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PILOT STUDY REPORT

SITE 73, OPERABLE UNIT 21

MARINE CORPS BASE
CAMP LEJEUNE, NORTH CAROLINA

Prepared for:

DEPARTMENT OF THE NAVY
ATLANTIC DIVISION
NAVAL FACILITIES
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Executive Summary

The team of MicroPact Engineering, Inc. (MicroPact) and Baker Environmental, Inc. (Baker) were authorized by the United States Department of the Navy and the United States Marine Corps to conduct a Pilot Study at a trichloroethene (TCE) "hot spot" located on Marine Corps Base, Camp Lejeune in North Carolina. The "hot spot" is located under the Amphibious Vehicle Maintenance Facility, known as Operable Unit 21, Site 73 and was so named due to groundwater TCE concentrations in excess of 1000 :g/L.

Numerous studies have been conducted at the site, dating back to the early 1980's. It was discovered that TCE concentrations in groundwater are decreasing due to natural attenuation - a result of anaerobic halorespiration, a form of reductive dechlorination.

After evaluating several treatment options and examining past experiences with in-situ treatments for groundwater contamination, both on- and off-site, hydrogen sparging was selected as a potential remedy. It was decided that increased hydrogen availability in the aquifer could result in increased rates of halorespiration, thus facilitating the reduction of TCE to daughter products (cis-1,2 DCE, trans-1,2 DCE, and vinyl chloride) and eventually ethene. The treatment area was selected as the volume of the plume bounded by a 100 μg/L TCE isoconcentration contour, which included the "hot spot." The goal of the Pilot Study was to achieve an order-of-magnitude reduction in TCE concentrations.

A horizontal injection well was selected, over a network of vertical injection wells, as a result of past experience with in-situ treatment of groundwater at Camp Lejeune; knowledge of the formation and aquifer conditions; and existing surface obstructions.

Groundwater Services, Inc. designed the Hydrogen Biosparge System based on the estimated zone of influence of the horizontal well, desired sparge volume, injection pressure, gas flow rate, sparge time, and sparge frequency. Horizontal Well and Environmental Consultants, LLC provided the well screen perforation design (hole size and spacing). Mears/Directional Drilling Technologies (DDT) installed the horizontal well during February 2004.

Groundwater from eleven monitoring wells was sampled before, during, and after the study in order to evaluate the effectiveness of the treatment. Three of the eleven wells were new and installed specifically to generate additional groundwater analytical results in support of the Pilot Study. In order to evaluate the distribution of hydrogen throughout the system, pressure transducers were installed in several wells and a helium tracer was injected at selected intervals.

Approximately 40 hydrogen injections were completed during the study, beginning on March 18, 2004 and ending on May 26, 2005. Groundwater was collected and analyzed on six occasions, two prior to the Pilot Study implementation, three during the study, and one at the conclusion of the study.

During the second injection (March 25, 2005 trip memorandum), short-circuiting was observed, resulting in a lowering of the design injection pressure for the remainder of the study.

By September 2004, preliminary evaluation of the chlorinated solvent concentrations, and the lack of detectable concentrations of hydrogen and helium in the system, resulted in a purge tank being installed at the distal end of the well. Two factors potentially contributed to the lack of detectable hydrogen and helium in the system. The first factor was the inability to overcome the system hydrostatic pressure using the initial design configuration. This factor was anticipated by the horizontal well designer (Dr. Fournier e-mails). The second factor was due to not taking the hydrogen demand of the soil into account during the design phase (Haselow et al, 2003). For the remainder of the study, nitrogen gas was used to remove the standing water from the horizontal well prior to hydrogen injection.

A final round of groundwater sampling was conducted in May 2005 at the conclusion of the hydrogen injections. Upon evaluating all the sampling results, it was found that TCE concentrations were reduced by 50% in the deep and intermediate well pair having the highest initial concentrations of TCE. Four wells experienced a modest reduction in TCE concentrations during the study, and TCE concentrations increased in three wells. Two wells had no detectable concentrations before and after the study.

The average TCE concentration decreased approximately 35% over the 15-month study period. The average total volatile concentration decreased approximately 8% during the same period. Hydrogen was never detected in any of the wells above the background concentration, which may be due to the underestimation of the hydrogen demand of the soil. Helium was detected in MW-63 only during one of the sampling events.

The project chronology is provided in Table 1. The data is tabulated in tables 2 though 7. The data is depicted graphically in Appendix A.

Preliminary remediation time frame calculations are presented in Appendix C.

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List of Acronyms and Abbreviations

ASTs	Aboveground Storage Tank
Baker	Michael Baker Jr., Inc.
bgs	below ground surface
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
DCE	Dichloroethene
DoN	Department of the Navy
DDT	Directed Drilling Technologies
FFA	Federal Facilities Agreement
FSAP	Field Sampling and Analysis Plan
GPS	Global Positioning System
GSI	Groundwater Services, Inc.
HASP	Health and Safety Plan
i	gradient
IDW	Investigation Derived Waste
k	hydraulic conductivity
LTM	Long-Term Monitoring
MCB	Marine Corps Base
n	effective porosity
NA	Natural Attenuation
NAE	Natural Attenuation Evaluation
NCDENR	North Carolina Department of Environment and Natural Resources
NPL	National Priorities List
NTU	Nephelometric Turbidity Unit
NWS	National Welders Supply
OU	Operable Unit
O&M	Operations and Maintenance
ORP	Oxidation-Reduction Potential
psi	pounds per square inch
QAPP	Quality Assurance Project Plan
RCRA	Resource Conservation and Recovery Act
RI	Remedial Investigation

scfm	Standard cubic feet per minute
SF_6	Sulfur Hexafluoride
TCE	Trichloroethene
TCL	Target Compound List
TOC	Total Organic Carbon
TOD	Total Oxidant Demand
:g/L	micrograms per liter
USDOT	United States Department of Transportation
USEPA	United States Environmental Protection Agency
UST	Underground Storage Tank
v	seepage velocity
VOCs	Volatile Organic Compounds

1. Introduction

This report documents the performance of a Pilot Study conducted at the trichloroethene (TCE) "hot spot" located at the Amphibious Vehicle Maintenance Facility, Operable Unit (OU) 21, Site 73, Marine Corp Base (MCB) Camp Lejeune, North Carolina. Previous investigations at Site 73, summarized in the Natural Attenuation Evaluation (NAE) (Baker, 2002), indicated the presence of fuel-related and chlorinated solvent contamination in the groundwater. The NAE also indicated that the TCE plume is undergoing reductive dechlorination as a result of natural processes in both the surficial and upper Castle Haynes aquifers. The portion of the TCE plume having the highest concentrations of TCE in groundwater was selected for this pilot-scale test.

1.1. Contractual Setting

Camp Lejeune was placed on the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) National Priorities List (NPL) effective 4 November 1989. Subsequent to this listing, the United States Environmental Protection Agency (USEPA) Region IV; North Carolina Department of Environment and Natural Resources (NCDENR); the United States Department of the Navy (DoN); and the Marine Corps entered into a Federal Facilities Agreement (FFA) for Camp Lejeune. The primary purpose of the FFA was to ensure that environmental impacts associated with past and present activities at the Base are thoroughly investigated and that appropriate CERCLA response and Resource Conservation and Recovery Act (RCRA) corrective action alternatives are developed and implemented, as necessary, to protect public health and welfare and the environment.

