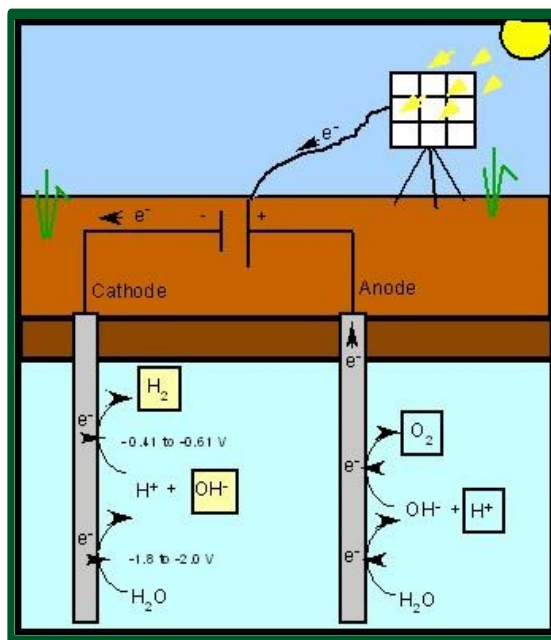# ESTCP
Cost and Performance Report

(ER-201033)

Solar-Powered Remediation and pH Control

April 2017

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ESTCP

ENVIRONMENTAL SECURITY
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COST & PERFORMANCE REPORT
Project: ER-201033

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ACRONYMS AND ABBREVIATIONS

µg	microgram(s)
2D	two-dimensional
AFB	Air Force Base
AW	anode well
bgs	below ground surface
BMW	background monitoring well
cis-DCE	*cis*-1,2-Dichloroethene
CSM	conceptual site model
cVOC	chlorinated volatile organic compound
CW	cathode/injection well
DC	direct current
DHC	*Dehalococcoides* sp.
DMW	demonstration monitoring well
DNAPL	Dense Non-Aqueous Phase Liquid
DO	dissolved oxygen
DoD	U.S. Department of Defense
ESTCP	Environmental Security Technology Certification Program
EW	extraction well
Fe	iron
ft	foot/feet
GAC	granular activated carbon
gpm	gallon(s) per minute
H^+	hydrogen ion
H_2	molecular hydrogen
HMX	Her Majesty's Explosive; Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine
hr	hour(s)
IW	injection well
JB MDL	Joint Base McGuire-Dix-Lakehurst
L	liter(s)
LTM	long-term monitoring
m	meter(s)
mA	milliamp(s)

mg	milligram(s)
min	minute
MLS	multi-level sampler
mL	milliliter(s)
mmoles	millimoles
Mn	manganese
mV	millivolt(s)
NESDI	Navy Environmental Sustainability Development to Integration
NJDEP	New Jersey Department of Environmental Protection
nM	nanomolar
NPV	Net Present Value
O_2	oxygen
O&M	Operation and Maintenance
OH^-	hydroxide ion
ORP	oxidation-reduction potential
P&T	pump and treat
PCE	perchloroethylene
pH	potential of hydrogen
PMW	performance monitoring well
PRB	permeable reactive barrier
PRT	Proton Reduction Technology
PVC	polyvinyl chloride
qPCR	quantitative polymerase chain reaction
RDX	Royal Demolition Explosive; 1,3,5-Trinitroperhydro-1,3,5-triazine
SERDP	Strategic Environmental Research and Development Program
SU	standard unit(s)
TCE	trichloroethylene
TNT	trinitrotoluene
USEPA	U.S. Environmental Protection Agency
V	volt(s)
VC	vinyl chloride
VOC	volatile organic compound
yr	year
ZVI	zero-valent iron

ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

BACKGROUND

Chlorinated volatile organic compounds (cVOCs), such as trichloroethylene (TCE) and perchloroethylene (PCE), represent one of the largest remediation challenges and costs at U.S. Department of Defense (DoD) sites. Anaerobic bioremediation via organic carbon source addition (with or without bioaugmentation with dechlorinating bacteria) is a commonly used approach to remediate cVOCs *in situ*. One significant issue with this approach is that reductive dechlorination processes are typically inhibited at pH values <~5.5. Aquifers with lower pH values are common, especially in the eastern United States. Raising the groundwater pH is often not feasible because of the large amount of buffer needed, the large size of many plumes, and the need for long-term treatment and repeated reinjections.

OBJECTIVES

The primary goal of this project was to demonstrate a solar-powered technology to generate hydrogen (H_2) *in situ* and reduce aquifer acidity to promote reductive dechlorination. During operation, Proton Reduction Technology (PRT) uses a low voltage potential applied across electrodes installed within an aquifer to impress a direct current (DC) in the subsurface. PRT was tested in a low pH cVOC-contaminated aquifer at Joint Base McGuire-Dix-Lakehurst, NJ (JB MDL). A successful demonstration was expected to result in sustainable aquifer pH control and contaminant degradation at significantly lower cost than conventional approaches that require the addition of buffers and organic electron donors. Successful application of this technology would allow the DoD to economically treat contaminated low pH aquifers and remote contaminant plumes where electrical power is not readily available or where long treatment times are expected.

TECHNOLOGY DESCRIPTION

Biological reductive dechlorination of cVOCs relies on bacteria that use H_2 as an electron donor and the cVOC as an electron acceptor. The H_2 may be supplied directly or by fermenting organic carbon electron donors. PRT generates H_2 by electrolysis, with concurrent reduction of protons (hydrogen ions [H^+]) on the surface of cathodes powered by an impressed current. In addition to producing H_2, PRT consumes protons, thereby raising the pH of groundwater around and downgradient of the cathode. Thus, during this project, PRT technology was evaluated for its ability to foster dechlorination through *in situ* H_2 generation while also raising the groundwater pH to favorable levels. In addition, PRT can also support biological remediation of several other common DoD contaminants, including RDX, hexavalent chromium (Cr[VI]), and perchlorate.

This field demonstration project used electrodes inserted into polyvinyl chloride (PVC) wells within the cVOC-contaminated low pH aquifer. The electrodes (three cathodes and two anodes) were operated to generate H_2 to support biodegradation, and consume H^+ to increase aquifer pH. The PRT system was operated for 507 days from start-up to shut-down. The demonstration was divided into four phases of operation, which included PRT-only operation, and PRT operation with varying groundwater recirculation configurations. The contaminated aquifer was inoculated with a bioaugmentation culture (SDC-9™) to ensure that the appropriate dechlorinating bacteria were present to support biodegradation. Electricity to operate the system was provided by solar panels and deep cycle 12 volt (V) batteries. During the demonstration, groundwater pH, contaminant

concentrations, H_2 production, distribution, and utilization, and electrode performance were monitored.

DEMONSTRATION RESULTS

PRT resulted in partial reductive dechlorination of cVOCs in the low pH aquifer at JB MDL, but TCE dechlorination was not complete, at least not under the conditions of the demonstration. The lack of complete dechlorination, even after bioaugmentation, was likely due to the borderline pH and reducing conditions achieved in the aquifer. It is possible that dechlorination activity could have been improved if a higher pH (e.g., pH 6.5–7) or more reducing conditions (e.g., oxidation-reduction potential [ORP] < -100 millivolts [mV]) were consistently achieved.

Although PRT showed some potential for increasing pH and lowering ORP, the configuration of the system during this demonstration was not sufficient to achieve and maintain optimal geochemical conditions for extended periods. Because a circumneutral pH and highly-reduced environment could not be sustained, efficient dechlorination of TCE could not be achieved.

IMPLEMENTATION ISSUES

PRT was only partially successful in this test, but the results suggest it may be a useful component of an overall treatment system for remediating an acidic aquifer. However, additional treatments/amendments may be needed to better address and overcome the significant soil buffering capacity of many aquifers. For example, a large dose of buffer and a carbon substrate could be applied to a biobarrier at the start of treatment to overcome the initial acidity of the aquifer sediments and to produce a low ORP before applying current, and PRT could then be used as a long-term source of electron donor (H_2) and hydroxide ion (OH^-) to maintain aquifer pH.

Although this study showed that PRT can have significant limitations, it also has provided valuable guidance for the ongoing development of the technology. One recently-demonstrated strategy to overcome the limitations observed in this project is to use more closely-spaced electrodes, and to install the electrodes with metallurgical soil contact material (coke breeze) as backfill. This approach was tested successfully in the field under the U.S. Navy Environmental Sustainability Development to Integration (NESDI) program, during NESDI Project 501. This demonstration was conducted within a low pH cVOC-contaminated aquifer at Marine Corps Base Quantico, in Quantico, VA. During this one-year field demonstration, eight closely-spaced cathodes and two downgradient anodes were installed in a barrier configuration, and concentrations of cis-1,2-dichloroethene (*cis*-DCE) (the primary contaminant of concern) were reduced by 88–99% across the barrier.

1.0 INTRODUCTION

1.1 BACKGROUND

Chlorinated volatile organic compounds (cVOCs), such as trichloroethylene (TCE) and perchloroethylene (PCE) represent one of the largest remediation challenges and costs at U.S. Department of Defense (DoD) sites. Anaerobic bioremediation via carbon source addition (with or without bioaugmentation with dechlorinating bacteria) is a commonly used approach to remediate cVOCs *in situ*. One significant issue with this approach is that reductive dechlorination processes are typically inhibited at pH values $<\sim5.5$ (Vainberg et al., 2009).

Aquifer buffering has been attempted in some instances (Hatzinger et. al., 2006; Schaefer et al., 2010), but the amount of buffer required makes this process cost-prohibitive for other than very small sites.

Biological reductive dechlorination of cVOCs relies on the activity of dechlorinating bacteria, including members of the genus *Dehalococcoides* sp. (DHC), that use hydrogen (H_2) as an electron donor (He et al., 2002) and the cVOC as an electron acceptor. H_2 can also support the production of acetate by homoacetogenic bacteria, which DHC can use as a carbon source. During typical *in situ* remediation treatments, a carbon source such as vegetable oil, fatty acids, and carbohydrates, are added to the subsurface, and are subsequently fermented by other members of the microbial community to produce the H_2 and acetate necessary for growth and activity of the dechlorinating bacteria.

As shown in **Figure 1.1**, Proton Reduction Technology (PRT) (Zhang et al., 2001) relies on the generation of H_2 by electrolysis, and reduction of protons (hydrogen ions [H^+]) on the surface of electrodes inserted into the contaminated aquifer and powered by an applied current. In addition to the production of H_2, PRT—by consuming protons and producing hydroxide ions (OH^-) on the cathode—also has the potential to increase the pH of groundwater around and downgradient of the cathode. Thus, during this project, PRT technology was evaluated for its ability to adjust the pH of an acidic aquifer and to provide electron donor (i.e., H_2) to support the *in situ* remediation of an acidic TCE-contaminated aquifer.

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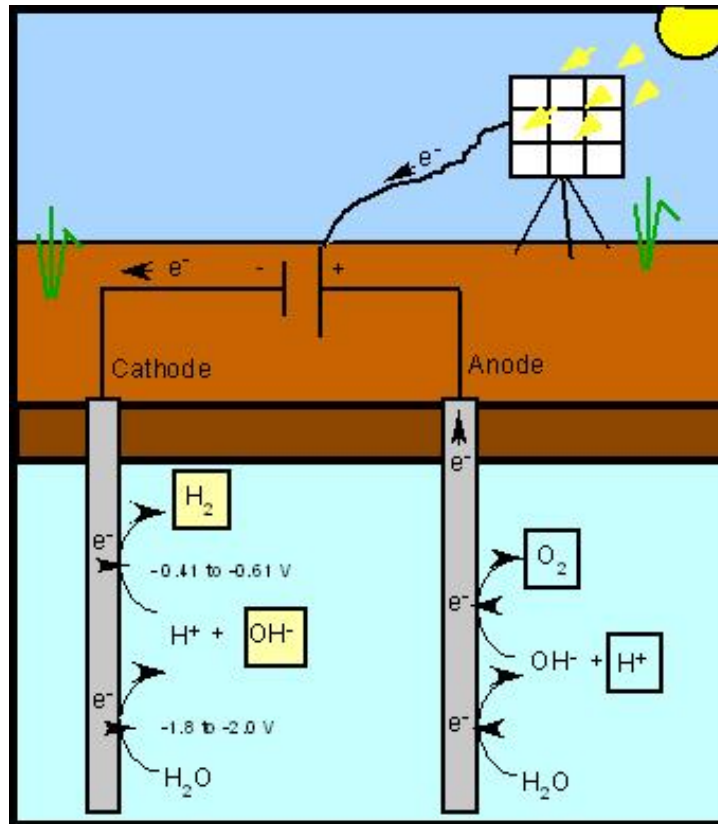
Figure 1.1. Schematic Representation of the PRT

1.2   OBJECTIVE OF THE DEMONSTRATION

The objective of this project was to demonstrate PRT as a sustainable approach for treating low-pH aquifers contaminated with cVOCs. Successful application of this technology would allow the DoD and the U.S. Department of Energy to economically treat contaminated low pH aquifers and remote contaminant plumes where an electrical source is not readily available or where long treatment times are expected.

1.3   REGULATORY DRIVERS

The Joint Base McGuire-Dix-Lakehurst (JB MDL) environmental restoration project, which includes the groundwater beneath the selected demonstration area, is operated under the requirements of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). JB MDL is under the jurisdiction of the U.S. Air Force, and the U.S. Environmental Protection Agency (USEPA) is the lead regulatory agency for JB MDL restoration activities. In the State of New Jersey, groundwater cleanup standards protective of groundwater classifications are based on the primary receptors within that class as established pursuant to the New Jersey Ground Water Quality Standards (GWQS) (New Jersey Administrative Code [N.J.A.C.] 7:9-6). As such, the New Jersey Department of Environmental Protection (NJDEP) has established natural groundwater quality as the cleanup standard for all contaminants in Class IA and I-Pinelands (Preservation Area) groundwater, which includes the groundwater at JB MDL. The numerical criterion for any organic contaminant discovered at a contaminated site that is not the result of natural

processes is zero. Since zero can only be measured with a certain degree of certainty, the Practical Quantitation Levels (PQLs) for groundwater have been selected for use in determining whether organic contaminant concentrations observed in groundwater meet the groundwater standard/criteria. The main contaminants of concern in the JB MDL groundwater plume are TCE and *cis*-1,2-dichloroethene (*cis*-DCE). Based upon the New Jersey criteria, the groundwater standard for TCE is 1 microgram per liter (µg/L) and the standard for *cis*-DCE is 2 µg/L. Based on USEPA National Primary Drinking Water Regulations (USEPA, 2009), the Maximum Contaminant Level in groundwater for TCE and *cis*-DCE are 5 µg/L and 70 µg/L, respectively.

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2.0   TECHNOLOGY

2.1   TECHNOLOGY DESCRIPTION

Most successful bioremediation applications have been performed in aquifers with circumneutral pH, or, less frequently, where pH has been adjusted by adding a buffering agent. Bioremediation in low pH aquifers, however, is usually ineffective, presumably because dehalogenating organisms do not dechlorinate well with a <5.5 pH (McCarty et al., 2007; Sung et al., 2003; Vainberg et al., 2009; Zhuang and Pavlostathis; 1995). In many cases, low pH is a function of the natural site geochemistry, but low pH conditions also can occur as a result of substrate fermentation and reductive dechlorination of target cVOCs (Adamson et al., 2004; Amos et al., 2008; Chu et al., 2004; Lee et al. 1998). In fact, many low pH aquifers appear to exhibit classic *cis*-DCE or vinyl chloride (VC) stalls, leading to the accumulation of these daughter products that are more toxic than the parent PCE or TCE.

Proton reduction refers to the production of elemental hydrogen (H_2) by direct electrical reduction of dissolved H^+ in a soil/water solution (**Figure 1.1**) in the absence of oxygen (O_2). This process has been exploited recently for efficient H_2 production in microbial fuel cells, without electrolysis of water (Call and Logan, 2008; Cheng and Logan, 2007). Proton reduction occurs at a potential of ~-0.5 volts (V), which can be supplied easily with solar powered batteries. In addition, the polarity of the proton reduction system can be periodically alternated (i.e., the anode becomes a cathode) to increase the size of the treatment area, to control the production of H_2 to minimize methane production, and to control changes in pH that can occur if necessary. The technology was recently demonstrated in laboratory studies for supporting the biodegradation of cVOCs (Lohner and Tiehm, 2009; Lohner et al., 2011).

2.1.1   Role of H_2

Molecular hydrogen (H_2) is an important energy source and electron donor in anaerobic metabolism, including dehalorespiration (Holliger et al., 1999; Maymó-Gatell et al., 1995). Remediation strategies have been developed that attempt to stimulate dehalogenation *in situ* by applying carbon sources that can be fermented to H_2. Direct *in situ* H_2 generation by electrical reduction of free protons (H^+) is a novel alternative to carbon source addition. Yang and McCarty (1998) and Ballapragada and colleagues (1997) have demonstrated that cVOC-degrading bacteria have a high affinity for H_2, and that even H_2 concentrations as low as 2 nanomolar (nM) (4 nanograms per liter [ng/L]) can support reductive dechlorination. The direct addition of H_2 has been used to support reductive dechlorination *in situ* (Fisher et al. 1997, Ma et al., 2003) and in bioreactors (Carr and Hughes, 1998; Chung et al., 2008). H_2 can support the biological reduction of other important contaminants including explosives (RDX, HMX, TNT; Adrian et al., 2003), perchlorate (Nerenberg et al., 2006; Hatzinger, 2005; Hatzinger et al., 2006), and Cr(VI) (Wang and Shen, 1995), so the technology is expected to be widely applicable.

