FINAL REPORT

Sustained In situ Chemical Oxidation (ISCO) of 1,4-Dioxane and Chlorinated VOCs Using Slow-release Chemical Oxidant Cylinders

ESTCP Project ER-201324

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14. ABSTRACT

This study demonstrated the use of slow-release chemical oxidant cylinders to treat a plume containing dioxane and chlorinated volatile organic compounds. The objectives were to demonstrate/evaluate the technology effectiveness, sustainability/longevity, oxidant transport and destruction, implementability/secondary water quality impacts, and technology reproducibility. Unactivated persulfate embedded in a slow-release paraffin wax formulation was emplaced in two 4-inch wells which were housed inside 18-inch diameter boreholes. The majority of the performance objectives were met.

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ACRONYMS AND ABBREVIATIONS

AOP	advanced oxidation process
bgs	below ground surface
CCL3	Third Contaminant Candidate List
CCL4	Fourth Contaminant Candidate List
cis-1,2-DCE	cis-1,2-dichloroethene
cm/d	centimeters per day
cm/s	centimeters per second
CPT	cone penetrometer tool
CVOC	chlorinated volatile organic compound
1,1-DCA	1,1-dichloroethane
1,1-DCE	1,1-dichloroethene
1-D	one-dimensional
2-D	two-dimensional
DI	de-ionized
DoD	Department of Defense
DOT	Department of Transportation
ER	Environmental Restoration
ERPIMS	Environmental Restoration Program Information Management System
ESTCP	Environmental Security Technology Certification Program
ft	feet
ft/d	feet per day
ft/ft	foot/foot
F&G	funnel and gate
gpm	gallons per minute
HRT	hydraulic residence time
IATA	International Air Transport Association
ISCO	*in situ* chemical oxidation
k	rate constant
k_1	first-order rate constant
k_2	second-order rate constant
lb	pounds
L $mmol^{-1}$ d^{-1}	liters per millimole per day
M	molar

MCL	maximum contaminant level
mg	milligrams
µg/L	micrograms per liter
mg d^{-1} cm^{-2}	milligrams per day per square centimeter
mg/L	milligrams per liter
mg L^{-1} d^{-1}	milligrams per liter per day
mL/min	milliliters per minute
M^{-1} s^{-1}	per molar per second
MTBE	methyl tertiary-butyl ether
mV	millivolts
NAS NI	Naval Air Station North Island
NIRIS	Naval Installation Restoration Information Solution
NOD	natural oxidant demand
O&M	operations and maintenance
ORP	oxidation-reduction potential
OU11	Operable Unit 11
P&T	pump and treat
PRB	permeable reactive barrier
PV	pore volume
PVC	polyvinyl chloride
QA/QC	quality assurance/quality control
ROI	radius of influence
RPD	relative percent difference
SDWA	Safe Drinking Water Act
SOP	standard operating procedure
SR	sustained release
1,1,1-TCA	1,1,1-trichloroethane
TCE	trichloroethene
US	United States
USEPA	US Environmental Protection Agency
UV	ultraviolet
VC	vinyl chloride
W	watts

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EXECUTIVE SUMMARY

BACKGROUND AND TECHNOLOGY DESCRIPTION

1,4-Dioxane (dioxane) is increasingly recognized as a challenging contaminant at sites where 1,1,1-trichlorethane (TCA) was released to soil and groundwater. A Navy query of the Naval Installation Restoration Information Solution (NIRIS) indicated that over 200 sites have detected dioxane above 3 micrograms per liter (µg/L). In addition, based on a query of United States Air Force Environmental Restoration Program Information Management System (ERPIMS), dioxane has been observed in 17.4% of the monitoring wells with records for trichloroethene (TCE) and/or TCA. Often dioxane is comingled with co-contaminants such as chlorinated volatile organic compounds (CVOCs) that also require treatment.

Dioxane is not easily treated. *Ex situ* advanced oxidation processes (AOPs) are the most developed approach for dioxane treatment. Because of high operation and maintenance (O&M) costs associated with AOPs, successful deployment of *in situ* approaches would grant remedial project managers a far more flexible and cost effective remedial approach. Traditional *in situ* chemical oxidation (ISCO) is not a solution to large and persistent plumes because the oxidants are relatively short-lived.

Slow-release chemical oxidant cylinders match the contaminant destruction rate to the contaminant transport rate with a sustainable, simple, and low O&M approach. The technology concept involves use of slow-release chemical oxidant cylinders to treat large plumes of dioxane and CVOCs. Chemical oxidant (e.g., sodium persulfate) embedded in a slow-release paraffin wax "cylinder" can be emplaced in groundwater wells, a funnel & gate (F&G) configuration (described further below), permeable reactive barrier (PRB), or directly installed using direct push technology. The oxidant/wax mixtures have been designed to allow oxidant to gradually diffuse into the groundwater and oxidize contaminants. They are slowly consumed and persist sufficiently long enough to result in contaminant destruction as the plume migrates through the treatment zone created by these cylinders. Contaminants can be oxidized by permanganate and unactivated persulfate as described below. Any contaminant that is capable of being oxidized by the released oxidant can potentially be treated with this technology. Because of the flexibility in distribution methods, this technology can be used in a permeable reactive zone or in a grid configuration, and can be used in multiple hydrogeologic environments. For large contaminant plumes or sites with access restrictions, a PRB or F&G configuration may be the best remediation approach.

PERFORMANCE OBJECTIVES AND RESULTS

Technology Effectiveness

This objective focused on demonstrating the ability to destroy dioxane and CVOCs in the reactive zone. The CVOCs that were quantified included 1,2-dichloroethene (1,2-DCE), 1,1-dichloroethane (1,1-DCA), cis-1,2-dichloroethene (cis-1,2-DCE), and TCE. The success criterion was established at a minimum of 90% reduction in concentration. The maximum destructions observed were 99.3% and 99.0% for dioxane and total CVOCs, respectively. The upgradient dioxane and total CVOC concentrations in a upgradient location were 20,000 µg/L each. The downgradient concentrations of dioxane and total CVOCs the downgradient boring location were 140 and 200 µg/L, respectively. Thus, the 90% minimum destruction criteria were exceeded.

Sustainability/Longevity

This objective focused on demonstrating the ability to consistently distribute the oxidant in the reactive zone and to meet the above Technology Effectiveness objective for a minimum time of four weeks. Two methods were used to evaluate this objective. First, the change in oxidant concentration over time at a given location was evaluated. If the oxidant concentration was stable and did not decrease over a period of one year then the objective was considered met. Second, if 90% contaminant removal was sustained for 4 weeks or longer then the criterion was considered met. Sodium persulfate concentrations decreased in an exponential pattern over time with 42% remaining at the final sampling event (134 days) and 31% and 9% predicted to be remaining after 6 and 12 months, respectively. Thus, the hypothesis that persulfate concentrations would remain relatively constant over time until the cylinders were spent was disproved; the performance objective was not met based on this criterion. During the second oxidant cylinder deployment, dioxane and CVOC removal was ≥ 99% after 119 days further corroborating high contaminant destruction for extended time periods even when oxidant concentrations may be variable or declining. Thus, the criterion of contaminant destruction effectiveness being maintained for greater than 4 weeks was exceeded.

Oxidant Transport and Destruction

This objective focused on demonstrating that oxidants will not be transported significantly past the reactive zone. Success criteria for this objective, which were met, are either non-detectable oxidant concentrations in a downgradient monitoring well or concentration trends demonstrating oxidant destruction along the flow path. Sodium persulfate decreased from a maximum concentration of 2100 milligrams per liter (mg/L) in a boring located 14 feet (ft) downgradient of the cylinders to 21 mg/L in a boring located 26 ft downgradient. This represents a 99% reduction in oxidant concentration. pH and oxidation-reduction potential (ORP) trends also indicate that groundwater downgradient of the oxidant returned to natural conditions. For example, the pH and ORP upgradient of the cylinders were 7.72 and 75 millivolts (mV), respectively. The pH and ORP at the location of maximum persulfate were 7.03 and 217 mV. The pH and ORP values observed 7.9 m downgradient were 7.67 and 55 mV, respectively, which are similar to upgradient values.

Technology Implementability/Secondary Impacts

This objective focused on demonstrating that secondary groundwater quality impacts are either acceptable or transient. The goal of this performance objective was to determine if any secondary impacts to the aquifer result from the oxidant cylinder deployment. Potential secondary impacts include elevated dissolved metals including hexavalent chromium and generation of bromate as a product of bromide oxidation. A treatability study conducted prior to the field demonstration indicated the potential for hexavalent chromium generation in the present of sodium persulfate. Success criteria during the field demonstration were initially based on filtered metals and bromate concentrations, but these analyses were not conducted because of project constraints. Rather, the potential impacts were evaluated considering secondary parameters including pH and ORP trends downgradient of the oxidant cylinders. pH decreased and ORP increased in response to the presence of sodium persulfate. Downgradient of the maximum sodium persulfate concentration, pH increased and ORP decreased to background values. Hexavalent chromium and bromate can be chemically or biologically reduced. Thus, elevated dissolved metal concentrations could be expected to decline to background levels as background pH and ORP values were re-established.

Technology Reproducibility

Two replicate cylinder installations were used to characterize reproducibility in this qualitative performance objective. The approach for assessing reproducibility was comparison of oxidant release in the two replicate boreholes. Two methods of comparison were used including: 1) the relative percent difference of oxidant concentrations within the two boreholes, and 2) comparison of the sodium persulfate flux from the cylinders in the field demonstration and in the treatability study. The relative percent difference of the sodium persulfate concentrations in the cylinder borehole monitoring wells was 66±50% and represented three sampling events where the concentration in one oxidant cylinder monitoring well was consistently greater than that in the other. Density driven flow effects resulted in a gradient of oxidant concentration increasing as depth increased. Therefore, it is reasonable that the oxidant concentrations in the two boreholes were different. Still, at most, the concentration in one monitoring well was four-fold greater than that in the other. The estimated sodium persulfate flux from the cylinders ranged from 4 to 17 milligrams per day per square centimeter (mg d^{-1} cm^{-2}) from which is reasonable when compared to the maximum flux of 22 mg d^{-1} cm^{-2} measured during the treatability test.

COSTS

Capital and operating costs were estimated for a hypothetical site approximately 400 ft in length and 100 ft in width, with a treatment thickness of 20 ft ranging between 20 and 40 ft below ground surface (bgs), a 1,4-dioxane concentration in groundwater of approximately 10,000 µg/L, and a groundwater velocity of approximately 5 feet per day (ft/day). Various remediation scenarios were evaluated including:

1. PRB with persulfate cylinders as demonstrated with cylinder changeouts being performed every 6 months for 30 years at different cylinder spacings of 1, 2.5, 5, and 10 feet.
2. PRB with persulfate cylinders as demonstrated with a cylinder spacing of 5 feet for 30 years with cylinder changeouts being performed every 3, 6, 12 or 18 months.
3. PRB via traditional aqueous ISCO reagent injection with an injection radius of influence (ROI) of 5 feet and reinjection performed every 30, 45, 60 or 90 days for 30 years.
4. F&G with persulfate cylinders as demonstrated with cylinder changeouts being performed every 6 months.
5. Pump and treat using pump and treat using AOP and re-injection for 30 years.

A PRB with persulfate cylinders (Scenarios 1 and 2) had a total project cost of $2.9 million, which is less than an F&G (Scenario 4) $3.7 million. It was also less than AOP (Scenario 5) at $4.3 million and a PRB with periodic manual injection of the same mass of aqueous sodium persulfate (Scenario 3) at $6.2 million. The results indicate that persulfate cylinders in a passive PRB configuration may potentially result in significant cost saving over traditional approaches. Site-specific cost evaluations should be conducted to determine whether slow-release oxidant cylinders are the best solution for a given site and how they should be implemented.

IMPLEMENTATION ISSUES

A variety of end-use considerations are relevant when considering and implementing the persulfate cylinder technology for *in situ* treatment of 1,4-dioxane, CVOCs, and other contaminants.

Technology selection should keep in mind the intended use of slow-release oxidant cylinders – passive and long-term treatment of contaminated groundwater. Applicable contaminants include those that are capable of being oxidized by chemical oxidants that are released by the oxidant cylinders. At this site dioxane was demonstrated to be oxidized by unactivated persulfate (i.e., no activator was added either via incorporation in the slow-release oxidant cylinder formation or by direct injection into groundwater). It may or may not be oxidized at sufficient rates at other sites and engineering, treatability, or pilot studies should be conducted. Other contaminants including CVOCs, petroleum hydrocarbons such as benzene and methyl tertiary butyl ether (MTBE) are also potentially applicable. Specific target contaminants will have different reaction rates with the chemical oxidants. These differences should be evaluated during design.

Other technologies that should be considered are pump and treat and *in situ* bioremediation not to mention other potential technologies. The technology selection process conducted as part of a feasibility study will consider effectiveness, implementability, cost, and other factors. The most common applications are envisioned to be implementation of passive PRBs or F&G systems for treatment of persistent plumes as an alternate to pump and treat. Like other *in situ* techniques, the ultimate goal of utilizing the slow-release oxidant cylinders should be to treat the groundwater in an aquifer rather than groundwater in monitoring wells. Therefore, careful consideration should be made prior to deploying the oxidant cylinders in existing monitoring wells at a site because monitoring wells are designed and placed with the intent of monitoring and not remediation.

Regulatory aspects to be considered include shipping by air or ground and health and safety considerations while handling the cylinders. In addition, slow-release oxidant cylinders that contain persulfate can result in transient pH reduction and metal mobilization as a result of the persulfate degradation and subsequent generation of sulfuric acid. Often these geochemical are transient.

Design of a remediation system using slow-release oxidant cylinders must consider cylinder spacing; changeout frequency; groundwater velocity; contaminant plume width, depth, and length; reaction kinetics of the released oxidant with target contaminants as well as natural oxidant demand in the aquifer; the potential for density driven flow; and the optimal configuration (e.g., PRB vs. F&G).

The oxidant cylinders are commercially available off the shelf from Carus Corporation. Equipment for suspending cylinders in wells or reactive gates are not standardized and will require engineering design and possible custom fabrication.

1.0 INTRODUCTION

Environmental Security Technology Certification Program (ESTCP) Project Number Environmental Restoration (ER)-201324 involves demonstration and validation of sustained *in situ* chemical oxidation (ISCO) of 1,4-dioxane (dioxane) using slow-release oxidant cylinders. This demonstration includes two phases: Phase I – Laboratory treatability study and engineering design tool development and Phase II – Field demonstration of permeable cylinder barrier. A complete discussion of Phase I activities was provided in the Treatability Study Report (**Appendix B**). This Final Report describes methods and results from treatability study and field demonstration.

1.1 BACKGROUND

Dioxane is increasingly recognized as a challenging contaminant at sites where 1,1,1-trichlorethane (1,1,1-TCA) was released to soil and groundwater. In 1985, 90 percent (%) of all United States (US) production of dioxane was used to stabilize TCA. At that time, there were about 25,000 vapor degreasers in operation, which consumed about 165 million pounds of 1,1,1-TCA per year. A Navy query of the Naval Installation Restoration Information Solution (NIRIS) indicated that over 200 sites have detected dioxane above 3 micrograms per liter (µg/L). In addition, based on a query of United States Air Force Environmental Restoration Program Information Management System (ERPIMS), dioxane has been observed in 17.4% of the monitoring wells with records for trichloroethene (TCE) and/or 1,1,1-TCA. In fact, 64.4% of all dioxane detections were collocated with TCE with the presence of 1,1,1-TCA (Anderson et al. 2012).

Once released into groundwater, dioxane can migrate more rapidly than chlorinated volatile organic compounds (CVOCs) due to its miscibility with water, low affinity for sorption to soil organic matter, and resistance to biodegradation and abiotic breakdown (Mohr et al. 2010). Dioxane also has the capacity to diffuse into and occupy the large pore volumes in silts and clays due to its high solubility and molecular charge distribution that favors invasion of clays by breaking the tightly held mono-layer of water on clay surfaces (Mazurkiewicz and Tomasik 2006, Mohr et al. 2010, Payne et al. 2008, Zhang et al. 1990). As with CVOCs, a significant mass of dioxane may reside in fine-grained deposits, slowly diffusing back into the aquifer resulting in persistent plumes (Payne et al. 2008).

Dioxane is not easily treated. *Ex situ* advanced oxidation processes (AOPs) are the most developed approach for dioxane treatment (USEPA 2006). Because of high operation and maintenance (O&M) costs associated with AOPs, successful deployment of *in situ* approaches would grant remedial project managers a far more flexible and cost effective remedial approach. As an example, natural attenuation of dioxane is being evaluated at the Air Force Plant 44. While evidence of dioxane-oxidizing bacteria exists, site data show rates are insufficient to contain the plume (Mora et al. 2011). Previous research indicates the major reason is these bacteria have low specific growth rates, low cell yields, and high half-saturation constants (Adamus et al. 1995, Evans 2007, Mahendra and Alvarez-Cohen 2006, Parales et al. 1994). Cometabolism via propane sparging is a promising approach (Hatzinger et al. 2017) but may result in high O&M costs and safety issues for continued treatment of persistent plumes. Traditional ISCO is also not a solution to persistent plumes because the reactants are relatively short-lived (Siegrist et al. 2011).

Slow-release chemical oxidant cylinders, described further in subsequent sections, match the contaminant destruction rate to the contaminant transport rate with a sustainable, simple, and low O&M approach. Using innovative oxidation chemistries in concert with innovative deployment strategies, cost-effective treatment of persistent dioxane plumes is possible.

Slow-release chemical oxidant cylinders is an innovative approach that has the potential to provide low-cost and passive long-term treatment of persistent groundwater plumes containing dioxane and co-contaminants such as CVOCs. Slow-release oxidant cylinders used in this demonstration were comprised of unactivated sodium persulfate (i.e., no activator was added either via incorporation in the slow-release oxidant cylinder formation or by direct injection into groundwater) embedded in paraffin wax. These cylinders were placed in groundwater wells where sodium persulfate was released passively into groundwater and oxidized dioxane and CVOC co-contaminants. More detailed description of the technology demonstration is provided in the subsequent sections.

1.2 OBJECTIVE OF THE DEMONSTRATION

The overall objective of this project was to demonstrate the use of slow-release chemical oxidants to destroy dioxane and CVOCs in groundwater *in situ*. Because dioxane is highly miscible in water, has a low Henry's Law constant, has a low octanol/water partitioning coefficient, and is slowly biodegradable; it often forms long, relatively low concentration groundwater plumes. Therefore, the use of slow-release technology can be advantageous to treat persistent dioxane plumes in a variety of barrier-type applications as they slowly migrate from the original source.

The technical objectives of this demonstration/validation project were:

- Demonstrate the use of slow-release chemical oxidant cylinders for sustained *in situ* treatment of dioxane and CVOCs.
- Demonstrate the use of unactivated persulfate in the slow-release cylinders to couple the oxidant release rate, the contaminant transport rate, and the contaminant destruction rate.
- Demonstrate that the slow-release cylinder delivery vehicle can minimize potential secondary effects such as metals mobilization.

1.3 REGULATORY DRIVERS

In September 2013, United States Environmental Protection Agency (USEPA) published the *Toxicological Review of 1,4-Dioxane* (USEPA 2013). In this review, USEPA revised the 1×10^{-6} cancer risk assessment level for dioxane to 0.35 µg/L from 3.0 µg/L. As a result, the proposed minimum reporting level (MRL) for dioxane as part of the *Unregulated Contaminant Monitoring Regulation (UCMR 3) for Public Water Systems* (Federal Register 2012) was reduced to 0.07 µg/L. Although there is no federal maximum contaminant level (MCL) in drinking water established for 1,4-dioxane to date, there have been federal screening levels determined based on a 1 in 10^{-6} lifetime excess cancer risk (USEPA 2017). In 2017, USEPA calculated a screening level for tap water of 0.46 µg/L. State drinking water guidance limits have been put in place by various states. See **Table 1.1** below for drinking water and groundwater guidelines established by state (USEPA 2014).

Table 1.1. State Drinking Water and Groundwater Guidelines for 1,4-dioxane.

State	Guideline (µg/L)
Alaska	77
California	1.0
Colorado	0.35
Connecticut	3.0
Delaware	6.0
Florida	3.2
Indiana	7.8
Maine	4.0
Massachusetts	0.3
Mississippi	6.09
New Hampshire	0.25
New Jersey	0.4
North Carolina	3.0
Pennsylvania	6.4
Texas	9.1
Vermont	3.0
Washington	0.438
West Virginia	6.1

Notes: µg/L – micrograms per liter

New-found dioxane contamination will likely influence decisions regarding Department of Defense (DoD) monitoring and cleanup. Although no federal drinking water standards have been established to date, USEPA has established an "action level" of 3 µg/L for dioxane and it was listed on the third Contaminant Candidate List (CCL3) (Federal Register 2014). In November 2016, the EPA published the Fourth Contaminant Candidate List (CCL4) including 1,4-dioxane (Federal Register 2016). Contaminants on the CCL4 are currently not held to any national primary drinking water regulations, but may require future regulation under the Safe Drinking Water Act (SDWA) (USEPA 2016).

The DoD has hundreds of sites contaminated with chlorinated solvents, which represents a large remediation liability (Parsons 2004). Dioxane can form persistent plumes that require ongoing treatment. While these large plumes may contain relatively low concentrations of dioxane (e.g., less than 100 µg/L), sites with concentrations greater than the health-based drinking water standards continue to involve active remediation. These plumes present significant challenges to the DoD as they can be costly to contain and clean up (Steffan 2007).

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2.0 TECHNOLOGY

This section provides an overview of the technology that was demonstrated.

2.1 TECHNOLOGY DESCRIPTION

The technology concept involves use of slow-release chemical oxidant cylinders shown in **Figure 2.1** to treat persistent plumes of dioxane and CVOCs. Chemical oxidant (i.e., sodium persulfate or potassium permanganate or mixtures thereof) embedded in a slow-release wax formulation "cylinder" can be emplaced in groundwater wells, using a Funnel and Gate (F&G) configuration (described further below), permeable reactive barrier (PRB), or directly installed into boreholes. The oxidant/paraffin mixtures have been designed to allow oxidant to gradually diffuse into the groundwater and slowly oxidize dioxane and CVOCs. They are slowly consumed and persist sufficiently to result in dioxane destruction as a dilute plume migrates through the treatment zone created by these cylinders. Dioxane and CVOCs can be oxidized by permanganate and unactivated persulfate as described below. Because of the flexibility in distribution methods, this technology can be used in a permeable reactive zone or in a grid configuration, and can be used in multiple hydrogeologic environments. For large and dilute dioxane plumes or sites with access restrictions, a PRB or F&G configuration may be the best remediation approach.

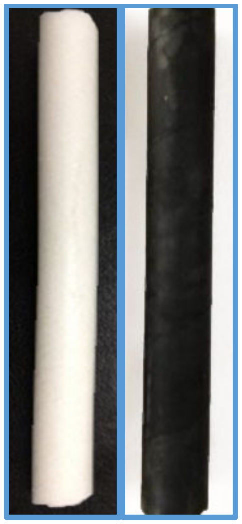

Figure 2.1. Persulfate (left) and Permanganate (right) Slow-release Oxidant Cylinders.

The fundamental advantage of slow-release forms of oxidants over traditional injection of liquid solutions is the ability to release the oxidant over a period of years which will minimize rebound, treat persistent plumes, and minimize O&M costs. The mechanism for release of the oxidant from the paraffin wax matrix is a dissolution-diffusion process (Lee and Schwartz 2007a). In the case of potassium permanganate ($KMnO_4$), oxidant particles exposed at the surface of the cylinder rapidly dissolve, resulting in a large spike in permanganate flux. As the $KMnO_4$ particles dissolve, the surface of the exposed particles retreats into the core of the cylinder creating secondary porosity. The $KMnO_4$ release rate from the cylinder becomes limited by the $KMnO_4$ diffusion rate through the porous structure, eventually reaching a nearly steady state flux rate until the oxidant is consumed. Additionally, the slow-release oxidant can effectively treat the dioxane as it slowly diffuses from less mobile pore spaces into groundwater. A similar mechanism occurs with sodium persulfate.

Selection of the correct oxidant depends on a variety of site-specific factors including natural oxidant demand (NOD), oxidant release rates, contaminant degradation efficiency, cost, and potential secondary aquifer geochemistry effects. Dioxane oxidation by unactivated persulfate is slower than by activated persulfate which is advantageous for this technology because it results in greater oxidant persistence.

2.1.1 Funnel and Gate (F&G) Concept

The F&G concept is a variation of a permeable reactive barrier (ITRC 2011). The principle is based on use of sheet pile or impermeable materials (e.g., grout) to create an impermeable barrier to groundwater flow and then to include openings in this barrier (i.e., gates) through which water flows as shown in **Figure 2.2**. Hydraulic modeling is critical to ensure groundwater does not flow around, under, or over the impermeable funnel. Various processes (e.g., air sparging) or materials (e.g., chemical oxidants) can be included in these gates. In the case of the subject technology being demonstrated, slow-release chemical oxidants would be emplaced in the gates. Emplacement technologies for amendments in gates has been described (ITRC 2011).

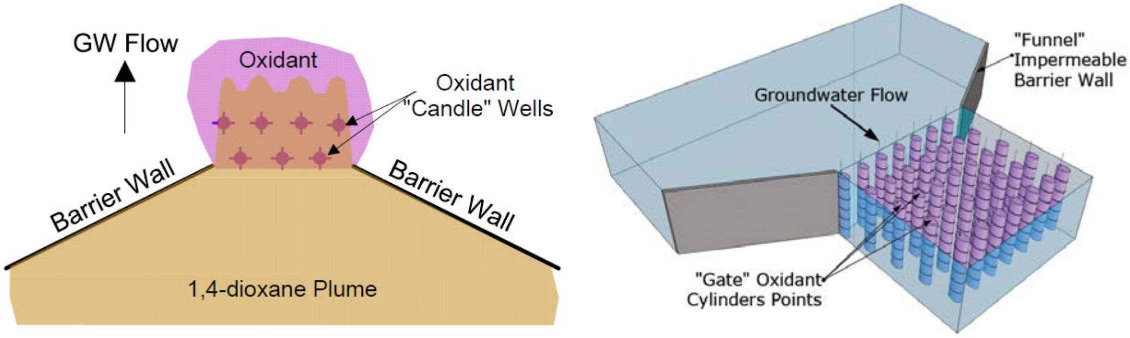

Figure 2.2. Funnel and Gate Concept.

This barrier can be envisioned as part of a PRB or the gate of an F&G. The F&G approach is ideal in many ways because it is a passive method to control the velocity – a key cylinder installation design parameter. The funnel can be designed to achieve a groundwater velocity that will result in an optimized target oxidant concentration tailored to site contaminants, their concentrations, and the NOD.

2.1.2 Cylinder Spacing

Required cylinder spacing in a PRB may be required to be on the order of feet if the only means of oxidant mixing with the aquifer is dispersion. Use of close cylinder spacing to intercept a large plume may not be cost-effective. Use of a F&G may be a preferable approach to mitigate the issues associated with close cylinder spacing. By funneling groundwater into a gate, cylinders can be spaced closely and still be cost-effective. The reason is the width of the gate is much less than the width of the plume that is being intercepted. Additional approaches include: 1) providing baffles in the gate, and 2) providing means for mixing within the gate. Baffles can create a serpentine flow pattern that can greatly enhance mixing. Active mixing either by pumping or gas sparging can also be used to promote mixing. Researchers at The Ohio State University conducted modeling simulations to investigate a semi-passive approach of intermittent pumping downgradient from a row of slow-release permanganate cylinders to enhance mixing and lateral dispersion as shown in **Figure 2.3** (Lee et al. 2008).

On the left side, a lack of lateral dispersion is occurring which would reduce cylinder treatment efficiency and could require close spacing. With wider cylinder spacing, methods to promote mixing and enhanced dispersion may be needed. This was accomplished in their studies with well-based mixing and zero net injection/withdrawal pumping that facilitated lateral spreading and reagent mixing as illustrated on the right side of **Figure 2.3**. Pneumatic circulators can also be used but the risk of VOC volatilization would need to be considered (Christenson 2011). Pneumatic circulators have been used in the Cozad, Nebraska cylinder field site (Christenson et al. 2012). Modeling is often performed to assess the potential impact of these gate modifications (i.e., baffling, pumping, or pneumatic mixing) on cylinder spacing. Nevertheless, it is estimated the cylinder spacing can be increased by a factor of 3 to 10 with these approaches.

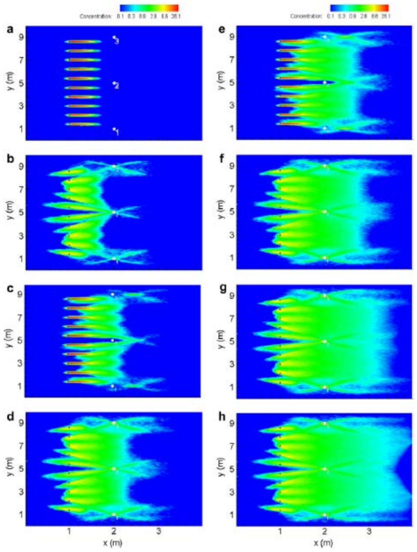

Figure 2.3. Distribution and Mixing of the Oxidant Promoted by Periodic Pumping (Lee et al. 2008).

2.1.3 Longevity

The longevity of slow-release oxidant cylinders will be a function of a number of parameters including: oxidant flux, cylinder diameter, ground water velocity, hydraulic conductivity, and NOD. Dissolution rates from slow-release oxidants are characterized by an initial flush followed by slower and sustained first order release (Kang et al. 2004, Lee and Schwartz 2007b). Oxidant release from the paraffin wax matrix occurs through the processes of dissolution and diffusion. The release of permanganate from a slow-release permanganate cylinder is illustrated schematically in **Figure 2.4**. As solid potassium permanganate dissolves and void spaces are created, newly created void spaces expose new solid potassium permanganate for dissolution and diffusion. This process occurs radially starting at the outer circumference of the cylinder progressing to the cylinder “core”. Eventually the oxidant is completely released from the cylinder and it is considered “spent” (**Figure 2.5**).

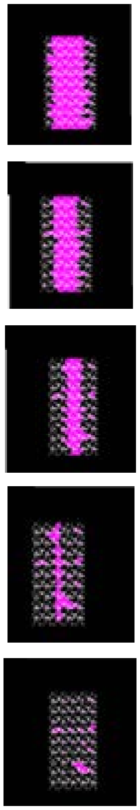

Figure 2.4. Time Series Progression of Oxidant Release from a Cylinder.

Figure 2.5. New (left) and Spent (right) Permanganate Cylinders.

2.2 TECHNOLOGY DEVELOPMENT

During the past decade, significant efforts have been devoted to developing innovative remedial technologies. ISCO is a relatively mature technology involving the injection of liquid oxidants into contaminated aquifers. Permanganate is an established remedial technology, widely accepted as an efficient oxidant for ISCO applications, and extremely effective for rapidly oxidizing chlorinated ethenes. Persulfate is a relatively newer oxidant capable of generating free radical chemistries that degrade a wide variety of contaminants of concern. While the ISCO chemistries are sound, the application and delivery of oxidants to the contaminants can be a challenge at many sites. Most ISCO treatments to date have involved injecting oxidants into aquifers as liquid solutions. A problem with any chemical injection; however, is that many sites have aquifers with finer textured soils and lenses of low permeability that do not readily accept liquid injections.

When this occurs, the chemical oxidant will be transported preferentially through zones of higher conductivity or can be observed coming back out of the injection borehole because it offers the path of least resistance. Difficulty in addressing contamination in low permeable soils may be alleviated to some degree by taking a more passive approach where a slow-release oxidant cylinder is inserted into the formation and the oxidant is allowed to intercept the contaminant plume over many years.

Reactive amendments have been used to create *in situ* treatment barriers and zones that passively degrade contaminants. PRBs have shown great promise as a tool for *in situ* remediation of chlorinated organics, heavy metals, and other contaminants. Operating under natural hydraulic gradients, PRBs facilitate *in situ* plume capture and treatment, simultaneous treatment of multiple types of contaminants, and low operation and maintenance costs. Although zero-valent iron has been the reactive media used in the majority of PRBs, other amendments, for example oxidants, may offer advantages for the treatment of emerging and recalcitrant contaminants. However, the properties of oxidants make them poorly suited to forming reactive barriers or zones that remain viable for long periods of time. Permanganate and persulfate salts are highly soluble, so they readily dissolve and become mobile in ground water. One approach for creating an oxidant-based reactive barrier in a fixed location is to combine an insoluble delivery approach using paraffin wax with the oxidants to prevent their instant dissolution and serve as a sustained and slow-release oxidant delivery system. Necessary properties of the wax matrix properties include:

- Stable and non-reactive with the oxidant;
- Isolates reactants from instant dissolution in groundwater;
- Nontoxic; and
- Facilitates slow sustained release of reactant(s) over long periods of time (e.g., many months).

Development of a sustained-release form of permanganate was proposed several years ago (Kang et al. 2004, Ross et al. 2005) followed by a number of publications documenting the efficacy of slow-release oxidant release systems to remove chlorinated solvents in laboratory and large flow-tank systems (Lee et al. 2009, Lee et al. 2008, Lee and Schwartz 2007a, Lee and Schwartz 2007b). More recently research efforts proposing the use of the sustained-release oxidant technology for other organic contaminants of concern such as benzene, toluene, ethylbenzene, xylenes, and polycyclic aromatic hydrocarbons have been published (Kambhu et al. 2012, Rauscher et al. 2012).

Carus Corporation began early prototype laboratory and manufacturing development work on the RemOx sustained-release (SR) technology using potassium permanganate in early 2009, followed by Persulfate SR and the mixed oxidant cylinder technology RemOx SR+ in 2012. Pictures of the three types of cylinders (RemOx SR, RemOx SR+, and Persulfate SR) are shown in **Figure 2.6**.

Figure 2.6. RemOx SR (left), RemOx SR+ (center), and Persulfate SR (right) Cylinders Shown in 1.5- and 2.5-inch Diameters

A detailed product development timeline for the SR technology product lines is provided below:

- April 2009 – Development work begins on the RemOx SR technology;
- September 2009 – Optimization of RemOx SR oxidant mass loading and oxidant release profile experiments;
- 2010 – 1-D-column and 2-D tank experimentation with RemOx SR and chlorinated solvents;
- October 2011 – Pilot-scale manufacturing begins;
- October 2011 – First RemOx SR field implementation;
- August 2012 – Persulfate SR and RemOx SR+ Technology Development work begins (1-D columns and 2-D tanks);
- October 2012 – Notified of ESTCP funding for SR field demonstration;
- February 2013 – Initial evidence of MnO2 coating causing inhibition of permanganate release;
- March 2013 – RemOx SR+ Provisional patent submitted;
- March 2014 – RemOx SR+ Utility patent submitted;
- August 2014 – ESTCP Persulfate SR field implementation; and
- September 2015 – First RemOx SR+ Technology Field implementation.

A cylindrical shape was the initial geometry that was created and evaluated in lab-scale tests and later in the product development cycle, cubes and small circular beads or pastilles were also assessed (**Figure 2.7**).

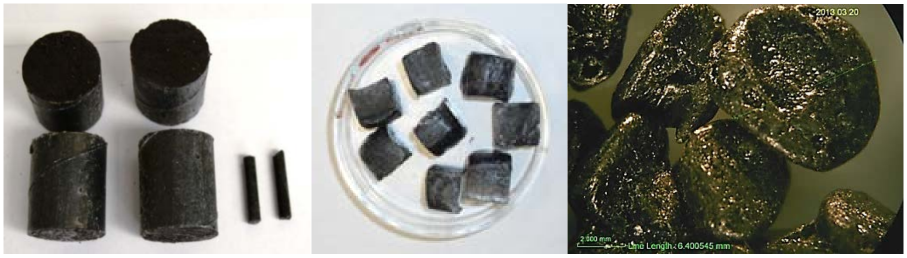

Figure 2.7. Early Permanganate SR Laboratory Cylinder Prototypes (left), SR Permanganate Cubes (center), and SR Permanganate Pastilles (right).

Initial SR laboratory tests involved optimizing the oxidant mass to paraffin wax loading (e.g., 30%, 60%, 70% 80% by weight) and characterizing the permanganate releases rate profiles. The dissolution release rate experiments were conducted in one-dimensional (1-D) column and two-dimensional (2-D) tanks packed with clean silica sand with deionized water influent (**Figure 2.8**). The purpose was to evaluate permanganate release characteristics and begin to understand the longevity of the cylinder technology based on the oxidant mass loadings.

Figure 2.8. 1-D Column Tests (left), and RemOx SR Mini-cylinder 2-D Tank Experiments (right).

The graph below illustrates the results of 1-D column experiments using 60% permanganate SR mass loading and the resulting dissolution characterizations (**Figure 2.9**). Permanganate release profiles were characterized by higher concentrations at the beginning of the experiments followed by a long “tail” of lower but sustained-release concentrations of permanganate.

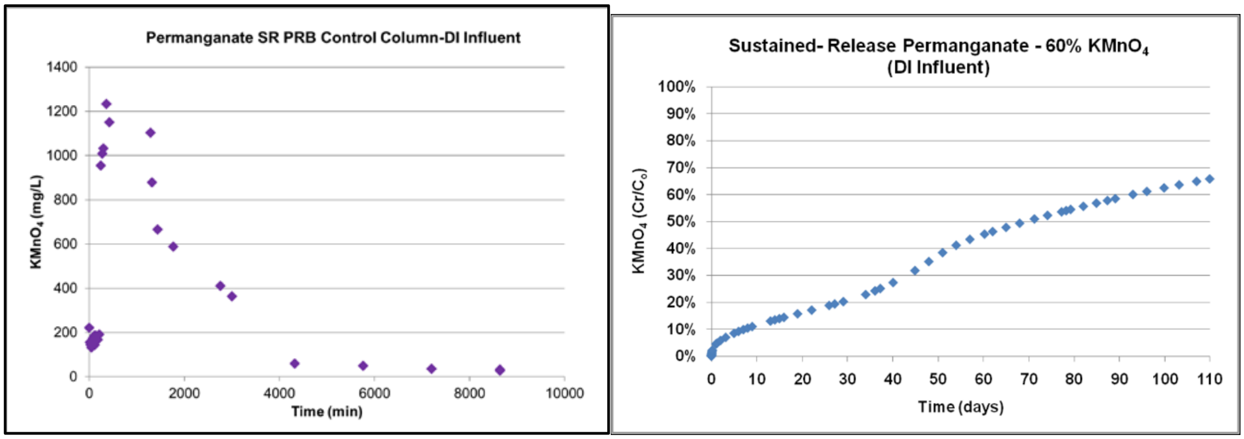

Figure 2.9. **1-D Column Tests: Permanganate Release Profiles Showing Instantaneous Concentrations (left) and Cumulative Concentrations (right).**

Early mass loading optimization efforts revealed that oxidant loadings of 70% or less resulted in unreacted oxidant particles due to complete coating by the wax as illustrated in **Figure 2.10** below.