1.2. Site Location

Site 73 is located within the boundary of the Amphibious Vehicle Maintenance Facility, in the Courthouse Bay area of Camp Lejeune. The site is roughly bounded by State Route 172 (Sneads Ferry Road) to the north, Courthouse Bay to the south, and unnamed tributaries of Courthouse Bay to the east and west. Courthouse Road, which bisects the study area, is used to enter the complex. The terrain is primarily flat. Storm water run-off tends to drain directly south to Courthouse Bay or to two small-unnamed tributaries located east and west of the facility, ultimately discharging to Courthouse Bay. A broad marshy area is associated with the western tributary. Directly north of the site is another large marsh and a stream that discharges north into the New River. The latter marsh is separated from the site by State Route 172, which represents a local topographical high and surface water runoff divide.

The study area consists of numerous buildings, aboveground storage tanks (ASTs), underground storage tanks (USTs), vehicle wash racks, and oil/water separators. Most of the USTs in the fenced area around Building A47 were located and some were removed. Non-petroleum type wastes are routinely handled at an active Hazmat Storage Area located near UST A47/3. Other USTs are or were located near Buildings A1, A2, and A10. The Remedial Investigation (RI) (Baker, 1997) contains profiles of the various

USTs. Numerous site improvements were made, including building construction and utility replacement along Courthouse Bay Road.

1.3. Background

This section summarizes the site setting, including geology/hydrogeology, and environmental conditions. Detailed descriptions of site conditions are contained in previous documents referenced herein. The environmental conditions presented in Section 1.3.2 provide an overview of the nature and extent of contamination. The environmental conditions were used to evaluate the treatment options leading to this Pilot Study and are documented in the Final Technology Evaluation Report for Site 73 (Baker, 2003) and the Final Project Plans (Baker, 2003).

1.3.1. Site Geology/Hydrogeology

This section presents the geological and hydrogeological characteristics of Site 73 in the context of base-wide conditions and was obtained from the Final NAE Report (Baker, 2002).

Undifferentiated Formation/Surficial Aquifer

The undifferentiated formation is generally uniform throughout the study area. Typically, the shallow sediments consist of unconsolidated deposits of sand and silty sand separated by a discontinuous clay layer that thickens and thins across the site. These sediments overlay the Belgrade and River Bend Formations. The observed sequence of deposition in the Pilot Study area of the undifferentiated formation (from top to bottom) includes fine sand, clay, and fine sand. The paragraphs that follow provide additional detail.

The upper sand is predominately fine sand, with silt in the northeastern portion of the study area and some silt in the southwestern portion. These upper sands extend from ground surface to 15 to 19 feet below ground surface (bgs). Groundwater is encountered in the upper sand, from 4 to 8 feet bgs.

The clay layer has been generally described as containing varied amounts of silt, sand, and wood fragments. The clay is laterally discontinuous, with a considerable thickness variation. The clay layer is present in the Pilot Study area and contains some fine sand in the southwestern portion of the study area, and some silt in the northeastern portion. This clay has been observed to be wet and approximately 2 to 3 feet thick, with relative density ranges from very soft to soft. Laboratory grain size analysis determined that approximately 50 percent of the material was clay, 34 percent silt and 16 percent fine sand. The vertical permeability was measured to be 2.6×10^{-7} cm/sec (7.4×10^{-4} ft/day) in the lab.

The lower sands were observed throughout the site and appear to be distinguishable from the upper sands by color. The upper sands are generally brown, while the lower sands are generally gray. In the Pilot Study area, the lower sands are found beginning at 18 to 20 feet bgs and are approximately 25 feet thick. Results of standard penetration tests performed during RI drilling indicate that the sands have a relative density of very loose to medium dense.

Recharge to the surficial aquifer is by rainfall. The aquifer receives more recharge in the winter than in the summer when much of the water evaporates or is transpired by plants before it can reach the water table. Most of the surficial groundwater is discharged to local streams, but some water passes through the underlying semi-confining unit. Water levels in the wells tapping the surficial aquifer vary seasonally. The water table is generally highest in the winter and spring, and lowest in the summer and early fall. Typical groundwater flow in the surficial aquifer is described in the Long Term Monitoring (LTM) Report (Baker, 2002a).

Hydraulic conductivity tests were performed at the site on June 4, 1999 at well 73-MW27, which is located in the Pilot Study area within the surficial aquifer. Based on hydraulic conductivity measurement summary in the modeling report (Baker, 1998), the estimated conductivity was 14.8 feet/day. This value appears to be high compared with slug test hydraulic conductivity ranges from the RI (0.14 feet/day to 4.4 feet/day), but is similar to pumping test data (5.1 feet/day to 14.7 feet/day). Using a hydraulic conductivity (k) range of 5 to 15 feet/day, a gradient (i) of 0.006 feet/foot and an effective porosity (n) of 0.4, the groundwater seepage velocity ($v = k*i/n$) would range from approximately 27 feet/year to 82 feet/year.

<u>River Bend Formation/Castle Hayne Aquifer</u>

The principal water supply aquifer for MCB, Camp Lejeune is the Castle Hayne aquifer. This aquifer primarily resides within the River Bend Formation, which is generally comprised of interbedded partially cemented sands, shell fragments and limestone fragments and silts and clays. The thickness of the aquifer in the Courthouse Bay area is more than 300 feet. In this context, only the upper portion of the Castle Hayne aquifer has been investigated at Site 73.

In the Pilot Study area, these sediments were observed to be primarily fine to medium calcareous sands, with trace silt and shell fragments. The top of the River Bend formation in the study area is approximately 48 feet bgs. The sediments were observed to be wet with a relative density of medium dense to very dense. The bottom of the River Bend formation has not been observed at the site.

Slug test estimates from the RI of hydraulic conductivity of the upper portion of the Castle Hayne aquifer range from 0.09 feet/day to 0.65 feet/day (Baker, 1998). Hydraulic conductivity estimates from other studies at Camp Lejeune show values of at least an order of magnitude higher than the RI test values, ranging from 2.3 feet/day to 4.9

feet/day. Based on professional judgment and knowledge of the Base, hydraulic conductivity in the Pilot Study area would be on the order of 1 to 10 feet/day.

Recharge of the Castle Hayne aquifer at MCB, Camp Lejeune is primarily received from the surficial aquifer. Natural discharge is to the New River and its major tributaries. The Castle Hayne aquifer provides roughly seven million gallons of water to MCB, Camp Lejeune. Groundwater pumping has not significantly affected natural head gradients in the aquifer. Typical groundwater flow in the upper portion of the Castle Hayne aquifer at Site 73 is described in the LTM report (Baker, 2002a). Using a range of hydraulic conductivity of 1 to 10 feet/day, a gradient of 0.00045 feet/foot, and an effective porosity of 0.3, the estimated groundwater seepage velocity is 0.55 to 5.5 feet/year.

1.3.2. Environmental Conditions

This section provides information regarding nature and extent of contamination at Site 73. This information was obtained from the NAE (Baker, 2002), subsequent deep well installation and sampling, and LTM sampling events completed prior to the Pilot Study implementation.

1.3.3. Previous Investigations

Environmental investigations conducted at Site 73 are as follows:

Initial Assessment Study (Water and Air Research, 1983)
Confirmation Study (ESE, 1990)
UST SA-21 Investigation (ATEC, 1991)
Additional investigations on UST SA-21 in 1992 and 1993 (Baker)
UST A47/3 Investigation (GSI, 1993)
UST A47/3 Investigation (Law-Catlin, 1993)
Preliminary Investigation (1994, included in the RI)
Remedial Investigation/Feasibility Study Work Plan (Baker, 1995)
Remedial Investigation Report (Baker, 1997) including an Aerial Photography Review
Feasibility Study (Baker, 1998a)
Groundwater Modeling Report (Baker, 1998)
Supplemental Groundwater Investigation (Baker, 1998b)
Natural Attenuation Evaluation – Fieldwork in 1998 and 1999, Draft NAE in 2000, and Final NAE in 2002 (Baker, 2002)
Letter Report for New Deep Well Installation (Baker, 2001)
Final Technology Evaluation Report (Baker, 2003)

The results of the earlier investigations are summarized in each document previously prepared by Baker and are only referenced in this section.

