Permeable Reactive Barriers

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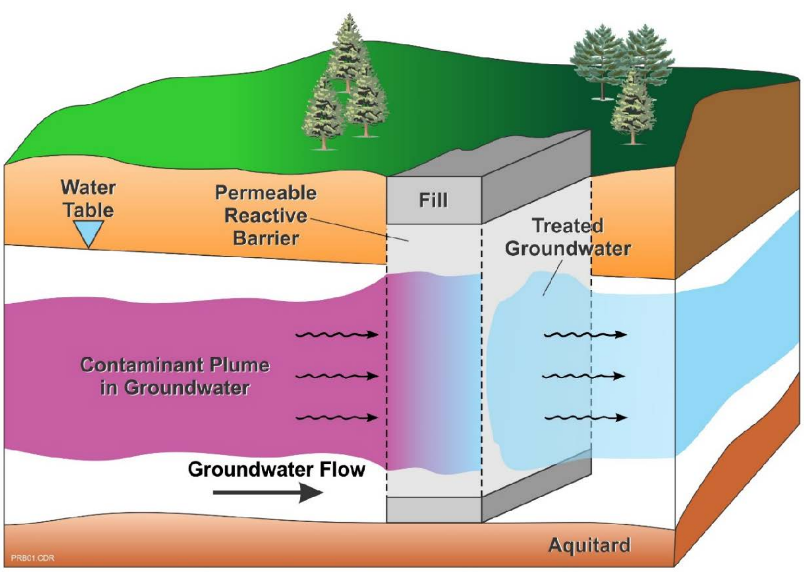
Schematic



Permeable Reactive Barrier Schematic

Introduction

Many types of permeable reactive barriers (PRBs) are used to passively treat groundwater in situ. A PRB typically involves the installation of reactive media within a trench, a series of overlapping borings, or grouped injection points to create a permeable "wall" positioned perpendicular to the direction of groundwater flow, through which the contaminant plume passively flows. The media are selected to adsorb, precipitate, or chemically degrade the groundwater contaminants within, or close to, the treatment media. PRBs can leverage physical, chemical, and/or biological processes to remove contaminants of concern (COCs). This profile focuses on abiotic (physical/chemical) degradation processes while a separate biowall profile describes a similar technology focused on biodegradation processes.

Other Technology Names

Passive/Reactive Treatment Wall
Iron Wall
Funnel and Gate
Zero Valent Iron (ZVI) Curtain
ZVI Wall

Description

PRBs are installed across the flow path of a contaminated groundwater plume such that the plume is intercepted and remediated. One of the most common configurations is a continuous reactive barrier, where the treatment medium extends across the entire width and depth of the contaminant plume (NAVFAC, 2018). Another common configuration is the funnel-and-gate, where impermeable walls guide groundwater through one or more treatment gates (NAVFAC, 2018).

PRBs have evolved since their inception in 1995 from trenches filled with iron filings to include a wide range of installation methods and treatment media. The optimum installation method is site- and application-specific, based on factors such as depth and width of the PRB, type of media used, geology and hydrogeology, and existing surface and subsurface infrastructure. Installation options include:

