Overview of Permeable Reactive Barriers

Presented To:
Dr. Norman Jones
Civil Engineering Dept., BYU

By:
David H. Snow
April 5, 1999

Abstract

Permeable reactive barriers are a practical, low cost alternative to traditional pump and treat methods. After very extensive site characterization, the location, design, thickness and length, and reactive media of the barrier can be determined. A common reactant is zero valent iron because of it's availability and effectiveness in removing many contaminants but specifically chlorinated solvents. Advantages of permeable reactive barriers are their cost effectiveness, ability to treat multiple contaminants, the limiting of cross contamination as well as many others. The disadvantages are that they are restricted to shallow plumes, loss of reactant potency and permeability, and possible aesthetic problems. There is a lack of reliable field data and long term testing nevertheless, permeable reactive barriers are quickly proving to be a preferred choice in remediating contaminated groundwater.

Table of Contents

Introduction

Traditional methods of cleaning up contaminated groundwater have been to pump and treat the water on the surface. Costs of this type of remediation are often very large while its effectiveness at removing subsurface contaminants is not. In fact, contaminant concentrations are rarely lowered below required levels using “pump and treat” alone (Puls, 1997). Permeable reactive barriers (PRBs) are considered a low cost, effective alternative for remediating contaminated sites.

Overview of Permeable Reactive Barriers

The principle behind a PRB is to let the contaminated groundwater flow through a reactive media that will degrade or change the contaminant into a harmless or easily degradable compound. Figure 1 shows the basic concept of the PRB.

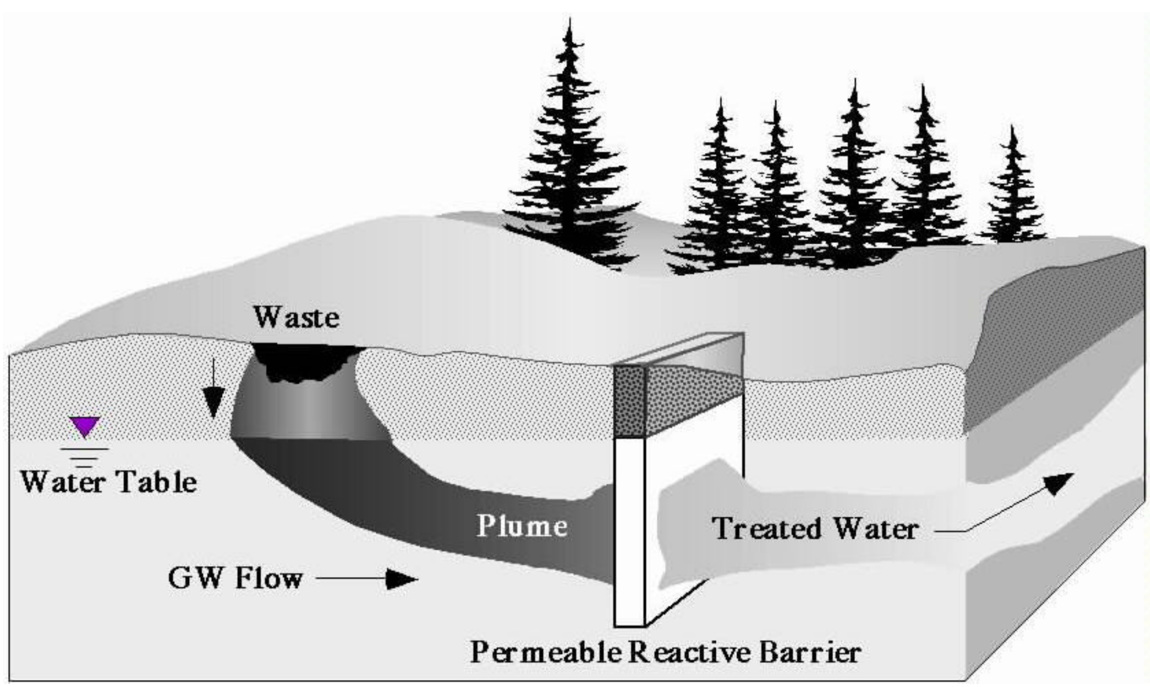

Figure 1: Basic concept of the Permeable Reactive Barrier (PRB). As the contaminant flows with the groundwater, it passes through a barrier of reactive media.