1.3.4. Groundwater Contamination

Investigations at Site 73 revealed that approximately 400,000 gallons of waste oil was discharged directly onto the ground surface, primarily near Building A47. In addition to the waste oil, approximately 20,000 gallons of waste battery acid were also disposed in the area northeast of A47. Currently, structures or pavement cover most of the ground surface where waste disposal occurred. One report (Law-Catlin, 1993) indicated the possibility of solvent disposal at the site, although no specific disposal locations or dates were identified.

Current groundwater contamination in the upper Castle Hayne aquifer, the target location for this Pilot Study, includes chlorinated solvent contamination and minor fuel-related contamination. At Site 73, the Castle Hayne aquifer begins 48 feet below the ground surface (bgs) and extends to more than 300 feet bgs. Several monitoring wells are located both in and around Site 73 for use in identifying and monitoring TCE concentrations in the groundwater.

Within the TCE plume located at Site 73, a "hot spot" (having TCE concentrations > 1000 µg/L) exists, bounded by monitoring wells 73-MW 46DW to the south, 73-MW 39DW to the east, and 73-MW 13DW to the northeast.

Monitoring well 73-MW 49DW exhibited the highest concentrations of chlorinated solvent contamination in the upper Castle Hayne aquifer. The NAE reported TCE at 4,600 µg/L, cis-1,2-dichloroethene (cis-1,2-DCE) at 940 µg/L, vinyl chloride at 20 µg/L, and benzene at 13 µg/L. More recently, the April 2003 LTM data for well 73-MW49DW indicated a decrease in parent compound levels and a slight increase in daughter compounds over time, with TCE at 1,800 µg/L, cis-1,2-DCE at 420 µg/L, vinyl chloride at 27 µg/L, and benzene at 11 µg/L. At monitoring well 73-MW44DW, the NAE reported TCE at 1,600 µg/L, cis-1,2-DCE at 1,200 µg/L, vinyl chloride at 39 µg/L, and benzene at 8.5 µg/L. The April 2003 LTM data and other recent LTM events show a general decrease in TCE concentrations over time at 73-MW44DW. TCE was detected at 680 µg/L, cis-1,2-DCE at 410 µg/L, vinyl chloride at 39 µg/L, and benzene at 8 µg/L. Small amounts of 1,1-dichloroethene, trans-1,2- dichloroethene, ethylbenzene, and o-xylene have also been detected in the upper Castle Hayne aquifer at these two locations (October 2002).

Because of the sustained high TCE concentrations in the Upper Castle Hayne aquifer, this portion of the TCE plume was selected for the Pilot Study.

1.4. Basis for Design and Project Goals

Hydrogen sparging was selected as a potential remedial technology for the TCE in groundwater and evaluated during this Pilot Study. Hydrogen injection, a variation of biosparging, is a recently developed method designed to directly stimulate anaerobic halorespiration, a form of reductive dechlorination. For reductive dechlorination to occur, halorespirators must compete successfully against hydrogen utilizers for the

available hydrogen, which is present at low concentrations. Increased hydrogen availability may result in increased rates of halorespiration, provided that adequate nutrients and a suitable microbial consortium are present to facilitate reduction to ethene. This technology was tested with favorable results at Cape Canaveral Air Station (Newell, et al., 1997).

During the NAE, it was determined that the TCE is undergoing reductive dechlorination at the site, as evidenced by the presence of TCE degradation products, and that a suitable microbial consortium is present to enable the degradation to occur.

Hydrogen sparging is a remediation method whereby compressed hydrogen gas is injected in to water-saturated soils, at controlled pressures and volumes, in order to facilitate the dechlorination process by providing additional electron donors (hydrogen). For sparging to be successful, the required volume of gas must be injected evenly throughout the system, at pressure sufficient to overcome the overburden and hydrostatic pressures without fracturing the formation.

The following two sections summarize the design basis for both the horizontal well and the hydrogen injection process. Detailed design information may be found in Attachment A - Hydrogen Biosparge System, Conceptual Design and Attachment B - Detailed Design Draft, Site 73, Camp Lejeune, Horizontal Sparging Well Perforation Design.

1.3.5. Horizontal Well Design and Location

Background

The primary reason for use of a horizontal sparge well was existing surface obstructions, limited site access, and past experience at Site 73. Many treatment systems use a network of vertical wells to inject sparge gas into an aquifer. However, the TCE "hot spot" at Site 73 is located under a fenced parking area, currently used for amphibious vehicle storage, offering limited access. Vertical sparge wells would have required significant above-ground equipment. Furthermore, the schedule of hydrogen injections would have required weekly disruptions in parking lot service. Additional disruptions would have occurred as a result of the performance monitoring groundwater sampling. Because the area is secure, well installation and treatment system operations and maintenance (O&M) would have been limited to hours of facility operation. An aboveground network of injection wells and associated appurtenances was impractical due to the high-traffic nature of the parking area. To install a vertical well injection system below-grade would have added significant cost to the project. Therefore a horizontal well allowing injection equipment to be installed aboveground, outside the parking area, was preferable. Additionally, using a horizontal well offered the potential elimination of many of the problems associated with gas injection at Camp Lejeune. At Site 73, an air injection system installed in 2002 resulted in short-circuiting and insufficient injection into the surficial aquifer due to the fine-grained nature of the materials. Typically, a vertical well has a very small zone of influence (the maximum

formation volume exposed to the injected gas) and channels develop in the formation. Horizontal wells have a larger zone of influence and are more efficient in a deeper target zone (Newell, et al., 2001).

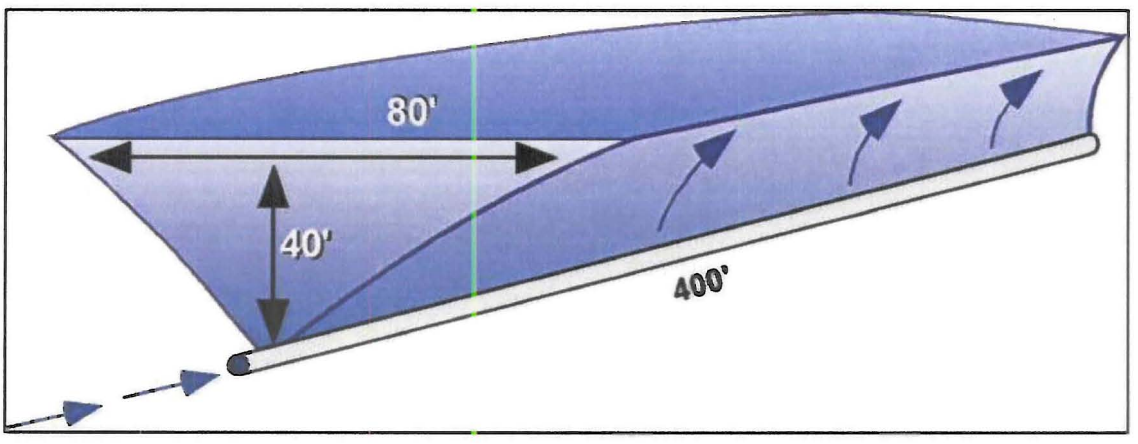
Design

The design parameters were dictated by the depth and aerial extent of the 100 µg/L TCE isoconcentration curve identified as the treatment area. Groundwater Services, Inc. designed the Hydrogen Biosparge System based on the estimated zone of influence of the horizontal well, desired sparge volume, injection pressure, gas flow rate, sparge time, and sparge frequency.