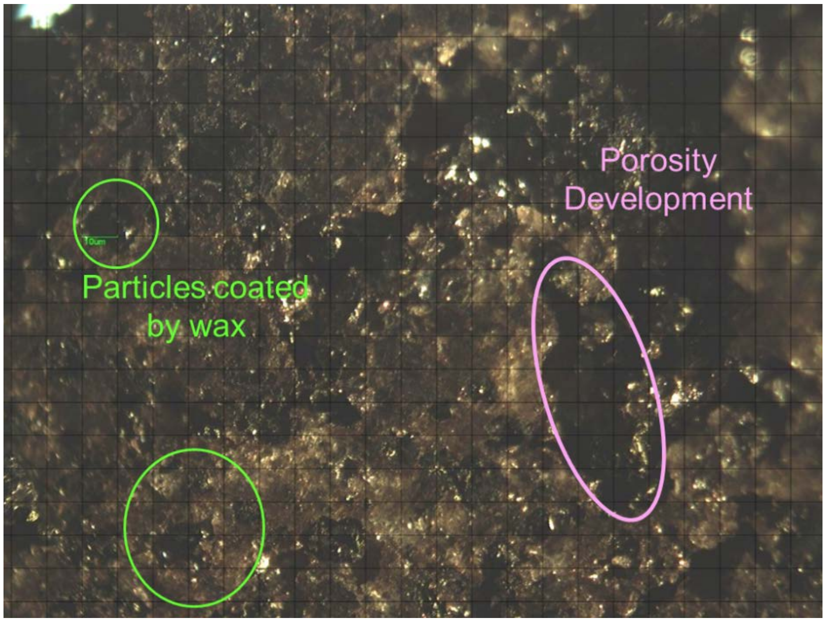

Figure 2.10. **Microscope Picture of Porosity Development and Unreacted Permanganate Crystals Embedded in the Paraffin Wax Matrix.**

After the permanganate release characteristics were understood and the mass loading was in process of being optimized, 1-D column experiments were conducted in clean sand with TCE-spiked de-ionized (DI) water. For these early experiments small cubes of the sustained-release product were used to simulate a RemOx SR PRB application (**Figure 2.11**).

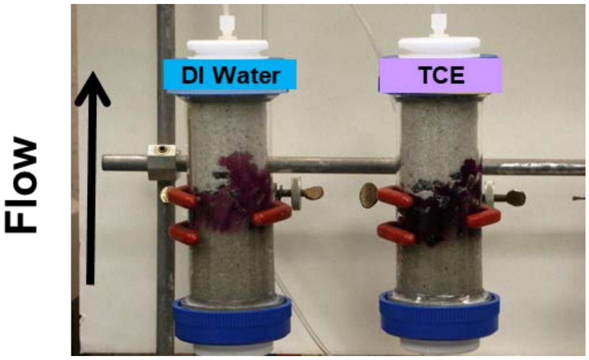

Figure 2.11. PRB Column Tests with TCE-spiked DI Water, and a DI Water Control.

The performance assessment results of these column tests are provided below as a function of time and pore volumes (PVs) flushed through the columns where TCE mass removal ranged from 86% - 100% over 170 days or > 470 PVs (**Figures 2.12**).

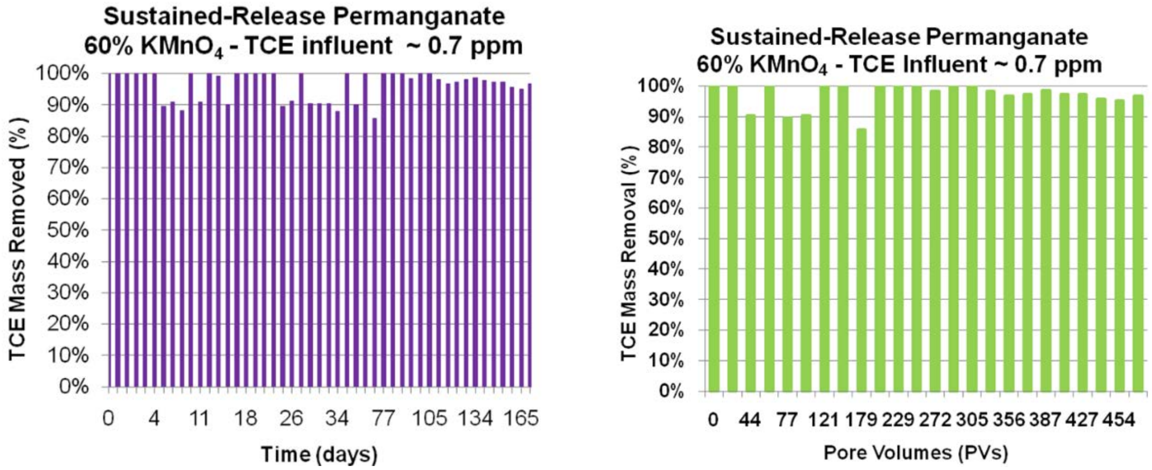

Figure 2.12. Performance Assessment Results for 1-D PRB Column Tests with TCE Influent as a Function of Time (left), and Pore Volumes (right).

Oxidant mass loading experimentation was completed by late 2013. Column testing results revealed the optimized permanganate mass loading of 80%-83% percent allowed for near complete utilization of the oxidant and was also a product that could be manufactured on a pilot-scale. The 1.35-inch and 2.5-inch diameters for the SR cylinder technology was based on dimensions that what would readily fit inside 2-inch and 3-inch direct push tooling. The cylinders were initially 3-feet long, but shipping trials revealed that the cylinders were getting broken in transit. For this reason, an 18-inch length was chosen which eliminated the breakage issue. **Figure 2.13** illustrates the release rate profiles for laboratory made cylinders as well as 1.35 and 2.5-inch RemOx SR cylinders. The laboratory data illustrated in **Figure 2.13** was also fitted with a model initially developed by Ohio State University (Lee and Schwartz 2007b) and later refined by Clarkson University as part of this ESTCP project. This early work helped verify that the RemOx SR release profiles scaled as a function of cylinder diameter (from small lab-scale to pilot-scale manufactured cylinders) and were also able to be fitted with a model for predictive purposes.

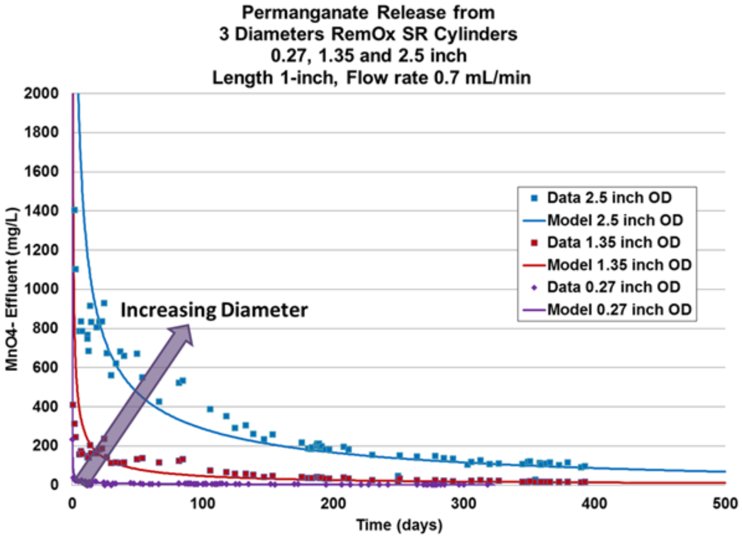

Figure 2.13. 1-D Column Tests Permanganate Release Rate Profiles and Model Fit.

The next step of SR development involved designing a variety of cylinder holder options that were tested in the laboratory and field. The first generation of cylinder holders were stainless steel mesh tubes with open spaces to allow for the release of permanganate (**Figure 2.14**). During early RemOx SR field trials (late 2011-2012) it became apparent that the stainless-steel mesh holders were impeding the release of permanganate. This was evidenced by initial high concentrations being recorded during early deployment (e.g., 1,000's of mg/L) followed by very low concentrations (e.g., > 10 mg/L). This result was validated in laboratory testing and as a result a new design was developed using off the shelf plastic mesh tubing with the maximum open space available that could have flexibility in length (**Figures 2.15**).

Figure 2.14. Stainless-steel Mesh Cylinder Holder.

Figure 2.15. Mesh Cylinder Holder Prototypes.

The next SR product that was developed was the Persulfate SR cylinder. The product development approach was the same as used for RemOx SR where initial 1-D column tests packed with clean sand and DI water influent were conducted to characterize the persulfate release profile (**Figure 2.16**).

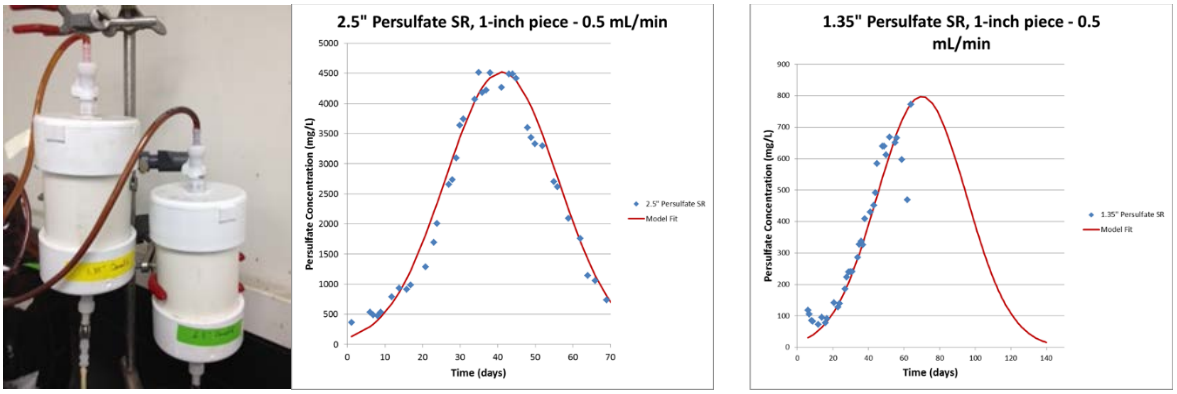

Figure 2.16. Persulfate SR Columns (left), 2.5-inch Persulfate SR Release Curve (center), and 1.35-inch Persulfate SR Release Profile (right).

The next step with the Persulfate SR was to evaluate petroleum hydrocarbon contaminant removal. **Figure 2.17** illustrates the results.

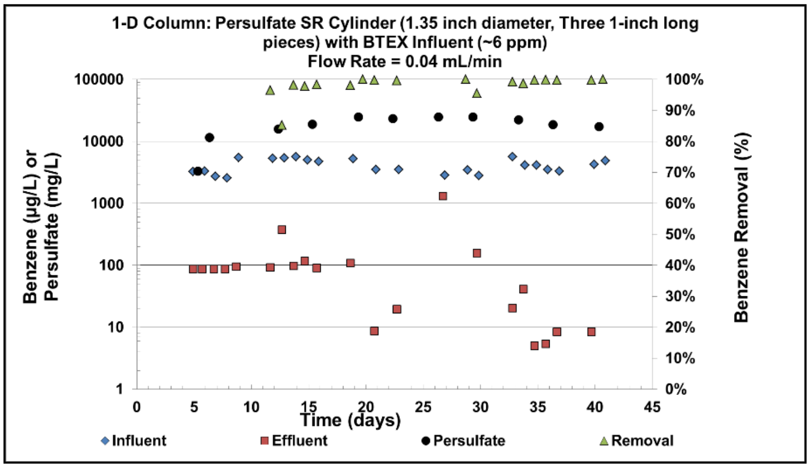

Figure 2.17. Persulfate SR 1-D column (left) and, 1-D column: Benzene Removal Results from Persulfate SR Cylinder (right).

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Advantages of sustained ISCO of dioxane and CVOCs using slow-release chemical oxidant cylinders include:

- This technology provides an *in situ* application to treat persistent plumes of dioxane.
- This technology is also applicable to a multitude of co-contaminants such as CVOCs and benzene.
- Sustained ISCO is implementable in a variety of configurations with different oxidants.
- This flexible and adjustable technology can be configured to match the rate of oxidant release to the mass flux of dioxane and solvents and control cylinder replacement frequency.
- It can be used in heterogeneous aquifers.
- The technology mitigates rebound problems with ISCO.
- *In situ* application is a sustainable application, which significantly reduces energy usage and overall costs.
- It offers an excellent health and safety profile.
- Can be deployed at active sites with minimal infrastructure required for deployment and monitoring.
- The technology does not depend on biodegradation which may require cometabolism to be successful (Hatzinger et al. 2017).
- It does not require injection of gases for cometabolic biodegradation.

Limitations of sustained ISCO of dioxane and CVOCs using slow-release chemical oxidant cylinders currently include:

- Technology applicability for a given site will depend on several factors including but not limited to: 1) reaction rate(s) of the released oxidant with the contaminant(s) of concern, 2) groundwater velocity, 3) available flow path length for the contaminant(s) to be destroyed, and 4) the remediation goal that must be achieved for the contaminant(s) by the end of the available flow path length. The technology is only applicable to sites where these four factors are such that adequate contaminant removal is achieved within an acceptable distance. For example, if the reaction rate of a released oxidant with a given contaminant is too slow to result in attainment of the remediation goal in the required treatment flow path, then the technology may not be applicable. Installation of more cylinders can potentially overcome this limitation but economics must also be considered. Engineering calculations along with treatability and/or pilot tests can be conducted to make this determination. Published rate constants (Waldemer and Tratnyek 2006, Waldemer et al. 2007) can also be useful in this regard.

- Secondary environmental effects can occur including mobilization of metals, low pH resulting from persulfate decomposition (Crimi and Siegrist 2003, Tsitonaki et al. 2010), and oxidation of chromium and bromide to hexavalent chromium or bromate. These risks are minimized in the cylinder configuration because of the lower concentration of oxidant involved in the reactions. Note that potential adverse effects associated with metal mobilization as a result of oxidation and/or pH depression are generally transient and limited to the target treatment area only.

- Potential for low transverse dispersion of oxidants may require close spacing between cylinders perpendicular to migration direction. The use of a F&G-style system could be used to overcome this limitation.

- Generation of oxidation byproduct such as manganese dioxide (in the case of permanganate) or iron hydroxides may lead to decrease in oxidant release rate or, possibly, preferential flow due to plugging within the reactive zones.

- Density-driven flow and non-uniform oxidant transport may be exacerbated at sites with low horizontal groundwater gradient. However, this can be mitigated by proper site investigation, modeling, and engineered measures to induce an artificial gradient or facilitate vertical mixing.

- Depending on site-specific mineralogy, persulfate may be activated to varying extents resulting in variable NOM oxidation thereby impacting the effectiveness towards contaminants of concern.

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3.0 PERFORMANCE OBJECTIVES

Performance objectives for the demonstration are presented in **Table 3.1**. A description of each performance objective, specific data requirements, and success criteria are detailed below.

3.1 QUANTITATIVE PERFORMANCE OBJECTIVE: TECHNOEFFECTIVENESS

This objective focused on demonstrating the ability to destroy dioxane and CVOCs in the reactive zone. The CVOCs that were quantified included 1,2-DCE, 1,1-DCA, cis-1,2-DCE, and TCE. The success criterion for dioxane was established at a minimum of 90% reduction from the up-gradient sampling location to a downgradient sampling location, or if the concentration in the downgradient sampling location was less than 3 µg/L. The success criterion for CVOCs was a minimum of 90% reduction from the upgradient sampling location to the downgradient sampling location.

3.1.1 Data Collected to Evaluate Performance Objective

Concentrations of dioxane and CVOCs were measured in groundwater samples collected along the presumed groundwater flow path in deep (12.5-14.5 ft below water table) and shallow (2.5-4.5 ft below water table) locations using the Hydropunch™ groundwater sampling technique. Samples were collected upgradient and downgradient of the oxidant cylinders as well as at a variety of locations along the groundwater flow path.

3.1.2 Data Interpretation and Results

The maximum dioxane and total CVOC destructions along the flow path were used to assess performance. The maximum destructions (99.3 and 99.0% for dioxane and total CVOCs, respectively) were observed in one sample collected in the deep zone. The upgradient dioxane and total CVOC concentrations in a upgradient boring location were 20,000 µg/L each. The downgradient concentrations of dioxane and total CVOCs in the downgradient boring location were 140 and 200 µg/L, respectively. Thus, the 90% minimum destruction criterion for dioxane was met.

Table 3.1. Performance Objectives

	Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives	Technology Effectiveness	Dioxane and chlorinated ethene concentrations	90% reduction in 1,4-dioxane concentration or concentration reduced to < 3 µg/L	**Exceeded.** 99.3% reduction.
			90% reduction of chlorinated ethene co-contaminants	**Exceeded.** 99.0% reduction in sum of 1,2-DCE, 1,1-DCA, cis-1,2-DCE, and TCE.
	Sustainability / Longevity	Oxidant and contaminant concentrations along flow path	Rate of oxidant concentration change at any given location ≥ 0 mg L^{-1} d^{-1} over 1 year	**Not met.** Observed exponentially decreasing persulfate concentrations over time in cylinder wells with 9% predicted to be remaining after one year.
			90% contaminant removal is sustained for at least 4 weeks	**Exceeded.** Dioxane and CVOCs destruction ≥99% observed in deep groundwater 119 days after cylinder deployment.
	Oxidant Transport and Destruction	Oxidant concentrations along flow path	Oxidant consumed to below detection at final downgradient monitoring point or trends support its destruction along the flow path	**Met.** 21 mg/L in deep sample from boring B21 26 ft downgradient compared to 2,100 mg/L in deep sample from boring B14 14 ft downgradient. Trends also support further attenuation. See text for explanation.
	Technology Implementability / Secondary Impacts	pH, ORP, persulfate, filtered metals (As, Ba, Be, Cd, Cr, Cu, Hg, Pb, Se, Tl, and U), and bromate.	Filtered metals and bromate below background (upgradient well concentration) in the final downgradient monitoring point or demonstrated decrease in concentration along flow path. pH, ORP, and persulfate concentrations will be used to evaluate attenuation trends.	**Met** for pH, ORP, and persulfate. Not analyzed for bromate and metals. See text for discussion as well as treatability study results.
Qualitative Performance Objectives	Technology Reproducibility	Oxidant concentrations in cylinder boreholes and seepage velocity estimated using a chloride tracer test	Oxidant concentrations over time will be compared and relative percent difference will be calculated to characterize reproducibility. Persulfate flux will be calculated and compared to treatability test results.	The relative percent deviation of persulfate concentrations in the two-cylinder borehole monitoring wells was 66%±50%. Estimated sodium persulfate flux from the cylinders ranged from 4 to 17 mg d^{-1} cm^{-2} which compares well to the maximum treatability flux of 22 mg d^{-1} cm^{-2}.
	Engineering Design Tool Utility	Simulations based on site data including dioxane and chlorinated ethene concentrations, oxidant concentrations, and seepage velocity (using chloride tracer)	Reasonable prediction of oxidant release rate and contaminant destruction with the engineering design tool	Not evaluated.
	Design Tool Ease of Use	User feedback	Accessible by typical anticipated users (e.g. engineers and scientists)	Not evaluated.
	Applicability to Multiple Site Conditions	Compare design requirements for different plume and soil characteristics	Engineering tool can be applied to multiple site conditions (e.g. hydraulic conductivity, soil oxidant demand, dioxane concentrations)	Not evaluated.

3.2 QUANTITATIVE PERFORMANCE OBJECTIVE: SUSTAINABILITY/LONGEVITY

This objective focused on demonstrating the ability to consistently distribute the oxidant in the reactive zone and to meet the above Technology Effectiveness objective for a minimum time. Two methods were used to evaluate this objective. First, the change in oxidant concentration over time at a given location was evaluated. If the oxidant concentration was stable and did not decrease (i.e., rate of oxidant concentration change ≥ 0 mg L^{-1} d^{-1}) over a period of one year then the objective was considered met. Second, if 90% contaminant removal was sustained for 4 weeks or longer then the criterion was considered met.

3.2.1 Data Collected to Evaluate Performance Objective

Sodium persulfate concentrations were measured in oxidant cylinder borehole monitoring wells over time. Hydropunch sampling was conducted 119 days after a second oxidant cylinder deployment to evaluate longevity with respect to contaminant destruction.

3.2.2 Data Interpretation and Results

Sodium persulfate concentrations in the oxidant cylinder borehole monitoring wells decreased in an exponential pattern over time with 42% remaining at the final sampling event (134 days) and 31% and 9% predicted to be remaining after 6 and 12 months, respectively. Thus, the hypothesis that persulfate concentrations would remain relatively constant over time until the cylinders were spent was disproved. The performance objective was not met based on this criterion.

During the second oxidant cylinder deployment, dioxane and CVOC removals were both ≥ 99% after 119 days. Thus, the criterion of contaminant destruction effectiveness being maintained for greater than 4 weeks was exceeded. This criterion is considered more relevant and important than the first criterion.

3.3 QUANTITATIVE PERFORMANCE OBJECTIVE: OXIDANT TRANSPORT AND DESTRUCTION

This objective focused on demonstrating that oxidants will not be transported significantly past the reactive zone. Success criteria for this objective are either non-detectable oxidant concentrations in the downgradient monitoring well or concentration trends demonstrating oxidant destruction along the flow path.

3.3.1 Data Collected to Evaluate Performance Objective

Sodium persulfate concentrations were measured in multiple Hydropunch groundwater sampling locations upgradient and within the treatment zone along the groundwater flow path. In addition, supporting data including pH and ORP were measured in these samples.

3.3.2 Data Interpretation and Results

Sodium persulfate decreased from a maximum concentration of 2,100 mg/L in boring B14 located 14 ft downgradient of the cylinders to 21 mg/L in boring B21 located 26 ft downgradient.

This represents a 99% reduction in oxidant concentration. At the time of sampling (119 days after cylinder installation), persulfate was estimated to have been transported between 26 (based on groundwater modeling) and 49 ft (based on a tracer study) downgradient and thus at or beyond downgradient boring B21. pH and ORP trends also indicate that groundwater downgradient of the oxidant returned to natural conditions. For example, the pH and ORP upgradient of the cylinders were 7.72 and 75 mV, respectively. The pH and ORP at the location of maximum persulfate were 7.03 and 217 mV. The pH and ORP values observed 26 ft downgradient were 7.67 and 55 mV, respectively, which are similar to upgradient values.

3.4 QUANTITATIVE PERFORMANCE OBJECTIVE: TECHNOLOGY IMPLEMENTABILITY/ SECONDARY IMPACTS

This objective focused on demonstrating that secondary groundwater quality impacts are either acceptable or transient. The goal of this performance objective was to determine if any secondary impacts to the aquifer result from the oxidant cylinder deployment. Potential secondary impacts include elevated dissolved metals including hexavalent chromium and generation of bromate as a product of bromide oxidation. Success criteria were to be based on filtered metals and bromate concentrations. However, these analyses were not conducted because of project constraints. Rather, the potential impacts were evaluated considering secondary parameters including pH and ORP trends downgradient of the oxidant cylinders.

3.4.1 Data Collected to Evaluate Performance Objective

pH and ORP were monitored along the flow path as described in **Section 3.3.1**.

3.4.2 Data Interpretation and Results

As described in **Section 3.3.2**, pH decreased and ORP increased in response to the presence of sodium persulfate. Downgradient of the maximum sodium persulfate concentration, pH increased and ORP decreased to background values. Thus, elevated dissolved metal concentrations could be expected to decline to background levels as background pH and ORP values were re-established. Hexavalent chromium and bromate can potentially be chemically or biologically reduced. As the ORP decreased these constituents may also have declined in concentration. For comparison, the treatability study (see **Section 5.3**) demonstrated elevated dissolved chromium (assumed to be hexavalent chromium) concentrations ranging from 200 to 300 µg/L. These values are greater than the California State Maximum Contaminant Level (MCL).

In general, groundwater concentrations of dissolved metals (including hexavalent chromium) and bromate in the furthest downgradient monitoring well should be less than background (upgradient) concentrations or less than applicable standards. As persulfate decomposition is known to decrease pH via production of sulfuric acid, metal dissolution can potentially occur. Additionally, persulfate can potentially oxidize trivalent chromium to hexavalent chromium and bromide to bromate. The site aquifer is naturally reducing and will also have some pH neutralization capacity. Oxidation products including bromate and hexavalent chromium may be produced and subsequently reduced downgradient of the reactive zone containing persulfate. Elevated metals concentrations may decrease downgradient of the reactive zone because the aquifer may naturally neutralize acid generated during persulfate decomposition.

3.5 QUALITATATIVE PERFORMANCE OBJECTIVE: TECHNOLOGY REPRODUCIBILITY

Two replicate cylinder installations were used to characterize reproducibility in this qualitative performance objective. Two methods of comparison were used including: 1) the relative percent difference of oxidant concentrations within the two boreholes, and 2) comparison of the sodium persulfate flux from the cylinders in the field demonstration and in the treatability study.

3.5.1 Data Collected to Evaluate Performance Objective

Data collected to evaluate the reproducibility of the technology used in the demonstration included oxidant concentrations within the two boreholes containing the oxidant cylinders. In addition, seepage velocity estimates in combination with oxidant concentrations were used to estimate flux.

3.5.2 Data Interpretation and Results

The relative percent deviation of the sodium persulfate concentrations in the cylinder borehole monitoring wells was 66±50% and represented three sampling events where the concentration in DCW-02 was consistently greater than that in DCW-01. Surging of the borehole monitoring wells mobilized a large amount of silt resulting in the bottom sampling intervals being different by about 3 ft. As discussed in **Section 5**, density driven flow effects resulted in a gradient of oxidant concentration increasing as depth increased. Therefore, it is reasonable that the oxidant concentrations in the two boreholes were different. Still, at most, the concentration in DCW-02 was four-fold greater than that in DCW-01. The estimated sodium persulfate flux from the cylinders ranged from 4 to 17 mg d^{-1} cm^{-2} from which is reasonable when compared to the maximum flux of 22 mg d^{-1} cm^{-2} measured during the treatability test.

3.6 QUALITATIVE PERFORMANCE OBJECTIVE: ENGINEERING DESIGN TOOL UTILITY

The engineering design tool was not completed because of project constraints.

3.7 QUALITATIVE PERFORMANCE OBJECTIVE: DESIGN TOOL EASE OF USE

The engineering design tool was not completed because of project constraints.

3.8 QUALITATIVE PERFORMANCE OBJECTIVE: APPLICABILITY TO MULTIPLE SITE CONDITIONS

The engineering design tool was not completed because of project constraints.

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4.0 SITE DESCRIPTION

This section provides a concise summary of the demonstration site.

4.1 SITE LOCATION AND HISTORY

Operable Unit 11 (OU11) of Naval Air Station North Island (NAS NI) (**Figure 4.1**) was selected for this demonstration. The area used for the demonstration is shown in **Figure 4.2**. The seepage velocity at NAS NI is historically around 0.1 ft/d. However, because the gradient is generally flat and groundwater flow directions can vary, an induced gradient was created by pumping for the purposes of this demonstration, as discussed further below.

Figure 4.1. NAS North Island Location Map.

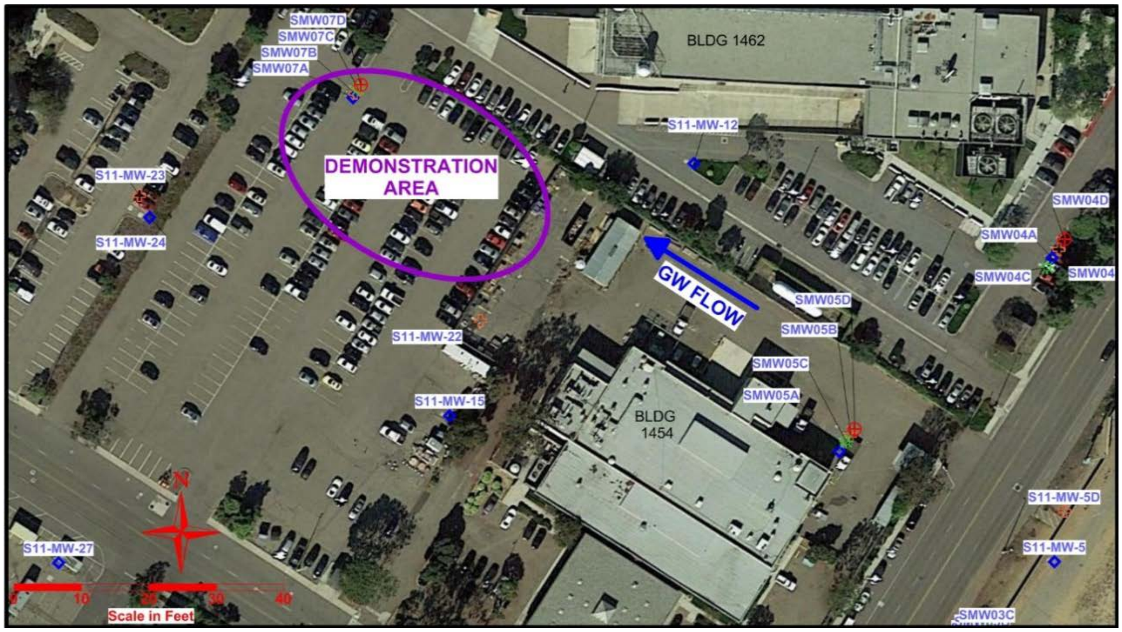

Figure 4.2. Demonstration Area – NAS NI OU11.

4.2 SITE GEOLOGY/HYDROGEOLOGY

Groundwater flow direction in the proposed demonstration area is to the northwest with a flow rate about 0.1 ft/d and a hydraulic gradient of approximately 0.00037 foot per foot (ft/ft) (Accord Mactec 2013). The groundwater is comprised of a lens-shaped layer of freshwater on top of saltwater. The thickness of the freshwater body varies throughout the site. NAS NI is part of the Coronado hydrologic basin (Unit No. 10.10), which is designated as a non-beneficial use aquifer by the San Diego Regional Water Quality Control Board (California Regional Water Quality Control Board 1994). Lithology at OU11 includes a thick sequence of fine to very fine sand and silty sand to a depth of approximately 40 ft bgs. Below these layers are several fine-grained layers of silt and clay. The geology at the site is comprised of the Bay Point Formation and primarily consists of marine, fossiliferous, loosely consolidated, fine- to medium-grained sand (Kennedy 1975). The primary fine-grained lithologic layers at the site are called the A silt and the B, B1, and C clays, which occur at approximately 40, 80, 100, and 115 ft bgs, respectively. Identified thicknesses of these fine-grained layers are 1 to 5 feet thick for the A silt, 5 to 15 ft thick for the B clay, and about 20 to 40 ft thick for the C clay (Barajas & Associates 2008).

4.3 CONTAMINANT DISTRIBUTION

Based on OU11 groundwater quality data collected in 2012 (Accord Mactec 2013), dioxane concentrations are as high as 6,500 µg/L upgradient of the demonstration area (OU11-SMW05A). Similarly, the dioxane concentration was 6,000 µg/L in OU11-SMW07A on the downgradient portion of the demonstration area. TCE, cis-1,2-DCE, 1,1-DCE, 1,1-DCA, vinyl chloride, and hexavalent chromium are co-contaminants at the site. 2012 TCE concentrations within the proposed demonstration area were 9,200 µg/L in OU11-SMW05A and 3,500 µg/L in OU11-SMW07A. Other VOC concentrations (cis-1,2-DCE, 1,1-DCE, 1,1-DCA, and vinyl chloride were generally similar to TCE (350-6,400 µg/L) except vinyl chloride, which was detected at 39 µg/L in OU11-SMW07A. The estimated dioxane and CVOC concentration contours groundwater are shown in **Figure 4.3.**

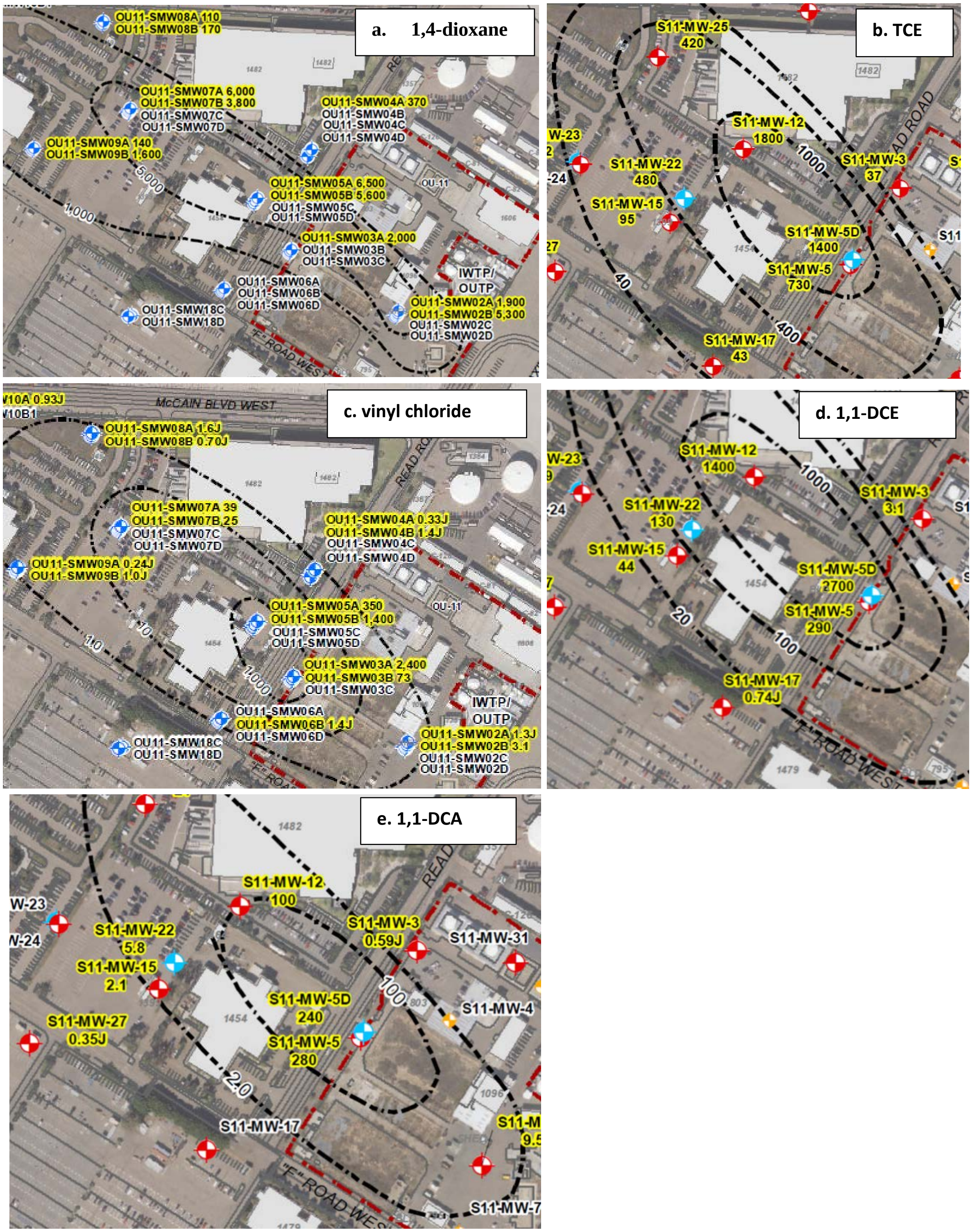

Figure 4.3. **Estimated 1,4-dioxane (a), TCE (b), Vinyl Chloride (c), 1,1-DCE (d) and 1,1-DCA (e) Groundwater Concentration Contours. Data from 2012. See Figure 4.2 for general groundwater flow direction.**

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5.0 TEST DESIGN

This section presents the design and results of the demonstration tasks. **Section 5.1** presents the conceptual design of the field demonstration. **Sections 5.2** and **5.3** present results of the baseline characterization and treatability tests, respectively. **Sections 5.4** through **5.6** present details on the field demonstration design and methods. Finally, **Section 5.7** presents results of the field demonstration.

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

The general and detailed design layouts of the technology demonstration are illustrated in **Figures 5.1** and **5.2**, respectively. Upgradient cylinder wells containing the oxidant cylinders were installed to simulate a small-scale F&G design. Due to the flat gradient observed at the site, a recirculation system consisting of a downgradient extraction well and a further-downgradient reinjection well was constructed to facilitate better hydraulic control. A series of upgradient and downgradient monitoring wells were used to aid performance monitoring, evaluation, and optimization. A number of important design parameters pertinent to the demonstration layouts were obtained using numerical groundwater modeling and an engineering design tool as described in the Technology Demonstration Plan (**Appendix C**) and the Design Tool Technical Report (**Appendix D**).

Numerical groundwater modeling was used to aid estimating the natural versus induced groundwater extraction rate, groundwater seepage velocity, groundwater transverse dispersion, oxidant transport, and contaminant transport. In addition, the numerical groundwater modeling results indicated that application of an artificial gradient would not result in significant downgradient migration of the dioxane plume.

The design tool was developed on an Excel platform and was used to predict contaminant destruction along the groundwater flow path based on user inputs. These inputs included hydrogeologic parameters (gradient, hydraulic conductivity, effective porosity, and/or seepage velocity), rate constants (second-order natural oxidant demand and second-order contaminant rate constants with persulfate or permanganate), site data (aquifer thickness and width), design assumptions (number of oxidant cylinders, cylinder spacing), oxidant cylinder characteristics (oxidant flux, cylinder dimensions, cylinder change-out time), and economic parameters (cylinder cost, drilling cost).

Data from the numerical model were then used as inputs to the engineering design tool which was then used to determine the appropriate well spacing, anticipated contaminant destruction, and oxidant longevity. Specifically, under the conditions created by inducing the gradient, the tool provided estimates of when the oxidant cylinder would need to be changed out (6 months) and the distance from the cylinders at which 90% dioxane removal would occur (37 feet after 7 months). The two major assumptions that were made for the design tool were the unactivated persulfate NOD (estimated to be 0.0001 liters per millimole per day (L mmol^{-1} d^{-1}) based on OU20 pilot study results (Shaw Infrastructure 2007) [Table 4.1 in the referenced document]) and the dispersion factor used in the spreadsheet tool. This factor is dimensionless and ranges from 0 to 1. When a value of 0 is selected, no dispersion occurs and the persulfate is released into a cross sectional area with a width of 2.5 inches (i.e., the cylinder diameter). When a value of 1 is selected, the persulfate is dispersed across the distance between the center points of the two-cylinder boreholes (i.e., 5 feet). A value of 1 was assumed for the design based on results from dispersion modeling.

