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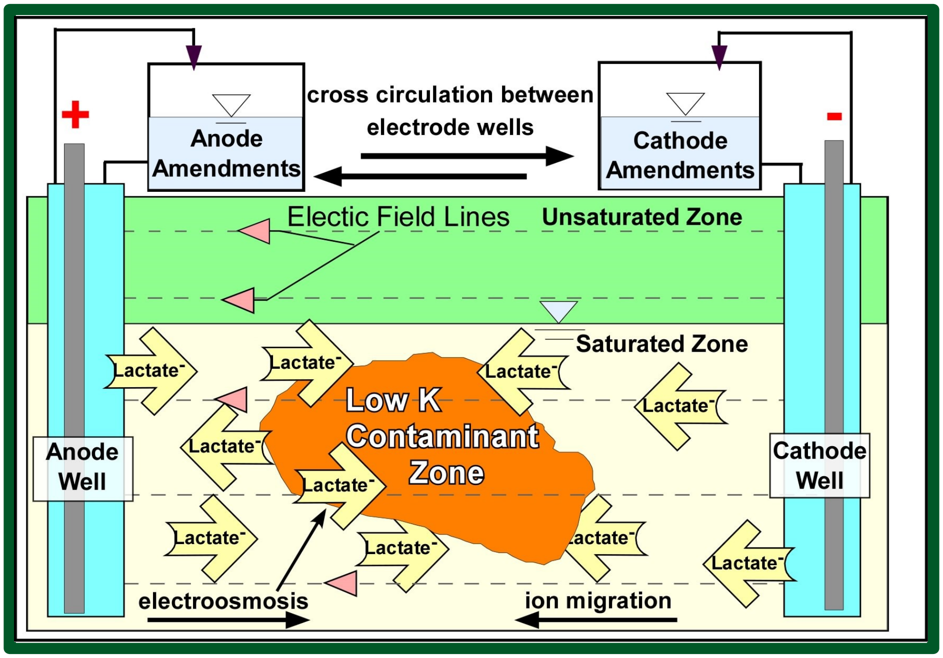

Electrokinetic-Enhanced (EK-Enhanced) Amendment Delivery for Remediation of Low Permeability and Heterogeneous Materials

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This project demonstrated and validated electrokinetic(EK)-enhanced amendment delivery for in-situ bioremediation (EK-BIO) via enhanced reductive dechlorination (ERD) of a tetrachloroethene source area in clay. The EK-enhanced amendment delivery technology entails the establishment of an electric field in the subsurface using a network of electrodes. The electrical current and voltage gradient established across a direct-current electric field provide the driving force to transport remediation amendments, including electron donors, chemical oxidants, and even bacteria, through the subsurface. This project showed that EK could achieve relatively uniform transport in low-permeability materials. This technology also represents a remedial alternative with excellent environmental performance.

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ACRONYMS AND ABBREVIATIONS

A	amp
bgs	below ground surface
cm	centimeter
cm/sec	centimeter per second
CVOC	chlorinated volatile organic compounds
cDCE	cis-1,2-dichloroethene
k_e	coefficient of electroosmotic permeability
Dhb	*Dehalobacter*
Dhc	*Dehalococcoides*
Dem/Val	Demonstration/Validation
DoD	Department of Defense
DO	dissolved oxygen
dc	*direct-current*
DPT	Direct Push Technology
EK-BIO	EK-enhanced amendment delivery for in-situ bioremediation
EK	electrokinetic
K_{eo}	electroosmotic permeability
ERH	electrical resistance heating
ERDC	Engineer Research & Development Center
EISB	enhanced in-situ bioremediation
ERD	enhanced reductive dechlorination
ESTCP	Environmental Security Technology Certification Program
EVO	Emulsified Vegetable Oil
ft	feet
g/L	grams per Liter
gpm	gallons per minute
hp	horsepower
K_h	hydraulic conductivity
H_2	hydrogen
ISCO	in-situ chemical oxidation
kW-hr	kilowatt hour
L	Liter
low-K	low-permeability

µg/L	microgram per Liter
mg/kg	milligram per kilogram
mV	millivolts
NAS	Naval Air Station
NAVFAC	Naval Facilities Engineering Command
OU3	Operable Unit 3
ORP	oxidation-reduction potential
O_2	oxygen
PVC	Polyvinyl chloride
K_2CO_3	potassium carbonate
PLC	programmable logic controller
qPCR	quantitative polymerase chain reaction
ROI	radius of influence
SERDP	Strategic Environmental Research and Development Program
TTA	target treatment area
PCE	tetrachloroethene
TCE	trichloroethene
TOC	total organic carbon
USACE	United States Army Corps of Engineers
VC	vinyl chloride
vcrA	vinyl chloride reductase
VFA	volatile fatty acid
VOC	volatile organic compound
V	volts
V/m	Volts per minute
W	watt

EXECUTIVE SUMMARY

This Demonstration/Validation (Dem/Val) project, performed at Naval Air Station (NAS) Jacksonville to target a tetrachloroethene (PCE) source area in clay materials, was conducted to validate the performance of an electrokinetic (EK) technique to promote uniform and effective distribution of remediation amendments (e.g., electron donors, electron acceptors, chemical oxidants) in low-permeability (low-K) and heterogeneous subsurface materials.

OBJECTIVES OF THE DEMONSTRATION

Recent advances in the understanding of mass distribution in subsurface environments has highlighted that in many cases a significant portion of the source mass is stored in low-K materials. The main limitation of current in-situ remediation applications in low-K materials using conventional hydraulic recirculation or injection techniques is the inability to effectively deliver the required amendments to the target contaminant mass. Estimated costs to Department of Defense (DoD) for adopting hydraulic containment at more than 3,000 chlorinated hydrocarbon sites could surpass $100 million annually, with estimated life-cycle costs of more than $2 billion (SERDP/ESTCP, 2006). EK-enhanced amendment delivery will: (1) broaden the applications of cost-effective in-situ remedial alternatives at many DoD sites where the presence of low-K materials previously precluded the consideration of in-situ technologies; and (2) provide an effective source remediation solution at sites where source mass in low-K materials would otherwise result in long-term hydraulic containment with significant remediation life-cycle costs.

The overall goal of this Dem/Val is to demonstrate and validate EK-enhanced amendment delivery for in-situ bioremediation (EK-BIO) via enhanced reductive dechlorination (ERD) of a PCE source area in clay. Based on the Dem/Val performance monitoring data, this Dem/Val met the following performance objectives:

I. *Achieved uniform distribution of the remediation amendments and relative uniformity of the established electrical field within the target treatment area (TTA).*

II. *Achieved effective reductive dechlorination by EK-BIO operation within the TTA.*

III. *Demonstrated suitability of this technology for full-scale implementation, including stable system operation conditions (voltage and current), >75% operation up-time, and low energy consumption.*

IV. *Validation of the technology as a safe (no lost-time incidents), reliable, and easy-to-implement remedial alternative.*

TECHNOLOGY DESCRIPTION

The EK-enhanced amendment delivery technology entails the establishment of an electric field in the subsurface using individual electrodes installed in a network of electrode wells. An EK control system is used to power the electrodes with direct current (*dc*) and supply amendment solutions to treatment wells. The electrical current and voltage gradient established across the *dc* electric field in the subsurface provide the driving force to transport remediation amendments, including electron donors, chemical oxidants, and bacteria throughout the treatment area.

The TTA for this Dem/Val had dimensions of approximately 40 feet by 40 feet, with a treatment depth interval (a clay layer) of 19 to 23 feet below ground surface (bgs). The EK system constructed for this Dem/Val included nine (9) electrode wells and eight (8) supply wells located within the TTA. The remediation amendments distributed by the EK remediation system included electron donor (lactate, provided as potassium lactate), pH control reagents (potassium carbonate), and a dechlorinating microbial consortium (KB-1®) containing *Dehalococcoides* (*Dhc*). Following the system startup, initial site conditioning, and bioaugmentation of the TTA, the Dem/Val included two (2) separate active EK operational stages of five months each, with a six-month incubation period between the two active stages.

DEMONSTRATION RESULTS

Groundwater monitoring data from EK application showed that within the TTA: (1) total organic carbon (TOC) or volatile fatty acids (VFAs, such as acetate, propionate, etc) increased by more than 5x from baseline; (2) PCE concentrations decreased by more than 80%, coupled with evident increases of dechlorination daughter products and ethene; and (3) biomarkers (*Dhc* and vinyl chloride reductase gene [*vcrA*]) increased by several orders of magnitude over the course of the Dem/Val. Soil sampling data showed that within the TTA, PCE concentrations in the clay decreased by an average of 88%.

This Dem/Val demonstrated a critical and distinct advantage of the EK-enhanced amendment delivery technique, namely the effective delivery of remediation amendments and ensuing PCE treatment in low-K materials. EK-enhanced delivery was shown to be a safe and controllable approach. This technology also represents a remedial alternative of excellent environmental performance with a very low energy demand. The total energy usage by the EK system during the 14 active months of the Dem/Val was 1,585-kilowatt hour (kW-hr), which is equivalent to operating two 100-watt (W) lightbulbs over the same time interval.

IMPLEMENTATION ISSUES

EK-BIO is mainly a variation on standard enhanced in situ bioremediation (EISB), whereby EK is used to more effectively deliver the required amendments through low-K materials. Based on the information and experience obtained from this Dem/Val, there are three main cost drivers and technical aspects to consider in future implementation, including: (1) footprint, depth interval, and volume of target treatment zone and contaminant mass; (2) presence and location of above-ground and subsurface utilities; and (3) site geochemistry, particularly pH, iron, and potential corrosion related to geochemical conditions.

The project team is currently in the process of preparing a manuscript for journal publication to disseminate the results of this Dem/Val. In addition, the results of the Dem/Val will be presented at multiple conferences. An announcement of project success and completion will be posted on Geosyntec's internet home page and will be provided to Environmental Security Technology Certification Program (ESTCP) for use in its various social media outreaches. The project team is also working to create several videos of technology design and operation that can be distributed via social media.

1.0 INTRODUCTION

This project, with collaboration from Naval Facilities Engineering Command (NAVFAC) and the United States Army Corps of Engineers (USACE) Engineer Research & Development Center (ERDC), demonstrated/validated (Dem/Val) the application of electrokinetic (EK) mechanisms to achieve effective distribution of remediation amendments (e.g., electron donors, electron acceptors, chemical oxidants) in low-permeability (low-K) and heterogeneous subsurface materials. This Dem/Val was performed at Naval Air Station (NAS) Jacksonville to target a tetrachloroethene (PCE) source area in clay materials.

1.1 BACKGROUND

After decades of experience, it is understood that in-situ remediation approaches tend to be more cost effective compared to more aggressive ex-situ methods. However, in-situ remediation techniques, such as enhanced in-situ bioremediation (EISB) and in-situ chemical oxidation (ISCO), while capable of treating various contaminants in permeable sandy aquifers, often fail to effectively target contaminants in silt and clay materials, or combinations of sand and low-K materials, thus extending remedial duration and substantially increasing remediation costs. Recent advances in the understanding of mass distribution in plumes has highlighted that in many cases a significant portion of the mass released from the source is held in storage in low-K materials, and that the release rate from low-K storage is many times slower than the loading rate. The main limitation of EISB and ISCO applications in low-K materials is the inability to effectively deliver the required amendments to the target mass contained within using conventional hydraulic recirculation or injection techniques.

While hydraulic fracturing has shown some promise in improving amendment distribution in low-K materials, the success of this approach has been limited by site access constraints, surface structure impact concerns, high cost, and consistency and predictability of induced fractures. Other technologies such as large diameter auger mixing and thermal treatment have shown promise in low-K materials. However, these approaches have been expensive and are also limited by site access and re-use limitations. Conventional thermal remediation approaches also face the challenges of removing and treating gaseous phase contaminants. Lower cost, and ideally more environmentally-sustainable, remediation approaches or improvements to existing technologies are required to reduce overall remediation costs at Department of Defense (DoD) and defense contractor sites.

The EK-enhanced amendment delivery technology entails the establishment of an electric field in the subsurface using a network of electrodes. The electrical current and voltage gradient established across a direct-current (*dc*) electric field provide the driving force to transport remediation amendments including electron donors, chemical oxidants, and even bacteria, through the subsurface. One reason why EK represents a fundamentally more effective delivery technique compared to an advective hydraulic approach is the relatively uniform electrical properties of various soil materials. As a result, EK-enhanced amendment delivery can achieve effective and uniform amendment distribution at sites where heterogeneous subsurface materials often limit the applications of hydraulic methods.

1.2 OBJECTIVE OF THE DEMONSTRATION

The overall goal of this project is to Dem/Val the use of EK-enhanced amendment delivery to achieve uniform and effective distribution of remediation amendments into and through low-K and heterogeneous materials in the subsurface, thereby improving the effectiveness of in-situ remediation (in this case EISB) and reducing the costs of remediation at DoD sites impacted by chlorinated and recalcitrant contaminants. Based on the performance monitoring data collected, this Dem/Val met the following performance objectives:

I. Achieved uniform distribution of the amendments and relative uniformity of the established electrical field.

The Dem/Val met this objective by meeting the success criteria, including:

- At groundwater monitoring locations within the target treatment area (TTA), after the completion of active EK operation, post-EK concentrations of total organic carbon (TOC) were at least 5x baseline and in many cases 10x baseline; and
- No local focusing of the electric field was observed within the TTA.

II. Achieved effective treatment of PCE by EK-enhanced amendment delivery for in-situ bioremediation (EK-BIO) operation within the TTA.

The Dem/Val met this objective by meeting the success criteria, including:

- >60% reduction in average PCE concentrations in soil and groundwater within the TTA. Groundwater data also showed coupled and comparable increases of dechlorination daughter and end products;
- Ethene was detected at 100% of groundwater monitoring wells within the TTA following EK-BIO application; and
- >10x increases of *Dehalococcoides* (*Dhc*) from baseline at >60% of soil and groundwater samples collected from within the TTA.

III. Demonstrated suitability of this technology for full-scale implementation.

The Dem/Val met this objective by meeting the success criteria, including:

- System operations (voltage and current) were maintained within ± 50% of the designed target conditions;
- Amendment supply up-time was >75% of target; and
- Energy consumption was within ± 30% of design estimates.

IV. Demonstrated safe, reliable, and easy-to-implement remedial alternative.

The Dem/Val met this objective by meeting the success criteria, including:

- Maintained stable system operation conditions (voltage and current);
- No lost-time incidents; and

- Required only conventional construction techniques and single operator for regular operation and maintenance (O&M) activities.

1.3 REGULATORY/TECHNICAL/COST DRIVERS

In 2011, a Strategic Environmental Research and Development Program /Environmental Security Technology Certification Program (SERDP/ESTCP)-sponsored workshop on *Investment Strategies to Optimize Research and Demonstration Impacts in Support of DoD Restoration Goals* identified treatment of contaminants in low-K subsurface materials (i.e. silts, clays, and bedrock) as a high-priority area for additional investment. The workshop participants noted that treatment of low-K zones would require adoption of cost-effective techniques that can target delivery of remedial agents to these regions and prevent continued back-diffusion of contaminants.

Estimated costs to DoD for adopting hydraulic containment at more than 3,000 chlorinated hydrocarbon sites could surpass $100 million annually, with estimated life-cycle costs of more than $2 billion (SERDP/ESTCP, 2006). EISB has generally been considered as one of the more cost-effective remedial options available for chlorinated solvent sites. However, there are sites where the effectiveness of EISB is limited by the presence of low-K zones, or sites where more expensive alternatives are the presumed options due to the concerns of low-K materials. EK-enhanced amendment delivery will: (1) broaden the application of cost-effective in-situ remedial alternatives at many DoD sites where the presence of low-K materials previously precluded the consideration of in-situ technologies; and (2) provide an effective source removal solution at sites where source mass in low-K materials will result in long-term hydraulic containment with significant remediation life-cycle costs.

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2.0 TECHNOLOGY

This section provides an overview of the EK-enhanced amendment delivery technology that was demonstrated in this project. Advantages and potential limitations associated with this technology are also discussed.

2.1 TECHNOLOGY DESCRIPTION

The EK-enhanced amendment delivery technology entails the use of electrodes and *dc* electrical current to establish an electric field in the subsurface. The voltage gradient established across the *dc* electric field is then the driving force for transporting remediation reagents, including electron donors for microorganisms, chemical oxidants, and even bacteria, through low-K soils or uniformly through heterogeneous formations. This Dem/Val project focused on the amendment transport facilitated by two EK transport mechanisms:

- ***Electromigration*** *(or ion migration)* – the movement of charged dissolved ions through an aqueous medium in response to the applied electric field; and
- ***Electroosmosis*** – the movement of pore fluid (and dissolved constituents) within a porous medium in response to the applied electric field.