The hydrogen injection pressure required to induce gas flow through the soil, but prevent formation fracture (assuming hydrostatic pressure from a 70-foot water column, overburden pressure, and a 30% factor of safety) was calculated in the range of 31 psi to 60 psi.

It was predicted (based on literature and previous horizontal well injection systems) that the hydrogen sparge zone of influence would be triangular in shape, extend above the horizontal well screen 40 feet, and extend outward 40 feet in each direction perpendicular to the injection well. From this it was determined that a sparge time of approximately 2.6 minutes would be required to deliver 2600 cubic feet of hydrogen at a design flow rate of 1000 scfm. The hydrogen injections were scheduled to occur once a week for nine months.

Figure 1 - Projected Hydrogen Sparge Volume



In order to determine distribution of hydrogen over the treatment zone, a helium tracer was to be injected along with the hydrogen at a rate of approximately 0.1 percent by volume of injection.

Once the design parameters were calculated, the process and materials were selected. A custom regulator and manifold system (hydrogen skid) was made by National Welders Supply to deliver gas from the cylinder pack to the horizontal well. The skid was assembled at the well entrance located on the southwest side of the AAV lot. Hydrogen was supplied using 12 Size-A cylinders mounted together in a 3 by 4 arrangement. Each cylinder pack had a capacity of 216 scf for a total hydrogen volume of approximately 2600 scf. The system also included a relief valve, to avoid over-pressurization of the system, and an AC powered timer-initiated actuator. The desired gas flow rate was achieved using a diaphragm valve and measured using a differential pressure flow meter. A check valve prevented back flow. A sampling port was placed between the pressure gauge and diaphragm valve to measure the tracer mixture.

A 400-foot long well screen, approximately 75 feet below ground surface was installed under the 100 :g/L TCE contour. Based on the existing surface features and horizontal well technology, a continuous well bore using 4-inch diameter well casing was installed, consisting of three sections - the entry riser pipe (250 feet in length), the 400-foot well screen, and the exit riser pipe (also 250 feet in length). This allowed for the entry and distal ends of the well to be placed outside the Site 73 vehicle storage area while achieving the required treatment depth and length.

Horizontal Well and Environmental Consultants, LLC provided the well screen perforation design (hole size and spacing). The goal of the screen design was to deliver 2600 scf of hydrogen once a week, at a flow rate equivalent to 1000 scfm of air, uniformly along the screen length. The hole size and spacing were iteratively varied in order to minimize the pressure drop along the length of the screen. The well screen consisted of 266, 7/64-inch diameter holes, spaced 18 inches apart. Each successive hole was drilled at the prescribed spacing and rotated 60 degrees from the previous hole, forming a helix along the length of the screen. This design was estimated to result in a pressure drop of less than 5% along the length of the pipe (0.2 psi per 100 feet of pipe and 60 psi injection pressure). The Horizontal Sparging well Perforation Design report can be found in Attachment A.

A continuous well installation, having both entry and exit points, was used for the Pilot Study. Advantages of a continuous well over a blind well (no exit point) included:

- reduced cost of drilling
- easier well installation
- increased well performance testing flexibility
- easier maintenance *and*
- improved well development

It should be noted that these design parameters could not be modified once the horizontal well was installed.

1.3.6. Pilot Study Goal

The objective of this Pilot Study was to determine if the applied in-situ technology could reduce the concentration of chlorinated compounds in groundwater by one order of magnitude. The Pilot Study was scheduled for one year, with the technology applied for nine months, and final groundwater sampling approximately three months after the last treatment. Originally, the treatment area considered for this Pilot Study was inside the 1,000 µg/L TCE isoconcentration contour. Because pre-Pilot Study analyses indicated a downward TCE trend due to natural attenuation, it was proposed that the target area for the Pilot Study be expanded to the 100 µg/L TCE contour. It was recognized that the treatment goal might not be achieved with the proposed technology within the time allotted; however, this goal was considered acceptable for a Pilot Study.

1.5. Report Organization

The following sections are presented in this Pilot Study Report.

Section 2.0 – Project Timeline
Section 3.0 – Pilot Study Implementation
Section 4.0 – Performance Monitoring
Section 5.0 – Conclusions and Recommendations
Section 6.0 – Costs
Section 7.0 – References

Additional tables and figures are provided after the report body.

2. Project Timeline

The Pilot Study commenced in September 2002 with the evaluation of different treatment options as described in the Technology Evaluation (Baker, 2002) and concluded in May 2005 with the final round of groundwater sampling. Table 1 summarizes the activities that took place during the Pilot Study. A more detailed timeline may be found in Section 3.

3. Pilot Study Implementation

3.1. Pre-Pilot Study Investigation

Three groundwater monitoring wells were installed during July 2003 in the Amphibious Assault Vehicle (AAV) compound in order to generate additional groundwater analytical results in support of the Pilot Study. These wells were located and installed in accordance with the Work Plan (Baker, 2003) and included two deep wells (73-MW63DW and 73-MW27DW) and one intermediate-depth well (73-MW49IW). Soil boring and well construction records for these wells are included in Attachment D.

The wells were installed by Parratt-Wolff, Incorporated under the supervision of Baker personnel. The driller advanced a sample borehole using 2-3/4-inch hollow-stem augers (HSAs). Split-spoon samples were collected, at intervals specified by Baker, to locate the uppermost clay layer (semi-confining unit). Samples were collected using a 2-inch inside diameter (ID), 2-foot long stainless steel split-spoon sample barrel. 8-1/4-inch HSAs were used to ream the borehole to accommodate an 8-inch diameter steel casing. This casing was installed at least 2-feet into the clay layer to seal off the surficial aquifer. Bentonite grout was used to seal the casing in place. Casings were installed at all three well locations during one day and allowed to cure at least 24-hours. The borehole was advanced using mud rotary methods with a 5-7/8 tri-cone roller bit. Once the desired depth was reached (approximately 55-feet for the intermediate well and 75-feet for the deep wells), well installation commenced. The sand pack and bentonite seal thicknesses were increased because of the well depths. The filter sand pack was placed 2.5- to 3-feet above the top of the well screen. The bentonite seal was approximately 4-feet thick. Finally, a bentonite-cement grout was backfilled to the surface. A flush-mount steel protective casing was installed at the ground surface.

Total oxidant demand (TOD) was determined for soil samples collected between 52 and 54-feet bgs at all three well bores. Additionally, grain size distributions were determined for the two deep wells using samples collected between 67 and 69 feet bgs. The results of the TOD analyses are provided in Appendix B.

Investigation-derived waste (IDW), including drilling fluids and soil cuttings were stored in one 20-cubic-yard roll off box located just outside the AAV compound. Shaw personnel managed storage, sampling, and disposal of the IDW.

All three wells were developed prior to sampling and at least 24 hours after completion. A hydraulic lift pump was used, with virgin polyethylene tubing (1/2-inch ID). The intake was initially placed at the bottom of each well and a flow rate of 1 to 2 gallons per minute (gpm) was established. The pump intake was fitted with a check value and surge disk. The up and down motion of the pump provided some surging of water through the screen. The intake was periodically raised to develop the entire screen length. Development at each interval was continued until stability in clarity was observed.

Development for the entire well was completed when five to ten well volumes were removed. The development water was temporarily stored in 55-gallon drums. Water was transferred to a 1,000-gallon polyethylene storage tank. Shaw personnel managed storage, sampling, and disposal of the IDW.

3.2. Baseline Monitoring

A baseline sampling event for the monitoring wells, both new and existing, was conducted in October 2003. The purpose of baseline sampling was to determine the target-contaminant concentrations in the groundwater prior implementation of the hydrogen injections. Because of various delays in the start of the Pilot Study program, an additional baseline sampling event occurred in January 2004. The target analytes and analytical methods are discussed in Section 4.

