# Construction and Performance Monitoring of In Situ Reactive Barriers

by

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**ABSTRACT:** In situ reactive barriers have been constructed by a variety of means and with a range of reactive materials. Zero valent iron reactive permeable barriers have been installed to remediate chlorinated solvent contaminated groundwater by abiotic degradation of the halogenated volatile organic compounds into harmless daughter products. Alternative reactive materials are used for precipitation, sorption or biodegradation of various groundwater contaminants. The conventional means of installing such reactive barriers in a funnel and gate configuration is by braced gate excavation, and for continuous permeable barriers by slurry wall, augering, trenching, jet grouting and hydraulic fracturing techniques. This paper addresses those monitoring activities necessary to ensure a reactive barrier is constructed as envisaged, and that the barrier performs as designed. Construction monitoring activities involve quantifying barrier geometry and in situ properties, and impact of the barrier on the surrounding groundwater flow regimes. Performance monitoring activities involve groundwater chemistry data, up and down gradient of the barrier, tracer and hydrogeological tests, and field sampling and analysis of barrier in situ materials. Field case studies are used to elaborate on what monitoring activities are essential for performance monitoring of reactive barriers.

## BACKGROUND

Zero valent metals have been known to abiotic degrade certain compounds; such as, pesticides as described by Sweeny and Fisher (1972), and halogenated compounds as detailed in Gillham and O'Hannesin (1994). The abiotic reduction of trichloroethene (TCE), tetrachloroethene (PCE), vinyl chloride (VC) and isomers of dichlorethene (DCE) by zero valent iron metal has been described by a number of workers, (Gillham and O'Hannesin, 1994 and Matheson and Tratnyek, 1994). In the case of zero valent iron, the abiotic degradation of halogenated aliphatics, such as trichloroethene (TCE), is complete with ethene and ethane as the final carbon containing daughter compounds (Sivavec and Horney, 1995; Orth and Gillham, 1996). The prime degradation pathway of TCE in the presence of iron is via chloroacetylene and acetylene to ethene and ethane, and only a small proportion $< 5\%$ (Orth and Gillham, 1996; Sivavec et al, 1997) to the less chlorinated hydrocarbons.

The placement of iron filings in the subsurface for passive in situ treatment of contaminated groundwater was first discussed by Gillham (1993). The mode of placing the iron filings has been by conventional technologies such as braced excavation and trenching, and of late by hydraulic fracturing (Hocking and Wells, 1997, Hocking et al, 1998b & c). Experimental pilot scale reactive barriers have been constructed by augering, slurry wall, vibrating beam and jet grouting techniques. Full scale in situ iron passive reactive barriers have been placed at a number of sites, following the successful performance of the first pilot scale barrier constructed at CFB Borden in 1991. The rapid increase in the number of barriers installed recently, reflects the increasing maturity and acceptance of the zero valent iron technology. Five (5) year performance data of the Borden reactive barrier indicated no decline in degradation performance over time, minimal precipitation, and with expectations that the reactive barrier will continue performing satisfactory for at least another five years, O'Hannesin and Gillham (1998).


FIGURE 1. Various Reactive Barrier Construction Techniques; Braced Excavation, Slurry Wall, Vibrating Beam and Trenching.

Full scale iron reactive barriers installed by braced excavation, trenching and hydraulic fracturing have performed satisfactory, and in many cases have reduced the prime contaminants by greater than 95%. Early iron reactive barriers were based on the funnel and gate concept, Starr and Cherry (1994), with the impermeable funnels constructed by sheet piling or slurry wall technology, and the permeable gate by braced excavation. The funnel and gate system impacts the natural groundwater flow regime, and are thus being phased out with preference for continuous permeable iron reactive barriers.

Due to the low potentiometric head gradient across a reactive barrier, considerable care needs to be taken to ensure groundwater flow passes through the reactive barrier with minimal impact. In the case of barriers constructed by braced excavation, trenching, slurry wall, augering and vibrating beam, particular attention needs to be directed to minimize skin effects;

especially since such skin is difficult or impossible to remove after construction. Skin effects in conventional wells are removed by aggressive surging, jetting and well development techniques; however, it is practically impossible to hydraulically stress the skin of a reactive barrier. Even a small amount of skin can have significant impact on an iron reactive barrier's performance; either by modifying flow rates and thus reducing residence times in heterogeneous strata, or in certain cases directing groundwater flow around the reactive material.