- **One-pass trencher:** A one-pass trencher is a track mounted, heavy construction vehicle with an extended cutting boom (a linked chain belt with cutting teeth) similar to a chain saw. These are capable of cutting trenches 12 to 36 inches wide and 20 to 50 feet deep (though greater depths are possible with benching the excavation site). Continuous one-pass trenchers emplace the PRB media while simultaneously cutting the trench.
- **Excavators:** Excavators are track mounted, heavy construction vehicles with a bucket or clamshell on the end of a boom, controlled from within a cab on a rotating platform. Excavators are commonly used for depths of 45 feet and shallower, but they have the potential to trench to a depth of 200 feet below ground surface. Excavators are used to create an open trench (shored if necessary), which is backfilled with the PRB media as a granular material or a slurry.
- **Soil mixing:** Soil mixing using large augers of up to 30 inches in diameter can be advanced to depths up to 60 to 100 feet beneath ground surface, although the deeper portion of this range may be cost prohibitive at many sites. In this method, the PRB media are pumped as a slurry or placed as a granular material through the hollow auger stem and mixed into the soil as the auger turns and is withdrawn from the subsurface. Placement of several borings in overlapping arrays creates a continuous PRB. PRB borings can also be created using the caisson method, in which a steel cylinder up to 15 feet in diameter is driven into the ground and the soil within the cylinder is removed and replaced with the PRB media.
- **Injection of aqueous phase reactants through direct injection points or permanent wells:** PRB media in a carrier fluid are injected under pressure, with the goal of achieving a continuous reactive zone. This method typically results in a less continuous reactive zone than trenching or borings, because of the soil heterogeneity impacts on adequate distribution of amendments inherent with injection technologies. However, injection technics can be used at some sites where other methods are not practical. Additional guidance to inject and distribute aqueous amendments can be found here.
- **Alternative, lesser used methods (ITRC, 2011) such as vibrating beam, direct emplacement via hydraulic and pneumatic fracturing techniques, and hydrofracturing horizontal media-packed wells (under study):** These methods focus contaminated groundwater flow through preferential treatment pathways.

PRBs based on physical and/or chemical processes can be constructed using a variety of media. The selected media are based on the type of contaminants being treated and an understanding of the chemical and physical characteristics that govern how the media will remove a contaminant (ITRC, 2011). Some of the more commonly used media include:

- ZVI
- Zeolite and apatite to address radionuclides
- Slag
- Organophilic clays to control non-aqueous phase liquid (NAPL)
- Activated carbon to treat polycyclic aromatic hydrocarbons (PAHs) and other volatile organic compounds (VOCs)
- Mixed iron and organic substrates such as activated carbon impregnated with ZVI (ITRC, 2011)
- Bauxite, limestone, and other mineral ores to treat a variety of metals including arsenic, cadmium, lead, and mercury (NAVFAC, 2018)

The location of a PRB relative to the contaminant plume at a site depends on the treatment objectives and how the PRB is incorporated with other technologies in a "treatment train." PRBs can be used to reduce the mass flux from a source zone by positioning the PRB at the immediate downgradient edge of the source zone. PRBs can alternatively be installed mid-plume to reduce dissolved concentrations at a location. Key performance factors for PRBs are:

- Establish and maintain the hydraulic conditions necessary for effective treatment, including sufficient residence time for contaminated groundwater within the media and effective routing of the contaminated groundwater through the media without deflection or bypass (ITRC, 2011).
- Treat the target contaminant(s) to meet the remedial action objective at the specified distance downgradient of the PRB.

Development Status and Availability

The following checklist provides a summary of the development and implementation status of PRBs:

☐ At the laboratory/bench scale and shows promise

☐ In pilot studies

☒ At full scale

☒ To remediate an entire site (source and plume)

☐ To remediate a source only

☒ As part of a technology train

☒ As the final remedy at multiple sites

☐ To successfully attain cleanup goals in multiple sites

PRBs are available through the following vendors:

☒ Commercially available nationwide

☐ Commercially available through limited vendors because of licensing or specialized equipment

☐ Research organizations and academia

Applicability

Contaminant Class Applicability Rating for PRBs
(Rating codes: ● Demonstrated Effectiveness, ◐ Limited Effectiveness, ○ No Demonstrated Effectiveness, I/D Insufficient Data, N/A Not Applicable)

Nonhalogenated VOC	Halogenated VOC	Nonhalogenated SVOC	Halogenated SVOC	Fuels	Inorganics	Radionuclides	Munitions	Emerging Contaminants
●	●	●	●	◐	◐	○	●	I/D

PRBs are applicable to a wide range of COCs, however the PRB media must be selected to match the contaminant. Understanding the processes by which the COCs degrade, sorb, or precipitate is crucial to choosing the PRB medium or media (ITRC, 2011). PRBs relying on physical and chemical processes such as sorption, reduction, or oxidation are commonly used. For instance, chlorinated compounds can be treated using PRBs constructed of ZVI or zero valent zinc. Long-lived oxidants (e.g., potassium permanganate) and sorbent materials such as activated carbon or clay can be used to remove VOCs and semi-volatile organic compounds (SVOCs), fuels, and other compounds. Depending on site conditions and the combination of COCs present, PRBs may require several types of medium applied within a single trench.