The results from the design tool are provided in the Technology Demonstration Plan. Once the objective output was predicted (90% dioxane removal), 75%, 99%, and 99.9% removal distances were also calculated to determine the appropriate locations of additional monitoring wells (5, 10, and 20 feet from cylinders for 80, 95, and >99% removal, respectively) in addition to an upgradient monitoring well located five feet upgradient from the cylinder locations.

A cross-sectional view of the demonstration well network is provided in **Figure 5.3**. As shown in this cross section, the demonstration was performed in the 15-ft saturated thickness above a semi-confining unit located approximately 40 ft bgs. This treatment thickness is within the depth interval where dioxane and other contaminants were observed.

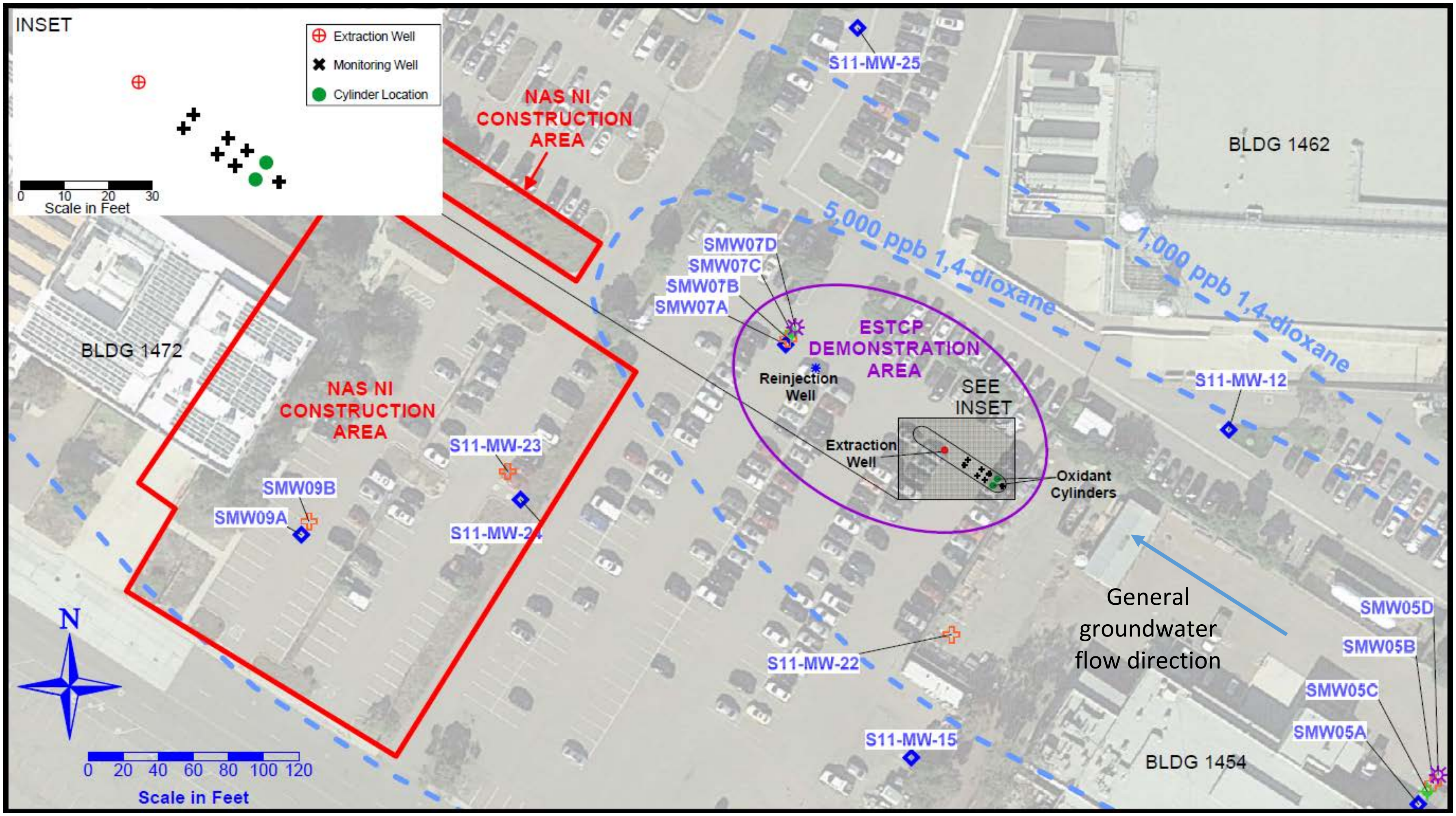


Figure 5.1. Demonstration Layout.

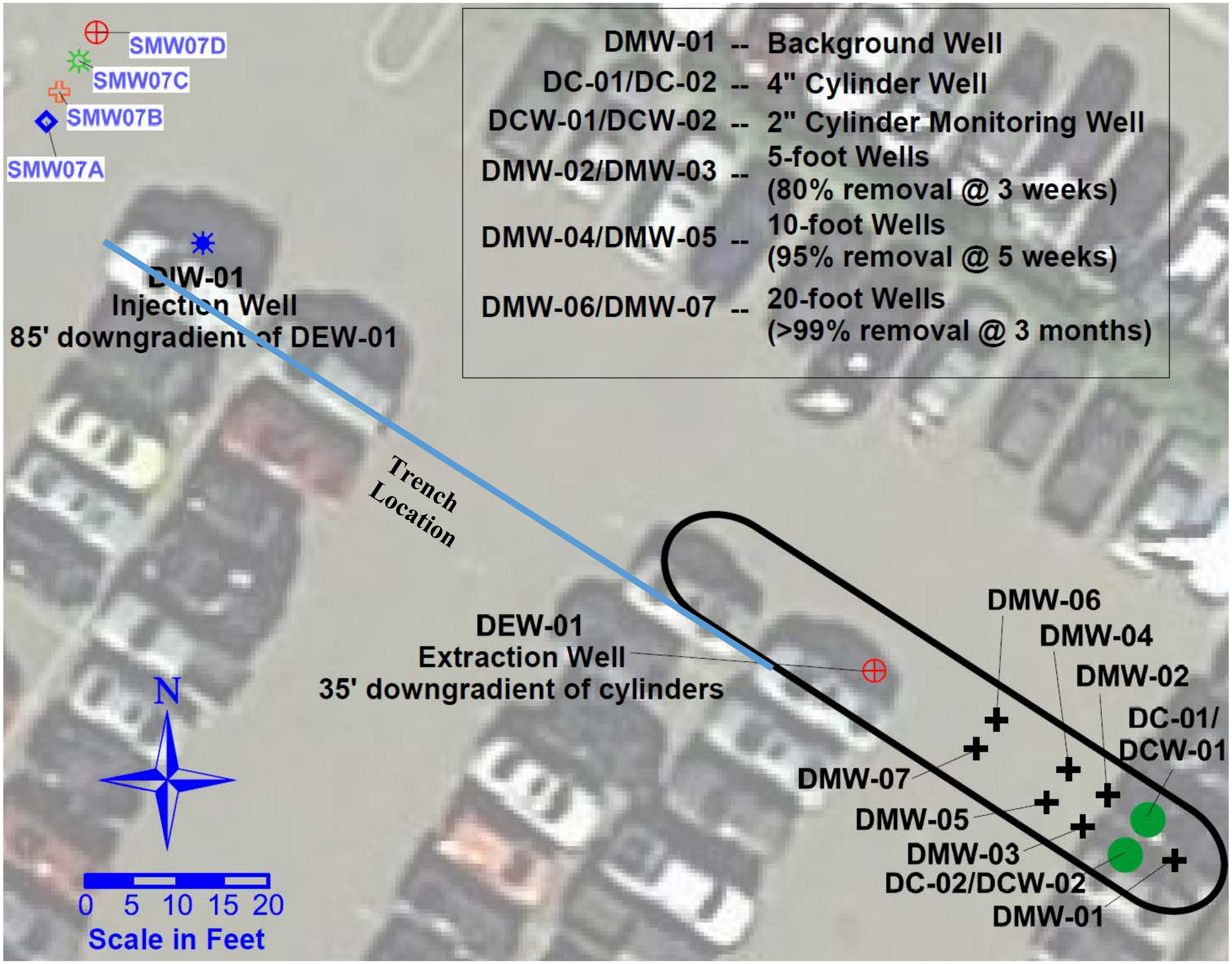


Figure 5.2. Detailed Demonstration Layout with Tool-estimated Removal Distances and Times.

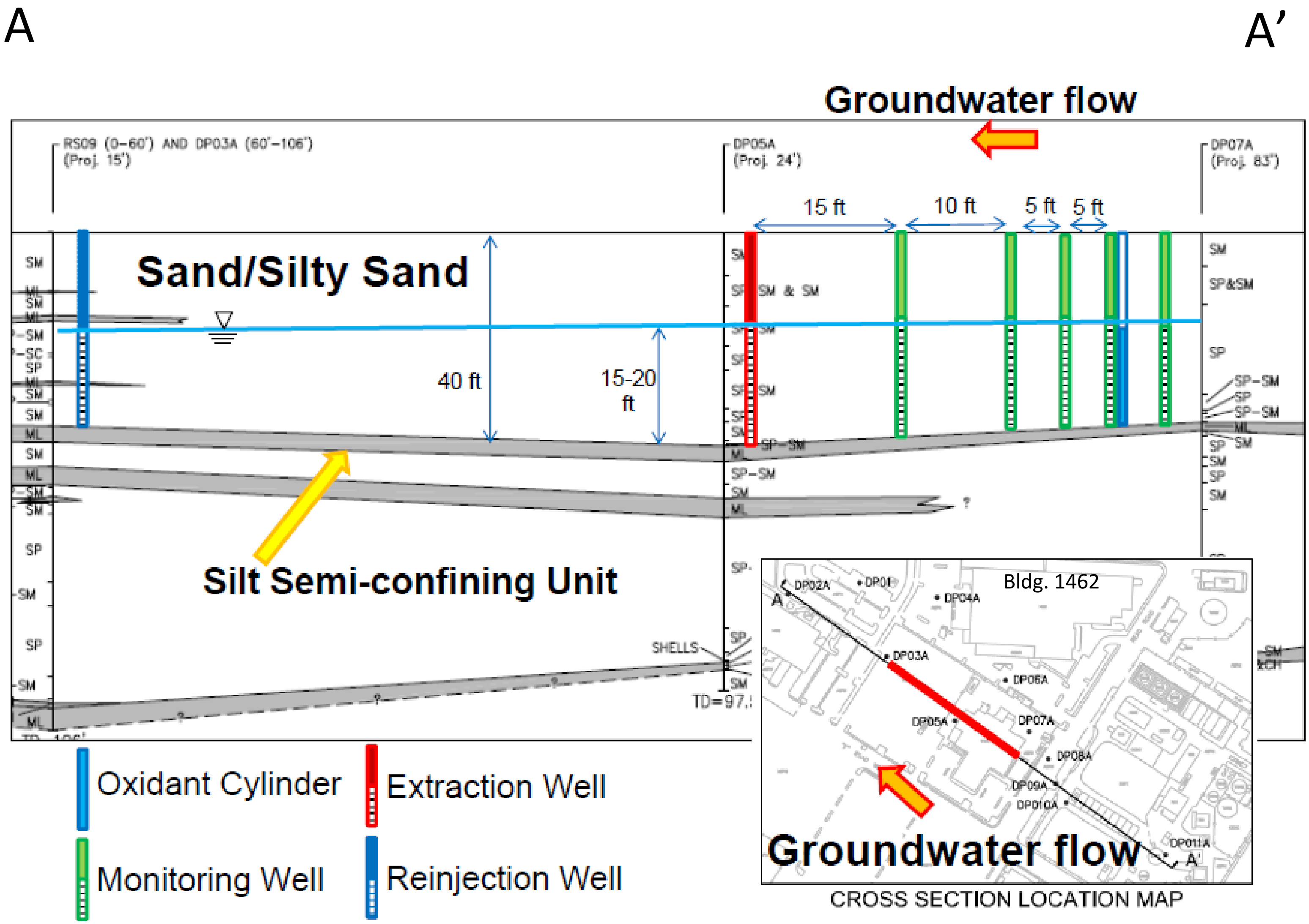


Figure 5.3. Cross-sectional View of the Demonstration Well Network.

5.2 BASELINE CHARACTERIZATION

Groundwater and soil characterization was conducted at the Site by NOREAS, Inc. on December 5, 2013 as described below. Prior to commencement of any subsurface work, utility clearance and geophysical survey were performed by ULS Services Corporation on November 25, 2013. No obstructions or utility mains/manholes were within the planned area for drilling. Cascade Drilling drilled two boreholes (B1A and B2A) using hollow-stem auger for soil sampling (see **Figure 5.4**) on December 5, 2013. The boreholes were advanced to 40 feet below ground surface (ft bgs), and soil samples were collected from approximately 25 to 40 ft bgs using a 2.5-inch inner diameter continuous barrel sampler. Boreholes were abandoned in accordance with the State of California Well Standards (California Department of Water Resources 1991). Fifty-five kilograms of soil were collected, and soil was handled to minimize disturbance (aeration) to the extent practicable and packed (compressed) in multiple 1-gallon plastic sealable bags. These individual bags were placed in labeled 5-gallon buckets and sealed with a lid, tape, and wrapped with plastic wrap.

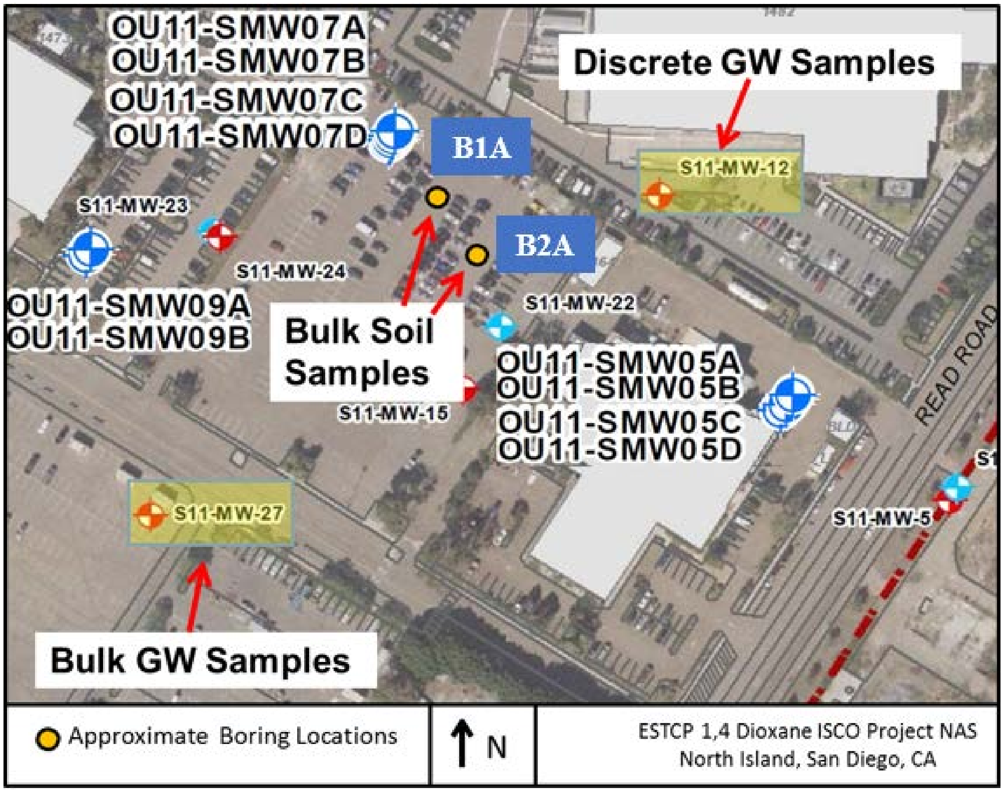


Figure 5.4. Site Plan Showing Soil and Groundwater Sampling Locations.

A total of 345 liters of groundwater was collected from monitoring well S11-MW-27 (**Figure 5.4**) for the treatability study. Groundwater was collected using low-flow sampling procedures, and water was collected once purge parameters (e.g., pH, conductivity, temperature, and turbidity) stabilized to ±0.1 standard units for pH, 3% for conductivity, and 10% for temperature and turbidity from three consecutive readings taken 3 to 5 minutes apart. Collected groundwater was placed into two labeled Department of Transportation (DOT)-approved 30-gallon poly drums. Groundwater from this well did not have appreciable levels of contamination based on historical data and was located within close proximity to the plume and the proposed demonstration area.

This allowed tests to be conducted with relatively uncontaminated groundwater and with the same groundwater amended with specific site contaminants. In addition, Snap Samplers® (ProHydro, Inc.) were deployed at 29-31, 33-35, and 37-39 ft bgs in well S11-MW-12 to determine the relative distribution of contaminants over different stratigraphic units. Concentrations are reported in **Table 5.1**, indicating that contaminant concentrations were generally lowest in the shallowest groundwater horizon. Dioxane in particular had the greatest concentration in the deepest groundwater horizon. Bulk soil and groundwater were shipped by truck without refrigeration to Carus Corporation in LaSalle, Illinois on December 6, 2013 and were received on December 18, 2013. Soil from both borings was homogenized at Carus prior to testing.

Table 5.1. Groundwater Concentrations of Select Analytes in Well S11-MW-12.

Analyte	Concentration (µg/L)		
	29-31 ft bgs	33-35 ft bgs	37-39 ft bgs
1,1-Dichloroethane (1,1-DCA)	35	85	80
1,1-Dichloroethene (1,1-DCE)	560 D	1,600 D	1,000 D
cis-1,2-Dichloroethene (cis-1,2 DCE)	18	38	34
Trichloroethene (TCE)	570 D	1,600 D	850 D
1,4-Dioxane	53 J	90	250

Notes: µg/L – microgram per liter D – Diluted sample J – Estimated value

5.3 TREATABILITY OR LABORATORY STUDY RESULTS

This section summarizes the treatability study work performed to evaluate the effectiveness of oxidant cylinders for destruction of dioxane and to determine the most appropriate oxidant for use at OU11. A complete description of treatability study methods and results is provided in the Treatability Study Report included in **Appendix B**. Batch kinetic tests and column tests were performed during the treatability study with soil and groundwater collected at the Site.

5.3.1 Batch Kinetics Tests

5.3.1.1 Dioxane Oxidation in De-Ionized Water

Figure 5.5 shows the change in dioxane concentrations in DI water upon exposure to various concentrations of permanganate in tests conducted by CDM Smith. The linearity of the trends on this semi-logarithmic graph indicates first-order kinetics. Negligible dioxane loss was observed in the control (i.e., no oxidant), and the greatest rate of removal was observed in the presence of the high permanganate concentration. The slopes of the curves in **Figure 5.5** were used to estimate first-order rate constants.

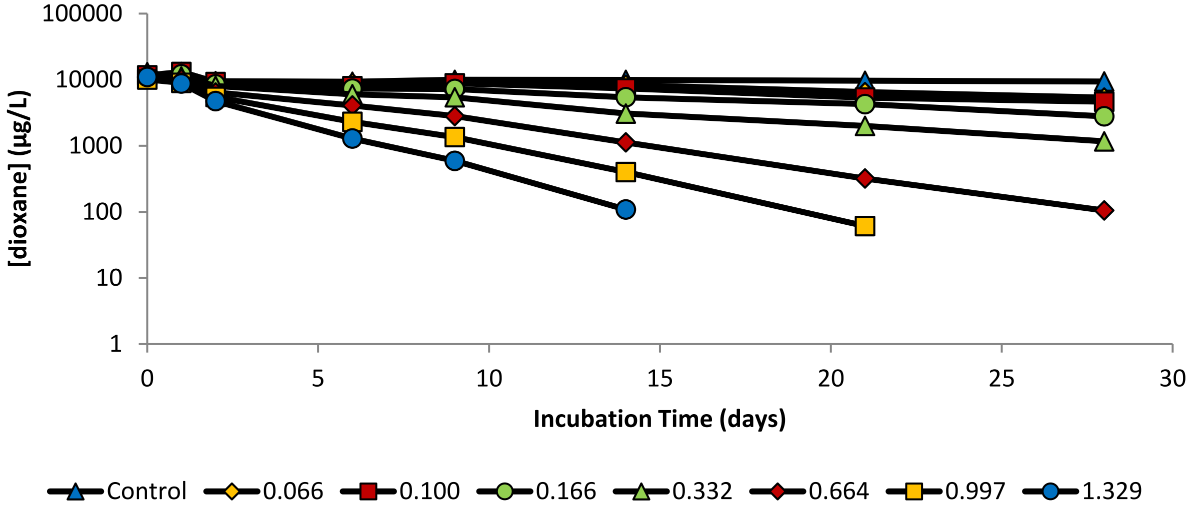


Figure 5.5. **Dioxane Oxidation in De-ionized Water in the Presence of Various Concentrations (%) of Potassium Permanganate ($KMnO_4$).**

These rate constants were then plotted as a function of the initial permanganate concentrations in **Figure 5.6**. The linearity ($r^2 = 0.999$) of the curve indicates that a second-order kinetic model was appropriate, and the second-order rate constant was estimated at 4.3×10^{-5} per molar per second ($M^{-1}\ s^{-1}$). Permanganate concentrations decreased during the tests an average of 5.6±1.4%, and the maximum decrease was 6.9%. Therefore, the assumption of relatively constant oxidant concentrations was valid, and use of initial oxidant concentrations in **Figure 5.6** was appropriate. A separate test conducted under identical conditions by Carus yielded an average second-order rate constant of $3.3 \times 10^{-5}\ M^{-1}\ s^{-1}$. The relative percent difference between these two estimates is 53%. This variability of the two tests provides an order-of-magnitude rate constant estimate that was sufficient for pilot study planning purposes.

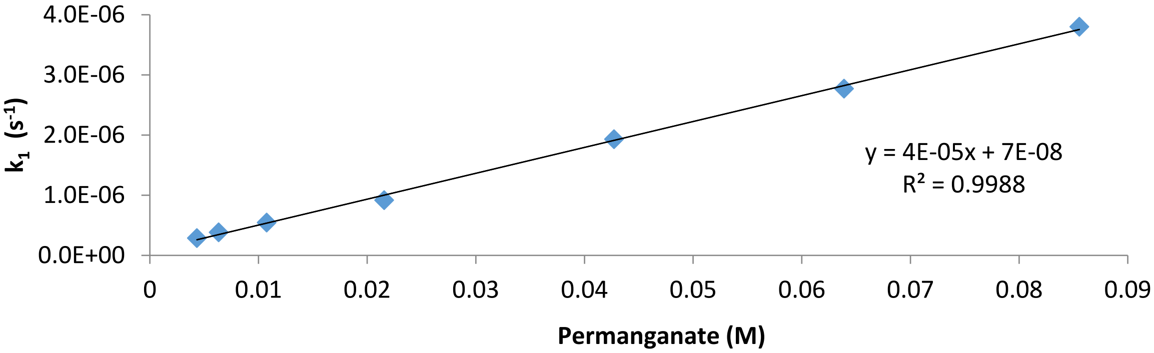


Figure 5.6. **Relationship Between First-order Rate Constants for Dioxane Removal in DI Water and Initial Permanganate Concentration.**

Figure 5.7 shows the change in dioxane concentrations in DI water upon exposure to various concentrations of persulfate conducted by CDM Smith. The nonlinearity of the trends on this semi-logarithmic graph indicates non-first-order kinetics. The slopes of the curves – which are equal to the pseudo first-order rate constants – increase over time, suggesting some type of persulfate activation. However, no intentional activation of persulfate (e.g., hydrogen peroxide, iron or other metal ions, high pH, heat, etc.) was conducted. As with permanganate, negligible decrease of dioxane concentration was observed in the absence of oxidant, and the greatest rate was observed with the greatest concentration of persulfate. The average slopes of the curves in **Figure 5.7** were used to estimate pseudo first-order rate constants. The r^2 values of these regressions ranged from 0.822 to 0.974.

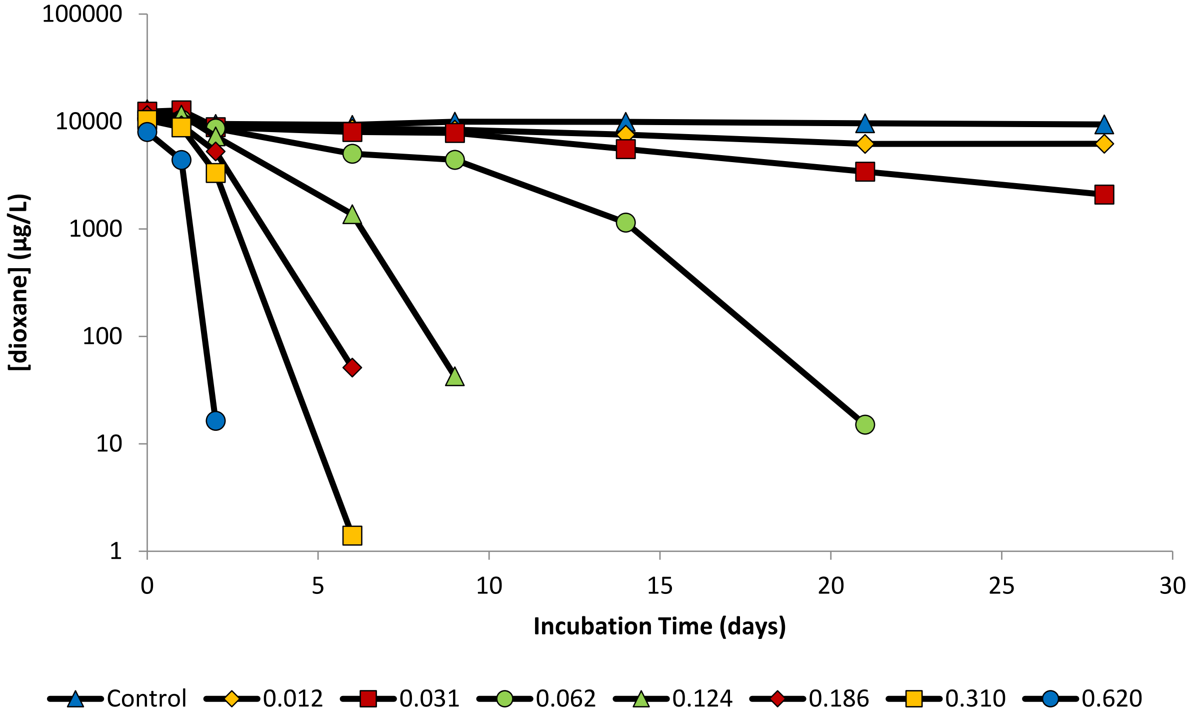


Figure 5.7. Dioxane Oxidation in DI Water in the Presence of Various Concentrations (%) of Sodium Persulfate ($Na_2S_2O_8$).

These pseudo first-order rate constants were then plotted as a function of the initial persulfate concentrations in **Figure 5.8**. The linearity ($r^2 = 0.998$) of the curve indicates the reaction was apparently second-order with respect to the oxidant concentration. However, these data are not sufficient to inform the actual mechanism of oxidation. The pseudo second-order rate constant was estimated at 1.4×10^{-3} M^{-1} s^{-1}. This value is about 30-fold greater than that for permanganate. Persulfate concentrations began to decrease after approximately 5 days, with an average of 5.4±6.3% and a maximum decrease of 19% during the study. The 19% persulfate loss was associated with the test condition that contained 0.05% persulfate (0.0027 molar [M]). A separate test conducted under identical conditions by Carus yielded an estimate for the second-order rate constant of 1.2×10^{-3} M^{-1} s^{-1}. The relative percent difference between these two estimates is 24% and both were the same order-of-magnitude.

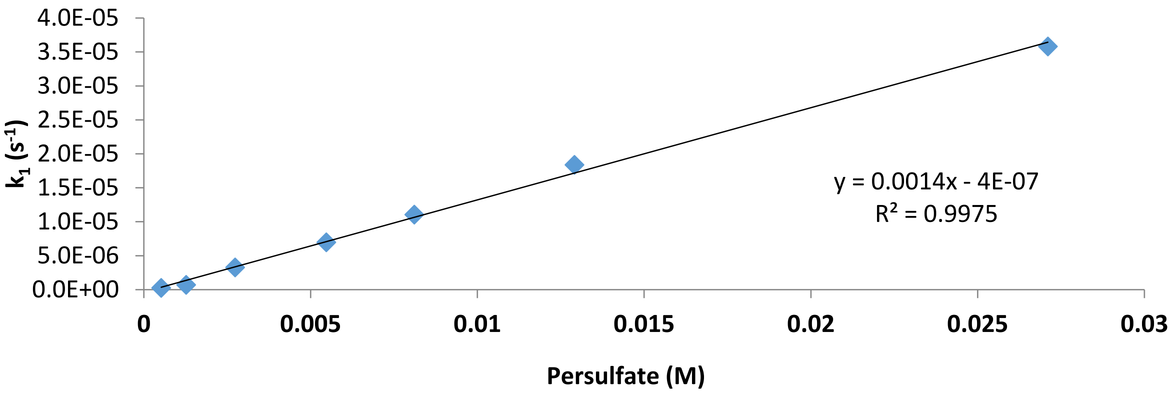


Figure 5.8. Relationship Between First-order Rate Constants for Dioxane Removal in DI Water and Initial Persulfate Concentration.

5.3.1.2 Dioxane Oxidation in Site Soil and Groundwater

A second series of batch tests were conducted in the presence of site soil and groundwater. In addition, the tests were conducted with a mixture of dioxane, TCE, cis-1,2-DCE, 1,1-DCE, and 1,1-DCA. **Figure 5.9** presents the result for dioxane and demonstrates increasing dioxane removal rates with increasing permanganate concentration. The curves generally followed first-order kinetics; however, the dioxane removal rate appeared to decline near the end of the study and especially with lower initial permanganate concentrations. Therefore, the 500-hour data points were not used to estimate first-order rate constants. The 10,000 mg/L and 5,000 mg/L starting doses of potassium permanganate were sufficient to reduce dioxane by 90%.

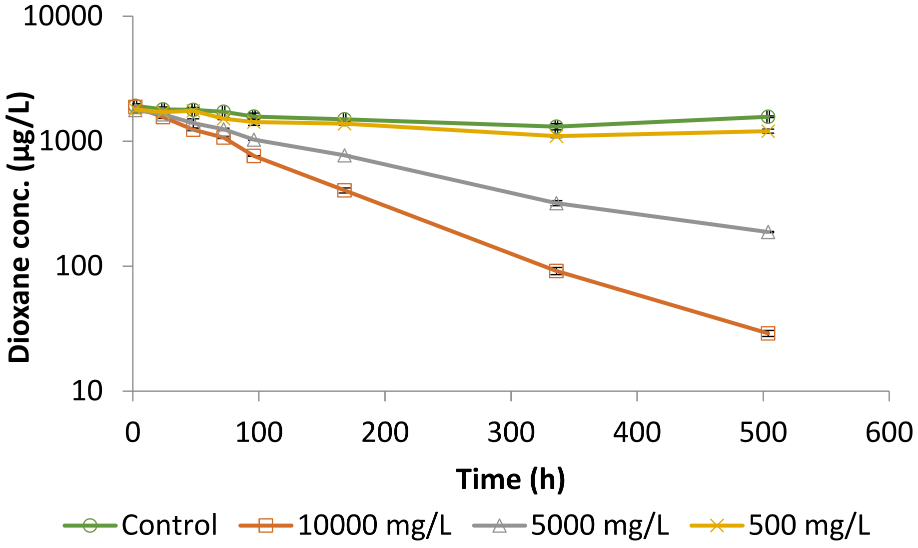


Figure 5.9. Dioxane Removal by Various Concentrations of Potassium Permanganate in the Presence of Soil and Groundwater, Error Bars Denote Standard Deviation on Duplicate Runs.

The reason for the rate decline may have been attributable to soil oxidant demand and relatively greater losses of oxidant in test conditions having lower initial oxidant concentrations. **Table 5.2** shows the percent loss of potassium permanganate at various initial doses.

Table 5.2. Site Soil and Groundwater Potassium Permanganate Kinetics Testing Results.

Potassium Permanganate Dose (mg/L)	Condition	Percent Loss of Potassium Permanganate (%)
10,000	With contaminants	0.3
	Without contaminants	0.9
5,000	With contaminants	1.6
	Without contaminants	2.1
500	With contaminants	13
	Without contaminants	16

Figure 5.10 illustrates the relationship between the first-order rate constants for dioxane removal in the presence of soil, groundwater, and CVOCs and the initial potassium permanganate concentration. The estimate of the second-order rate constant is 3.4×10^{-5} M^{-1} s^{-1}, which is similar to the Carus estimate in de-ionized water (3.3×10^{-5} M^{-1} s^{-1}). These data indicate that the presence of soil, groundwater, and CVOCs did not affect the second-order rate constant for dioxane oxidation by permanganate. The data are also similar to previous research (Waldemer and Tratnyek 2006) where the second order rate constant in phosphate buffer was 4.19×10^{-5} M^{-1} s^{-1}.

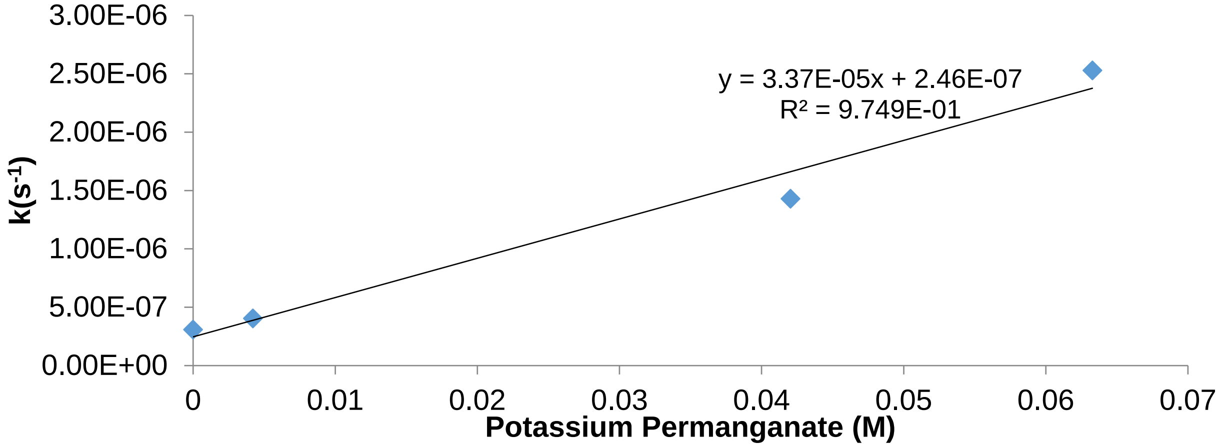


Figure 5.10. Relationship Between First-order Rate Constants for Dioxane Removal and Initial Permanganate Concentration in the Presence of Soil, Groundwater, and CVOCs.

Figure 5.11 illustrates the concentration trends of the CVOCs in soil and groundwater along with dioxane in the presence of various permanganate concentrations. The data indicate that chlorinated ethene concentrations were reduced by over 99% compared to the no-oxidant control at the first sampling time (2 hours). The sole chlorinated ethane (1,1-DCA) was not removed. These results are consistent with expected reactivity of permanganate (Waldemer and Tratnyek 2006). Permanganate is capable of oxidizing chlorinated ethenes containing carbon double bonds but not chlorinated ethanes. The rapid reactivity complicated estimation of rate constants, which is discussed below.

Nevertheless, the data demonstrate that chlorinated ethenes were capable of being rapidly oxidized by permanganate in the presence of dioxane and site soil and groundwater.

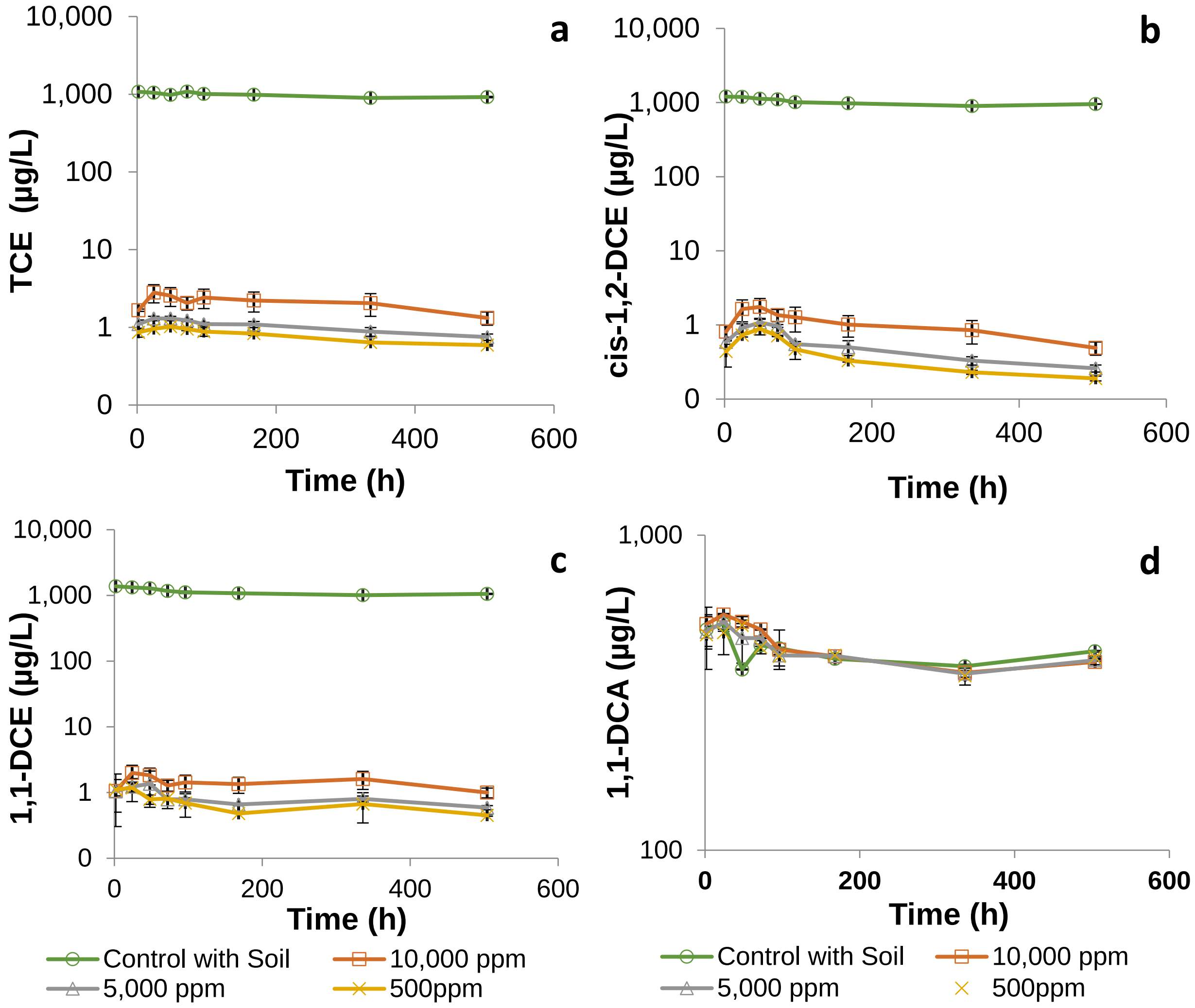


Figure 5.11. Potassium Permanganate (KMnO4) Effect on Concentrations of TCE (a), cis-1,2-DCE (b), 1,1-DCE (c), and 1,1-DCA (d) in the Presence of Dioxane, Soil, and Groundwater. Error bars denote standard deviation on duplicate runs.