In the case of iron reactive permeable barriers constructed by hydraulic fracturing, slurry wall and jet grouting, considerable care needs to be directed to the impact of the gel slurry on the iron's reactivity and its in situ placed permeability. Column reactivity tests and ultra low head permeameter tests on the iron gel slurry need to be conducted at typical groundwater temperatures to quantify such impacts. Speciality food grade water based gels can be adapted, Hocking and Wells (1997), to have minimal impact on the iron's reactivity and its in placed permeability.

In situ permeable iron reactive barriers have been placed at a number of sites to abiotic degrade chlorinated solvents in groundwater. Laboratory column iron reactivity tests are conducted utilizing site groundwater to determine contaminant degradation rates and degradation pathways, i.e. daughter products. The abiotic degradation of halogenated aliphatics in the presence of iron can be approximated by a first order reduction process. The compounds are progressively degraded to daughter products and eventually broken down into ethanes and ethenes. From the degradation rates, required residence time and hence barrier thickness can be calculated for the desired level of contaminant reduction.

## DESIGN METHODOLOGY

An overview of the design methodology for a permeable iron reactive barrier is given on Figure 2. First the site is characterized to determine the detailed geology, hydrogeology, contaminant and groundwater chemistry data. Next a risk assessment of the site is conducted to assess the need for remedial action at the site. If remedial action is required, a focused feasibility study is generally conducted to determine what is the most appropriate form of the remedial activity. In this case a permeable iron reactive barrier has been selected due to it's cost benefit and effective remediation of the site. The risk assessment along with regulatory requirements provides the basis for selecting either target effluent contaminant levels or risk reduction factors as deemed most appropriate for the performance of the reactive barrier.

The design criteria for the permeable iron reactive barrier are quantified to ensure the barrier is designed and constructed to meet the risk reduction or target effluent levels as set in the risk assessment. These design criteria also address issues regarding impact on groundwater flow regimes, variability of input parameters on system performance, construction quality assurance, long term monitoring and health and safety.

The reactive barrier design activity requires additional data over conventional site characterization data; namely, column reactivity data and iron permeability design data. These data are generated from laboratory tests conducted on site groundwater and soils. Laboratory column tests utilizing site groundwater quantify the degradation reaction rates and pathways (daughter products) of the particular contaminant specie in the presence of iron filings. From