2.1.2   Electrochemical Reactions in Soil

Rahner et al. (2002) demonstrated that applying a low direct current (DC) to soils resulted in the production of "microcapacitors" that acted as diluted electric chemical solid bed reactors.

The theory states that electrochemical reactions can be induced in wet soils if the soil matrix contains particles or films with electronic conducting properties (Rahner et al., 2002). In effect, soil particles can act as capacitors that store enough energy, even if charged with a low energy current, to perform high energy chemical reactions. These microcapacitors could reduce mobile oxidized chemicals in water. Reactive materials in soils that could potentially support this activity included graphite and some iron (Fe) minerals. Follow-on studies by the same group (Röhrs et al., 2002) showed that electrical current could be used to reduce chlorinated hydrocarbons in soils from an industrial site, and concluded that these "microconductors" in the soil probably play a role in the reactions. In a more recent study, electrical current was used to reduce cVOCs in clay soils at low electrical potential (Jin and Fallgren, 2010). These researchers described the process as involving the formation of "microcapacitors" (**Figure 2.1**), whereby hydrated clay particles become redox reactive particles and form a reactive matrix on which these redox reactions (e.g., electrolysis) can occur. The researchers postulated that an induced electrical field in soils is created with the soil particles acting as capacitors that discharge and recharge electricity that can perform electrolysis of water, thereby generating H_2. In addition, they reported up to 90% reduction in TCE concentrations in the clays over 7 days under an applied current of only 6 V per meter (m), and suggested that the decrease was due to electrically induced reduction, and not due to electrokinetic ion migration or electrophoresis.
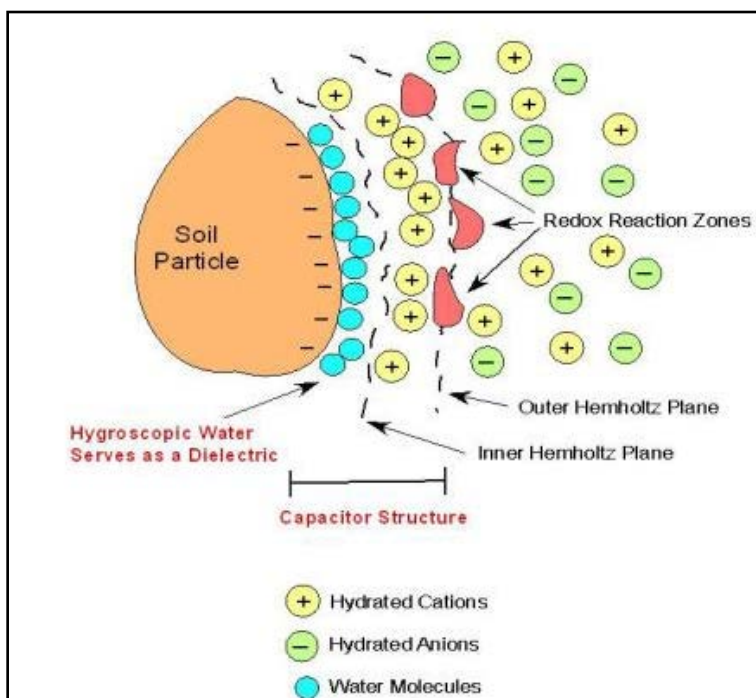
Figure 2.1. Proposed Microcapacitor Structure Generated in Clay Soils Exposed to an Electrical Field

2.1.3   Hydrolysis-driven pH adjustment

In addition to H_2 production, electrical current can be used to increase aquifer pH. At an electrical potential of ~ -2 V, water molecules are split into H^+ (proton) and OH^-. This process is commonly called electrolysis or hydrolysis. The produced protons are then reduced to H_2, thereby increasing

aquifer pH. In theory, any amount of H^+ can be consumed using this process, allowing neutralization of even very low alkalinity groundwater, like that present at JB MDL. Natural groundwater flow can be used to distribute the OH^- via diffusion and convection, and provide a mechanism for increasing pH downgradient of the cathode(s), thus effectively neutralizing a portion of the aquifer (i.e., treatment zone).

2.2   TECHNOLOGY DEVELOPMENT

CB&I has used proton reduction for H_2-driven bioremediation of cVOCs at multiple sites, but the overall success of the approach was difficult to determine because either other technologies were also applied (e.g., carbon source addition plus PRT) or because only limited sampling was performed. At one site, three electrodes were successfully operated by using two 12 V automotive batteries with an inexpensive solar charger. At another site in the Southwest, a 750-foot (ft) permeable reactive barrier (PRB) was created by using electrodes to prevent off-site migration of mixed cVOCs including chloroform. The system operated successfully for >1 year (yr) with the original electrodes. A third application performed by CB&I utilized a circular array of electrodes to remediate a dry cleaner site. The polarity of the electrodes was periodically reversed to generate H_2 throughout the treatment zone. During operation of these other systems, high pH values (up to pH 12) were periodically measured in cathode wells during system operation optimization, leading to the hypothesis that this process could also be used to neutralize acidic groundwater. In addition, Gent et al. (2009) demonstrated that electrical current could be used to increase the pH of groundwater to a level sufficient to hydrolyze RDX. Those experiments, however, were performed at much higher voltages (up to 600 V) than those used during this PRT demonstration.

2.3   ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Treatment of low pH sites with buffers to increase groundwater pH is often not practical because of the large amount of buffer needed and the large size of many of the affected plumes. In other cases, contaminants accumulate in low permeability matrices or as free product (e.g., Dense Non-Aqueous Phase Liquid [DNAPL]) and become long-term sources of contamination that require prolonged and costly treatment. For these sites, an inexpensive and long-term source of electron donor and pH buffering to support *in situ* bioremediation is desirable. A potential advantage of PRT is that it would be suitable for use in most cVOC-contaminated aquifers, for treating low pH aquifers, and potentially for treating any contaminant that can be remediated by H_2-driven bioremediation (e.g., cVOCs, energetic compounds, and perchlorate). PRT also has the potential to be suitable for prolonged treatment at sites where a persistent source of contaminant will lead to long-term remediation challenges (e.g., DNAPL sources or consolidated sediments), and for treating remote sites where accessing or maintaining electrical feeds is cost prohibitive.

Potential limitations of this process include (1) production of H^+ and O_2 at the system anode(s), (2) poor H_2 distribution in the aquifer, and (3) scale formation on or corrosion of inserted electrodes. O_2 inhibits dechlorinating organisms, and the produced H^+ at the anode surface can reduce aquifer pH. Poor distribution of H_2 within the designed treatment zone could also limit the remedial performance of the electrolysis system. As discussed in Section 2.1.2, generation of H_2 between inserted electrodes via the electrolysis of water on clay surfaces could have significant impacts on the required spacing between cathodes, and the effectiveness of H_2 distribution. H_2 generation solely at the inserted cathode surface would limit its distribution in the subsurface

primarily to advection and dispersion mechanisms. Finally, scale formation or corrosion of electrodes could reduce the amount of current generated at a given voltage, thereby reducing H_2 and hydroxide generation at the cathodes and the overall efficiency of the proton reduction system. The electrode materials selection, PRT system operation, and in-field configuration were performed in anticipation of these limitations to the extent possible.

3.0   PERFORMANCE OBJECTIVES

The performance objectives for this project are listed in **Table 3.1**. The main objective of the demonstration was to effect sustainable aquifer neutralization and cVOC degradation at treatment costs significantly lower than common treatment approaches, which require addition of buffers and exogenous electron donor compounds. A summary of the data analysis to support the assessment of the performance objectives is provided in **Section 6.0**.

Table 3.1. Performance Objectives Evaluated

TYPE OF OBJECTIVE	PRIMARY PERFORMANCE METRICS	EXPECTED PERFORMANCE METRICS	ACTUAL PERFORMANCE	WAS PERFORMANCE METRIC ACHIEVED?
Quantitative	Effectiveness	Increase and maintain pH to between 6 and 8 SUs within the designed treatment zone	pH was not successfully increased down-gradient of the cathodes, but after the creation of a second recirculation loop, some pH increases were observed approximately 5 ft. from the system cathode.	Partially
Quantitative	Effectiveness	Measured H_2 concentrations >160 µg/L (10% solubility) at cathode wells	H_2 consistently measured >160 µg/L during Phase 1 and 2 of the demo.	Yes
Quantitative	Effectiveness	Measurable H_2 one meter down gradient of cathode.	Sporadic detections of hydrogen at monitoring wells.	Partial
Quantitative	Effectiveness	95% reduction of TCE and *cis*-DCE (2 µg/) in test plot	TCE and *cis*-DCE degradation was achieved, but we did not achieve 95% reduction, nor consistent treatment	No
Quantitative	Effectiveness	Complete and prolonged biodegradation of TCE and *cis*-DCE to ethene	Although some ethene was measured, we could not confirm sustainable VC degradation	No
Quantitative	Effectiveness	Distribution and growth of added DHC to >10^7 DHC/L	No evidence of growth or distribution of DHC was demonstrated.	No
Quantitative	Effectiveness	Electrode stability (performance and physical) for >1 yr of field operation.	Electrodes performed for 2 years without measurable loss of performance	Yes
Qualitative	Implementable	Design and implementation of a field demo. system	System allowed flexible operation and sufficient monitoring	Yes
Qualitative	Implementable	Sustained solar-power output sufficient to promote pH increase and H_2 production.	Sustained solar output for 2 years	Yes
Qualitative	Safety	No safety hazard/incidents	No safety incidents or hazardous conditions occurred.	Yes

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4.0   SITE DESCRIPTION

4.1   SITE LOCATION AND HISTORY

After reviewing and analyzing data from several potential sites, Area SS-36 at JB MDL, NJ
(**Figure 4.1**) was selected as the demonstration site for this project. The following characteristics
made the selected area a suitable location for the demonstration:

- TCE or *cis*-DCE in the range of 0.1–10 milligrams per liter (mg/L),
- No or incomplete (i.e., *cis*-DCE stall) dehalogenation of TCE occurring,
- <100 DHC/mL based on quantitative polymerase chain reaction (qPCR),
- Low natural groundwater pH (i.e., pH<6),
- A shallow aquifer (<30 ft below ground surface [bgs]),
- Relatively permeable soils,
- Available site characterization data,
- Sufficient space for demonstration plots,
- Potential for full-scale implementation upon successful demonstration,
- Receptive interested parties and regulators,
- Located close to CB&I Lawrenceville, NJ, laboratory, and
- Ongoing remedial activities being performed by CB&I at the site.
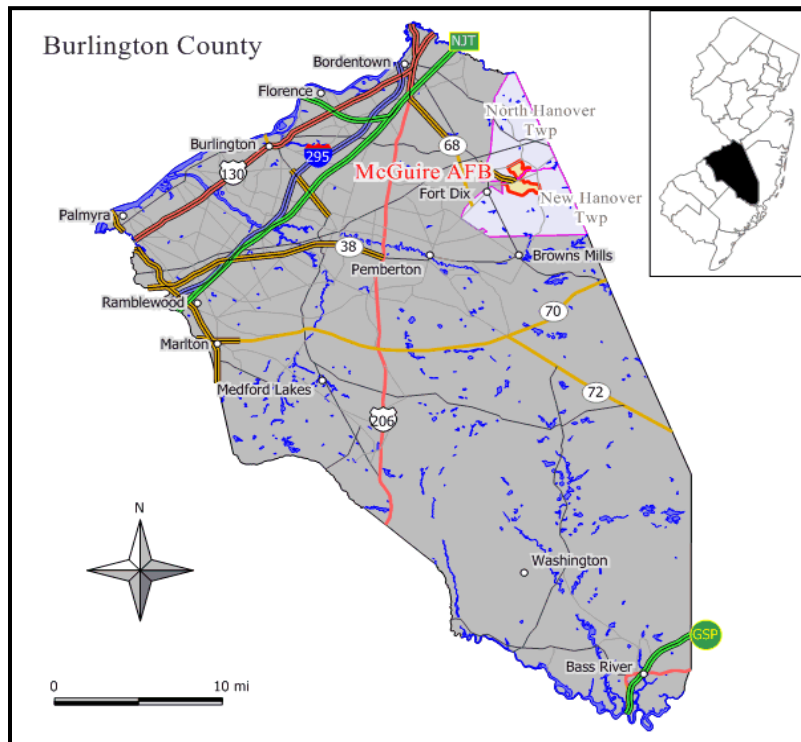
Figure 4.1. Location of JB MDL in New Jersey

Area SS-36 is located in a developed portion of JB MDL, and includes buildings, parking lots, and
paved roads. A large, open, grassy area that appeared suitable for this demonstration lies
downgradient of Building 2305 (**Figure 4.2**). Historical site investigations identified soil
contamination (polycyclic aromatic hydrocarbons [PAHs] and pesticides) and groundwater

contamination (volatile organic compounds [VOCs], semi-volatile organic compounds [SVOCs], and metals). Area SS-36 includes a partial grouping of industrial facilities that encompasses many of the buildings shown in **Figure 4.2**. Some of the industrial activities performed in this area involve aircraft maintenance and ground equipment support.
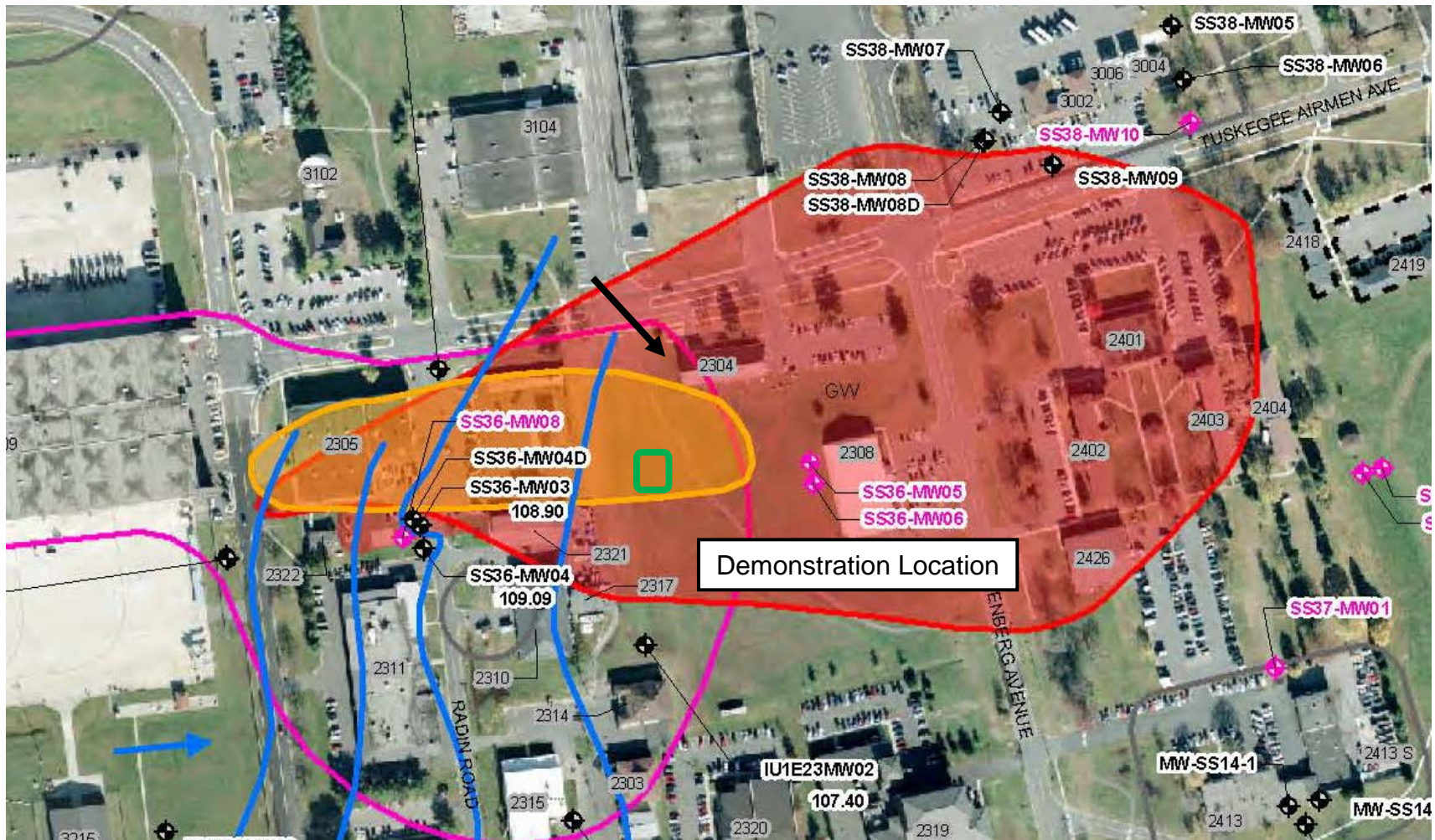
Figure 4.2. 2009 Map of the TCE Plume Extending Downgradient from Building 2305 in Area SS-36

The orange area identifies TCE in upper portion of the Kirkwood Formation and the red area indicates TCE in the lower portion of the Kirkwood Formation at concentrations >1 µg/L.

