Groundwater Performance Monitoring of an Iron Permeable Reactive Barrier

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ABSTRACT: Azimuth controlled vertical hydraulic fracturing technology constructed a full scale in situ iron permeable reactive barrier (PRB) at moderate depth at a Superfund site for remediation of groundwater contaminated with chlorinated solvents, primarily trichloroethene (TCE). The iron permeable reactive barrier was completed in late 1999 and was two hundred and forty (240) feet in length, three (3) inches in average thickness and constructed down to a total depth of seventy five (75) feet. The permeable barrier was constructed across the contaminated plume, perpendicular to the groundwater flow direction, and is a source control reactive barrier with the remnant plume downgradient of the PRB being naturally attenuated. Groundwater monitoring wells were installed prior to the PRB construction both upgradient and downgradient of the proposed PRB alignment. The groundwater monitoring wells have been sampled pre and post PRB construction for volatile organic compounds (VOCs) and other parameters to assess the performance of the PRB. Laboratory column iron reactivity and native soil column desorption tests were conducted for quantifying the design of the PRB and for prediction of monitoring well response immediately downgradient of the PRB. Eighteen (18) months of post-PRB groundwater monitoring data confirm the PRB is abiotically degrading the halogenated volatile organic compounds into harmless daughter products, ethene and ethane. The groundwater concentrations of VOCs downgradient of the PRB have declined at rates and are at levels close to or below those predicted during the PRB design stage.

SITE BACKGROUND

A former manufacturing facility in South-Central Iowa was contaminated with trichloroethene (TCE) in both the soils in the vadose zone and in the groundwater. Groundwater concentrations of TCE were detected up to levels of 14,000 ppb. The record of decision (ROD) was modified to an enhanced dual phase soil vapor extraction (SVE) system in the vadose zone for the soil remedy and an in situ iron permeable reactive barrier for groundwater remediation. The iron permeable reactive barrier (PRB) replaced an earlier proposed pump and treat system, because the PRB was considered a more effective remedy, both in terms of time to remediate and cost. The remnant plume downgradient of the reactive barrier is expected to be in situ bio-remediated by the natural attenuation mechanisms active at the site.

The soil and groundwater contamination are a result of earlier manufacturing activities at the site, with the prime contaminated areas being directly beneath the building and in the groundwater plume as shown on Figure 1. The site consists of medium to fine channel sands underlain and overlain by over consolidated stiff to very stiff till, designated as till units #1, 2 and 3. The sands are generally classified as medium to fine sand and characterized as loose flowing sands with a permeability of approximately 1 Darcy. The tilt units are all over consolidated and of low permeability.

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A enhanced dual phase soil vapor extraction system was installed inside of the former manufacturing building to extract chlorinated solvents in the vadose zone from the upper till unit #3, Hocking et al (2002).