One reason why EK represents a fundamentally more effective delivery technique for low-K and heterogeneous soils compared to an advective hydraulic approach is the relatively uniform electrical property of various soil materials. For example, as presented in **Figure 2-1**, while the hydraulic conductivity of fine sand and kaoline materials can vary by several orders of magnitude, the coefficient of electroosmotic permeability of fine sand (4.1E-05 square centimeters per second-volts [cm^2/sec-V]) is comparable to that of kaoline (5.7E-05 cm^2/sec-V) and clayey till (5.0E-05 cm^2/sec-V).

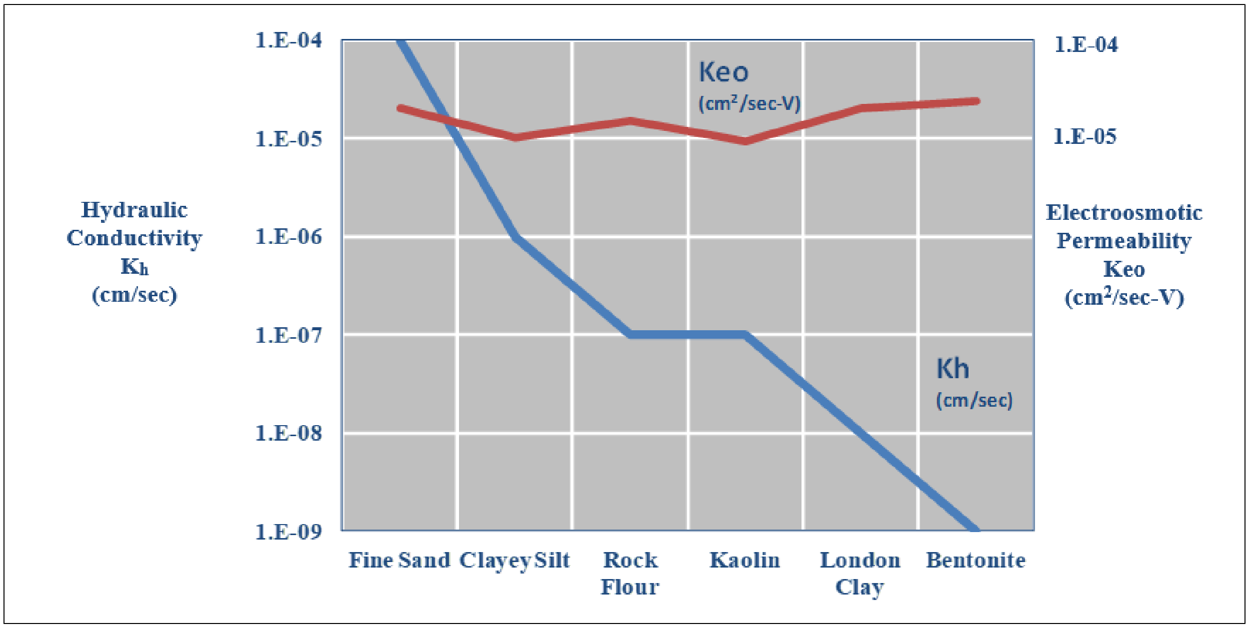


Figure 2-1. Hydraulic and Electrical Properties of Various Soils (rev. Mitchell, 1993)

The application of electric current will also result in electrolytic reactions at the electrodes. If inert electrodes (such as graphite or ceramic-coated electrodes) are used, water oxidation produces oxygen gas and acid (H_3O^+) at the anode (positively charged electrode), while water reduction produces hydrogen gas and base (OH^-) at the cathode (negatively charged electrode). Electrolytic reactions of water are shown below in Equations 1 and 2,

$$2H_2O \quad \text{==>} \quad 4e^- + 4H^+ + O_2 \qquad \text{(at Anode)} \qquad (1)$$

$$2H_2O + 2e^- \quad \text{==>} \quad 2OH^- + H_2 \qquad \text{(at Cathode)} \qquad (2)$$

Faraday's law for equivalence of mass and charge can be used to calculate the rate of redox reactions that will occur at the electrodes (Koryta and Dvorak, 1987). Therefore, it is possible to engineer and control the electrolytic processes at the electrodes to produce hydrogen (H_2) and oxygen (O_2) or to control pH conditions, depending on the system design objectives.

To implement the EK-enhanced delivery technology in the field, remediation amendments are added to electrode wells and potentially additional supply wells located intermediary to the electrode wells, mainly to shorten amendment travel distance versus consumption rate (**Figure 2-2**). Electrodes of selected inert materials are installed in electrode wells and connected to a *dc* power source. The power supply unit will supply electrical energy to electrodes at designed settings of voltage and/or current. The electrical field will transport the amendments from the electrode wells and supply wells into and through the formation materials to achieve a relatively uniform transport and distribution. Cross-circulation and pH-balancing can be employed at the electrode wells to overcome the effects of water electrolysis and retain the natural in-situ pH of the system (as required). Slight subsurface heating may occur with application of the electrical field. However, results from field trials have shown that temperature increases are minor (less than 10^{o}C). A modest increase in temperature often results in an improvement in the bioremediation process, as has been shown for *Dhc* during trichloroethene (TCE) dechlorination, where dechlorination was faster at 30^{o}C than 15^{o}C (Friis et al., 2007).

Results from many studies conducted at both bench-scale and field-pilot scale have shown the potential of EK-enhanced amendment transport (Mao et al., 2012; Gent, 2001; Wu et al., 2007; Reynolds et al., 2008; Hodges et al., 2011; SERDP ER-1204). Bench-scale studies conducted at ERDC effectively delivered acetate through loess soil ($K=10^{-7}$ centimeters per second [cm/sec]) and vertically deposited clay ($K=10^{-9}$ cm/sec) at rates of 2.1 and 2.5 centimeters per day (cm/day), respectively, with a voltage gradient near 0.5 volts per centimeters (V/cm) (Gent, 2001). An average lactate transport rate of 3.4 cm/day under a unit voltage gradient of 1 V/cm was achieved in a bench-scale study conducted using a silty clay ($K=10^{-7}$ cm/sec) (SERDP ER-1204). The observed EK-enhanced transport rate in that SERDP study was more than 120 times higher than the transport rate achievable in the same type of soil but under a unit hydraulic gradient. The use of EK-enhancement for ISCO has also been demonstrated at the bench scale in both column and sandbox experiments (Roach et al., 2006; Reynolds et al., 2008; Robertson, 2009; Hodges et al., 2011). Common oxidants such as permanganate and persulfate are charged compounds and will migrate under the driving force of the imposed electric gradient. Migration rates of mono-valent and divalent oxidants have been measured in the laboratory at levels in excess of 500 times higher than that achievable through diffusion alone.

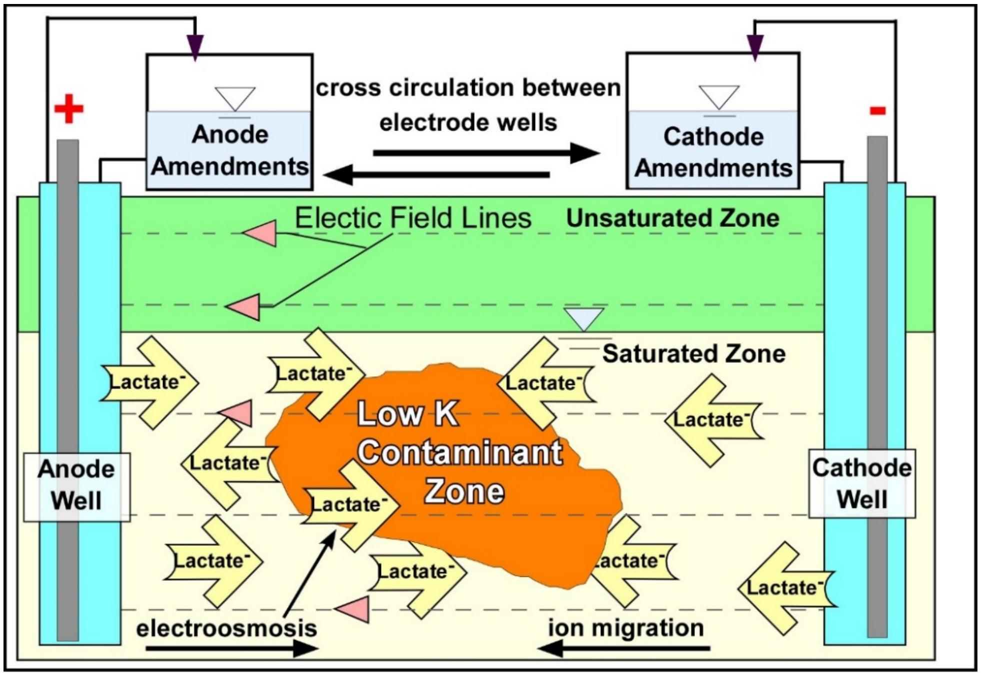


Figure 2-2. Schematic of EK-Enhanced Amendment Delivery Technology

Geosyntec, in collaboration with ERDC, completed a field pilot test of EK-BIO at a site in Denmark, which achieved a lactate transport rate between 2.5 and 5 cm/day through clay materials. The pilot test involved simultaneous biostimulation (using lactate) and bioaugmentation (using dechlorinating culture KB-1®) targeting a PCE source area. Active EK operation for lactate distribution was conducted for approximately 8 weeks, followed by 16 weeks of post-EK monitoring. Results from the pilot test (both groundwater samples and clay cores) indicated general uniformity of distribution of electron donor, rapid establishment and growth of the bioaugmented *Dhc* within the clay, and rapid dechlorination of PCE, TCE, and cis-1,2-dichloroethene (cDCE) to vinyl chloride (VC) and ethene. Results from both laboratory studies and the field pilot test for this site showed that the applied electrical field had no deleterious impacts on the microorganisms or subsurface conditions. During the EK field pilot test, the average groundwater temperature in the demonstration area increased from 17°C to 25°C, which was believed to provide improved conditions for PCE dechlorination by the introduced *Dhc*.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

A critical and distinct advantage of the EK technology over most other amendment delivery approaches is that EK can achieve relatively uniform transport in inter-bedded clays and sands, even when the hydraulic conductivities of the subsurface materials vary by orders of magnitude. EK-enhanced transport, which relies primarily on the electrical properties of aquifer materials instead of the hydraulic properties, represents a solution to the limitations of preferential pathways facing conventional advective-based hydraulic technologies.

EK-enhanced delivery is a safer, and more controllable approach compared to current high-pressure/ fracturing injection and thermal approaches. The migration of remediation reagents is directed by the electrical field established between electrodes; high injection pressures are not involved.

EK-enhanced delivery also represents a remediation technology with good environmental performance. Unlike other technologies that repeatedly deliver/flush amendments through a small number of preferential pathways in the subsurface, the EK technology can uniformly deliver the amendments, maximizing treatment effectiveness and reducing treatment cost and duration. When coupled with existing in-situ remediation technologies (i.e., EISB and ISCO), EK-BIO and EK-ISCO can achieve direct treatment and destruction of target contaminants in-situ instead of transferring contaminants to the gas phase, which requires additional containment/collection and treatment. The electrical energy usage of EK-enhanced delivery is relatively low compared to current thermal remediation technologies. As discussed in Section 6.1 of this report, the electrical power used in this Dem/Val (generally maintained at <30 Volts [V] and <10 Amps [A]) demonstrated the excellent energy efficiency of this technology.

There are several aspects of this technology that will require appropriate considerations and control measures:

- Safety considerations related to potential stray current/voltage to ground surface.
- If the technology is to be implemented near (laterally and/or vertically) utilities that are sensitive to electric interference or corrosion concerns, some protection measures, such as cathodic (grounding) protection, may be required. Depending on the locality/facility-specific requirements, local or facility power/electrical departments should be consulted.
- Although conceptually there is no depth limit for this technology, shallow treatment zones too close to the ground surface and/or utilities, or in a vadose zone, can limit the feasibility of this technology.
- Certain site hydrogeology or geochemical conditions may limit the applications or impact the costs of this technology, including
    - Very high levels of sulfate or nitrate that challenge the supply of electron donors for promoting and sustaining reductive dechlorination. This limitation is not specific to EK amendment delivery, instead, it is a limitation for anaerobic in situ bioremediation.
    - High natural groundwater flow velocity in the permeable portion of a target treatment zone may potentially limit the EK transport in the direction against the natural groundwater flow.
    - High levels of chloride and/or iron that require particular engineering control measures (e.g., corrosion protection) or more operational maintenance efforts for fouling controls. Iron fouling is also a common challenge to other in situ remediation technologies.

3.0 PERFORMANCE OBJECTIVES

The overall goal of this Dem/Val is to demonstrate and validate EK-enhanced amendment delivery for in-situ bioremediation via enhanced reductive dechlorination (ERD) of a PCE source area in clay. Performance objectives were identified and approved by ESTCP and provided the basis for evaluating the performance and costs of the technology. **Table 3-1** presents a summary of the quantitative and qualitative performance objectives, which are further discussed in the following subsections.

Table 3-1. Performance Objectives

Performance Objective	Data Requirements	Success Criteria	Assessment
Quantitative Performance Objectives			
I. Demonstrate uniform distribution of the amendments and relative uniformity of the established electrical field	• Pre- and post-EK monitoring of the concentrations of amendments • Monitoring of voltage and electrical current within the EK system during operation	• At groundwater monitoring locations within the TTA after the completion of active EK operation − post-EK concentration of TOC is at least 5x baseline, or 10x detection limit if baseline is below detection • No local focusing of electric field within the TTA – no electrical potential gradient between any individual pair of cathode-anode is 5x the average electrical gradient between all pairs of electrodes • Electrical potential gradient between electrode pairs maintained at level no more than 5x target gradient at design current	Objective Met (see Section 7.1)
II. Demonstrate effectiveness of treatment established by EK-BIO operation within the TTA	• Pre- and post-EK concentrations of chlorinated ethenes in soil and groundwater • Pre- and post-EK concentrations of ethene in groundwater • Pre- and post-EK concentrations of biomarker (quantitative polymerase chain reaction [qPCR] analysis of *Dhc* and/or vcrA) in soil and groundwater	• > 60% reduction in average PCE concentrations in soil and groundwater within the TTA, with coupled and comparable molar concentration increases of dechlorination daughter and end products • Ethene/ethane detected at > 75% of groundwater monitoring wells within the TTA before the completion of post-EK monitoring • > 10x increases of *Dhc* from baseline at > 50% of soil and groundwater samples collected from within the TTA before the completion of post-EK monitoring	Objective Met (see Section 7.2)
III. Demonstrate suitability of this technology for full-scale implementation	• EK system operational parameters, amendment usage, and energy consumption	• System operation conditions (voltage and current) within ± 50% of the designed target conditions • Amendment supply up-time > 75% of target • Energy consumption within ± 30% of design estimates	Objective Met (see Section 7.3)

Table 3-1. Performance Objectives (Continued)

Performance Objective	Data Requirements	Success Criteria	Assessment
Qualitative Performance Objectives			
IV. Safe and reliable operation	• Monitoring of system operational parameters	• Operational conditions remain stable within the normal designed ranges over the course of the demonstration period • No lost-time incidents	Objective Met (see Section 7.4)
V. Ease of implementation	• Feedback from field personnel on installation and operation of technology and system	• Ability to construct using conventional techniques and contractors • A single field technician able to effectively monitor and maintain normal system operation	Objective Met (see Section 7.5)

4.0 SITE DESCRIPTION

The target area for this Dem/Val was located within Operable Unit 3 (OU3) at NAS Jacksonville in Duval County, Florida (**Figures 4-1 and 4-2**). This section provides a summary of site information most relevant to this technology Dem/Val.