Figure 5.12 illustrates the concentration trends of the CVOCs in soil and groundwater along with dioxane in the presence of 10,000 mg/L persulfate. Preliminary experiments conducted with lower persulfate concentrations (100 to 1,000 mg/L) did not result in reductions of dioxane or CVOCs within the testing duration of 14 days (data not shown). A second test with 10,000 mg/L persulfate was conducted and resulted in 90% or more removal of dioxane and chlorinated ethenes (**Figure 5.12**). 1,1-DCA was removed only by 22%, again indicating the relative recalcitrance of chlorinated ethanes. Non-first-order behavior was apparent with dioxane and chlorinated ethenes in the presence of soil and groundwater similar to that observed with dioxane in DI water (**Figure 5.7**). Thus, some type of apparent persulfate activation was occurring in the presence of soil and groundwater as was observed in DI water alone without CVOCs (**Figure 5.7**).

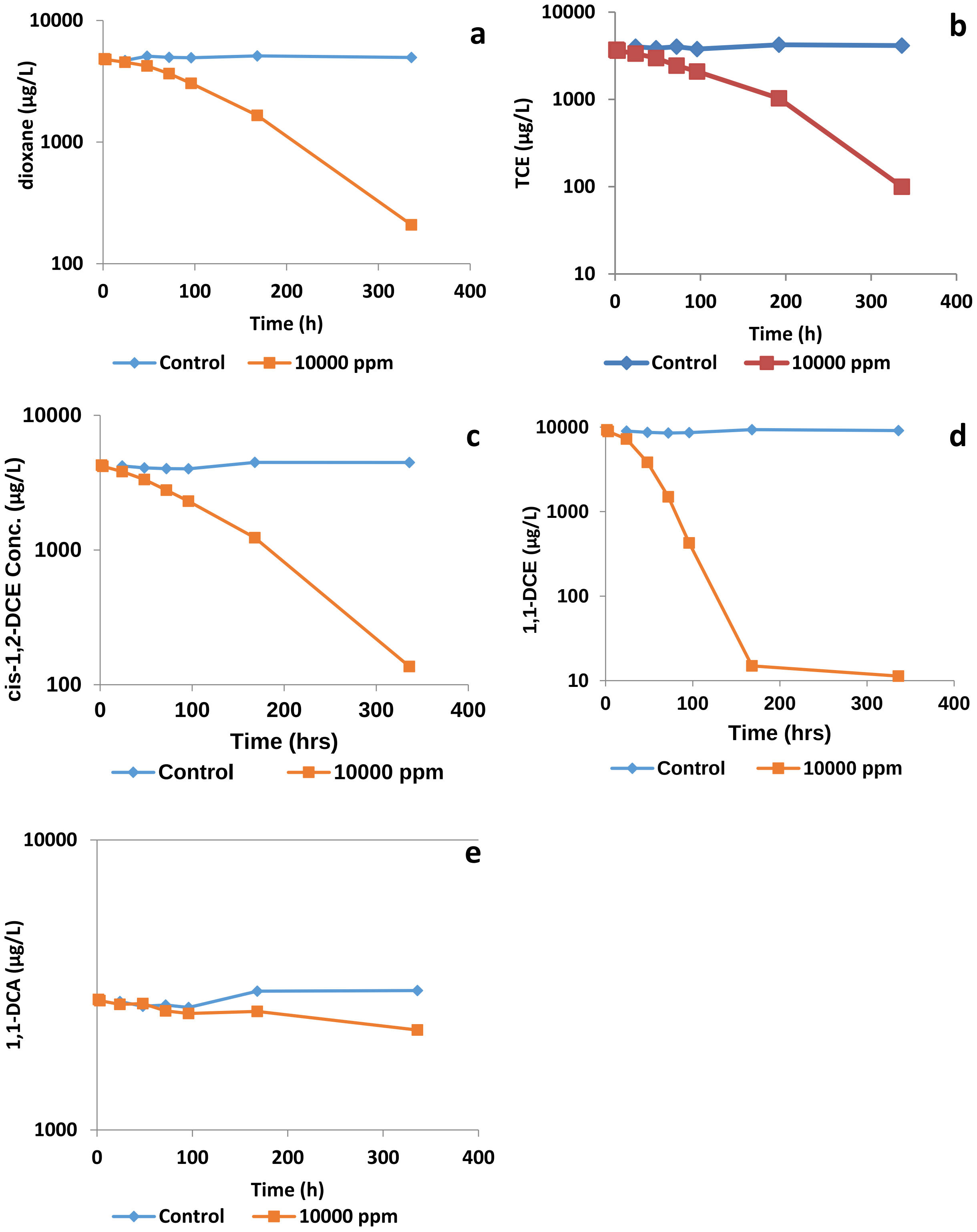


Figure 5.12. Persulfate Effect on Concentrations of Dioxane (a), TCE (b), cis-1,2-DCE (c), 1,1-DCE (d), and 1,1-DCA (e) in the Presence of Soil and Groundwater.

Table 5.3 presents a compilation of pseudo second-order rate constants for all of the tests presented above. Second-order rate constants for dioxane oxidation with permanganate in DI water or in soil and groundwater were similar to each other and within the range previously reported in the literature (Waldemer and Tratnyek 2006). These data corroborate the ability of permanganate to oxidize dioxane. Chlorinated ethene oxidation with permanganate in soil and groundwater was more rapid than dioxane oxidation, and accurate rate constants were not estimable. Minimum estimates for the rate constants were calculated and are consistent with literature values (Waldemer and Tratnyek 2006). 1,1-DCA was not oxidizable by permanganate as has been reported for other chlorinated alkanes (Waldemer and Tratnyek 2006).

Table 5.3. Estimated Pseudo Second-order Rate Constants.

Contaminant	Oxidant	Matrix	k_2 (M^{-1} s^{-1})	Reference
Dioxane	Permanganate	DI water	4.3 x 10^{-5}	This study (CDM Smith)
		DI water	2.5 x 10^{-5}	This study (Carus)
		Phosphate buffer	4.19 x 10^{-5}	(Waldemer and Tratnyek 2006)
		Soil and groundwater	2.7 x 10^{-5}	This study (Carus)
TCE		Soil and groundwater	> 0.24	This study (Carus)
		Phosphate buffer	0.46 to 0.76	(Waldemer and Tratnyek 2006)
cis-1,2-DCE		Soil and groundwater	> 0.26	This study (Carus)
		Phosphate buffer	0.69 to 0.71	(Waldemer and Tratnyek 2006)
1,1-DCE		Soil and groundwater	> 0.24	This study (Carus)
		Phosphate buffer	0.21 to 0.25	(Waldemer and Tratnyek 2006)
1,1-DCA		Soil and groundwater	No removal	This study (Carus)
1,2-dichloroethane (DCA)		Phosphate buffer	< 1 x 10^{-5}	(Waldemer and Tratnyek 2006)
Dioxane	Persulfate	DI water	1.4 x 10^{-3}	This study (CDM Smith)
		DI water	1.1 x 10^{-3}	This study (Carus)
		DI water	1.7 x 10^{-3}	Estimated from (Felix-Navarro et al. 2007)
		Soil and groundwater	4.6 x 10^{-5}	This study (Carus)
TCE		Soil and groundwater	5.3 x 10^{-5}	This study (Carus)
		DI water	2.4 x 10^{-4}	Estimated from (Liang et al. 2007)
cis-1,2-DCE		Soil and groundwater	5.0 x 10^{-5}	This study (Carus)
1,1-DCE		Soil and groundwater	1.9 x 10^{-4}	This study (Carus)
1,1-DCA		Soil and groundwater	3.3 x 10^{-6}	This study (Carus)

The second-order rate constant for dioxane oxidation by persulfate in de-ionized water (1.2 to 1.4 × 10^{-3} M^{-1} s^{-1}) was similar to a value of 1.7 × 10^{-3} M^{-1} s^{-1} estimated using data reported in the literature (Felix-Navarro et al. 2007). Rate constants for dioxane oxidation with sodium persulfate in the presence of CVOCs, soil, and groundwater were 4.7% of those measured in de-ionized water and in the absence of CVOCs (5.7 × 10^{-5} versus 1.2 × 10^{-3} M^{-1} s^{-1}). Rate constants for oxidation of TCE and cis-1,2-DCE were similar to those for dioxane in the presence of soil and groundwater (i.e., 6×10^{-5} and 5×10^{-5} M^{-1} s^{-1}, respectively). Compared to the rate constants for TCE and cis-1,2-DCE, the rate constant for 1,1-DCE was about one order of magnitude greater, and the rate constant for 1,1-DCA was about one order of magnitude lower. A second-order rate constant for TCE in de-ionized water was not estimated, but data in the literature (Liang et al. 2007) were used to estimate a value of 2.4×10^{-4} M^{-1} s^{-1} for TCE, which is one order-of-magnitude greater than the value measured in soil and groundwater. These data suggest that the soil and/or groundwater inhibited oxidation of the organic compounds but did not completely prevent oxidation. The inhibition of persulfate oxidation by soil and groundwater resulted in the rate constants for dioxane oxidation with permanganate and persulfate being similar (3.4×10^{-5} versus 5.7×10^{-5} M^{-1} s^{-1}) in the presence of CVOCs, soil, and groundwater.

5.3.2 Column Tests

Figure 5.13 shows the removals of individual contaminants in the permanganate column study. Dioxane was not appreciably removed by permanganate even though removal was observed in the batch kinetics study. The chlorinated ethenes TCE, cis-1,2-DCE and 1,1-DCE were removed to non-detectable concentrations. 1,1-DCA was not removed, which is consistent with the batch kinetic study results. The observed second-order reactor rate constants were calculated from the influent and effluent contaminant concentrations, hydraulic residence time (HRT), and effluent oxidant concentration by the following equation:

$$k_{reactor} = \ln\left(\frac{[Influent]}{[Effluent]}\right)\left(\frac{1}{[Oxidant]}\right)\left(\frac{1}{HRT}\right) \tag{3}$$

The second-order reactor rate constant for dioxane removal from the reactor was estimated to be $1.1\pm0.6 \times 10^{-4}$ M^{-1} s^{-1}. This value is about one order-of-magnitude greater than that observed in the batch kinetics test, suggesting that kinetic limitations of dioxane oxidation did not occur in the column study. Rather, dioxane removal was low apparently because of low permanganate concentrations, which ranged from 260 to 2,100 mg/L. Minimum second-order reactor rate constants were estimated for the chlorinated ethenes because the effluent concentrations were less than the detection limit. These minimum reactor rate constants for TCE, cis-1,2-DCE, and 1,1-DCE were similar and estimated to be $2.2\pm0.6 \times 10^{-3}$ M^{-1} s^{-1}. The values are about two orders-of-magnitude lower than second-order rate constants estimated from the batch kinetic tests (see **Table 5.3**). Thus, the permanganate concentrations and residence time in this column were more than sufficient for chlorinated ethene oxidation. The second-order reactor rate constant for 1,1-DCA continually declined during the column test, and the final values were about 10^{-6} to 10^{-5} M^{-1} s^{-1}. This range of values is consistent with negligible removal and literature data for chlorinated ethanes (**Table 5.3**).

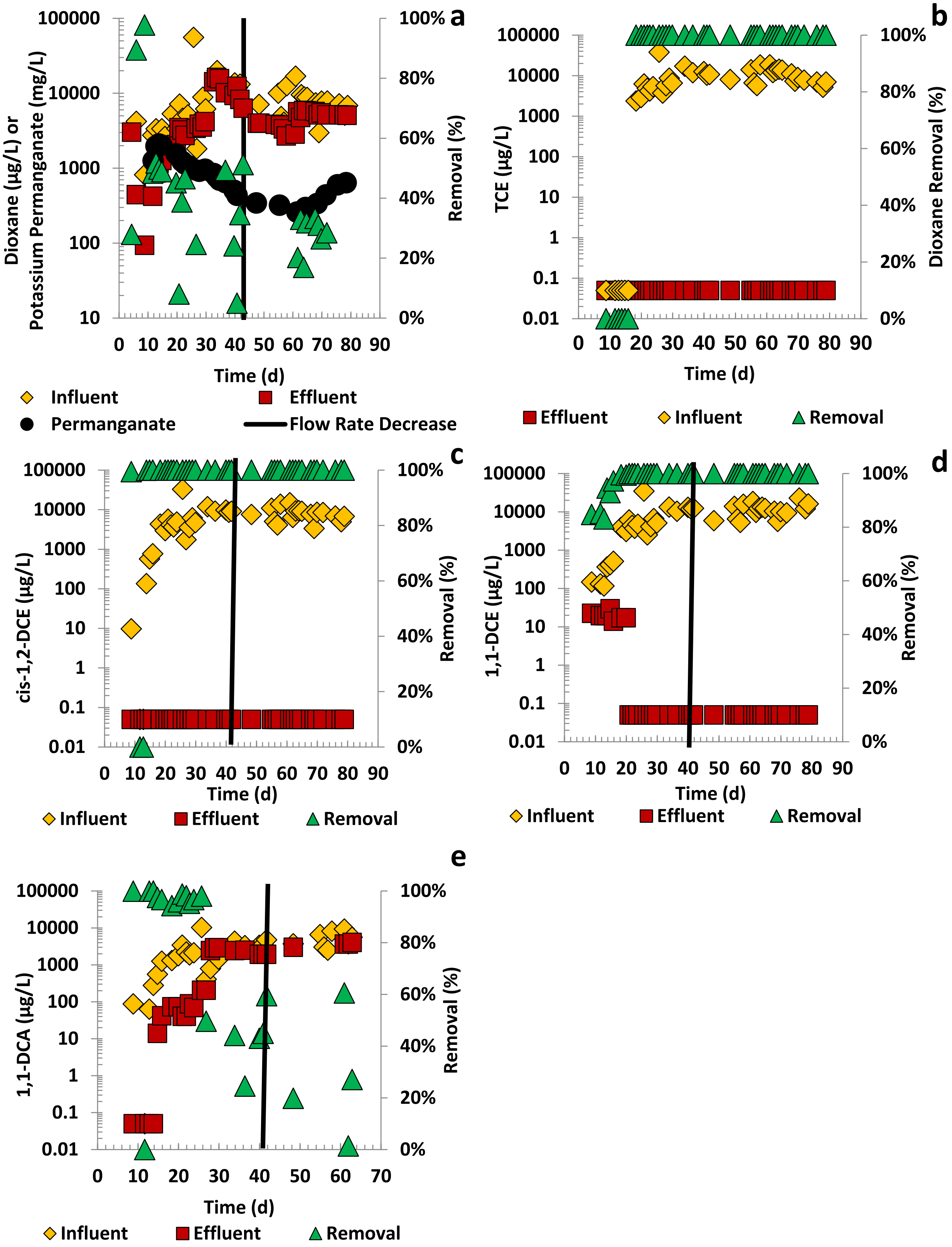


Figure 5.13. Removal of Dioxane (a), TCE (b), cis-1,2-DCE (c), 1,1-DCE (d), and 1,1-DCA (e) by Potassium Permanganate (KMnO4) in the Column Study.

Figure 5.14 shows the removals of individual contaminants in the persulfate column study. Initially, dioxane was not appreciably removed. The flow rate was decreased from 0.15 to 0.05 milliliters per minute (mL/min) on day 40 to determine if dioxane removal could be increased. Dioxane removal did increase however the increase appears to have started about two days earlier. Nevertheless, dioxane removal continued to increase and effluent concentration decreased to less than 100 µg/L on day 74 (> 99% removal). Persulfate concentrations increased gradually over time to 44,000 mg/L on day 89 when the study ended. The second-order reactor rate constant was estimated to be $2.2\pm0.9 \times 10^{-5}\ M^{-1}\ s^{-1}$, which is similar to that the rated constant measured in the batch kinetics study in the presence of soil and groundwater ($4.6 \times 10^{-5}\ M^{-1}\ s^{-1}$). Thus, the apparent inhibition by soil and groundwater observed in the batch kinetic study was also observed in the column study. Still, dioxane was removed by over 99%. Steady state (i.e., after day 50) TCE, cis-1,2-DCE, and 1,1-DCE removals were also at or greater than 99% and reactor rate constants were 2.4±1.0, 3.3±1.2, and $3.9\pm1.5 \times 10^{-5}\ M^{-1}\ s^{-1}$, respectively. The values for TCE and cis-1,2-DCE are similar to those for the batch kinetic study, but the value for 1,1-DCE is about one order-of-magnitude lower. The second-order reactor constant for 1,1-DCA was $4.8\pm3.2 \times 10^{-6}\ M^{-1}\ s^{-1}$ and consistent with the observed lack of appreciable removal in the column study.

Figure 5.15 illustrates the second-order reactor rate constant for dioxane oxidation by permanganate was generally greater than that by persulfate even though dioxane removal was greater with persulfate. Average second-order reactor rate constants were greater for permanganate than persulfate for dioxane and CVOCs as shown in **Figure 5.16**. The reason the rate constant for permanganate was greater than for persulfate is attributable to the relative different in oxidant concentrations. Permanganate ranged from 260 to 650 mg/L after flow rate was decreased whereas persulfate ranged from 15,000 to 42,000 mg/L (see **Figure 5.17**). Permanganate concentrations decreased steadily over time. However, about 20 days after the flow rate was decreased from 0.15 to 0.05 mL/min, the permanganate concentration started to increase. This increase was not sufficient to increase overall dioxane removal in the column.

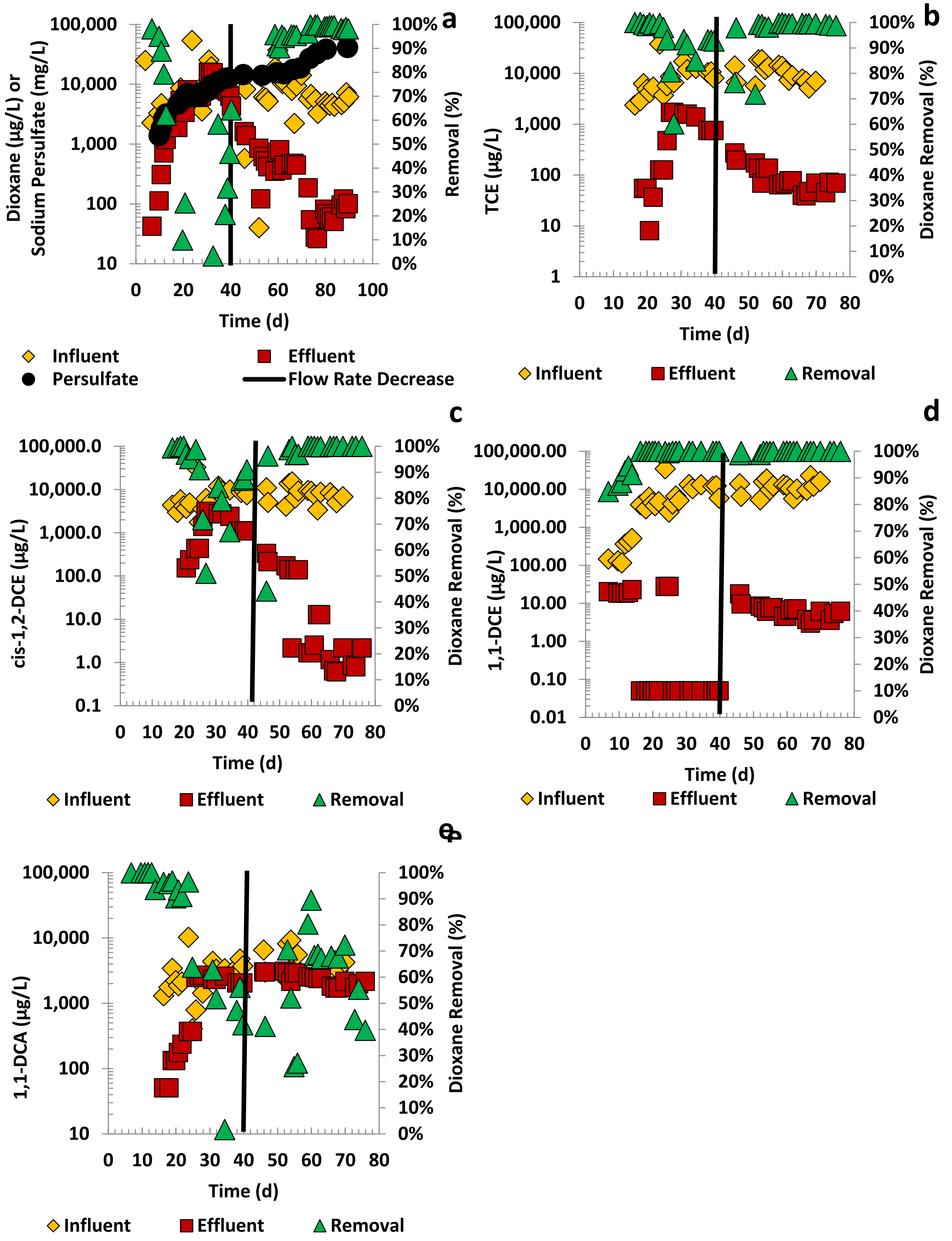


Figure 5.14. Removal of Dioxane (a), TCE (b), cis-1,2-DCE (c), 1,1-DCE (d), and 1,1-DCA (e) by Sodium Persulfate ($Na_2S_2O_8$) in the Column Study.

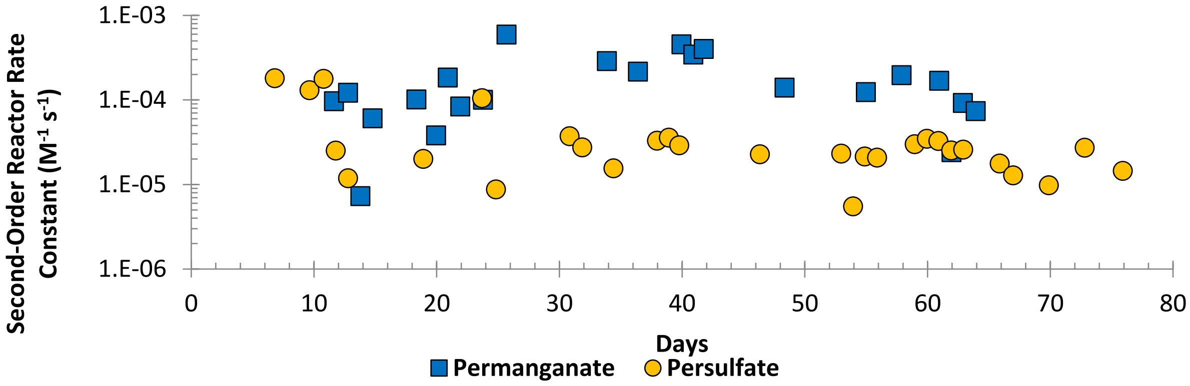


Figure 5.15. Comparison of Second-order Reactor Rate Constants Over Time for Dioxane with Permanganate and Persulfate.

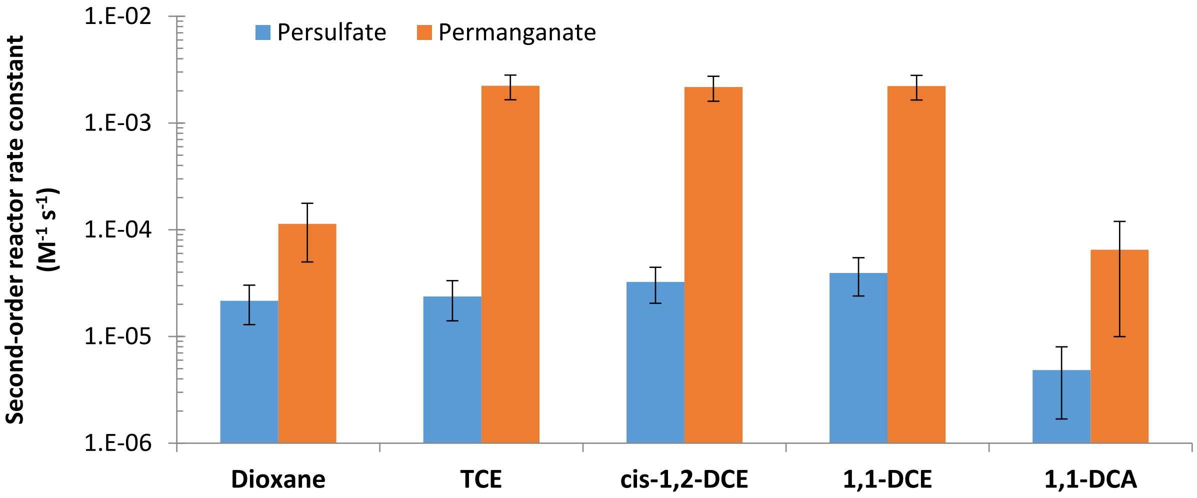


Figure 5.16. Comparison of Average Second-order Reactor Rate Constants for Dioxane and CVOCs with Permanganate and Persulfate.

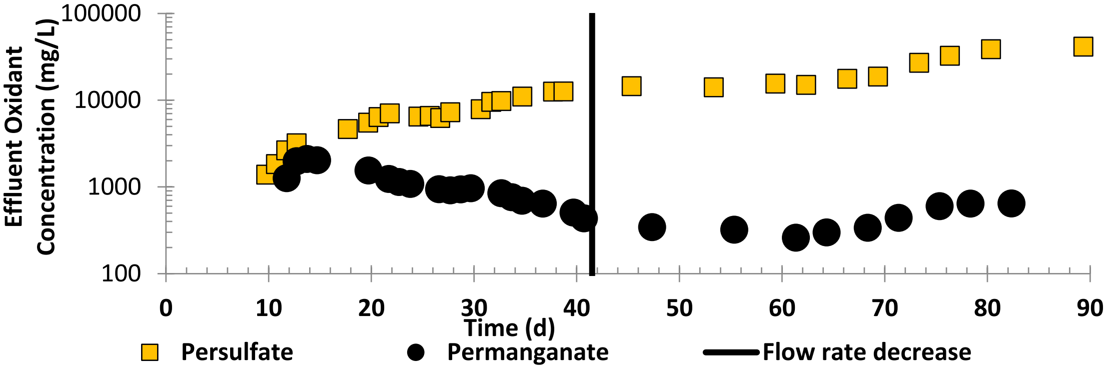


Figure 5.17. Comparison Column Effluent Oxidant Concentrations of Potassium Permanganate ($KMnO_4$) and Sodium Persulfate ($Na_2S_2O_8$).

5.3.3 Oxidant Flux

The different oxidant concentrations in the column effluents was attributable to different oxidant release rates from the cylinders as shown in **Figure 5.18**. The final persulfate release rate was 15 mg cm^{-2} d^{-1}. This release rate was similar to the release rate of 15 mg cm^{-2} d^{-1} estimated just before the flow rate was decreased. The persulfate release rates were greater than the final release rate estimated for permanganate (0.3 mg cm^{-2} d^{-1}). The oxidant release rates were initially similar as shown in **Figure 5.18** but diverged after about 10 days of operation. **Figure 5.18** also shows the cumulative percent mass of oxidant released (based on effluent concentrations) from each cylinder over time. Only 2.4% of the permanganate was released compared to 37% of the persulfate.

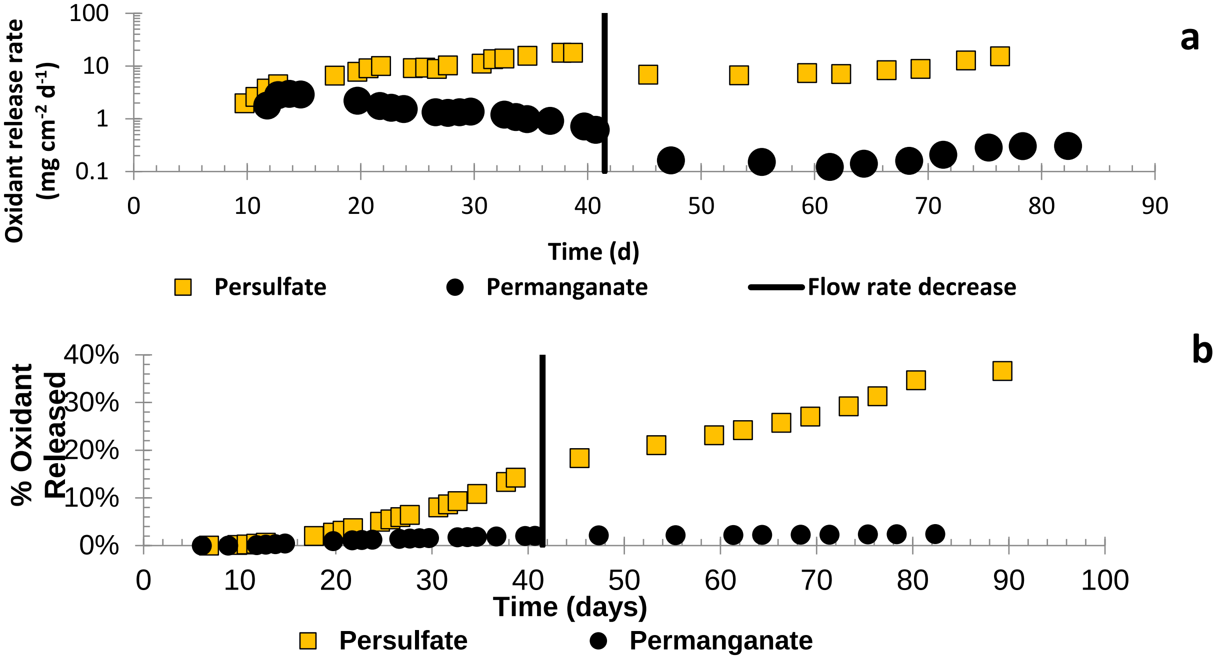


Figure 5.18. Oxidant Release Rates (a) and Percent Mass Released (b) from the Potassium Permanganate ($KMnO_4$) and Sodium Persulfate ($Na_2S_2O_8$) Cylinders in the Column Study.

Further confirmation of the oxidant release was attempted by extracting the oxidants from the new and used cylinders. Analysis of new and used permanganate cylinders indicated the MnO_4 mass decreased from 620 milligrams (mg) to 610 mg for a 1% reduction. This value is about half the above estimate of 2.4%. Analysis of new and used persulfate cylinders indicated the S_2O_8 mass decreased from 660 mg to 140 mg for an 80% reduction. This value is about twice the above estimate. Thus, further work is needed to develop reliable estimates of oxidant loss from the cylinders. Such estimates are necessary to estimate cylinder lifetime. Nevertheless, the extraction data do confirm that relatively less oxidant remained in the persulfate cylinder compared to the permanganate cylinder.

Figures 5.19 and 5.20 show photographs of the cylinders at the conclusion of column operation. A rind, possibly manganese dioxide (MnO_2), is evident around the circumference of the permanganate cylinder. This rind may have inhibited oxidant release from the cylinder, which resulted in the relatively low permanganate concentrations. The photographs of the persulfate cylinders show some staining but no clear evidence of a coating as was observed on the permanganate cylinder.

The temporal patterns of oxidant release from the cylinders were also qualitatively different as illustrated in **Figure 5.21**. Permanganate concentrations rapidly increased and then gradually decreased. The patterns were qualitatively similar in columns packed with sand and operated with DI water and in columns packed with soil and operated with both contaminated and uncontaminated groundwater. On the other hand, persulfate concentrations in all three column conditions increased gradually and did not decrease over the period of the study.

Figure 5.19. Photographs of Permanganate (a) and Persulfate (b) Column Cylinders at the Conclusion of the Study.

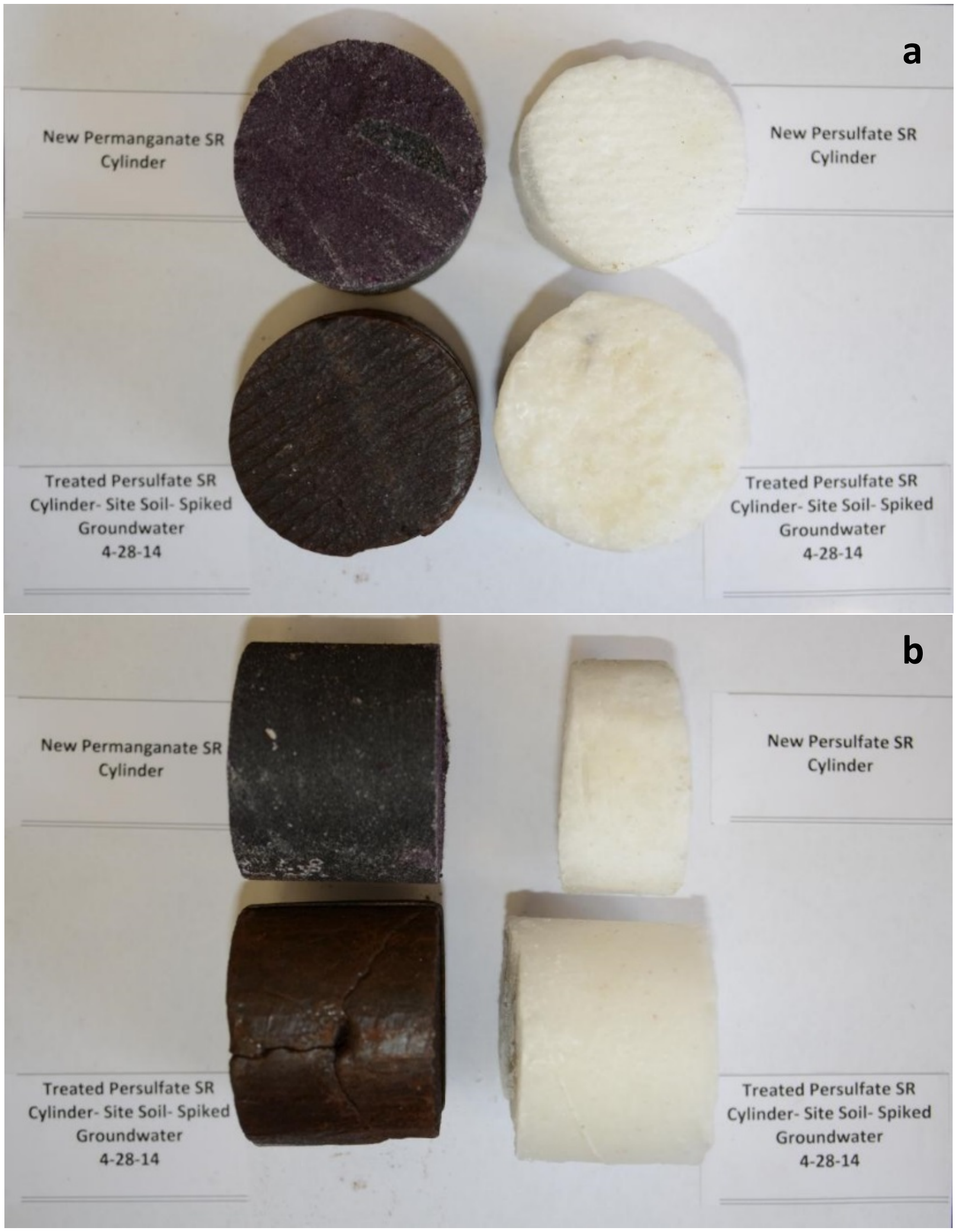


Figure 5.20. Photographs of Permanganate and Persulfate Column Cylinders at the Beginning and Conclusion of the Study – Cross Section (a) and Side View (b).

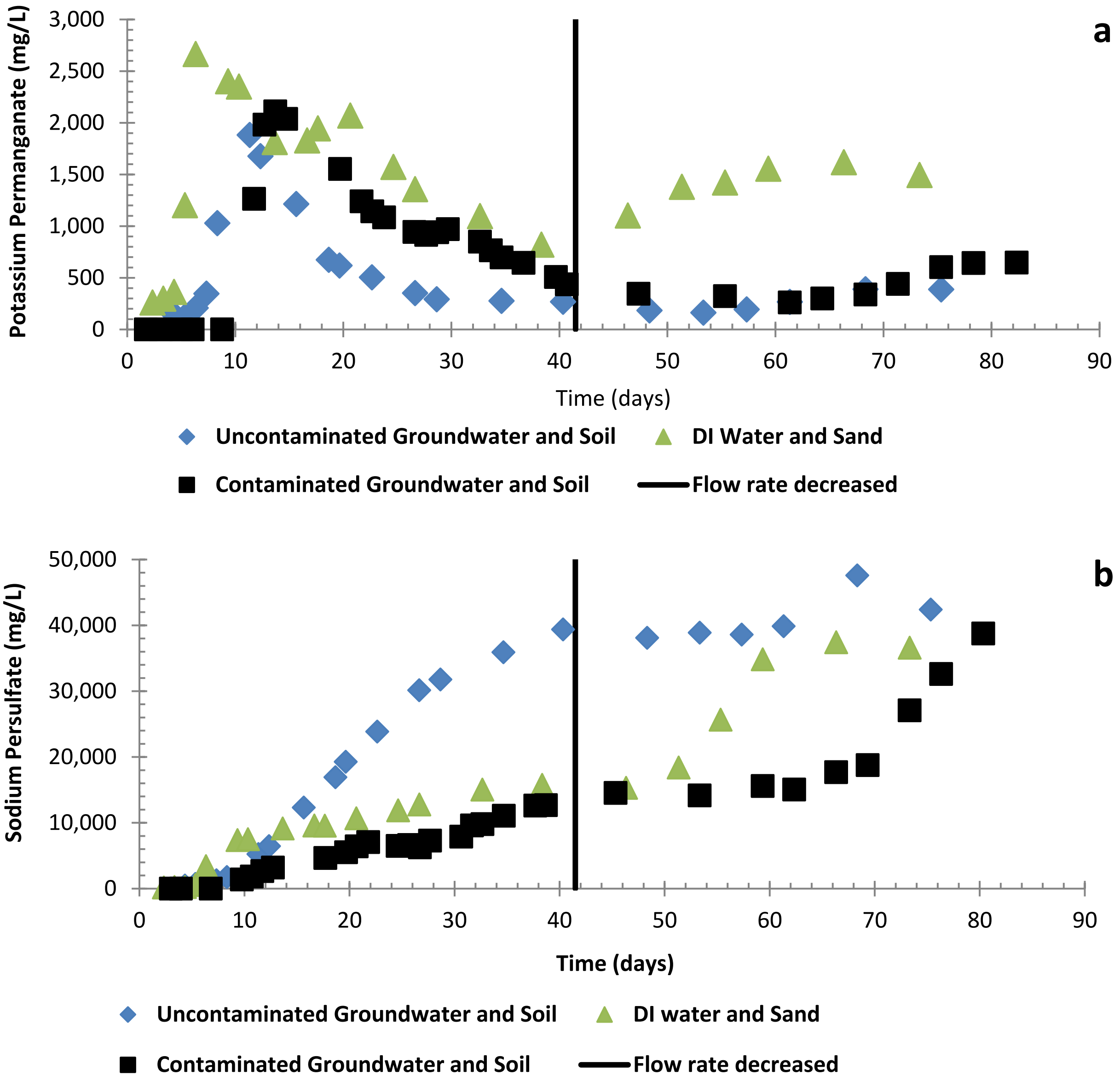


Figure 5.21. Oxidant Release Profiles for Potassium ($KMnO_4$) Permanganate (a) and Sodium Persulfate ($Na_2S_2O_8$) Cylinders (b) Based on Effluent Concentrations.

