Installation of Permeable Reactive Barrier at Tinker Air Force Base, Oklahoma City, Oklahoma

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ABSTRACT: A permeable reactive barrier (PRB) was installed in July 2004 to intercept a groundwater plume migrating off-base toward a residential neighborhood adjacent to Tinker Air Force Base (AFB). Chlorinated solvents, migrating from sludge pits on top of a landfill in the central portion of the Base during the 1950s and 1960s, have resulted in the development of a solvent plume that has begun migrating toward the Base boundary. The solvent, primarily trichloroethene (TCE), is a common contaminant that is routinely detected in groundwater at Department of Defense Installations due to the ongoing support and maintenance requirements of air support missions. The contaminant distributions on-Base, as well as the lithologic and hydrogeologic setting, has been previously investigated in support of the Installation Restoration Program at Tinker AFB. This paper describes the design and construction of the PRB, installed as part of an environmental cleanup project at Tinker AFB in Oklahoma City, Oklahoma. The PRB was constructed in the southwest portion of Tinker AFB at site (Site) CG038 within Groundwater Management Unit (GWMU) 2 and across the Subunit 2D Plume. Groundwater at site (Site) CG038 is contaminated with relatively low TCE concentrations. The as built PRB is 500-feet in length and was installed from a depth of approximately 70- to 95-feet below ground surface (bgs). The verified iron-effective thickness ranges from 3.0- to 4.5-inches. The PRB consists of iron filings which were injected into the ground, using specially designed well casings installed to 100-feet bgs. The iron filings react with the solvents by stripping off chlorine ions, resulting in decreased contaminant concentrations. The objective of the PRB is to reduce the amount of TCE in groundwater and to prevent any adverse impacts to the off-Base areas where the groundwater discharges.

INTRODUCTION

Tinker AFB is located in central Oklahoma, in the southeast portion of the Oklahoma City metropolitan area in Oklahoma County. The Base encompasses approximately 5,000 acres. Tinker AFB, originally known as the Midwest Air Depot and then as Tinker Field, began operations in July 1941. Historically, the Base served as a worldwide repair depot for a variety of aircraft, weapons, and engines. Repair activities employ hazardous materials and result in the generation of hazardous wastes. These wastes have included spent organic solvents; waste oils; waste paint strippers and sludge; electroplating wastewater and sludge; alkaline cleaners; acids; Freon™; jet fuels; and radium paints. Wastes are currently managed at the long-term storage facility. However, prior to enactment of RCRA, industrial wastes were discharged into unlined landfills and waste pits, streams, sewers, and ponds. Past disposal practices and possible continued releases from the landfills resulted in numerous sites on Base with soil, groundwater, and surface water contamination (IT Corp., 1994).

Site Geology: The zone targeted for treatment by the PRB is designated as the upper saturated zone (USZ), comprising sediments of the Garber Sandstone and is characterized by sandy and silty water-transmissive beds that are interbedded with fine-grained beds of relatively low hydraulic conductivity. The Garber Sandstone is distinguished by sandy and silty water-transmissive beds and represents a geological formation that ranges from a permeable formation made of sandstone to an impermeable zone composed of shale or clay (Figure 2). The saturated thickness of the USZ appears to range from slightly more than 25 feet to less than 15 feet across Site CG038. The hydraulic conductivity of the USZ is 6.5 feet per day (2.3×10^{-3} cm/sec).

The horizontal hydraulic gradient across Site CG038 ranges from 0.006 to 0.023 feet per foot (ft/ft), based on the differences in groundwater elevation contours across the area. Local variations in the hydraulic gradient and groundwater flow direction are potentially the result of local recharge from the Hennessey water bearing zone (HWBZ), interaction with creeks, and changes in hydraulic conductivity and/or thickness of the formation. The USZ and the HWBZ are in direct hydraulic communication over a portion of Site CG038. Although groundwater flow in the USZ is generally west-southwest across most of Site CG038, the pattern changes west of the Base boundary. Measured groundwater levels in established USZ monitoring wells along the western boundary indicate that groundwater in the USZ west of Tinker AFB is flowing generally southeast. There is also a northeast-southwest trending groundwater divide in the USZ across the northwestern corner of Site CG038. In the Site CG038 area, the USZ receives recharge from the HWBZ above (vertical leakage) and from lateral inflow of groundwater in the USZ from the eastern part of the Base.