4.1 SITE LOCATION

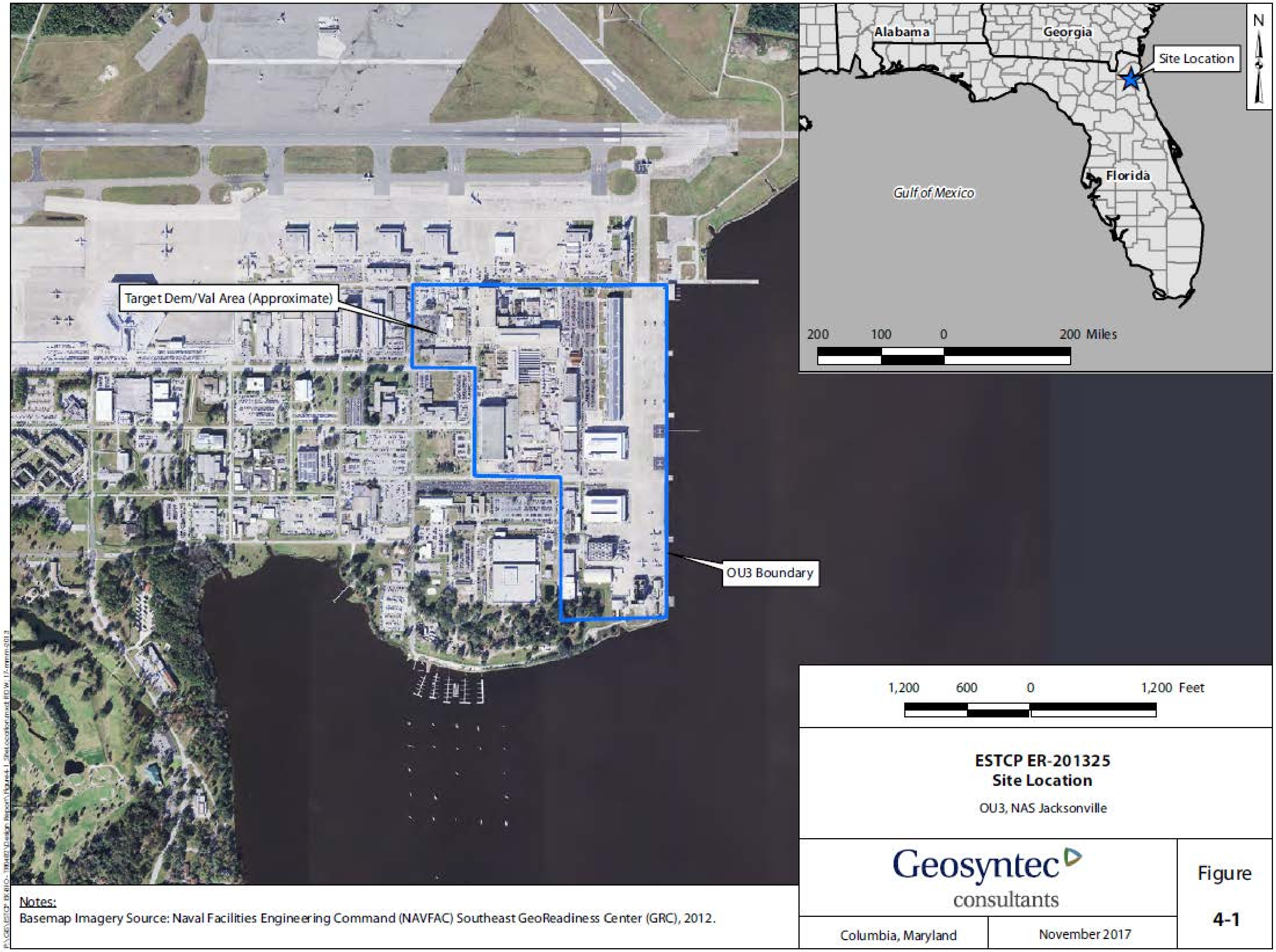
The EK-BIO Dem/Val was conducted at NAS Jacksonville, which is located on the west bank of the St. Johns River in Duval County, Florida (**Figure 4-1**). The Dem/Val area was in OU3 in the vicinity of former Building 106, where the station's dry-cleaning facility once existed (**Figure 4-2**).

PCE and its dechlorination daughter products, including TCE, cDCE, and VC, have been detected in this area in permeable sand layers within the shallow aquifer (5 to 16.5 feet [ft] bgs). Site characterization results also indicate that chlorinated volatile organic compounds (CVOC) mass present in the low-K clay layer beneath the shallow sand aquifer can serve as a long-term source of contamination to the shallow aquifer (EISB Workplan, Geosyntec, 2013). This low-K clay layer beneath the shallow sand aquifer was the target for this EK technology Dem/Val.

4.2 SITE GEOLOGY/HYDROGEOLOGY

Site geology was characterized as part of a previous ESTCP Project (ER-0705), as described in the *Data Analysis Report for Field Event 4: NAS Jacksonville* (ESTCP, 2012b). Lithology at OU3 consists of inter-bedded layers of sand, clayey sand, sandy clay, and clay. Soil cores collected and logged at OU3 (ESTCP, 2012a) indicate that the site lithology generally consists of:

- 0.5 to 5 ft bgs: Fine sand with gravel and silt/clay;
- 5 to 7.5 ft bgs: Clay with trace sand and organic matter;
- 7.5 to 16.5 ft bgs: Fine sand/silt to fine sand with silt/clay;
- 16.5 to 18.5 ft bgs: Clay/silt with trace fine sand;
- 18.5 to 25 ft bgs: Clay with trace sand; and
- 25 to 30 ft bgs: Fine sand with silt/clay to fine sand.



Notes:
Basemap Imagery Source: Naval Facilities Engineering Command (NAVFAC) Southeast GeoReadiness Center (GRC), 2012.

Figure 4-1. Site Location

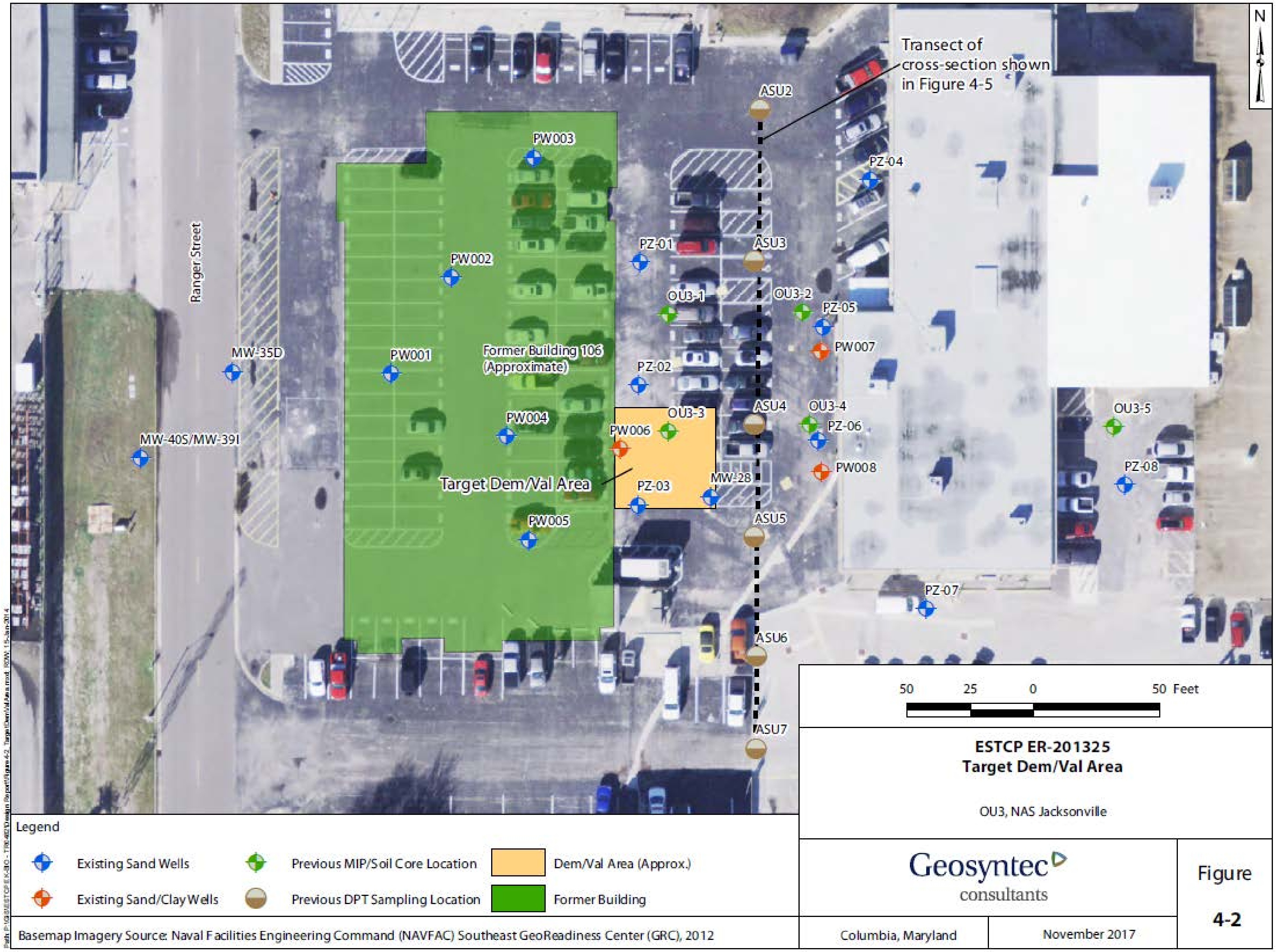


Figure 4-2. Target Dem/Val Area

A transition layer between the shallow sand and clay layers has been observed in some soil cores, generally between 13 and 16.5 ft bgs. Photographs of a soil core, OU3-4 (location shown in **Figure 4-2**), exhibiting the lithology representative of the target area, are presented below in **Figure 4-3**. The same lithology was again observed during this Dem/Val with a representative soil core collected from within the TTA during monitoring well installation (EKMW-02). Photographs are presented for this location (**Figure 4-3**) for comparison. The EK-BIO Dem/Val specifically targeted the CVOCs (predominately PCE) in the clay layer between approximately 16.5 to 24 ft bgs underneath the shallow sand unit in this area.

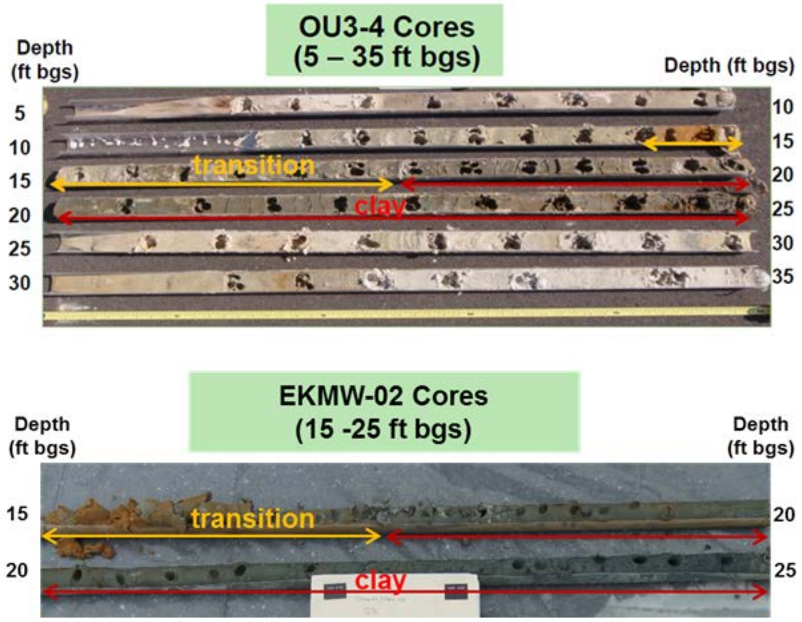


Figure 4-3. Lithology of the Target Dem/Val Area

(OU3-4 from ESTCP ER-201032; EKMW-02 from this Dem/Val)

Groundwater in this area was first encountered approximately 5 ft bgs and flows towards the east with gradients ranging from 0.005 to 0.02 (ESTCP, 2012b). Past hydraulic testing estimated the mid-range hydraulic conductivity of the shallow sand aquifer at 5×10^{-3} cm/sec (ESTCP, 2012b). The linear groundwater velocity was estimated as high as 101 ft/year (using a gradient of 0.005 and the mid-range conductivity).

ESTCP Project ER-0705 conducted depth-discrete, aquifer specific-capacity tests at various locations in this area, including along a transect from ASU-2 through ASU-7 shown in **Figure 4-2**. Depth-discrete hydraulic conductivity estimates for the clay unit beneath the shallow sand aquifer showed that, at approximately 17 ft bgs, the average K was 4×10^{-5} cm/sec (September 2011 data); however, there was not enough water at 6 of the 7 locations tested at the depth of 22 ft bgs to provide steady-state flow rates needed for the specific-capacity testing. Based on the soil core lithology observation and the orders of magnitude decrease of K from the shallow sand (5×10^{-3} cm/sec) to the clay at a depth of 17 ft (4×10^{-5} cm/sec), it is believed that the clay material below 17 ft bgs has a hydraulic conductivity lower than 10^{-5} cm/sec.

4.3 CONTAMINANT DISTRIBUTION

Site investigations prior to the Dem/Val showed that PCE and degradation daughter products (TCE, cDCE, and VC) were present in permeable sand layers within the shallow aquifer (5 to 16.5 ft bgs). Chlorinated ethenes have also migrated, in part through diffusion, into the clay layer (generally from 16.5 to 24 ft bgs) present beneath the shallow sandy aquifer. PCE is the dominant groundwater CVOC in this area, with TCE, cDCE and VC detected at lower concentrations. The groundwater quality data collected in January 2013 before this Dem/Val (Tetra Tech, 2013) indicate that groundwater monitoring wells screened in the shallow aquifer within the target area have total chlorinated ethene concentrations ranging from 194 micrograms per liter (µg/L) in well PZ-04 to 51,000 µg/L in well PZ-02 (**Figure 4-4**).

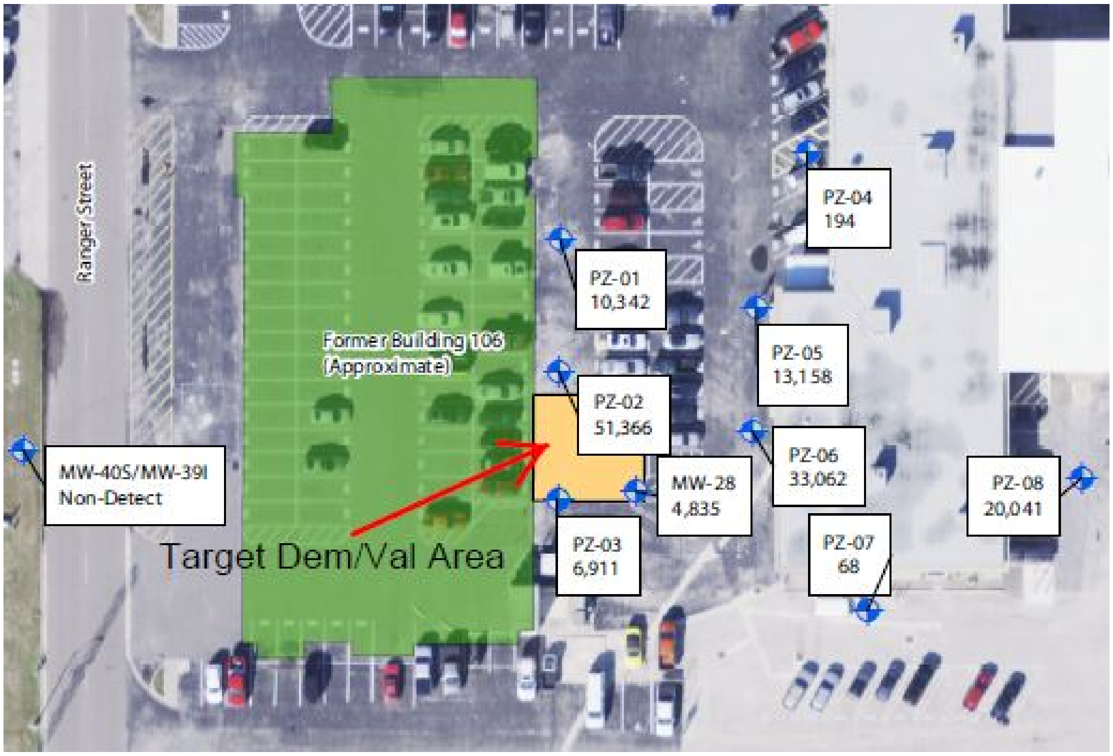
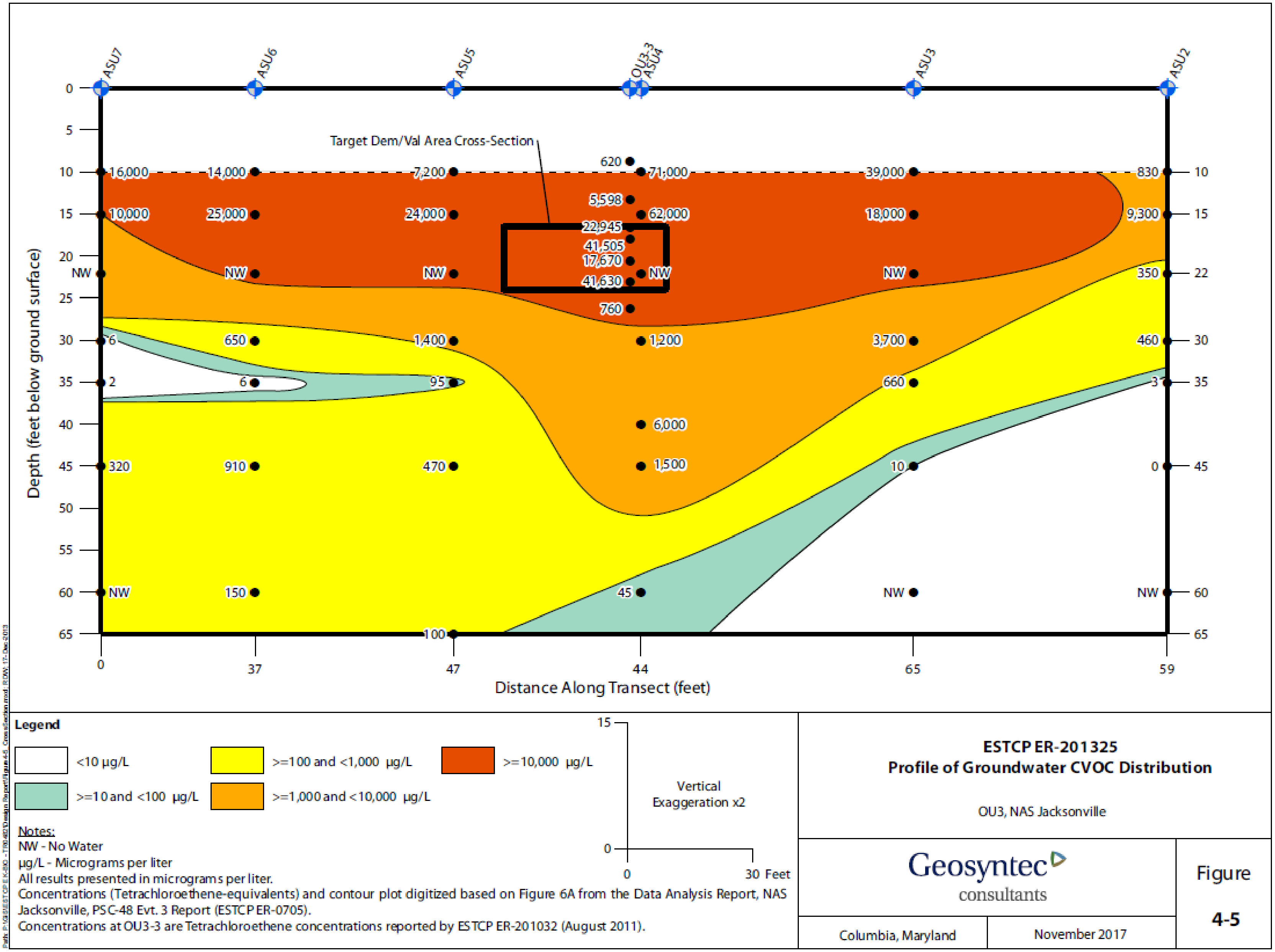


Figure 4-4. Total Chlorinated Ethenes in Select Groundwater Monitoring Wells in Shallow Sand Aquifer

(January 2013; concentration unit: µg/L)

Previous SERDP/ESTCP projects have profiled the distribution of CVOCs across both the sand and clay units in the target Dem/Val area (**Figures 4-5 and 4-6**). **Figure 4-5** presents the distribution of CVOCs in groundwater along a north-south cross section just to the east (downgradient) of the target Dem/Val area (transect along ASU2 through ASU7 shown in **Figure 4-2)**.



