# Installation of Permeable Reactive Barriers in Urban Residential Environments Surrounding Federal Installations

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**ABSTRACT:** A full scale iron permeable reactive barrier (PRB), of over 2,000 feet in length comprised of three segments, was constructed down to a depth of approximately 40-feet below ground surface (bgs) in an off-Base residential area surrounding the former Kelly Air Force Base (AFB) in San Antonio, Texas. The two main objectives of the remediation strategy included preventing further off base migration of groundwater contaminated with volatile organic compounds (VOCs), primarily trichloroethene (TCE) and tetrachloroethene (PCE) and to ensure groundwater concentrations in off-Base areas meet acceptable groundwater standards. The PRB was constructed by azimuth controlled vertical hydraulic fracturing technology in a residential neighborhood with numerous subsurface and overhead utilities. Trenching was considered a less desirable installation option because of the numerous underground and above ground utilities. The site is in a busy urban area with businesses, schools, and residences; and minimal work space (a two-lane road) where one lane had to remain open during the day and both lanes had to be reopened at night. All sections of the PRB were constructed to the design specifications of approximately three (3) inches in thickness from a depth of approximately twenty (20) feet to a total depth of forty (40) feet bgs. Daily requirements during the drilling portion of the project included limited work hours and the requirement that all equipment be removed from the City of San Antonio (COSA) right-of-way (ROW) on a daily basis. The site conditions existing during frac well installation and PRB construction presented unique challenges to the project and involved the coordination and management of numerous activities from utility clearances, traffic control, material and equipment handling, and environmental controls; while at all times minimizing citizen disruptions to their normal daily environment. This paper describes the construction challenges and logistics that had to be managed to satisfy site-specific constraints for installing an in situ PRB within a residential neighborhood as part of the overall site remediation strategy for the former Kelly AFB.

## INTRODUCTION

The Former Kelly AFB (the Site) is located about 7 miles southwest of downtown San Antonio, consists of about 4,660 acres in Bexar County, Texas, and includes former main Kelly AFB and the former East Kelly AFB. Kelly AFB is located in south-central Texas, in the southwest section of the San Antonio proper in Bexar County (see Figure 1). The base encompasses approximately 4,660 acres. Kelly AFB was founded in May 1917. Aircraft repair and maintenance activities were continuous at the base since its inception, but in 1921 the base became a major overhaul and logistics center when the Army Air service moved its Aviation Repair Depot to Kelly AFB from Dallas creating the San Antonio Intermediate Depot renamed the San Antonio Air Logistics Center (SA-ALC) in 1954. Kelly AFB continued to be involved with the logistics and maintenance of an extensive inventory of military equipment including aircraft engines, weapons systems, and support equipment. In 1995, the independent Base Realignment and Closure Commission (BRAC) selected the eastern portion of the base for closure of the SA-ALC. Perchloroethene (PCE) and trichloroethene (TCE) were common solvents used at the base as a degreaser during equipment maintenance. The chemicals entered the groundwater through leaks, spills, and disposal practices that were approved at the time prior to the enactment of RCRA.