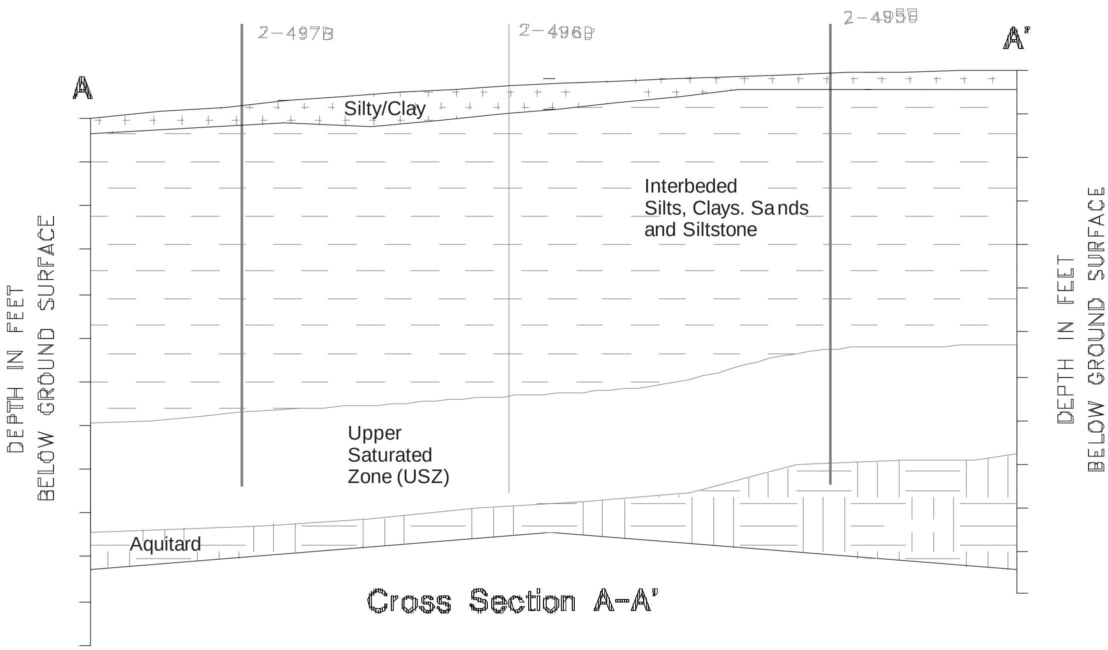

Figure 1: Geologic Cross Section along PRB Alignment

Site Contamination: A variety of activities combined with complex manufacturing processes have generated numerous hazardous chemicals and their associated wastes at Tinker AFB. GeoSierra was retained for the installation of an in situ remedial system to cleanup groundwater contaminated with volatile organic compounds (VOCs). Based on the sampling of groundwater monitoring wells along the CG038 2D plume, groundwater in the USZ unit contains elevated concentrations of TCE and daughter products cis-1,2-dichloroethene (cis-1,2-DCE), and vinyl chloride (VC). The plan view of the PRB and associated groundwater monitoring wells are shown on Figure 2. The primary groundwater contaminant of concern at the Site is TCE in the vicinity of the PRB with concentrations in the groundwater at least two (2) orders of magnitude greater than the cis-1,2-DCE concentrations. Groundwater contaminant concentrations indicate that the VOC plume migrates to the southwest in the vicinity of the PRB.

