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The Use of Permeable Reactive Barriers for In-situ Remediation of Groundwater Contaminants

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ABSTRACT

The treatment of contaminated groundwater is among the most difficult and expensive environmental problems and often the primary factor limiting closure of contaminated sites. The most common technology used historically for remediation of groundwater has been ex-situ pump-and-treat systems. Pump and treat systems are still suited for certain site-specific remediation scenarios; however, the limitations of pump-and-treat technologies have also been recognized. This has been accompanied by the recognition for the need for new innovative solutions for the treatment of contaminated groundwater.

Over the past decade, permeable reactive barriers (PRBs) have provided an increasingly important role in the passive interception and in situ treatment of groundwater as a component of remedial action programs. PRBs have been used to remove a wide range of organic and inorganic contaminants from groundwater including petroleum hydrocarbons, chlorinated solvents, nutrients, metals and radionuclides.

The concept of PRBs is relatively simple. A reactive material is placed in the subsurface at a location that intercepts a groundwater contaminant plume, such as a deep backfilled trench installed across the plume. The contaminants pass through the PRB with the flow of groundwater, typically under its natural gradient, thereby creating a passive treatment system. As the contaminants move through the material, reactions occur that transform it to less harmful or immobile species.

Many reactive media types have been tested or are currently being investigated for treatment of a variety of contaminants by PRBs. Iron metal, otherwise known as $Fe^{(0)}$ or zero-valent iron (ZVI), is the most common reactive media used in the majority of PRB installations. To-date, over 80 pilot-scale and full-scale PRBs have been installed worldwide, with over 58 in the United States. Various forms of organic carbon have also proven to be successful and effective at removing a wide range of inorganic metals. However, the number of installations has been lower than zero-valent iron PRB's.

This paper / presentation will focus on design and installation considerations of the use of the PRB technology and will provide site-specific examples.

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1 INTRODUCTION

The commercial application of Permeable Reactive Barriers (PRBs) has emerged during the last decade for *in situ* passive treatment of contaminated groundwater and is gradually becoming more widely accepted as a viable alternative to conventional groundwater remediation methods such as pump-and-treat (Blowes et al., 1995; Naftz, 2002; Richardson and Nickelow, 2002). The first commercial full-scale installation of a PRB for the remediation of chlorinated solvents using zero valent iron (ZVI) occurred only as recent as 1994. Similarly, the first full-scale installation of a PRB using organic carbon for the treatment of nickel, iron and sulphate occurred in 1995.

This paper has been prepared to introduce and describe the application of PRBs, and focuses on design and installation considerations. Site-specific examples of design and installation considerations are presented. This paper will provide general information and considerations on the following:

1. Technology Description
2. Practical Considerations For PRB Application and Design
3. Practical Considerations For PRB Installation
4. Post-installation Monitoring

2 TECHNOLOGY DESCRIPTION

PRBs are defined as “an emplacement of reactive treatment materials in the subsurface designed to intercept a groundwater contaminant plume, provide a flow path through the reactive media, and transform the contaminant(s) into environmentally acceptable forms and to attain groundwater remediation concentration goals down gradient of the barrier” (Powell and Powell, 1998; Powell and Puls, 1997a) (Figure1). Thus, PRB’s are a “barrier” to groundwater contaminants but not to groundwater flow. Because PRB’s rely on the natural gradient of the groundwater aquifer and require no post-installation infrastructure other than a monitoring well network, PRB’s are considered “passive”.

While the principle of operation of a PRB is relatively simple in concept, factors that require an in-depth technical knowledge of science and engineering principles includes the proper site characterization, selection of a reactive treatment media, design, installation and post-installation compliance monitoring.

