. At the ZVI section, initial dissolved uranium concentrations range from 1,510 to 8,550 ppb, and decrease to below the reporting level of 0.06 ppb within the iron. Initial concentrations of dissolved uranium flowing into the AFO section range from 14,870 to 17,590 ppb, and drop to less than 500 ppb within the reactive material.

The estimate of design costs for Fry Canyon is $23,000, which includes all labor, management, and overhead. It does not include bench-scale testing of the candidate barrier materials. Installation costs are estimated to be $120,000.

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References:
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- "Environmental Assessment for Fry Canyon Ground-Water Clean-Up Demonstration Project", T. 36 S., R. 16 E., Section 34 in San Juan County, Utah, March, 1997.

5. U.S. Department of Energy Monticello Mill Tailings, Monticello, Utah

The Monticello Mill tailings site is a US Department of Energy site located in the Montezuma Creek Valley, east of the Abajo Mountains, Utah. The mill began operations producing vanadium in 1942, then in 1944 began production of a uranium/vanadium sludge. Milling operations at the site ceased in 1961.

Approximately 2.1 million cubic yards of mill tailings abandoned at the site have contaminated soil and groundwater with uranium, arsenic, selenium, molybdenum, manganese, and vanadium. The aquifer is an alluvium about 10 feet thick, the upper surface of which is about 15 feet below ground surface. Bedrock (the Dakota Formation) lies beneath the aquifer at 25 feet below ground surface. Hydraulic conductivity is from 0.01 to 0.1 cm/s. The uranium plume is over one mile long, discharging into Montezuma Creek. Concentrations of uranium in groundwater are as high as 500 pico Curies per Liter (pCi/L); vanadium concentrations are 500 ppb, and molybdenum concentrations are 200 ppb.

The PRB will be 100 feet long, 6 feet thick, and installed to a depth of 17 feet. Zero-valent iron will be used as the reactive material.

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Reference: - http://www.epa.gov/region08/sf/fact/r808e4.htm

6. U.S. Department of Energy Oak Ridge National Laboratory, Oak Ridge, Tennessee

Oak Ridge National Laboratory is a US Department of Energy site in Oak Ridge, Tennessee. Disposal ponds in the Y-12 area were used from 1952 until 1981 for the disposal of uranium, technetium and nitric acid. The site was capped in 1983. Leaching from these basins has contaminated surface and groundwater.

The site is underlain by a low-permeability clay from 10 to 20 feet thick. Below the clay is a more permeable, weathered bedrock unit. Below that is fractured shale bedrock. Depth to groundwater is 10 to 15 feet.

Two PRBs have been installed in the shallow unconsolidated zone for technology demonstration. The first of these barriers was installed in November 1997, oriented parallel to the direction of groundwater flow of flow pathway 2. It is a continuous barrier, 225 feet long, with a 26 feet long section in the middle, filled with zero-valent iron; the two side sections are filled with gravel. The upgradient gravel section funnels groundwater into the reactive iron. The downgradient gravel section directs treated groundwater away from the treatment zone.

A funnel and gate system was installed in December, 1997 to treat flow pathway 1. It consists of two gravel-filled funnel walls that direct groundwater to a zero-valent iron treatment module and treatment cells below ground. This funnel and gate system is 250 feet long with side walls installed to a depth of 25 feet.

A monthly monitoring program was instituted to evaluate effectiveness of both PRB systems. Numerous piezometers and monitoring wells have been installed within and adjacent to the treatment zones. Preliminary data show effective removal to non-detect levels of uranium and technetium by reductive precipitation, and effective degradation to non-detect levels of the nitric acid. Modifications to the flow pathway 2 system are planned in 1999 to improve treatment efficiency. Plans include extending the wall to increase groundwater capture and installing an additional treatment zone.

The total installation cost for both walls was about $ 1,000,000.

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References:
- http://www.rtdf.org/prbsumms/oakridge.htm
- "Monitoring and Sampling Plan for the Reactive Barrier Trench Project", Prepared by Baohua Gu for Oak Ridge National Laboratory, August, 1998.

7. U.S. Department of Energy Rocky Flats Environmental Technology Site, Golden, Colorado

The Rocky Flats Mound Site is an area of contaminated groundwater adjacent to South Walnut Creek, north of Central Avenue, at the Rocky Flats Environmental Technology Site outside of Denver, Colorado. From 1954 until 1958, over 1,400 drums of uranium, beryllium, possibly plutonium, and contaminated coolant (hydraulic oil and carbon tetrachloride), were stored on the ground surface and covered with soil. All drums (some of which were leaking) and some radionuclide-contaminated soil were removed from the site in 1970. The present medium of concern is shallow groundwater. Primary contaminants are tetrachloroethene (up to 520 ppm), trichloroethene (up to 18 ppm), americium (up to 0.25 pCi/l) and uranium (up to 17.6 pCi/l). The shallow plume discharges directly into South Walnut Creek and also to ground surface through a surface water seep adjacent to the Creek.

The area impacted by the Mound Site groundwater plume is underlain by a clay-rich colluvium. The depth of the colluvium is variable, as there have been numerous landslides and regrading activities in the area over the years. Weathered claystone bedrock lies beneath the colluvium at depths ranging from five to as much as 25 feet below ground surface. Groundwater elevations are shallow, from ground surface at the stream and seep to about three feet in the treatment area. Groundwater flows north into the Creek. Discharge from the seep averages less than 0.5 gallons per minute. Groundwater flow for the overall plume area is estimated to be between 0.1 and 2 gallons per minute.

In mid-1998 a subsurface groundwater collection system was installed south of South Walnut Creek to intercept the contaminant plume and minimize impacts to surface water. A collection trench was excavated by conventional excavation/trenching techniques. It consists of a trench from 15 to 20 feet deep, two to three feet thick, and 230 feet long, keyed into the underlying claystone. A perforated collection pipe was placed at the bottom of the trench. An impermeable geomembrane was emplaced along the downgradient side, and the trench was backfilled with filter pack. A two foot thick impermeable cap was placed at the top of the trench to prevent infiltration. Contaminated groundwater flowing into the trench is conveyed by the collection pipe to a series of buried cells containing reactive iron filings. The iron degrades the chlorinated hydrocarbons and removes the radionuclides by reduction and/or absorption. Water is treated to meet surface water action levels and is discharged to South Walnut Creek. A series of piezometers and downgradient wells are monitored regularly for water quality and hydraulic head to measure system effectiveness.

The first treatment cell of iron filings will remove radionuclide contamination, as well as degrade VOCs. When the absorptive capacity is reached, the iron filings will be removed, managed, and disposed of appropriately as determined by analysis at time of disposal. The second treatment cell of iron filings will finish degradation of the chlorinated organics. When material in this cell is exhausted, it will be replaced. It is expected that the iron filings will require replacement every five to ten years.

Two larger PRB installations are proposed for Rocky Flats. A 1300-foot long collection system will be coupled with a centralized below-surface reactive metals treatment system similar to the design for the Mound Site Plume. A PRB system is also proposed to remediate a nitrate and uranium plume emanating from Solar Evaporation Ponds.

Installation costs of the collection trench and reactive iron treatment system was approximately $300,000.

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Reference: - "Final Mound Site Plume Decision Document, RF/RMRS-97-024; Major Modification to the Final Surface Water Interim Measures/Interim Remedial Action Plan/Environmental Assessment and Decision Document for South Walnut Creek", September 30, 1997.

APPENDIX C

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