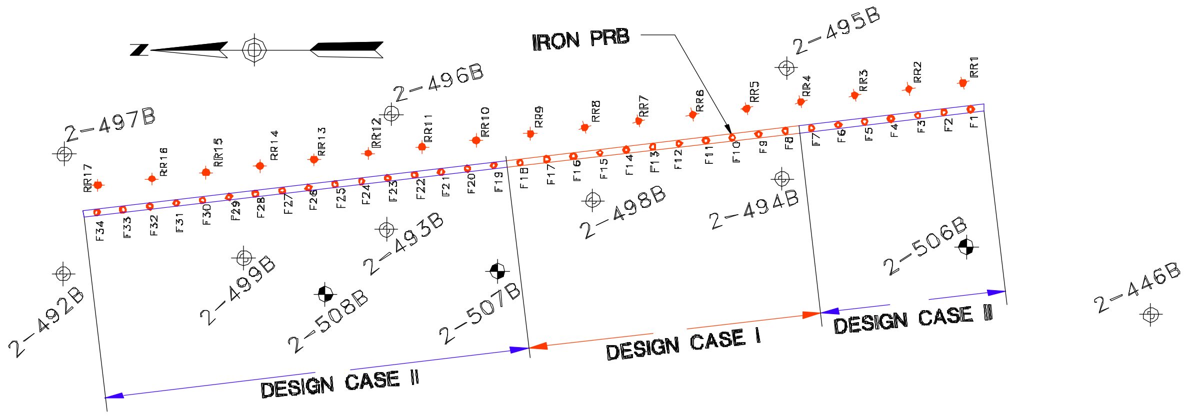

Figure 2: Plan View of PRB Alignment and Groundwater Monitoring Wells

PRB PROBABILISTIC DESIGN

The probabilistic design methodology, as outlined in Hocking et al (1998 & 2000), has been refined to incorporate both the degradation of VOCs within a PRB and by natural attenuation mechanisms active downgradient of the PRB. This 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.

The design criteria for the permeable iron reactive barrier are quantified to ensure the PRB is designed and constructed to meet target effluent levels of below maximum contaminant levels (MCLs) for each of the respective contaminants. These design criteria such issues as impact on groundwater flow regimes, variability of input parameters on system performance, construction quality assurance, long term monitoring, and health and safety. Chlorinated solvents, such as TCE, will be abiotically reduced in the PRB to harmless products, such as chloride ions, ethene, and ethane, Gillham and O'Hannesin (1994) and Roberts et al (1996). A well designed reactive barrier 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, and also address issues such as potential precipitation and clogging of the reactive barrier.

The concentration of a particular species is quantified along the column length at a particular time, i.e. after the column is swept by a certain number of pore volumes of the Site groundwater. Concentrations of VOCs were monitored along the column until the values at each point in the column reached a relatively "steady-state migrating" condition. "Steady state migrating" condition is reached when the column test shows a steady (i.e. unchanging) concentration profile plotted on a constant rate migrating passivation front along the column length. Elevated levels of nitrate in the Site groundwater create an iron passivation front that migrates through the iron column, Schlicker et al (2000). It is imperative that the migration of this passivation front be quantified in the bench scale treatability test, and the half lives calculated for the VOC degradation model account for the presence of this migrating front. The flow rate used in the test was used to calculate the residence time of groundwater relative to the influent end of the column at each sample point. First the migration rate of the passivation front was computed, and then the residence time and concentration profiles for each of the VOCs based on this migrating front was calculated and degradation half lives quantified for each VOC compound of interest. A first-order multi-species kinetic model closely matched the degradation rates of the VOCs in the presence of zero valent iron for each of the chloroethene VOC compounds.

Probabilistic distributions for the design input parameters (formation hydraulic conductivity, groundwater flow gradient, VOCs concentrations, VOCs degradation half lives, iron passivation rate, iron

PRB porosity and iron PRB effective thickness) were developed, resulting in computed probabilistic distributions for PRB effluent VOC concentrations. The PRB probabilistic model 85-percentile VOC effluent concentration levels were used to determine the minimum iron PRB average-effective thickness required to bring VOC concentrations to below target effluent levels for the entire planned life of the iron PRB. Degradation rates of the remnant groundwater plume downgradient from the PRB were quantified by the probabilistic fate and transport model, enabling predictions of PRB downgradient monitoring well performance with time.