A common reactive media used in PRBs is zero valent iron (Fe III) because of it's ability to degrade chlorinated solvents as well hazardous metals such as chromium, selenium, technetium, and uranium.

Not only are PRBs efficient in degrading contaminants, but they are also cost effective as well. The main costs of reactive barriers are in the characterization, design, and construction after which the only other cost involved is compliance monitoring to again characterize the plume once it has passed through the barrier.

PRBs are best suited for shallow plumes that are found in non-fractured media where flow can be easily characterized and monitored. They are most effective in areas of little seasonal variation of the ground water table since they cannot adapt to changing conditions.

Using Permeable Reactive Barriers

Site Characterization

Many things must be known before a PRB can be successfully designed and implemented to remediate the groundwater. Such things are the contaminant concentration, the degradation rate with the proposed reactive media, the presence of daughter products of the original contaminant, groundwater velocities, preferential flow paths through the substrate, any natural groundwater sources and sinks, and plume depth and width. This important information allows designers to determine the contaminant's necessary residence time in the reactive zone and subsequently the barrier thickness as well as how long and deep it must be (Powell & Associates Science Services).

Design of the Structure

There are two basic designs of PRBs being used in full scale remediation projects, the continuous trench and the funnel and gate. A continuous trench is the most

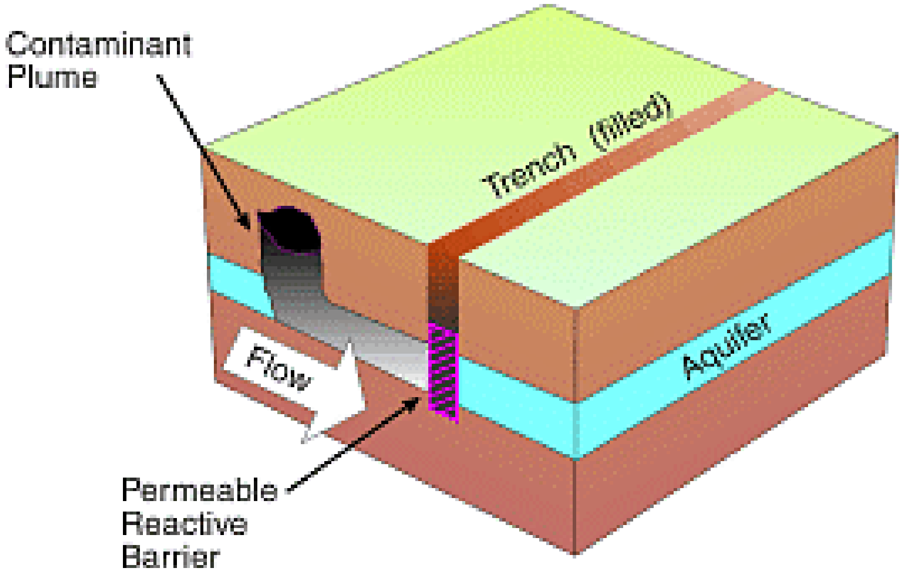

Figure 2: Continuous trench design is simply a trench filled with the reactive material (Permeable Reactive Barriers).

basic design since it is nothing more that a trench filled with the reactive media (Figure 2). The groundwater is allowed to move along it's natural gradient as it passes through the barrier (Puls, July 1997).

The funnel and gate design, on the other hand, literally funnels the groundwater through the reactive material by using impermeable barriers on either side to direct the flow of the water (Figure 3) (Emcon Technology Update). These impermeable barriers are typically interlocking sheet piles or slurry cutoff trenches. This design must prevent flow around the funnel barriers and also take into account the accelerated groundwater velocity since a large volume of water is being forced through a much smaller area (Puls, 1997)