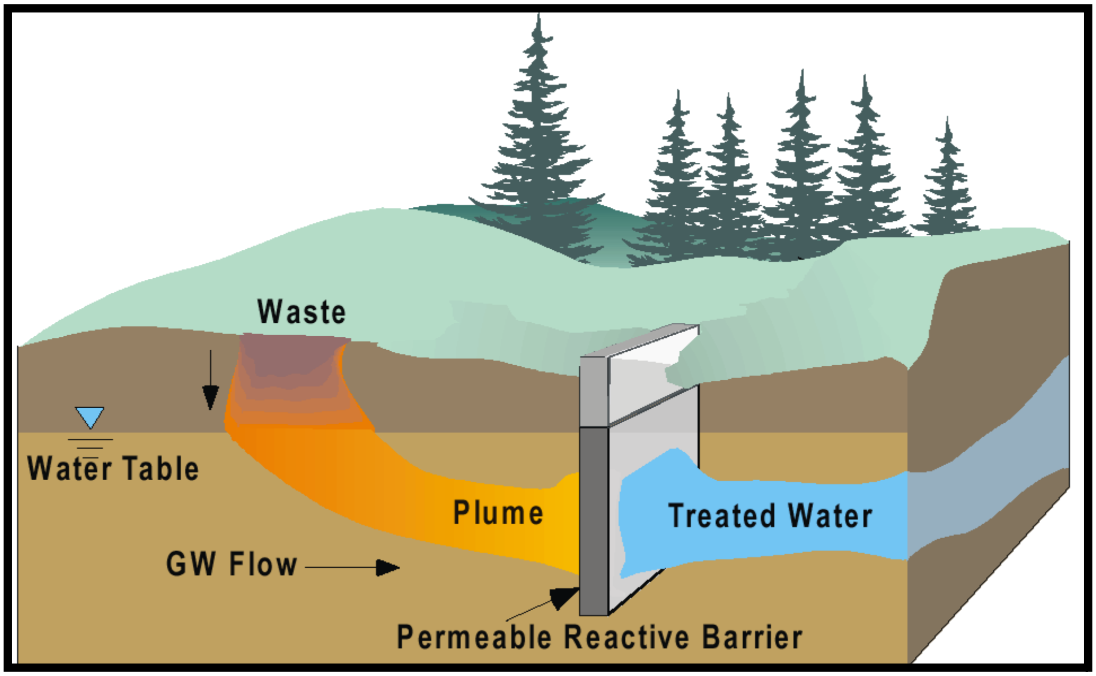

FIGURE 1: Conceptual Schematic of an *In Situ* Permeable Reactive Barrier

The main advantages of PRB application are:

- PRB's are particularly well suited to locations where the contaminants exist as a soluble or mobile phase in the subsurface groundwater aquifer and can change oxidation state upon contact with the reactive treatment media.
- PRB's are particularly well suited to contaminant plumes that are heterogeneous in composition and concentration (US EPA, 2000).
- On-going operation and maintenance functions are generally limited to compliance monitoring and where necessary, replenishment or replacement of reactive treatment media. Therefore, operating costs are typically significantly lower than traditional pump and treat systems.
- PRB operation does not alienate land use above the PRB. Therefore active site restoration and development can occur above a PRB without affecting its performance and in some cases can improve performance by reducing surface water infiltration into the contaminant plume.

The main disadvantages of PRB application are:

- PRB's are not well suited to treatment of insoluble/immobile contaminants (i.e. some DNAPLs).
- PRB's installed in groundwater aquifers with low hydraulic conductivities or groundwater velocities are likely to require a long residence times to treat the contaminants-of-concern. This may result in a significant increase in PRB installation costs and offer no cost advantage over conventional pump and treat systems.

- Precipitates that may form in a PRB can reduce permeability and long-term effectiveness.
- Thorough and careful site characterization is required pre-design to allow for consideration of potential changes to groundwater flow or contaminant migration, as post-installation improvements to PRB performance can be difficult and costly.

2.1 Treatable Contaminants and Reactive Treatment Media Types

Research has been conducted over the past several years to identify reactive materials that can be used in PRBs to treat a variety of groundwater contaminants. Contaminants that have been demonstrated to be successfully removed from groundwater include a wide range of organic and inorganic substances. Organic substances include halogenated organic compounds, such as trichloroethylene (TCE) and tetrachloroethylene (PCE). Inorganic compounds include redox-sensitive inorganic anionic contaminants, such as SO_4^{2-}, NO^{3-}, PO_4^{3-}, Cr(VI), As(III), As(V) and Se(VI). A list of groundwater contaminants treatable by PRBs is shown in Table 1.