Notes:
NW - No Water
µg/L - Micrograms per liter
All results presented in micrograms per liter.
Concentrations (Tetrachloroethene-equivalents) and contour plot digitized based on Figure 6A from the Data Analysis Report, NAS Jacksonville, PSC-48 Evt. 3 Report (ESTCP ER-0705).
Concentrations at OU3-3 are Tetrachloroethene concentrations reported by ESTCP ER-201032 (August 2011).

ESTCP ER-201325
Profile of Groundwater CVOC Distribution

OU3, NAS Jacksonville

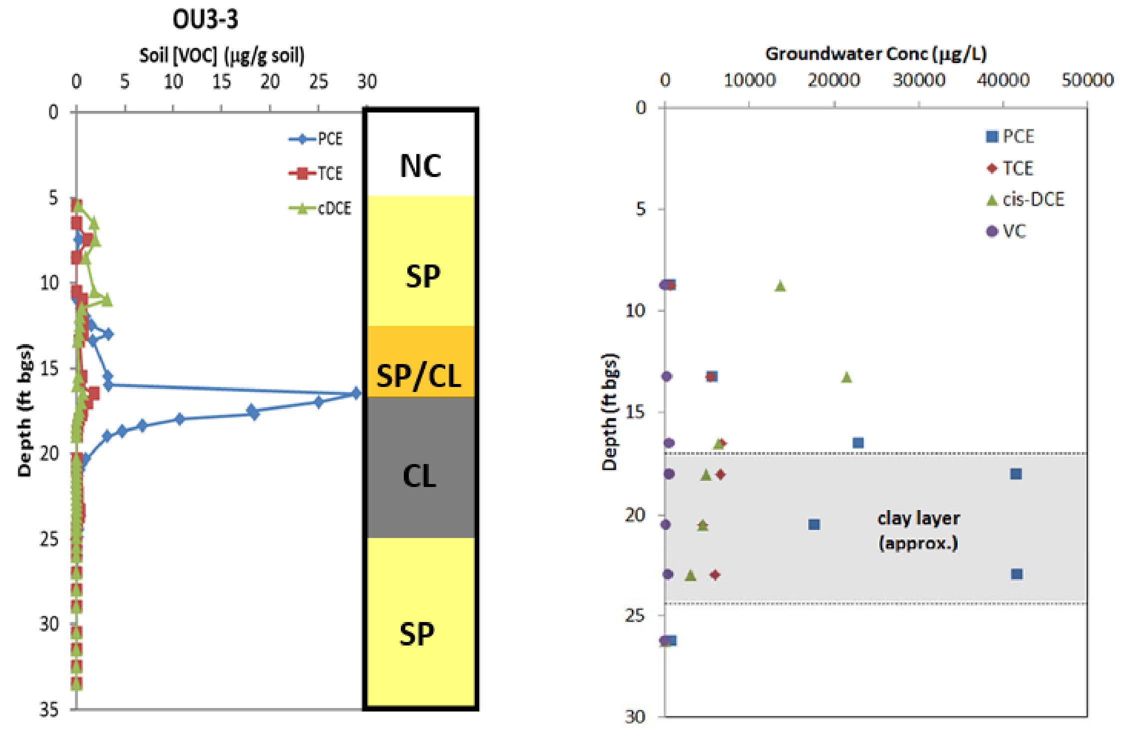
Geosyntec consultants

Columbia, Maryland
November 2017

Figure 4-5

Figure 4-5. Profile of Groundwater CVOC Distribution

As shown in **Figures 4-2** and **4-5**, previous sampling location OU3-3 is located within the target Dem/Val footprint. **Figure 4-6** presents a conceptualized geologic cross section derived from high-resolution coring conducted at OU3-3 (ESTCP project ER-201032). At OU3-3, the vertical distribution of PCE, TCE, and cDCE in soil and groundwater at depths above, within, and below the clay unit depicts a classic PCE diffusion profile, with PCE penetration into approximately the upper 5 feet of the clay unit. Porewater PCE concentrations detected at OU3-3 at various depths across the clay unit ranged from 15,000 to 40,000 µg/L, indicating significant contamination within the depth interval targeted by the Dem/Val (~ 16.5 to 24 ft bgs).



NC – not characterized; SP – sand; CL – clay

Figure 4-6. Profiles of Soil and Groundwater CVOC Concentrations at OU3-3

(Source: ESTCP Project ER-201032)

Based on the site characterization results discussed above, the CVOCs residing in the clay unit in the proximity of OU3-3 represent a long-term continuing source for groundwater CVOC contamination in this area. Previous efforts to obtain water samples from the clay unit using conventional approaches were reported to be difficult, highlighting the expected limitations that would be encountered in an attempt to hydraulically migrate remediation amendments into this clay unit. Therefore**,** the Dem/Val footprint (as shown in **Figure 4-2**) and the target depth interval of 16.5 ft bgs to 24 ft bgs were deemed appropriate for this Dem/Val. Subsequent characterization data collected during the Dem/Val baseline characterization are presented in Section 5.3.

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5.0 TEST DESIGN

This section provides the details pertaining to the design, installation, and implementation of the EK-BIO technology in the target Dem/Val area.

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

As presented in **Figure 5-1**, the overall EK system consists of nine (9) electrode wells [E1 through E9] and eight (8) supply wells [S1 through S8] located within a TTA measuring approximately 40 feet by 40 feet. Also presented in **Figure 5-1**, are seven (7) monitoring wells [EKMW1 through EKMW-7] located within the TTA and four (4) located outside the TTA.

The remediation amendments distributed by the EK system included electron donor (lactate, provided as potassium lactate), pH control reagents (potassium carbonate), and KB-1® containing *Dhc*. The power supply unit, amendment supply units and manifolds, and system operation monitoring and control unit were housed in a shed located adjacent to an existing utility building approximately 35 feet south of the TTA. Amendment conveyance tubing and electrical wiring conduit were installed along a trenched corridor to connect the EK control/amendment supply system to the well network in the TTA.

Table 5-1 presents a summary of major project milestones for this Dem/Val. To support the Dem/Val design, a bench-scale EK column test was conducted. The bench test and test results are discussed in Section 5.2. A baseline characterization event was conducted prior to the system construction and installation. Baseline characterization results are presented in Section 5.3. After the completion of system construction/installation and system startup, the overall Dem/Val involved two separate stages of EK operations. Each stage was operated with varying anode and cathode configurations to alter the primary direction of electric fields. **Figures 5-2** and **5-3** present conceptual orientations of the electric field established during each EK operational stage. Bioaugmentation of the TTA with reductive dechlorination culture (KB-1®) was conducted during Stage 1 operation. There was an incubation period of approximately 6 months between the two stages of active operation. Following the completion of the second EK operation stage in March 2017 and a subsequent incubation period of 3 months, a post-EK performance monitoring event was conducted in June 2017 to complete the Dem/Val.

During each stage of operation, the EK system was operated to achieve and maintain a constant current supplied to the overall electrode network. The voltage that was required to achieve and sustain this constant current is a site-specific characteristic related to the electrical resistance of the subsurface materials.

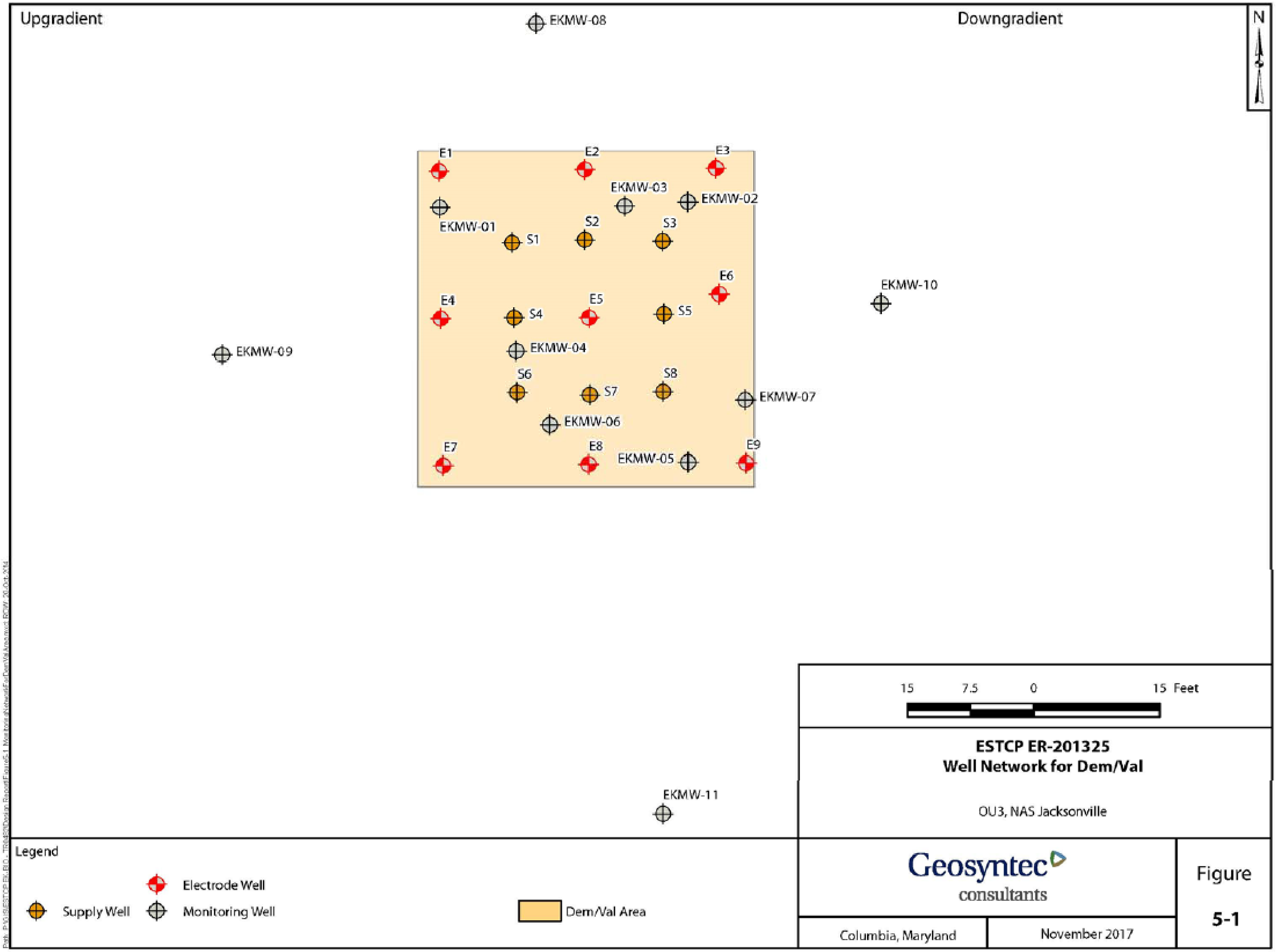

Figure 5-1. Well Network for Dem/Val

Table 5-1. Major Project Milestones

Well Installation	September 2014
Baseline Characterization	October 2014
System Fabrication / Field Construction / System Installation & Shakedown	October 2014 – June 2015
System Startup & Initial Field Conditioning	June – August 2015
Stage 1 Operation Period	August 2015 – Mach 2016
Bioaugmentation (Supply Wells and Electrode Wells)	October 29, 2015
End-of-Stage 1 Monitoring Event	March 2016
Post-Stage 1 Incubation Period	March – September 2016
Stage 2 Operation Period	October 2016 – March 2017
End-of-Stage 2 Monitoring Event	March 2017
Post-Stage 2 Incubation Period	March – June 2017
Final Sampling Event	June 2017

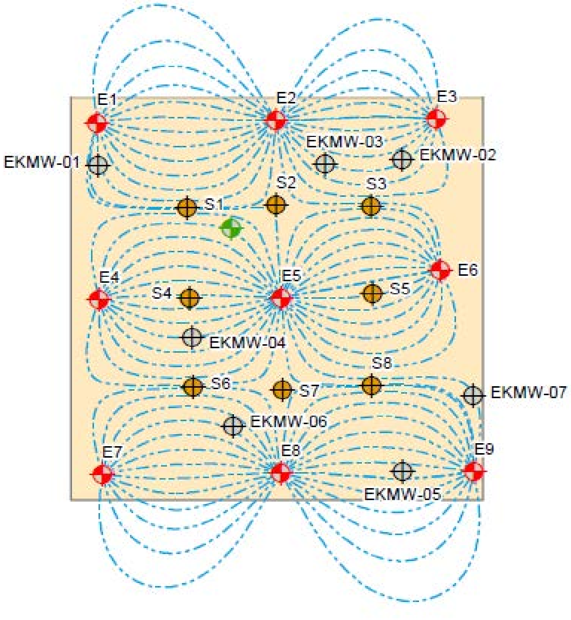

Figure 5-2. Stage 1 Conceptual Electric Field

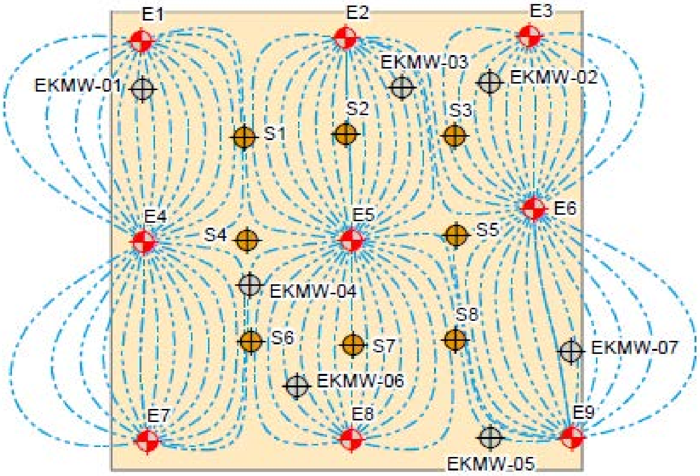

Figure 5-3. Stage 2 Conceptual Electric Field

Potassium lactate was used to provide electron donor for ERD of CVOCs. Lactate was supplied to all electrode wells and all supply wells during the system operation. In addition to lactate, potassium carbonate (K_2CO_3) was added to all supply wells during EK operation as a pH buffer due to the low baseline pH (<6) in the TTA (which is not optimal for ERD). The EK system would also cross-circulate electrolytes (fluids in electrode wells) between cathodes and anodes, as well as provide supplemental acid or base, as needed, to individual electrode wells for overall pH control. The following sections provide specific details of individual phases completed under this Dem/Val.