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4.2   SITE GEOLOGY/HYDROGEOLOGY

McGuire Air Force Base (AFB) is underlain by a succession of aquifers and confining layers. The two shallow aquifers are the Cohansey Sand/Kirkwood Formation aquifer system and the Vincentown Formation. The two aquifers are believed to be hydraulically connected, forming a shallow aquifer system that is about 75-ft thick. The shallowest stratigraphic unit at Area SS-36, and the formation that was targeted for this demonstration, was the Kirkwood Formation. This unit forms the uppermost aquifer system where groundwater occurs under unconfined conditions. The Cohansey Formation, observed in other portions of the base, is not present at this location. The Kirkwood Formation, consisting of a gray to yellow-brown, fine micaceous quartz sand with local beds of clay and silt, reached a thickness of approximately 29 ft in the demonstration location.

On a regional scale, the shallow groundwater at McGuire AFB flows to the east-southeast. The estimated linear groundwater velocity in the demonstration area ranged from 0.06 to 0.22 ft/day, or 22–80 ft/yr. Groundwater flow within the Kirkwood Formation in Area SS-36 was determined to be generally to the east, as shown in **Figure 4.2**. Groundwater depth was generally between 7 ft and 9 ft of the ground surface in the demonstration area during the demonstration. The series of aquifers and low-permeability confining units underlying JB MDL minimizes the impact of shallow groundwater contamination to the deeper aquifers. Preliminary groundwater sampling performed by CB&I in August 2010, demonstrated that groundwater pH throughout most of the proposed test area was <6 standard units (SU).

4.3   CONTAMINANT DISTRIBUTION

The nature and extent of subsurface soil and groundwater contaminants (e.g., cVOCs, metals, pesticides, and polychlorinated biphenyls [PCBs]), including potential cVOC source areas, were not fully delineated at Area SS-36 prior to the demonstration. **Figure 4.2** provides a 2009 map of the TCE plume extending downgradient from Building 2305 in Area SS-36 of JB MDL. The area shaded orange in the figure identifies TCE at measured concentrations >1 µg/L in the upper portion (generally above 19 ft bgs) of the Kirkwood Formation. This portion of the aquifer generally includes Layer 1, which is detailed above. The area shaded in red indicates TCE at measured concentrations >1 µg/L in the lower portion (approximately 19–25 ft bgs) of the Kirkwood Formation. This portion of the aquifer generally includes Layers 2, 3, and the upper portion of Layer 4.

As part of ongoing remedial investigations at the site, a direct-push groundwater sampling program was conducted in September 2009, by CB&I (formerly Shaw Environmental) under a separate contract. The results indicated that TCE concentrations in the lower portion of the Kirkwood ranged from approximately 2,000 µg/L to >120,000 µg/L, with the highest concentrations observed towards the centerline of the plume. The presence of significant concentrations of *cis*-DCE, and negligible concentrations of VC and ethene, indicate that biological degradation of TCE has stalled at *cis*-DCE.

5.0   TEST DESIGN

5.1   CONCEPTUAL EXPERIMENTAL DESIGN

This PRT field demonstration project used electrodes inserted into polyvinyl chloride (PVC) wells in a cVOC-contaminated, low-pH aquifer at JB MDL. During operation, the PRT system used a low voltage potential applied across the electrodes to impress a DC in the subsurface. The electrodes were operated to generate H_2 to support biodegradation, and consume H^+ to increase aquifer pH. The demonstration was divided into four phases of operation, which included PRT-only operation, and PRT operation with varying groundwater recirculation configurations. The contaminated aquifer was inoculated with a bioaugmentation culture to ensure that the appropriate dechlorinating bacteria were present to support biodegradation. Electricity to operate the system was provided by solar panels and deep-cycle 12 V batteries. During the demonstration, groundwater pH, contaminant concentrations, H_2 production, distribution and utilization, and electrode performance were monitored. The experimental design included the components described below.

5.1.1   Conceptual Site Model (CSM)

The site hydrogeologic and geochemical data collected during site characterization activities (**Section 5.2**) were used to construct the CSM. The CSM indicated that groundwater and dissolved contaminants flowed preferentially in an eastern horizontal direction (**Figure 4.2**) through a high permeability, medium-coarse sand layer (Layer 2, **Figure 5.1**). Some of these contaminants have diffused (or continue to diffuse) into an underlying silt and very fine sand layer (Layer 3), and the upper portion of a lower permeability clayey silt/sand layer (Layer 4). The direction of vertical diffusion is dependent on the concentration gradient between these layers. However, based on the soil cVOC data collected, it is likely that, in addition to upgradient sources, Layer 3 and the upper portion of Layer 4 act as continuing sources of contamination to Layer 2 (i.e., back-diffusion is occurring). Site characterization data indicate that Layer 1 has low levels of contamination, when compared to Layers 2 and 3, and Layer 5 exhibits no contamination in the demonstration area. Therefore, *in situ* treatment during this demonstration focused on Layers 2 and 3. The upper portion of Layer 4 was also monitored to determine if H_2 can be distributed or produced within this clayey silt/sand material.
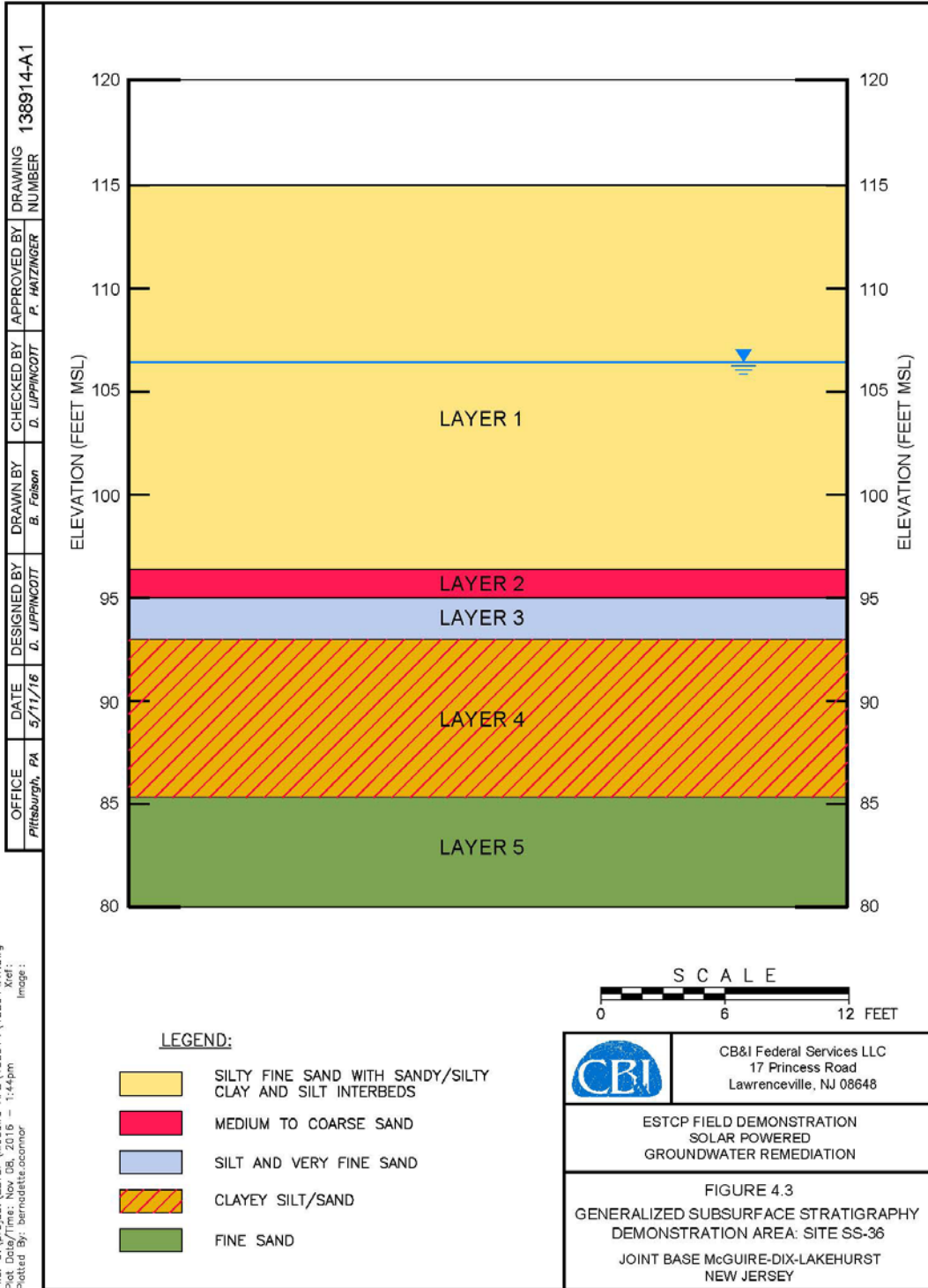
Figure 5.1. Generalized Subsurface Stratigraphy at Site SS-36

5.1.2 Design Calculations

The amount of electrical current needed to increase aquifer pH and to produce sufficient amounts of H$_2$ for biological reductive dechlorination of cVOCs was calculated by applying Faraday's law

of induction. Assuming a current of 500 milliamps (mA), and applying Faraday's law, the rate of H_2 production at each cathode was calculated to be 9.5 millimoles per hour (mmoles/hr) (approximately 0.22 L/hr). The rate of OH^- production—assuming 500 mA and applying Faraday's law—was calculated to be 19 mmoles/hr.

5.1.3   Groundwater Modeling

Groundwater modeling for the conceptual groundwater recirculation system design was based on a MODFLOW/RT3D simulation using data from the preliminary site characterization. The MODPATH module was used determine the location and screen intervals for injection well (IWs) and extraction wells (EWs), IW/EW flow rates, location of additional monitoring wells, and the location of electrodes.

5.1.4   Demonstration Layout

Two extraction wells (EW-1 and EW-23) and two injection wells (IW-1 and IW-2) were installed as part of a groundwater recirculation system designed to increase groundwater velocity through the demonstration test plot. Additionally, one extraction well (EW-3) and one injection well (IW-3) were installed to increase groundwater velocity through the demonstration control plot. The test plot and control plot were both the same length, with 30 ft between IWs and EWs (**Figure 5.2**).

As exhibited in **Figure 5.2**, the anode and cathode wells were spaced approximately 10 ft apart, and perpendicular to groundwater flow. Two cathode wells (CW-1 and CW-2) and two anode wells (AW-1 and AW-2) were installed near the test plot, and one cathode well (CW-3) that shared an anode well with one of the test plot anodes (AW-2) was installed in the control plot.

Solinst continuous multichannel tubing (CMT) multi-level monitoring wells were selected to monitor various stratigraphic layers defined in the CSM. These intervals are shown in **Figure 5.3**, and include Layers 2 and 3, which contain the bulk of the contaminant mass. Layer 4 was also monitored to determine if H_2 could be distributed or produced within this clayey silt/sand material, as distribution via groundwater flow was expected to be negligible.
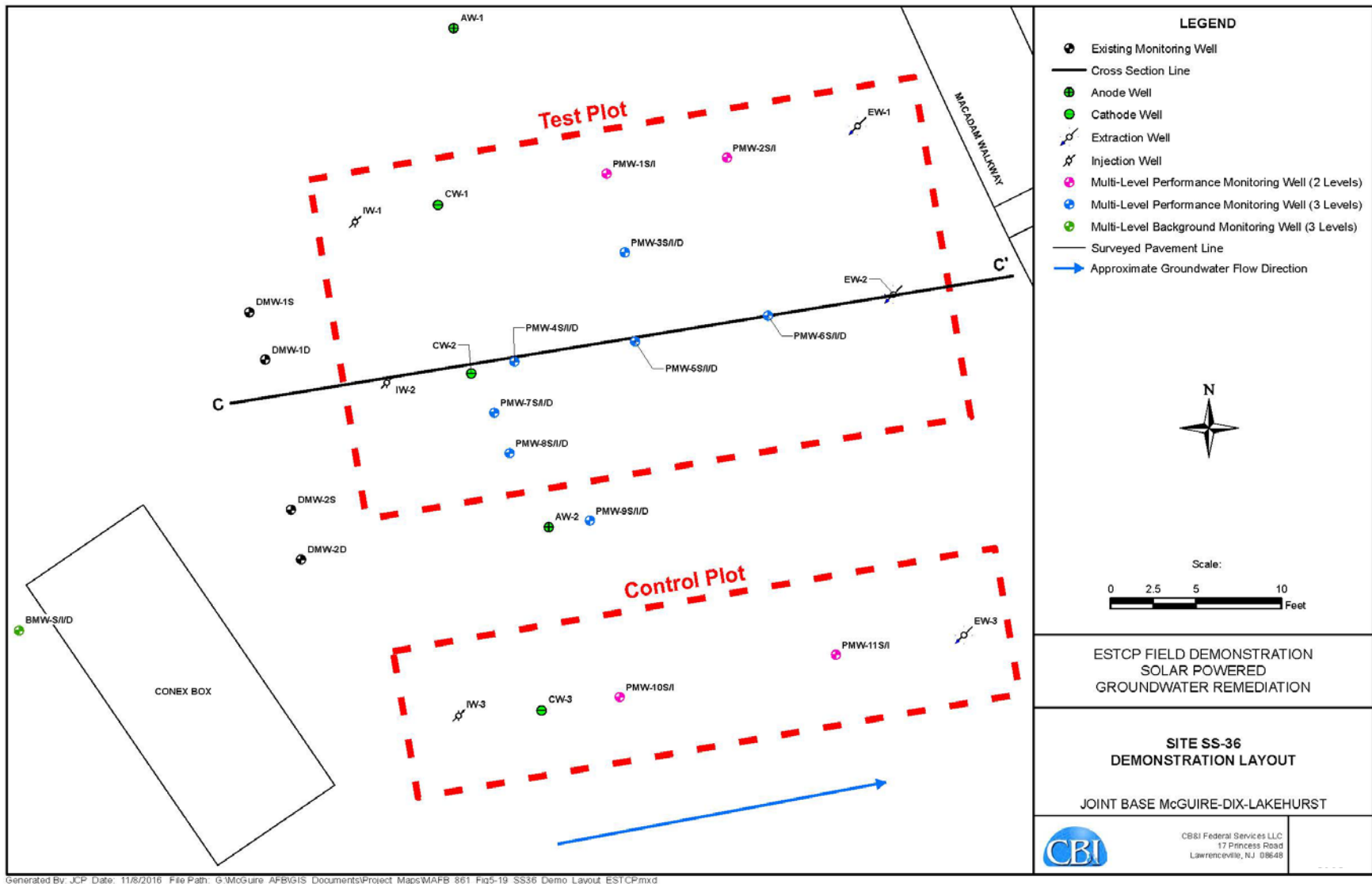
Figure 5.2. Plan View of the Proton Reduction Demonstration Plots in Area SS-36
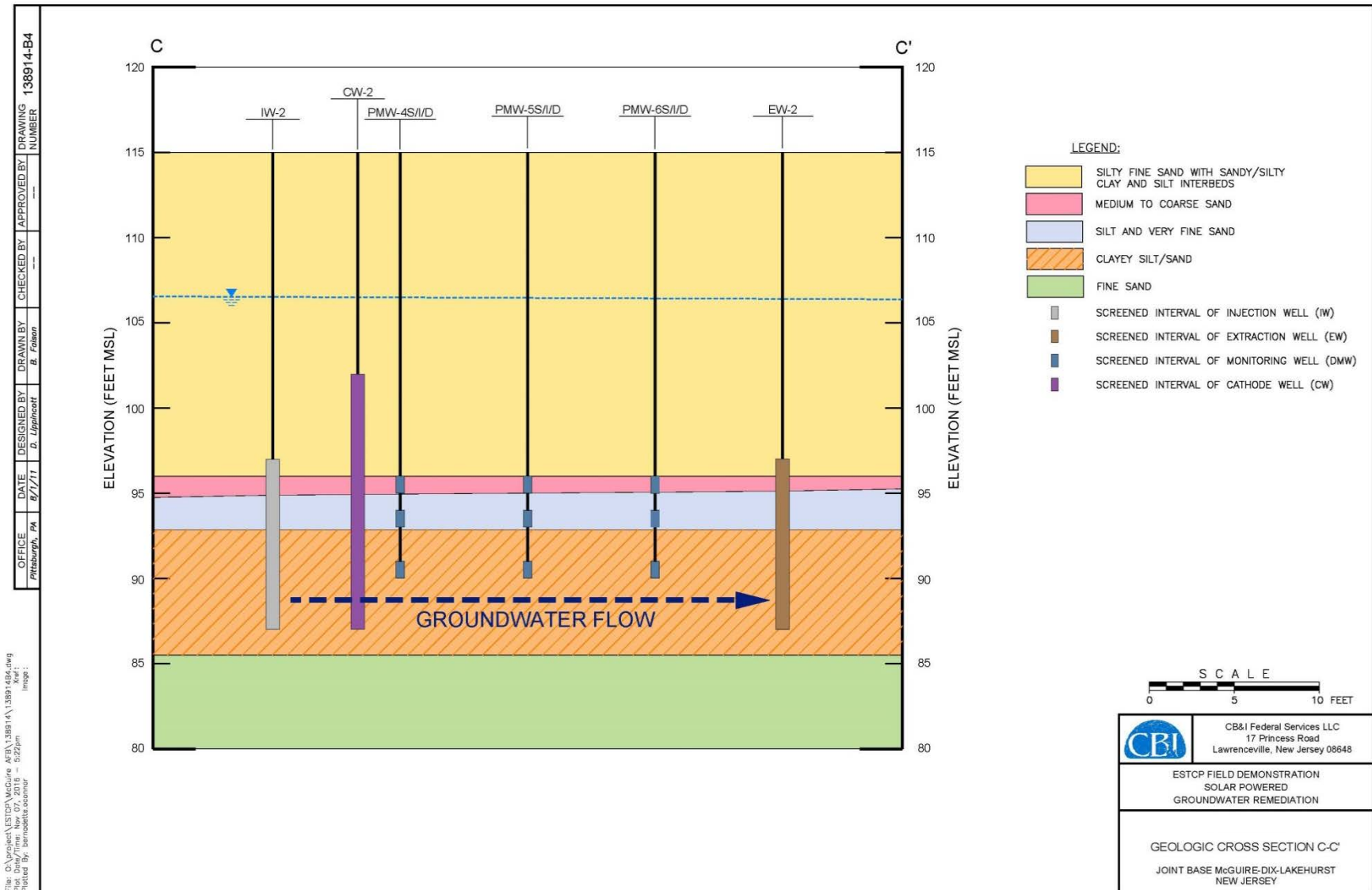
Figure 5.3. Cross-Sectional View of the Proton Reduction Demonstration Test Plot

5.2 BASELINE CHARACTERIZATION

Baseline testing and site characterization were performed to generate the data needed to design the field system. Testing included a direct-push site investigation to evaluate aquifer geology and contaminant distribution, monitoring well installation and hydrogeologic testing to evaluate site hydrogeology, geochemical characterization of site groundwater and soils, and geochemical modeling. The following summarizes the baseline testing and site characterization activities that were performed prior to the field demonstration.