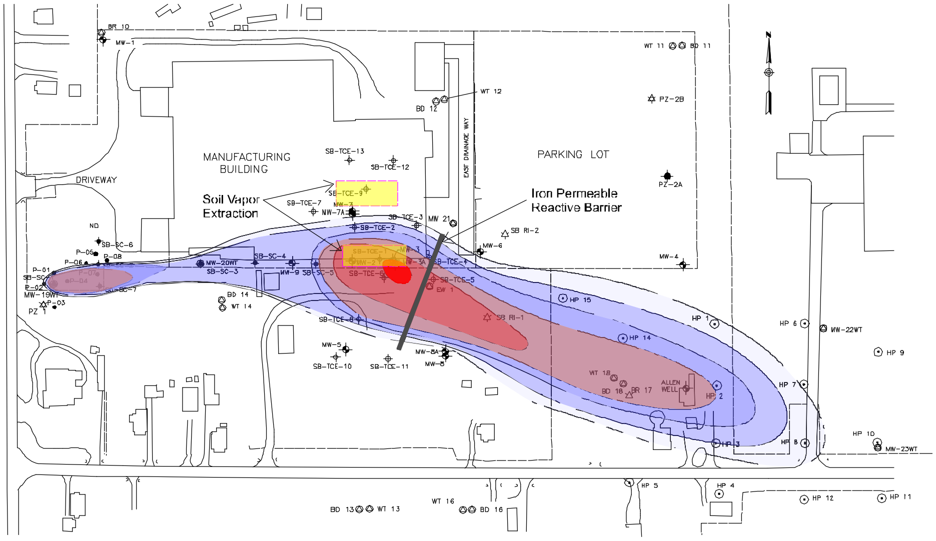

FIGURE 1. Plan View of Site and Contaminated Areas.

An aerial view of the Site showing the PRB location, hydrofracturing and instrumentation equipment is shown on Figure 2. The groundwater monitoring wells are shown on Figure 1 and the immediate PRB groundwater performance monitoring wells are shown in the photograph on Figure 2.

FIGURE 2. Aerial View of Site and PRB Alignment.

PROBABILISTIC DESIGN METHODOLOGY

The design methodology for the groundwater remedy involved a probabilistic design approach as outlined in Hocking et. al. (1998a) and further refined to incorporate both the degradation of VOCs within the PRB and by natural attenuation mechanisms active downgradient of the PRB. The methodology incorporates a probabilistic multi-specie VOC degradation model for degradation within the PRB and a probabilistic fate and transport model for VOC natural attenuation downgradient of the PRB, see Hocking et al (2001). Deterministic design procedures, whilst adequate for feasibility evaluation design, are not sufficient for final iron permeable reactive barrier design because factors of safety from past practices are not available for such systems. Probabilistic methods, on the other hand, can accommodate variability in parameter data and are ideally suited for system design such as an iron permeable reactive barrier. The probabilistic method enables quantification of the degree of confidence that contaminant effluent concentrations are not exceeded. Probabilistic analyses quantify the impact of parameter variability on overall system performance and thus rank the parameter by sensitivity.

Detailed site characterization involved groundwater contamination delineation, hydrogeological characterization of the site, quantification of natural attenuation at the site and specialized tests for the azimuth controlled vertical hydraulic fracturing PRB placement technology. The input parameters, site soil hydraulic conductivity, iron porosity and site hydraulic gradients determine the groundwater flow velocity within the barrier. The iron column test quantified the degradation pathways and half lives of the contaminants in the presence of the zero valent iron, and addressed potential impacts of any precipitation or clogging mechanisms within the iron PRB. The influent contaminant concentration and the target effluent contaminant concentration (the design criteria), enabled quantification of the minimum residence time and hence barrier thickness to achieve the required target effluent concentrations. The design of the iron reactive material required optimizing the hydraulic conductivity of the iron filings to be greater than the native soils, but also to ensure the PRB maintained a high porosity without violating the filter pack design criteria with the native soils to avoid commingling. Thus by optimizing the iron reactive mixture, the greatest residence time was achieved resulting in the use of less iron which lowered the cost of the PRB.

The VOC degradation half lives determined for the site field conditions using medium-fine Connelly iron filings transported in a proprietary water based cross link gel, hydroxypropylguar (HPG), were calculated as 0.6 hrs for TCE, 1.4 hrs for cis-DCE and 2hrs for VC. The iron PRB was selected to be 3” in average iron thickness, extend approximately 240’ in plan across the groundwater plume as shown on Figure 1, and extend vertically downwards through all the sand units including the channel sands down to the underlying till unit. The Site groundwater was determined from the column test to be ideal for an iron permeable reactive barrier with minimal precipitation and clogging concerns.