PRB CONSTRUCTION

The construction of the PRB required the injection of approximately 85,000 gallons of cross-linked iron/gel mixture transporting 333.5 tons of iron filings into the subsurface. Thirty-four (34) hydrofracturing frac casings, and seventeen (17) resistivity receiver strings were installed for the construction and quality assurance/quality control (QA/QC) real time monitoring during installation of the PRB. The injected quantities of iron into each frac casing zone were based on the amount of iron required to achieve the range of PRB thickness varying from 3.0- to 4.5-inches, depending on the design case requirements. The final geometry of the constructed PRB extended 500-feet in overall length from a depth of approximately 70-feet down to a maximum depth of 95-feet bgs, as shown on Figure 3. The PRB has a cross-sectional area of 12,975 square feet (ft^2).

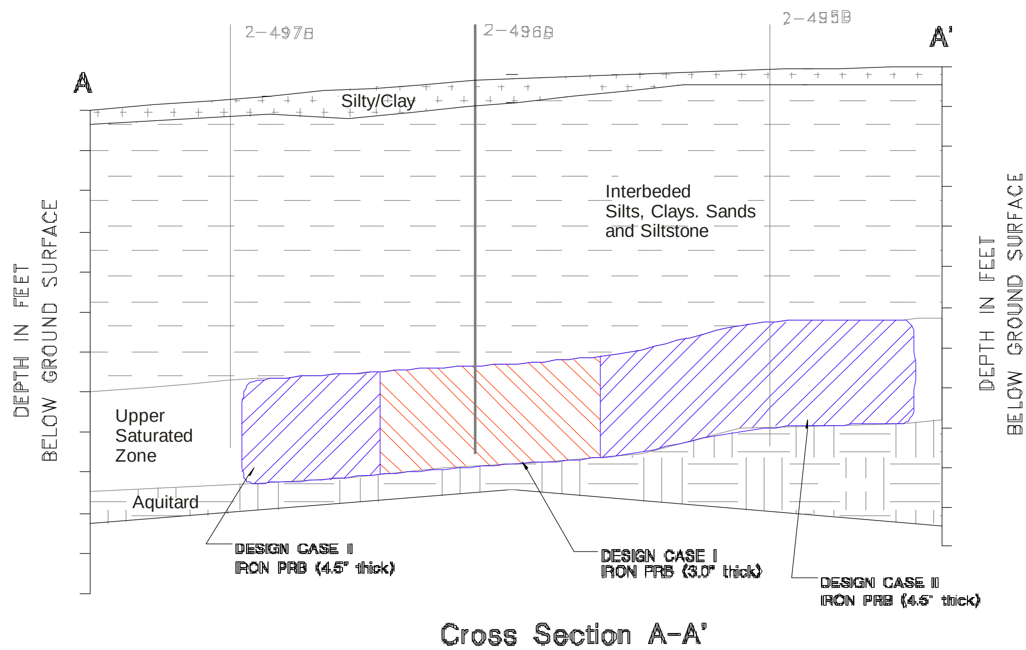

Figure 3. As Built Cross-Section of Constructed PRB

Quality Assurance/Quality Control Processes in PRB Construction: A variety of QA/QC processes were incorporated as part of the PRB construction activities. These include the following:

Groundwater Bench Scale Column Tests: Column tests, using groundwater from the Site, were conducted to determine the contaminants of concern, daughter products, and half lives. The column test helped to verify that the Site geochemistry was appropriate for a PRB and helped to quantify such design parameters as effective thickness.

Hydraulic Pulse Interference Tests (HPIT): Pre-construction and post-construction hydraulic pulse interference tests were conducted to determine the hydraulic conductivity of the soils where the PRB was to be placed and to establish a benchmark of the permeability of the formation. The test was also conducted following construction of the PRB to verify permeability of the barrier and to confirm that the PRB has not disturbed the permeability of the surrounding formation.

Active Resistivity Imaging: The construction of the PRB was monitored in real-time implementing GeoSierra's active resistivity imaging technology. The real-time images were produced by exciting the gel and iron filings with a low voltage charge, a 100 Hertz signal, which was picked up by downhole receivers found along the PRB alignment. The real-time imaging also provided an approximate thickness of each injection segment.