Direct-Push Investigation

- Advancement of four continuous soil borings, and collection of eight discrete interval groundwater samples from four borings at four separate locations within the Site SS-36 plume;
- Advancement of four continuous soil borings, and collection of eight cVOC soil samples in the selected demonstrations area;
- Collection of eight discrete interval groundwater samples at four borings within the selected demonstration area; and
- Advancement of six addition soil borings to collected discrete zone soil cores for analysis of soil geochemical properties or use in the various laboratory testing detailed in **Section 5.3**.

Monitoring Well Installation and Sampling

- Installation of four demonstration monitoring wells (DMW-1S, DMW-1D, DMW-2S, and DMW-2D) using direct-push drilling methods, and
- Groundwater sample collection for VOCs and numerous geochemical parameters at all four monitoring wells.

Hydrogeologic Testing

- Performance of rising head and falling head slug tests at the four monitoring wells, and
- Performance of a short-term (~3 hr) constant rate pump test at monitoring well DMW-2S.

Geochemical Modeling

- Performance of geochemical modeling to predict how groundwater pH can be increased and to assess the impact of the pH increase on mineral precipitation,
- Evaluated at what pH the cathode water should be maintained to limit precipitation, and
- Assessed the potential for aquifer plugging as a result of mineral precipitation.

Detailed discussions of these baseline activities and their results are provided in the project *Final Report* (CB&I Federal Services, 2017).

5.3 TREATABILITY AND LABORATORY STUDY RESULTS

In preparation for the field demonstration, a series of laboratory studies were performed. The results of these studies are summarized in the following subsections.

5.3.1   Buffer Testing

Laboratory studies were performed to analyze the aquifer soils and groundwater and evaluate the amount of H^+ consumption or base addition required to adjust the aquifer pH and then maintain it at circumneutral. The data were then used to estimate the potential impact of PRT on the aquifer pH, and to estimate the amount of time required to increase the pH of the aquifer downgradient of the proton reduction system cathodes (location of H^+ reduction and OH^- production). Testing results indicated that approximately 16–24 millimolars (mM) bicarbonate was required to adjust the pH in the aquifer to 6.5 SUs.

5.3.2   Treatability Testing

A laboratory treatability test was performed with anaerobic soil and groundwater samples. The objective of the treatability testing was to demonstrate that the contaminants can be degraded under site (or modified site) conditions, and to evaluate the need to augment the site with an exogenous cVOC-degrading culture. A microcosm test with site soil and groundwater that compared dehalogenation under ambient and circumneutral pH was conducted. The study evaluated dehalogenation, homoacetogenesis, methanogenesis, and H_2 consumption, and also compared the activity of indigenous microbes to an added bioaugmentation culture. The microcosms were fed H_2 to mimic the use of cathodic H_2. Results of the testing showed that both pH adjustment and bioaugmentation were required to support complete TCE dechlorination under site conditions and that the addition of H_2 alone could support complete TCE dechlorination when the SDC-9™ bioaugmentation culture was added to the samples

5.3.3   2D Flow Cell Testing

In addition to microcosm studies, a simple two-dimensional (2D) flow cell was constructed to evaluate cathodic and microcapacitor proton reduction (**Section 2.1.2**) and to evaluate the transport of cathodic and microcapacitor H_2 and changes in soil pH (**Figure 5.4**). The cell was filled with low permeability soils collected from the demonstration site during site characterization activities (**Section 5.4**). Two electrodes were installed near the bottom corners of the cell, as shown in **Figure 5.4**. Twenty sampling ports were installed throughout the flow cell for collection of H_2, pH, and tracer samples.
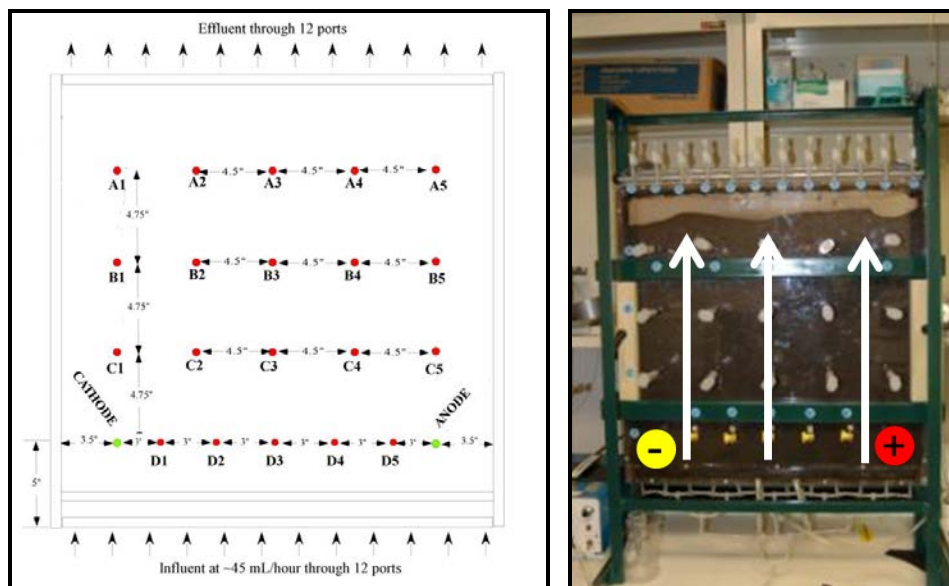
Figure 5.4. Representation and Photos of a 2D Flow Cell to Evaluate Microcapacitor-Generated H₂

The cell was operated at 20 V and 4 mA. Calculated H_2 production was 0.15 mg/hr H_2, and calculated OH^- production was 1.5×10^{-4} mg/hr OH^-. This H^+ consumption and OH^- production resulted in changes in groundwater pH that allowed neutralization of soil and groundwater acidity near and downgradient (upward in the 2D cell) of the cathode. Likewise, H_2 generated at the cathode was transported downgradient of the cathode, with concentrations as high as 217 µg/L being measured at one of the sample ports downgradient of the cathode.

5.3.4   Electrode Testing

A key component of the proton reduction system is the electrode material used in the subsurface for electrochemical reactions. Laboratory testing of various materials was performed in a test cell. The two materials that performed the best during testing were the mixed metal oxide-coated titanium (Elgard 150) and the graphite felt. Based on the cost, availability, and the results of earlier work by Gilbert and colleagues (2008), it was determined that the Elgard 150 material was most suitable for long-term PRT field application (**Figure 5.5**).
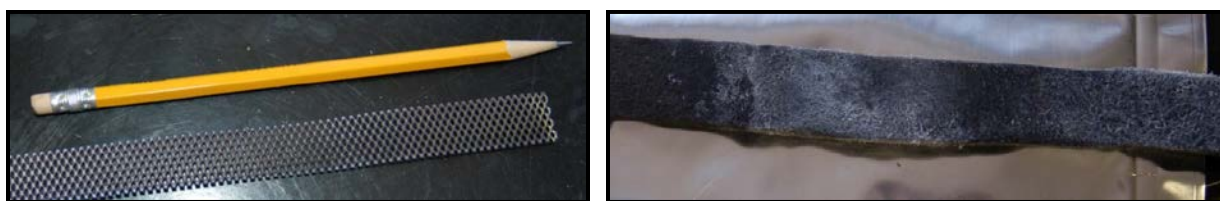
Figure 5.5. Photographs of Two Tested Electrode Materials.

Left, Elgard 150 mixed metal oxide coated titanium mesh. Right, graphite felt.

5.4 FIELD TESTING

A timeline of major activities and system operational phases is provided in **Table 5.1.** Field testing activities included well and system installation, two baseline sampling events, tracer testing, and four different phases of system operation with performance monitoring.

Table 5.1. Summary of Proton Reduction Demonstration Major Activities and Phases

Activity/Demonstration Phase	Start Date	Completion Date	Demonstration Timeline	Duration (Days)
Well Instllations and System Construction	8/11/2011	11/4/2011	Days -123 through -38	85
Baseline Sampling Event #1	10/26/2011	10/27/2011	Days -47 and -46	2
Baseline Sampling Event #2	11/9/2011	11/10/2011	Days -33 and -32	2
Tracer Testing	11/14/2011	11/28/2011	Days -28 through -14	15
Phase 1-Proton Reduction Only (no groundwater recirculation)	12/12/2011	4/3/2012	Days 0 through 113	114
Phase 2-Proton Reduction & Groundwater Recirculation (extraction & injection wells)	4/4/2012	6/26/2012	Days 114 through 197	84
Phase 3-Proton Reduction & Groundwater Recirculation (extraction wells, re-injecting in cathode wells)	6/27/2012	7/31/2012	Days 198 through 232	35
Phase 4-Proton Reduction & Operation of Small Recirculation Loop (extracting from AW-2, injecting in CW-2)	8/1/2012	12/20/2013	Days 233 through 739	507

5.4.1 Well and System Installation

Demonstration well and system installation activities were performed between August and November 2011, and included:

- Installation of 5 electrodes (3 cathodes and 2 anodes),
- Installation of 3 EWs and 3 IWs (3 loops),
- Installation of 12 multi-level monitoring wells,
- Construction and testing of the groundwater recirculation system, and
- Construction and testing of the PRT and solar power systems.

The groundwater recirculation system was constructed within a 20-ft long conex box, located within the demonstration area (**Figure 5.2**). A photograph of the Conex box is provided in **Figure 5.6**. A process flow diagram (PFD) showing the general design of the groundwater recirculation system, including EWs and IWs and the associated equipment, is provided in **Figure 5.7**.

Figure 5.6. Conex Box and PRT Control Panel
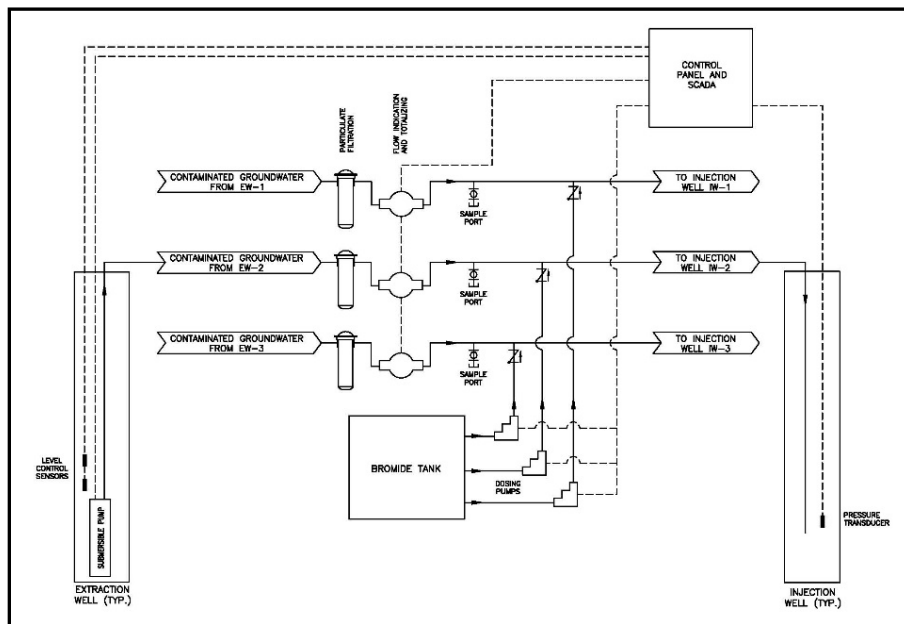
Figure 5.7. Process Flow Diagram of the Groundwater Recirculation System

The PRT system was powered via an off-the-grid solar power system. The system consisted of four 85-watt photovoltaic solar panels, and four deep-discharge 80 amp hour 12 V batteries. The batteries were connected in parallel, with two batteries in each series, providing a 24 V DC power supply. A solar charge controller regulated the charging of the batteries when there was sufficient sunlight, and the system used stored battery power when sunlight was not sufficient. The five electrodes were connected to a commercially-constructed control panel (**Figure 5.6**).

5.4.2 System Operation and Performance Monitoring

Prior to the startup of the PRT and groundwater recirculation systems, two baseline groundwater sampling events were performed. Baseline groundwater samples were collected from all 11 multi-level sampler (MLS) performance monitoring wells (PMW-1 through PMW-11) and from MLS background monitoring well BMW-1. Sample analysis and quantities are summarized in **Table**

5.2. Once the second round of baseline sampling was complete, the recirculation system was started and operated for two weeks prior to operation of the PRT system. The system was operated continuously between November 14, 2011, and November 28, 2011 (**Table 5.1**). During this two-week testing period, injection of the conservative tracer bromide and tracer sampling events were performed in the test plot to evaluate/verify local hydrogeologic characteristics, including hydraulic conductivity, heterogeneity, and vertical components of groundwater flow, and to determine the travel time between the IWs and EWs.

Table 5.2. Total Number and Types of Samples Collected During the Demonstration

Phase	Event	Occurrence	Number of Samples	Analyte	Location
Baseline Sampling	Baseline Sampling #1	Day -46	32	VOCs, reduced gases, dissolved hydrogen, anions	Every interval at all 11 PMWs and BMW-1
	Baseline Sampling #2	Day -33	32	VOCs, reduced gases, dissolved hydrogen, anions, dissolved Fe and Mn	Every interval at all 11 PMWs and BMW-1
Recirculation System Startup and Testing	Bromide Tracer Testing #1	5 Events (Days -26, -24, -21, -19, and -14)	32 sample points; 160 total samples	Anions (bromide)	Every interval at all 11 PMWs, all 3 EWs
Phase 1	Dissolved Hydrogen Sampling	8 Events (Days 0,16, 24, 28, 31, 35, 57, and 113)	19 sample points; 152 total samples	Dissolved hydrogen	PMW-4, 5, 7, 9, 10 (all depths), all 3 CWs, both AWs
	Performance Sampling	Day 105	32	VOCs, reduced gases, dissolved hydrogen, anions	All 11 PMWs, all 3 BMWs
Phase 2	Dissolved Hydrogen Sampling	Day 128	25	Dissolved hydrogen	PMWs 4, 5, 6, 7, 10, 11 (all depths), All 3 BMWs, All 3 CWs, All 3 EWs
		Day 135	3		PMW 4 (all depths).
		Day 142	9		PMWs 4S, 4I, 4D, 5S, 5I, All 3 BMWs, CW-2
		Day 170	21		PMWs 4, 5, 7, 8, 10 (all depths), All 3 EWs, All 3 CWs, AW-2
		Day 178	19		PMWs 4S, 4I, 4D, 5S, 5D, 7S, 7I, 7D, 8S, 8I, 8D, 10S, 10I, All 3 EWs, All 3 CWs
	Bromide Tracer Testing #2	4 Events (Days 182, 184, 186, and 190)	33 sample points; 132 total samples	Anions (bromide)	PMWs 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 (all depths), All 3 EWs, All 3 CWs
Phase 3	Performance Sampling Event	Day 231	9	VOCs, reduced gases, dissolved hydrogen, anions	PMWs 4, 7, and 8 (all depths)
Phase 4	Bromide Tracer Testing #3	4 Events (Days 294, 295, 296, and 298)	11 sample points; 44 total samples	Dissolved hydrogen, anions	PMWs 4, 7, and 8 (all depths), CW-2, AW-2
	Performance Sampling Event #1	Day 316	12	VOCs, reduced gases, dissolved hydrogen, anions, dissolved metals, alkalinity	PMWs 4, 7, and 8 (all depths), BMW-1S, CW-2, AW-2
	Dissolved Hydrogen Sampling	Day 339	11	Dissolved hydrogen	PMWs 4, 7, and 8 (all depths), CW-2, AW-2
		Day 547	10		PMWs 4, 7, and 8 (all depths), CW-2
	Dissolved Hydrogen & Anion Sampling	Day 358	11	Dissolved hydrogen, anions	PMWs 4, 7, and 8 (all depths), CW-2, AW-2
	Performance Sampling Event #2	Day 372	7	VOCs, reduced gases, dissolved hydrogen, anions, dissolved and total metals	PMWs 7 and 8 (all depths), CW-2
	Performance Sampling Events #3 (pre-bioaugmentation), 4, 5, and 6	2 Events (Days 402 and 423)	7	VOCs, reduced gases, dissolved hydrogen, anions, TOC	PMWs 7 and 8 (all depths), BMW-1S.
		2 Events (Days 458 and 499)	8		PMWs 7 and 8 (all depths), BMW-1S, CW-2
	Performance Sampling Event #7	Day 568	6	VOCs, reduced gases, dissolved hydrogen, anions, dissolved metals	PMWs 7 and 8 (all depths)
	Performance Sampling Events #8, 9, and 10	Day 645	6	VOCs, reduced gases, dissolved hydrogen, anions	PMWs 7 and 8 (all depths).
		2 Events (Days 701, and 737)	7 sampling points; 14 total samples		PMWs 7 and 8 (all depths), BMW-1S

PMW – Multi-level Performance Monitoring Well
BMW – Multi-level Background Monitoring Well
EW – Extraction Well
CW – Cathode Well
AW – Anode Well

After system start-up and tracer testing, system operation during the demonstration was divided into the following four distinct stages (**Table 5.1**):

Phase 1 – Proton Reduction Only: This phase involved operation of the PRT system for 114 days without the groundwater recirculation system operating. This initial operational phase was used to optimize operation of the PRT system, as well as to monitor geochemical changes within the electrode wells and nearby PMWs. This phase allowed for assessment of H_2 production and changes in groundwater pH within the cathode wells. It also allowed for evaluation of any potential generation of H_2 between cathodes and anodes, and transport of H_2 or downgradient changes of pH under natural groundwater gradients.