The ability of a PRB to remove any of these contaminants from groundwater is determined primarily by the type of reactive treatment media. The most commercially successful reactive treatment media used to-date is ZVI, also known as Fe^0 or iron-filings. Other reactive treatment media include: limestone, organic carbon (compost and wood chips), metal oxides such as iron and calcium, surfactant modified zeolites (SMZ), hydrated lime, sodium, dithionite, phosphate, bone char and a polysulphide compound.

TABLE 1: Groundwater Contaminants Treatable by PRB's

Organic Compounds	Methanes	tetrachloromethane, trichloromethane, dichloromethane
	Ethanes	hexachloroethane, 1,1,1-trichoroethane, 1,1,2- trichoroethane, 1,2-dichoroethane
	Ethenes	tetrachloroethene, trichloroethene, cis-1,2-dichloroethene, trans-1,2-dichloroethene, 1,1-dichloroethene, vinyl chloride
	Propanes	1,2,3-trichloropropane, 1,2-dichloropropane
	Aromatics	benzene, toluene, ethylbenzene
	Other	hexachlorobutadiene, 1,2-dibromoethane, freon 113, N-nitrosodimethylamine
Inorganic Compounds	Trace Metals	chromium, nickel, lead, uranium, technetium, iron, manganese, selenium, copper, cobalt, cadmium, zinc, mercury
	Anion Contaminants	sulphate, nitrite, phosphate, arsenic

Note: Adapted from EPA/600/R-98/125, Table 3.

2.2 Key Design Elements

As with all passive *in situ* treatment systems, a main element of PRB design is conducting a thorough site characterization. Key elements required during site characterization include development of a site conceptual model that includes detailed subsurface soil stratigraphy, and hydrogeological and geochemical characterization. Accurate estimates of groundwater flow are essential and temporal variations should also be investigated. When combined with the calculated contaminant removal rates, the required residence time per unit thickness of the reactive treatment media can be determined. An understanding of the subsurface stratigraphy will reveal whether there is the presence of any subsurface layers or units that influence groundwater flow and/or contaminant migration. For example, the PRB can be keyed into aquitard layers (i.e. confining layers), to provide capture of the groundwater plume. Similarly, geochemical characterization is essential to understanding the horizontal and vertical extents of groundwater contamination and temporal variations in contaminant concentrations. This information is critical to determining an appropriate length and depth of the PRB.

The selection of an appropriate reactive treatment media can be assessed from literature research, laboratory batch tests and characaterization of the hydraulic conductivity of the groundwater aquifer. As previously mentioned, the calculated contaminant removal rates are also a key PRB design parameter. This information is best obtained through conducting laboratory columns tests using a reactive treatment media composition based on geochemical site characterization and laboratory batch test results. Ideally, the columns tests should be conducted using contaminated groundwater collected from the site. Characterization of the hydraulic conductivity of the groundwater aquifer is required to ensure the hydraulic conductivity of the reactive treatment media is the same or higher to maintain the natural groundwater flow through the PRB and prevent side or underflow of the contaminant plume.

2.3 Installation Options

Permeable Reactive Barriers are installed in two basic configurations, continuous or funnel and gate (Figure 2). The selection of the appropriate configuration is primarily dictated by the ability of the PRB to capture the full contaminant plume with a minimal disruption to the natural groundwater flow regime. Numerical groundwater and/or contaminant transport modelling may be required to assess the effects of the selected design configuration. Depending on the complexity of the site subsurface stratigraphy, groundwater flow and contaminants, it may be advisable to proceed with the installation of a demonstration or pilot-scale PRB to provide the necessary evaluation and confidence in the PRB design and installation methods.