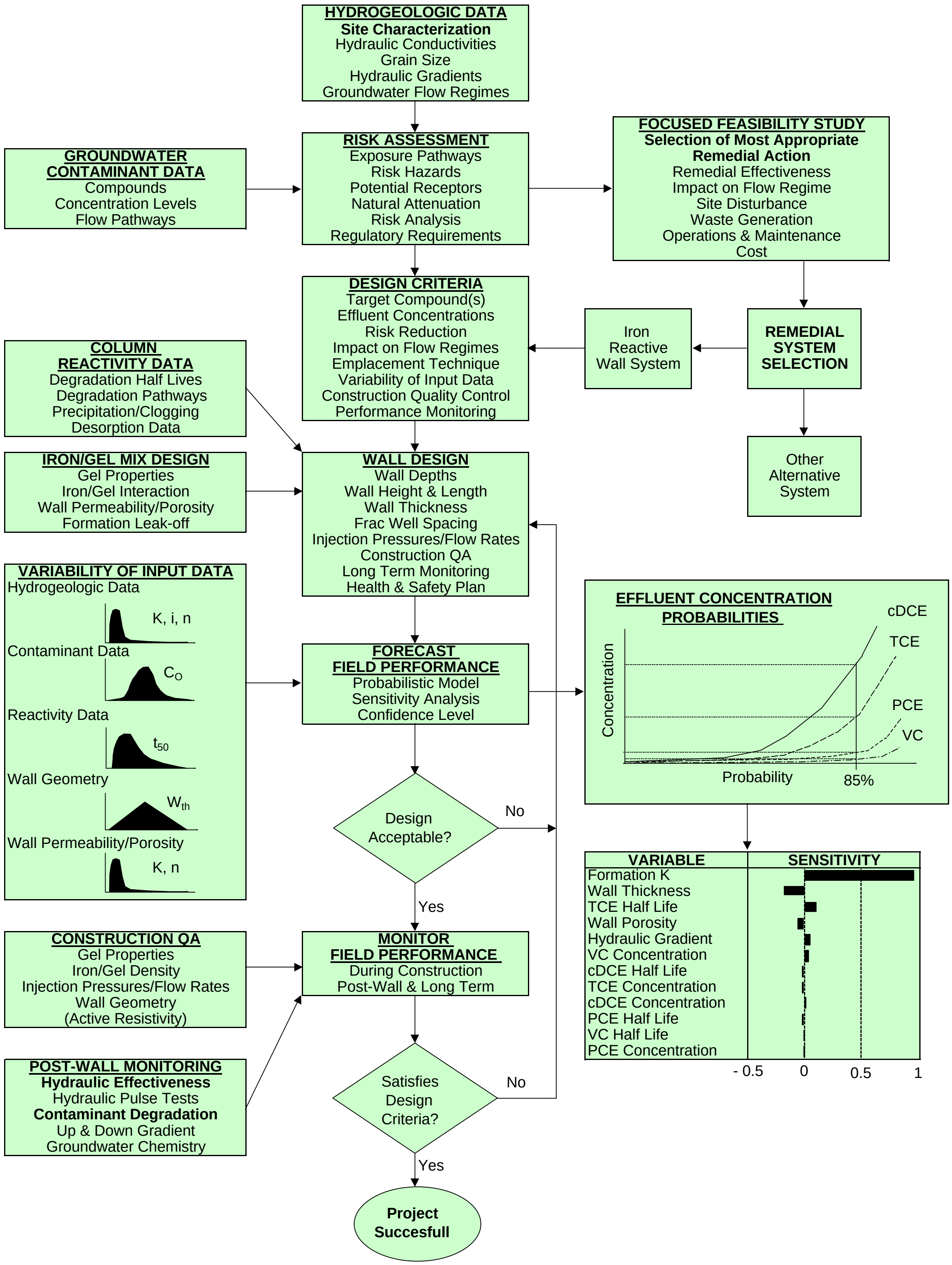


FIGURE 2. Iron Reactive Permeable Barrier Design Methodology

detailed chemical analysis of column effluent water, additional issues are addressed such as potential precipitation and clogging of the reactive barrier.

A probabilistic model is utilized in the design process to enable confidence limits to be placed on barrier performance and to quantify the impact of parameter variability on overall system performance. Probabilistic distributions are assigned to all of the system's parameters based on their expected variability. Not only are site charterization data; such as, hydraulic conductivity, porosity and hydraulic gradient, system parameters, but so are barrier thickness, barrier porosity and contaminant degradation data. As illustrated in Figure 2, the probabilistic analysis determines confident levels of system performance; such as contaminant degradation or overall risk reduction, and also ranks each parameter's impact on system performance from the most to the least sensitive. From the probability distributions, the confidence levels can be computed for the system performance on a specie by specie basis or as an overall system risk reduction factor. The reactive barrier system design confidence level is selected based on previous experience, risk factors and system behavior and consequences.

## ORIENTATED VERTICAL HYDRAULIC FRACTURING

Hydraulic fracturing field experiments in unconsolidated sediments have demonstrated, (Hocking, 1996), that a) vertical fractures can be placed at any required azimuth or bearing, and b) by injection in multiple well heads, continuous coalesced fractures are formed. The technology involves initiating the fracture at the correct orientation at depth and by controlled injection a continuous reactive barrier is created, see Figure 3. The hydraulic fracture iron reactive permeable barrier is constructed by injecting through multiple well heads spaced along the barrier alignment. A special down hole tool is inserted into each well and a controlled vertical fracture is cut and initiated at the required azimuth orientation and depth. Upon initiation of the controlled fracture, the tool is withdrawn and a packer is set in the well. Multiple well heads are then injected with the iron gel mixture to form a continuous permeable iron reactive barrier.