Degradation rates of the remnant groundwater plume downgradient from the PRB were quantified by the fate and transport model. The treated effluent groundwater emanating from the PRB flushes adsorbed/absorbed contaminants from the native soils downgradient from the PRB. A VOC soil column desorption test was conducted to quantify the desorption phenomena of VOC from the native soils. The desorption test data enabled predictions to be made of downgradient monitoring well performance and the time necessary to remediate the remnant downgradient groundwater plume to below MCL levels by natural attenuation. Predictions of PRB downgradient monitoring well performance were made and it was assessed that the remnant plume would be remediated by natural attenuation in approximately 10 to 12 years after PRB installation.

PRB CONSTRUCTION

The azimuth controlled vertical hydraulic fracturing placed iron PRB is constructed from conventionally drilled wells installed along the barrier alignment with a specialized frac casing grouted into the boreholes as shown diagrammatically on Figure 3. A controlled vertical fracture is initiated at the required azimuth orientation and depth in each well inside of the specialized frac casing using downhole frac initiation tools. The iron filings are blended and injected in the form of a highly viscous degradable food grade quality gel, hydroxypropylguar (HPG). Multiple well heads are injected with the iron-gel mixture to form a continuous PRB. The PRB is constructed by the injection of the iron filings into these frac casings with real time quality assurance monitoring of the injections to quantify the PRB geometry and iron loading densities. The gel biodegrades into water and sugars by the use of a suitable enzyme, and leaves in situ a permeable iron reactive treatment zone. The azimuth controlled vertical hydraulic fracturing technology has installed full scale iron permeable barriers from 3” to 9” in thickness from moderate (~50') to significant depth (>120'), Hocking et. al. (1998 b, c and 2000).

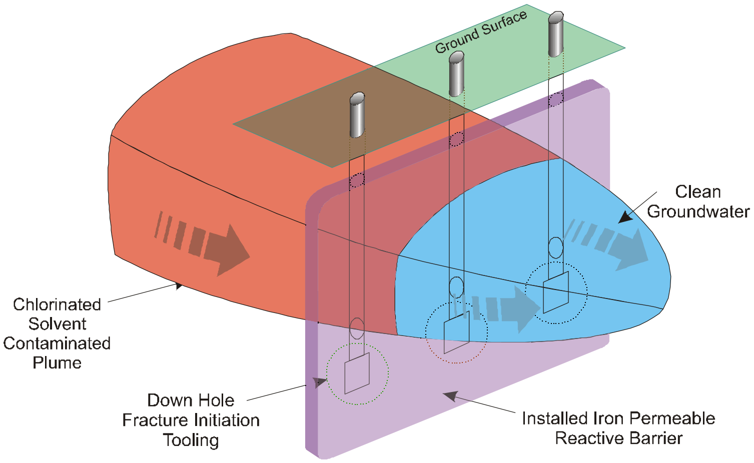

FIGURE 3. Hydraulic Fracture Iron Permeable Reactive Barrier.

The iron PRB was constructed from sixteen (16) frac initiation casings installed at approximately fifteen (15) foot centers along the PRB alignment as shown in plan and section on Figure 4. Split spoon samples were taken in each of the borings, F-1 through F-16, to ensure the frac casings were installed down and into the underlying till unit. Downhole resistivity receivers were installed in strings denoted as RR1 through RR7 as shown on Figure 4 and also resistivity strings were installed attached to the two downgradient groundwater monitoring wells, GW-1 and GW-2. A special down hole packer, frac casing and well head system were inserted into each well, F-1 through F-16, and a controlled vertical fracture was initiated at the required azimuth orientation and depth. Each of the frac casings in each well were individually initiated at approximately ten (10) foot vertical increments within the sand units. These multiple injections ensured the iron filings were uniformly distributed throughout the PRB cross section. Upon initiation of the controlled fracture within the well, the gel/iron mixture was then injected to form a continuous permeable iron reactive barrier.