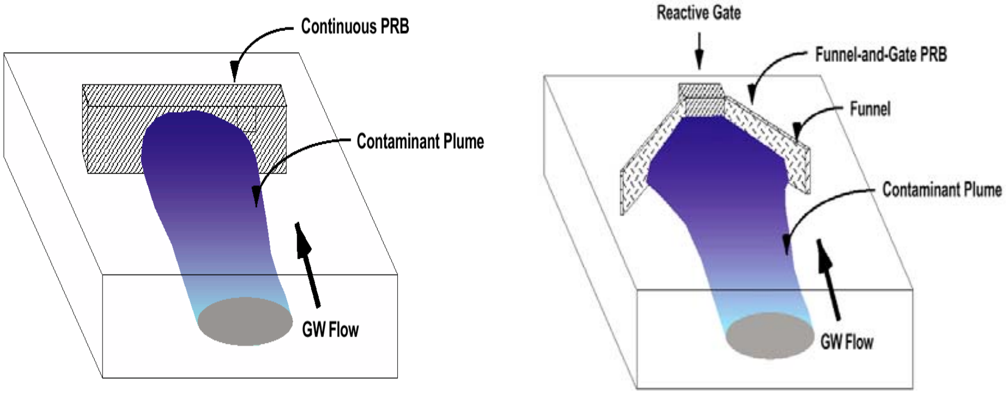

FIGURE 2: (left) Plume capture by a continuous PRB trenched system. The plume moves unimpeded through the reactive zone; (right) Plume capture by a funnel-and-gate system. Sheet piling funnels direct the plume through the reactive gate.

Various construction techniques have been used to emplace PRB's. These include: conventional excavation and back filling, trenching machines, tremie tubes or mandrels, deep soil mixing, high-pressure jetting in conjunction with vertical hydraulic fracturing and reactant sand sealing. Among these methods, conventional trenching and backfilling has most commonly been applied to continuous PBRs, while sheet-pile driving and slurry walls have been most commonly used for the impermeable section of funnel and gate PRB configurations. No single technique is applicable to all PRB installations; the objective being to apply a technique that is both technically feasible and cost effective under site-specific constraints. A quality assurance program must form an integral part of the overall emplacement program. This is most critical in continuous PRB configurations to confirm that the PRB design dimensions have been achieved. During emplacement, depth sounding and surveying are commonly employed. Post-emplacement, geophysical techniques such as natural gamma, electrical resistivity, conductivity and surface radar may also provide limited useful information. Tracer tests and standard hydrogeological characterization techniques such as hydraulic conductivity can also provide useful information.

3 PRACTICAL CONSIDERATIONS FOR PRB APPLICATION & DESIGN

The examples below draw on our collective knowledge and experience from several heavy metal-impacted sites. Environmental investigations conducted at these sites have determined that sediments/soils are contaminated with sulphide minerals and as a result of the on-going oxidation and metal leaching of these sulphides, dissolved sulphate, heavy metals and acidity have migrated downward into and contaminated the underlying groundwater aquifer.

Where practical, the remedial action plan (RAP) for heavy metal contamination should consider the removal of the sulphides in sediments/soils as much as practically and cost-effectively as possible from the site (i.e. remove the "source" of on-going heavy metal release). As noted in Table 1 above, the application of PRBs is well suited to the treatment and prevention of residual heavy-metal contaminated groundwater from migrating away from the source area and entering into nearby surface water bodies.

Key elements of PRB design include determination of the reactivity of the treatment media, the level of required treatment (reduction in contaminants), and the maximum anticipated groundwater velocity through the wall. Laboratory column tests are conducted to assess the reactivity of the treatment media with the selected design treatment media types. The required level of treatment is based on regulatory requirements, which may include risk-based remediation objectives. Groundwater velocities can be determined through tracer tests, pump tests, and hydraulic conductivity calculations, which are components of detailed hydrogeological site characterization. Further information on column testing and site characterization is provided below.

Other requirements for design may involve: the installation and monitoring of a pilot-scale PRB, the installation of a test-section of the full-scale PRB, and The purpose of a pilot-scale PRB is to test the ability of the PRB technology to effectively treat the level of contaminant concentrations in groundwater under site-specific conditions. Long-term monitoring data from pilot-scale PRBs at several sites have demonstrated that PRB technology is a cost-effective option for the removal of the heavy metal contaminants from groundwater. In some cases installation of a test section the full-scale PRB may also be required to evaluate site-specific technical and construction details of the full-scale PRB design, such as installation to the design depth and width, installation options or technical challenges associated with the most cost-effective installation technique.