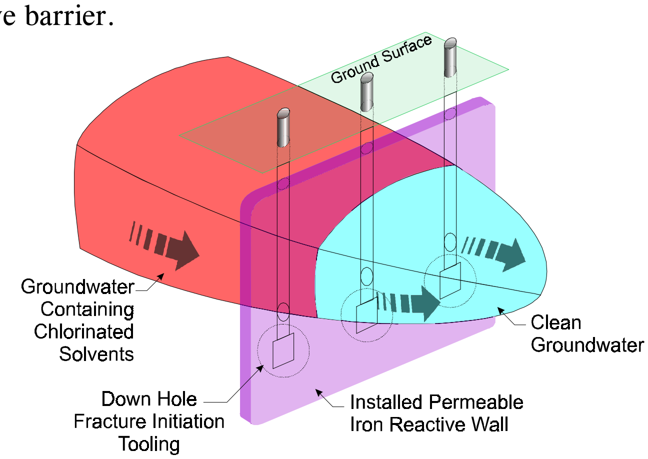


FIGURE 3. Hydraulic Fracture Iron Reactive Permeable Barrier.

The gel is injected into the formation and carries the iron filings to the extremes of the fracture. The gel is a water based cross link gel, hydroxypropylguar (HPG), which is a natural polymer used in the food industry as a thickener. HPG is used in the process because it has minimal impact on the iron's reactivity and upon degradation leaves an extremely low residue. The gel is water soluble in the uncross linked state, and water insoluble in the cross linked state. Cross linked, the gel can be extremely viscous, ensuring the iron filings remain suspended during the installation of the barrier. An enzyme breaker is added during the initial mixing to controllably degrade the viscous cross linked gel down to water and sugars. Once the gel is degraded, a permeable iron reactive barrier remains with a barrier thickness typically of 3” to 4” in sand and gravel formations.

## CONSTRUCTION MONITORING

The gel is dispersed and hydrated in 3000 gallon batches prior to injection. The hydrated gel is pumped to the mixing and blending unit at the required rate. The iron filings are pre-loaded into 250 cft hoppers and fed to the mixing and blending system via calibrated inclined screw conveyors. The feed of gel and iron filings is controlled to ensure the mix is of the correct consistency and density. Computerized instrumentation records and controls flow rates, volumes, iron feed rate, tonnages and mix density. The mix density is monitored by a precise in line mass flow meter. Following mixing and blending, the iron gel mix is pumped to a plunger hydraulic fracturing pump for injection into the prepared well heads. The gel and iron filings are fed to the pumping unit and cross linked in line, to form a highly viscous cross linked gel of a specific gravity of typically around 2.

The iron reactive barrier installation is monitored in real time during injection to determine it’s geometrical extent and to ensure fracture coalescence or overlap occurs. The quantities of iron reactive mixture injected are continuously monitored to ensure sufficient reactive iron is injected through the individual well heads. During injection, the iron gel mix is electrically energized with a low voltage 100 Hz signal. Down hole resistivity receivers are monitored to record the in phase induced voltage by the propagating fracture, see Figure 4. From monitoring the fracture fluid induced voltages and utilizing an incremental inverse integral model, the fracture fluid geometry can be quantified during the installation process. The active resistivity method requires the fracture fluid to be at least thirty times (30x) more conductive than the ground to provide a high contrasting image.

An alternative technique to monitor the hydraulic fracture barrier geometry is to utilize real time data acquisition of outputs from high precision tiltmeters installed either on the surface or at depth. By monitoring the induced tilts during the injection process, and utilizing an incremental inverse integral model, the fracture fluid injected geometry can be quantified during installation. The induced earth tilts enable a detailed image of the fracture geometry to be generated, regardless of the earth’s electrical conductivity. Also the tiltmeters can be used to monitor tilts and thus horizontal strains in adjacent buildings and structures to ensure these facilities are not disturbed by the injection process. The disadvantages of the tiltmeters are that additional effort is required for tiltmeter installation and the inability to eliminate in real time certain noise spectra. Provided the site is reasonably devoid of transient earth movement noise, tiltmeters are very effective in mapping the fracture geometry.