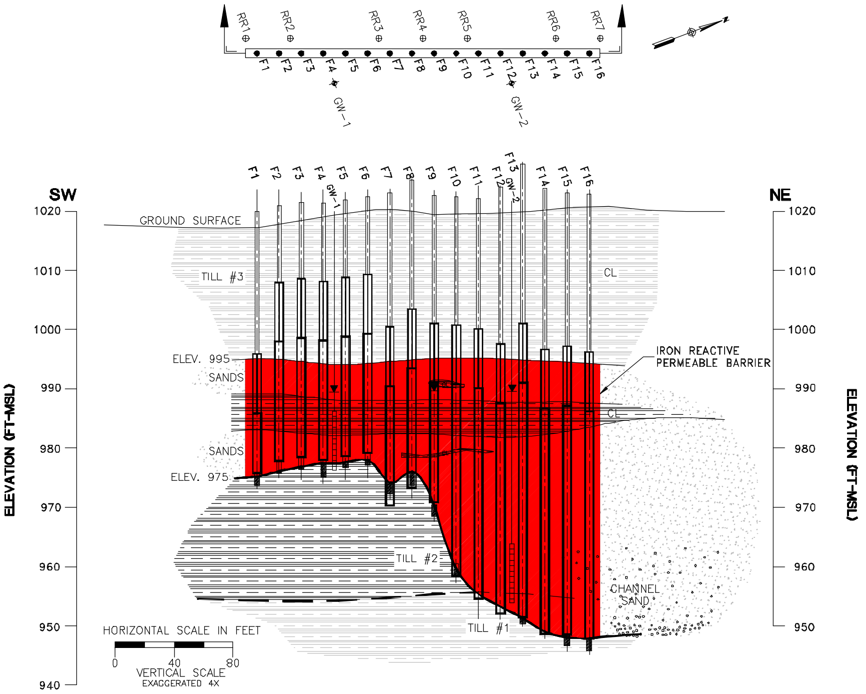

FIGURE 4. Plan & Sectional View of Iron Permeable Reactive Barrier.

The completed PRB, shown in cross section on Figure 4, required the injection of 30,300 gallons of gel and granular iron mixture at an average unit weight of 110 pcf, for a total weight of granular iron injected into the subsurface of 115 tons. The final geometry of the constructed PRB extended approximately 240 feet in overall length from a depth of approximately 25 feet down to a maximum depth of 75 feet. The as-built PRB had a cross sectional area of 7,040 sft, as determined from a composite of images/injections recorded during construction, and of an average iron thickness of 3”.

PRB PERFORMANCE

The immediate downgradient performance of the PRB on groundwater quality was predicted by the fate and transport model as described earlier in the PRB design section above. Predicted downgradient groundwater concentrations of VOCs were made for the monitoring wells GW-1 and GW-2. The groundwater emanating from the PRB was expected to have VOC concentrations well be below their respective MCL levels resulting in the VOC concentrations in the downgradient wells being reduced by the flushing action of the cleaner groundwater exiting the PRB. Due to the low groundwater flow velocities the downgradient wells were not expected to see any reduction in VOC concentrations for at least three (3) months; thereafter, the concentration of TCE would fall with time as shown by the predicted trend for the downgradient monitoring wells as given on Figure 5. This prediction for the downgradient monitoring wells assumed a slightly conservative (slower) groundwater flow velocity in order to conservatively predict the fall off of contaminant concentrations with time. All other VOCs, including daughter products of TCE were not expected to be observed in the two immediate downgradient monitoring wells, since the daughter products of TCE; namely, cis-1,2-DCE and VC would be degraded to well below their MCL levels within the iron PRB.