Because of the wide variety of installation methods, PRBs are applicable at a relatively wide range of sites. Continuous wall and trenched PRBs are most applicable to sites with treatment zones 40 feet deep or less, with minimal subsurface and overhead obstructions (utilities), and substantial access for construction equipment at the surface. PRBs can be constructed to greater depths using caissons, auger soil mixing, or pneumatic or hydraulic fracturing, or caisson technologies. PRBs constructed by injecting various amendments can be installed with a smaller surface footprint required for the construction equipment, and with the ability to work around some surface and subsurface infrastructure (see case studies included in Appendix A of ITRC, 2011).

Cost

Cost drivers for PRBs include the type and quantity of media required, and the emplacement methods needed. As with all in situ technologies, application costs vary according to site conditions and contaminants. Major cost drivers include:

Upfront Costs

- Area and depth of contaminants. Extent of contamination impacts the length and depth of the PRB, and therefore the quantity of media required and the emplacement methods that can be selected.
- Groundwater flow rate. The mass flux of the contaminants through the PRB is a key design factor that impacts the thickness of the PRB necessary to achieve the required residence time, and therefore the quantity of PRB media required.
- Nature of the contaminants and degradation pathways. Determines the type of PRB media required (e.g., oxidants, reductants, sorptive) and impacts the

longevity of the media.

- Construction requirements. PRB construction requires the use of heavy equipment to install the system. Installation activities include monitoring well installation, trenching and/or drilling, reactive media emplacement, and transportation of materials. Drill rigs, continuous trenchers, backhoes, delivery trucks, and other large equipment are usually required. Fracturing and media injection require pumping and/or high pressures, often using substantial amounts of water and/or gases.
- Type of media required.
- Investigation-derived waste (IDW). Costs to dispose of IDW generated during drilling and/or excavation activities.
- Number and depth of injection points. At some sites, PRBs may be installed by injecting media through a series of injection points or wells. The number and depth of the points/wells can have a significant impact on cost.
- Remedial goals. More stringent remedial goals may require a greater biobarrier thickness, and hence greater material and construction cost, to ensure sufficient residence time.

Operation and Maintenance Costs

- Longevity of media. Short-lived media may require frequent replacement/replenishment. Longevity is impacted by media properties, types of COCs, contaminant concentrations, groundwater geochemistry, groundwater flow and other aquifer characteristics.
- Performance criteria. Performance criteria can impact the frequency that the biobarrier must be replenished with additional amendments to ensure proper operation.
- Changes in hydraulic conductivity. Periodic testing of hydraulic conductivity may be required to ensure that the barrier is not adversely impacting groundwater flow. Fouling could cause a portion of the contaminated groundwater to flow around the barrier requiring mitigation that could include the application of anti-fouling agents, replacement of material, or extending the PRB, among others.

The list above highlights those cost dependencies specific to PRBs and does not consider the dependencies that are general to most in situ remediation technologies. Click here for a general discussion on costing which includes definitions and repetitive costs for remediation technologies. A project-specific cost estimate can be obtained using an integrated cost-estimating application such as RACER® or consulting with a subject matter expert.

Duration

PRBs are passive in nature and typically require longer times to achieve cleanup goals than do other more aggressive remedial technologies. If PRBs are employed at a site where an aggressive technology is used to treat a source area, the duration needed for the PRB may be shorter. Also, in many cases, PRBs are used with monitored natural attenuation, in which case the duration that the PRB is operated will increase. The longevity of PRBs is dependent on many factors, including the following conditions.