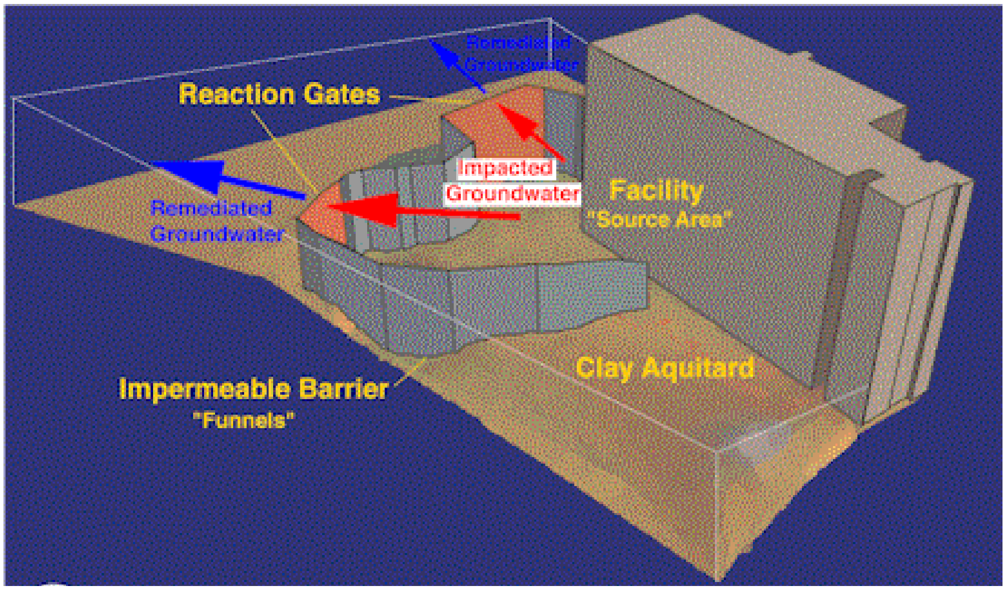

Figure 3 : Funnel & gate system (Emcon Technology Update).

Compliance and Performance Monitoring

Compliance monitoring simply ensures that the barrier is in compliance with state and federal regulatory agency requirements. General parameters include monitoring of the contaminants and daughter products that result because of natural degradation and reaction with the barrier media. Also, routine general water quality parameters must be determined such as pH, hardness, etc.(Puls, 1997).

Performance monitoring gauges the effectiveness of the barrier in removing the targeted contaminant. Some goals of performance monitoring are to determine whether or not there is contaminant breakthrough or if the water is flowing around the barrier altogether. Also, it is necessary to know the amount of precipitate buildup on the surface of the reactive material and at what rate it is forming. Performance monitoring also helps to determine if there has been a loss of reactivity, decrease in permeability, or a decrease in the reactive zone residence time.

Wells used for monitoring should be placed in strategic locations in order to properly gauge the barrier's effectiveness. Wells should be placed upgradient of the plume to determine the baseline water quality that is entering the contaminated zone as well as immediately before the reactive zone to monitor concentrations and possible daughter products that enter the reactive substrate. There should also be wells within the reactive zone as well as immediately down gradient of the reactive zone discharge. Wells on each end of the trench or funnel allow monitoring of flow around the barriers (Puls, 1997). Figure 4 shows a general layout of monitoring wells for a continuous trench barrier system.

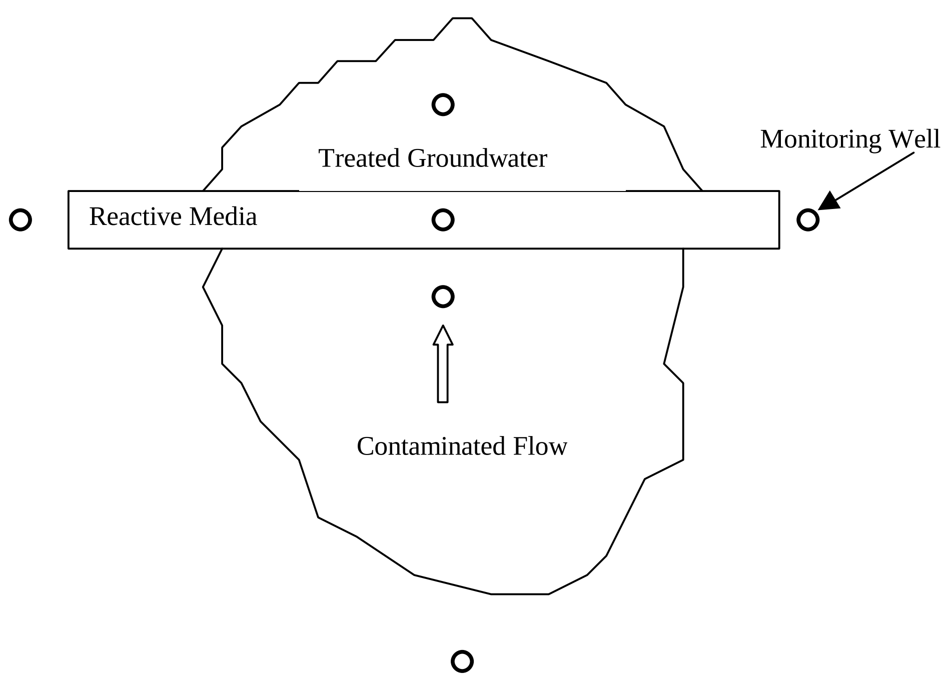

Figure 4: Typical well locations for compliance and performance monitoring.