5.3.4 Potential Secondary Effects on Groundwater Quality

Secondary effects on groundwater quality, including pH and dissolved metals, were evaluated in the column study. **Figure 5.22** shows the temporal changes in oxidant concentration and pH in the permanganate and persulfate column effluents. The pH in the permanganate column effluent remained near neutral. The pH in the persulfate column effluent was about 6 during the steady state period (i.e., after about day 50). However, the final pH was 4.6. It is not known whether this low pH was representative or an anomaly. Nevertheless, persulfate decomposition is known to result in decreased pH. Hydrogen ions are generated per the following equation for sodium persulfate with dioxane:

$$C_4H_8O_2 + 6H_2O + 10\ Na_2S_2O_8 \rightarrow 4CO_2 + 20SO_4^{2-} + 20H^+ + 20Na^+ \qquad (4)$$

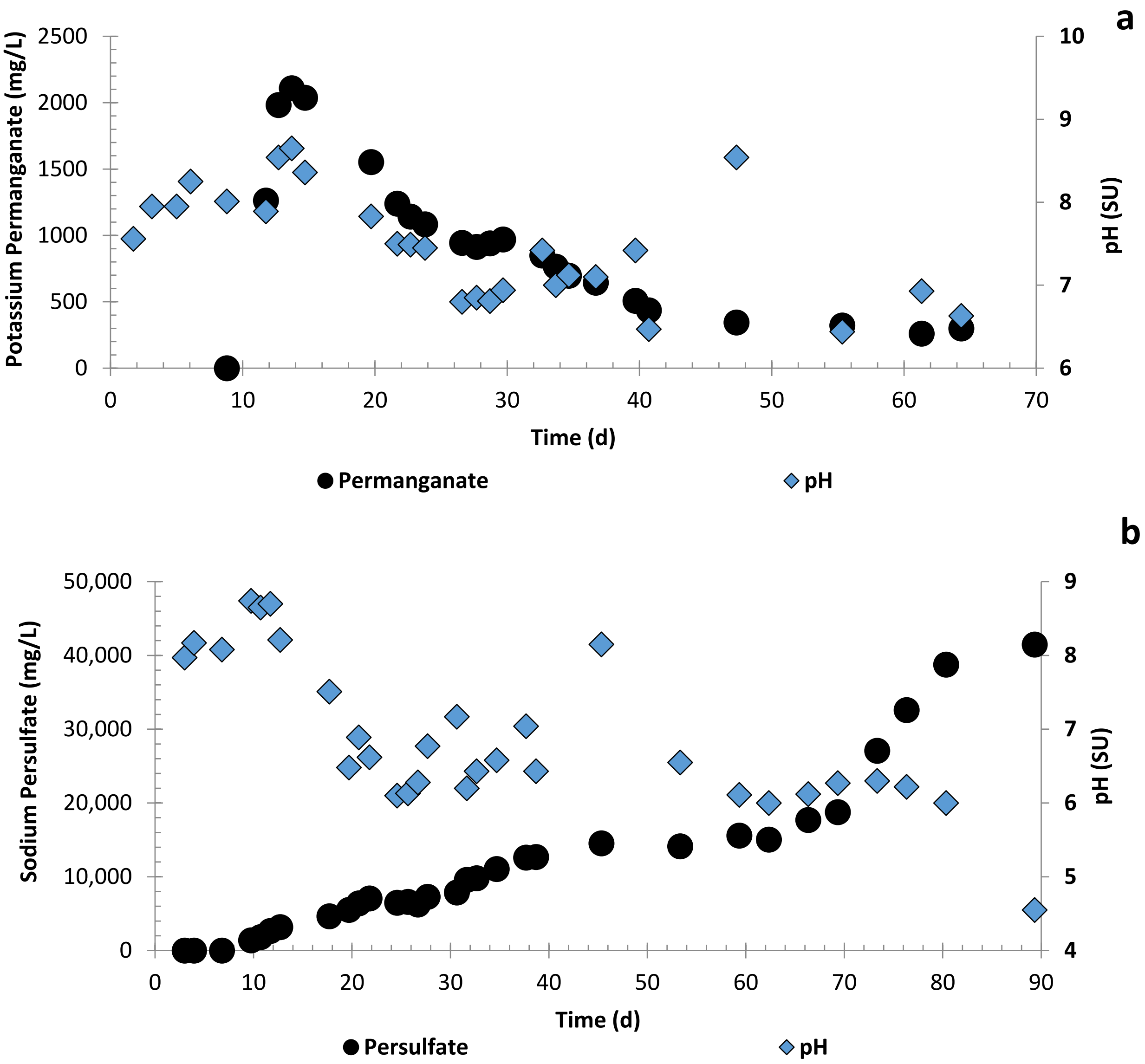


Figure 5.22. Effluent Oxidant Concentrations and pH in the Potassium Permanganate ($KMnO_4$) (a) and Sodium Persulfate ($Na_2S_2O_8$) (b) Columns.

Dissolved metals were analyzed by Carus and an independent laboratory (OnSite Environmental). **Table 5.4** shows the site groundwater contained non-detectable concentrations of dissolved metals with the possible exception of nickel, which was detected by Carus at 6.2 µg/L (less than the California MCL of 100 µg/L).

Table 5.4. Filtered Metals Concentrations in Site Groundwater and Column Effluent Samples.

Laboratory	**NAS North Island Groundwater**		**Permanganate Column Effluent**				**Persulfate Column Effluent**			
	OnSite Env.	**Carus**	**OnSite Env.**	**Carus**			**OnSite Env.**	**Carus**		
	Metal (µg/L)									
Sample Date	December 5, 2013		Day 90	Day 90	Day 2 to 89		Day 87	Day 97	Day 45 to 87	
					avg	stdev			avg	stdev
Arsenic	<3	<1	<3	**39**	**68**	**72**	<3	<1	1.0	0.0
Cadmium	<4	NA	<4	<0.1	0.1	0.0	<4	2	1.4	0.5
Chromium	<10	<2	**220**	**570**	**280**	**330**	**290**	**300**	**230**	**66**
Lead	<1	<1	<1	<1	9.6	**20**	5.5	<1	**49**	**35**
Mercury	<0.5	NA	<0.5	NA	NA	NA	<0.5	NA	NA	NA
Nickel	<20	6.2	<20	9.1	5.1	5.0	92	63.9	**120**	83
Silver	<10	NA	<10	NA	NA	NA	<10	NA	NA	NA

Notes: Concentrations greater than the California State MCL are denoted in bold.

NA = Not tested

Arsenic was detected in the permanganate column by Carus but not OnSite. Neither laboratory observed arsenic in the persulfate column effluent. Thus, Carus arsenic results may be high estimates of the actual arsenic concentration. The California MCL for arsenic is 10 µg/L. Cadmium was not detected above the California MCL of 5 µg/L. Chromium was present at concentrations greater than the California MCL of 50 µg/L in both column effluents, and chromium was likely present in the hexavalent form, which has a California MCL of 10 µg/L. Hexavalent chromium is likely to be reduced to insoluble trivalent chromium hydroxide once groundwater migrates downgradient to reducing areas of the plume. Lead was not detected above the California MCL of 15 µg/L in the snapshot sampling of the column effluents. However, lead was detected above this regulatory limit periodically in both column effluents as evidenced by the average concentration results. Thus, lead release from the soil in the presence of the chemical oxidants may be transient. Mercury and silver were not detected. Nickel was not detected above the California MCL of 100 grams per liter (g/L) in the snapshot sampling of the column effluents but was periodically detected in the persulfate column effluent. Nickel was not detected above the California MCL in the permanganate column effluent.

5.3.5 Treatability Study Conclusions

Unactivated persulfate was successfully demonstrated to oxidize dioxane and chlorinated ethenes (TCE, cis-1,2-DCE, and 1,1-DCE) in the presence of site soil and groundwater. The chlorinated ethane 1,1-DCA was not oxidized with persulfate as expected. Oxidation was observed in batch reactors with dissolved persulfate and in continuous flow column studies with a slow-release persulfate cylinder.

Over 99% removal was observed in the column study, which exceeded the project go/no-go criterion of 90%. The pseudo second-order rate constant for dioxane removal in site soil and groundwater (4.6×10^{-5} M^{-1} s^{-1}) was less than that measured in DI water (1.1×10^{-3} M^{-1} s^{-1}). These data suggest some form of partial inhibition by site soil and groundwater. Dioxane removal did not follow first-order kinetics (i.e., the slope of the semi-logarithmic plot of concentration versus time was not linear, and the absolute value of the slope increased over time), suggesting some type of activation. This behavior was observed in DI water and in the presence of soil and groundwater. While intentional activation was not conducted (e.g., hydrogen peroxide, iron salts, heat, or high pH), activation may have occurred nevertheless. Dioxane oxidation by persulfate in the absence of an activator has been previously observed (Felix-Navarro et al. 2007). Considering the pseudo second-order rate constant was lower in the presence of soil and groundwater, we hypothesize that some property of the soil and groundwater may have partially inhibited the activation process which led to the lower oxidation rates. The measured pseudo second-order rate constant for TCE in the presence of site soil and groundwater (5.3×10^{-5} M^{-1} s^{-1}) was less than that calculated using previously published data (Liang et al. 2007) further suggesting some form of inhibition. Even though partial inhibition was observed, dioxane was removed by over 99% in the column with a steady-state second-order reactor rate constant of $2.2 \pm 0.9 \times 10^{-5}$ M^{-1} s^{-1}, which is similar to the rate constant measured in the batch kinetics study in the presence of soil and groundwater (4.6×10^{-5} M^{-1} s^{-1}). These data further substantiate the ability of unactivated persulfate to consistently oxidize dioxane in a continuous-flow system in the presence of site soil and groundwater.

Permanganate was capable of oxidizing dioxane and chlorinated ethenes in batch reactor studies. 1,1-DCA was not oxidized as expected. The column study demonstrated greater than 99% removal of chlorinated ethenes but little to no removal of dioxane. The reason for the low removal of dioxane was attributable to low permanganate concentrations rather than a kinetic inhibition per se – the second-order reactor rate constant for dioxane in the column $1.1 \pm 0.6 \times 10^{-4}$ M^{-1} s^{-1}) was actually greater than that measured in the batch reactors (2.7×10^{-5} M^{-1} s^{-1}) in the presence of site soil and groundwater. Low permanganate concentrations were attributed to site-specific chemistry.

In spite of similar second-order rate constants (i.e., measured in the batch reactors) for dioxane with permanganate and persulfate in the presence of site soil and groundwater, the persulfate column performed better than the permanganate column with respect to dioxane removal. The reason was the difference in oxidant release rate and thus oxidant concentrations. The permanganate release rate decreased over time in part because of the formation of a rind around the exterior surface of the cylinder. This rind inhibited mass transfer of permanganate from the cylinder into the groundwater. The persulfate cylinder did not develop such a rind, and release rates increased over time. Different release mechanisms for the oxidants may have also played a role; however, this was not explored in this study. The maximum release rate for the persulfate cylinder was 18 mg cm^{-2} d^{-1} and was used for design of the field demonstration.

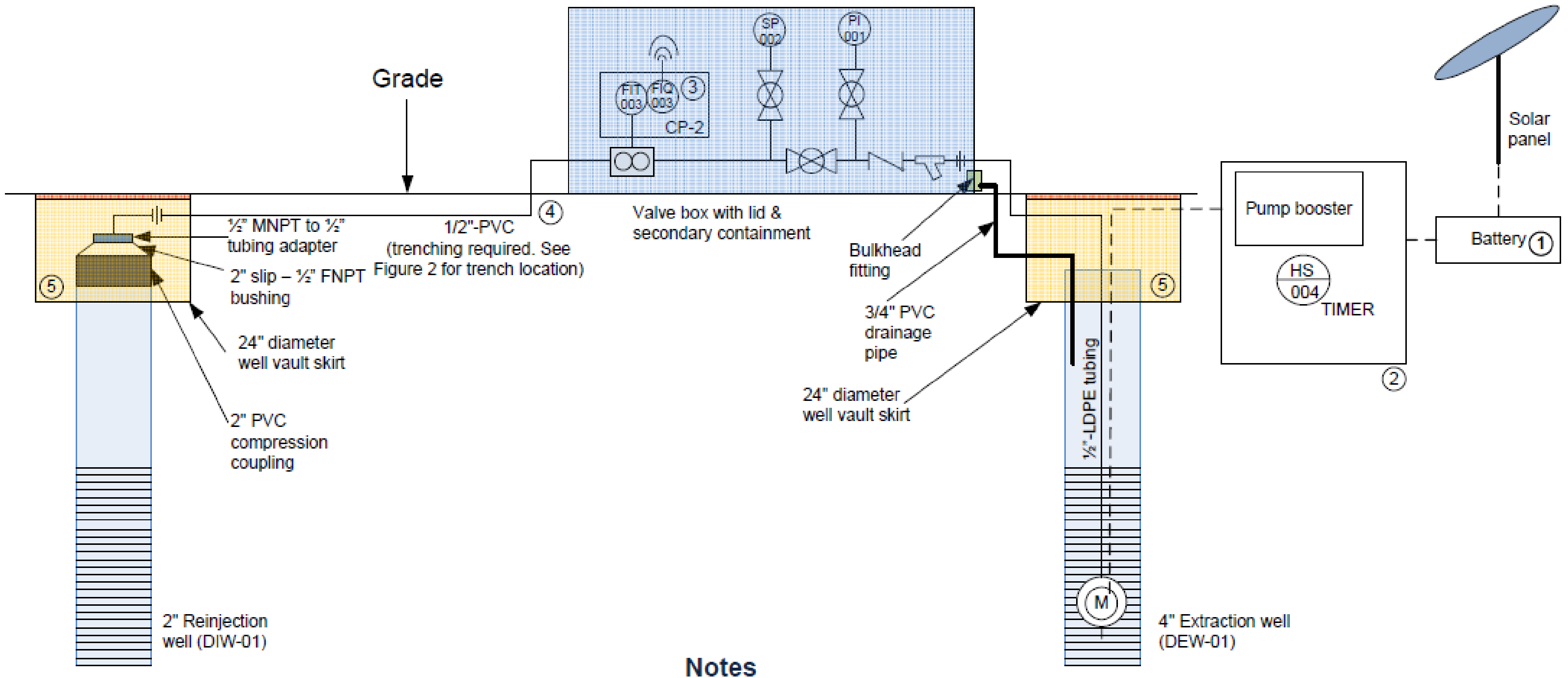
Secondary effects on groundwater quality were observed in the column study. These included pH depression and elevated concentrations of certain heavy metals. In the persulfate column, pH was trending downward near the end of the study, and the final measured pH was 4.6. Dissolved metals were also observed in the persulfate column effluent. In particular, dissolved chromium, most likely in the hexavalent form, was present at concentrations in excess of the California MCL of 10 µg/L. Other metals, including lead and nickel may also have exceeded the MCLs at times; however, there is some uncertainty regarding the analytical data. Decreased pH, elevated metal concentrations, and formation of hexavalent chromium are typical observations during ISCO.

Downgradient geochemical conditions, especially if they are reducing, can be expected to attenuate these secondary effects. For example, hexavalent chromium is easily reduced to trivalent chromium hydroxide [$Cr(OH)_3$] which precipitates. Natural soil alkalinity will buffer the acidity produced during persulfate decomposition. Other dissolved metals can be expected to precipitate as the pH increases.

In summary, the treatability study demonstrated that slow-release persulfate cylinder technology without intentional activation was capable of treating site groundwater contaminants with the exception of 1,1-DCA. Slow-release permanganate cylinder technology was successful for treatment of chlorinated ethenes but not dioxane. Presumed MnO_2 deposition decreased permanganate release rates, which affected contaminant oxidation rates. This effect may be dependent on site-specific groundwater chemistry rather than a general technology limitation. Based on the treatability study results, a field demonstration using slow-release persulfate cylinders was conducted as the next step in the demonstration and validation of this technology.

5.4 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

As discussed in **Section 5.1**, the demonstration system was designed to simulate the use of persulfate to treat groundwater contaminated with dioxane and CVOCs in an induced groundwater gradient. The system consisted of two boreholes/wells containing the persulfate cylinders, one upgradient and eight downgradient monitoring wells, an extraction well, and a reinjection well as shown previously in **Figure 5.2**. A solar panel equipped with battery packs was used to provide power to the recirculation system. Specifically, a submersible pump housed inside a 4-inch diameter extraction well was used to extract groundwater and promote a controlled hydraulic system. To achieve the design extraction rate of 0.35 gallons per minute (gpm) the submersible pump was cycled operating at approximately 1.5-1.75 gpm for four to six hours per day to achieve the target extraction rate. The extracted water was then injected into the downgradient reinjection well. A simplified process and instrumentation diagram for the pilot system is presented in **Figure 5.23** while the solar panel layout is presented in **Figure 5.24**. Details associated with the various process equipment, process controls, installation, commissioning, O&M, decommissioning, and inspections and documentations are discussed below.



Legend

- Ball valve
- Flow totalizer with pulse output (FIQ 003)
- Check valve
- Pressure gauge (PI 001)
- Sampling port (SP 002)
- Submersible pump
- Union
- Y-strainer
- Flow transmitter with Cellular reception (FIT 003, FIQ 003)
- Flow meter

Notes

① 12 VDC battery (2 x 85 Ah) system that will power the internal components and will be recharged by the solar panel.

② Solar charger with pump timer, pump booster, liquid detector and float incorporated into weatherproof enclosure.

③ The flow meter transmitter shall be mounted above the drainage pipe exit level. Flowmeter with pulse output shall be installed inline and connected to transmitter.

④ Minimum pipe connections shall be used in the trench to connect the extraction well valve box to the reinjection well. This will minimize the likelihood of leaking in the trench.

⑤ Hole shall be drilled on the side of the DEW-01 and DIW-01 well vault skirt for pipes, tubing, and electrical wires.

Figure 5.23. Process and Instrumentation Diagram.

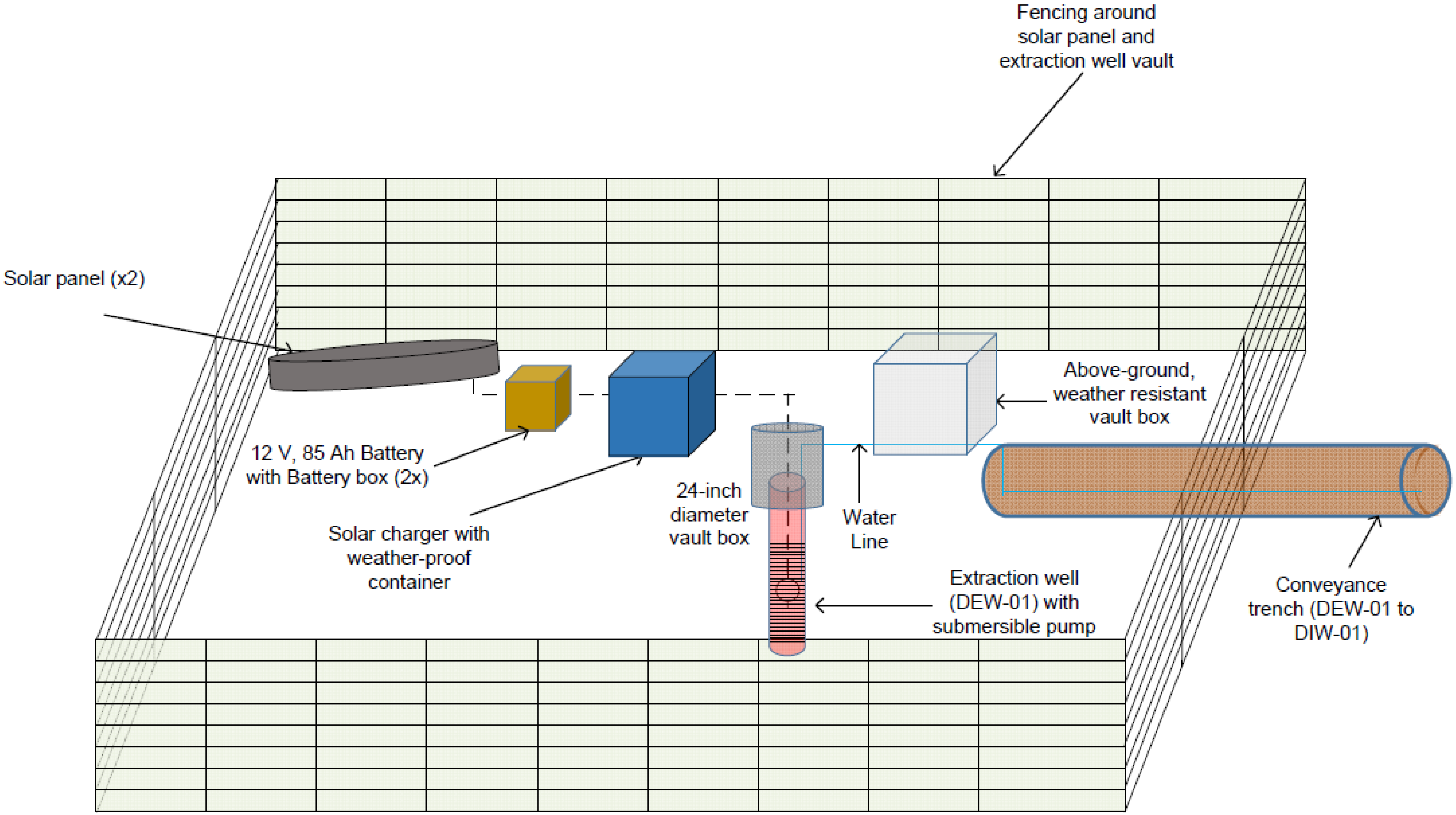


Figure 5.24. Solar Panel Layout.

5.4.1 Process Equipment

The main process equipment used for this technology demonstration is described as follows:

<u>Extraction and reinjection well</u>

A groundwater extraction well (DEW-01) and a disposal reinjection well (DIW-01) were installed to 40 ft bgs. The extraction well was located 35 feet downgradient of the cylinder wells and the reinjection well was located 85 feet downgradient from the extraction well, as shown in **Figure 5.2**.

The extraction and disposal reinjection wells were installed using hollow-stem auger drilling technology and were constructed through the augers to avoid the natural collapse of native material around the well. The extraction well was constructed using 4-inch diameter, schedule 40 polyvinyl chloride (PVC) casing with the screen set at approximately 20 to 40 ft bgs. The construction diagram for the extraction well is shown in **Figure 5.25**. The reinjection well was installed in the same manner except it was constructed using 2-inch diameter materials, as shown in **Figure 5.26**. Both of the well screens were constructed with factory slotted, 0.020-inch openings, and fitted with a PVC bottom cap. A graded sand filter pack consisted of clean, 10-20 size silica sand was installed from the bottom of the hole to 2 feet above the top of the well screen. A seal was installed above the filter pack using bentonite. The bentonite seal was a minimum of 2 feet thick and was hydrated in place with potable water. The seal was overlain by a bentonite/cement grout that extended to within 4 feet of the ground surface. The reinjection and extraction well surface completions were completed within a 2-ft diameter by 2-ft deep concrete vault box. The top of casing terminated at approximately 3 ft bgs to allow for the installation of subsurface well head components. **Table 5.5** provides construction details for the extraction and disposal wells.

An electric submersible groundwater extraction pump was installed in the extraction well, controlled by a pump charger. The pump was hung from the surface using braided polyethylene rope and the intake of the pump was placed approximately 35 ft bgs. A check valve was fitted on top of the pump, and water was conveyed to the surface through 1/2-inch schedule 80 PVC piping. Water was conveyed from the extraction to the reinjection well through 1/2-inch diameter, schedule 80 PVC pipe buried in a trench at a minimum depth of 24 inches bgs. A pressure gauge was used for visual pressure monitoring during scheduled site visits. A remote water meter reading system was installed to record the volume of groundwater extraction/reinjection.

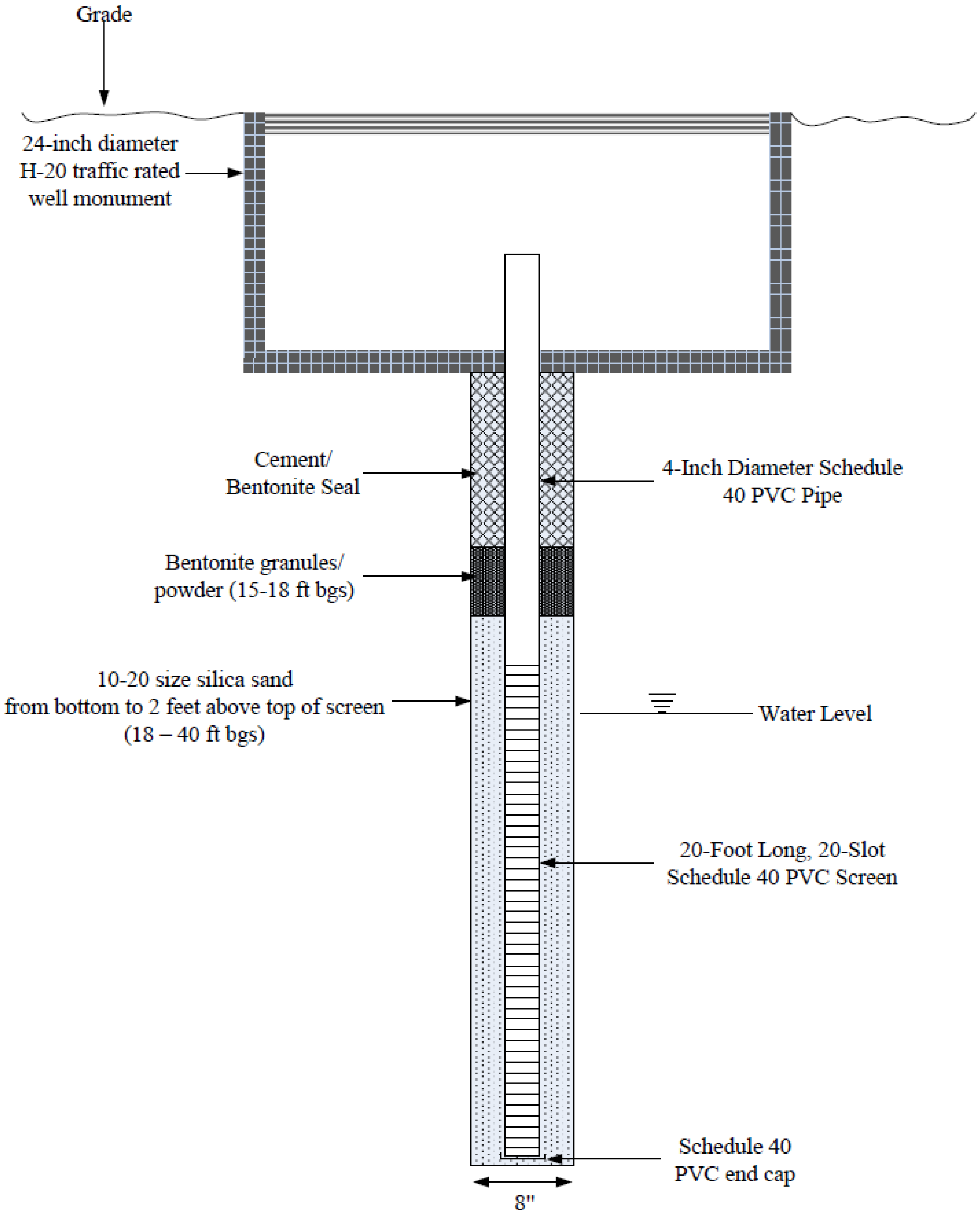


Figure 5.25. Extraction Well Construction Diagram (not to scale).

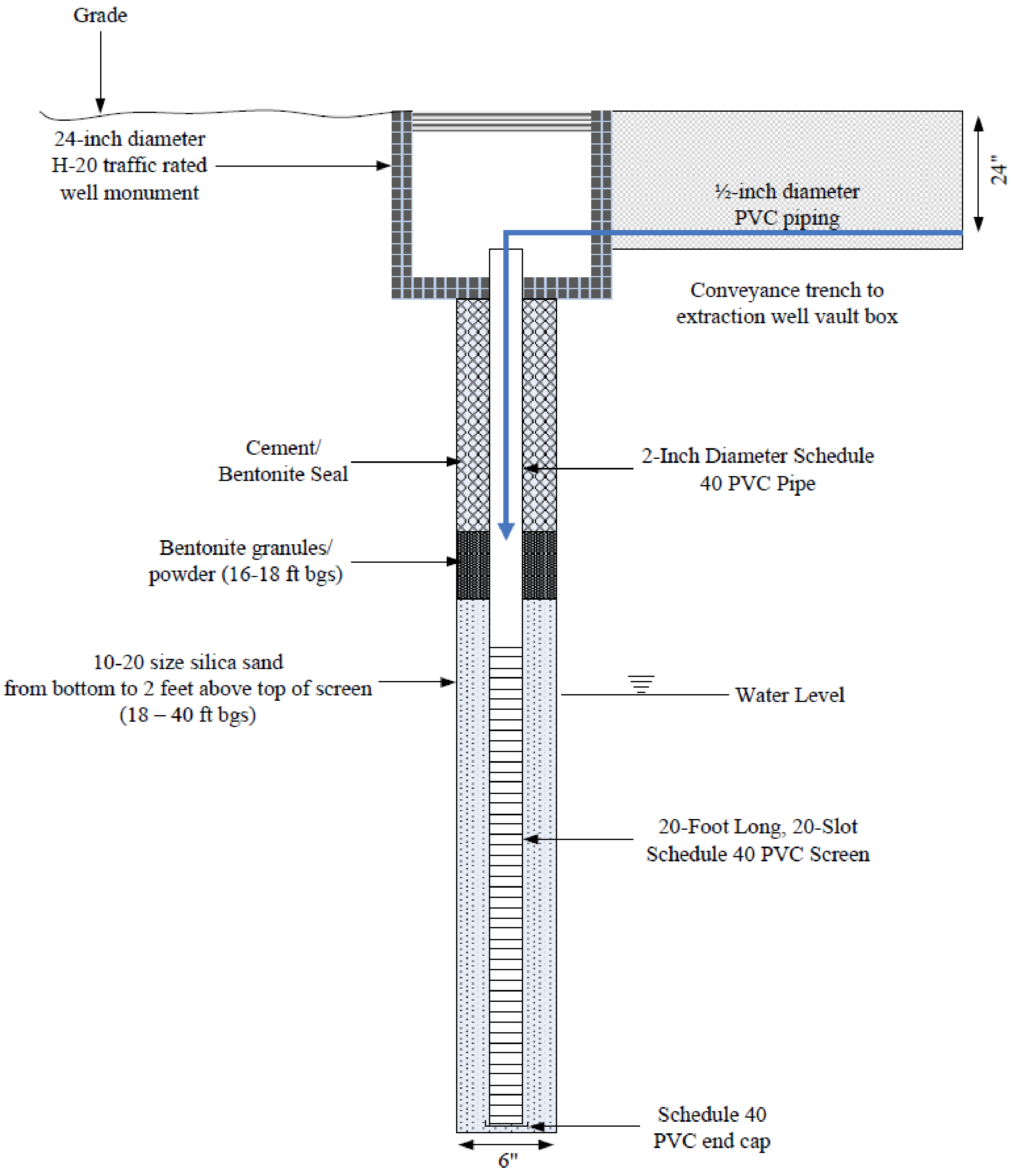


Figure 5.26. Reinjection Well Construction Diagram (not to scale).

Table 5.5 Well Construction Details.

Well ID	Description	Borehole Diameter (inches)	Well Diameter (inches)	Total Depth (ft bgs)	Screened Interval (ft bgs)	Top of Casing (ft above mean sea level)	Screened Interval (ft above mean sea level)	Well Material	Screen Size	North[2]	East[2]	Latitude[2] (decimal degrees)	Longitude[2] (decimal degrees)	Elevation[3] (ft)
DMW-01	Upgradient monitoring well	6	2	40	20-40	30.14	-9.86 - 10.14	Sch 40 PVC	20-slot	1836612.36	6268046.64	32.7021866	-117.2044568	30.14
DC-01[1]	Cylinder oxidant well	18	4	40	20-40	29.98	-10.02 - 9.98	Sch 40 PVC	20-slot	1836613.47	6268041.05	32.7021896	-117.2044750	29.97
DC-02[1]	Cylinder oxidant well	18	4	40	20-40	30.05	-9.95 - 10.05	Sch 40 PVC	20-slot	1836617.68	6268043.73	32.7022012	-117.2044664	29.89
DCW-01[1]	Cylinder monitoring well	18	2	40	20-40	29.98	-10.02 - 9.98	Sch 40 PVC	20-slot	1836613.47	6268041.05	32.7021896	-117.2044750	29.98
DCW-02[1]	Cylinder monitoring well	18	2	40	20-40	30.05	-9.95 - 10.05	Sch 40 PVC	20-slot	1836617.68	6268043.73	32.7022012	-117.2044664	30.05
DMW-02	Downgradient monitoring well	6	2	40	20-40	30.13	-9.87 - 10.13	Sch 40 PVC	20-slot	1836620.39	6268039.54	32.7022085	-117.2044801	30.13
DMW-03	Downgradient monitoring well	6	2	40	20-40	30.15	-9.85 - 10.15	Sch 40 PVC	20-slot	1836616.18	6268036.95	32.7021969	-117.2044884	30.15
DMW-04	Downgradient monitoring well	6	2	40	20-40	30.08	-9.92 - 10.08	Sch 40 PVC	20-slot	1836623.16	6268035.48	32.7022160	-117.2044934	30.08
DMW-05	Downgradient monitoring well	6	2	40	20-40	30.09	-9.91 - 10.09	Sch 40 PVC	20-slot	1836618.89	6268032.85	32.7022042	-117.2045018	30.09
DMW-06	Downgradient monitoring well	6	2	40	20-40	29.95	-10.05 - 9.95	Sch 40 PVC	20-slot	1836628.31	6268027.10	32.7022300	-117.2045208	29.95
DMW-07	Downgradient monitoring well	6	2	40	20-40	30.00	-10.00 - 10.00	Sch 40 PVC	20-slot	1836624.09	6268024.53	32.7022183	-117.2045291	30.00
DEW-01	Extraction well	8	4	40	20-40	29.69	-10.31 - 9.69	Sch 40 PVC	20-slot	1836634.84	6268012.85	32.7022476	-117.2045673	29.69
DIW-01	Reinjection well	6	2	40	20-40	29.26	-10.74 - 9.26	Sch 40 PVC	20-slot	1836680.77	6267943.10	32.7023721	-117.2047954	29.26

****Notes***:

- [1]: 4-inch cylinder well and 2-inch monitoring well installed within the same 18-inch borehole.
- [2]: coordinates shown are based upon the California Coordinate System (CCS83), Zone 6, 1983 Datum.
- [3]: elevations shown are based upon the San Diego County ROS 14387 benchmark. Control station used is the San Diego GPS 23 with an elevation of 412.98 feet (NAVD 88)

Cylinder wells

Two wells (DC-01 and DC-02) housing the slow-release oxidant cylinders were constructed. Specifically, each 4-inch inside-diameter oxidant cylinder well was constructed using schedule 40 PVC, factory-slotted with 0.020-inch openings, fitted with a PVC bottom cap, and screened from 20 to 40 ft bgs. Each cylinder well was housed inside an 18-inch borehole backfilled with pea gravel to 40 ft bgs. In addition, 2-inch monitoring wells were installed within each 18-inch borehole, since multi-level monitoring was not possible within the 4-inch wells. The 2-inch wells were also constructed of schedule 40 PVC, factory-slotted with 0.020-inch openings, fitted with a PVC bottom cap, and screened from 20 to 40 ft bgs. A construction well diagram for the cylinder wells is shown in **Figure 5.27**.

Monitoring wells

A series of monitoring wells (DMW-01 through DMW-07) located 5 feet upgradient and 5, 10, and 20 feet downgradient of the cylinder wells were installed via HSA drilling to facilitate performance monitoring. Specifically, each monitoring well was constructed of 2-inch diameter, schedule 40 PVC, factory-slotted with 0.020-inch openings, fitted with a PVC bottom cap, and screened from 20 to 40 ft bgs. Well construction details are provided in **Figure 5.28**. As described in the subsection above, one 2-inch monitoring well was also installed within each 18-inch borehole which contained the oxidant cylinders, as shown in **Figure 5.27**.

Conveyance Trenching

Conveyance trenching was installed between the vault box connected to the extraction well and the reinjection well as shown in **Figure 5.24**. The trench was installed with the following specifications:

- Minimum 24 inches between ground surface and pipe
- Minimum 3 inches of bedding sand emplaced on either side of and below pipe
- Minimum 6 inches of bedding sand emplaced above pipe
- Conveyance pipe must be schedule 80 PVC
- Minimum 18 inches of 1.5 concrete sack slurry above bedding sand to bottom of asphalt
- Asphalt patch to restore parking lot to pre-existing condition, as approved by site facility
- Backfilling after startup activities were completed
- Bedding sand used had the following characteristics:
    - 100% passing ¾-inch sieve
    - No more than 15% passing No. 8 sieve

All investigation-derived waste (IDW) generated was stored separately from drilling IDW in a roll-off container for proper characterization and disposal.