Pressure transducers were installed in four wells to monitor changes in water levels as a response to hydrogen injection. Transducers were placed in three wells located inside the boundary of the 100 µg/L TCE concentration contour, adjacent to the horizontal well (73-MW13DW, 73-MW49DW, and 73-MW49IW) and one outside the 100 µg/L contour, outside the zone of influence of the horizontal well (73-MW39DW). Northwest PT2X Smart Sensor pressure transducers were installed and programmed on February 11, 2004.

3.3. Horizontal Well Installation

Mears/Directional Drilling Technologies (DDT) installed the horizontal well in February 2004.

Possible entry and exit points were investigated in July 2003. Utilities at the entry and exit locations were cleared on 2 February 2004. Mears/DDT mobilized on 3 February 2004. Mears/DDT noticed two obstacles in the drill path - the corner of Building A47 (an on-grade guidance system obstacle) and the water treatment system (a drill tool obstacle). Mears/DDT submitted an alternate location for the horizontal well, which was surveyed (using GPS equipment) and compared with the TCE contours and original proposed well location. The Partnering Team approved the alternate location. The revised horizontal well design consisted of a 420-foot entrance riser casing, a 400-foot long screen (at 85-feet bgs), and a 350-foot exit riser casing, for a total length of approximately 1,170 feet.

Utilities at the new entry and exit locations were cleared. Drilling began on 5 February 2004 and was completed on 7 February 2004. Well assembly began on 6 February 2004 in accordance with the Work Plan (Baker, 2003). The well sections (entrance riser casing, screen, and exit riser casing) were placed inside a sealed outer carrier casing for protection while the well was being installed in the boring. A continuous pilot hole was drilled from the entry to the exit using a directional drilling tool and wire-line guidance system. In addition to the wire-line, a secondary guidance system was located on the surface to confirm the location of the well boring. The pilot hole was enlarged by back-drilling from exit to entry using a 12-inch diameter reamer. The carrier casing, with the

well materials inside, was pulled into the well bore. The entry side seal was removed, the well was filled with fresh water (to prevent drill spoils from entering the well screen) and the carrier casing was pulled from the well bore, leaving the well in place. The formation was allowed to collapse around the well screen. A bentonite plug and cement grout was injected into the annular space of the well bore. A 10-foot by 4-foot concrete pad was constructed at the entry point to accommodate the hydrogen injection equipment and horizontal well stick-up. A concrete pad was constructed at the distal end and the well exit was capped.

Horizontal well installation IDW, including drilling fluids and soil cuttings, were stored in two 20-cubic-yard roll-off boxes located just outside of the AAV compound. Shaw personnel managed storage, sampling, and disposal of the IDW.

The well construction was completed on 10 February 2004. Photographs of the horizontal well installation are located in Attachment C.

3.4. Hydrogen Skid Installation

Mobilization for the hydrogen skid installation began on February 8, 2004 to coordinate the well and skid installations. The skid was designed by Groundwater Services, Inc. (GSI) and fabricated by National Welders Supply (NSW). Christine Harwood from Baker and Jim Doesburg from Mears/DDT provided oversight. GSI arrived on site on 10 February 2004 and NWS arrived on site on 11 February 2004.

NWS assembled the skid at their off-site facility and transported it to Site 73. The well entrance had a cast-iron flange designed to connect to the hydrogen injection skid. However, it was decided that a stainless steel flange was safer. A stainless steel flange was ordered and sent to Mears/DDT on site. Mears/DDT removed the old flange and installed the new one using the HDPE trimming and welding equipment. The Base Fire Department issued NWS a one-day welding permit in order to complete the welds necessary to connect the skid to the horizontal well entrance. Compressed nitrogen was used to fit test the skid. No leaks were found.

A safety fence and appropriate signage were installed around the skid. The skid installation was completed on 12 February 2004.

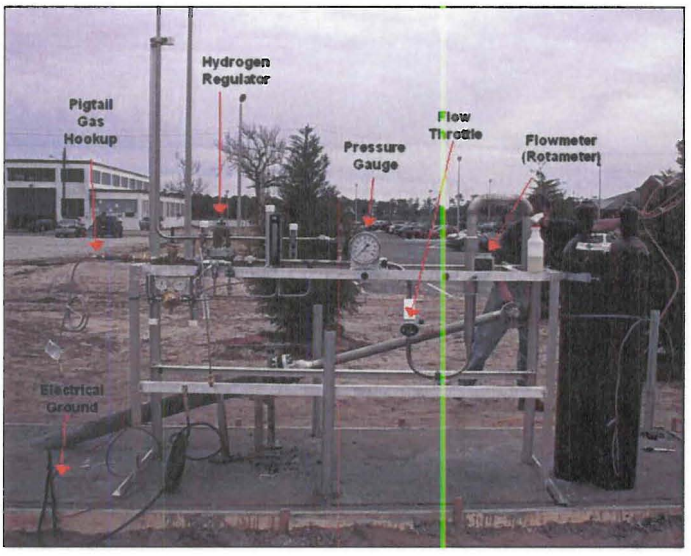


Figure 2 - Hydrogen Skid

Additional photographs documenting the skid installation are located in Attachment C.

3.5. Surveying

The horizontal coordinates of the three new monitoring wells and the horizontal well entrance and exit points were surveyed using a Global Positioning System (GPS) unit to a horizontal accuracy of 0.1 feet.

3.6. Hydrogen Sparge Activities

The hydrogen injections were scheduled to begin immediately following the hydrogen skid installation. However, Mears/DDT expressed concern about the formation collapsing around the well in such a short time frame. The issue was discussed during a conference call, held on 10 February 2004, between Travis McGuire of GSI, Jim Doesburg of Mears/DDT, John Haselow of Micropact, and Richard Bonelli and Christine Harwood of Baker. It was agreed that the hydrogen injections would be postponed for two weeks in order to allow the formation sufficient time to collapse around the well screen. A subsequent mobilization by GSI and NWS was planned for two weeks post construction.

Approximately 40 hydrogen injections were completed during the Pilot Study, beginning in March 2004 and ending in May 2005. A detailed timeline of the hydrogen injections and related events may be found in the table and text that follow.

Hydrogen Injection Summaries - Camp Lejeune, NC		
Injection Number	Date Injection Completed	Comments
1	12 March 2004	Initial Injection Event
2	18 March 2004	
3	25 March 2004	Increased flow rate and pressure and had daylighting
4	8 April 2004	
5	15 April 2004	
6	22 April 2004	
7	28 April 2004	
8	5 May 2004	
9	12 May 2004	
10	19 May 2004	
11	25 May 2004	Post-Injection Sampling started after this event -- Injections temporarily halted
	August 2004	Agreed to evacuate well prior to injection
12	17 September 2004	Initial Evacuation Test
13	24 September 2004	Added Helium
14	30 September 2004	
15	7 October 2004	
16	14 October 2004	Insufficient nitrogen to completely purge the well - Regulator on site
17	19 October 2004	
18	25 October 2004	
19	24 November 2004	
20	27 December 2004	
21	25 January 2005	
22	25 February 2005	
23	16 March 2005	
24	23 March 2005	
25	30 March 2005	
26	6 April 2005	
27	12 April 2005	

Hydrogen Injection Summaries - Camp Lejeune, NC		
Injection Number	Date Injection Completed	Comments
28	19 April 2005	
29	25 April 2005	There was a crack at the injection end of the well. Returned April 30, 2005 to complete injection. Very little hydrogen injected on April 25, 2005.
30	30 April 2005	
31	4 May 2005	Crack at distal end of horizontal well -- no injection completed.
32	11 May 2005	
33	18 May 2005	
34	25 May 2005	
35	1 June 2005	
36	10 June 2005	Final Injection Event

12 March 2004

The first hydrogen injection was performed. Sixteen cylinders of hydrogen gas were injected. The duration of the injection was 4 minutes, with an initial injection pressure of 90 psi and a final injection pressure of 65 psi. The flow rate varied between 125 and 170 cfm. During the injection, the distal end of the well was checked for leaks, none were found.