Phase 2 – Proton Reduction and Groundwater Recirculation (EWs and IWs): This phase of system operation began on April 4, 2012, and consisted of an 84-day period during which groundwater recirculation was performed using the three recirculation loops, and the PRT system was in continuous operation. Groundwater was recirculated at a rate of 0.25 gallons per minute (gpm) for 15 days, and at a rate of 0.4 gpm for the remaining 69 days at each of the three loops. The PRT system was operated between approximately 10 V and 16 V, with currents between approximately 140 mA and 250 mA measured in the test plot. These were the approximate designed operational settings, and were intended to be the normal operating conditions for the remainder of the demonstration. However, because of apparent groundwater flow paths, and the lack of dissolved H_2 distribution and pH increases observed at test plot wells during this 84-day period, the duration of this operational phase was shortened and modifications were made as described in Phase 3 below.

Phase 3 – Proton Reduction and Groundwater Recirculation (EWs, re-injecting in cathode wells): Phase 3 of system operation began on June 27, 2012, and lasted 35 days. To better distribute the H_2 and high pH water being generated in the cathode wells, the groundwater recirculation system was reconfigured so that the extracted groundwater was re-injected directly into the three cathode wells, rather than the three IWs. Groundwater recirculation rates were reduced to 0.1 gpm at each loop during this phase of the demonstration. Dissolved H_2 and pH data collected during this phase of the demonstration indicated that groundwater being re-injected into the cathode wells was still not reaching nearby downgradient MLS monitoring wells. Thus, additional changes to the plot configuration were made as described in Phase 4 below.

Phase 4 – Proton Reduction and Operation of Small Recirculation Loop: Phase 4 of system operation began on August 1, 2012, and lasted 507 days. To adjust for the limitations observed during Phases 2 and 3, and to take advantage of the observed connection between cathode well CW-2 and MLS monitoring well PMW-7S/I/D, the groundwater recirculation system was modified to create a small recirculation loop (**Figure 5.8**) to move groundwater between well AW-2 (which served as the EW) and well CW-2 (which served as both a cathode and an IW). The electrode in well AW-2 was removed, and well CW-1 was converted into an anode for the remainder of the demonstration. A submersible air-driven bladder pump was installed in well CW-2, and a small air compressor and a solar-powered pump controller were installed to operate the bladder pump. MLS monitoring wells PMW-7S/I/D and PMW-8S/I/D served as PMWs during this final phase of the demonstration. This 507-day operation phase was where most of the useful project data were derived.
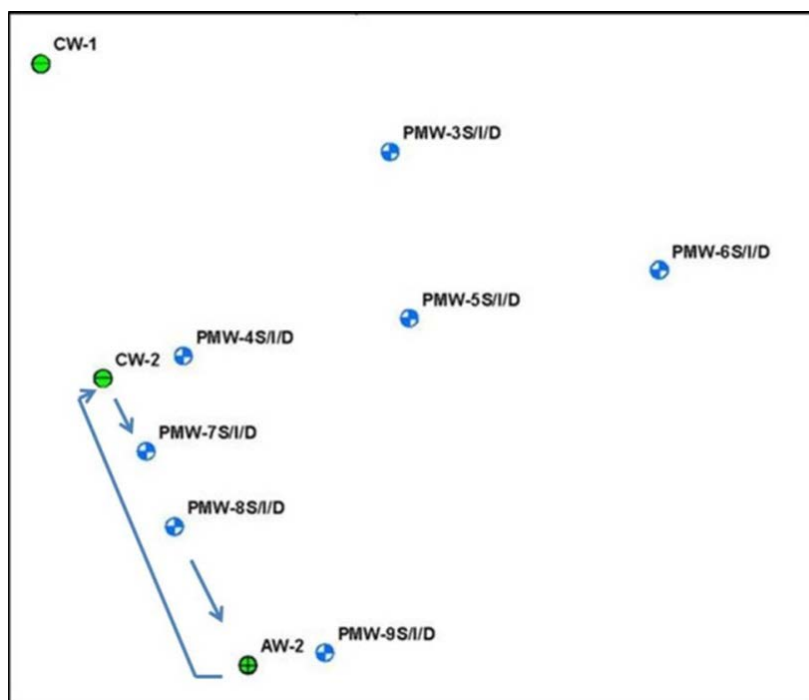
Figure 5.8. Plan View of the Proton Reduction Test Plot Used During Phase 4 of the Demonstration

The blue arrows show the orientation of the recirculation loop constructed using well AW-2 (extraction) and well CW-2 (injection).

During Phase 4, groundwater was recirculated at a rate of approximately 80 milliliters per minute (mL/min) for the first 61 days, and at a rate of approximately 400–500 mL/min for the remaining 446 days within the new groundwater recirculation loop. The PRT system was operated continuously at 16 V, with currents between approximately 350 mA and 450 mA measured in the new test plot area.

Bioaugmentation injections with CB&I's SDC-9™ dechlorination culture were performed at well CW-2 on January 17, 2013, and October 10, 2013 (days 402 and 668, respectively).

5.5   SAMPLING METHODS

Groundwater samples were collected by CB&I utilizing low-flow purging in general accordance with NJDEP Low Flow Purging and Sampling Guidance (NJDEP, 2003). The procedures used in collecting groundwater samples during the demonstration, including quality assurance sampling and analysis, are described in detail in the *Project Final Report*. Groundwater samples were submitted to the CB&I Analytical and Testing Laboratory, Lawrenceville, NJ, for analysis of VOCs, reduced gases, anions, dissolved H_2, volatile fatty acids (VFAs), and for quantification of DHC via qPCR. Dissolved Fe and manganese (Mn) analyses were performed by Chemtech, located in Mountainside, NJ. The numbers and types of groundwater samples collected during the demonstration are provided in **Table 5.2**. The analytical methods for groundwater samples collected during the field demonstration are summarized in **Table 5.3**.

Table 5.3. Analytical Methods for Groundwater Samples

Analyte[1]	Method/ Laboratory	Preservative	Bottle	Hold time
VOCs	EPA 8260 CB&I	4^oC with HCl	40 mL VOA vial x 2, no headspace	14 days
Anions	EPA 300.0 CB&I	4^oC	100 mL polyethylene screw-cap	2 days (NO_3, PO_4); 28 days all others
Volatile Fatty Acids (VFAs)	EPA 300.0m CB&I	4^oC	100 mL polyethylene screw-cap	14 days
Dehalococcoides (DHC)	qPCR CB&I[2]	4^oC	950 mL sterile screw-cap	NA[3]
Reduced Gases	EPA 3810, RSK175 CB&I[2]	4^oC with HCl	40 mL VOA vial x 2 No headspace	14 days
Dissolved Hydrogen	EPA 3810, RSK175 CB&I[2]	4^oC with HCl	125 mL serum bottle, Teflon-lined butyl rubber septa and crimp seal, No headspace	7 days
Metals	EPA 200.7 Chemtech	4^oC with HNO_3	250 mL polyethylene screw-cap	6 months
Redox Potential	Field Meter	--	--	NA
Dissolved Oxygen	Field Meter	--	--	NA
pH	Field Meter	--	--	NA
Conductivity	Field Meter	--	--	NA

[1]All analyses are in groundwater

[2]Not a standard EPA Method.

[3]NA, Not applicable

5.6   SAMPLING RESULTS

The results from tracer testing and performance monitoring during the four operational phases are summarized in the following subsections. As summarized in **Table 5.2**, the majority of the performance sampling was conducted during Phase 4 of the demonstration. The results for each well parameter are provided in the project *Final Report* (CB&I Federal Services, 2017).

5.6.1   pH Adjustment

One of the primary goals of this demonstration was to use PRT to increase aquifer pH via electrolysis and proton reduction. **Figure 5.9** shows groundwater pH measured in the three cathode wells. During Phase 1 of the demonstration, when only the PRT system was operating (no groundwater recirculation), the pH in the cathode wells increased to >10. During Phase 2, the PRT system was operated at varying voltages/currents. Even with active groundwater recirculation, pH in the cathode wells could be maintained at >10 when system voltage was ~16

V and the measured current was >250 mA. However, during Phases 3 and 4, when groundwater was recirculated directly into the cathode wells, pH measured in the wells was only slightly higher than the pH of the recirculated groundwater. Although high pH (up to pH 11.5) was achieved in the cathode well groundwater during Phases 1 and 2 of the demonstration, the impact of the treatment was not observed in any of the downgradient MLS monitoring wells, including PMW-4S/I/D located 2.5 ft downgradient of well CW-2. The lack of observed impact at this MLS monitoring well was possibly due to a lack of hydraulic connection between the cathode well and the monitoring well (as confirmed during tracer testing), which prevented the transport of water from the cathode well to this monitoring well.
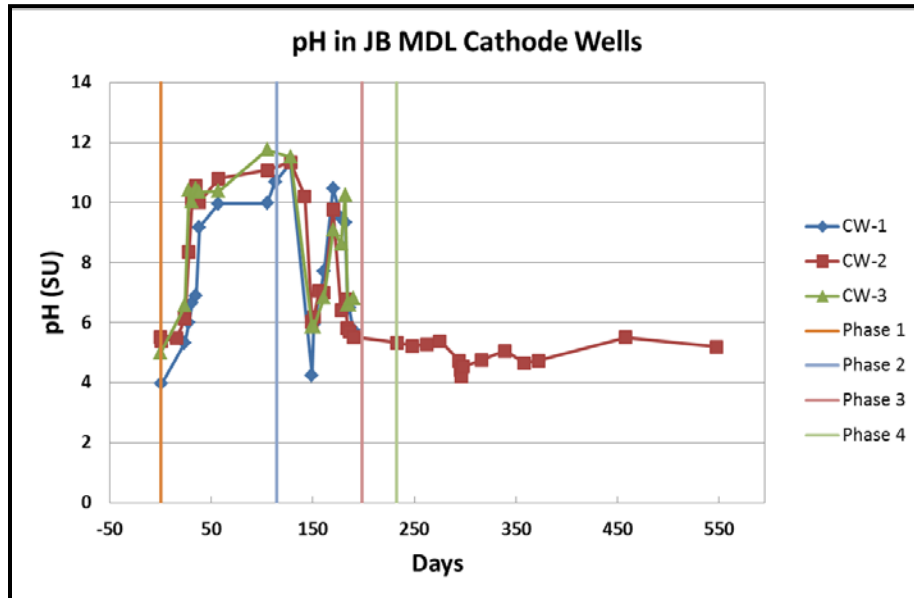
Figure 5.9. Groundwater pH Measured in Cathode Wells

No significant increases in aquifer pH were observed in the PMW-7 (**Figure 5.10**) and PMW-8 well intervals during Phase 1 through Phase 3 of the demonstration. Upon initiating operation of the small recirculation system on day 233 (Phase 4), groundwater pH at some of the PMW-7 and PMW-8 well intervals (especially in well PMW-7S) began to increase, and pH values near pH 6 were achieved. However, a pH >6 was unable to be maintained throughout much of the treatment zone, which likely would have improved biological degradation of TCE.
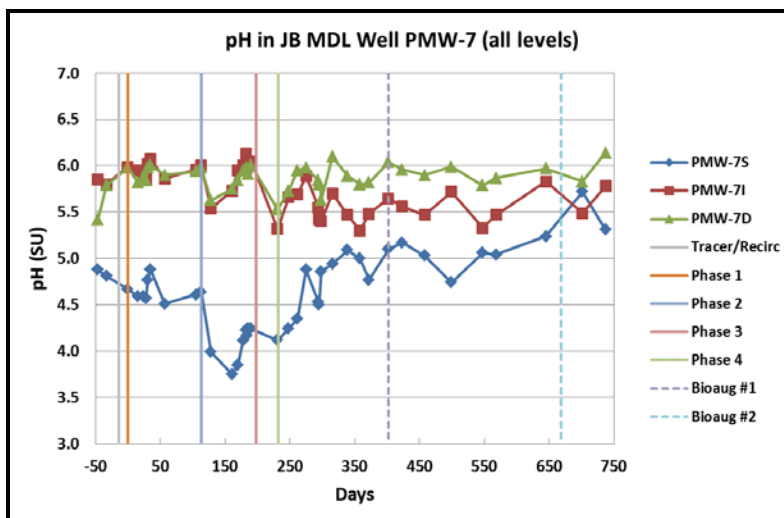
Figure 5.10. Groundwater pH Measured in MLS Well PMW-7

5.6.2 Hydrogen Production and Distribution

H_2 concentrations in the demonstration plot cathode wells reached concentrations up to approximately 1,200 µg/L (**Figure 5.11**). H_2 concentrations in the cathode well groundwater remained saturated during Phase 1 and Phase 2 of the demonstration. During Phases 3 and 4, H_2 concentrations in the cathode well(s) decreased because the addition of extracted water to the cathode well (i.e., IW) continually diluted H_2 concentrations and forced the H_2-containing groundwater into the aquifer. Hydrogen concentrations measured during Phase 4 of the demonstration occasionally exceeded the target concentration of 0.010 µg/L at MLS well PMW-7, located closest to the cathode wells (**Figure 5.12**). However, H_2 concentrations were typically below the detection level (<0.008 µg/L) at this well. Considering H_2 concentrations at well CW-2 (cathode/IW) were often >50 µg/L during this Phase, this suggests that there was a substantial sink for H_2 between CW-2 (cathode/IW) and the MLS well PMW-7 (located 2.5 ft away, and within the recirculation loop).
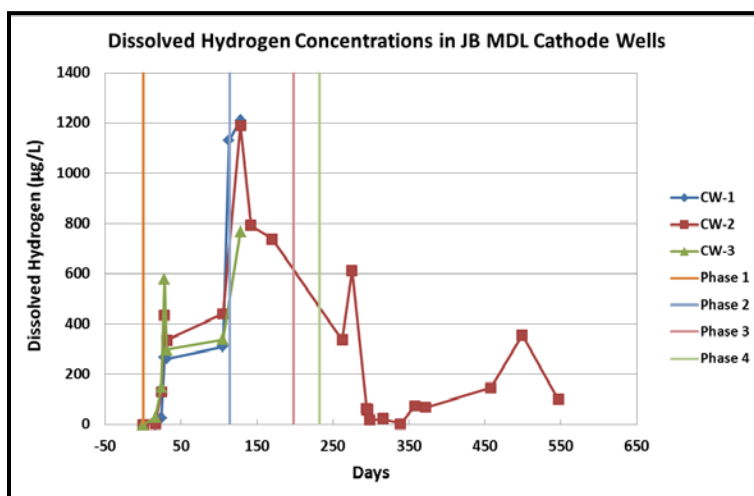
Figure 5.11. Dissolved H_2 Concentrations Measured in Cathode Wells