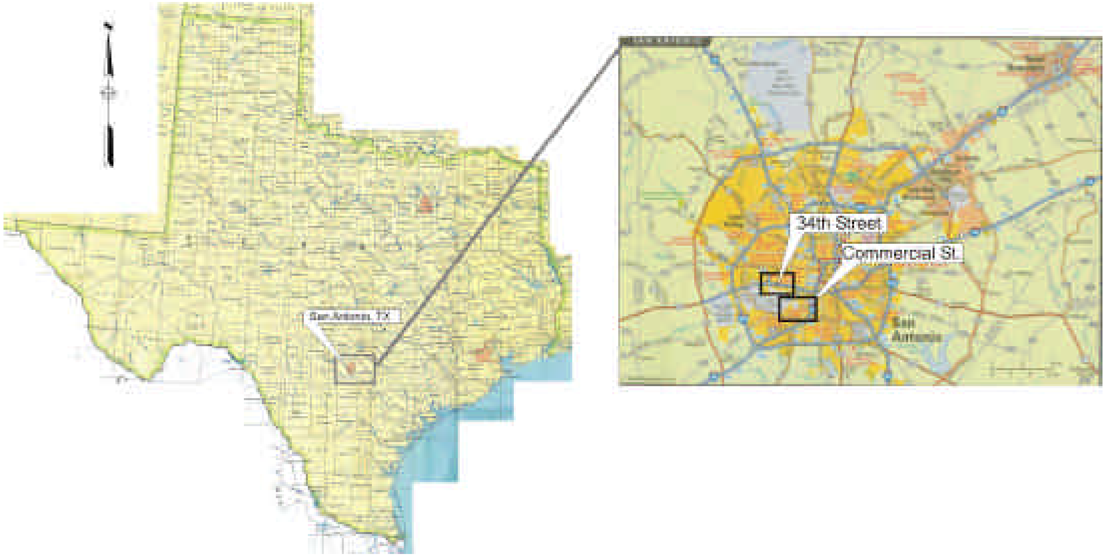

**Figure 1: Site Location**

The PRBs installed included Zone 4 Commercial Street Areas, Section Nos. 1 and 2, and Zone 5, 34th Street Extension, Section No. 3, located east and north of the former Kelly AFB in San Antonio, Texas. The project was divided among three phases. Phase I (Southern PRB) was located within the Commercial Street right of way between Stonewall Street and Crystal Street. This phase of the PRB has a length of approximately 1,180 feet and was installed from approximately twenty-two (22)-feet to a total depth of approximately thirty-five (35)-feet below ground surface (bgs). Phase II (Northern PRB) was installed in the Collingsworth Avenue right of way south of Gladstone Avenue and through private property immediately south and east of the intersection of Britton and Collingsworth Avenues. The Northern PRB extends approximately 720 feet with a treatment depth of approximately twenty-two (22)-feet to a total depth of thirty-five (35)-feet bgs. The Phase III PRB was an extension to the north of an existing PRB in the 34th Street right of way north of Growdon Drive. This extension was approximately 120 feet in length and installed from approximately twenty-two (22)-feet to a total depth of thirty-five (35)-feet bgs.

**Site Geology:** Kelly AFB is located above a shallow aquifer with a deeper, confined aquifer (the Edwards Aquifer). The upper saturated zone (USZ) is comprised of alluvial sediments above a lean clay aquitard to approximately 50 feet. The clay layer is approximately 450 feet thick presented an impermeable layer separating the USZ from the Edwards Aquifer which is the main source of drinking water for the city of San Antonio. The USZ consists of a low permeable clay with silt, sand, and caliche from a depth of approximately 5 to 20 feet, and underlain by a highly permeable gravel zone with silt, sand and clay to the interface with the lean clay aquitard at an approximate depth of 40 feet.

The groundwater hydraulic gradient is generally towards the east with variability in gradient and direction most likely due to the variability of the thickness of the underlying gravel zone. The hydraulic conductivity of the USZ ranges from 0.18 feet/day to 90.4 feet/day from data acquired from single well slug tests. These results are indicative of well screens installed in different soil matrices and inconsistent strata. Hydraulic pulse interference testing within the gravel unit have determined very high variability in the hydraulic conductivity of the highly permeable gravel layer ranging from virtually impermeable up to ~200 feet/day.

**Figure 2: Photographs of PRB Installation**

**Site Contamination:** The use of hazardous chemicals during equipment maintenance over a long period of time and unregulated disposal practices led to contamination of groundwater in the USZ beneath the base. GeoSierra was retained to install an in situ remedial system to remediate groundwater contaminated with volatile organic compounds (VOCs), primarily PCE and TCE. Based on groundwater contaminant concentrations and groundwater potentiometric data obtained during early environmental assessment activities indicate that a groundwater contaminant plume is migrating towards the east in the vicinity of the PRB.

## PRB PROBABLISTIC DESIGN

The probabilistic design methodology, as outlined in Hocking et al (1998 & 2001), 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 PRBs were constructed from a series of boreholes drilled along the PRB alignment with the iron filings injected into the subsurface to create a continuous zone of iron filings from a depth of approximately twenty-two (22) feet bgs down to a total depth of thirty-five (35) feet bgs. To minimize disruption to traffic flow and to the residents, the construction of the PRBs was completed over a construction segment of two hundred and fifty (250) feet at any one time during the PRB installation. That is the one lane traffic disruption was only over a 250 foot footprint at any one time. The PRB system was designed to minimize disruption to both road traffic and the neighboring residences and businesses. Particular attention had to be paid to the location of the PRB alignment considering all underground and overhead utilities and residence and business driveways.

One hundred eighty-eight (188) hydrofracturing casings were installed for the construction of the PRBs. The boreholes drilled for the installation of the hydrofracturing casings were advanced by rotosonic or mud-rotary drilling techniques. Continuous soil core samples were observed from each of the sonic drilled holes to establish the final depth of the frac casing.

Mud-rotary drilling was used on only a limited number of the frac wells with overhead restrictions, and the final depth was based on the observations of adjacent wells previously drilled by sonic methods. After installing the aluminum frac casing with steel pipe risers into the borehole, grout with a composition of 95% cement and 5% bentonite by weight was mixed in a portable, trailer-mounted grout mixer or steel tub and pumped slowly through a tremie pipe until grout was observed to be flowing freely from the borehole. All water discharged from the hole during grouting was collected and disposed of in the appropriate liquid waste containers.

The construction of the PRB required the injection of approximately 150,000 gallons of cross-linked iron/gel mixture transporting 510.4 tons of iron filings into the subsurface. Twelve (12) groundwater monitoring wells, one hundred and eighty eight (188) hydrofracturing casings, and seventy (70) 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 well zone were based on the amount of iron required to achieve the range of PRB thickness of 3.0-inches. The final geometry of all three constructed PRBs extended over 2,035-feet in overall length from a depth of approximately 23 down to a depth of 35 feet bgs. The as-built PRBs had a total cross-sectional area of 22,700 ft$^2$.