5.2 TREATABILITY STUDY RESULTS

A bench-scale EK column test was initially conducted using core material from the site to estimate the migration rate of amendments prior to the Dem/Val. Three 10-centimeter (cm) sections of core materials were individually compacted using a piston into a 10-cm polyvinyl chloride (PVC) column (3-inch diameter). A filter assembly was used at each end of the PVC column to connect the soil column to the electrode cells. A conservative bromide tracer (1 grams per liter [g/L] of sodium bromide solution) was added to the cathode cell reservoir. Sodium phosphate solution (1.3 g/L) was added to both cathode and anode cells as electrolyte and buffer. The electrodes were connected to a *dc* power supply unit and a constant current of 25 mA was applied during the EK column test. At the completion of 72 hours of testing, the column was detached from the electrode cells and frozen. The frozen core was subsequently cut into a total of eight 1-cm sections along the direction from anode toward cathode. These samples, plus a background soil sample, were analyzed for bromide concentrations. The results presented in **Table 5-2** show that bromide migrated across the entire length of the 10-cm column from the cathode to the anode within 72 hours. These results suggest a minimum electromigration rate of 3.3 cm/day.

Table 5-2. Bromide Tracer Test Results

Sample	Background Soil	3-cm from cathode	5-cm from cathode	7-cm from cathode	10-cm from cathode
Bromide (mg/kg)	**<1**	**295**	**158**	**157**	**284**

5.3 BASELINE CHARACTERIZATION

To establish the baseline geochemical conditions, microbial conditions, and contaminant distribution specifically within the Dem/Val footprint, a baseline characterization event was performed in October 2014 following the completion of well installation. **Table 5-3** presents a summary of the overall monitoring program for the Dem/Val, including the baseline characterization discussed in this section.

5.3.1 Baseline Groundwater Sampling

Groundwater samples were collected from the 11 groundwater monitoring wells (EKMW-01 through EKMW-11; seven within and four outside the TTA) shown on **Figure 5-1**. Baseline geochemical characterization of groundwater included measurements of field parameters (dissolved oxygen [DO], oxidation-reduction potential [ORP], conductivity, and temperature) and laboratory analyses for metals, inorganic anions (chloride, sulfate and nitrate), CVOCs, TOC, volatile fatty acids (VFAs), and dissolved hydrocarbon gases (DHGs: methane, ethene and ethane). Baseline measurement of various carbon indicators, such as TOC and VFAs, allowed the subsequent tracking of electron donor distribution.

Baseline groundwater microbial characterization included quantitative analysis of *Dhc* and *Dehalobacter* (*Dhb*), as well as the key biomarker, *vcrA*. These microbial characterization data were collected to establish the baseline conditions regarding the specific microbiological capacity within the Dem/Val footprint.

The baseline groundwater sampling results of select key parameters are presented in **Figure 5-4a and 5-4b**. Baseline data indicated that groundwater within the TTA was generally acidic and slightly oxidizing with low DO between 0.2 to 0.6 milligrams per liter (mg/L). Baseline TOC and VFAs were relatively low (mostly below 6 mg/L), and, with the exceptions of EKMW-01 and EKMW-05, there was no detectable levels of *Dhc, Dhb,* and *vcrA*. Additional detailed discussions of groundwater baseline characterization results are presented in Section 6.3.

5.3.2 Baseline Soil Sampling

Baseline soil cores were collected from nine (9) locations within the TTA and two (2) locations outside the TTA (**Figure 5-4c**). At each location, a soil core was collected using Direct Push Technology (DPT) to a target depth of 24 feet. With each collected soil core, three (3) discrete soil samples were collected from approximately 18.5, 21, and 23 ft bgs. Baseline soil characterization included laboratory analyses for metals and CVOCs, as well as quantitative analyses of *Dhc, Dhb,* and *vcrA*. In addition, the baseline soil characterization included soil grain size analysis.

The baseline soil sampling results of soil PCE concentrations are presented in **Figure 5-4c**. The baseline soil characterization data indicated that there was very little apparent reductive dechlorination activity within the TTA prior to the Dem/Val. The data also suggested that the majority of soil PCE within the TTA appeared to be present above the depth of 21 ft. Additional detailed discussions of soil baseline characterization results are presented in Section 6.2.

Table 5-3. Summary of Monitoring Program

Phase	Matrix	Frequency	Analyses	Location
Baseline Characterization	Soil	Three depths(1) per boring	Volatile Organic Compounds (VOCs)(2), Metals(3), Microbial (*Dhc*, *Dhb* & *vcrA*), Grain-size	9 locations within the TTA and 2 locations outside the TTA
	Groundwater	One Time	VOCs, DHGs(4), VFAs(5), Metals, Anions(6), TOC, Field Geochemistry(7), Microbial (*Dhc*, *Dhb* & *vcrA*)	All 11 monitoring wells (EKMW-01 through EKMW-11)
System Start-up Phase	Groundwater	Weekly	Field Geochemistry, Electric Field(8)	7 Monitoring wells within TTA
Stage 1 Operations	Groundwater	Weekly	Electric Field	6 Monitoring wells within the TTA (EKMW-01 through EKMW-07 except EKMW-06)
		Monthly	TOC, VFAs	
End of Stage 1 Operation & End of Incubation Period between Stage 1 and Stage 2 Operations	Soil	Three depths(1) per boring	VOCs, Microbial (*Dhc, Dhb & vcrA*)	9 select locations within the TTA and 1 location outside the TTA
	Groundwater	One Time	VOCs, DHGs, VFAs, Metals, Anions, TOC, Field Geochemistry, Microbial (*Dhc*, *Dhb* & *vcrA*)	All 10 monitoring wells (EKMW-01 through EKMW-11 except EKMW-06)
Stage 2 Operations	Groundwater	Weekly	Electric Field	6 Monitoring wells within TTA (EKMW-01 through EKMW-07 except EKMW-06)
		Monthly	TOC, VFAs	
Post-Operation Final Monitoring (3 months)	Soil	End of 3-month post-operation incubation period; Two depths(1) per boring	VOCs, Microbial (*Dhc*, *Dhb* & *vcrA*); and Metals	9 locations within TTA and 1 location outside TTA
	Groundwater	End of 3-month post-operation incubation period	Field Geochemistry; TOC, VOCs, DHGs Metals, Microbial (*Dhc*, *Dhb* & *vcrA*)	All 10 monitoring wells, including 6 Monitoring wells in TTA

(1) Baseline event: discrete soil samples collected from approximately 18.5, 21, and 23 ft bgs. Subsequent events: two sampling depths per location at 18.5 and 21 ft bgs.
(2) VOCs: PCE, TCE, cDCE, and VC.
(3) Iron, Manganese, Calcium, and Magnesium.
(4) Methane, Ethene, and Ethane.
(5) Lactate, Acetate, Propionate, Formate, Butyrate, and Pyruvate.
(6) Nitrate, Sulfate, and Chloride.
(7) Conductivity, Temperature, Redox, pH, and Dissolved Oxygen.
(8) Voltage measurements taken at select wells. Readings of electric currents to individual electrodes recorded at wellhead using portable current clamp.

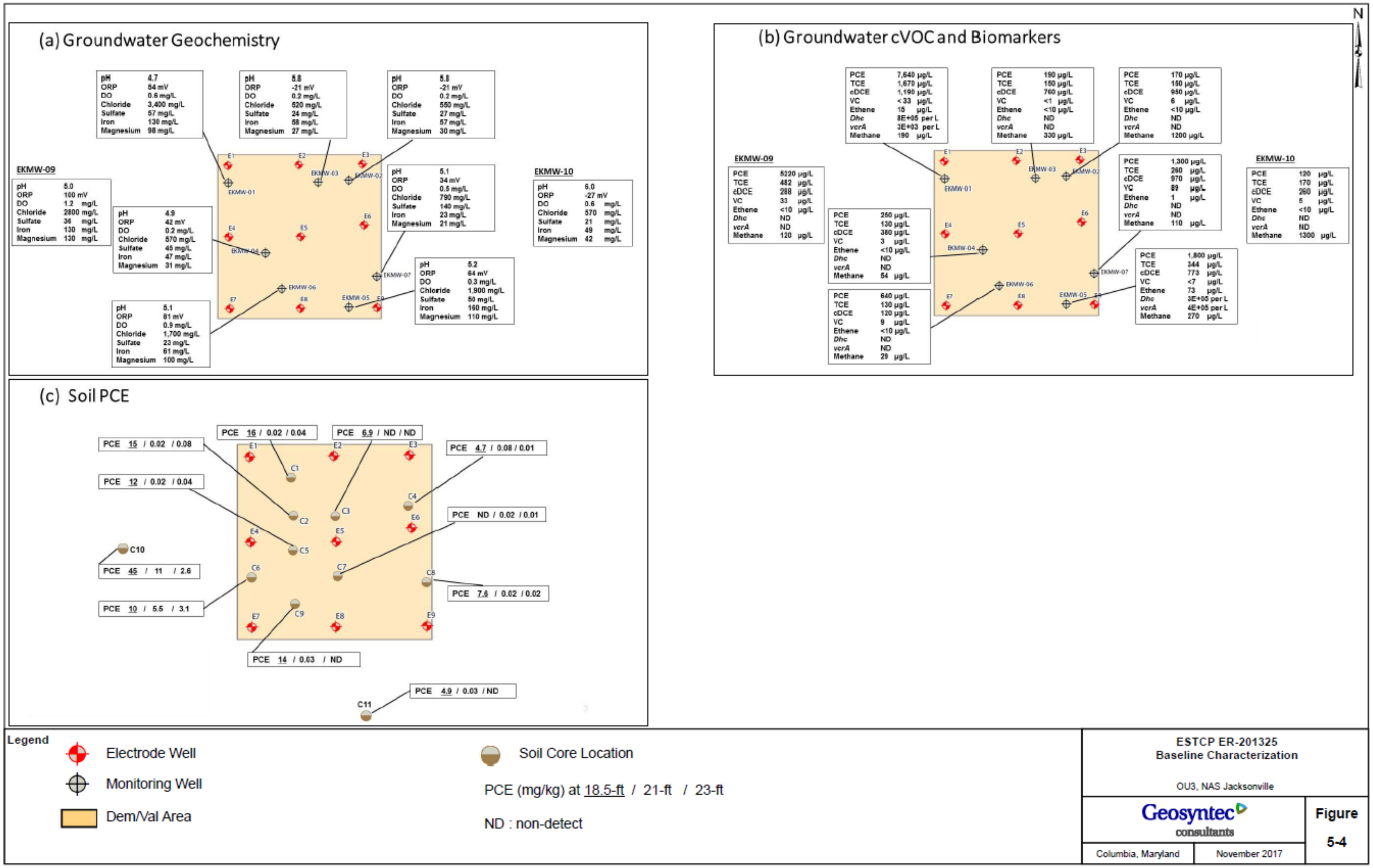

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Figure 5-4. Baseline Characterization

5.4 FIELD TESTING

This section provides a description of each significant phase of operation and the activities conducted during that phase. A schedule illustrating the sequence and duration of individual phases of operation is presented in **Table 5-4**.

Table 5-4. Dem/Val Field Testing Phases

System Startup & Initial Field Conditioning	June 2015 – August 2015
Stage 1 Operation	August 2015 – March 2016
During Stage 1 Operation – Bioaugmentation (Supply Wells and Electrode Wells)	October 29, 2015
End-of-Stage 1	March 2016
Post-Stage 1 Incubation Period (no operation)	March 2016 – September 2016
Stage 2 Operation	October 2016 – March 2017
End-of-Stage 2	March 2017
Post-Stage 2 Incubation Period (no operation)	March 2017 – June 2017

5.4.1 System Start-Up

During the system start-up, carbonate (K_2CO_3) solution was delivered to the supply wells in order to condition the pH in the formation around the supply wells prior to the addition of electron donor in the next phase. The duration of the start-up period for buffer addition was approximately 60 days. Buffer addition continued during the subsequent two active EK operational phases (Stage 1 and Stage 2) together with lactate amendment supply.

During the start-up operation, daily remote-monitoring of system control data and weekly system field inspections were conducted to monitor and assess system operations. The distribution of the electric field within the TTA was confirmed by lowering an insulated reference electrode into a given monitoring well and using a hand-held voltage meter to measure the voltage difference between that location and a universal reference cathode, which in our case was the power supply unit in the system shed. Relatively uniform electric fields were confirmed based on the voltage measurements taken at all monitoring wells within the TTA.

5.4.2 Stage 1 EK Operations and Monitoring

Following system start-up, electron donor (lactate solution) was added to the TTA during Stage 1 EK operation. This operational stage included 2 segments – before bioaugmentation and after. The electrode polarity arrangement for Stage 1 operation is shown in **Figure 5-2** with E2, E5, and E8 operated as anodes.

Lactate solution was supplied to all electrode wells and all supply wells as individual short pulses several times per day. Other system operation activities included buffer amendment to supply wells, cross-circulation between electrodes, and supplemental acid and base addition, as needed, to electrode wells.

Bioaugmentation of the TTA with dechlorination microbial culture containing *Dhc* was performed to establish adequate reductive dechlorinating populations. After approximately 75 days of active operation, when geochemistry monitoring data indicated anaerobic and reducing conditions at supply wells and monitoring wells within the TTA, the system was shut down 48 hours prior to the bioaugmentation event, which occurred on 29 October 2015. To bioaugment the TTA, 4 liters (L) of KB-1® culture (SiREM Laboratory, Ontario, Canada) was added to each supply well, and 1.5 liters to each electrode well. The KB-1® culture selected for this project contain *Dhc* that are capable of fully degrading chlorinated ethenes under mildly acidic (i.e., pH <6.0) conditions. The system operation resumed 48 hours after the bioaugmentation event.

The Stage 1 operation continued for approximately 5 months following bioaugmentation. During the operation, system inspections were conducted generally twice per week by a field operator to monitor and record system operational conditions and perform routine maintenance, mainly related to filter cleaning/replacement and amendment stock solution replenishment. The distribution of electric field within the TTA was confirmed by measuring voltages at monitoring wells as described above. Groundwater sampling and analysis for performance monitoring was conducted in accordance with **Table 5-3**.

5.4.3 Post-Stage 1 Incubation

Following the completion of Stage 1 operations, the system was shut down and the project entered a 6-month post-Stage 1 incubation period. An end-of-Stage 1 monitoring event was completed in March 2016 immediately following the system shut down. An end-of-post Stage 1 incubation monitoring event was completed in September 2016. Sampling and analysis for these monitoring events were performed in accordance with **Table 5-3**.

5.4.4 Stage 2 EK Operations and Monitoring

After the 6-month post-Stage 1 incubation, the electrode polarity arrangement was adjusted to start Stage 2 operation with E4, E5, and E6 as anodes (**Figure 5-3)**. The system operational program for electron donor amendment, buffer addition, cross-circulation between electrodes, and supplemental acid and base addition essentially followed the same approach as that of Stage 1 operation. There was no bioaugmentation in Stage 2 operation.

The Stage 2 operation continued for approximately 5 months from October 2016 through March 2017. During the operation period, system inspections and maintenance, as well as field measurements, were conducted following the same program and procedures as described above for the Stage 1 operation.

5.4.5 Post-Stage 2 Incubation

Following the completion of Stage 2 operations, the system was shut down and the project entered a 3-month post-Stage 2 incubation period. An end-of-Stage 2 monitoring event was completed in March 2017 immediately following the system shut down. An end-of-post Stage 2 incubation monitoring event (also as the final performance monitoring event) was completed in June 2017. Sampling and analysis for these monitoring events were performed in accordance with **Table 5-3**.

5.5 SAMPLING METHODS

In addition to operational data related to the system (i.e., electrical current and voltage, flow rates of amendments and cross-circulation), an overall field monitoring and sampling program for the Dem/Val is presented in **Table 5-3**. The Dem/Val monitoring program included both measurements of field parameters and collection of environmental samples (soil and groundwater) for laboratory analyses. **Table 5-5** summarizes the laboratory analytical methods.

For soil sampling, DPT tooling was used to collect one continuous core from ground surface to approximately 24 feet bgs at each of the 11 soil sampling locations (C1 through C11) shown in **Figure 5-5**. Soil cores were collected in acetate sleeves for observation and sampling. Discrete soil samples were collected for laboratory analyses from the selected depths. For the baseline event, samples were collected at each location from approximately 18.5, 21, and 23 ft bgs. The field personnel documented that clay was the predominant geologic material at all the locations and all these sampling depths.