Inclined Profile: Post-PRB inclined thickness profiling using a soil magnetometer was conducted at two (2) locations along the PRB alignment and verified that the PRB thickness was within specification, as detailed on Figure 4.

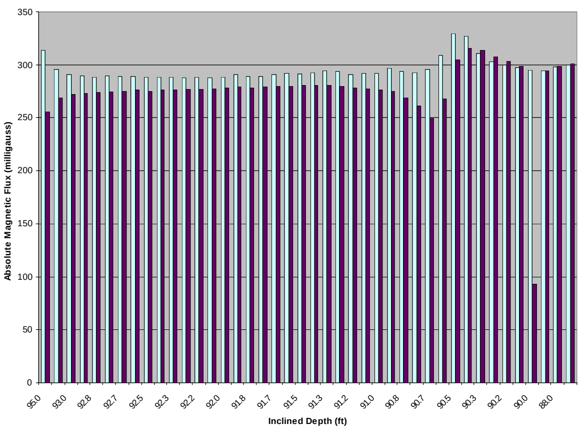

Figure 4. Inclined Magnetometer Profiling to verify PRB thickness

GROUNDWATER PERFORMANCE MONITORING

Two rounds of groundwater sampling and analyses have been conducted from up and down gradient PRB groundwater performance monitoring wells at Site CG038. Monitoring results for the downgradient wells are shown on Figure 5 for actual TCE concentrations and those predicted during the design phase. The formation hydraulic conductivity varies by a factor of 2 between the up and down gradient wells, and the hydraulic gradients also vary between the up and down gradient wells by a factor of 4. These variations result in the groundwater velocity within the formation being significantly different (by a factor of 2.5) for the three (3) downgradient wells and accounts for the differing rates of reduced TCE concentration observed.

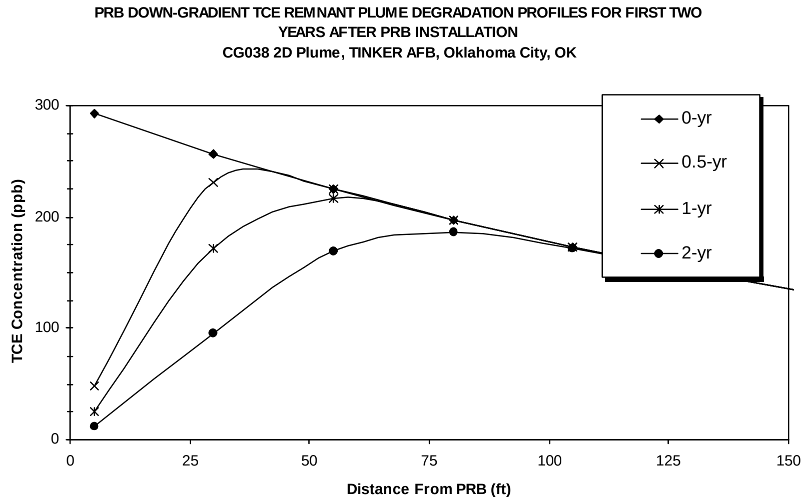

Figure 5. PRB Downgradient Predicted and Actual TCE Groundwater Concentrations.

CONCLUSIONS

Permeable reactive barriers are suitable cost effective remedies for contaminated groundwater, both for plume remediation and as source control. Iron permeable reactive barriers are most efficient in dehalogenating chlorinated solvents in groundwater and are a viable cost effective alternative to pump and treat. 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 500 feet in length from a depth of 70 feet down to a total depth of 95 feet bgs. A total of 334 tons of iron filings were injected into the subsurface to create the iron PRB with a cross-sectional area of 12,975 ft^2 and with an average iron thickness of 3.0 to 4.5-inches. The in situ constructed geometry of the PRB was quantified in real time during injection by the active resistivity imaging technology. Pre- and post-PRB construction hydraulic pulse interference tests across the PRB alignment determined that the constructed PRB would not impede or impact the site's groundwater flow. Preliminary groundwater monitoring data indicate that the PRB is performing as expected with downgradient TCE concentrations below those predicted during the design phase.

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