3.1 Site Characterization

Hydrogeological investigations are essential to determining the hydrogeologic properties of the aquifer. This may be challenging to adequately characterize where a site is adjacent to a tidally-influenced waterbody, has a high groundwater flow rate or in the aquifer is composed of highly permeable coarse sediments. Hydrogeological investigations required may include: water level monitoring using pressure transducers, hydraulic conductivity testing, pump tests and tracer tests. Water level monitoring is conducted to investigate temporal variations in the net or mean groundwater flow direction and hydraulic gradients in the vicinity of the proposed PRB location. Where tidal influences occur, simultaneous use of pressure transducers in multiple wells are required to provide sufficient data that filter out the effects of tidal fluctuations. Pump tests provide date for determination of the transmissivity and hydraulic conductivity of the aquifer.

3.2 Column Tests

Laboratory column tests are used to provide a controlled environment for the evaluation of the reactivity of the proposed reactive treatment media. Where practical, input water for columns should consist of groundwater from monitoring well located near the proposed location of the full-scale PRB, which represent a worst case scenario for dissolved metal contaminant concentrations on the site. In most cases, it is recommended that multiple column tests be conducted simultaneously to evaluate different reactive treatment media or optimization the reactive treatment media by varying the amounts of each component.

For organic carbon-based PRB's, a Monod-type rate expression (i.e. bacterially-mediated sulphate reduction) is fitted to the chemistry profile to determine appropriate reaction rate constants. Based on use of the Monod-type equation for organic carbon PRBs, both zero and first order rate constants are determined.

For reactive treatment media containing iron-filings, which have a significantly faster reaction rate and substantially high reactivity than organic carbon, a first-order kinetics equation is normally used to determine an appropriate reaction rate constant.

4 PRACTICAL CONSIDERATIONS FOR PRB INSTALLATION

The type of PRB, type of reactive treatment media and site-specific factors determine the necessary requirements for each phase of the PRB project. Site activities for the installation of a PRB consist of three main components: pre-installation, installation and post-installation activities.

4.1 Use of Different/Multiple Reactive Treatment Media Types

Depending of the site-specific requirements and design, multiple types of reactive treatment media can be installed within a single PRB. For example, one recent installation used several distinct reactive treatment media types. Compost provided an organic carbon source for most of the PRB; however, iron-filings were mixed into the reactive treatment media and placed in a zone of highest metal input concentrations in groundwater to provide sufficient reactivity for the calculated residence time. At locations where tidal fluctuations and/or seasonal changes in the groundwater table can affect PRB performance, the amount of compost in the zone of fluctuation can be increased to increase the degree of water saturation thus preventing oxygen infiltration and promote more consistent PRB performance, without negatively impacting the PRB permeability relative to the surrounding aquifer.

4.2 Treatment Media Mixing and Testing

In PRBs where the reactive treatment media consist of several components, design and installation considerations must include appropriate QA/QC protocols to ensure of the consistency of and create a homogeneous reactive treatment media. After mixing, testing protocols may include compositional and hydraulic conductivity testing. Where compositional specifications are not met, adjustments can be made to the stockpiles by recalculating and then adding the required volume of component to meet specifications.

Ideally, the permeability of the reactive treatment media should be an order of magnitude greater than that of the surrounding aquifer and in no case less than that of the surrounding aquifer. The permeability of the reactive treatment media should tested on using constant and or falling-head permeameter tests. Where specifications are not achieved, the reactive treatment media can be remixed and retested until the target specifications were met. Figure 3 provides an example of the ideal hydraulic conductivity contrast between three different reactive treatment media types and a coarse-grained aquifer.