25 March 2004

Sixteen cylinders of hydrogen gas were injected using injection pressures between 50 and 65 psi, with flow rates varying between 40 and 100 cfm. Approximately four minutes into the injection, daylighting of the injection gas was observed 150 feet northwest of the injection skid. The injection was suspended for three minutes and re-started at reduced pressure (40 psi). No further short-circuiting was observed. The duration of the injection was a total of eleven (11) minutes.

It was determined that the daylighting was likely caused by either non-linear gas flow through the screen or incomplete formation collapse around the screen, or a combination of both. The daylighting blowhole was grouted and the next hydrogen injection was postponed for two weeks to allow additional time for the formation to collapse. It was decided to decrease the injection pressure to less-than 50 psi for all subsequent injections.

8 April 2004

Sixteen cylinders of hydrogen gas were injected using injection pressures between 40 and 43 psi, with flow rates varying between 17 and 35 cfm. The duration of the injection was

27 minutes. After the hydrogen injection, one cylinder of helium gas was injected at a pressure of 40 psi. A slight leak was observed in the hydrogen pigtail and repaired.

15 April 2004

Sixteen cylinders of hydrogen gas were injected using injection pressures between 38 and 43 psi, with flow rates varying between 20 and 30 cfm. The duration of the injection was 24 minutes. After the hydrogen injection, one cylinder of helium gas was injected at a pressure of 38 psi.

21 April 2004

Pressure transducer readings for the four wells in which transducers were installed were analyzed

22 April 2004

Sixteen cylinders of hydrogen gas were injected using injection pressures between 40 and 45 psi, with flow rates varying between 15 and 30 cfm. The duration of the injection was 37 minutes. After the hydrogen injection, one cylinder of helium gas was injected at a pressure of 45 psi. Groundwater samples were collected from eleven (11) monitoring wells.

28 April 2004 – 19 May 2004

Sixteen cylinders of hydrogen gas were injected using injection pressures between 41 and 45 psi, with flow rates varying between 15 and 400 cfm. The duration of the injection was approximately 38 minutes.

25 May 2004

Sixteen cylinders of hydrogen gas were injected using injection pressures between 42 and 45 psi, with flow rates varying between 15 and 30 cfm. The duration of the injection was 23 minutes. After the hydrogen injection, one cylinder of helium gas was injected at a pressure of 45 psi. Groundwater samples were collected from eleven (11) monitoring wells for analysis.

At this point, based on the groundwater analytical results and helium tracer test, the Partnering Team decided to make a modification to achieve more linear gas flow through the well and improve treatment performance. A nozzle and aboveground storage tank were installed at the distal end of the well. Nitrogen gas would be used to purge the groundwater from the well prior to hydrogen injection. The system was not operated again until September 30, 2004.

30 September 2004 – January 13, 2005

Sixteen cylinders of hydrogen gas were injected using injection pressures between 42 and 45 psi, with flow rates varying between 15 and 30 cfm. The duration of the injection was 23 minutes.

13 January 2005

The injections were halted to determine if the partnering team would be interested in doubling the amount of hydrogen for the final set of injections. The team decided not to increase the volume but to perform the remaining injections consistent with the former injections.

14 March 2005

Nitrogen gas was used to purge the well prior to sparging. Sixteen cylinders of hydrogen gas were injected at pressures between 35 and 45 psi with flow rates varying from 30 to 50 cfm. One cylinder of helium was injected with the hydrogen, beginning approximately 3 minutes into the hydrogen injection. The duration of the injection was 21 minutes.

23 March 2005

Nitrogen gas was used to purge the well prior to sparging. Sixteen cylinders of hydrogen gas were injected at approximately 40 psi. The injection was completed after 10 minutes.

6 April 2005

Nitrogen gas was used to purge the well prior to sparging. Sixteen cylinders of hydrogen gas were injected at approximately 40 psi. The injection was completed after 10 minutes.

12 April 2005

Nitrogen gas was used to purge the well prior to sparging. Sixteen cylinders of hydrogen gas were injected at approximately 40 psi. The injection was completed after 10 minutes.

20 April 2005

Nitrogen gas was used to purge the well prior to sparging. Sixteen cylinders of hydrogen gas were injected at approximately 40 psi. The injection was completed after 10 minutes.

30 April 2005

Nitrogen gas was used to purge the well prior to sparging. Sixteen cylinders of hydrogen gas were injected at approximately 40 psi. One cylinder of helium was injected with the hydrogen. The duration of the injection was 10 minutes.

4 May 2005

A planned injection was cancelled due to complications at the distal end of the well (discharge valve wouldn't close).

11 May 2005

The discharge valve was repaired. Nitrogen gas was used to purge the well prior to sparging. Sixteen cylinders of hydrogen gas were injected at pressures between 35 and 45 psi with flow rates varying from 25 to 50 cfm. One cylinder of helium was injected with the hydrogen, beginning approximately 1 minute into the hydrogen injection. The duration of the injection was 15 minutes.

18 May 2005

Nitrogen gas was used to purge the well prior to sparging. Sixteen cylinders of hydrogen gas were injected at approximately 40 psi. One cylinder of helium was injected with the hydrogen. A round of groundwater and vapor (tracer) samples were collected the week of 18 May 2005.

25 May 2005

Nitrogen gas was used to purge the well prior to sparging. Sixteen cylinders of hydrogen gas were injected at approximately 40 psi.

10 June 2005

Nitrogen gas was used to purge the well prior to sparging. Sixteen cylinders of hydrogen gas were injected at pressures between 36 and 41 psi with flow rates varying from 30 to 45 cfm. One cylinder of helium was injected with the hydrogen, beginning approximately 1 minute into the hydrogen injection. The duration of the injection was 17 minutes. This concluded the Pilot Study injections.

4. Performance Monitoring

4.1. Groundwater Sampling Methods and Frequency

During the Pilot Study, groundwater was collected in order to evaluate the effectiveness of the treatment. Groundwater was collected from eleven wells on the following five dates -

- 24 October 2003
- 29 January 2004
- 22 April 2004
- 25 May 2004
- 18 October 2004
- 18 May 2005

All groundwater was analyzed for Target Compound List (TCL) volatile organic compounds using SW 846 Method 8260B; dissolved gases (ethane, ethene, and methane); nitrate, sulfate, chloride, and hydrogen. Additionally, water quality parameters were collected (dissolved oxygen, conductivity, pH, temperature, turbidity, and oxidation-reduction potential) and on-site analysis of ferrous iron and alkalinity were performed.

The Pilot Study Work Plan originally called for groundwater sampling after treatment initiation using the following schedule:

- two weeks after treatment initiation
- two months after treatment initiation
- six months after treatment initiation
- 12 months after treatment initiation, or three months after treatment completion

The groundwater monitoring schedule deviated from the WP in order to coordinate the Pilot Study sampling with the on-going, long-term monitoring, and as a result of the system modifications and mid-study evaluation.

4.2. Soil Sampling Methods

Soil was collected from three boreholes during monitoring well installation (new wells 73-MW63DW, 73-MW64IW, and 73-MW27DW). Soil from all three well bores was analyzed for Total Oxidant Demand (TOD) and the grain size distributions were calculated for the two deep well bores.