Reactive Media

The knowledge that metals can react with certain organic chemicals has been common for quite some time. However, the realization that metals could be used to treat subsurface contaminants (mainly chlorinated solvents) is relatively new, only originating in the late 1980s and early 1990s (Powell & Associates Science Services). Therefore, only now is extensive research being conducted on the limitless possibilities metals and other reducing compounds can afford in treating contaminants. As of right now, the main focus has been the use of zero-valent iron (Fe^0) in treating chlorinated solvents because of iron's availability and low cost. However, Fe^0 is not limited to only chlorinated solvents. It has also been found to effectively treat uranium, selenium, chromium, as well as technetium.

Zero-Valent Iron (Fe^0)

Zero-valent iron reacts with subsurface contaminants by giving up electrons and causing a reducing reaction. Two examples would be the reduction of trichloroethylene TCE) to ethene and the reduction of Cr(VI) to Cr(III). Figure 5 shows the step by step

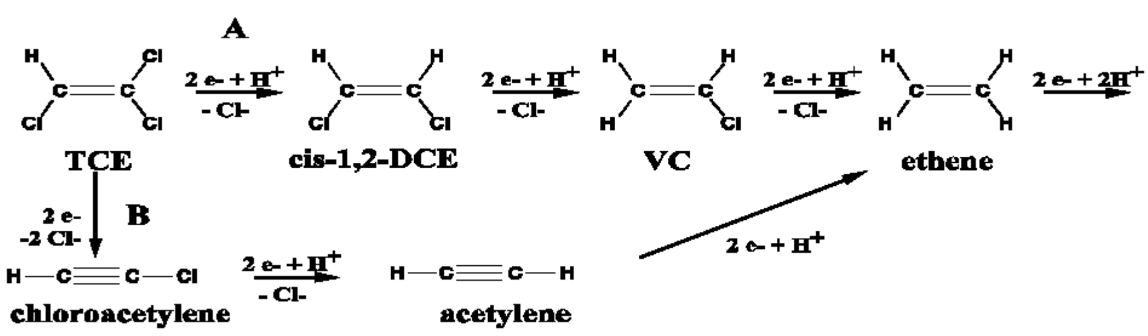

Figure 5: Degradation of TCE due to reduction by zero valent iron (Puls, 1997).

reduction of TCE by two competing pathways, hydrogenolysis (A) and reductive β-elimination (B). Figure 6 shows the reduction of Cr(VI), a very mobile and toxic carcinogen to Cr(III), which is a significantly less toxic and mobile contaminant.

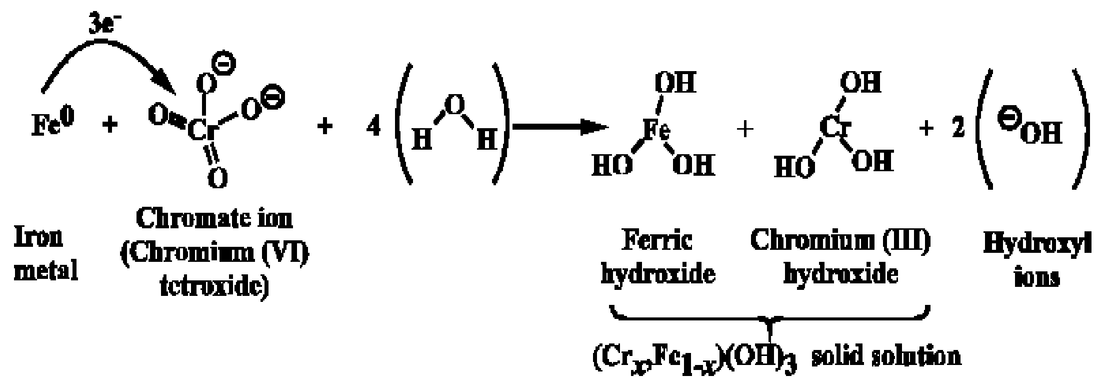

Figure 6: Reduction of Cr(VI) to Cr(III) by zero valent iron.