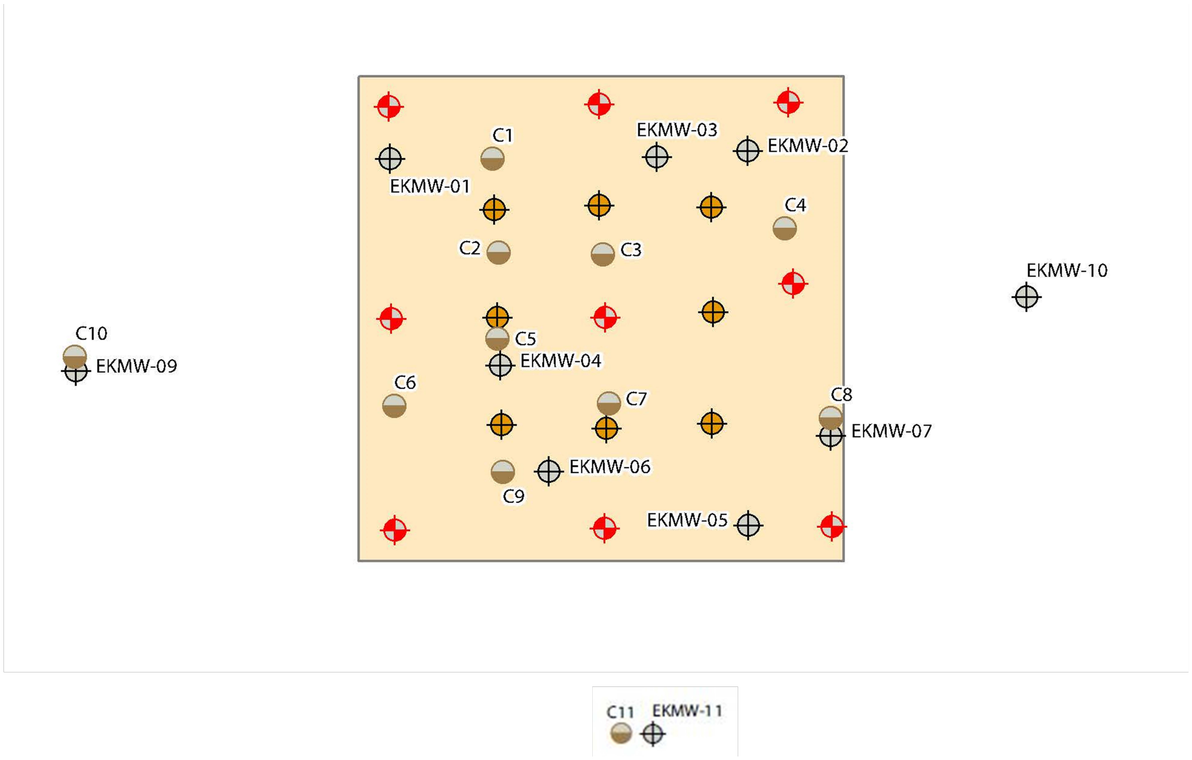

Figure 5-5. Soil Sampling Locations (C1 through C11)

Table 5-5. Analytical Methods for Sample Analysis

Matrix	Analyte	Method	Container	Preservative[1]	Holding Time
Soil	VOCs	8260B	3x 10-gram Terra Cores	2 with NaHSO4; 1 with methanol; 4 ± 2°C	14 days
	Metals (Ca, Fe, Mn, Mg)	6010B	2-oz glass jar	4 ± 2°C	6 months
	Tracer (Br^-)	300.0	2-oz glass jar	4 ± 2°C	28 days
	Biomarkers (*Dhc, Dhb,* and *vcrA*)	Gene-Trac® Method	50 mL conical tube provided by laboratory	4 ± 2°C	14 days
Groundwater	VOCs	8260B	40 mL VOA vial	HCl; 4 ± 2°C	14 days
	VFAs	Ion Chromatography	40 mL VOA vial	4 ± 2°C	14 days
	DHGs (methane, ethane, ethane)	RSK-175	40 mL VOA vial	HCl; 4 ± 2°C	14 days
	Total Metals (Ca, Fe, Mn, Mg)	6010B	250 mL polyethylene	HNO_3; 4 ± 2°C	6 months
	Anions (NO_3^-, SO_4^{-2}, Cl^-) and Tracer (Br^-)	300.0	250 mL polyethylene	4 ± 2°C	28 days (except NO_3^- at 48 hours)
	TOC	9060A	125 mL amber glass	HCl: 4 ± 2°C	28 days
	Biomarkers (*Dhc, Dhb,* and *vcrA*)	Gene-Trac® Method	500 mL polyethylene	4 ± 2°C	14 days

The groundwater monitoring well network for the Dem/Val is presented in **Figure 5-1**. Groundwater elevation was measured for each monitoring well prior to sampling. Groundwater sampling was conducted following low-flow purging protocols. During purging, in-line water quality parameters were monitored continuously for temperature, pH, specific conductance, DO, and ORP.

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6.0 SAMPLING RESULTS AND DISCUSSIONS

This section presents a summary and discussions of all monitoring/sampling results. Select baseline characterization data are incorporated in this section, as appropriate, with other performance monitoring data to support analyses and discussions related to changes of soil and groundwater conditions during the Dem/Val.

6.1 SYSTEM OPERATION MONITORING

The voltage (V) and current (A) readings recorded at the power supply unit over the duration of operation have been used to calculate the electrical power usage (kilowatt-hour [kW-hr]). The system was designed and operated to supply a constant current, determined after the start-up phase, and the power supply unit would then operate at a voltage level that was required in response to field electrical resistivity in order to maintain the supply of constant current. The power supply unit's voltage output remained generally steady between approximately 18V and 28V (Stage 1) and 12V and 20V (Stage 2). The total power consumption was calculated for Stage 1 at 1,037 kW-hr and Stage 2 at 548 kW-hr. As a comparison, the total energy usage by the EK system during the 14 active months of the Dem/Val (1,585 kW-hr) is equivalent to operating two 100-W lightbulbs over the same time interval.

In addition to monitoring the power supply unit, field measurements were taken to confirm the establishment of electric field within the TTA. The voltage measurements taken at individual monitoring wells were used to assess if a uniform electric field was established within the TTA. Voltage measurements at individual wells relative to a common cathode reference at the EK control system were between 5.3V and 6.2V with an average of 5.6V and a standard deviation of 0.31V (5% variation from the average) indicating that an electric field was established in the area between electrode wells.

6.2 GROUNDWATER SAMPLING RESULTS

The locations of groundwater monitoring wells are presented in **Figure 5-1**. One monitoring well within the TTA, EKMW-06, was found to not produce sufficient groundwater volume for sampling likely due to blockage. Therefore, EKMW-06 was not included in the monitoring program.

6.2.1 Groundwater Geochemistry

The baseline groundwater sampling results presented in Section 5.3 showed that groundwater within the TTA was generally acidic (pH below 5.5) and slightly oxidizing with low DO between 0.2 to 0.6 mg/L. Baseline TOC and VFA concentrations were relatively low (mostly below 6 mg/L). Geochemistry data collected from within the TTA following approximately 3 months of system operation adding buffering reagent, showed pH increases generally from baseline to between pH 5.5 and pH 6. The data showed negative ORP at all wells, except at EKMW-05 where ORP changed from 64 millivolts (mV) baseline to 17 mV. DO was at or below 0.2 mg/L at all wells.

Within the TTA following bioaugmentation and through Stage 1 and Stage 2 operations, groundwater pH generally remained between 5.5 and 6.6 and ORP was mostly negative after the Stage 1 and Stage 2 operations. Notable changes of certain geochemical conditions over the duration of Dem/Val include:

- Data suggest that some migration and redistribution of chloride (and likely other anions) might have occurred within the TTA as a result of the EK application.
- Sulfate concentration data suggest the occurrence of sulfate reduction in the TTA.
- Iron concentration data suggest that some migration and redistribution of iron (and likely other cations) occurred within the TTA as a result of the EK application.

6.2.2 Groundwater Chemical and Microbial Analytical Results

The discussion of groundwater sampling results is organized in this section with respect to assessment of: (1) amendment distribution; and (2) reductive dechlorination of CVOCs.

Amendment Distribution

Groundwater TOC and VFA concentrations at monitoring wells provided an assessment of amendment distribution across the TTA. With respect to TOC data, every monitoring well within the TTA saw an increase in TOC concentration >8x baseline levels, with the exception of EKMW-04 where the maximum TOC detected was 1.8x the baseline. With respect to VFA data, every monitoring well within the TTA saw an increase in VFA concentration >9x baseline levels, with the exception of EKMW-05 where the maximum VFA detected was 4x the baseline. These data show substantial increase in TOC and VFA concentrations across the TTA affected by EK application.

Additional grab groundwater samples were collected during the final post-Stage 2 sampling event at several DPT soil sampling locations (C2, C3, C6, C7, and C9 in **Figure 5-5**). These samples were collected at each location generally from the depth of 21 ft, which approximately corresponded to the mid-screen interval of the monitoring wells within the TTA. Significant TOC concentrations (160 to 950 mg/L) were detected at all three sample locations (C2, C3, and C7) between the supply wells and electrode well E5. These data confirmed that significant amendment had been distributed to the most interior area of the TTA (i.e., between the supply wells and central anode E5).

Enhanced Reductive Dechlorination

Figure 6-1 presents a comparison of groundwater CVOC and biomarker monitoring results at six monitoring wells within the TTA and two outside the TTA. **Figure 6-1** presents the data collected from five (5) milestone events: baseline event in October 2014; end of Stage 1 operation in March 2016; end of post-Stage 1 incubation in September 2016; end of Stage 2 operation in March 2017; and end of post-Stage 2 incubation in June 2017.

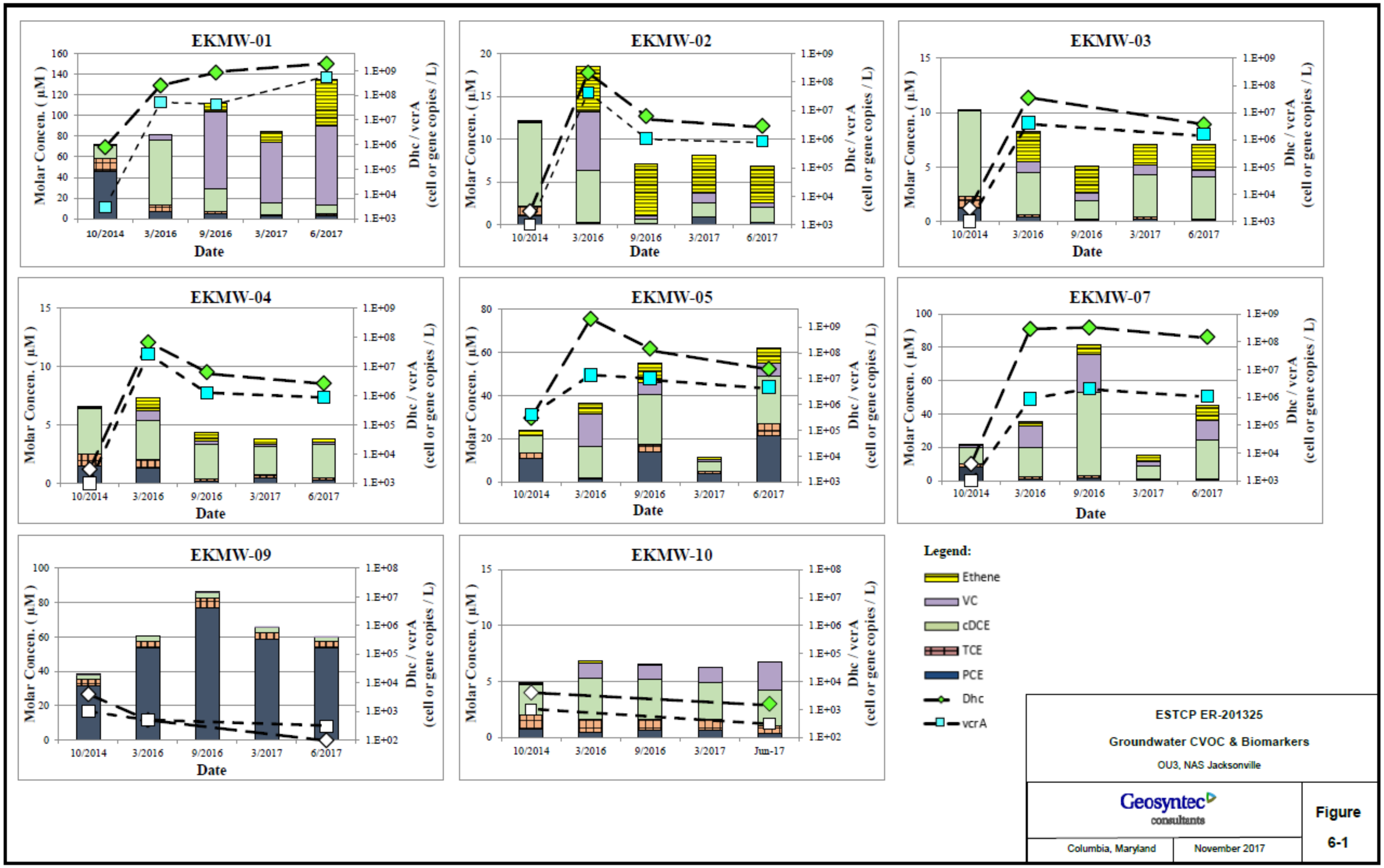

Figure 6-1. Groundwater CVOC & Biomarkers

The upgradient well, EKMW-09, is in the general area of the suspected PCE source (the former Building 106 area). The PCE concentrations at EKMW-09 remained above the baseline level during the Dem/Val, with no apparent increase of reductive dechlorination intermediates, and no detectable levels of biomarkers (below 1E+03 cell/L) throughout the Dem/Val.

At downgradient well EKMW-10, the baseline cis-1,2-DCE concentration was 260 µg/L, while the baseline methane concentration was 1,300 µg/L, both indicative of some natural reductive biological activity in this area prior to the Dem/Val. Between the baseline event and the post-Stage 2 event, no significant changes in PCE and other PCE dechlorination intermediate concentrations were observed, except an increase in VC from 5 µg/L to 157 µg/L. It is also noted that while biomarkers were below detection in the baseline event, a low level of *Dhc* (1.6E+03 cell per L) was detected at EKMW-10 in the post-Stage 2 event. Overall, the data at EKMW-10 suggest slight influence from the operation in the TTA approximately 20 ft away (to electrode well E6). As a comparison, the upgradient well EKMW-09 is located approximately 25 ft away from the closest electrode well E4.

Among the monitoring wells within the TTA, EKMW-01, located closest to the upgradient edge of the TTA, contained the highest baseline PCE concentration at 7,640 µg/L. Significant PCE dechlorination was observed at EKMW-01, with PCE concentrations decreasing from the baseline by 90% and 95% after Stage 1 and Stage 2 operations, respectively, while dissolved ethene concentrations were 15x and 85x (228 µg/L and 1,280 µg/L, respectively) the baseline level. Both biomarkers (*Dhc* and *vcrA*) increased by 1,000x or more from the baseline levels.

The data for monitoring wells EKMW-02, -03, and -04, were relatively similar, with baseline PCE concentrations ranging from 170 to 250 µg/L, and low to no detectable baseline VC (<6 µg/L), ethene (all below detection), and biomarkers (all below detection). Enhanced reductive dechlorination was evident at all these wells and both biomarkers at all these wells also increased by >1,000x from non-detect baseline levels to above 1E+06 in their respective units.

EKMW-05 and EKMW-07 had relatively high baseline PCE concentrations at 1,800 and 1,300 µg/L, respectively. At EKMW-07, PCE concentrations significantly decreased from baseline to 92 µg/L at the end of Dem/Val. *Dhc* and *vcrA* increased from non-detect baseline levels to over 1E+08 cell/L and 1E+06 gene copies/L, respectively, and dissolved ethene continued to increase from baseline (11 µg/L) to post-Stage 2 incubation (260 µg/L).

At EKMW-05, PCE concentrations significantly decreased from baseline (1,800 µg/L) to end of Stage 1 operation (180 µg/L) but then rebounded during the 6-month post-Stage 1 incubation period (to 2,280 µg/L). During the post-Stage 1 incubation (no active EK operation) when PCE rebounded, methane and ethene both increased from 210 to 587 µg/L and 144 to 255 µg/L, respectively, indicating continuing methanogenic and reductive dechlorination activities in the area. During Stage 2 operation, PCE concentrations decreased from 2,280 µg/L to 603 µg/L, but again rebounded (to 3,540 µg/L) during post-Stage 2 incubation. The reason for this rebound is unclear, but may indicate the presence of residual PCE source material in the proximity. Both biomarkers increased by almost 100x to 10,000x from baseline (1E+05 cell/gene copies per L) through Stage 1 operation, and remained above 1E+06 to 1E+07 cell/gene copies per L throughout the Dem/Val.

DPT groundwater samples collected from select interior locations (C2, C3, and C7; see **Figure 5-5**) during the post-Stage 2 event were analyzed for CVOCs, dissolved gases, and biomarkers to supplement the data collected from monitoring wells. These groundwater sampling data showed significant methanogenesis and reductive dechlorination, with methane concentrations above 2,400 µg/L and dissolved ethene concentrations ranging between 474 and 1,880 µg/L. *Dhc* and *vcrA* were detected in these samples at levels between 1E+05 and 2E+07 cell/gene copies per liter.