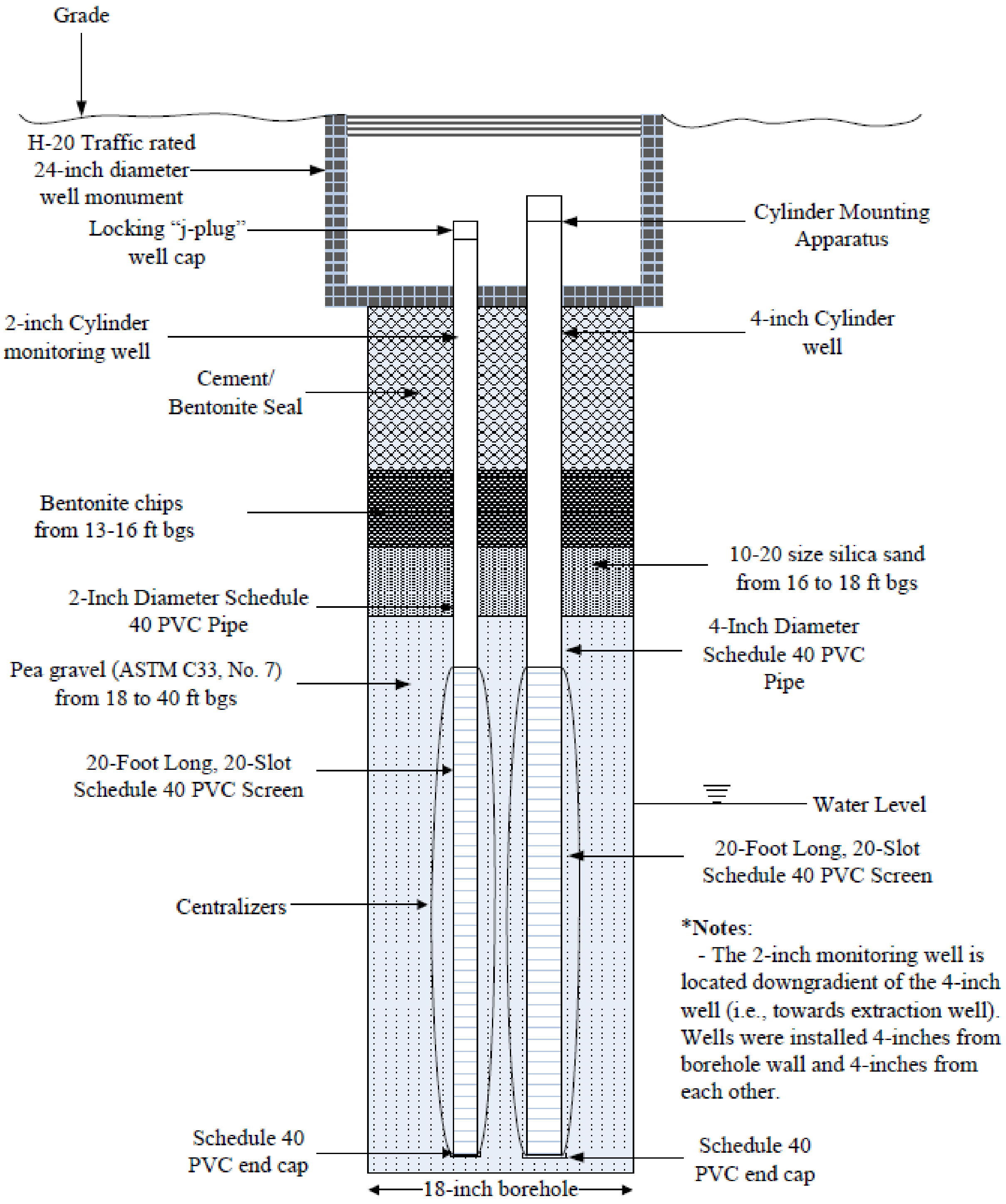


Figure 5.27. Cylinder Borehole Construction Diagram (not to scale).

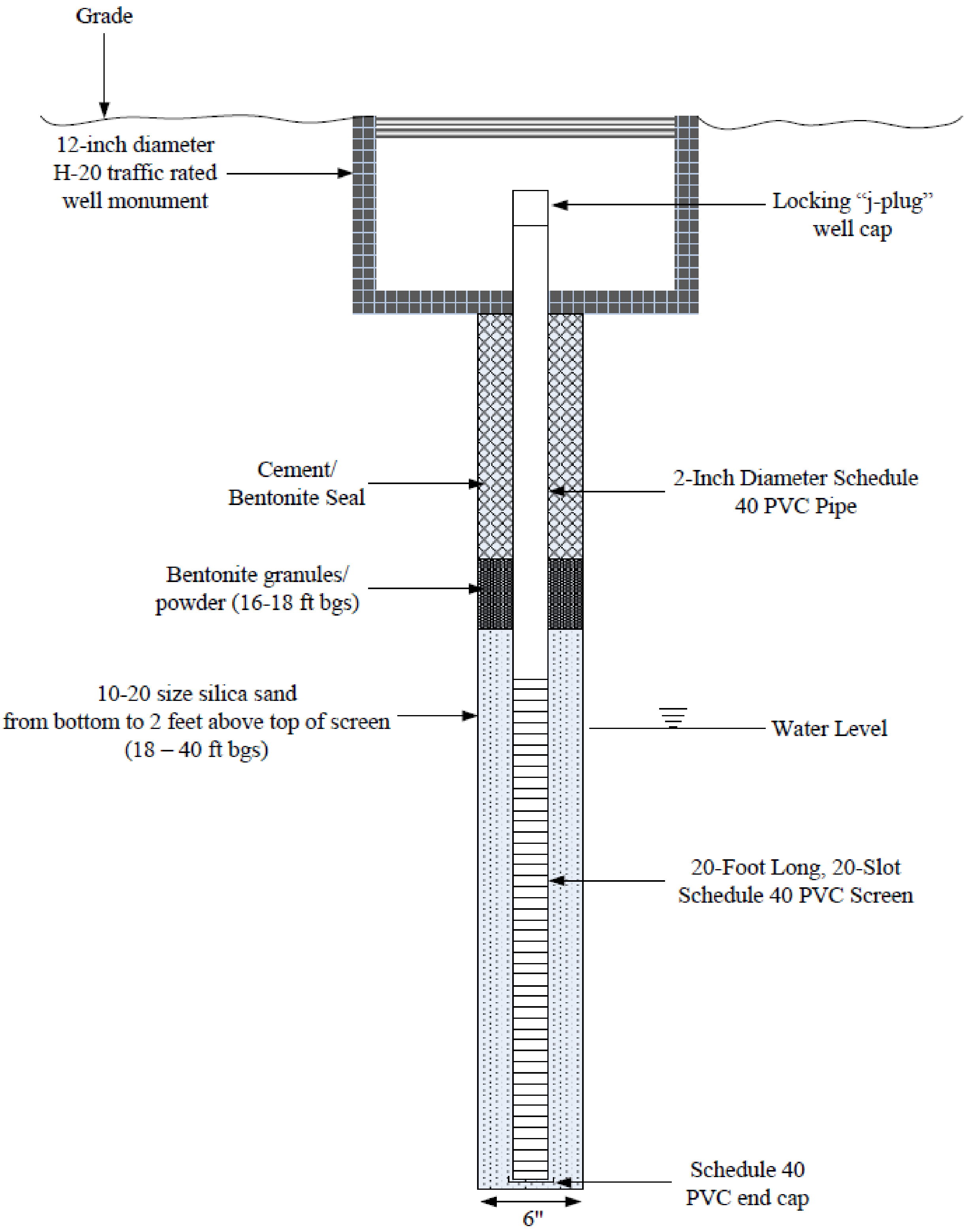


Figure 5.28. Monitoring Well Construction Diagram (not to scale).

Solar Panel

A solar panel kit and battery pack capable of powering the system continuously for one year was installed as the sole energy source for the demonstration system. Assuming an estimated total of 200 watts (W) for all electrical appliances running 20-25% of the time and a minimum sun-hours for the winter of 4.29 for site location, the total wattage requirement of the solar panel was calculated to be 222 W. Assuming 3 days of backup power for cloudy/rainy days and 50 degrees Fahrenheit as the lowest temperature the battery pack will experience, and a 50% battery discharge to optimize battery life, it was calculated that two-250 W solar panels and two 12-volt, 85 amp-hour batteries would sufficiently power the entire demonstration system. A list of equipment is presented in **Table 5.6**.

Table 5.6. Demonstration System Construction Equipment.

Description	Manufacturer	Part number	Qty	Comments	Dimensions
Downhole Extraction pump	Proactive	Abyss 220ft	1	Max power consumption 90W at 12V; max amp output: 8A	Fits standard 4-inch well. Connects to 3/8" or 1/2" ID LDPE tubing
80 Amp Solar Charger	Proactive		1	Self-contained solar charger with up to 8 on/off cycles per day	-
Cold-water flow meter	Dwyer	WMT2-A-C-01	1	Pulse output 0.1 gpm	5/8" male fittings
Y-strainer	McMaster-Carr	1090N11	1	To protect flow meter	1/2" female NPT connection
Remote water meter reading system	Flows.com	RRS-1PC-050-R/1P-CC	1	Self-powered and equipped with cellular modem and annual subscription of $360/year	-
24V, 250W Solar panel	Amerisolar	AS-6P30-250	2	Assuming 4-6 hrs of operation/day, total wattage of 200 for all appliances, 100% dependence on solar energy, and 4.29 hours of peak sun/day, the online calculator shows a minimum system size of 222 W. The system selected has a total wattage of 250W.	Panel = 65.04 × 39.37 × 1.5 inches; 48.4 lbs
Solar Battery	VMAX	SLR-85	2	12V, 85 Ahr deep cycle battery	L=10.2" W=6.6" H=8.2", 55 lbs

5.4.2 Process Control

The demonstration system included controls to facilitate remote transmission of daily totalizer reading, to protect the extraction pump from pumping dry, to allow for precise adjustment of the extraction rate, and to allow for the designed periodic operation of the pump. Specifically, a water meter transmitter equipped with cellular signal connection modem was installed to facilitate remote retrieval of daily totalizer reading via the internet. A pump controller was used in tandem with the extraction pump to allow for precise adjustment of the extraction rate. A timer was used to allow for periodic operation of the extraction at the designed frequency of 20-25% of the time.

5.4.3 System Installation

Well installation and development comprised the first main component of system installation. Subsequently, other main components of system installation were executed including:

- Installation of a 24-inch diameter vault in the extraction well – traffic rated for parking lot.
- Installation of approximately 85 ft of ½ inch schedule 80 PVC water conveyance line – with connection between extraction well and injection well.
- Installation and electrical connection of pump, water meter, solar charger (with pump booster and timer), and valves.
- Installation of water meter transmitter and cellular signal connection.
- Installation of two 250 W solar panels and connection to two 85 amp-hour battery in series.
- Installation of fencing around extraction well, solar charger panel, solar panel, and battery, with pedestrian access gate and lock.

Construction was completed on December 17, 2015 and the system was then operated for 15 days from December 22, 2015 to January 5, 2016 to identify and resolve any issues. Tracer addition and oxidant cylinder deployment was then conducted. The tracer solution (described below) was prepared and added into the cylinder wells. Subsequently, a surge block was used to facilitate uniform distribution of such solution into the surrounding formation. A series of oxidant cylinders (12 per well) housed in cylinder holders illustrated in **Figure 5.29** was assembled and lowered into the cylinder wells. A cable was tied to each set of holders and secured inside the cylinder well vaults to allow for easy retrieval, inspection, and replacement. In addition, 1-inch PVC pipe was connected between the top of the cylinder setup and the top of the well. The 1-inch PVC pipe was used to restrict the cylinders from floating as the density decreases during oxidant release.

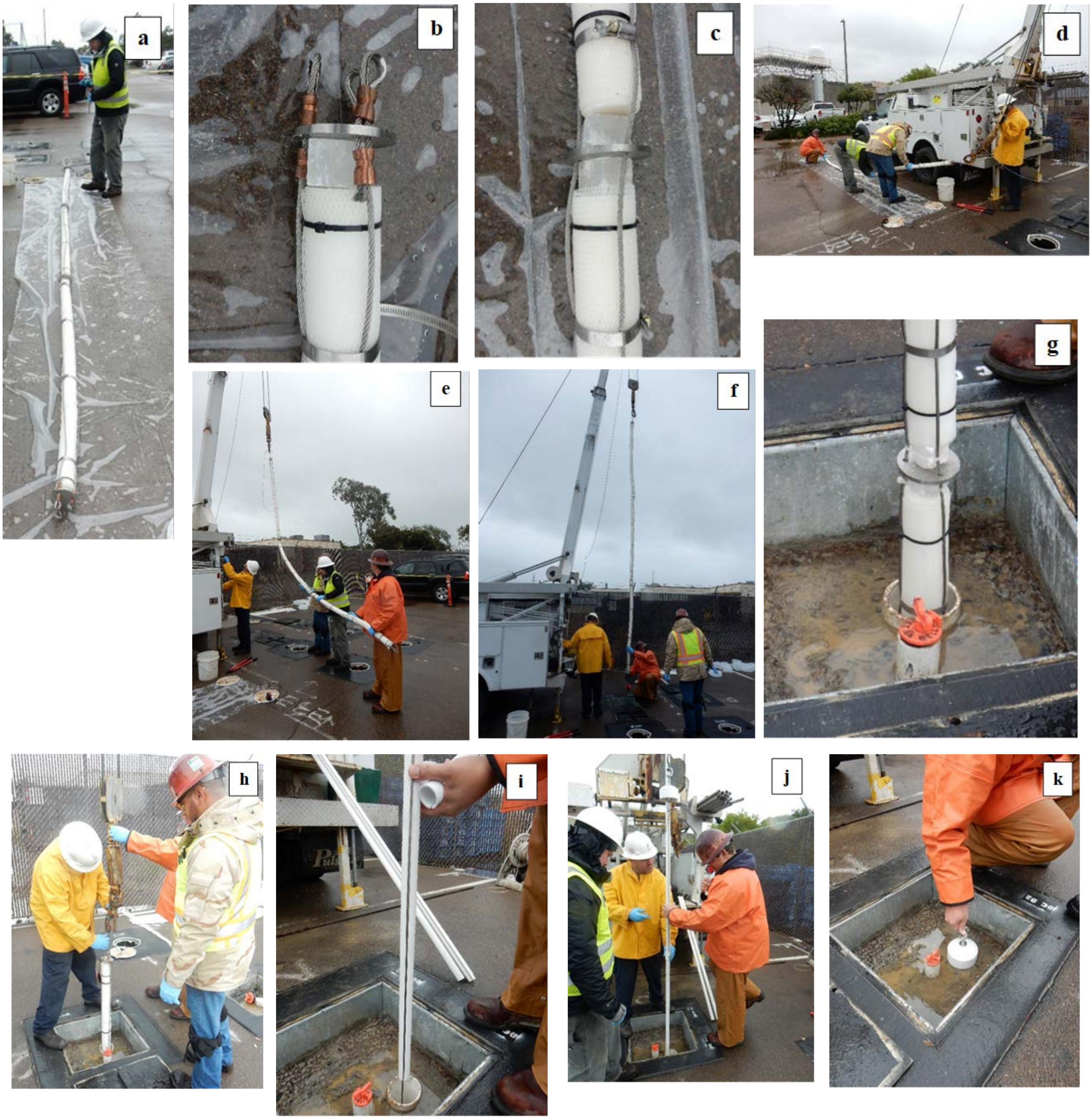


Figure 5.29. Cylinder Holder Design and Installation Showing 12 Cylinders Assembled in Holder (a), Close-up of Top of Holder Showing Stainless Steel Cables, Stainless Steel Alignment Disk, Wax Separator Block, and Plastic Cable Ties for Stainless Steel Securement (b), Interconnection Between Two Cylinders (c), Raising the Holder Using a Drill rig (d,e,f), Lowering into Well (g,h), Attachment of PVC Pipe with Slit to Support Cable to Prevent Cylinder Floating (i,j), and Attachment of Well Cap (k).

5.4.4 Tracer Study

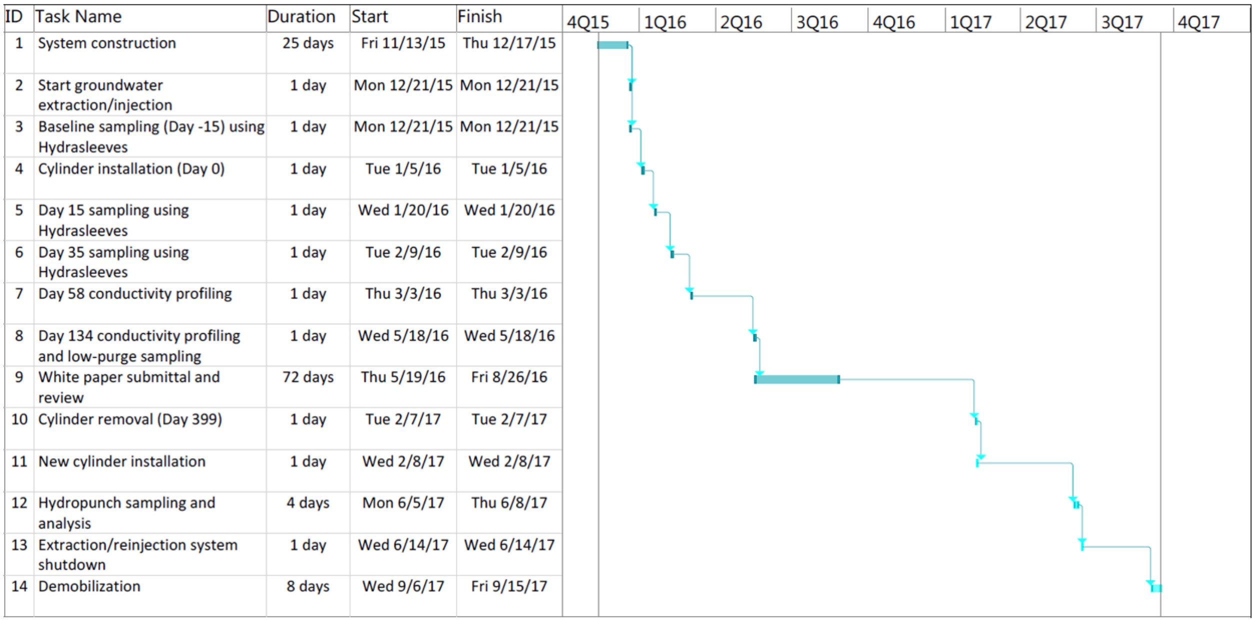
A chloride tracer (sodium chloride) was added concurrently with the deployment of the persulfate oxidant cylinders to measure seepage velocity. Specifically, a 10,000-mg/L chloride pulse surrounding each cylinder well was created by dissolving 4 kilograms of sodium chloride in 15 gallons of deionized water. The slug of tracer added in the cylinder wells was estimated to result in chloride concentrations ranging between approximately 300 and 1,500 mg/L at downgradient monitoring wells, which was sufficient to determine tracer breakthrough analytically. One data-logging conductivity probe was installed DMW-07 for continuous measurement of tracer and water level. The probe was installed at approximately 38 ft bgs, which corresponded to 13.6 ft below the water table.

5.4.5 Soil and Water Management and Site Restoration

All IDW generated during drilling and during the technology demonstration was handled and disposed in an appropriate manner. IDW that was generated from this work included water during drilling, well development, and equipment decontamination; purge water from sampling; drill cuttings; field test kit wastes, sampling equipment decontamination wastes; and personal protective equipment.

5.5 FIELD TESTING

This section describes the various field activities that were performed in support of this demonstration. Specifically, system construction activities including well installation, trenching, installation of pumping and pertinent monitoring equipment, and installation of the power source (solar panel). Upon completion of system construction and startup testing, groundwater extraction/ injection commenced and baseline groundwater sampling was conducted using HydraSleeves. Cylinder deployment and a tracer study were conducted two weeks later and then periodic sampling events were conducted using HydraSleeves or low-flow sampling. Following the initial investigation indicating density-driven flow and lack of apparent persulfate transport, these results as well as recommendations for a second oxidant cylinder deployment and revised sampling approach were summarized in a white paper that was submitted to and accepted by ESTCP. Cylinder changeout and was subsequently conducted and Hydropunch^{TM} sampling then completed 119 days after cylinder installation. The major field activities are depicted in a Gantt chart in **Figure 5.30**.



ID	Task Name	Duration	Start	Finish
1	System construction	25 days	Fri 11/13/15	Thu 12/17/15
2	Start groundwater extraction/injection	1 day	Mon 12/21/15	Mon 12/21/15
3	Baseline sampling (Day -15) using Hydrasleeves	1 day	Mon 12/21/15	Mon 12/21/15
4	Cylinder installation (Day 0)	1 day	Tue 1/5/16	Tue 1/5/16
5	Day 15 sampling using Hydrasleeves	1 day	Wed 1/20/16	Wed 1/20/16
6	Day 35 sampling using Hydrasleeves	1 day	Tue 2/9/16	Tue 2/9/16
7	Day 58 conductivity profiling	1 day	Thu 3/3/16	Thu 3/3/16
8	Day 134 conductivity profiling and low-purge sampling	1 day	Wed 5/18/16	Wed 5/18/16
9	White paper submittal and review	72 days	Thu 5/19/16	Fri 8/26/16
10	Cylinder removal (Day 399)	1 day	Tue 2/7/17	Tue 2/7/17
11	New cylinder installation	1 day	Wed 2/8/17	Wed 2/8/17
12	Hydropunch sampling and analysis	4 days	Mon 6/5/17	Thu 6/8/17
13	Extraction/reinjection system shutdown	1 day	Wed 6/14/17	Wed 6/14/17
14	Demobilization	8 days	Wed 9/6/17	Fri 9/15/17

Figure 5.30. Field Demonstration Schedule.

5.6 SAMPLING METHODS

This section provides a brief description of the quality assurance/quality control (QA/QC) procedures followed during various sampling efforts throughout the field demonstration. In addition, details pertinent to the different groundwater sampling methods including HydraSleeve® sampling, low-flow sampling utilizing bladder pumps, and Hydropunch sampling are discussed herein. Information regarding the cone penetrometer tool (CPT) tests performed to delineate site-specific stratigraphy is also provided. Methods for sampling and analysis are presented in **Table 5.7** and **Table 5.8**.

5.6.1 Quality Assurance and Quality Control (QA/QC)

QA/QC procedures outlined in the approved demonstration plan (**Appendix C**) were employed for all sampling activities performed throughout the field demonstration project. QA/QC samples collected during groundwater sampling include one trip blank and one temperature blank for each cooler containing CVOC/dioxane samples as well as field duplicates at a frequency of approximately 5%. QA/QC samples including blanks, matrix spikes, matrix spike duplicates, and other laboratory control samples were also collected in accordance with the laboratory's standard operating procedures. Similarly, all field equipment was calibrated in accordance with manufacturer-provided recommendations. Sample collection, documentation, decontamination, and handling was performed in accordance with the Technology Demonstration Plan.

Table 5.7. Performance Monitoring Schedule.

Component	Matrix	Collection method	# of Field Samples	Analyte	Location
Pre-demonstration sampling	Soil	Hollow-stem auger	1	Bench-scale testing	B1 and B2 boring locations; homogenized upon receipt at the laboratory
	Groundwater	Low-flow	1	Bench-scale testing	S11-MW-12
	Groundwater	HydraSleeves®	3	VOCs and dioxane	S11-MW-12
Technology performance sampling - Day -15	Groundwater	HydraSleeves®	9	VOCs and dioxane Field parameters	All cylinder and monitoring wells except DEW-01 and SMW-07A at 40 ft bgs
	Groundwater	Low-flow with extraction pump	2	VOCs and dioxane Field parameters	DEW-01 and SMW-07A at 40 ft bgs
	Groundwater	HydraSleeves®	4	VOCs and dioxane Field parameters	DCW-01, DMW-03, DMW-05, and DMW-07 at 32.5 ft bgs
Technology performance sampling - Day 15	Groundwater	HydraSleeves®	6	VOCs and dioxane Field parameters	DCW-01, DCW-02, and DMW-01 through -05
Technology performance sampling - Day 35	Groundwater	HydraSleeves®	9	VOCs and dioxane Field parameters	DCW-01, DCW-02, and DMW-01 through -07
Technology performance sampling - Day 134	Groundwater	Low-flow with bladder pump	9	VOCs and dioxane Field parameters	All cylinder and monitoring wells except DEW-01 and SMW-07A at 27 ft bgs
	Groundwater	Low-flow with bladder pump	9	VOCs and dioxane Field parameters	All cylinder and monitoring wells except DEW-01 and SMW-07A at 32 ft bgs
	Groundwater	Low-flow with extraction pump	2	VOCs and dioxane Field parameters	DEW-01 and SMW-07A
Post-demonstration sampling - Day 400	Groundwater	Hydropunch™	16	VOCs and dioxane Field parameters	B1 through B11, B15, B17, B18, B19, B20 at 28 ft bgs
	Groundwater	Hydropunch™	1	VOCs and dioxane Field parameters	B20 at 33 ft bgs
	Groundwater	Hydropunch™	20	VOCs and dioxane Field parameters	B1 though B20 at 38 ft bgs

Table 5.8. Analytical Methods for Sample Analysis.

Analyte	Analytical Methods	Minimum Sample Volume	Container (number, size, and type)	Preservative	Holding Time
VOCs	SW 846 EPA 8260B	120 mL	4 x 40-mL vials with Teflon-lined septum	Preserve with HCl to pH <2; Cool to 4ºC; No headspace.	14 days
1,4-dioxane	SW 846 EPA 8260 SIM			Preserve with ascorbic acid; Cool to 4ºC; No headspace.	
Sulfate	EPA 300.1	100 mL	1-250-mL polyethylene bottle	Cool to 4ºC	28 days for chloride and sulfate
Chloride					
pH	Multiparameter water quality meter	50 mL	NA	Analyzed immediately	NA
Conductivity			NA	Analyzed immediately	NA
Temperature			NA	Analyzed immediately	NA
ORP			NA	Analyzed immediately	NA
Ferrous iron	HACH ferrous iron AccuVac® Ampoules		NA	Analyzed immediately	NA
Persulfate	Chemetrics kit K-7870		NA	Analyzed immediately	NA

Data were evaluation with respect to quality (**Appendix E**). Notable observations with regards to the primary contaminants of concern including 1,4-dioxane and chlorinated ethenes as well as relevant geochemical parameters are presented as follows:

- None of the analytes of interest were detected in the blank samples.
- Relative percent differences (RPDs) were calculated for 1,1,1-TCA, 1,1-DCA, 1,1-DCE, 1,4-dioxane, chloroform, TCE, cis-1,2-DCE, vinyl chloride, chloride, and sulfate. In general, the majority of the calculated RPDs for the duplicate pairs were less than 40%. In fact, the only analytes whose average RPDs exceeded 40% were 1,1-DCE and cis-1,2-DCE.
- Percent recoveries for matrix spike samples ranged between approximately 90 and 120%.
- The RPDs associated with the matrix spike and the matrix spike duplicate samples were also less approximately 10% for all analytes of interest except for vinyl chloride whose RPD was 27%.
- Recoveries for all laboratory control samples were within the acceptable range as specified by the laboratory standard operating procedures.

In summary, all of the data collected are suitable for their intended use and are considered usable for project decisions.

5.6.2 Groundwater Sampling

HydraSleeves were used to facilitate collection of formation-representative groundwater samples during the first three sampling events at 15 days prior to cylinder deployment, 15 days following cylinder deployment, and 35 days following cylinder deployment (denoted herein as Day -15, Day 15, and Day 35 sampling events, respectively). HydraSleeve sampling was performed in accordance with manufacturer-provided recommendations as shown in **Appendix F**. Note that during the Day -15 and the Day 35 sampling events, HydraSleeves were deployed at two different depths (bottom of HydraSleeves at 32.5 ft bgs and 40 ft bgs) at select monitoring locations to aid stratified sampling as shown in **Table 5.7**. In addition, samples were collected at the extraction well DEW-01 and SMW-07A using installed and dedicated pumps.

Based on results of the initial rounds of sampling, which indicated that density driven flow was occurring, low-flow sampling techniques utilizing bladder pumps were utilized for the Day 134 sampling event. Note that at each cylinder well and monitoring well including DCW-01 and -02 as well as DMW-01 through DMW-07, samples were collected at two different depths of 27 and 32 ft bgs. At each sampling location, low-flow sampling was initiated at the deeper depths (32 ft bgs). Following field parameter stabilization, groundwater samples were collected at the 32-ft bgs sampling depth. Subsequently, the bladder pump was raised to the upper sampling depth (27 ft bgs) and the aforementioned procedures were repeated for all sampling locations.

Hydropunch groundwater sampling was performed 119 days after deploying the second set of slow-release oxidant cylinders at twenty borings as shown in **Figure 5.31.** These locations can be compared to the general site layout shown on **Figure 5.2**. The Hydropunch tooling equipped with a 2-foot, stainless steel, extendable screen was first deployed to a depth of interest. Subsequently, the tooling was pulled up 2 foot and knock-out rods were used to expose the 2-foot screen. A disposable bailer was then used to collect the depth-discrete groundwater samples. For example, samples at the boring location B1 at 28 ft bgs were collected following deployment of the 2-foot screen to between 27 and 29 ft bgs. Note that two depth-discrete groundwater samples were collected at approximately 28 and 38 ft bgs at all boring locations except for B20 where groundwater sampling was performed at three depth-discrete intervals of 28, 33, and 38 ft bgs and B12, B14, B16, and B21 where samples were only collected at the 38-ft-bgs interval.

5.6.3 Cone Penetrometer Tool Evaluation

During the Hydropunch investigation, CPT testing was also performed in select locations to facilitate delineation of site-specific stratigraphy. Measurements of tip resistance, sleeve resistance, and penetration pore water pressure were taken continuously during penetration to provide a nearly continuous profile. A dissipation test was performed prior to commencement of CPT at each borehole in accordance with the CPT subcontractor’s SOP. Upon completion, each CPT borehole location was abandoned in accordance with state and local regulations. Details pertinent to the CPT work performed at the site are provided in **Appendix G**.

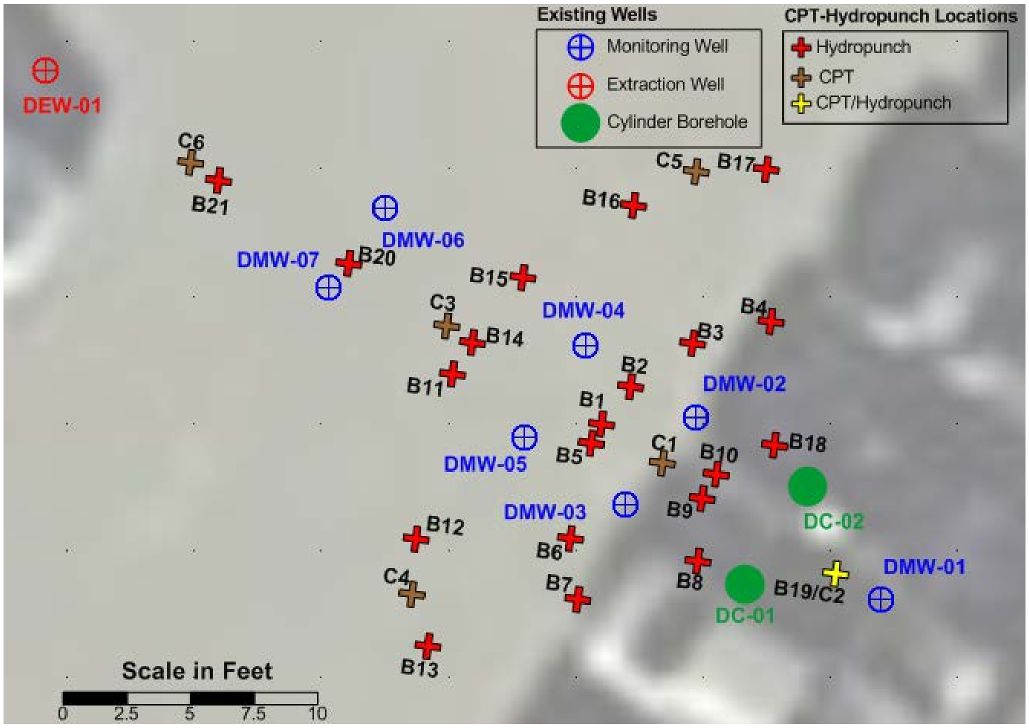


Figure 5.31a. CPT Boring and Sample Locations.

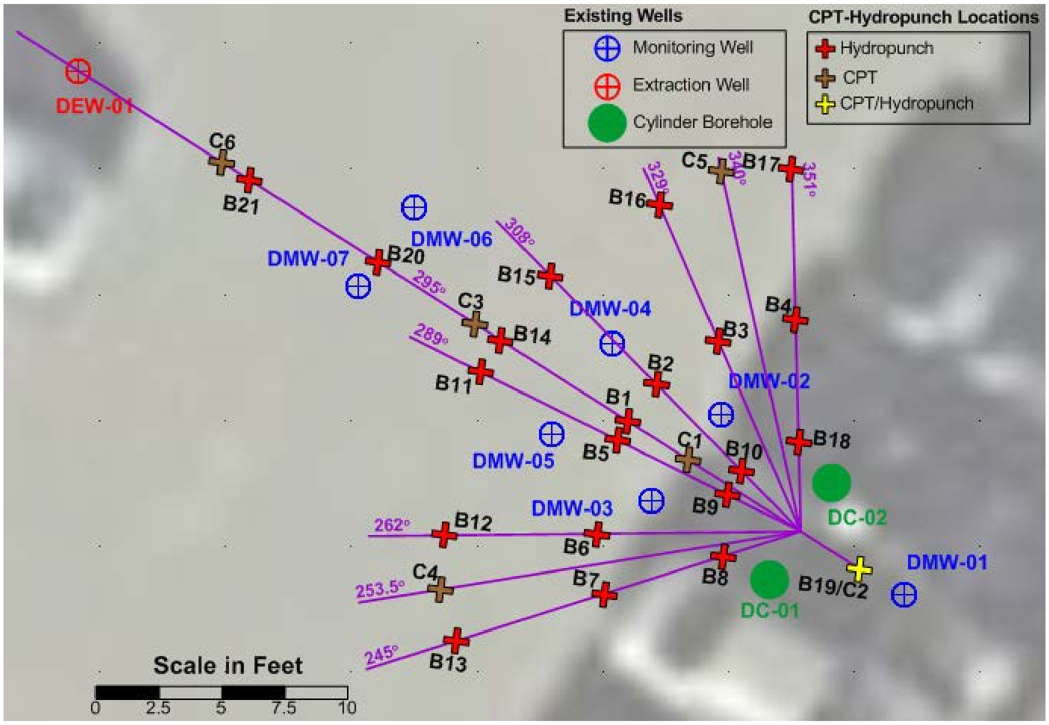


Figure 5.31b. CPT Boring and Sample Locations with Transects Based on Field Compass Readings.

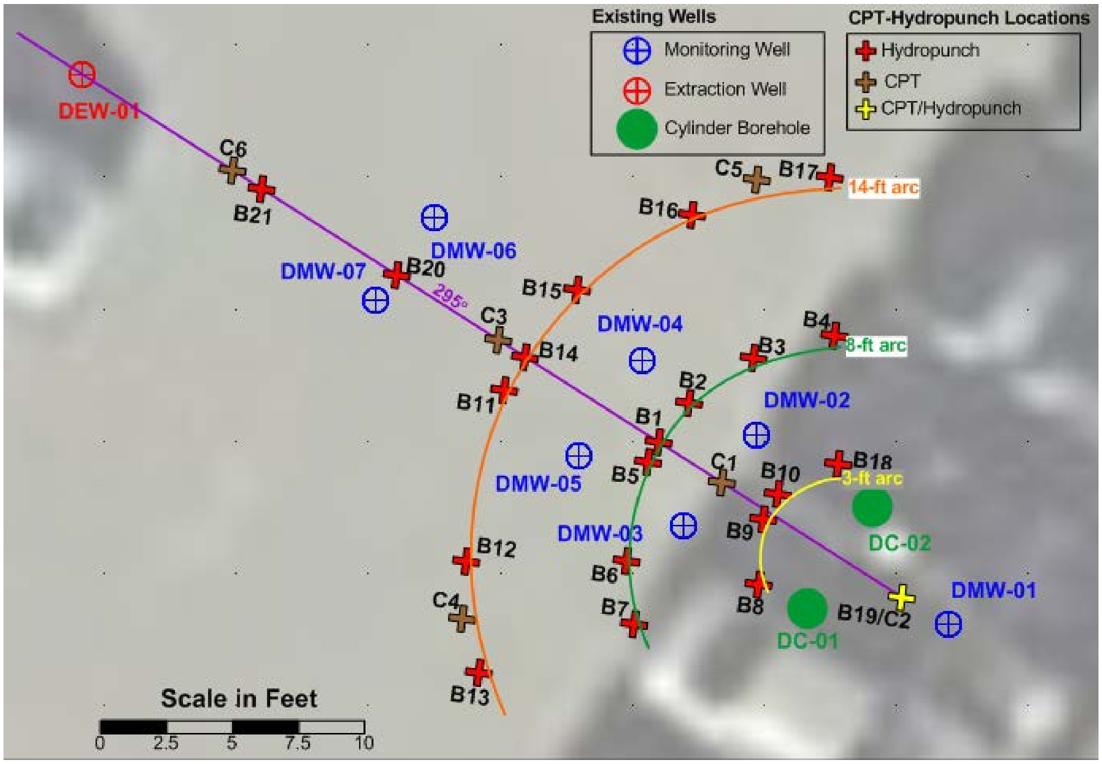


Figure 5.31c. CPT Boring and Sample Locations 3-ft, 8-ft, and 14-ft Arcs from Cylinder Locations. The 295° Design Flow Path is Shown.

5.7 SAMPLING RESULTS

5.7.1 Groundwater Well Sampling

Maximum sodium persulfate concentrations were observed in the deep samples from cylinder monitoring wells (DCW-01 and DCW-02) located 1 ft downgradient of the persulfate cylinders (**Figure 5.32**). These concentrations decreased from 3,900 mg/L 15 days after cylinder installation to 1,800 mg/L 134 days after installation. Sulfate – a persulfate decomposition product – was also observed to be elevated relative to background (i.e., -5 ft upgradient) indicating persulfate decomposition. No sodium persulfate transport further downgradient was observed after 15 and 34 days where HydraSleeves were used for sample collection. On day 134 low-purge sampling was conducted at a depth of 37 ft bgs (12 ft below water table) because density driven flow was thought to be promoting downward transport of sodium persulfate as discussed later. **Figure 5-32d** provides some evidence of downgradient transport of sodium persulfate albeit at lower concentrations than in the cylinder monitoring wells. The sodium persulfate concentrations in the cylinder monitoring wells were somewhat different (**Figure 5.33**) possibly because the bottom of monitoring well DCW-01 was filled with about 5 feet of silt. As discussed later, density driven flow resulted in downward migration of sodium persulfate. Therefore, part of the difference in sodium persulfate concentrations in the two-cylinder monitoring wells was attributed to the depth interval from which samples were collected and associated density effects.