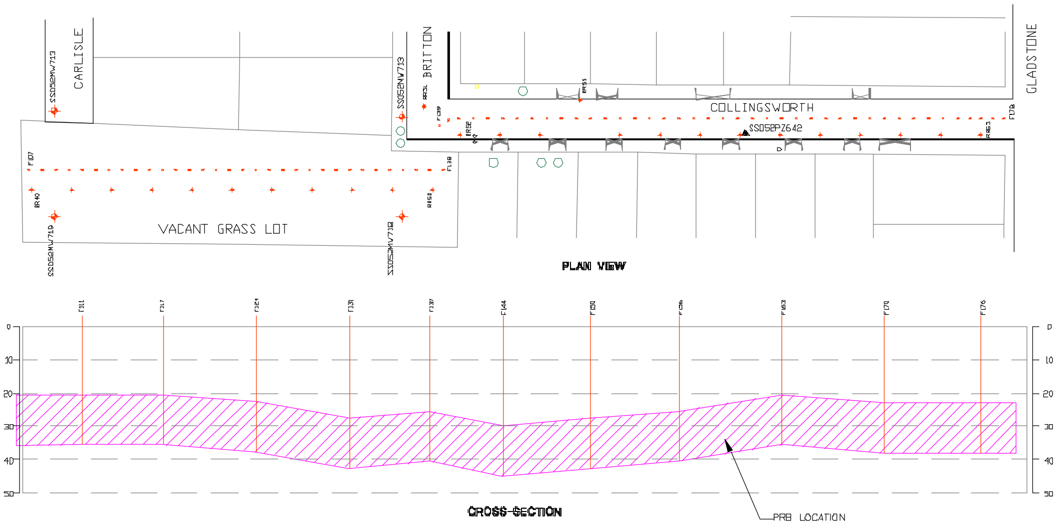

Figure 3. As Built Plan and Cross-Section of the PRB

**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:

*Iron and Gel QA/QC Tests:* The supplied iron fillings were tested for grain size distribution, mineralogy, permeability, and reactivity; while the gel for iron injection was tested for pH, viscosity, and resistivity.

*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 installed along the PRB alignment. The real-time imaging along with measured injected quantities provided an approximate thickness of each injection segment.

*Inclined Profile:* PRB thickness verification measurements were conducted by inclined profiling at approximately 30? from the vertical to intersect the PRB at the desired depth. A total of four (4) inclined magnetometer profiles were completed through the PRB and verified that the PRB thickness was within specification.

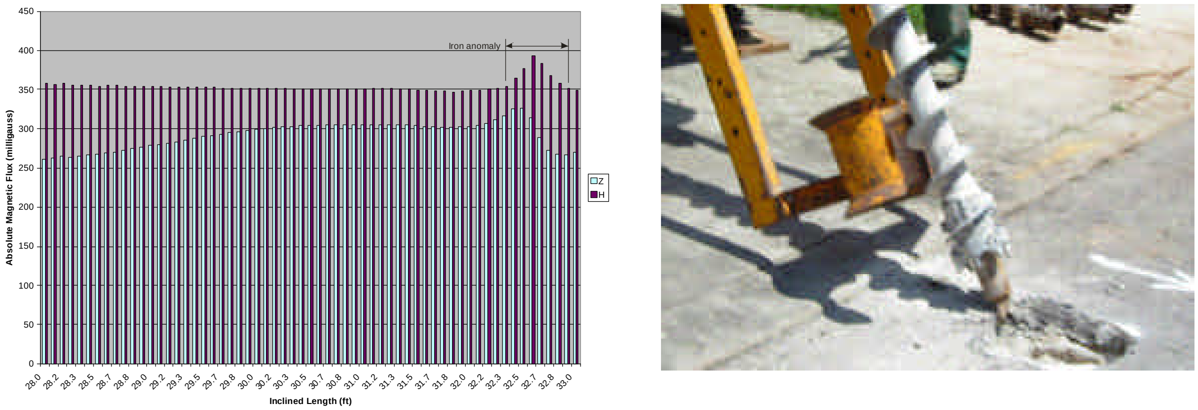

**Figure 4. Inclined Magnetometer Profiling to verify PRB thickness**

## CONCLUSIONS

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 some 2,000 feet in length along busy two-lane streets in an urban neighborhood of a major city. The final geometry of the constructed PRB extended approximately 2,035 feet in overall length from a depth of approximately 20 feet down to a maximum depth of approximately 40 feet bgs. The as-built PRB has a cross-sectional area of 22,700 ft$^2$, with a total of 510 tons of iron filings were injected into the subsurface to create the three segments of the iron PRB with an average iron thickness of 3.0-inches. The in situ constructed geometry of the PRB was quantified in real time during injection by the active resistivity imaging technology. Post-PRB QA/QC verification testing was completed to evaluate the impact on the groundwater flow regime by the installation method and to quantify the in place installed PRB average thickness. Post-PRB hydraulic pulse testing indicated that the installed PRB did not impact the formation hydraulic characteristics. Post-PRB inclined thickness profiling by soil magnetometer probing determined that the PRB thickness was within specification at four (4) locations along the PRB alignment.

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