- Groundwater flowrate and mass flux of contaminants
- Native and anthropogenic electron acceptor demand impacting the media use rate
- Iron and sulfate availability and usage (determines biogeochemical transformation process rates)
- Initial quantity and reactivity of the media used in the PRB

Coarse-grained ZVI can persist for several decades. Solid carbon-based substrates have demonstrated 5 to 15 years of productivity before replacement was warranted. Injectable substrates derived from solid carbon are intended to perform for 5 to 10 years before replenishment is needed. The longevity of potassium permanganate or other chemical treatments used in PRBs is similar to that for other in situ chemical oxidation (ISCO) configurations. ISCO is described in a separate profile.

Implementability Considerations

The following are key considerations associated with implementing PRBs:

- Performance may decrease over time.
- Proximity of the plume to site boundaries or receptors.
- Depth and width of the contaminant plume.
- Need for treatability testing. Batch jar or column tests may be performed. Results may be used to calculate reaction rates and residence time required to estimate mass of media needed and thickness of the barrier.
- Cost of treatment media.
- Size of the treatment media. Finer particles have greater surface area and therefore exhibit greater reactivity than larger particles; however, they may be expended faster.

- Fine particles result in reduced hydraulic conductivity, which can impact groundwater flow and treatment effectiveness. Larger particles, comprised of inert materials (e.g., sand), may be combined with the reactive media to improve conductivity.
- PRBs will not treat residual plumes present downgradient of the barrier. Secondary treatment may be necessary to address residual contamination. Multiple parallel PRBs may be installed at specific intervals within the contaminated plume to facilitate complete treatment.
- Longevity of reactive media.
- Deed restrictions for groundwater use may be required if the upgradient source area is not remediated or until COCs are adequately treated.
- Generation of precipitates may limit the permeability of the treatment barrier.
- Nearby dynamic loading (future pile driving, dewatering, excavation) can compromise the structure of the PRB media.
- For excavated trenches, care is needed to assure stability of the trench walls prior to amendment placement, or there is a risk of trench wall collapse and the creation of a "hole" through which groundwater could pass through untreated.

Resources

EPA. Clu-In Technology Focus on Permeable Reactive Barriers, Permeable Treatment Zones, and Application of Zero-Valent Iron
This EPA website provides an overview of PRB technologies, with links to additional resources.

ITRC. PRB Technology Technical Update (July 2011) (PDF) (234 pp, 7.58 MB)
Most recent update to four previous ITRC guidance documents on PRBs.

ITRC. PRB Reference Documents
ITRC web page providing PDF downloads of all five ITRC documents regarding PRBs.

NAVFAC. Permeable Reactive Barrier Cost and Performance Report (2012) (PDF) (85 pp, 3.40 MB)
This report provides an evaluation of cost and performance conducted for three full-scale PRBs representing a range of installation technologies, reactive media, and targeted contaminants. Injection media used ranged from ZVI that stimulates abiotic transformation of chlorinated solvents, to organic materials

(e.g., mulch; vegetable oil) that treat perchlorate and enhance reductive dechlorination of chlorinated solvents.

NAVFAC. Permeable Reactive Barrier Technology Transfer Tool (2018)
A PRB is a trench built across the flow path of a groundwater plume. The trench is filled with a suitable reactive or adsorptive medium that removes the contamination from the groundwater. This tool is designed to assist in the development and implementation of effective PRB applications.

SERDP-ESTCP. Evaluation of Performance and Longevity at DoD Permeable Reactive Barrier Site (October 2001) (PDF) (328 pp, 18.9 MB)
A study coordinated with companion studies through EPA and DOE to assess the long-term performance of PRBs.

SERDP-ESTCP. Remediation of TNT and RDX in Groundwater Using Zero-Valent Iron Permeable Reactive Barriers and Zero-Valent Iron In Situ Treatment Wells (May 2008) (PDF) (123 pp, 3.84 MB)
Two demonstration studies, one replacing traditional well sand pack with coarse granular iron to treat munitions constituents, and a second using a ZVI barrier wall.