DPT sampling location C9 was near a former monitoring well EKMW-06 not included in the monitoring program. The DPT groundwater sampling data for C9 showed significant TOC concentration (790 mg/L) and evident reductive dechlorination with an ethene concentration at 402 µg/L. As discussed below in Section 6.3, soil CVOC and soil microbial analyses of C9 also indicated reductive dechlorination activities in that area.

Collectively, with the evident reductive dechlorination observed in the groundwater samples collected from the interior portion of the TTA (C2, C3, and C7 locations) and the area of C9, as well as the network of Dem/Val monitoring wells, the EK-BIO application clearly promoted substantial dichlorination and treatment within the overall TTA, whereas very little change was observed in the upgradient well outside the TTA (i.e., the control location).

6.3 SOIL SAMPLING RESULTS

There were three (3) rounds of soil sampling over Dem/Val: baseline event (September 2014), post-Stage 1 event (April 2016), and post-Stage 2 event (June 2017). The 11 soil sampling locations are presented in **Figure 5-5**.

6.3.1 Soil Chemical Analyses Results

For the baseline event, at each sampling location, three (3) samples were collected from discrete depths. The baseline data showed that within the TTA, PCE was the only chlorinated ethene detected at a concentration above 1 milligrams per kiliogram (mg/kg), with the exception of cDCE at 1.9 mg/kg and 3.3 mg/kg at locations C3 (18.5 ft below ground surface [bgs]) and C7 (18.5 ft bgs), respectively. The baseline data indicated that there was no apparent reductive dechlorination activity within the TTA soil prior to the Dem/Val. It was also noted that PCE concentrations decreased significantly with depth from 18.5 ft to 23 ft. PCE concentrations were below 0.08 mg/kg in all samples collected from the 21 and 23 ft bgs depths, with the exception of location C6 (5.5 mg/kg at 21 ft bgs and 3.1 mg/kg at 23 ft bgs) located on the upgradient limit of the TTA and closest to the expected PCE source in the general area of former Building 106 (**Figure 5-5**). Based on the finding that PCE was overwhelmingly present only at the 18.5 ft bgs sample interval, subsequent soil sampling events collected samples only from 18.5 ft bgs and 21 ft bgs.

Figure 6-2 below presents a comparison of soil CVOC concentrations at corresponding locations between the three (3) sampling events. The data presented in **Figure 6-2** are arranged per individual locations and sampling depths. Overall, soil PCE concentrations of all samples collected from 18.5 ft bgs at the nine (9) locations within the TTA decreased by 78% (C6) to 99% (C3) from baseline to post-Stage 2, with an average decrease of 88%. With the exceptions of C1 and C6, the decreases of PCE concentrations were already significant (75% at C8 to 99% at C3) from the baseline event to the post-Stage 1 event. Both C1 and C6 showed evident PCE decrease from the post-Stage 1 event to the post-Stage 2 event. It was also noted that while C6 was the only location with a significant baseline PCE concentration at 21 ft bgs (5.5 mg/kg), the PCE concentration at 21 ft bgs of the C6 corresponding sampling location decreased to 0.21 mg/kg and below in subsequent post-operation sampling events.

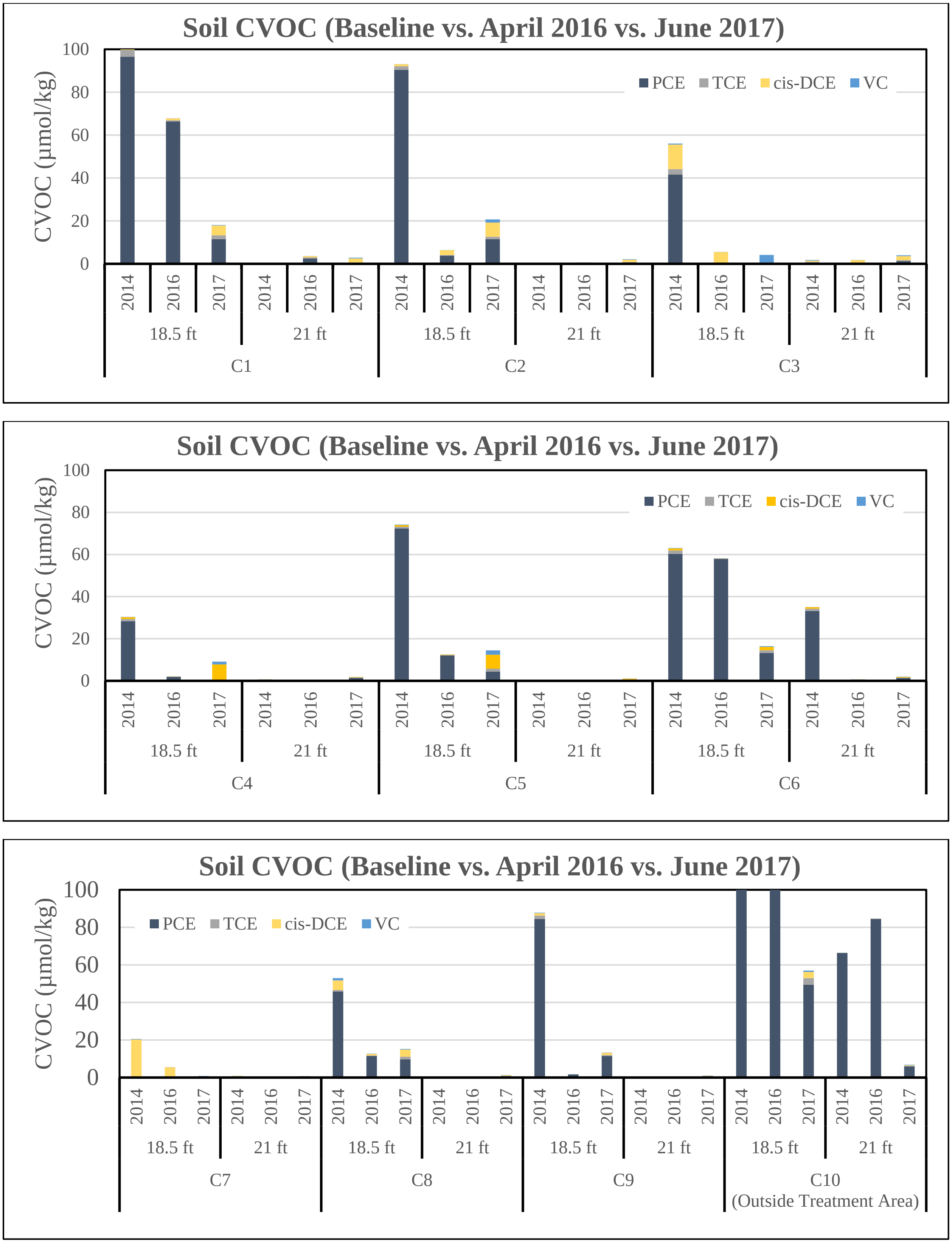

Figure 6-2. Soil CVOC Data – Comparisons Between Events

Location C10 was in the general area of former Building 106 and approximately 35 ft from the upgradient edge of the TTA. No decreases in PCE concentrations were observed at C10 at 18.5 ft bgs or 21 ft bgs between the baseline and post-Stage 1 events. PCE concentrations declined at both depths at this location from the post-Stage 1 event to the post-Stage 2 event. While the reason for the decline is unclear and may be due to heterogeneity (attempts were made to repeat boreholes as close as possible to prior co-located borings), a slight increase in dechlorination intermediates was observed in the 18.5 ft bgs sample, suggesting some increase in biological activity in this area over time.

While the decreases in soil PCE concentrations over the Dem/Val are evident, significant, and generally consistent among all sampling locations within the TTA, there were no clear, corresponding increases of dechlorination intermediates in the soil samples. Additional assessment of the effects of EK-BIO remediation on soil quality is further discussed below based on soil microbial analysis.

6.3.2 Soil Microbial Analytical Results

Soil samples from all three (3) events were analyzed for multiple biomarkers: reductive dechlorination bacteria *Dhc* and functional genes for TCE and VC dechlorination. The analyses of all soil samples collected during the baseline and post-Stage 1 events did not detect any of these biomarkers above the detection limit (6E+03 to 8E+03 enumeration or gene copies per gram). Given the observed PCE distributions and the lack of biomarkers in the first two events, only the soil samples from 18.5 ft bgs from the post-Stage 2 event were submitted for biomarker analyses.

Among the nine (9) post-Stage 2 samples from within the TTA, six (6) samples were reported with quantifiable levels, plus one with estimated level, of *Dhc*. Of these seven (7) samples with detected *Dhc*, five (5) samples (C2, C3, C5, C7, and C9) had detected functional genes for VC dechlorination. Among all the locations within the TTA, location C3 appeared to have the most established *Dhc* populations with VC reductase genes, followed by locations C2 and C5. It is noted that these are the locations in the interior of the TTA generally between supply wells and electrode well E5 which was an anode during both Stage 1 and Stage 2 operation. Electron donor would have been consistently migrating towards electrode well E5 during both Stages, and as such, it is not unexpected that the best electron donor availability and microbial growth would be detected in this area.

Overall, the soil sampling results presented in this section indicate that the EK-BIO operation resulted in significant decreases of PCE in clay soil across the TTA. The data also showed that microbial populations capable of reductive dechlorination of chlorinated ethenes, including VC, were established within the clay materials in at least part of the TTA.

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7.0 PERFORMANCE ASSESSMENT

This section provides an assessment of the performance of the Dem/Val relative to the performance objectives previously discussed in Section 3. Each subsection discusses the performance relative to an individual performance objective.

7.1 DEMONSTRATE UNIFORM DISTRIBUTION

The success criteria for this performance objective include:

<u>Criterion</u>

At groundwater monitoring locations within the TTA, groundwater TOC is at least 5x baseline, or 10x detection limit if baseline is below detection.

Every monitoring well within the TTA had TOC concentrations >8x of individual baseline level during Stage 1 and/or Stage 2 operation, with the exception of EKMW-04 where the maximum TOC detected was 1.8x of the baseline. However, at EKMW-04 the maximum VFA detected was >9x its baseline confirming suitable electron donor presence. With respect to VFAs, all but one monitoring well (EKMW-05) had concentrations >9x baseline levels. As such, the Dem/Val has met this criterion indicating that EK was able to substantially increase electron donor concentrations across the entire TTA.

<u>Criterion</u>

No local focusing of electric field within the TTA – no electrical potential gradient between any individual pair of cathode-anode is 5x the average electrical gradient between all pairs of electrodes.

The voltage measured at discrete locations within the TTA were between 5.3V and 6.2V, with a standard deviation of 0.31V (5%). Voltage gradients were calculated between locations of closest pairs and ranged between 0.1 to 0.26 V/m. The calculated voltage gradients between these pairs are within 3x of each other and within 2x of the average gradients (0.13 V/m) indicating no local focusing of electric field within the TTA. The Dem/Val has met this criterion.

<u>Criterion</u>

Electrical potential gradient between electrode pairs maintained at level no more than 5x target gradient at design current.

The EK system was designed and operated at a constant current. During Stage 1 and Stage 2 operation, the voltage required of the power supply unit was generally consistent between 15V and 30V, except for a few occasions when electrodes were in need of replacement. The electrical current supplied to individual wells during each stage of operation was generally steady (variation within 37% of average). Given that: (1) soil electrical resistivity is a soil property not expected to vary over the course of Dem/Val; and (2) the voltage output by the power supply unit and the current supplied to individual electrodes were generally steady, the electrical potential between electrode pairs within the TTA should maintain within 5x of target during operation. The Dem/Val has met this criterion.

7.2 DEMONSTRATE TREATMENT EFFECTIVENESS

The success criteria for this performance objective include:

Criterion

> 60% reduction in average PCE concentrations in soil and groundwater within the TTA, with coupled and comparable molar concentration increases of dechlorination daughter and end products.

Figure 6-1 presents a comparison of groundwater CVOC and biomarker monitoring results. The % decrease of PCE concentration and % increases of concentrations of dechlorination daughter products and ethene from the baseline levels are summarized below in **Table 7-1**.

Table 7-1. Changes of Groundwater CVOC and Ethene Concentrations*

	EKMW-01		**EKMW-02**		**EMKW-03**		**EKMW-04**		**EKMW-05**		**EKMW-07**	
	Stage 1	**Stage 2**	**Stage 1**	**Stage 2**	**Stage 1**	**Stage 2**	**Stage 1**	**Stage 2**	**Stage 1**	**Stage 2**	**Stage 1**	**Stage 2**
PCE Decrease	90%	95%	86%	74%	70%	83%	89%	72%	90%	67%	84%	93%
Increase of Products	310%	410%	65%	-41%	-13%	-24%	-18%	-34%	160%	200%	140%	200%
Increase of Ethene	14x	84x	58x	47x	30x	26x	11x	3.8x	1.0x	1.6x	13x	22x

* Calculations for each well are based on molar concentrations and comparing between Baseline to End-of-Stage 1 and Baseline to End-of-Stage 2. Calculations for increases of products include TCE, cis-1,2-DCE, VC, and ethene.

For each of the six monitoring wells located within the TTA, decreases of >80% in PCE concentration were achieved at the end of either Stage 1 and/or Stage 2. As presented in **Figure 6-1** and **Table 7-1**, the decreases of PCE from baseline at each well within the TTA were coupled with evident increases of dechlorination daughter products and/or ethene. The Dem/Val has met this criterion for groundwater.

Figure 6-2 presents a comparison of soil CVOC concentrations at corresponding locations between the three (3) sampling events. Overall, soil PCE concentrations of all samples collected from 18.5 ft bgs at the nine (9) locations within the TTA decreased by 78% (C6) to 99% (C3) from baseline to post-Stage 2, with an average decrease of 88%. It was also noted that while C6 was the only location with evident baseline PCE concentration at 21 ft bgs (5.5 mg/kg), the PCE concentration at this depth and location decreased to 0.21 mg/kg (96% reduction) and below in subsequent post-operation sampling events. As such, the Dem/Val met the criterion for soil PCE reduction.

Criterion

Ethene/ethane detected at > 75% of groundwater monitoring wells within the TTA before the completion of post-EK monitoring.

As presented in **Figure 6-1** and **Table 7-1**, every (100%) monitoring well within the TTA showed increased concentrations of ethene (up to >1,000 µg/L) during the Dem/Val. The Dem/Val has met this criterion.

Criterion

> 10x increases of Dhc from baseline at > 50% of soil and groundwater samples collected from within the TTA before the completion of post-EK monitoring.

For the groundwater, **Figure 6-1** shows that every monitoring well within the TTA showed significant increases (several orders of magnitude) of *Dhc* and *vcrA*. The Dem/Val has met this criterion for groundwater.

Among the nine post-Stage 2 soil samples collected from within the TTA, six samples were reported with quantifiable levels, plus one with estimated level, of *Dhc*, while all baseline soil samples did not contain detectable levels of *Dhc*. Of the seven samples with detected *Dhc*, five samples (C2, C3, C5, C7, and C9) showed functional genes for VC dechlorination. Thus, while not as impressive as the groundwater results, the Dem/Val has met this criterion for soil.

7.3 DEMONSTRATE SUITABILITY FOR FULL-SCALE IMPLEMENTATION

The success criteria for this performance objective include:

Criterion

System operation conditions (voltage and current) within ± 50% of the designed target conditions.

The EK system was designed and operated at a constant current, determined after the start-up period, during the Dem/Val. As discussed in Section 7.1 (criterion related to electrical gradient), the operating voltage and current remained relatively steady, and the overall system operation conditions were steady and within 50% of the average during each normal operation period. The Dem/Val has met this criterion.

Criterion

Amendment supply up-time > 75% of target.

Other than the scheduled major O&M events between the two stages of operation, there were only three occasions when the system was shut down to allow replacement of electrodes. Overall, the system up-time was >75% during the Dem/Val. The Dem/Val has met this criterion.

Criterion

Energy consumption within ± 30% of design estimates.

The EK system was designed and operated at a constant current, determined after the start-up period, during Stage 1 and Stage 2 operation. Given that the energy consumption is a function of voltage and current, and, as discussed above regarding the steady system operation condition criterion, the overall system operations and the energy usage were steady within the design estimate. The Dem/Val has met this criterion.

7.4 SAFE AND RELIABLE OPERATION

The success criteria for this performance objective include:

Criterion

Operation conditions remain stable within the normal designed ranges over the course of the demonstration period.

As discussed in Sections 7.1 and 7.3 above, the overall operation conditions remained relatively steady over the course of system operation. The Dem/Val has met this criterion.

Criterion

No lost-time incidents.

There were no safety-related lost-time incidents. The Dem/Val has met this criterion.

7.5 EASE OF IMPLEMENTATION

The success criteria for this performance objective include:

Criterion

Ability to construct using conventional techniques and contractors.

The Dem/Val involved only conventional field construction techniques, including well drilling, well installation, and trenching and piping, as well as remediation system assembly performed by regular, qualified subcontractors. The Dem/Val has met this criterion.

Criterion

A single field technician is able to effectively monitor and maintain normal system operation.