Active resistivity monitoring has the added benefit of determining when the individual fractures coalesce and thus become electrically connected. That is, by energizing each injected well head individually and in unison, the fracture electrical coalescence is clearly recorded. The imaging and inversion of the down hole resistivity data focuses on quantifying the continuity of the reactive barrier and assessing if any holes or gaps are present. Such monitoring enables construction procedures to be modified to ensure the barrier is installed as planned, and enable contingency measures to be implemented immediately, e.g. an additional fracture to patch any holes or additional injection volumes to ensure coalescence or sufficient overlap is attained.

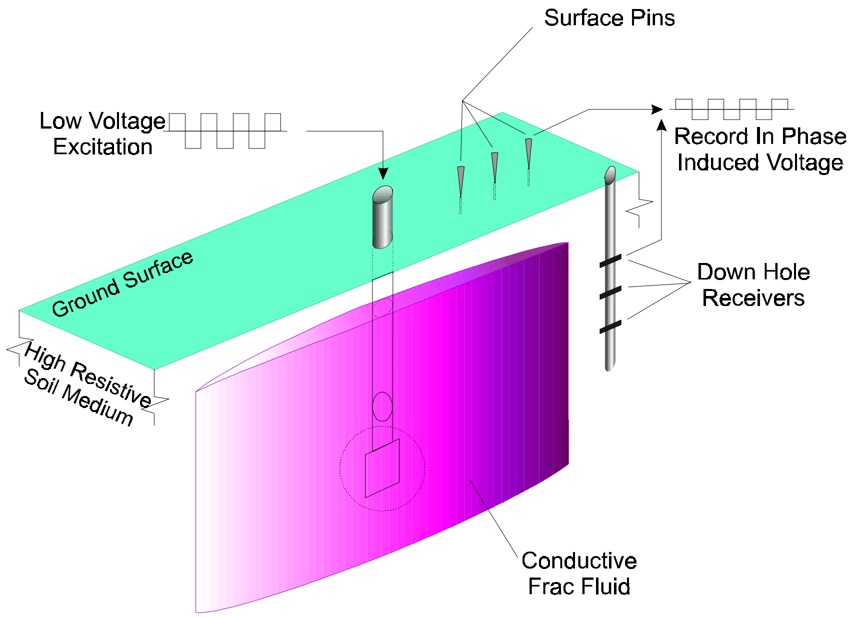


FIGURE 4. Fracture Mapping by Active Resistivity.

The down hole resistivitiy receiver locations are shown as squares on Figure 5 for the iron reactive barrier constructed in a highly permeable sand, gravel and boulder sequence. The resistivity receivers are copper collars attached to a cable connected to the instrumentation data acquisition system. The wells B1 and B2, see Figure 5, were injected and the fracture geometry was determined by the measured induced voltages at the down hole receivers locations, see Figure 5. The cross hatched area on this figure is the geometrical outline of the vertical hydraulic fracture, which was calculated to be 3.5” in average thickness. All of the thirty injections at this site were recorded with geometry delineated by active resistivity.

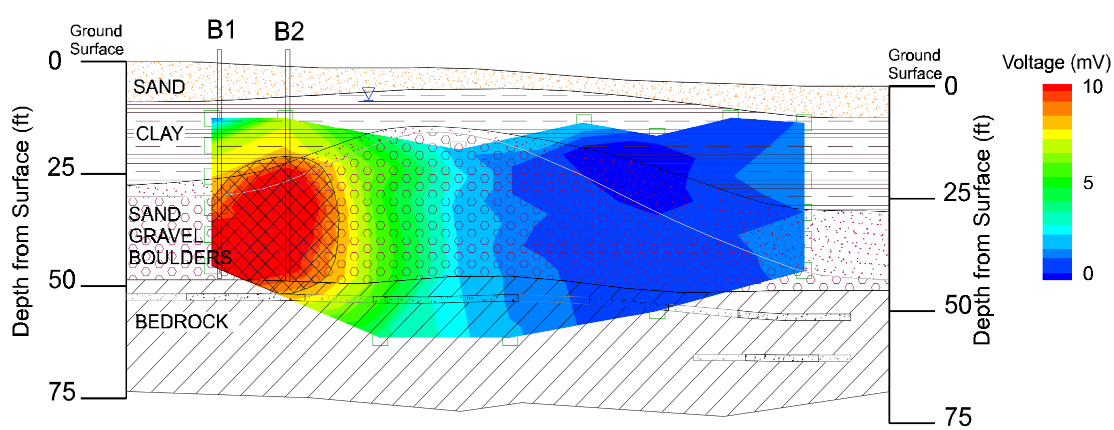


FIGURE 5. Induced Voltages from Propagating Fracture.