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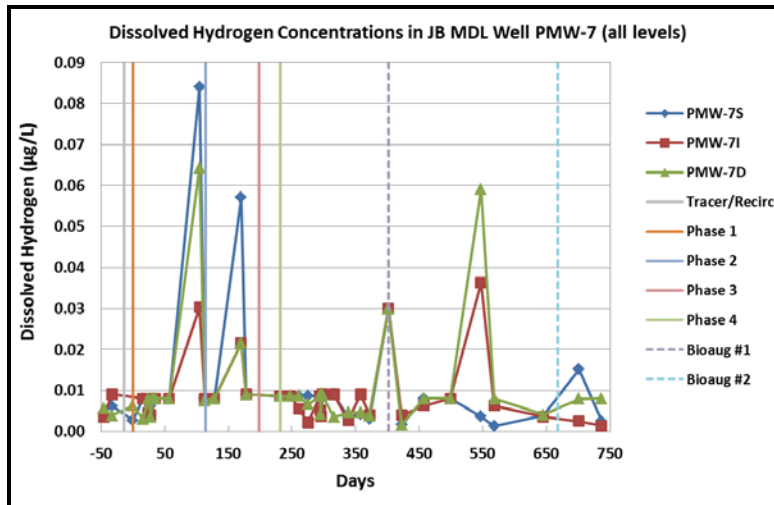
Figure 5.12. Dissolved H$_2$ Concentrations Measured in MLS Well PMW-7

5.6.3 Oxidation-Reduction Potential (ORP)

The ORP measured at MLS monitoring wells PMW-7 and PMW-8 fluctuated significantly during the demonstration, but did occasionally reach levels sufficient to support complete reductive dechlorination of TCE (<-100 millivolts [mV]). However, the ORP conditions were unfavorable through much of the demonstration. The ORP temporarily decreased to desirable levels in all of the PMW-7 and PMW-8 sample intervals immediately following both bioaugmentation injections (**Figure 5.13**). However, the ORP slowly increased again following both injections. The data show that target ORP levels were unable to be maintained within the treatment zone during most of the demonstration. While not presented, the dissolved oxygen (DO) concentrations measured in MLS wells PMW-7 and PMW-8 where typically <1.0 mg/L during Phase 4 of the demonstration. Baseline DO concentrations at these wells were between ~0.5 and 2.5 mg/L.
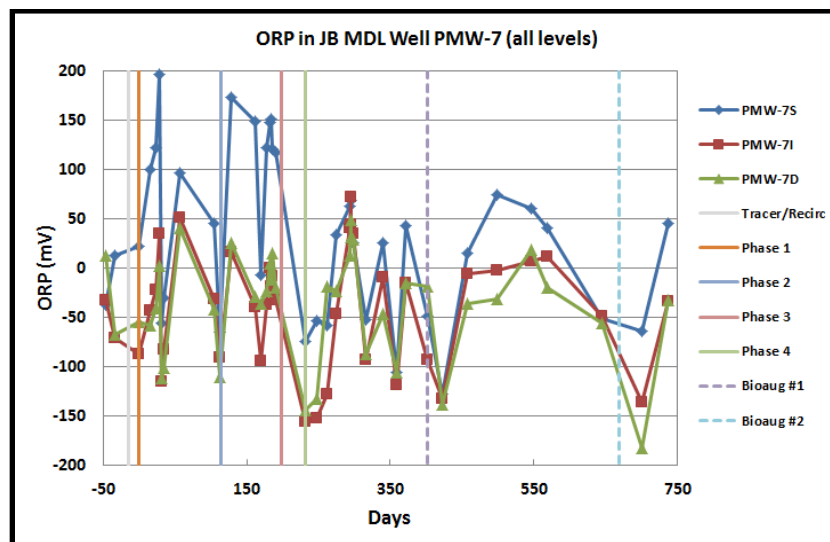
Figure 5.13. ORP Measurements in MLS Well PMW-7

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5.6.4   cVOC Treatment

With the exception of well PMW-7D, the concentration of TCE decreased notably in treatment zone monitoring MLS wells PMW-7 and PMW-8 during the demonstration (**Figure 5.14**). These decreases ranged from 31% (PMW-7S) to 89% (PMW-8I). As shown on **Figure 5.15**, notable transient increases in *cis*-DCE concentrations were observed in the treatment zone monitoring wells during the last ~100 days of the demonstration. Increases up to an order of magnitude were observed during this period. These data suggest that partial dechlorination of TCE was occurring within the treatment zone.   However, the lack of observed VC (not presented) or ethene concentrations (**Figure 5.16**) at these wells indicated that complete reductive dechlorination was not occurring at a significant rate. This is likely due (at least partially) to the sub-optimal pH and ORP levels that had been achieved within the treatment zone.
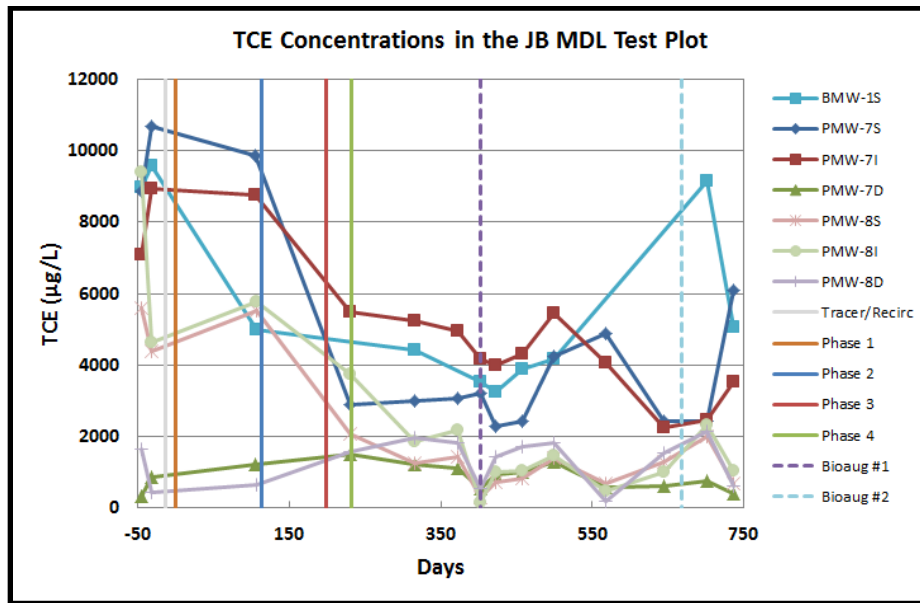
Figure 5.14. TCE Concentrations in MLS Wells PMW-7, PMW-8, and Background Monitoring Well BMW-1S

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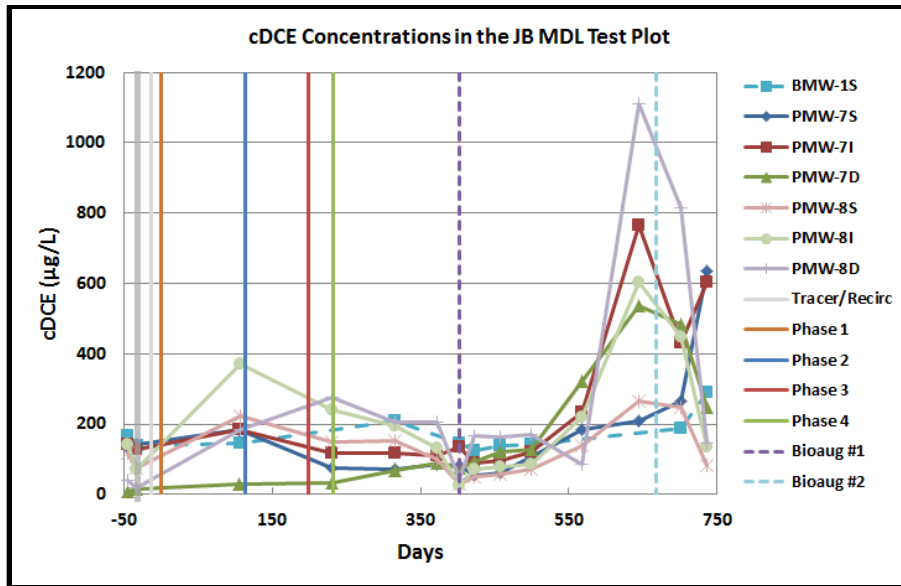
Figure 5.15. *cis*-DCE Concentrations in MLS Wells PMW-7 and PMW-8, and Background Monitoring Well BMW-1S
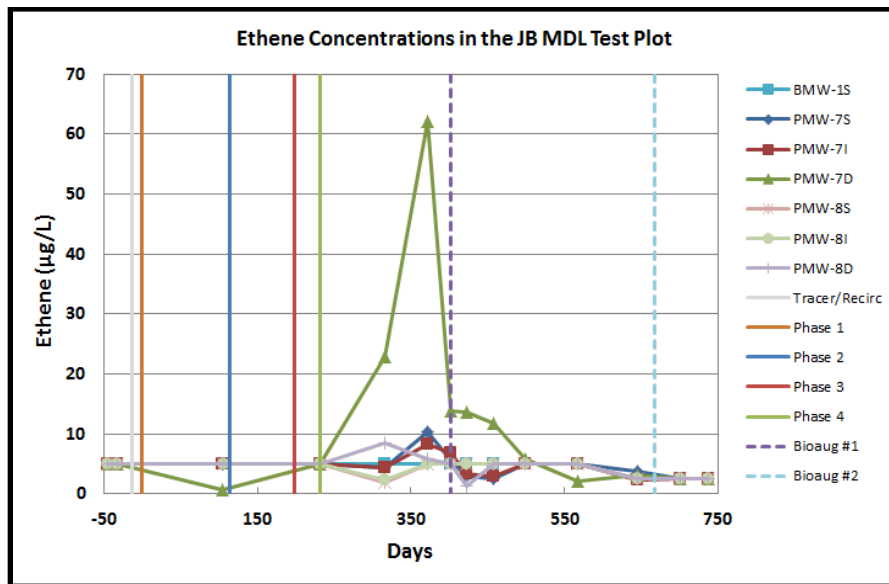
Figure 5.16. Ethene Concentrations in MLS Wells PMW-7 and PMW-8, and Background Monitoring Well BMW-1S

5.6.5   DHC Distribution and Growth

Groundwater samples for DHC quantification (via qPCR) were collected during Phase 4 from MLS monitoring wells PMW-7 and PMW-8 within the small recirculation loop immediately prior to and approximately two months after the first bioaugmentation event (**Table 5.2**). These data are summarized in **Table 5.4**. Some of the DHC data collected prior to bioaugmentation showed what is believed to be false positives due to cross-contamination from the ambient and

ubiquitous presence of SDC-9™ from the fermentation production center, which is located within the same facility as the analytical lab. DHC data collected following the first bioaugmentation injection during Phase 4 indicated a lack of distribution and long-term growth of the bioaugmentation culture during the demonstration.

Table 5.4. Enumeration of DHC Bacteria in Groundwater during Phase 4

Well	Day 402 DHC/L	Day 458 (DHC/L
PMW-7S	**2.49E+05***	3.20E+01 U
PMW-7I	**9.50E+03***	3.20E+01 U
PMW-7D	**1.02E+03***	3.20E+01 U
PMW-8S	3.40E+01 U	3.20E+01 U
PMW-8I	3.40E+01 U	ND
PMW-8D	**1.54E+05***	3.20E+01 U

U - The compound was not detected at the indicated concentration.

ND - No data.

DHC/L - *Dehalococcoides* cells per liter

*Positive results are believed to be the result of cross-contamination
  from the CB&I Fermentation facility.

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6.0   PERFORMANCE ASSESSMENT

Performance objectives were established for this demonstration to provide a basis for evaluating the use of solar-powered PRT to increase the pH of a naturally-acidic, TCE-contaminated aquifer at JB MDL, and to use the H_2 produced by proton reduction to support biological TCE dechlorination.   Performance criteria were selected based on factors that would likely be considered when bringing the proposed technology to full-scale application.   The performance objectives are provided in **Table 3.1**. A summary of the data for each given objective is provided in **Section 5.6**. As summarized in **Table 3.1**, not all of the critical performance objectives for this demonstration were achieved. The following subsections provide a summary and assessment of the data supporting the performance objectives.

6.1   INCREASE AND MAINTAIN NEUTRAL AQUIFER PH

For this performance objective to be considered successful, the pH of the groundwater in test plot monitoring wells immediately downgradient of the cathodes (i.e., treatment zone) needed to be increased and maintained to between 6 and 8 SUs. As detailed in **Section 5.6.1**, no significant increases in aquifer pH were observed at the monitoring wells located downgradient of the cathodes during Phase 1 through Phase 3 of the demonstration. Upon initiating operation of a small recirculation system on day 233 (Phase 4), groundwater pH at some of the MLS well intervals (particularly well PMW-7S) began to increase, and pH levels near pH 6 were achieved. However, consistent and significant pH increases throughout the designed treatment zone were not observed during Phase 4 of the demonstration. It is likely that the degree of electrolysis occurring at the cathode during Phase 4 was not sufficient to substantially increase the pH of acidic groundwater being continually re-circulated into the cathode/IW, as the high pH levels observed in the electrode/cathode wells during Phases 1–3 of operation were not observed during Phase 4. While increases in groundwater pH $\geq$6 SUs were observed at some of the MLS well intervals during the demonstration, the PRT system (as configured) was unable to maintain a consistent pH between 6.0 and 8.0 SUs within the designed treatment area. Therefore, this performance metric was only partially achieved.

6.2   PRODUCTION OF H_2 AT THE CATHODE

This performance objective was to be considered successful if groundwater dissolved H_2 concentrations of >160 µg/L (approximately 10% of solubility) were measured at each of the three cathode wells. As detailed in **Section 5.6.2**, once operation of the proton reduction system was optimized, H_2 concentrations in the demonstration plot cathode wells consistently exceeded 160 µg/L and reached concentrations up to approximately 1,200 µg/L (>90% of solubility). H_2 concentrations in the cathode well groundwater remained high during Phases 1 and 2 of the demonstration. During Phase 3 and 4 of the demonstration, H_2 concentrations in the cathode well(s) decreased because the addition of extracted water to the cathode wells (i.e., IWs) continually diluted H_2 concentrations and forced the H_2-containing groundwater into the aquifer. During operating phases where groundwater was not being re-injected into cathode wells (Phases 1 and 2), dissolved H_2 concentrations of >130 µg/L were consistently measured in the groundwater within the three cathode wells. Therefore, this performance metric was achieved.

6.3   DISTRIBUTION OF H₂ TO 1 METER DOWNGRADIENT OF THE CATHODE

This performance objective was to be considered successful if groundwater H_2 concentrations of >0.010 µg/L (2.5 times the concentration required to support reductive dechlorination) were present at least 1 m downgradient of the cathode wells. As discussed in **Section 5.6.2**, H_2 concentrations occasionally exceeded 0.010 µg/L at the MLS wells closest to the cathode wells during the demonstration. However, H_2 concentrations were more typically below the detection level (<0.008 µg/L) at these wells. Furthermore, dissolved H_2 concentrations at the two MLS wells monitored during Phase 4 of the demonstration were typically below 0.010 µg/L. Considering H_2 concentrations at well CW-2 (cathode/IW) were typically >50 µg/L during this Phase, this suggests that there was a substantial sink for H_2 between CW-2 (cathode/IW) and the MLS wells (located 2.5 ft and 5.0 ft away, and within the recirculation loop). While occasional detections of H_2 >0.010 µg/L were observed at some of the MLS well intervals during the demonstration, H_2 was not consistently observed at or above the target concentration within the designed treatment area. Therefore, this performance metric was partially achieved.

6.4   REDUCTION OF TCE AND *CIS*-DCE IN THE TEST PLOT

This performance objective was to be considered successful if TCE and *cis*-DCE concentrations in the test plot monitoring wells were reduced by >95%. As discussed in **Section 5.6.4**, measureable reductions in TCE concentrations, ranging between 31% and 89%, were observed at five of the six MLS well intervals monitored throughout the course of the demonstration. Notable transient increases in *cis*-DCE concentrations were observed in the treatment zone monitoring wells during the last ~100 days of the demonstration, with increases of up to an order of magnitude detected. These data suggest that partial dechlorination of TCE was occurring within the treatment zone. However, the lack of observed VC or ethene concentrations at these wells indicated that complete reductive dechlorination was not occurring at a significant rate. This was likely due (at least partially) to the sub-optimal pH and ORP levels that had been achieved within the treatment zone.   While significant reduction in TCE concentrations were achieved, complete reductive dechlorination was not observed, and reductions of TCE and cis-DCE by >95% were not achieved.

6.5   COMPLETE AND PROLONGED BIODEGRADATION OF TCE AND CIS-DCE TO ETHENE

This performance objective was to be considered successful if reductive dechlorination of TCE and *cis*-DCE were prolonged throughout the period of operation, and if TCE degradation proceeded completely to ethene without stalling at *cis*-DCE or VC. It was expected that *cis*-DCE and VC would be produced as transient intermediates of TCE degradation and also would be rapidly degraded. As discussed in **Section 5.6.4**, while some substantial transient increases in *cis*-DCE were observed at some of the test plot MLS wells, only traces of VC were observed. Furthermore, while some low levels of ethene were observed, the source of the measured ethene is not certain. These data suggest that partial dechlorination of TCE was occurring during the demonstration, and that complete reductive dechlorination was limited.   Therefore, this performance metric was not achieved.