Cr(III) precipitates from the groundwater as chromium hydroxide ($Cr(OH)_3$) at pH levels of 6 to 9. However, when iron is present Cr(III) precipitates as a mixed chromium-iron hydroxide solid which has a lower equilibrium activity than pure hydroxide. Therefore, the danger of Cr(III) is reduced.

Efficiency of Zero Valent Iron

The efficiency of zero valent iron in reducing various contaminants has been shown in field scale studies. In Fry Canyon, Utah, home of an abandoned uranium upgrader site, there was found in the groundwater a uranium concentration of 60 µg/L in a background well and up to 20,700 µg/L directly underneath the uranium tailings. The aquifer was about eight feet below the ground and ranged from one to six feet deep with a hydraulic conductivity of approximately 1.5 ft/ day. The conductivity of the iron was approximately 1,500 ft/day which created groundwater velocities of 4.5 ft/day within the reactive zone. Under these conditions, the zero valent iron consistently removed greater than 99.9% of the uranium (Fry Canyon Site, UT). Another site utilizing Fe^0 in Sunnyvale, CA needed to remove VOCs such as TCE, cDCE, VC, and Freon 113 from the aquifer. After installation of the PRB containing zero valent iron, the concentrations from monitoring wells in the reactive zone were reported as undetectable (Industrial Site, Sunnyvale, CA). A site in New York State also showed the removal of organic contaminants TCE, VC, and cDCE from initial concentrations of 250 µg/L, 125 µg/L, and 25 µg/L respectively. Figure 7 shows the results.

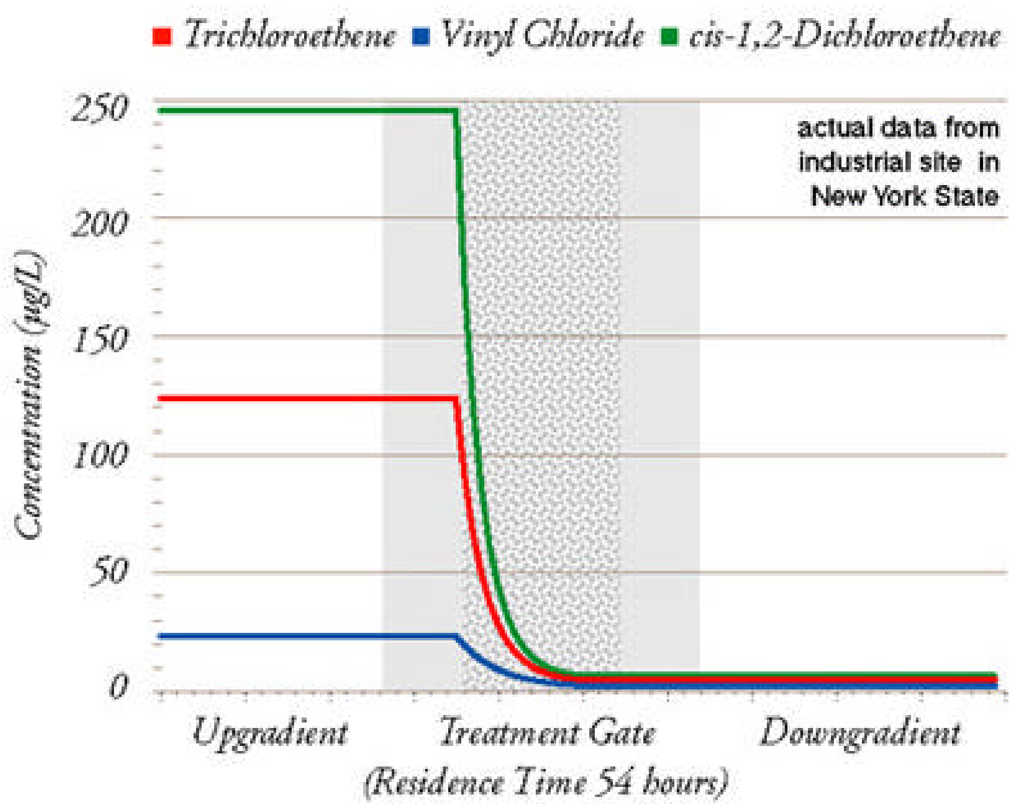

Figure 7: Removal of TCE, VC, cDCE due to reduction by zero valent iron.