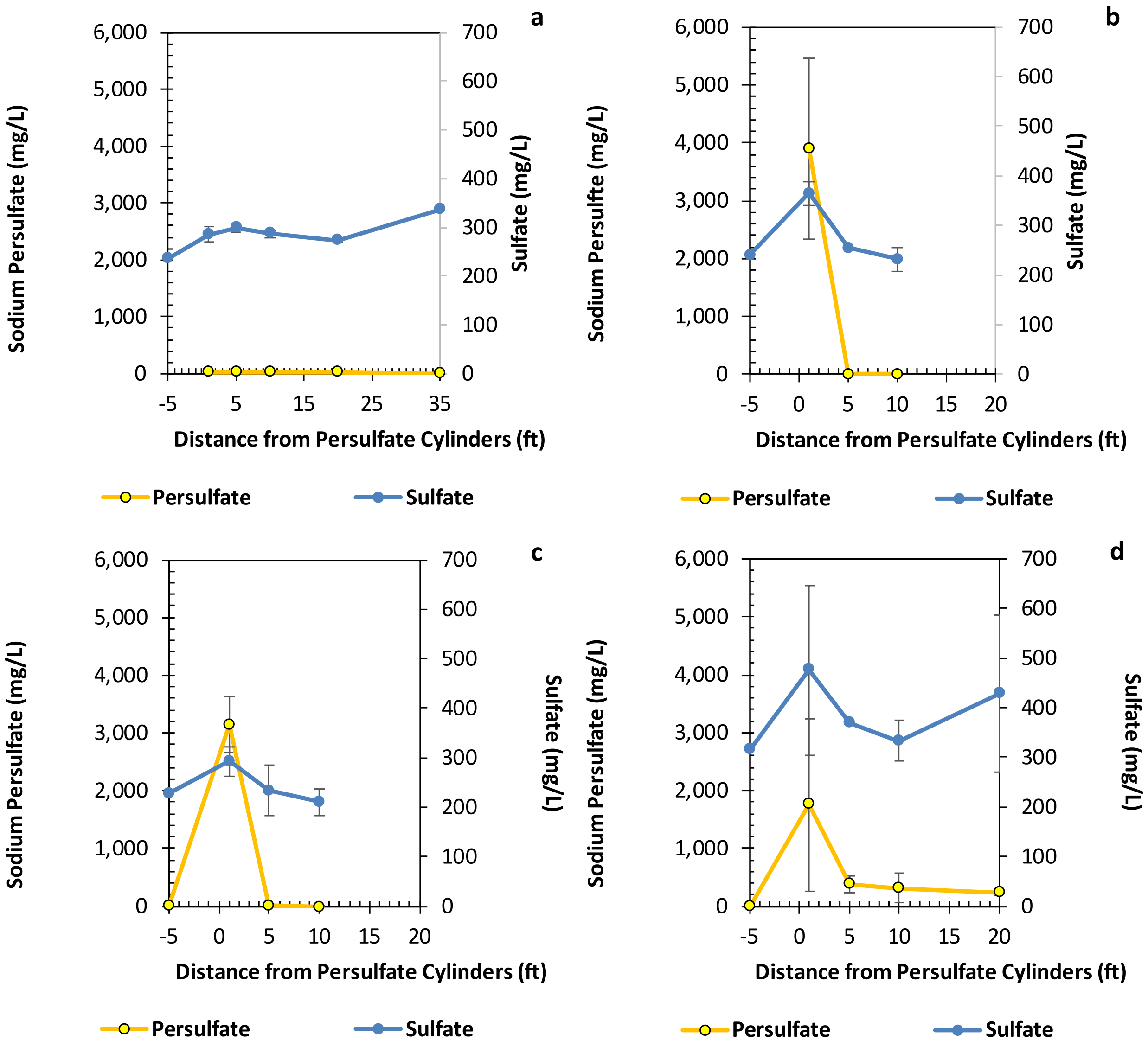


Figure 5.32. Average Sodium Persulfate and Sulfate Profiles in Deep Monitoring Well Samples Collected -15 Days (a), 15 Days, (b), 35 Days (c) and 134 Days (d) After Cylinder Installation. Error Bars Are ± 1 Standard Deviation.

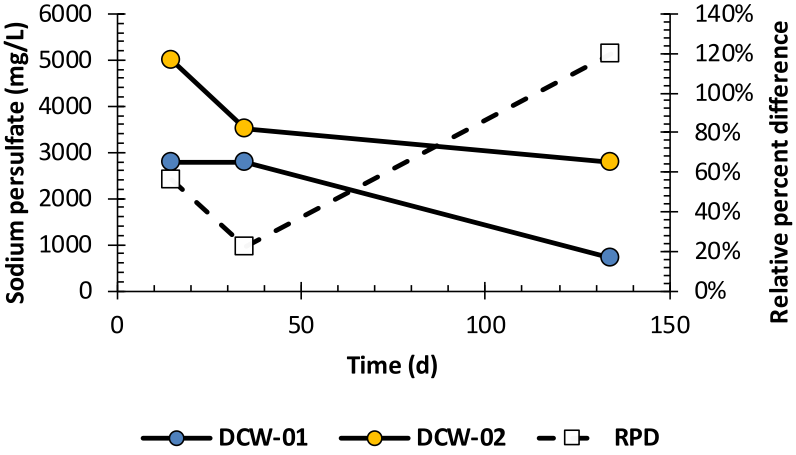


Figure 5.33. Sodium Persulfate Concentrations in Deep Cylinder Monitoring Wells and Associated Relative Percent Deviation.

Figure 5.34 shows the specific conductivity in monitoring well DCW-07 located 20 ft downgradient of the persulfate cylinders. The specific conductivity demonstrated a cyclic pattern over time that correlated to the pumping on/off cycle. When the pump cycled on the conductivity decreased and then increased after the pump cycled off. The likely explanation is that the pump was drawing in low-conductivity groundwater cross-gradient from the induced hydraulic flow path. Therefore, specific conductivity data corresponding to when the pump was off are shown in in **Figure 5.34**. The specific conductivity reached a maximum value of 49.8 days after the cylinders were installed which translates to a seepage velocity of 12.2 centimeters per day (cm/d) – greater than the design value of 7.8 cm/d. Based on the estimated seepage velocity, the sodium persulfate was expected to travel 6, 14, and 54 ft after 15, 35, and 134 days, respectively assuming that sodium persulfate was not retarded relative to the sodium chloride tracer. **Figure 5.32** does not show evidence of sodium persulfate transport over these distances based on HydraSleeve sample results (b,c) whereas it was transported at least these distances by day 134 based on low-purge sampling results (d). However, the peak sodium persulfate concentration observed at each sampling point corresponded to the cylinder monitoring well and this peak concentration did not persist downgradient. Further discussion of sodium persulfate transport based on Hydropunch sampling and analysis is presented later.

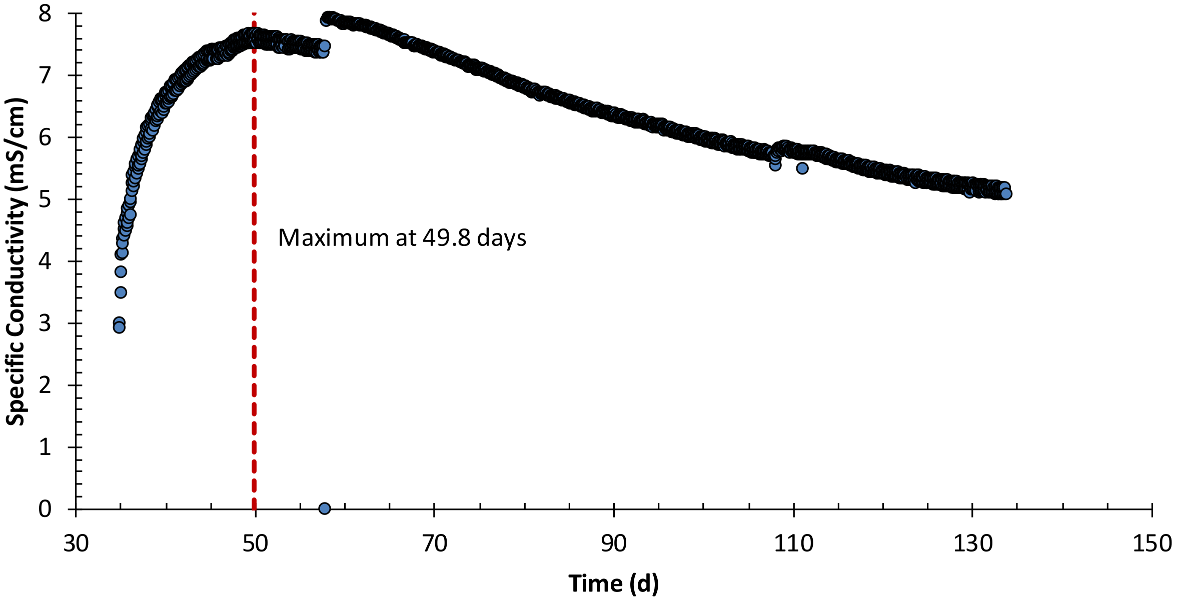


Figure 5.34. Specific Conductivity in Monitoring Well DMW-07 at 38 ft Below Ground Surface (13.6 feet below the water table) Under Non-pumping Conditions Following Sodium Chloride Tracer Injection in Persulfate Cylinder Monitoring Wells (DCW-01 and DCW-02) On Day 0. Transducer Was Removed for Data Downloads on Days 58 and 108 and Resulted in Discontinuous Changes in Specific Conductivity Readings Likely Attributable to Differences in Transducer Depth.

Dioxane, chlorinated ethenes, and 1,1-DCA concentrations were reduced in the cylinder monitoring well deep samples one foot downgradient of the cylinders and these reductions corresponded to the elevated sodium persulfate concentrations (**Figure 5.35**). No reductions were observed in these wells prior to cylinder installation (a). The reductions were sustained through the last sampling event 134 days after cylinder installation. No contaminant destruction at greater downgradient distances was evident during any sampling event even though sodium persulfate was detected at 134 days in downgradient wells. However, the sodium persulfate concentrations ranged from 250 to 390 mg/L compared to 1,800 mg/L in the cylinder boring monitoring wells and ≥1,400 mg/L in the column study (**Figure 5.14**). Thus, the observed persulfate concentration may have been too low to promote detectable dioxane and CVOC destruction in downgradient sampling locations. Reductions of all individual chlorinated ethenes were observed in the cylinder boring monitoring wells, but the degree of reduction varied (**Figure 5.36**). No reductions of the individual chlorinated ethenes downgradient of the cylinders were observed.

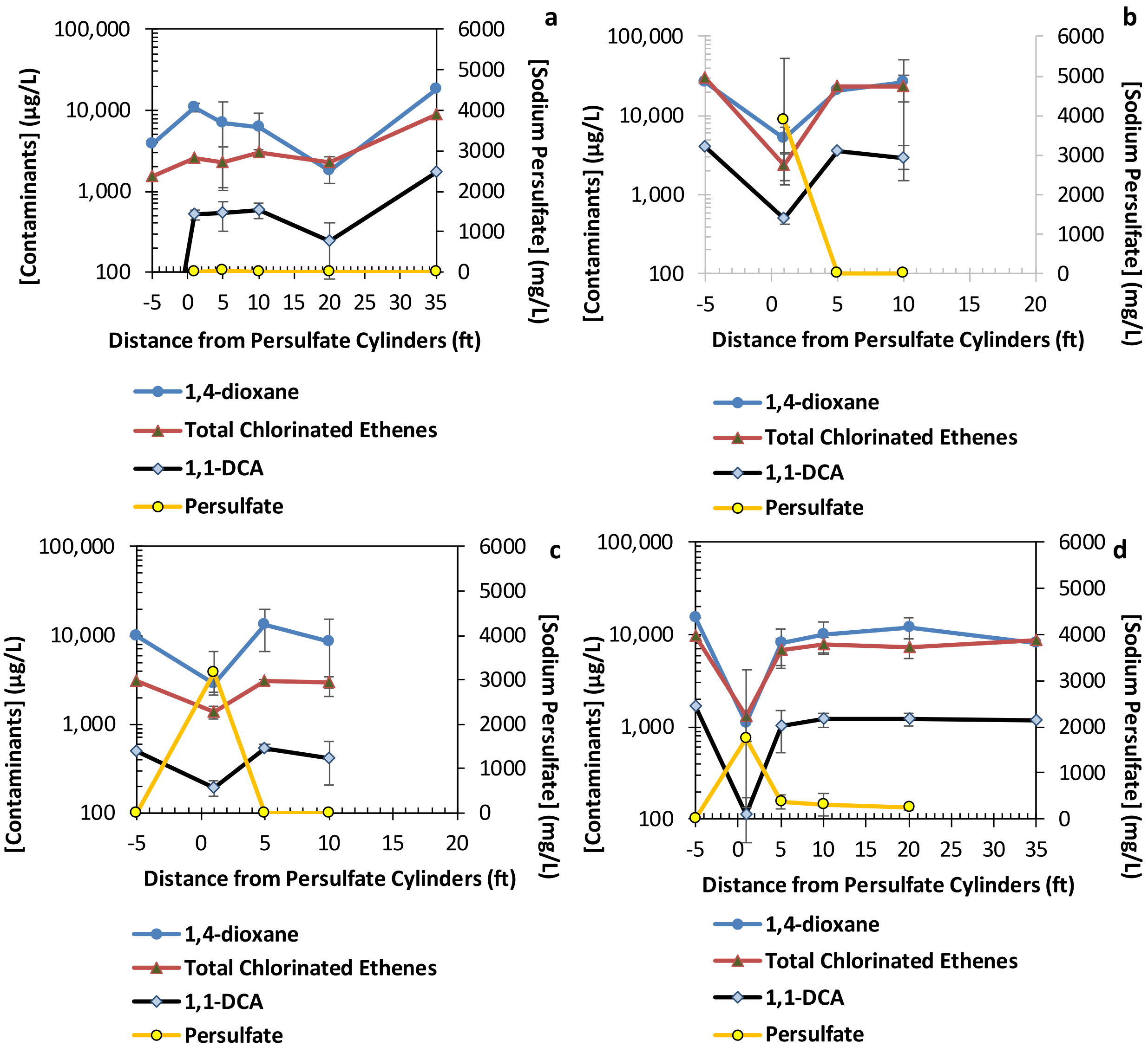


Figure 5.35. Average Sodium Persulfate, Dioxane, 1,1-DCA, and Total Chlorinated Ethenes (1,1-DCE, TCE, cis-1,2-DCE and Vinyl Chloride [VC]) in Deep Monitoring Well Samples Collected -15 (a), 15 (b), 35 (c) and 134 (d) Days After Persulfate Cylinder Installation. VC Was Not Analyzed on Day 134 and Is Not Included in Total Chlorinated Ethenes. Error Bars Are ± 1 Standard Deviation.

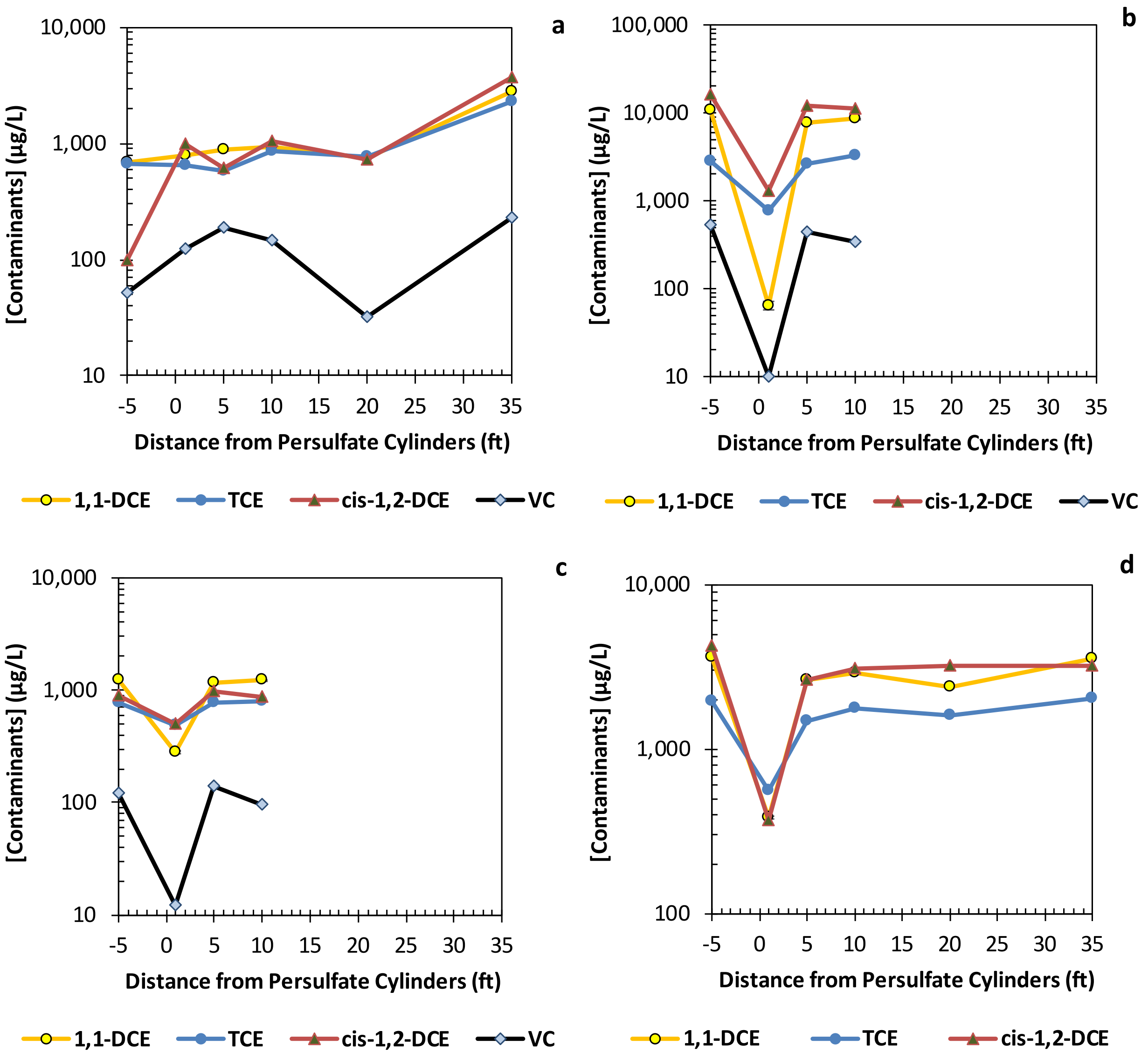


Figure 5.36. Average Individual Chlorinated Ethene Concentrations in Deep Monitoring Well Samples Collected -15 (a), 15 (b), 35 (c) and 134 (d) Days After Persulfate Cylinder Installation. VC Was Not Analyzed on Day 134 and Is Not Included in Total Chlorinated Ethenes.

Dioxane, total and individual chlorinated ethenes, and 1,1-DCA concentrations were reduced in the cylinder monitoring well shallow samples (33 ft bgs and 8 ft below water table) one ft downgradient of the cylinders and these reductions corresponded to the elevated sodium persulfate concentrations (**Figures 5.37** and **5.38**). No reductions were observed in these wells prior to cylinder installation (a). The reductions were sustained through the last sampling event 134 days after cylinder installation. No contaminant destruction at greater downgradient distances was evident during any sampling event even though sodium persulfate was detected at 134 days in downgradient wells. However, the sodium persulfate concentrations were variable and low.

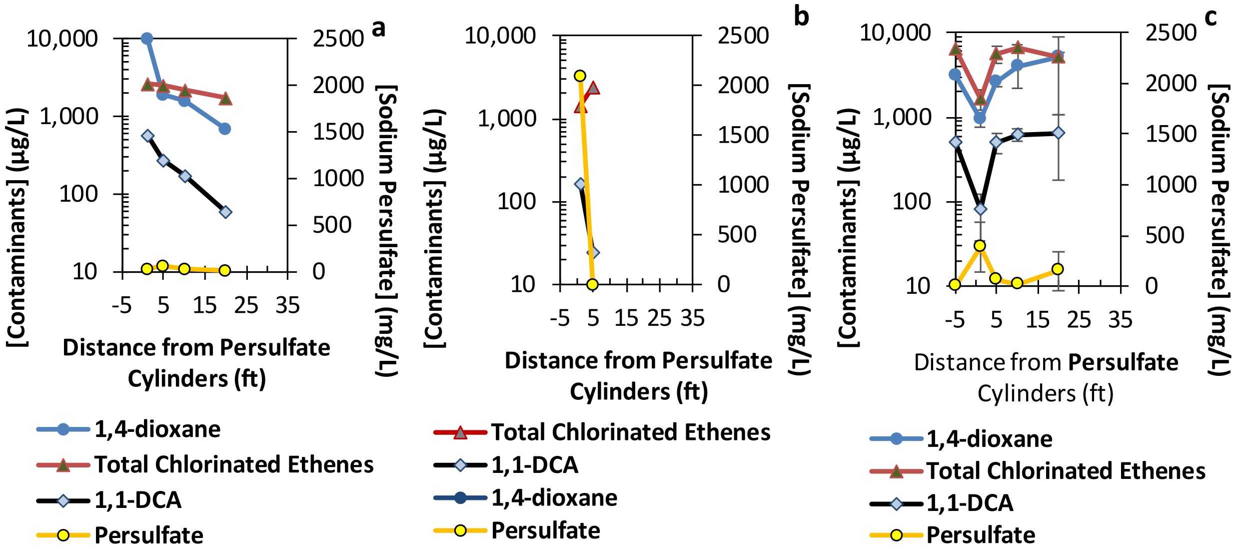


Figure 5.37. Sodium Persulfate, Dioxane, 1,1-DCA, and Total Chlorinated Ethenes (1,1-DCE, TCE, cis-1,2-DCE and VC) in Shallow Monitoring Well Samples Collected -15 (a), 35 (b) and 134 (c) Days After Persulfate Cylinder Installation. VC Was Not Analyzed on Day 134 and Is Not Included in Total Chlorinated Ethenes.

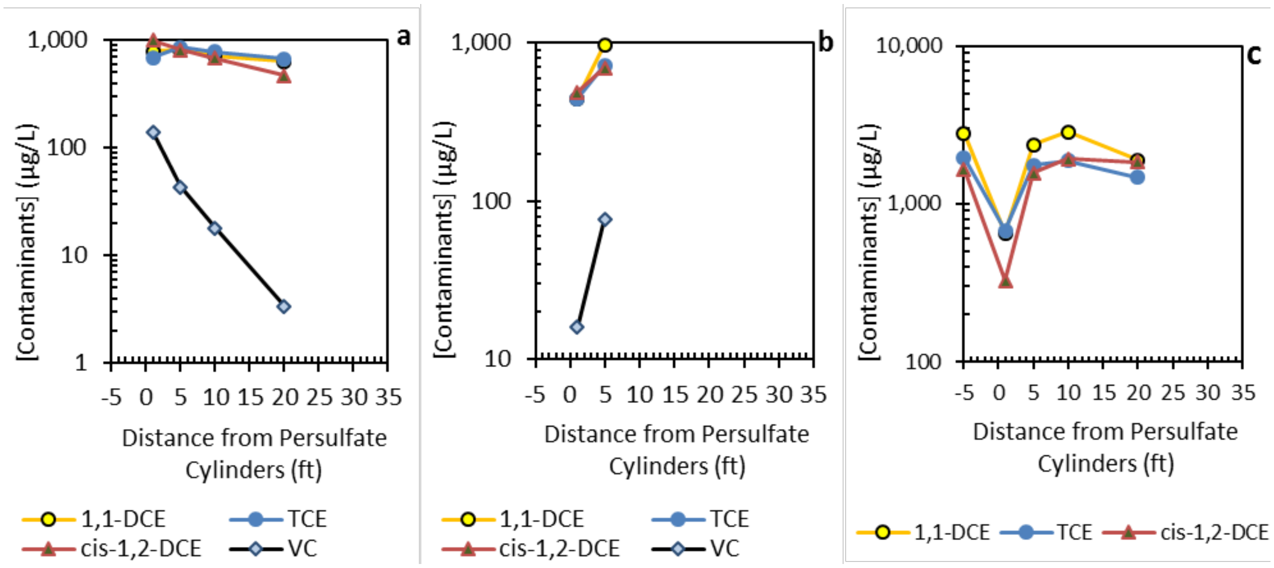


Figure 5.38. Individual Chlorinated Ethene Concentrations in Shallow Monitoring Well Samples Collected -15 (a), 35 (b) and 134 (c) Days After Persulfate Cylinder Installation. VC Was Not Analyzed on Day 134 And Is Not Included in Total Chlorinated Ethenes.

Reactivity of sodium persulfate with dioxane in the cylinder wells was evaluated. **Figure 5.39** presents the observed and predicted reductions in dioxane concentrations based on a second-order kinetic model. The rate constant determined in the treatability study (4.6×10^{-5} M^{-1} s^{-1}) was used in combination with the measured sodium persulfate concentrations to estimate first-order rate constants for dioxane destruction. These rate constants in combination with the observed dioxane concentrations at each time point were used to predict the reduction in dioxane concentration at the subsequent time point. Dioxane flux into and out of the cylinder borehole was neglected for the purposes of this calculation. The results demonstrate the observed decline in dioxane concentrations over time and the predicted declines are similar with the predicted declines being slightly greater. Based on this analysis it can be concluded that reaction chemistry was occurring in a manner similar to that observed in the treatability test.

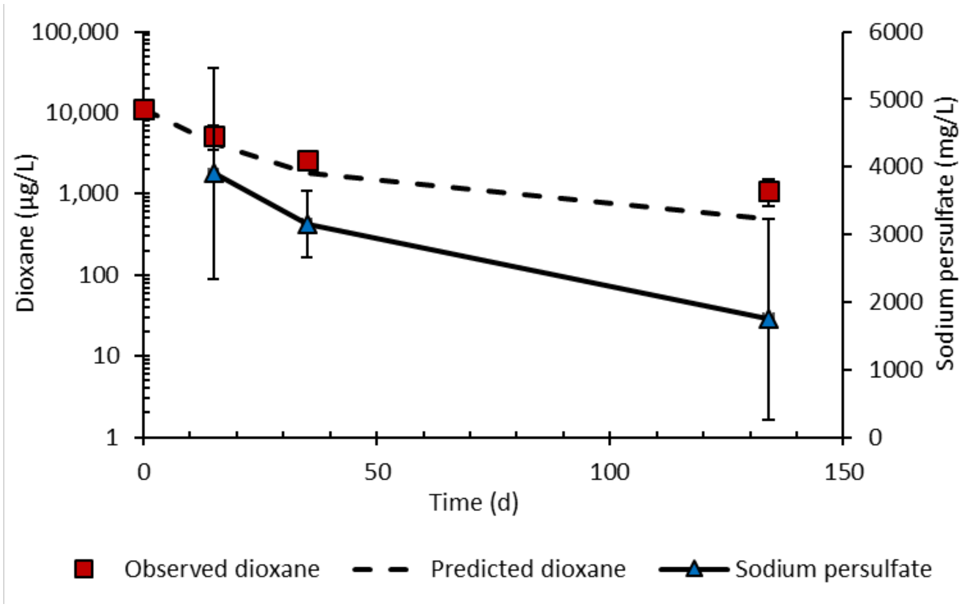


Figure 5.39. Observed and Predicted Average Deep Dioxane Concentrations in Cylinder Monitoring Wells DCW-01 and DCW-02. Predicted Values Based on Observed Deep Persulfate Concentrations and a Second-order Rate Constant of 4.6×10^{-5} M^{-1} s^{-1}. Error Bars are ± 1 Standard Deviation.

Sodium persulfate in the deep cylinder monitoring well samples decreased over time and an exponential model was used to fit the data (**Figure 5.40**). Even though sodium persulfate concentrations decreased over time, dioxane and total CVOCs also decreased over time indicating sustainability of contaminant destruction. Qualitatively similar results were observed in shallow samples (**Figure 5.41**). Based on the exponential model, 42% of the sodium persulfate remained at the 134-day sampling point and 8% remained when the cylinders were removed after 399 days (**Figure 5.42**). Thus, the design assumption that the cylinders have a lifetime at least 0.5 years was reasonable. A lifetime up to about 1 year may be possible.

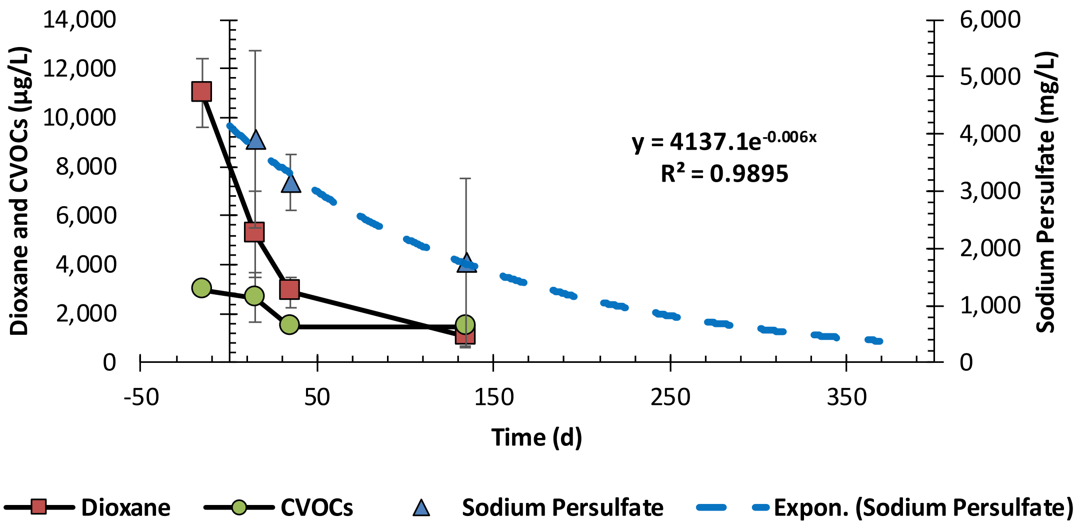


Figure 5.40. Average Sodium Persulfate, Dioxane, and Total CVOCs (1,1-DCA, 1,1-DCE, TCE and cis-1,2-DCE) in Deep Samples from Cylinder Monitoring Wells (DCW-01 and DCW-02). Dashed Line is An Exponential Fit Plus Extrapolation. Error Bars Are ± 1 Standard Deviation.

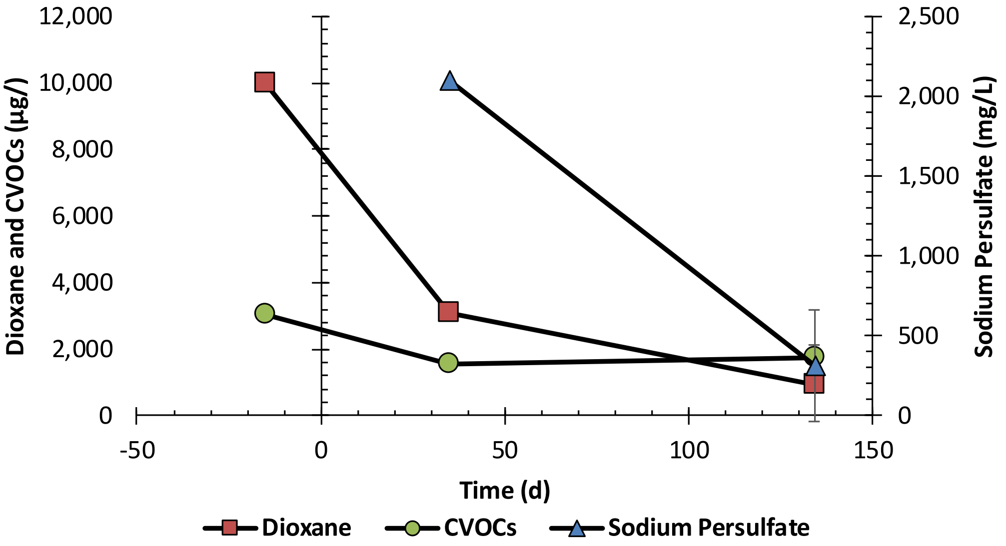


Figure 5.41. Sodium Persulfate, Dioxane, and Total CVOCs (1,1-DCA, 1,1-DCE, TCE and cis-1,2-DCE) in Shallow Samples from Cylinder Monitoring Wells (DCW-01 and DCW-02). Error Bars Are ± 1 Standard Deviation.

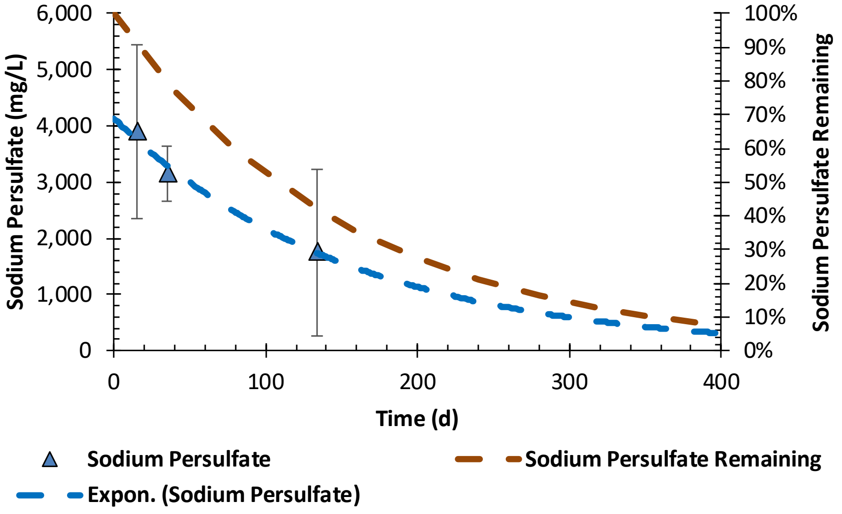


Figure 5.42. Sodium Persulfate Concentration in Deep Cylinder Monitoring Wells and Estimated Sodium Persulfate Remaining in Cylinders. Error Bars are ± 1 Standard Deviation.

Destructive analysis of the cylinders was conducted after removal on day 399 and results are presented in **Table 5.9**. The results indicate that persulfate was depleted in the cylinders that were submersed in water. Persulfate remained in cylinders that were above the water table (indicated by a negative depth below the water table). The destructive analysis indicates that the exponential model may have slightly overestimated the longevity of the cylinders. Nevertheless, the model was used in combination with estimated seepage velocities to predict the sodium persulfate flux from the cylinders (see **Appendix H**). Results are summarized in **Table 5.10**. The estimated sodium persulfate flux ranged from 7.3 to 17 mg d^{-1} cm^{-2} based on the estimated seepage velocity. These values are less than the flux of 22 mg d^{-1} cm^{-2} estimated during the treatability study, but are reasonable considering uncertainties in the model. In spite of these uncertainties, a mass balance on sodium persulfate indicated that 99% of the sodium persulfate originally present in the cylinders was accounted (**Table 5.10**). Therefore, a significantly decreased sodium persulfate flux from the cylinders is not considered to be the primary reason that sodium persulfate was not observed to transport downgradient of the cylinder wells.

Table 5.9. Cylinder Analysis.

Cylinder	Distance from bottom (ft)	Depth below water table (ft)	Sodium persulfate (weight percent)	Percent Sodium persulfate released
DC-01	1.5	12.8	< 2.2	>97.8
DC-01	2	12.3	< 2.2	>97.8
DC-01	9	5.3	3.3	95.8
DC-01	15	-0.7	< 2.2	>97.8
DC-01	17	-2.7	61.2	22.5
DC-02	2	12.3	<2.2	>97.8
DC-02	4	10.3	<2.2	>97.8
DC-02	10	4.3	<2.2	>97.8
DC-02	14	0.3	11.9	85
DC-02	16	-1.7	59.9	24.1

Table 5.10. Persulfate Mass Balance.

Parameter	Design	Measured
Seepage velocity (cm/d)	7.8	12
Sodium persulfate flux (mg d^{-1} cm^{-2}) based on seepage velocity values		
Maximum	11	17
Minimum	4.7	7.3
Average	7.4	12
Treatability study estimate	22	
Mass balance		
Sodium persulfate released (kg)	28.9	45.2
Sodium persulfate initially in cylinders (kg)	45.5	45.5
Released mass/Initial mass	64%	99%

The above calculations included an assumption that most of the persulfate mass was present in the deep-water horizon. **Figure 5.43** supports this assumption. While the shallow concentrations were 45 to 67% of the deep concentration in the deep cylinder monitoring wells (1 ft downgradient), the shallow concentrations were 15 to 22% of the deep concentrations in the 5-ft downgradient monitoring wells. These data suggest density driven persulfate transport.

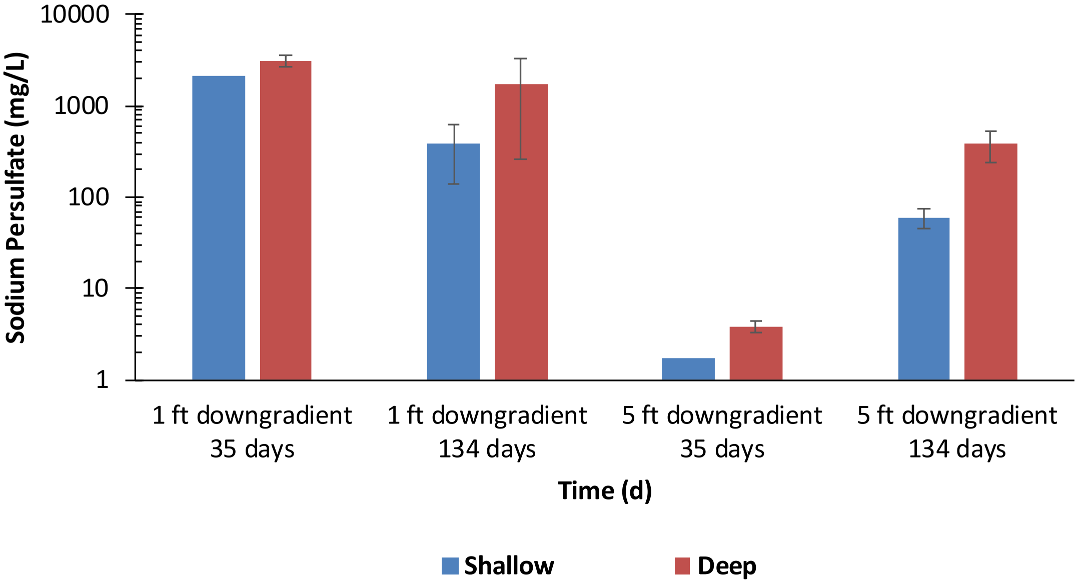


Figure 5.43. Comparison of Shallow and Deep Average Sodium Persulfate Concentrations in Cylinder and Downgradient Monitoring Wells. Error Bars are ± 1 Standard Deviation.