## POST CONSTRUCTION MONITORING

Permeable reactive barriers can be tested for their hydraulic effectiveness by pulse interference tests. Pulse interference tests, Johnson et. al., (1966) and Kamal (1983), involve a cyclic injection of fluid into the source well, and by high precision measurement of the pressure pulse in a neighboring well, detailed hydraulic characterization between wells can be made, see Figure 6. The pulse interference test is highly sensitive to hydrogeological properties between the wells, and relatively insensitive to conditions outside of the wells. For example, the hydraulic skin of a reactive barrier can be quantified by pulse interference tests.

For hydraulic fracture constructed barriers, the time delay and attenuation of the hydraulic pulse enables the hydraulic effectiveness of the barrier to be assessed. Before the gel cross link is broken, the reactive barrier acts as a temporary flow barrier, because the gel is an impermeable viscous fluid. If the barrier is continuous, significant attenuation of the hydraulic pulse will occur. If holes are present, the time delay and lack of attenuation of the pulse enables the gross area and approximate location of any holes to be delineated. Following breaking of the gel, a permeable iron reactive barrier remains, with minimal gel residue.

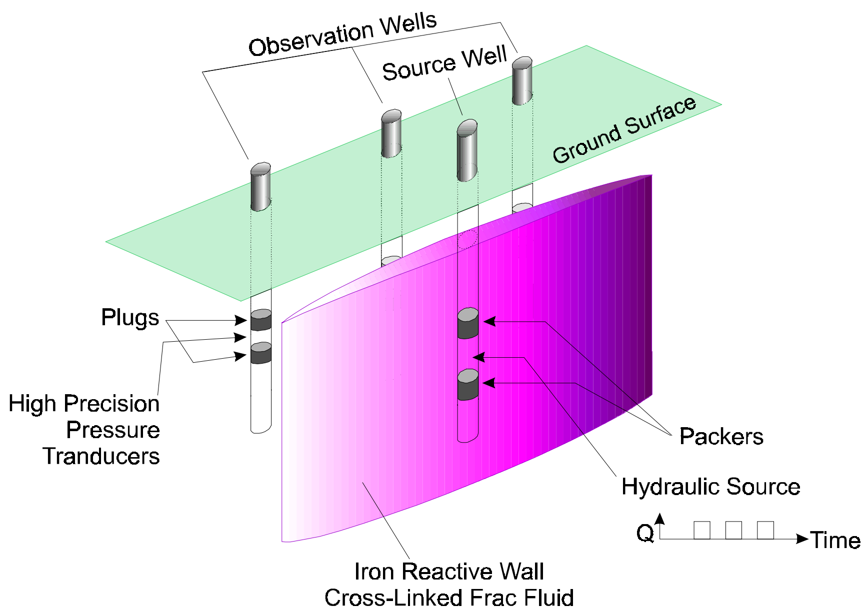


FIGURE 6. Hydraulic Pulse Interference Test.

## CALDWELL SUPERFUND SITE

The iron reactive permeable barrier at the Caldwell Superfund Site, Hocking et al (1998d), is for full scale remediation and intersects a risk exposure pathway of the contaminated groundwater upwelling into a seep. The Seep area geology consists of fractured basalt bedrock, overlain by a sand, gravel and cobble eskar deposit, with a competent clay overlying the eskar. The permeability of the eskar deposit varies widely from a low of 10 Darcy in fine sand deposits, to highs of hundreds of Darcy in the clean gravel and cobbles. The fractured bedrock also has a wide range of permeability from a tight fractured competent rock, to open channels and fissures. The horizontal groundwater gradient at the barrier location is approximately 0.01, with an upward vertical hydraulic gradient closer to the Seep. The groundwater flow velocities vary widely due to the variation in strata, and are estimated to be ~1-2'/day in the eskar and possibly an order of magnitude greater in the fractured bedrock. The flow rate emanating from the Seep is typically 30 to 60 gpm.