4.3. Groundwater Analytical Results

Groundwater results were reviewed both during the Pilot Study and at its conclusion in order to evaluate the effectiveness of the treatment. Results collected during the study provided information used to make mid-study adjustments to the system so as to improve overall performance. The results were also evaluated at the conclusion of the Pilot Study to determine if the project goal of an order-of-magnitude reduction in TCE concentrations was achieved.

The goal of this Pilot Study was to obtain an order-of-magnitude reduction in TCE concentrations in the groundwater at Site 73. TCE and the TCE-degradates cis-1,2 DCE (cis-DCE), trans-1,2 DCE (trans-DCE) and vinyl chloride (VC) were measured before, during, and after the Pilot Study in order to evaluate the treatment process and determine its ultimate effectiveness.

Eleven monitoring wells were sampled on five occasions. Baseline samples were collected in October 2003 and January 2004. Groundwater was analyzed during the study, in April 2004, May 2004, and October 2004 and also at the conclusion of the study in May 2005. Sample results for TCE, cis-DCE, trans-DCE, and VC are listed in Table 9.

Prior to the Pilot Study, the highest concentrations of TCE were detected in deep monitoring wells 73-MW27DW, 73-MW49DW, and 73-MW63DW, at concentrations of 850 µg/L, 1700 µg/L, and 820 µg/L, respectively; and intermediate well 73-MW49IW, at a concentration of 1400 µg/L. Wells 73-MW13DW and 73-MW44DW had baseline concentrations of 340 µg/L and 490 µg/L. Wells 73-MW39DW, 73-MW46DW, and 73-MW48DW had concentrations of 55 µg/L, 20 µg/L, and 22 µg/L, respectively. TCE was not detected in groundwater collected from intermediate wells 73-MW13 and 73-MW14.

Two wells experienced a 50% reduction in TCE concentrations, 73-MW49DW (from 1700µg/L to 850µg/L) and 73-MW49IW (from 1400µg/L to 760µg/L). These wells are the deep and intermediate well pair having the highest initial concentrations of TCE.

Four wells experienced a reduction in TCE concentrations - 73-MW13DW, 73-MW27DW, 73-MW39DW, and 73-MW46DW. 73-MW63DW.

Three wells experienced an increase in TCE concentrations - 73-MW44DW, 73-MW48DW, and 73-MW63DW.

However, it is highly likely that monitoring well 73-MW48DW did not experience any effects as a result of the Pilot Study hydrogen injections. The horizontal well zone of influence was projected to be 100-feet, 50-feet on either side of the well. Well 73-MW48DW is located approximately 260-feet downgradient of the horizontal well, making it 210-feet downgradient of the outside edge of the zone of influence.

Any increase in contaminant concentration at well 73-MW48DW was likely caused by the natural groundwater flow between wells 73-MW63DW and 73-MW48DW. This may have resulted in the movement of more contaminated groundwater, already present at the initiation of the Pilot Study in the vicinity of 73-MW63DW, to area surrounding well 73-MW48DW.

Well 73-MW48DW is directly downgradient of the contamination in the Castle Hayne aquifer. There are no wells in the Castle Hayne aquifer between wells 73-MW63DW and 73-MW48DW to verify the concentrations in this area, either in the past or present. However, typical groundwater flow would indicate that the plume is traveling toward 73-MW48DW. Therefore, any increase in concentrations at this well are likely the result of contaminated groundwater from outside the horizontal well zone of influence traveling downgradient toward well 73-MW48DW.

TCE was not detected in groundwater collected from wells 73-MW13 and 73-MW14 during any of the sampling events.

Graphs depicting the time trends of TCE, cis-DCE, trans-DCE, and vinyl chloride may be found in Appendix A.

Figure 3 - TCE Concentrations, January 2004

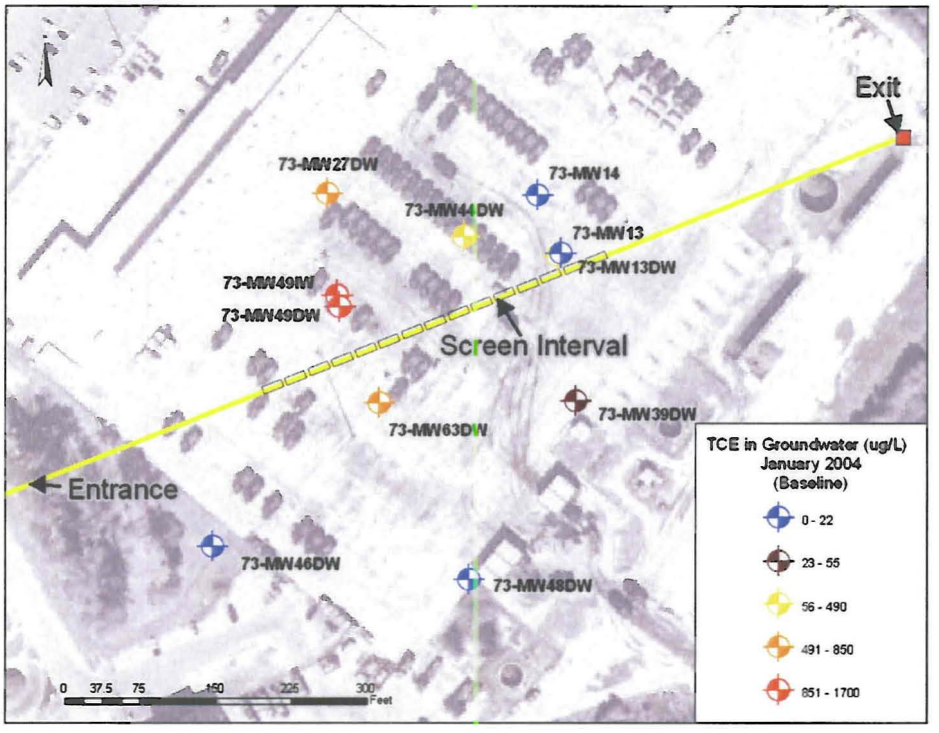
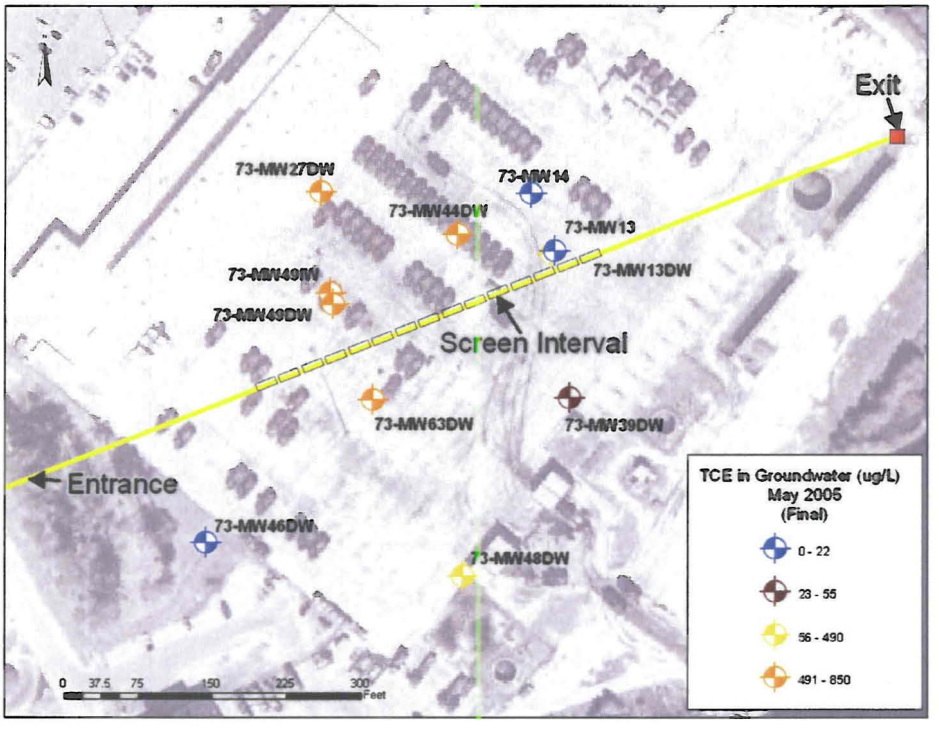