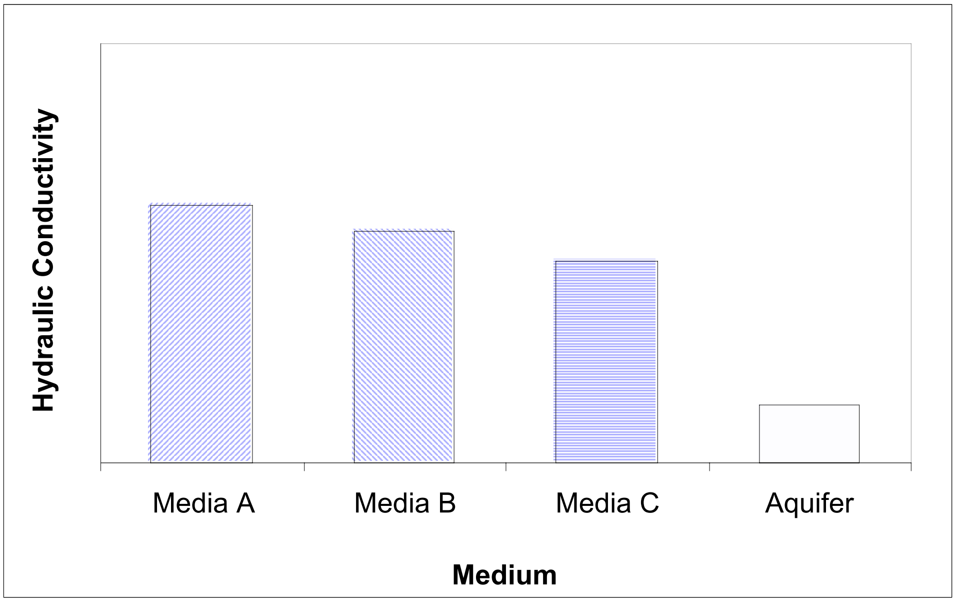

FIGURE 3. Hydraulic Conductivity of Media Types Compared to Aquifer

4.3 Excavation Sequence and Quality Control

On larger-scale PRB projects, the PRB should be installed in sections to minimize installation risks. This is particularly important where continuous excavation and biodegradable slurry is used to prevent trench failure. The excavation and reactive treatment media placement sequence should be continuous and designed to minimize the installation time.

4.4 Reactive Treatment Media Placement

The reactive treatment media placement is determined primarily by the chosen installation method. For example, where continuous trenching is used, reactive treatment media can be emplaced simultaneously. Where biodegradable slurry is used, reactive treatment media placement can be accomplished using a clam-shell bucket to lower the reactive treatment media to the bottom, “blind”. During this process, site personnel may be required to monitor and ensure that each bucket of reactive treatment media has reached the bottom before being released. The levels of reactive treatment media placement can be checked regularly by depth sounding, and recorded at regular pre-determined intervals.

4.5 Cover Installation

Where oxygen and/or surface water infiltration is a PRB performance concern, a geosynthetic cover can be installed over the PRB to reduce potential impacts from oxygen ingress and surface water infiltration. A sand layer, above and below geosynthetic cover, minimizes the risk of cover damage and will maintain the cover integrity.

4.6 Monitoring Well Network Installation

During the final post-installation phase of the project, a network of groundwater monitoring wells is required for compliance and performance monitoring purposes. The use of continuous multi-channel tubing (CMT) wells is a particularly useful well-type for PRBs, because of its ability to allow multiple sampling depths within a single borehole. Standard 5.1-centimetre diameter PVC wells are also commonly installed at locations up gradient, within and down gradient of the PRB.

5 POST-INSTALLATION MONITORING

The frequency of monitoring will be dependent on site-specific factors, regulatory requirements and the PRB performance itself. Generally, monitoring is most frequent (i.e. quarterly or semi-annually) earlier in the PRB life and may decrease over time. Components of a monitoring program may include groundwater chemistry sampling, geochemical modelling, groundwater level monitoring, hydraulic conductivity testing, tracer tests, and core sampling and mineralogical analyses.

6 CLOSING

This paper / presentation has provided overall design and installation considerations for PRB's and provided examples from collective knowledge and experience from several metal impacted sites. As more long-term performance data are collected from the limited number of PRB's installed to-date, these data will provide the necessary long-term evidence to demonstrate the long-term effectiveness from a performance and cost perspective, relative to other available treatment technologies.

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