The groundwater is contaminated with chlorinated solvents in the thousands of ppb, with TCE being the prime contaminant of concern. TCE concentration in the groundwater at the reactive barrier location vary from 5,000 to 10,000 ppb, and the Seep water has historically been in the mid five thousand range. The iron reactive permeable barrier's prime functional design requirements are to intersect groundwater flow pathways to the Seep and to reductively dechlorinate TCE to reduce the risk hazard posed by the Seep water.

The iron reactive permeable barrier was constructed by the orientated vertical hydraulic fracturing technology in the unconsolidated sediments and infill permeation injection in the fractured bedrock. The reactive barrier consists of two parallel vertical hydraulic fracture placed barriers in the eskar deposit, denoted as the B-Zone, orientated perpendicular to the groundwater flow regime, and an infilled permeation zone in the underlying fractured bedrock, the C-Zone. The zero valent iron installed in the barrier was medium-fine Master Builders iron filings, with a total of 250 tons of iron injected into the subsurface.

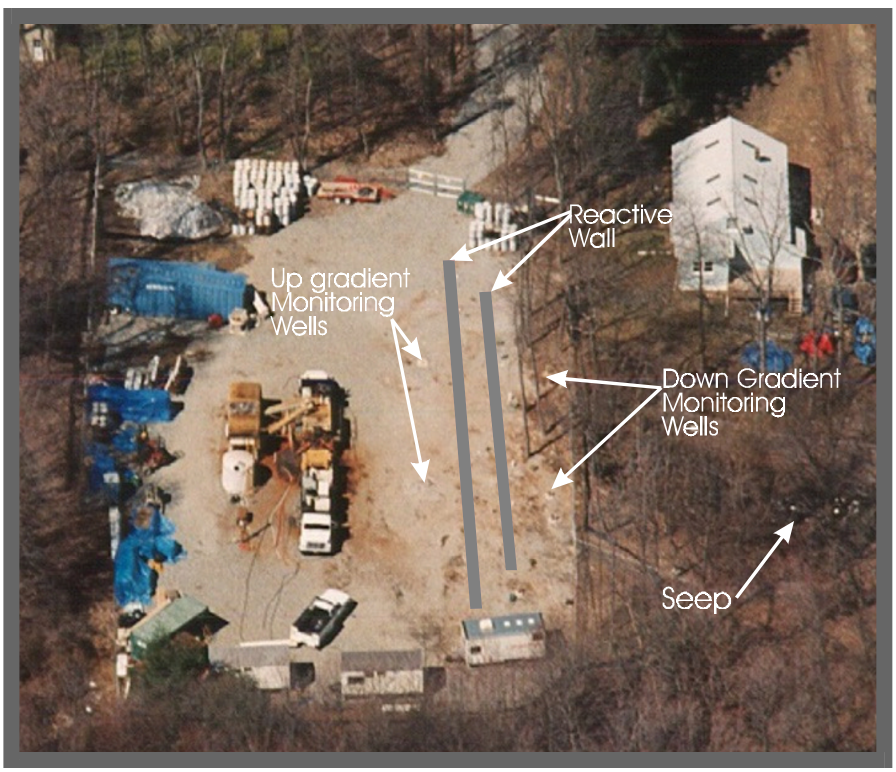


FIGURE 7. Aerial View of Reactive Barrier at Caldwell Superfund Site

As illustrated in the aerial view on Figure 7, the reactive barrier is located immediately upgradient of the Seep. The Seep is located in the midst of a residential neighborhood and the reactive barrier was constructed with minimal impact on the neighboring residents. The injection mixing and pumping equipment, instrumentation trailer and general site layout is also shown on

Figure 7. Contaminated waste was minimal, primarily from boreholes and cleaning of equipment, and surface impact was a series of wells located along the barrier alignment.

**BARRIER PERFORMANCE**

The reactive barrier performance is being monitored by sampling up and down gradient monitoring wells completed in the eskar deposit, the B-Zone, and the fractured bedrock, the C-Zone, and surface waters from the Seep and downgradient streams. The barrier has begun to degrade the chlorinated solvent groundwater contamination, with significant reductions in TCE concentrations observed during the past several months. The monitoring wells and surface waters have been sampled and analyzed at least monthly for volatiles, metals and other parameters.