Advantages of PRBs

Cost Effectiveness

There are many advantages of permeable reactive barriers compared to traditional pump and treat remediation systems. First and foremost is the cost of implementing this type of system. While the initial installation cost may be substantial, there is very little operation and maintenance involved. Because PRBs are a passive remediation technique, there are no active energy costs nor need for employees to monitor and maintain the equipment. Further, there is no disruption to the original use of the land which limits the inconvenience to the public and minimizes the economic impact to businesses so they can continue normal operations (Technologies – Fact Sheet).

The main costs of permeable reactive barriers are the preliminary site characterization, engineering, and installation. Depending upon the site and the type of engineering and characterization that needs to be done, this part of the project can be $30,000 or more. Construction and installation of the barrier can range in cost from $140,000 to well over $500,000. Such figures, compared to active treatment techniques, are very inexpensive. Once the characterization, design, and installation phases are complete, there is very little expense thereafter to maintain or operate the barrier (EnviroMetal Advantages).

Field scale implementation of reactive barriers demonstrate the low cost of this passive technology. In Fry Canyon, Utah, engineering and design work cost $30,000 while materials and installation was $140,000. In Mountain View, CA, a continuous trench 44 ft. long x 5 ft. deep x 4.5 ft. thick holding 90 tons of reactive fill was installed for $100,000. Installation of a 150 ft. long x 23 ft. deep x. 2 ft. thick continuous trench of 450 tons of reactive material in Elizabeth City, NC cost $500,000 and was installed in less than six hours (Field Scale Demonstration Installation – June 1996). A 200 ft. long trench in Belfast, Ireland with 15 tons of reactant cost $375,000 while an industrial facility in Coffeyville, Kansas needed a 1000 ft. funnel and gate system with 70 tons of reactive material which totaled only $400,000 (Powell & Associates Science Services). Such examples show the feasibility of the permeable reactive barrier compared against other more expensive treatment alternatives.

Treatment of Multiple Contaminants

Permeable reactive barriers allow the treatment of multiple contaminants since various reactive media can be placed within the barrier wall. Theoretically there is no limit to the number of contaminants that can be treated in this manner. Multiple cartridges of reactive material can be placed within the reaction zone such as zero valent iron filings, bone char phosphate, and amorphous ferric oxide (Fry Canyon Site, UT). Then when these cartridges have lost their potency or permeability due to excessive corrosion or precipitates, they can be removed and replaced with fresh ones. This greatly extends the life of the barrier (Technologies - Fact Sheet).

Little to no cross contamination

This type of treatment does not significantly alter the natural flow of the groundwater and therefore minimizes cross contamination of a contaminated aquifer and a clean one. There is no need for pumping or excavating contaminated water and soil and then paying for expensive disposal.

Disadvantages of PRBs

Physical Limitations

With the numerous advantages of PRBs there are still some fundamental limitations. They are still restricted to shallow plumes since creating trenches in extremely deep aquifers can become very impractical. Extensive site and plume characterization must be done in order to properly design and place the barrier. If fractured rock or soil is not planned for, preferential flow paths can form around the barrier and render it completely useless. Since this technology is still rather young, there is a lack of field data and long term testing on the barrier's longevity as well as the reactive media's effectiveness (Puls, 1997).

Seasonal changes in the groundwater table elevation affect the barrier's ability to treat a contaminant especially if it is an LNAPL. Placing a reactive barrier that is large enough to still be effective even with extreme fluctuations of the groundwater elevation has the potential to be very costly (Fry Canyon Site, UT).

Chemical Limitations

Due to the chemical reactions taking place within the reaction zone, precipitates can form on the media and limit it's permeability and effectiveness in treating the contaminant (Fry Canyon Site, UT). Also, down gradient water is subject to daughter products of the original contaminant that may not be treatable by the present reactive media. These products can sometimes be more harmful than the original.

Aesthetics

Erosion and ground settling after installation must also be accounted for. Erosion due to surface runoff can start to carry away reactive media as well as create very unsightly areas. This would not be acceptable for public lands or parks or to businesses that rely upon appearance and image to sell a product.