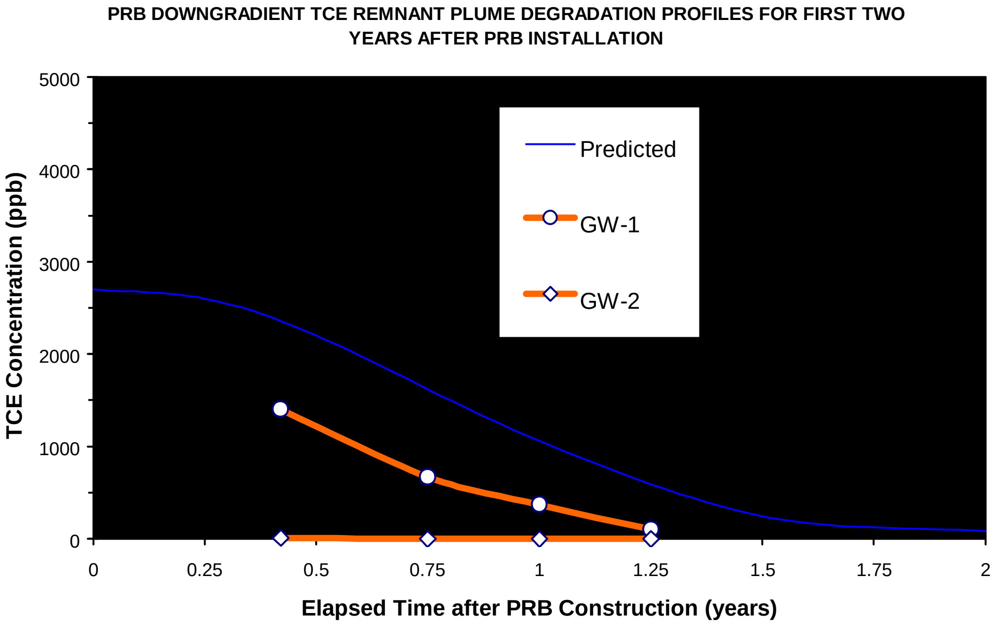

FIGURE 5. PRB Downgradient Groundwater Monitoring Data.

The measured groundwater contaminant concentrations in the two immediate downgradient monitoring wells GW-1 and GW-2 are shown on Figure 5 for eighteen (18) months of monitoring data following PRB construction. The TCE concentrations in GW-1 are decreasing at the same rate as predicted but are at a lower concentration than the conservatively predicted trend line. All other VOCs in both of the groundwater monitoring wells were below their detection limits. Other indicative PRB performance parameters recorded in the two monitoring wells indicate the PRB is functioning as expected. The similarity in the trend rate of reduction of TCE as predicted and as measured provide confidence in the laboratory column reactivity and soil desorption test data. The PRB appears to be functioning as predicted and given the close correlation between downgradient groundwater data compared to that predicted, the performance of the PRB is expected to continue functioning in the near term as designed. From experience of the Borden reactive barrier, the iron PRB is expected to continue performing satisfactory for at least ten to fifteen years, O'Hannesin and Gillham (1998). Ongoing groundwater performance sampling events are being continued to confirm that the PRB functions as expected and that the remnant downgradient plume degrades over time as predicted.

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 iron reactive barrier system compliments and enhances natural attenuation mechanisms active at the site. The design, construction and performance monitoring of in situ iron permeable reactive barriers warrant special attention due to the functional design requirements of these systems. The design methodology for the PRB incorporated a probabilistic multi-specie VOC degradation model for degradation within the PRB and a probabilistic fate and transport model for VOC natural attenuation downgradient of the PRB.

Azimuth controlled vertical hydraulic fracturing technology constructed the iron PRB 240 feet in length down to a total depth of 75 feet. A total of 115 tons of iron filings were injected into the subsurface to create the iron PRB with a cross-sectional area of over 7,000 sft and with an average iron thickness of 3”. Downgradient groundwater monitoring data following PRB construction demonstrate that the PRB is functioning as expected. The close correlation in trend reduction rates between predicted and measured groundwater VOC concentration data provide confidence that the PRB will function in the near term as designed. Ongoing groundwater performance sampling events are being continued to confirm that the PRB functions as expected and that the remnant downgradient plume degrades over time as predicted.

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