6.6   DISTRIBUTION AND GROWTH OF ADDED DHC

This performance objective was to be considered successful if qPCR data indicated that DHC was distributed downgradient of the injection point, and that DHC concentrations increases *in situ* to >1.0 x 10^7 cells/L as cVOCs were reduced. As discussed in **Section 5.6.5**, DHC data collected during the demonstration indicated a lack of distribution and growth of the bioaugmentation culture during the demonstration, therefore, this performance objective was not achieved.

6.7   ELECTRODE STABILITY FOR >1 YEAR

This performance objective was to be considered successful if the electrodes operated effectively, without measurable loss of performance for >1 yr. Additionally, electrode corrosion observed during inspections must have been minimal. Regular system operation measurements collected during the demonstration indicated that there was no significant decrease in electrode performance (i.e., loss of current at a given voltage) during two years of operation. While some fouling of the cathodes was observed during inspections, this did not appear to significantly impact electrode performance. Therefore, this performance metric was achieved.

6.8   DESIGN AND IMPLEMENTATION OF A FIELD DEMONSTRATION SYSTEM

This performance objective was to be considered successful if the solar-powered proton reduction system operated continually (i.e., for a minimum of 12 months) with minimal downtime and supervision (i.e., <8 hr of manpower per month required to successfully operate the system). Field observations and system operating records indicated that the system operated >95% of the time over a two-year period, with minimal operations and maintenance (O&M) required. Therefore, this performance metric was achieved.

6.9   SUSTAINED SOLAR OUTPUT TO OPERATE THE PRT SYSTEM

This performance objective was to be considered successful if the electrical output derived from the solar power was sufficient to power the proton reduction system for the course of the demonstration (i.e., a minimum of 12 months) with no additional external power required. Field observations and system operating records indicate that the solar power system operated >95% of the time over a two-year period, with minimal O&M required. Therefore, this performance metric was achieved.

6.10   NO SAFETY HAZARDS OR INCIDENTS DURING SYSTEM OPERATION

This performance objective was to be considered successful if there were no observed or recorded safety incidents or hazardous conditions during system operation and monitoring over the course of the demonstration. Safety observations and records indicated that there were no safety incidents or injuries that occurred during the demonstration. A build-up of H_2 gas was measured in the sealed cathode wells during early operation of the PRT system. H_2 buildup was mitigated by opening the valves on the cathode well heads, and drilling holes in the lids of the well vaults to allow H_2 to dissipate from the wells. No explosive conditions were measured (via combustible gas meter) during the demonstration. Therefore, this performance metric was achieved.

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7.0 COST ANALYSIS

7.1 COST MODEL

In order to evaluate the cost of a potential full-scale PRT system, and compare it against other remedial approaches, costs associated with various aspects of the demonstration were tracked throughout the course of the project. **Table 7.1** summarizes the various cost elements and total cost of the demonstration project. The costs have been grouped by categories as recommended in the Federal Remediation Technologies Roundtable Guide to Documenting Cost and Performance for Remediation Projects (FRTR, 1998). Many of the costs shown in this table are a product of the innovative and technology validation aspects of this project, and would not be applicable to a typical site application. Therefore, a separate "discounted costs" column that excludes or appropriately discounts these costs has been included in **Table 7.1** to provide a cost estimate for implementing this technology at the same scale as the demonstration (i.e., pilot scale).

Costs associated with the demonstration were tracked from March 2010, to September 2015. The total cost of the demonstration was $1,031,800 which included $339,487 in capital costs, $209,445 in O&M costs, and $482,868 in demonstration-specific costs (cost related to Environmental Security Technology Certification Program (ESTCP) requirements, site selection, and characterization).

7.1.1 Capital Costs

Capital costs (primarily system design and installation) accounted for $339,487 (or 33%) of the total demonstration costs. As indicated in **Table 7.1**, these costs exceed what would be expected (the discounted cost) during a typical remediation project due partially to the large number of PMWs (12 multi-level wells) installed within the relatively small (40-ft x 40-ft) demonstration area.

7.1.2 O&M Costs

O&M costs accounted for $209,445 (or 20%) of the total demonstration cost. These costs consisted primarily of groundwater monitoring (including analytical), system O&M, and reporting costs. System O&M costs were $32,110, or 3% of total demonstration costs. Extensive performance monitoring activities were conducted to effectively validate this technology including 2 baseline, 12 performance monitoring, 16 dissolved H_2, and 13 tracer testing groundwater sampling events.

7.1.3 Demonstration-Specific Costs

Other demonstration-specific costs (costs not expected to be incurred during non-research-oriented remediation projects) accounted for approximately $482,900 (or 47%) of the total demonstration cost. These costs included site selection, laboratory treatability studies, laboratory buffer testing, laboratory electrode testing, hydrogeologic testing, tracer tests, ESTCP demonstration reporting and meeting (Interim Progress Report) requirements, and preparation of extensive technical and cost and performance reports.

Table 7.1. Demonstration Cost Components

Cost Element	Details	Tracked Demonstration Costs	Discounted Costs[1]
CAPITAL COSTS			
Groundwater Modeling	Labor	$8,265	$4,132
System Design	Labor	$32,661	$16,331
Well Installation, Development & Surveying[2]	Labor	$51,978	$25,989
	Materials	$4,888	$2,444
	Subcontracts (driller/surveyor)	$67,129	$33,565
System Installation (electrical service, control panel, trenching, system materials)	Labor	$88,559	$88,559
	Equipment & Materials	$83,020	$83,020
	Subcontracts	$0	$0
Bioaugmentation	Labor and Materials	$2,987	$2,987
	Subtotal	**$339,487**	**$257,027**
OPERATION AND MAINTENANCE COSTS			
Groundwater Sampling	Labor	$73,384	$36,692
	Materials	$5,001	$2,500
Analytical	In-House Labor	$88,219	$44,110
	Outside Labs	$4,878	$2,439
System O&M (including testing & start-up)	Labor	$32,110	$16,055
	Materials	$0	$0
Reporting & Data Management	Labor	$4,280	$4,280
Travel		$1,573	$1,573
	Subtotal	**$209,445**	**$107,649**
OTHER TECHNOLOGY-SPECIFIC COSTS			
Site Selection	Labor	$33,317	$0
Site Characterization (drilling investigation, depth-dependent sampling, slug tests, pump tests)	Labor (including in-house analytical)	$48,749	$0
	Materials	$0	$0
	Subcontractor (driller)	$8,900	$0
Treatability Studies and Column Testing	Labor (including in-house analytical)	$55,120	$0
	Outside Lab	$0	$0
Lab Buffer Testing	Labor (including in-house analytical)	$21,072	$0
Lab Electrode Testing	Labor (including in-house analytical)	$58,677	$0
Hydrogeologic Testing	Labor & Travel	$10,249	$0
Tracer Testing	Labor & Travel	$21,108	$0
IPR Meeting & Reporting	Labor & Travel	$31,335	$0
Monthly and Quarterly Reports	Labor & Travel	$33,081	$0
Technology Transfer (presentations, papers)	Labor & Travel	$33,196	$0
Demonstration Plan/Work Plan	Labor	$42,104	$21,052
Final Report	Labor	$65,732	$32,866
Cost and Performance Report	Labor	$20,225	$0
	Subtotal	**$482,868**	**$53,918**
	TOTAL COSTS	**$1,031,800**	**$418,594**

Notes:

[1] Discounted costs are defined as estimated costs to implement this technology at the same scale as the demonstration. These costs do not include the technology validation apects of this ESTCP demonstrations, such as site selection, treatability studies, extensive groundwater sampling, ESTCP demonstration reporting and meeting (IPR) requirements, and preparation of technical and cost and performance reports.

7.2   COST DRIVERS

The expected cost drivers for installation and operation of a PRT system, and those that will determine the cost/selection of this technology over other options, include the following:

- Depth of the plume bgs;
- Width, length, and thickness of the plume;
- Aquifer lithology and hydrogeology;
- Regulatory considerations concerning secondary groundwater impacts (i.e., metals mobilization, sulfate reduction, etc.);
- Length of time for clean-up (e.g., necessity for accelerated clean-up);
- The presence of indigenous bacteria capable of degrading cVOCs;
- Concentrations of contaminants and alternate electron acceptors (e.g., nitrate [NO_3^-], sulfate [SO_4^{2-}], and O_2); and
- Presence of co-contaminants.

7.3   COST ANALYSIS

A cost analysis of PRT and two traditional cVOC groundwater treatment approaches was performed.   Cost estimates for full-scale application were developed for the following technologies:

1. PRT barrier;
2. Passive trench zero-valent iron (ZVI) PRB; and
3. Pump and treat (P&T).

These three technologies were selected for comparison because they are all applicable for treatment of low pH aquifers, and are typically applied as treatment barriers or for plume capture. The base case presented in Krug et al. (2009) is used as a template for the cost analysis of the above technologies/approaches.   The base case presents a situation where a shallow aquifer, consisting of homogeneous silty sands, is contaminated with TCE.   The contaminated groundwater extends from 10 to 50 ft bgs, along the direction of groundwater flow for 800 ft, and is 400 ft in width (**Figure 7.1**).   The specific base case site characteristics, including aquifer characteristics and design parameters for each of the remedial approaches analyzed, are summarized in **Table 7.2**. The costing for the template site assumes that the source zone has been treated and that there is no continuing source of groundwater contamination.   The cost analyses comparing the above approaches are presented below based on a 30-year operating scenario.
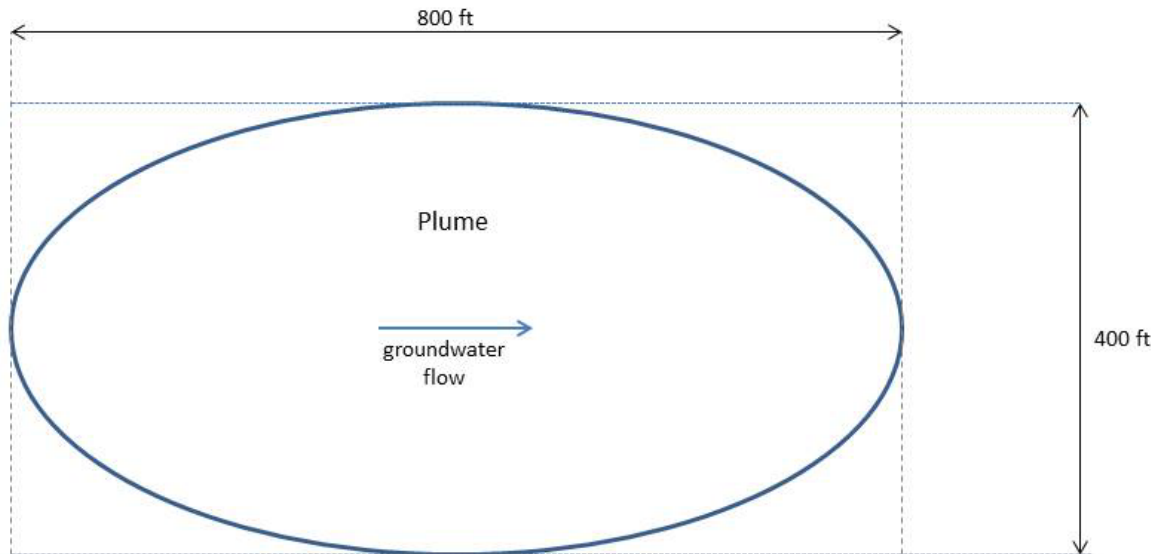
Figure 7.1. Base Case Plume Characteristics

Table 7.2. Summary of Base Case Site Characteristics and Design Parameters

Design Parameter	Units	Alternative		
		Proton Reduction Barrier	ZVI PRB	Pump and Treat
Width of Plume	feet	400	400	400
Length of Plume	feet	800	800	800
Depth to Water	feet	10	10	10
Vertical Saturated Thickness	feet	40	40	40
Porosity	dimensionless	0.25	0.25	0.25
Gradient	dimensionless	0.008	0.008	0.008
Hydraulic Conductivity	ft/day	2.8	2.8	2.8
Groundwater Seepage Velocity	ft/year	33	33	33
Nitrate Concentration	mg/L	15	15	15
Dissolved Oxygen Concentration	mg/L	5	5	5
Number of Barriers	each	1	1	1
Number of Monitoring Wells	each	10	10	10
Number of Sparge Wells	each	0	0	0
Number of SVE Wells	each	0	0	0
Number of Extraction/Injection Wells	each	0	0	9

The following subsections provide cost estimates for implementation of each of the three treatment approaches for the base case. The cost estimates provide insight into the comparative capital, O&M, and long-term monitoring (LTM) costs to better identify cost drivers for each technology/approach. Total costs and the Net Present Value (NPV) of future costs were calculated for each of the treatment approaches. Future costs (O&M and LTM costs) are discounted using a

1.5% real discount rate to determine the NPV estimates of these costs (OMB Circular A-94, 2016). Specifically excluded from consideration are the costs of pre-remedial investigations and treatability studies, assuming the costs for these activities would be similar for each alternative. The cost estimates for each of the alternatives also assume the long-term performance monitoring costs are identical for each alternative. Monitoring is assumed to be at a quarterly frequency for the first five years and an annual frequency thereafter.

7.3.1   Proton Reduction Technology (PRT) Barrier

The PRT barrier alternative assumes that a series of electrodes will be installed at the downgradient edge and perpendicular to the axis of the plume (**Figure 7.2**). The system will include 200 cathodes installed with 2-ft spacing across the 400-ft-wide plume. A system of 40 anodes will be installed downgradient of the cathodes. The electrodes would be installed by direct-push drilling methods, and consist of metal mesh electrode ribbon and coke breeze to provide electrical contact with the formation. A one-inch diameter PVC well would be installed with every fifth cathode.
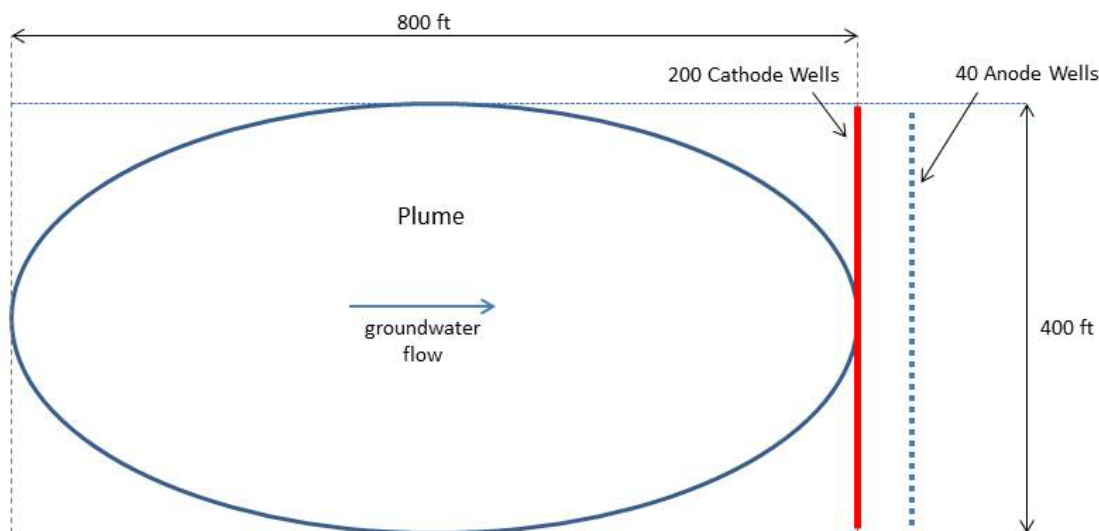
Figure 7.2. PRT Barrier Alternative for Plume Cutoff

Several electrical supply options for powering the PRT barrier were evaluated including the following:

1. Off-grid solar with daytime only operation,
2. Off-grid solar with 24-hr/day operation,
3. Solar tied to grid, and
4. Non-solar grid only.

A cost comparison of each of these options was performed, and the estimated costs for the electrical supply components are provided in **Table 7.3**. The cost estimates assume other cost elements remain the same for system design, well and electrode installation, system installation, O&M, and LTM.

Table 7.3. Cost Comparison of PRT System Electric Supply Options

Alternative	Capital Costs	NPV of 30 Years of O&M Costs	Total 30-Year Electrical Costs
Off-Grid Solar, Daytime-Only Operation	$31	$0	$31
Off-Grid Solar, 24-Hour Operation	$180	$260	$440
Solar Tied to Grid, 24-Hour Operation	$150	$0	$150
Non-Solar Grid-Only, 24-Hour Operation	$30	$205	$235

Notes:

All costs are in thousands of dollars

NPV - Net Present Value; current value of future costs based on a 1.4% annual discount rate

O&M - Operation and Maintenance

The electrical supply option chosen for the cost estimate to provide a comparison to the other remedial technologies was solar tied to grid with 24-hr operation. This option assumes the solar power system would be tied to the grid, and excess solar power generated during peak hours would be fed back to the grid to offset costs. The system would be powered by solar panels during daylight hours and by the electrical grid during non-daylight hours. The option would provide the necessary power by solar panels with no net cost for use of the grid. While not the lowest-cost electrical supply option, this option provides the flexibility of 24-hr operation coupled with renewable energy.

As summarized in **Table 7.4**, the estimated total costs for the PRT barrier alternative over 30 years are $2,907,344 with a total NPV of lifetime costs of $2,523,258. The capital cost including design, work plan, installation of electrodes and monitoring wells, and the electrical supply costs described above are $641,520. The NPV of the O&M is $1,061,326 for the 30 years of treatment. The O&M costs primarily include the labor and material costs associated with weekly inspections. The costs for material and other consumables are negligible with this alternative. The NPV of the 30 years of monitoring and reporting costs is $820,411.