During the operation, one field technician performed routine system O&M tasks twice per week with approximately 2 to 3 hours per visit. During the routine O&M visit, the tasks primarily included system visual inspections, recording the system operational parameters (voltage, current, amendment flow and pressure), and replenishing amendment solutions as needed. Other than sampling groundwater, there were fewer than 5 scheduled O&M events that involved two field technicians. The Dem/Val has met this criterion.

8.0 COST ASSESSMENT

This section provides cost information that a remediation professional could use to reasonably estimate the costs for implementing EK-BIO at a given site. The cost analysis is based on actual costs of the tasks completed for this Dem/Val, and supplemented with reasonable estimates based on our team's experience from similar projects.

8.1 COST MODEL

Table 8-1 presents a summary of cost elements and the cost tracking. Select cost elements are briefly discussed.

Table 8-1. Cost Model for EK-enhanced Amendment Delivery for In-Situ Remediation

(for a Source Area Measuring 35 ft by 35 ft by 5 ft Thick)

Cost Element	Tracked During the Demonstration	Costs
Bench-scale EK Tracer Test	• Aquifer sediment materials provided by NAS Jacksonville. • Laboratory bench-scale EK column tracer tests – $25K	$25K
Remedial Design	• System design and demonstration plan – professional labor $80K	$80K
Remediation Construction	• Well driller – 17 electrode/supply wells and 10 monitoring wells – $40K • EK system construction subcontractor – $120K • Site construction subcontractor – $127K • Field construction oversight and system shakedown professional labor (~ 7 weeks) – $40K	$327K
Baseline Characterization	• Field staff labor - $6K • Laboratory analytical costs - $28K	$34K
Remediation System Operation & Maintenance	• Field O&M subcontractor – over 14 months of active operation, $45K • Materials – lactate, $6K • Materials - buffer and other chemicals, $3K • Materials - system parts & consumables, $4K • Professional labor for startup and scheduled O&M visits - $20K	$78K (about $6K/month)
Field Sampling (Soil / Groundwater)	• 4 rounds of comprehensive sampling events and 4 rounds of limited scale sampling events • Standard soil and groundwater sampling activities • Field sampling staff labor (partially provided by NAS Jacksonville) • Laboratory analytical costs (partially provided by NAS Jacksonville)	-
Waste Disposal	• NAS Jacksonville provided waste disposal; no cost tracking	-
Reporting & Other Compliance Requirements	• Project reporting and meetings.	-

Cost Element – Bench-scale EK Column Testing

For this Dem/Val, the team conducted a bench-scale EK column tracer test to estimate the transport rate as a design basis. It is recommended that such bench-scale testing be considered as part of the remedial design for an EK-enhanced remedy. The scope of bench testing can vary depending on the test objectives. For example, the bench test can be designed to estimate EK transport rate only or to include assessment of treatment effectiveness facilitated by the enhanced amendment delivery, and the need for bioaugmentation. The costs of bench testing, therefore, vary based on the scope and objectives, but will typically range in cost between $15,000 to $40,000.

Cost Element – Remediation Construction

For this Dem/Val, no special drilling or field construction methods were required. The EK system, including an amendment supply system, a power supply system, and electrolyte cross-circulation system, was constructed by a remediation system vendor in accordance with the project-specific design. No special equipment or parts, other than off-the-shelf commercial products, were required for the EK system. The electrodes and power supply unit were also commercially available products. The EK system construction costs will vary depending on the project scale (e.g. number of electrode wells needed to cover a treatment area, number of electrodes used, etc.) and site conditions (e.g., the extent of instrument automation due to site access, iron fouling and control measures due to geochemistry, etc.). However, the cost increase for expanding the EK system constructed for this Dem/Val will only be marginal, primarily related to additional parts (e.g., electrodes ($240 each), valves, and pipe fittings, etc.). The EK control center used for this Dem/Val was capable of incorporating up to 13 electrodes, thereby expanding the treatment footprint (on the electrode spacing used) by approximately 45%.

Cost Element – Remediation System Operation & Maintenance

The system O&M costs can vary depending on the extent of instrument automation and site conditions and restrictions. For this Dem/Val, routine O&M tasks were performed by regular remediation field technicians without needing special personnel. The material costs for chemicals and system consumables are project-specific but generally scalable. Professional labor costs for this Dem/Val were related to initial system start-up operation and a system conditioning during the re-start transition from the end of Stage 1 incubation to Stage 2 operation.

8.2 COST DRIVERS

Based on the information and experience obtained from this Dem/Val, there are three main cost drivers to consider when evaluating implementation costs in future projects, including: (1) footprint, depth interval, and volume of target treatment zone and contaminant mass; (2) presence and location of above-ground and subsurface utilities; and (3) site geochemistry, particularly pH and iron. These are also the same cost drivers for many other in-situ remediation technologies and not unique to EK technology implementation. Each of these cost drivers is discussed below.

Cost Driver – Target Treatment Zone and Contaminant Mass

As for most remediation technologies, the size and volume of the target treatment zone as well as the amount of contaminant requiring treatment significantly affects the overall remediation costs. Particularly, the drilling and well installation costs for system wells (electrode wells and supply wells) vary based on the number and depth of these wells needed to adequately address the treatment zone. The spacing between electrode wells designed for this Dem/Val was approximately 18 ft, with supply wells located within the electrode well network. This level of well spacing, coupled with the phased operation program and the duration of operations, can be considered as within ranges of normal design for this technology. For this Dem/Val, active EK operation following bioaugmentation lasted approximately 10 months (two separate 5-month stages) and achieved an average soil PCE reduction of 88%. The overall duration of an EK remedy implementation will depend on the contaminant mass and the required mass reduction goal.

While there is no technical limit for applying EK technology in terms of depth, the costs for well construction increase as the depth of the target treatment zone increases. The depth interval (thickness) of target treatment zone may affect the number of electrodes within an electrode well and, therefore, the overall number of electrodes needed. A target treatment zone of shallow depth may need additional measures and costs related to utility protection as discussed below. This technology is suitable mainly in saturated formations; treatment within the vadose zone represents a challenge which is discussed in Section 9.

Cost Driver – Utilities

As with other active remediation technologies, a power source is required for this technology. Although not yet tested, the energy demand and the electrical operation conditions (voltage and current) demonstrated in this Dem/Val suggest that solar energy with battery units may be a feasible option.

Special considerations are warranted at sites with metallic subsurface infrastructure or subsurface utilities that may be electrically conductive. This evaluation should take into account the vertical separation of the electric field and the utility of concern. If needed, cathodic protection measures can be considered which can increase the implementation costs. In general, the EK technology is best suited for sites where the target treatment zone is deeper than 8 ft bgs (i.e., below utilities and conduits) and the groundwater table below 5 ft bgs, otherwise special design considerations are needed.

Cost Driver – Site Geochemistry

Concentrations of iron and other major cations (e.g., calcium and magnesium) in groundwater are an important factor that can affect the cost of system construction and O&M. While these geochemical parameters are an important factor for most in-situ remediation technologies, it requires a special consideration when implementing an EK remedy because the electric field will result in, at least temporarily, concentrated iron and cations in cathode wells which attract cations in groundwater. The EK system for sites with elevated concentrations of these cations will need to be sized and equipped with adequate units for handling the anticipated amount of precipitates.

More robust O&M programs and efforts will also need to be considered for such sites. Over the course of implementation, the O&M issues related to these do diminish, and as demonstrated with this Dem/Val, they can be readily managed.

8.3 COST ANALYSIS

For cost assessment, **Table 8-2** provides a cost comparison between EK-BIO, conventional direct-injection EISB, hydraulic fracturing DPT injection of zero-valent iron (ZVI), and electrical resistance heating (ERH) thermal treatment for a typical CVOC source site in low-K materials. The key characteristics of the framework site are as follows:

- The site characterization and conceptual site model have been completed. The characterization of the target treatment area is sufficient and no additional pre-design investigation data are needed to support the remedial design;
- The footprint of the target treatment area is approximately 80 ft x 80 ft;
- The depth interval for treatment is between 10 and 30 ft bgs;
- The geology consists of mainly fine-grained clayey material with low permeability (<1.0E-06 cm/sec);
- CVOC mass (chlorinated ethenes) is approximately 500 lbs;
- Treatability testing has already been completed to support bioremediation design. The site will require bioaugmentation with dechlorination cultures, which will dechlorinate target CVOCs to innocuous end products;
- The site has available potable water supply and adequate power utility; and
- The site has no unmanageable concerns for site access, subsurface obstruction, electrical interference or corrosion.

Table 8-2 presents estimated full-scale implementation costs and key assumptions associated with each technology on which the estimated costs are developed. Given that performance monitoring requirements can be highly project-specific, the estimated costs are presented as with and without the costs for performance monitoring. These estimates are prepared at the level of a feasibility study (e.g., +50%/-30%) for site remediation.

For baseline comparison, the costs of excavation with offsite disposal was also estimated. The feasibility-level cost estimate for an excavation-disposal option is in the range of $1,300,000 to $1,500,000. One variable in cost estimation for this option is the quantity of excavated soil that may need to be managed as hazardous waste. This can significantly increase the cost of this option.

Based on the cost estimates presented in **Table 8-2**, EK-BIO is likely to be more cost favorable than ERH ($688K to $1,183K before accounting for monitoring costs) and excavation-disposal. The cost saving of EK-BIO compared to ERH is smaller when factoring in the monitoring costs because ERH can complete the remediation within a shorter timeframe (<1 year with ERH compared to ~ 2 to 3 years with EK-BIO for the framework site). It is noted the significant difference in the electrical energy needed for these two technologies indicating a much more favorable environmental performance of EK-BIO over ERH.

The feasibility and effectiveness of a direct-injection EISB approach is highly dependent on whether direct injection can achieve a reasonable injection rate and a reasonable radius of influence (ROI) of injected amendments. For cost estimating purposes, an injection rate of 0.75 gallons per minute (gpm) to 1 gpm and a ROI of 7 ft were assumed based on experience at low-K sites. The estimated costs for direct-injection EISB are presented in **Table 8-2** as a range based on injection rates. It should be noted that it is possible that at certain low-K sites, these assumed injection rates and ROI may not be achievable. As presented in **Table 8-2**, the estimated cost for an EK-BIO approach is comparable to that of direct-injection EISB when factoring in the costs for repeat injection events (assumed two injection events over five years). When considering performance monitoring costs, which depend on the overall timeframe of the individual remediation technique, EK-BIO is potentially a more cost favorable alternative to direct-injection EISB. Therefore, at sites where low-K material and/or high-degree of heterogeneity limits the feasibility of applying direct injection, EK-BIO provides a cost-effective solution for implementing in-situ bioremediation.

Fracturing DPT injection has an overall estimated cost slightly higher than EK-BIO. Certain site conditions may present more constraints for fracturing DPT injection than EK-BIO, such as sensitive subsurface utilities, shallow treatment zone close to the ground surface, or oxidizing geochemical conditions requiring more site conditioning to facilitate reductive treatment. While fracturing DPT technology can enhance aquifer permeability, if a target treatment zone is in a heterogeneous formation the fracturing technique may still result in non-uniform distribution of injected amendment. Alternately, the depth interval for fracturing will need to be reduced, with associated increased costs to achieve uniform distribution.

Table 8-2. Cost Model for Full-Scale Implementation of Select Source Area Remediation Technologies

Cost Element	Tasks	Costs – EK-BIO	Costs - Injection EISB	Costs - ERH	Descriptions / Assumptions
Remedial Design and Permitting	EK-BIO – design, project workplans, UIC (underground injection control) permit Injection EISB – design, project workplans, UIC permit ERH – design, project workplans, air permit, water discharge permit	$70K	$50K	$80K	NA
Remedial Construction	EK-BIO – 1. Well installations 2. Site construction; utilities 3. EK system & control center fabrication / mobilization / field connections 4. Professional field oversight and system shakedown/startup	1. $53K 2. $140K 3. $160K 4. $60K			• 25 electrode wells and 15 supply wells; all 4-inc PVC wells • Electrode well spacing at ~ 18 ft • Two electrodes vertically spaced in each electrode well • One EK control / amendment supply system
	Injection EISB – 1. Well installations 2. Site construction; utilities 3. Injection system mobilization / field connections 4. Professional field oversight and system shakedown/startup		1. $70K 2. $35K 3. $20K 4. $40K		• 49 injection wells; 2-inch PVC wells • Injection well spacing at ~ 13 ft • Injection ROI (radius of influence) at ~ 7 ft • Up to three injection manifolds are constructed • Area is accessible during injection, and no trenching is required
	ERH – 1. Well installations 2. Site construction; utilities 3. ERH system mobilization / field connection / system shakedown/startup 4. Professional field oversight			1. $92K 2. $180K 3. $190K 4. $60K	• 25 electrode wells and 25 co-located vapor recovery wells • Electrode well spacing at ~ 18 ft • A surface cap will not be required • Include a 20-hp (horse power) vapor extraction blower • Adequate power supply is available for a 500-kW power unit
Remediation System Operation & Maintenance	EK-BIO – 1. Materials – chemicals 2. Materials – parts and supplies 3. Labor – O&M operator 4. Labor – professional 5. Utilities – water and electrical power	1. $60K 2. $25K 3. $65K 4. $50K 5. $5K			• Lactate as electron donor; also supply buffer and bioaugmentation culture • Approximately up to 3A current between each pair of cathode and anode • Four stages of operation over two years; each stage is four months of active EK operation followed by two months of incubation; alternate electric field orientation between each stage • Less than 5,000 kW-hr electrical energy required for EK operation • Weekly visit by a system operator; up to three major O&M events

Remedial System Operation & Maintenance	Injection EISB – (injection rate from 1 gpm to 0.75 gpm*) 1. Injection system rental 2. Materials – chemicals 3. Labor – field injection 4. Utilities – water and electrical power 5. Reinjection – 2 reinjection events * gpm: gallon per minute		1. $20K to $26K 2. $55K 3. $60K to $90K 4. $5K 5. $120K to $180K x 2 events		• Emulsified vegetable oil (EVO) as the electron donor; also inject buffer and bioaugmentation culture • Achievable injection rate from 1 gpm to 0.75 gpm • Up to two re-injection events over a period of five years
	ERH – 1. System rental and system operator 2. Labor – professional oversight 3. Utilities – electrical power 4. Permit monitoring (air and condensate) 5. Waste (activated carbon) disposal			1. $360K 2. $24K 3. $114K 4. $30K 5. $53K	• Total heating time of 180 days • Approximately 142,000 kW-hr electrical energy needed • Approximately 8,000 lb (pound) of activated carbon for regeneration/disposal • Vapor and condensate sampling and analysis in compliance with permits
Estimated Total (no performance monitoring costs)		**$688K**	**$355K to $386K + 2 reinjections $595K to $746K**	**$1,183K**	
Remediation Performance Monitoring	EK-BIO – Semi-annual groundwater monitoring for 3 years; Final soil sampling Injection EISB – Semi-annual groundwater monitoring for 5 years; Final soil sampling ERH – Two semi-annual groundwater following the active operation; Final soil sampling	$190K	$290K	$90K	For costing purpose, assuming $25K per semi-annual groundwater monitoring event; $40K for final soil sampling event.
Estimated Total (with performance monitoring costs)		**$878K**	**$885K - $1,036K**	**$1,273K**	

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9.0 IMPLEMENTATION ISSUES

EK-BIO is mainly a variation on standard EISB whereby EK is used to more effectively deliver the required amendments (electron donors, buffers and microbes) through low-K materials. As such, there are very few additional requirements or implementation issues that need to be addressed beyond those typically encountered with a standard EISB implementation. Some areas where additional attention may be required, on a site-specific basis, include:

- Safety considerations related to potential stray current/voltage to surface. To address this question, we checked the current and voltage at the manhole steel cover located within the treatment area while the EK system was in operation to confirm that there was no safety concern. Depending on the project site, and for sensitive and active facilities with dedicated safety departments, additional design and explanation effort may be required for project approvals.

- Iron fouling of filters and valves along the catholyte (well water from cathode wells) extraction line. In this Dem/Val, we re-plumbed the system to minimize potential flow restriction points. Scaling of the cathodes also required maintenance actions to clean the cathode surface. As indicated above, this issue diminished over the course of the Dem/Val.

- Corrosion of metallic parts in the manifold system & wellhead fittings due to elevated chloride concentrations. In this Dem/Val, we replaced most metallic contacting parts with plastic parts upon discovering that chloride levels were far higher (>1,000 mg/L) than initially known.

- The technology implementation did not require specialized/proprietary equipment. We used only standard commercial off-the-shelf equipment. We designed the manifold and control system and had a remediation system vendor assemble the system per design, but the overall system was similar to other “typical” in-situ remediation systems.

- If the technology is to be implemented near (laterally and/or vertically) utilities that are “sensitive” to electric interference or corrosion concerns, some protection measures, such as cathodic protection, may be considered.

- No special regulatory requirements or permits were required beyond what are typical for other EISB or ISCO projects, such as a UIC permit. Depending on the locality-/facility-specific requirements, local or facility power/electrical departments should be consulted.

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