Conclusion

Permeable reactive barriers are a relatively new technique for treating contaminated groundwater. There are two basic designs of barriers, continuous trench and the funnel and gate system. The continuous trench is the simplest and least expensive while the funnel and gate requires impermeable walls that funnel the water through the reactive media gate(s). These barriers can vary in length from less than 50 feet to well over 1000 feet.

Extensive site characterization must be done before deciding on the location, design, and reactive media of the barrier. Soil types and their respective permeability, groundwater velocities and general flow directions, hydraulic conductivities, fractured media, sources or sinks of groundwater flow, and any other possible preferential flow paths must be determined. Also, plume location, contaminant identification, concentration gradients, toxicity, and all possible daughter products must be known.

Reactive material placed with in the reaction zone can essentially be anything that is needed to eliminated the target contaminant. However, due to cost and availability, zero valent iron has been the preferred reactive media. Iron has proven very reliable in reducing chlorinated organic solvents such as TCE and all the daughter products by giving up electrons and removing the chlorine atoms. It can also remove or change to a less toxic, mobile, or harmful form other contaminants such as uranium, selenium, technetium, and chromium by the same process. Removal efficiencies for zero valent iron are consistently above 99.9%.

Determining the success of the permeable reactive barrier is by compliance and performance monitoring. Monitoring wells should be placed in strategic locations at the end of the both sides of the wall, up-gradient of the reactive zone to determine the plume concentrations entering the zone, in the middle of the reactive zone to monitor the process of the reactions taking place as well as media corrosion and permeability, and down-gradient from the reactive zone to determine overall removal efficiency. Wells in these locations allow the monitoring of possible errors such as flow around the edges or through cracks in the barrier.

The most obvious advantage of permeable reactive barriers to traditional pump and treat methods is cost. While pump and treat methods require large installation, operation, and maintenance costs, the main expense of PRBs is only design and installation while operation and maintenance expenses are essentially zero. PRBs do not significantly alter the groundwater flow nor ground surface therefore allowing normal pre-treatment use of the land. Also, multiple contaminants can be treated at the same time with various removable cartridges that greatly extend the life and treatment capability of the barrier.

However, limitations of PRBs do exist that do not allow them to be used in every situation. They are currently restricted to shallow plumes in aquifers that do not have fractured media that can create preferential flow paths around the barrier. The reactive media can lose it's permeability due to precipitates as well as reactivity and therefore lose efficiency. Seasonal changes in the water table also limit the barrier's effectiveness while erosion and ground settling must be considered in order to prevent unsightly views, especially in public areas.

As of right now, there is little field data and long term testing of reactive barriers. But, the field data that is available show that PRBs are a viable and very practical alternative to traditional pump and treat or active energy methods.

References

Puls, Robert W. "Permeable Reactive Subsurface Barriers for the Interception and Remediation of Chlorinated Hydrocarbon and Chromium (VI) Plumes in Ground Water"

Puls, Robert. W. "In Situ Remediation of Contaminants in ground Water and Soils Using Permeable Reactive Barriers" July, 1997.http://www.epa.gov/docs/ahaazvuc/rap2.html

Kaplan, Daniel and KirkCantrell "Reactive Permeable Barrier Using Iron Colloids for the Remediation of Groundwater Contaminants."

EnviroMetal Process "The Process" http://www.eti.ca/theprocess/html

"Technologies - Fact Sheet: Removable Cassettes for DNAPL Reactive Barriers" http://www.envnet.org/scfa/tech/dnapl/factsheets/reactive.html

"Fry Canyon Site, UT" http://www.rtdf.org/publisc/permbarr/PRBSUMMS/2Frycnyn.htm

"Industrial Site, Mountain View, CA" http://www.eti.ca/FieldReports/mountain.html

Powell & Associates Science Services "Contaminant remediation using permeable reactive barriers" http://www.powellassociates.com/sciserv/FeTeable1.html

"Industrial Site, Sunnyvale, CA" http://www.eti.ca/FieldReports/sunnyvale.html

"Permeable Reactive Barriers" http://www.doegjpa.com/perm-barr/index.htm

"Emcon Technology Update" http://www.emconinc.com/techup/prbinst.htm

"Field Scale Domonstration Installation – June, 1996" http://www.epa.gov/docs/ahaazvuc/eliz/full.html

"EnviroMetal Advantages" http://www.eti.ca/advantages.html