Table 7.4. Cost Components for PRT System

	Year Cost is Incurred							NPV of Costs*	Total Costs
	1	2	3	4	5	6	6 to 30		
CAPITAL COSTS									
System Design	70,000	-	-	-	-	-		70,000	70,000
Well Installation	214,735	-	-	-	-	-		214,735	214,735
System Installation	338,807	-	-	-	-	-		338,807	338,807
Start-up and Testing	17,978	-	-	-	-	-		17,978	17,978
SUBCOST ($)	641,520	-	-	-	-	-		641,520	641,520
OPERATION AND MAINTENANCE COSTS									
System Operation and Maintenance	32,227	33,227	33,227	33,227	33,227	33,227	32,227 every year	1,061,326	1,305,824
SUBCOST ($)	32,227	33,227	33,227	33,227	33,227	33,227		1,061,326	1,305,824
LONG TERM MONITORING COSTS									
Sampling/Analysis/Reporting	74,500	74,500	74,500	74,500	74,500	23,500	23,500 every year	820,411	960,000
(Quarterly through 5 years then Annually)									
SUBCOST ($)	74,500	74,500	74,500	74,500	74,500	23,500		820,411	960,000
TOTAL COST ($)	748,248	107,727	107,727	107,727	107,727	56,727		2,523,258	2,907,344

Notes:

NPV - Net Present Value

* - NPV calculated based on a 1.5% discount rate

This alternative ranks lowest in estimated total remedy cost and lowest in NPV of lifetime costs (see **Table 7.7**). The estimated capital cost for this approach is the lowest of the three alternatives because of the limited infrastructure required. The estimated long-term O&M costs are also the lowest of the three alternatives, which helps make this the least expensive of the alternatives. As with the other alternatives, total remedy costs will increase if the treatment needs to extend beyond 30 years.

7.3.2   Passive Trench ZVI PRB

The passive trench ZVI PRB alternative assumes an initial installation of a ZVI PRB in a trench at the downgradient edge and perpendicular to the axis of the plume (**Figure 7.3**). The PRB will consist of 25% ZVI filings and 75% coarse sand fill mixture (v/v). The PRB will be installed using the one-pass trenching/installation method, and will be 400 ft long, 2 ft wide, and extend down to 50 ft bgs. Pricing for this alternative assumes the PRB will need to be replaced every 10 years due to decline in ZVI reactivity or plugging. The PRB will be maintained for a period of 30 years, with replacements occurring in years 10 and 20. This alternative also assumes 30 years of associated O&M and LTM costs.
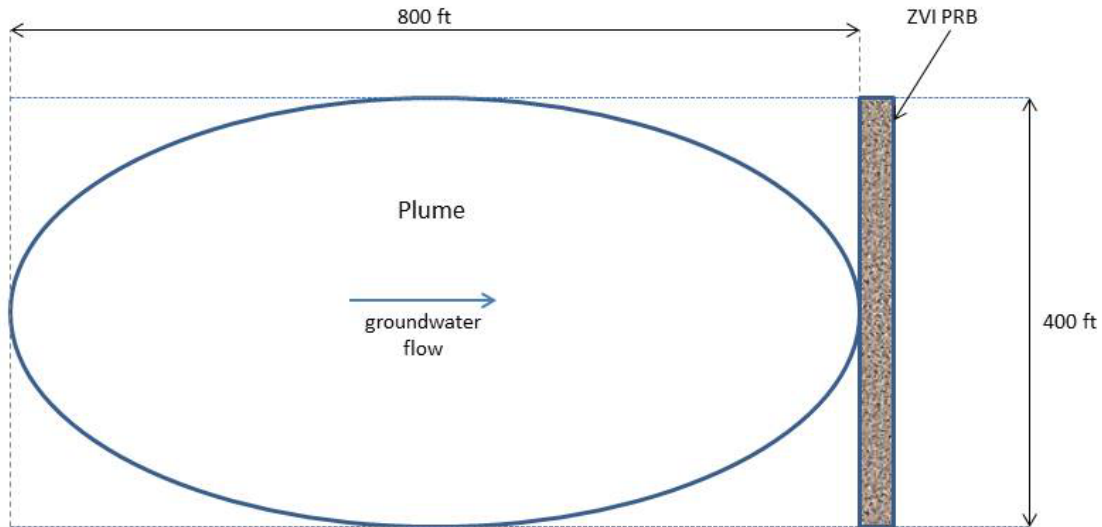
Figure 7.3. Passive PRB Alternative Utilizing ZVI for Plume Cutoff

As summarized in **Table 7.5**, the total costs for this alternative over 30 years are $3,648,342 with a total NPV of lifetime costs of $3,204,622. The capital cost including design, work plan, ZVI PRB installation, and installation of monitoring wells is $1,001,049. The NPV of the O&M is $1,383,162, which is the NPV associated with the replacement of the PRB every 10 years. The NPV of the 30 years of monitoring and reporting costs is $820,411.

Table 7.5. Cost Components for ZVI PRB

	Year Cost is Incurred								NPV of Costs*	Total Costs
	1	2 to 5	6	7	8	9	10	11 to 30		
CAPITAL COSTS										
System Design	70,000		-	-	-	-	-		70,000	70,000
Well Installation	54,495		-	-	-	-	-		54,495	54,495
Trench Installation	876,554		-	-	-	-	-		876,554	876,554
Start-up and Testing**	-		-	-	-	-	-		0	0
SUBCOST ($)	1,001,049		-	-	-	-	-		**1,001,049**	**1,001,049**
OPERATION AND MAINTENANCE COSTS										
ZVI Replacement Cost	-		-	-	-	-	843,647	843,647 year 20	1,383,162	1,687,294
SUBCOST ($)	-		-	-	-	-	843,647		**1,383,162**	**1,687,294**
LONG TERM MONITORING COSTS										
Sampling/Analysis/Reporting	74,500	74,500 years 2 to 5	23,500	23,500	23,500	23,500	23,500	23,500 every year	820,411	960,000
(Quarterly through 5 years then Annually)										
SUBCOST ($)	74,500		23,500	23,500	23,500	23,500	23,500		**820,411**	**960,000**
TOTAL COST ($)	**1,075,549**		**23,500**	**23,500**	**23,500**	**23,500**	**867,147**		**3,204,622**	**3,648,342**

Notes:

NPV - Net Present Value

* - NPV calculated based on a 1.5% discount rate

** - No "Start-up and Testing" costs are included because no operating equipment is left behind following PRB installation

This alternative ranks second in estimated total remedy cost and NPV of lifetime costs (**Table 7.7**). The estimated capital costs for this approach are the second lowest, due largely to the relatively high cost of the initial PRB installation. The long-term O&M costs associated with this alternative

are also the second lowest due to the lack of O&M requirements between PRB replacements. The total remedy costs for this alternative would increase significantly if the PRB lifespan was <10 years or if treatment extended beyond 30 years.

7.3.3   Active pump and treat (P&T)

The groundwater extraction and treatment (P&T) system alternative is similar to the other technologies in that a downgradient barrier is installed (**Figure 7.4**). The system includes a row of four EWs and five IWs, which would be used to create a groundwater capture zone at the downgradient edge perpendicular to the axis of the plume (**Figure 7.4**). The extracted groundwater would be treated above-ground by air stripping followed by treatment with granular activated carbon (GAC). The treated groundwater would be re-injected providing hydraulic control and mass removal at the downgradient edge of the plume. The P&T system would be maintained for a period of 30 years. This alternative also assumes 30 years of associated O&M and LTM costs.
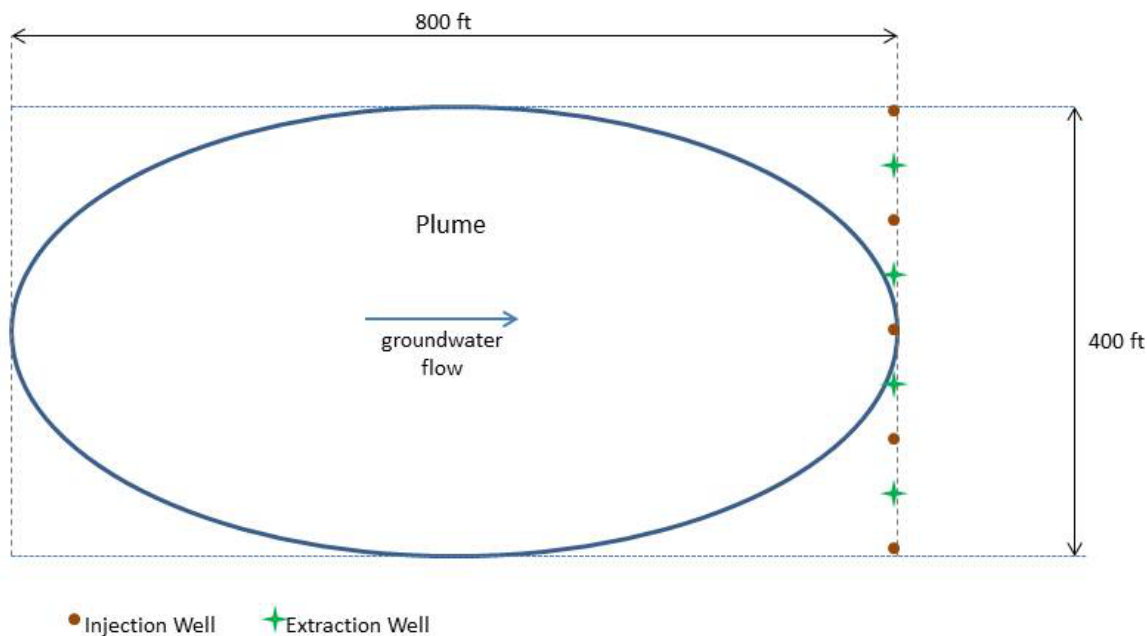
Figure 7.4. P&T Alternative for Plume Cutoff

As summarized in **Table 7.6**, the total cost for this alternative over 30 years is $7,049,118 with a total NPV of lifetime costs of $6,092,685. The capital cost including design, work plan, installation of IW/EW and monitoring wells, construction of the groundwater treatment system, and system start up and testing is $1,737,284. The NPV of the O&M is $3,534,990. The O&M costs include the labor costs associated with system O&M, costs for equipment repair and replacement, electrical costs, and cost for the replacement and disposal of the GAC. The NPV of the 30 years of monitoring and reporting costs is $820,411.

Table 7.6. Cost Components for P&T

| | Year Cost is Incurred | | | | | | | NPV of Costs* | Total Costs |
	1	2	3	4	5	6	6 to 30		
CAPITAL COSTS									
System Design	90,352	-	-	-	-	-		90,352	90,352
Well Installation	128,350	-	-	-	-	-		128,350	128,350
System Installation	1,492,333	-	-	-	-	-		1,492,333	1,492,333
Start-up and Testing	26,250	-	-	-	-	-		26,250	26,250
SUBCOST ($)	1,737,284	-	-	-	-	-		1,737,284	1,737,284
OPERATION AND MAINTENANCE COSTS									
System Operation and Maintenance	139,744	145,244	145,244	145,244	145,244	145,244	145,244 every year	3,534,990	4,351,834
SUBCOST ($)	139,744	145,244	145,244	145,244	145,244	145,244		3,534,990	4,351,834
LONG TERM MONITORING COSTS									
Sampling/Analysis/Reporting	74,500	74,500	74,500	74,500	74,500	23,500	23,500 every year	820,411	960,000
(Quarterly through 5 years then Annually)									
SUBCOST ($)	74,500	74,500	74,500	74,500	74,500	23,500		820,411	960,000
TOTAL COST ($)	1,951,529	219,744	219,744	219,744	219,744	168,744		6,092,685	7,049,118

Notes:

NPV - Net Present Value

* - NPV calculated based on a 1.5% discount rate

This alternative ranks highest in both estimated total remedy cost and NPV of lifetime costs (**Table 7.7**). The estimated capital costs for this alternative are higher than the other two alternatives because of the higher costs associated with constructing a groundwater treatment system. The high O&M costs associated with operating the P&T system are what makes this alternative one of the most expensive of the alternatives. As with the other approaches, total remedy costs will increase if the treatment needs to extend beyond 30 years.

Table 7.7. Summary of Costs for Treatment Alternatives.

Alternative	Capital Costs	NPV of 30 Years of O&M Costs	NPV of 30 Years of Monitoring Costs	NPV of 30 Years of Total Remedy Costs	Total 30-Year Remedy Costs
Proton Reduction Barrier	$642	$1,061	$820	$2,523	$2,907
ZVI PRB	$1,001	$1,383	$820	$3,205	$3,648
Pump and Treat	$1,737	$3,535	$820	$6,093	$7,049

notes:

All costs are in thousands of dollars

NPV - Net Present Value; current value of future costs based on a 1.5% annual discount rate

O&M - Operation and Maintenance

8.0 IMPLEMENTATION ISSUES

Results of the demonstration showed that PRT can elevate the pH of groundwater, but that the process is slow because it depends on effective distribution of the high pH groundwater that accumulated in the cathode well. During this demonstration, even the recirculation of groundwater through the cathode well resulted in slow pH increases. The primary source of pH buffering in the system was clearly the aquifer sediments. Thus, pH adjustments using proton reduction alone is likely to require extensive treatment times.

Evaluation of groundwater in the cathode wells at the site demonstrated that high levels of H_2 can be generated *in situ*, but distribution of this H_2 in the aquifer remains a challenge. Results of the demonstration suggested that the aquifer contained many potential sinks for H_2—including the reduction of Fe, Mn, and sulfate—that may need to be overcome to achieve high levels of sustained reductive dechlorination. The fact that dechlorination can be performed even with very low levels of H_2 (2 nM) suggests that even if distribution is limited, there may be sufficient H_2 *in situ* to support significant TCE dechlorination under better geochemical conditions (i.e., higher pH).

Results of the demonstration showed that reductive dechlorination can potentially be supported by PRT, but, under the conditions of the demonstration, TCE dechlorination was not complete. The lack of complete dechlorination, even after bioaugmentation, was likely due to the borderline pH and reducing conditions achieved in the aquifer. It is possible that dechlorination activity could have been improved if a higher pH (e.g., pH 6.5 to 7) or more reducing conditions (e.g., ORP <- 100 mV) were consistently achieved.

Overall, the results of this demonstration show that achieving and maintaining elevated pH levels in naturally acidic aquifers like those at JB MDL is a significant challenge. Although proton reduction showed some potential for increasing pH and lowering ORP, the configuration of the PRT system during this demonstration was not sufficient for achieving and maintaining optimal geochemical conditions over extended periods. Because a circumneutral pH and highly-reducing conditions could not be achieved, efficient dechlorination of TCE also could not be achieved. PRT, therefore, may be a useful component of a treatment system for remediating an acidic aquifer, with additional treatments/amendments needed to better address and overcome the significant soil buffering capacity of such aquifers. Alternatively, PRT could be reconfigured to better address the shortcoming observed during this demonstration.

The results of the study, however, have provided some guidance for future development and application of this technology. Clearly, the distribution of H_2 *in situ* is affected by both competitive H_2 consumption by non-dechlorinating bacteria, and by the relatively low solubility of H_2. Likewise, the distribution of high pH groundwater generated at the cathodes is limited, especially if groundwater flow is determined by natural flow gradients. One approach that has recently been shown to mitigate these limitations is using more closely-spaced electrodes. This approach has been successfully tested in the field under the U.S. Navy's Environmental Sustainability Development to Integration (NESDI) program, and is designated NESDI Project 501. This demonstration was conducted within a low pH cVOC-contaminated aquifer at the southern end of the Russell Road Landfill, located at Marine Corps Base Quantico, in Quantico, Virginia. During this one-year field

demonstration, eight closely-spaced cathodes and two downgradient anodes were installed in a barrier configuration to provide greater aquifer pH adjustment and H_2 delivery to contaminated groundwater passing through the barrier. Decreases in *cis*-DCE (the primary contaminant of concern) ranging from 88% to 99% were observed in the five treatment zone wells during this demonstration.

Furthermore, it was determined through the NESDI project laboratory and field studies that current through the aquifer can be significantly increased if better contact is achieved between the electrodes and the soil matrix. This increased matrix contact results in greater rates of hydrolysis, acid consumption, and H_2 production than when electrodes are suspended in groundwater only; placing electrodes within a PVC monitoring well with acidic, low-conductivity groundwater is equivalent to suspending the electrode in a resistor. Improved soil contact can be achieved by backfilling the annulus around the electrodes with a metallurgical soil contact material like coke breeze (Loresco® International, Hattiesburg, MS). These backfill materials are engineered to have low resistance and to improve contact between electrodes and soils. They are inexpensive and are used primarily in corrosion prevention systems (i.e., cathodic protection). Moreover, the use of this material eliminates the need for installation of a well for each electrode. This approach was used successfully during NESDI Project 501, and has been shown to reduce electrode installation costs, allowing more electrodes to be installed at closer spacing for the same cost. It is also believed that this electrode installation method (which includes a bentonite seal above the backfill) may reduce the loss of H_2 (as H_2 gas) that was observed through the top of the well casings during this project.

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