The time history of TCE concentration in the Seep water is shown on Figure 8 along with the period of barrier construction. The Seep water has historically had a TCE concentration of the order of 5,500 ppb and the recent rapid drop of TCE concentration is clearly seen in this figure. The Seep is located approximated 60' downgradient of the reactive barrier, as shown in the aerial view in Figure 7.

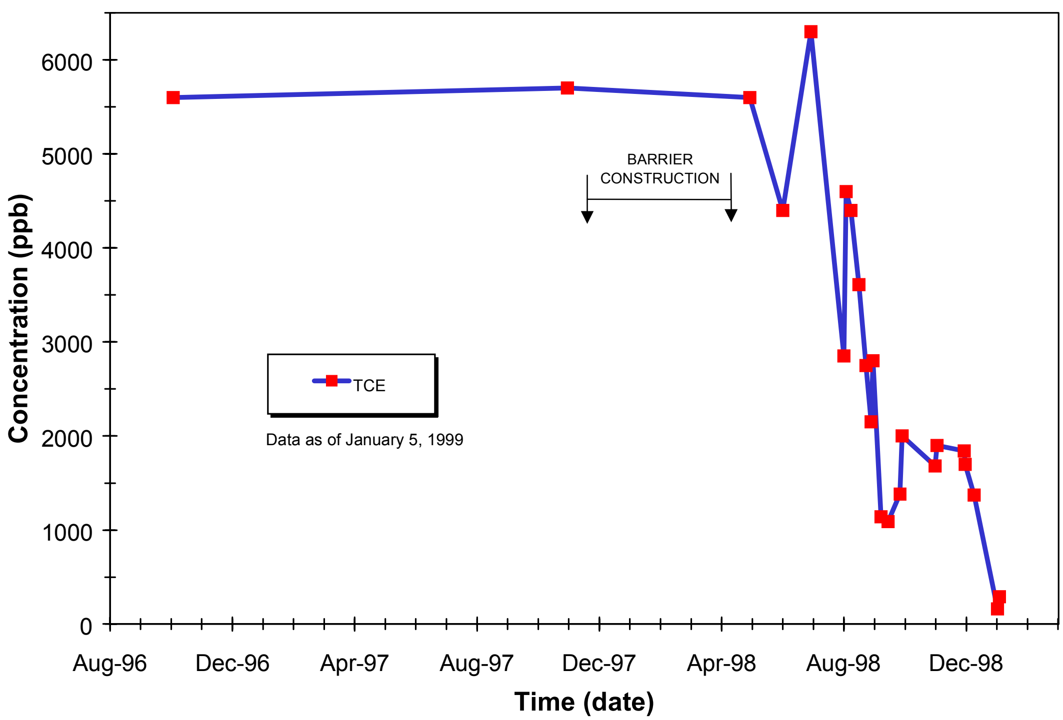


Figure 8. TCE Concentration in the Seep

**CONCLUSIONS**

Permeable reactive barriers are suitable cost effective remedies for contaminated groundwater, both for plume remediation and as source control. Iron permeable reactive barriers have been most efficient in dehalogenating chlorinated solvents in groundwater and are a viable cost effective alternative to pump and treat. The design, construction and performance monitoring of in situ reactive permeable barriers warrant special attention due to the functional design requirements of the systems and the low piezometric gradients across such systems. Particular attention needs to be paid to skin effects, and construction technique on iron reactivity and barrier permeability. Orientated vertical hydraulic fracturing technology has placed permeable iron reactive barriers of approximately 3.5" thick in highly permeable sands and gravel down to significant depths. Infill permeation injection has been successful in infilling a fractured and fissured bedrock with iron filings. The construction monitoring of the barrier by active resistivity has provided clear images of the barrier geometry during injection. Fracture coalescence between wells has been observed from both active resistivity and physical evidence. Hydraulic pulse interference tests have confirmed the presence of the iron barrier and have assessed its hydraulic effectiveness. The fracturing gel has been shown not to interfere with the barrier's permeability nor impact the iron's reactivity. The iron reactive permeable barrier installed by vertical hydraulic fracturing at the Caldwell Superfund Site has destroyed greater than 95% of the groundwater contaminant TCE as observed by monitoring upgradient and downgradient wells and surface waters.

## ACKNOWLEDGEMENT

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