Figure 4 - TCE Concentrations, May 2005



4.4. Tracer Results

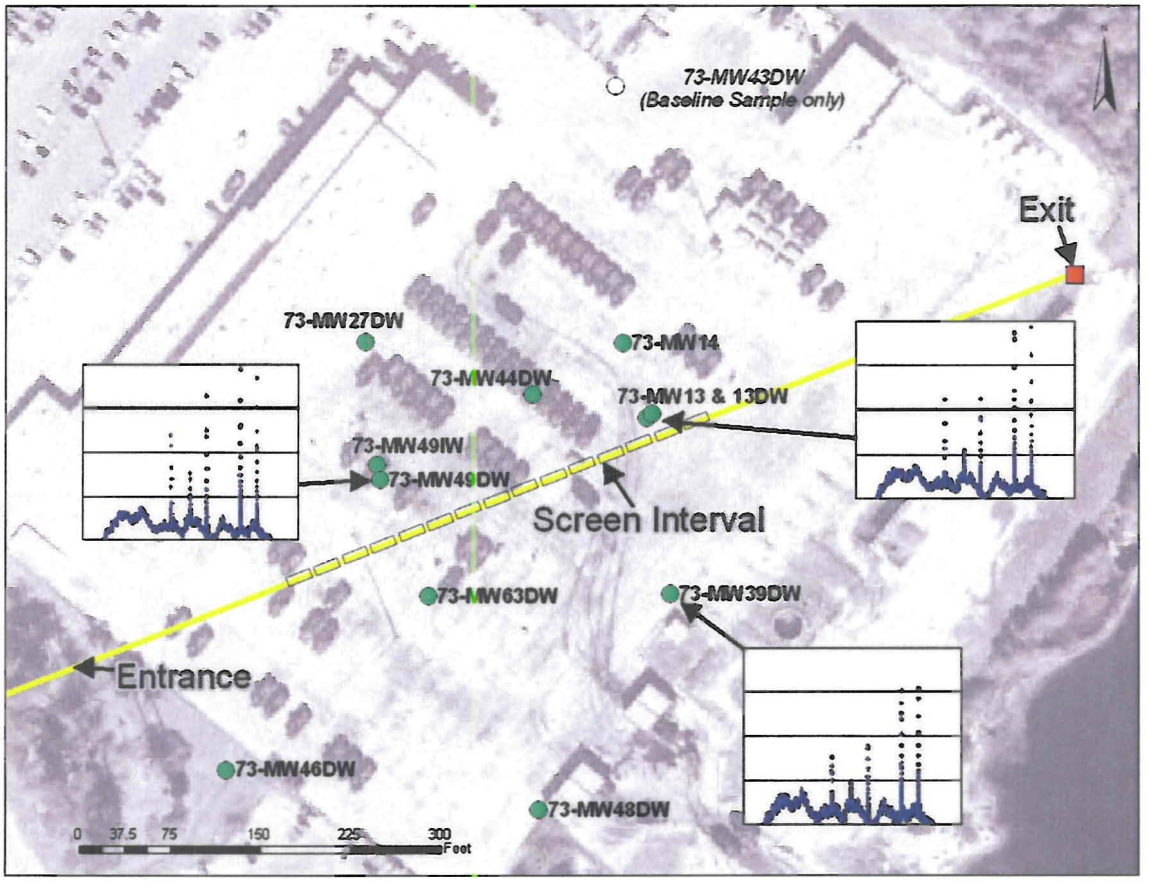
Helium gas was injected during several sparging events and hydrogen analysis was conducted on groundwater in order to evaluate the gas distribution through the treatment zone. Additionally, pressure transducers were placed three wells to evaluate system performance.

When pressure transducers were evaluated in April 2004, the pressure results were positive (Figure 5). However, no helium was detected in any of the eleven wells.

In October 2004, helium was detected in MW-63 only.

In May 2005, when helium analysis was conducted, no helium was detected in any of the eleven wells. (Table 10 - Hydrogen Helium Tracer Data)

Figure 5 - Pressure Transducer Results, April 2004



5. Discussion and Conclusions

This Pilot Study offered an opportunity to evaluate the effectiveness of injecting hydrogen into an aquifer using a horizontal well. The goal was to achieve order-of-magnitude reductions in TCE concentrations by providing excess hydrogen to the groundwater in order to stimulate the naturally occurring reductive dechlorination. However, groundwater results at the other monitoring wells evaluated during the study were variable, with increasing, decreasing and static concentrations. The average TCE concentration decreased approximately 35% over the 15-month study period. The average total volatile concentration decreased approximately 8% during the same period.

Initial calculations regarding the volume of hydrogen needed for treatment of the TCE "hot spot" failed to account for the soil demand. This resulted in a hydrogen volume design calculation that was only 39% of the actual requirement. Hydrogen was never detected in any of the wells above the background concentration, which may be due to the underestimation of the hydrogen demand of the soil. Helium was detected in MW-63 during only one of the sampling events.

Pressure transducers indicated an increase in pressure in the monitoring wells adjacent to the horizontal well screen during hydrogen injections. However, the tracer gas was not detected in any of the monitoring wells, with the exception of MW-63, during the study - even after the procedure was changed and groundwater was purged from the horizontal well prior to the hydrogen injections. Pressure transducer response probably recorded a temporary fluid displacement phenomenon and did not provide an indication of the actual post-injection gas distribution.

There were a number of important lessons learned from this project. In particular, the importance of injection well fluid dynamics and sufficient delivery of biostimulants (amendments). In the early stage of the injection events, the horizontal well bore was not fully evacuated. As a result, there was preferential flow of the injected gases over the well screen closest to the injection end of the well. In August 2004, it was agreed to modify the injection approach and use nitrogen to evacuate the well prior to the hydrogen injections. This enabled more even distribution of the hydrogen gas during short-term injection events.

The biology and geochemistry of hydrogen injection for in-situ biological reduction of chlorinated solvents appears sound. However, there are several issues associated with effective implementation the technology. There are distribution issues; inefficiencies in the use of the hydrogen; and natural variations in the site geochemistry, microbiology, and hydrogeology. It is important that the design carefully consider all of these natural variations and technical issues. Completion of a smaller-scale pilot test using a vertical well may have allowed for more effective design of a full-scale horizontal well hydrogen injection system.

6. Costs

Table 6 provides a comparison of the costs projected in the technical evaluation report verses the actual costs recorded during the pilot study.

Table 6 – Cost Comparison

Description	Projected	Actual
Horizontal Well Installation	$126,000	$205,000
Protective Enclosure	$18,000	$0.00
Hydrogen Skid plus Installation	$123,000	$29,000
O&M including Gas	$44,080	$75,000
Project Management	$20,000	$34,000
Sampling	$36,640	$38,000
Analysis/Validation	Not Provided	$32,921
Reporting	$40,000	$35,000
Total	$639,510	$683,847

Factors that account for the difference in the actual and projected costs include increased gas costs, not accounting for analytical costs and data validation costs, not accounting for the modification to vent the distal end of the well, underestimation of O&M costs and requirements, pressure transducers and other costs not included in the original cost estimate.

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