Figures 5.44 and **5.45** further support density effects in the aquifer. Specific conductivity increased with depth and the increases were evident in both upgradient (DMW-01) and downgradient wells. The greatest specific conductivities were measured in a 2-ft interval directly atop the semi-confining silt layer (**Figure 5.44**). These results, in combination with: 1) the increasing sodium persulfate concentration with depth (**Figure 5.43**) and 2) the detection of downgradient sodium persulfate during low-purge sampling and not during HydraSleeve sampling (**Figure 5.32**) suggest that sodium persulfate migrated downward after release from the oxidant cylinders and then was transported downgradient along the surface of the silt aquitard located about 40 ft bgs.

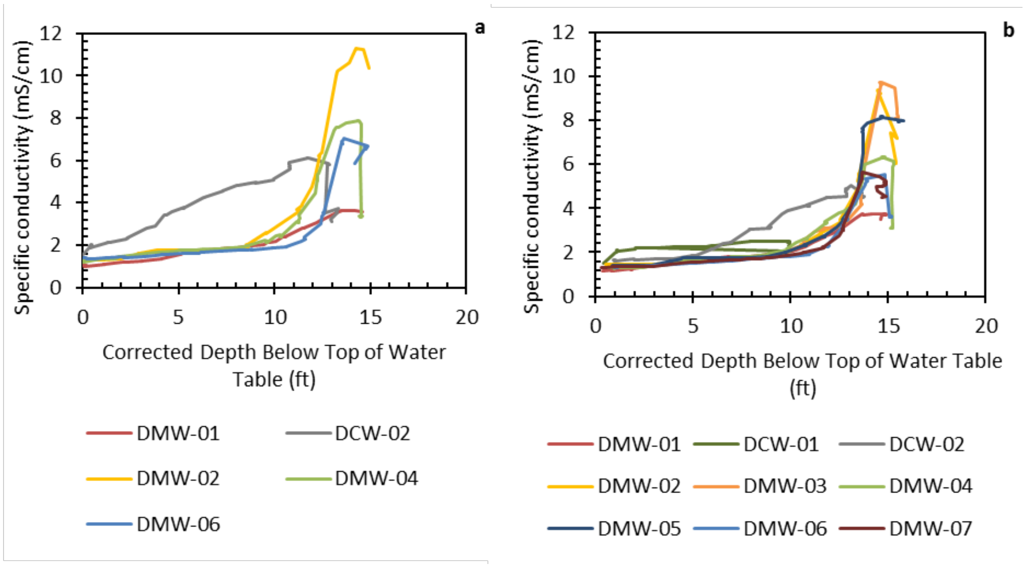


Figure 5.44. Specific Conductivity Profiles on 58 Days (a) and 134 Days (b).

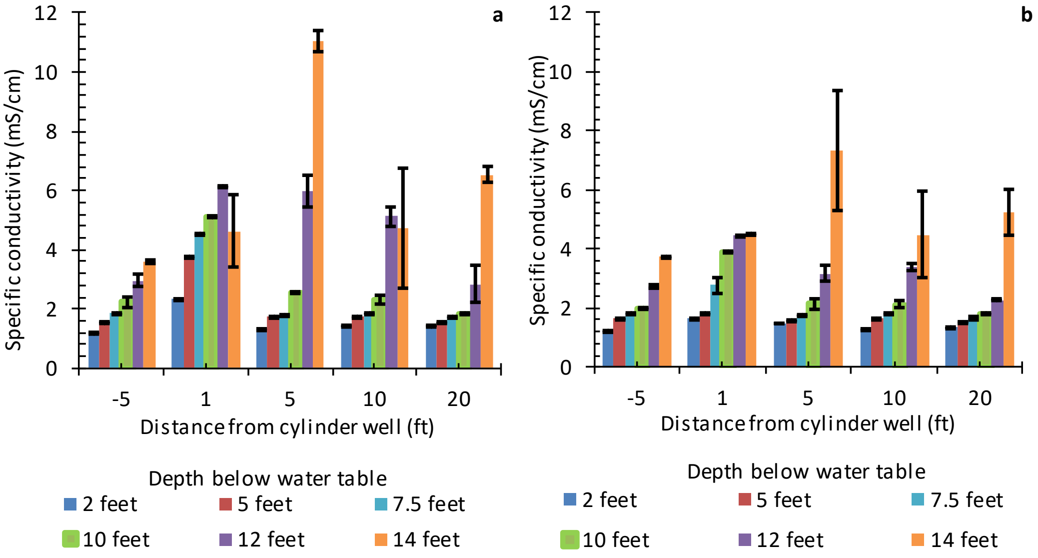


Figure 5.45. Specific Conductivities on 58 Days (a) and 134 Days (b) for Monitoring Wells DMW-01, DCW-02, DMW-02, DMW-04, and DMW-06 at Discrete Depths and Distances. Averages and Standard Deviations Were Calculated from the Conductivity Profiles Presented in Figure 5.44.

Density effects have previously been demonstrated to induce a relatively stronger vertical flow component in aquifers with low horizontal hydraulic gradients (Schillig et al. 2014). The natural gradient (non-pumping conditions) at the site has been reported to be 0.00037 ft/ft (Accord Mactec 2013). The observed horizontal gradients (**Figure 5.46**) were 0.00022 ± 0.00039 ft/ft and 0.00062 ± 0.00073 ft/ft along the DC-01 and DC-02 flow paths, respectively. These values are not significantly different from the natural gradient and less than the gradient of 0.00145 ft/ft expected to be induced by pumping. This apparent lack of induced gradient may have been because the actual hydraulic conductivity was greater than the reported hydraulic conductivity for the site of 17.24 ft/d or 6×10^{-3} centimeters per second (cm/s) (Accord Mactec 2013) which was used in the model for design of the hydraulic control system. For a sodium persulfate concentration of 1,000 mg/L and an average hydraulic gradient of 4×10^{-4} ft/ft, previously developed correlations (Schillig et al. 2014) suggest that the vertical flow component would be greater than 70% of the overall seepage velocity (**Figure 5.47**). These data further support the existence of sodium persulfate-induced density driven flow during the demonstration.

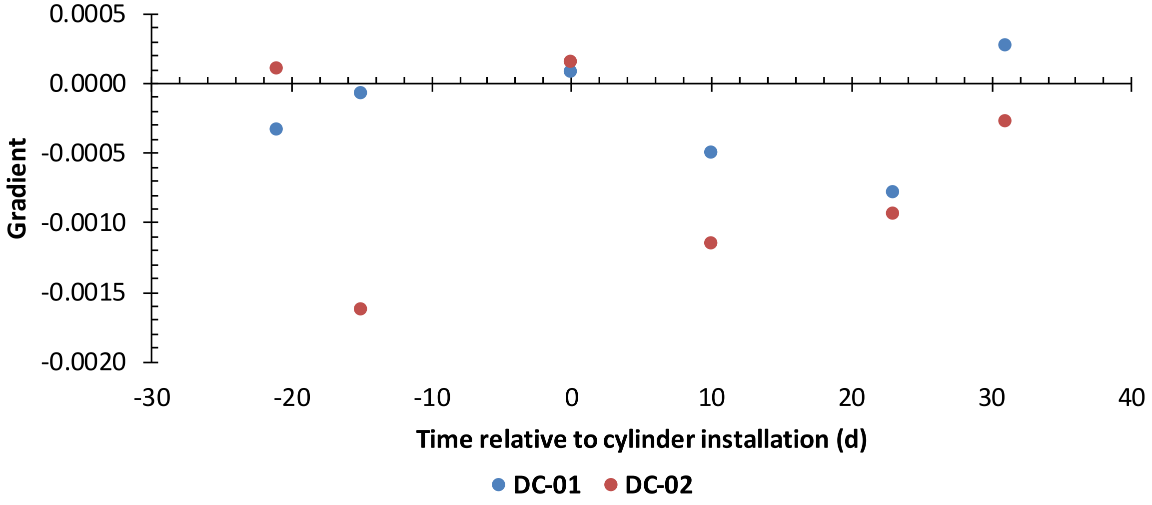


Figure 5.46. Horizontal Hydraulic Gradient Based on Groundwater Elevations Measured Along the Two Monitoring Well Transects.

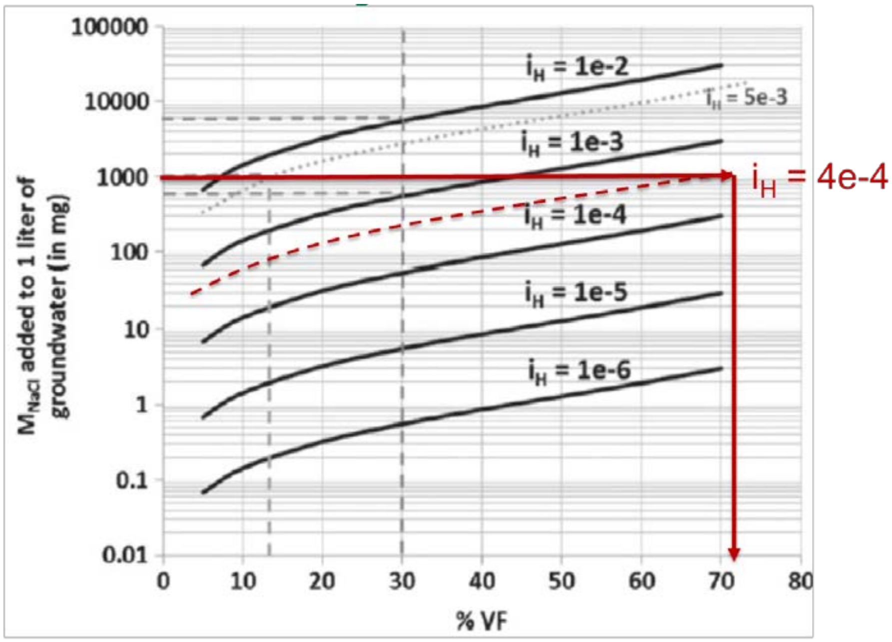


Figure 5.47. Predicted Vertical Flow Component (%VF) in Relation to Salt Concentration Based on Previously Published Data (Schillig et al. 2014). The Overlain Red Lines Indicate the Approximate Vertical Flow Component that Could Result from 1,000 mg/L Sodium Persulfate in an Aquifer with a Horizontal Hydraulic Gradient of 4×10^{-4} ft/ft.

Persulfate anion decomposes to sulfate anion and a conservative mass balance would be expected to show no change in the sum of the persulfate and sulfate concentrations downgradient of the oxidant cylinders. Sulfate concentrations would be expected to increase as persulfate decomposes due to reaction with natural organic matter and contaminants along the flow path. **Figure 5.48** indicates that the sum of persulfate and sulfate decreased along the flow path and sulfate did not increase in both shallow and deep samples. A possible explanation is the monitoring wells were not directly aligned with the designed hydraulic flow path. If this were the case, then the centroid of the sulfate flow path may have not been captured by the monitoring wells leading to an incomplete mass balance.

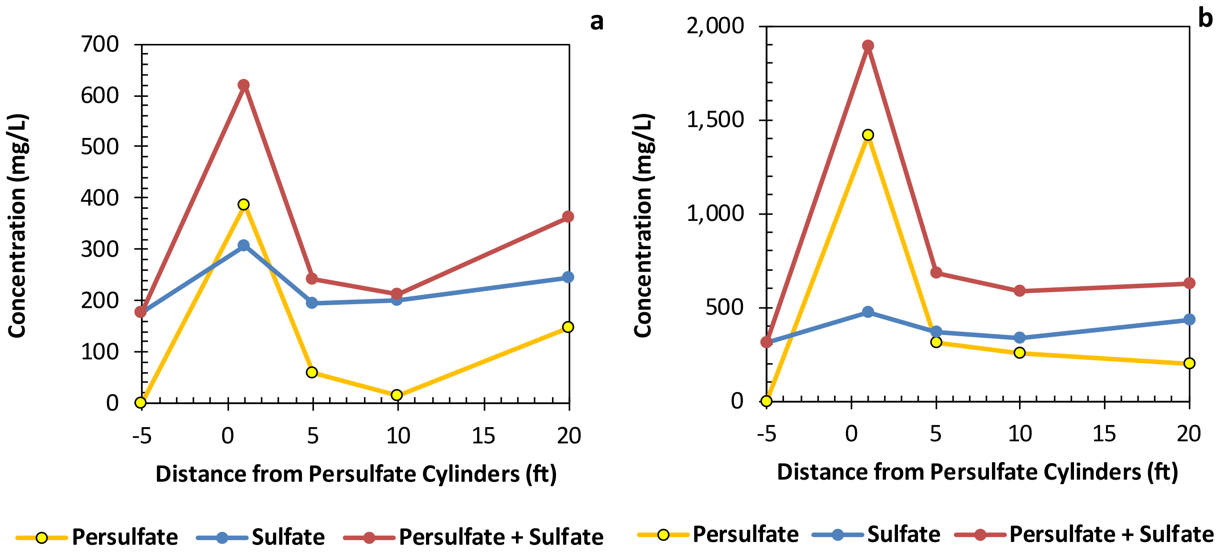


Figure 5.48. Mass Balance of Persulfate and Sulfate in Shallow (a) and Deep (b) Samples Collected on Day 134.

5.7.2 Discrete Interval Groundwater Sampling

Discrete interval sampling of groundwater using Hydropunch was used to further explore horizontal and vertical persulfate transport in light of the above results. This sampling was conducted 119 days after the second deployment of the slow-release oxidant cylinders. Locations of the borings were shown on **Figure 5.31**. **Figure 5.49** presents the soil lithologic results based on the CPT borings that were along the flow path and cross-gradient to the flow path. The results indicate the soil is similar to what has been previously reported for the site – a silt aquitard is present at 40 ft bgs and the overlaying aquifer is relatively uniform and comprised of sand and silty sand. The presence of the silt aquitard at 40 ft suggests that the lack of a persulfate/sulfate mass balance (**Figure 5.48**) was not attributable to downward migration beyond 40 ft bgs. Boring C2 was located adjacent to the 18-inch boreholes drilled for cylinder emplacement. The results indicate the soil was disturbed in this location especially below the water table located about 25 ft bgs. This disturbance may have contributed to the vertical migration of sodium persulfate.

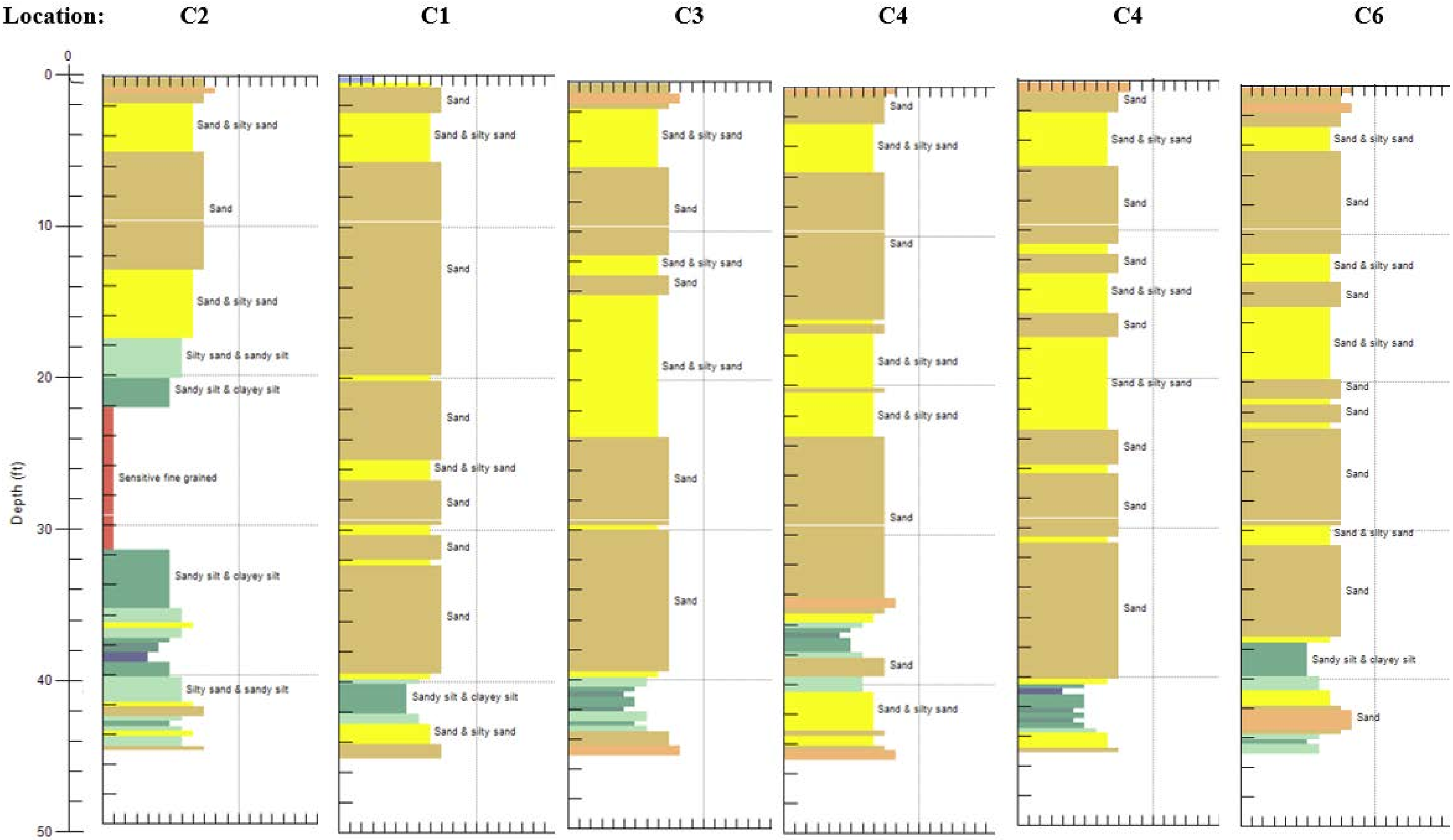


Figure 5.49. Cone Penetrometer Test Logs for Soil Borings C2 (just upgradient of the cylinder borings), C1 (3 feet downgradient of the cylinders), C3 (14 feet downgradient), C4 (35 feet downgradient), C5 and C6 (cross-gradient).

Groundwater samples were collected from a deep interval (37 to 39 ft bgs), a middle interval (32 to 34 ft bgs), and a shallow interval (27-29 ft bgs). The deep interval was located 1-3 feet above the silt aquitard to obtain samples that were representative of groundwater flowing along its surface because of density driven flow. The shallow interval was located 2.5-4.5 ft below the water table. The design flow path was oriented 295° based on field compass readings. Samples were collected in arc-shaped transects located 3, 8, and 14 ft downgradient of the cylinders and spanning 245 to 351° to identify the true flow path (**Figures 5.31 b and c**).

Figure 5.50 presents the results for transect concentrations of sodium persulfate, dioxane, and CVOCs along with percent removals of the contaminants. The results indicate the main flow path was at 289° and thus slightly westward of the design flow path. Thus, the results from samples collected from the monitoring wells installed along the design flow path do not appear to have been representative of the true flow path. The results also indicate that dioxane and CVOC removal was greatest along the 289° flow path. Removals of dioxane and CVOCs were 99% compared to upgradient sample concentrations at the 8-ft transect. Dioxane was reduced from 20,000 to 140 µg/L and CVOCs (1,1-DCE, 1,1-DCA, cis-1,2-DCE and TCE) were reduced from 20,000 to 200 µg/L. The data further illustrate that high removal was limited to a small arc or lateral zone of influence.

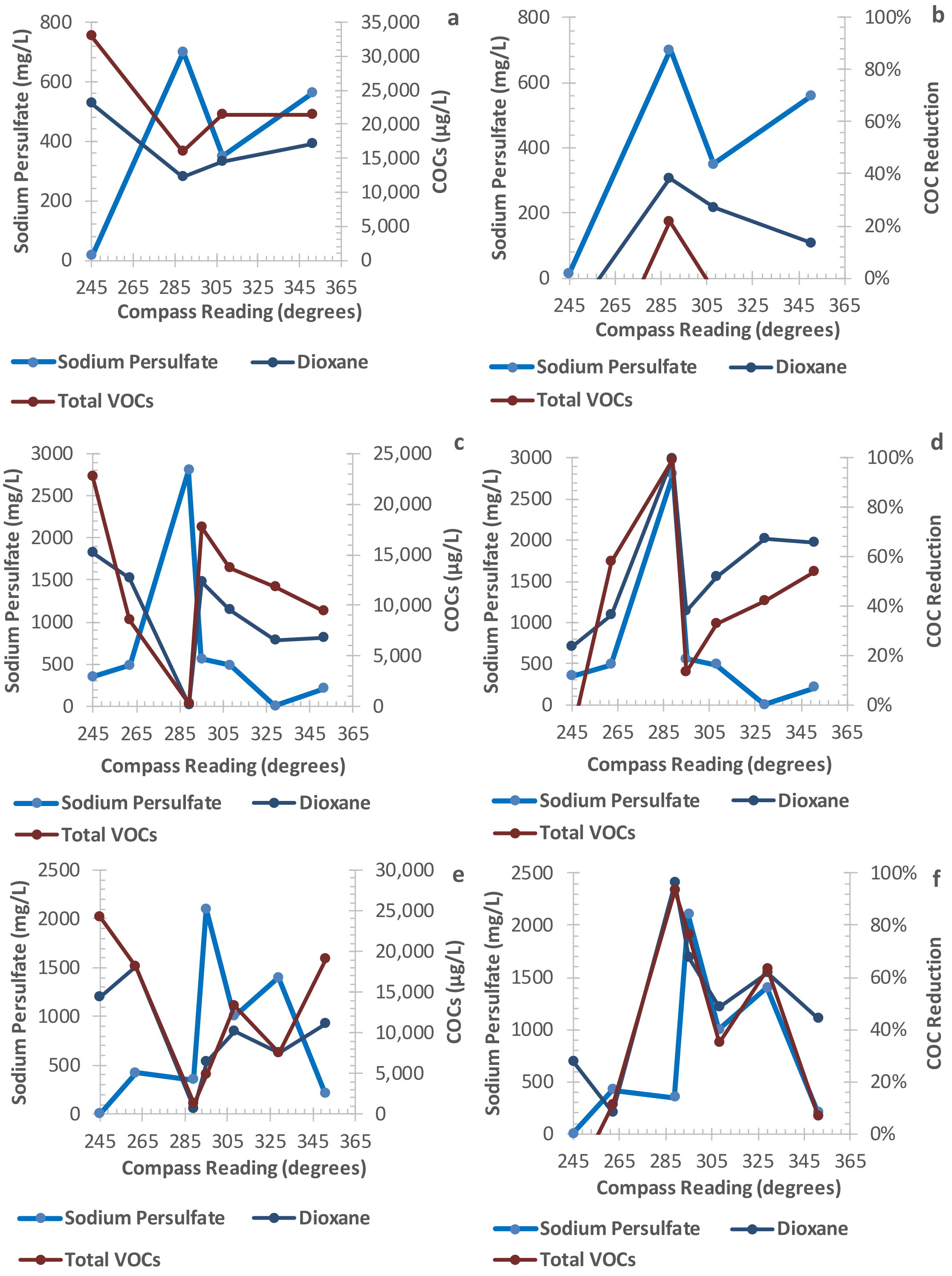


Figure 5.50. Hydropunch Boring Groundwater Sample Results for Sodium Persulfate, Dioxane and Total VOCs (1,1-DCE, 1,1-DCA, cis-1,2-DCE and TCE) Collected from the Deep Interval 12.5-14.5 ft Below the Water Table 119 Days after the Second Persulfate Cylinder Installation Event. Results Are Plotted as Transects Along Arc Compass Readings Located 3 ft (a,b), 8 ft (c,d) and 14 ft (e,f) Downgradient of the Cylinders.

Figure 5.51 further illustrates this conclusion where the results are presented along an arc distance scale rather than a compass reading scale. Large differences in sodium persulfate concentrations and contaminant percent removals were observed between the borings located 6.1 and 7.0 ft east of 245° along the 8-ft transect; dioxane removal decreased from 99 to 38% and CVOC removal decreased from 99 to 13%. The decreases were less along the 14-ft transect; dioxane removal decreased from 96% in the boring 11 ft east of 245° to 67% 12 ft east and CVOC removal decreased from 93 to 76%. These data suggest that while the lateral (i.e., orthogonal to the flow path) influence is small a short distance from the oxidant cylinders, the lateral influence increases as the distance from the cylinders increase likely because of dispersion.

High contaminant removal (i.e., > 90%) appears to have been limited to a small lateral influence (**Figure 5.51f**). On the other hand, contaminant removals exceeding 50% were observed across a 10-ft lateral zone ranging from 11 to 21 ft east of 245° (**Figure 5.51f).** The distance between the cylinder boreholes was only 5 ft. Therefore, greater lateral influence may be possible. Greater contaminant removals may have been limited by diffusion of contaminants from groundwater cross-gradient to the induced flow path. Use of a reactive barrier consisting of more than two-cylinder boreholes may promote greater contaminant removal because cross-gradient effects would be minimized.

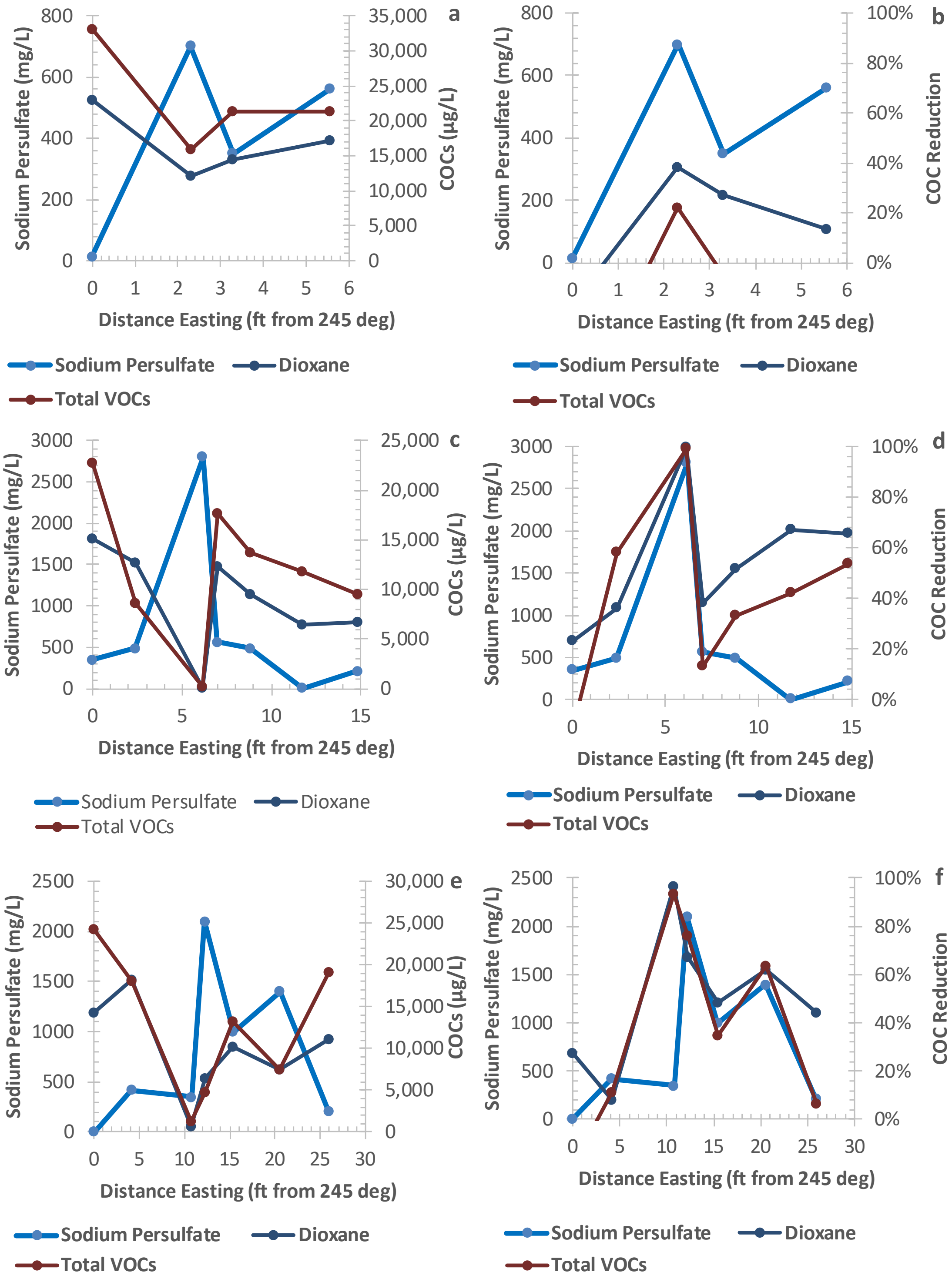


Figure 5.51. Hydropunch Boring Groundwater Sample Results for Sodium Persulfate, Dioxane and Total VOCs (1,1-DCE, 1,1-DCA, cis-1,2-DCE and TCE) Collected from the Deep Interval 12.5-14.5 ft Below the Water Table 119 Days After the Second Persulfate Cylinder Installation Event. Results Are Plotted as Transects Along Arc Easting Distances Located 3 ft (a,b), 8 ft (c,d) and 14 ft (e,f) Downgradient of the Cylinders.

Arc transect data from shallow boring samples are presented in **Figure 5.52**. Compared to the deep boring samples, persulfate concentrations were much lower especially in the 8- and 14-ft transect samples. The centroid of the sodium persulfate flow path is uncertain because of the variability of the results which is attributed to density driven flow – most of the persulfate mass was present in the deeper portion of the aquifer. Nevertheless, CVOC removals were observed though not as great as in the deep boring samples. Presumably, CVOCs in shallow groundwater upgradient of the oxidant cylinders would advectively transport through the cylinder boreholes and come into contact with released persulfate. Oxidation would then occur resulting in some contaminant oxidation. Dioxane concentrations upgradient of the cylinders on the other hand were much lower in the shallow samples (67 µg/L) than in the deep samples (20,000 µg/L). Therefore, dioxane concentrations observed in shallow boring samples downgradient of the cylinders may have resulted from back diffusion and definitive conclusions regarding dioxane destruction in the shallow portions of the aquifer cannot be made.

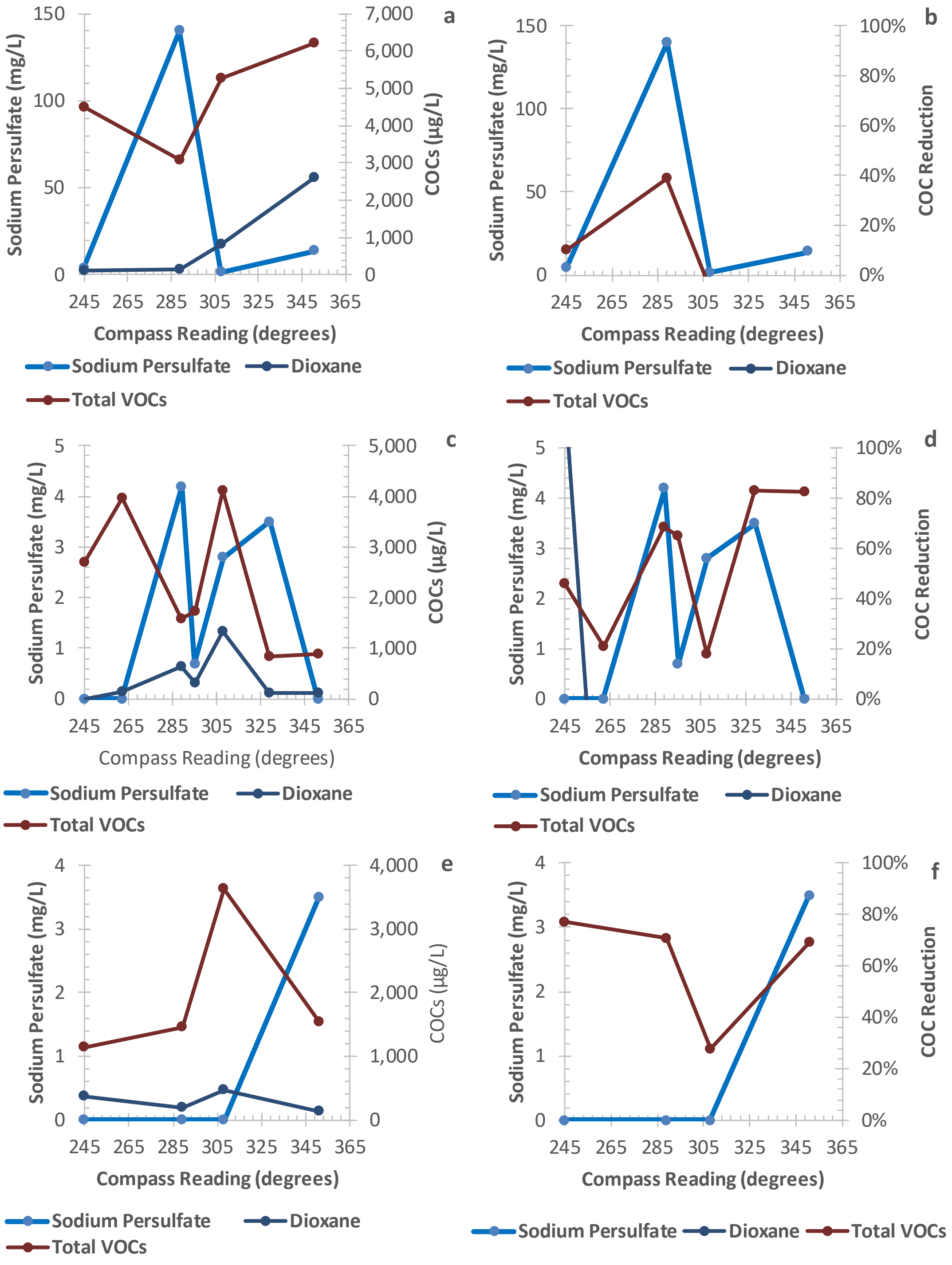


Figure 5.52. Hydropunch Boring Groundwater Sample Results for Sodium Persulfate, Dioxane and Total VOCs (1,1-DCE, 1,1-DCA, cis-1,2-DCE and TCE) Collected from the Shallow Interval 2.5-4.5 ft Below the Water Table 119 Days After the Second Persulfate Cylinder Installation Event. Results Are Plotted as Transects Along Arc Compass Readings Located 3 ft (a,b), 8 ft (c,d) and 14 ft (e,f) Downgradient of the Cylinders. Dioxane Percent Removals Are Not Shown Because Downgradient Concentrations Were Greater Than Upgradient Concentrations.

Concentrations trends of sodium persulfate and contaminants in deep boring samples along the observed 289° flow path were evaluated (**Figure 5.53**). Dioxane and CVOCs concentrations were reduced by 99% 8 ft downgradient of the oxidant cylinders which translates to 20-d travel time based on an estimated seepage velocity of 12.2 cm/d (0.40 ft/d). This result compares well to the predicted removal of >99% at 20 ft downgradient (**Figure 5.2**) and exceeds the performance objective of 90% removal. The percent removal was >90% 14 ft downgradient of the cylinders even though the sodium persulfate concentration decreased from 2,800 to 350 mg/L. This result is consistent with the design concept of the oxidant cylinders performing as a permeable reactive barrier. Maximum sodium persulfate concentrations were observed at 8 ft downgradient and were lower in samples collected at 1 and 3 ft downgradient. Based on the exponential model used to describe sodium persulfate concentration release from the oxidant cylinders (**Figure 5.42**), sodium persulfate concentration released from the cylinders after 119 days (i.e., the time of sampling) was predicted to be 46% of that at the time of cylinder installation. The observed sodium persulfate concentration in the cylinder monitoring wells was 30% of the maximum concentration compared to the predicted 46%. Considering experimental uncertainties, the observed profile of sodium persulfate concentrations is reasonable.

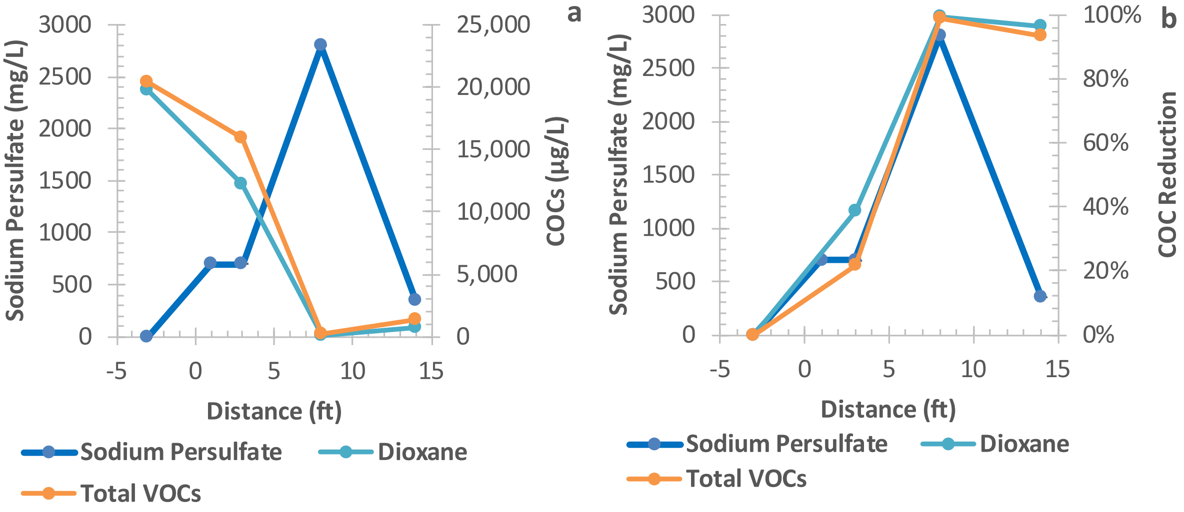


Figure 5.53. Total VOC (1,1-DCE, 1,1-DCA, cis-1,2-DCE and TCE) Concentrations (a) and Percent Removals (b) and Persulfate Concentrations (a,b) from Hydropunch Groundwater Samples Along the 289° Flow Path Downgradient of the Persulfate Cylinders and From the Deep Interval 12.5-14.5 ft Below the Water Table 119 Days After the Second Persulfate Cylinder Installation Event. Sodium Persulfate Concentrations 1 ft Downgradient Were Grab Samples Collected from Cylinder Monitoring Wells DCW-01 and DCW-02 Using Bailers.

Transects of sodium persulfate, dioxane, and total VOCs along the 289°, 295°, and 308° transects are shown in **Figure 5.54**. The 289°and 308° transects aligned fairly well with the DC-01 and DC-02 oxidant cylinder boreholes (see **Figure 5.31b**). However, the 289° transect did not demonstrate better contaminant removal just because it was aligned with the DC-01 oxidant cylinder borehole. If this were the case, then the 308° transect aligned with the DC-02 oxidant cylinder borehole should have also demonstrated better contaminant removal than the 295° transect in between the cylinder boreholes.

The opposite was observed – contaminant removal along the 308° transect was similar to that along the 295° transect and less than that along the 289° transect.

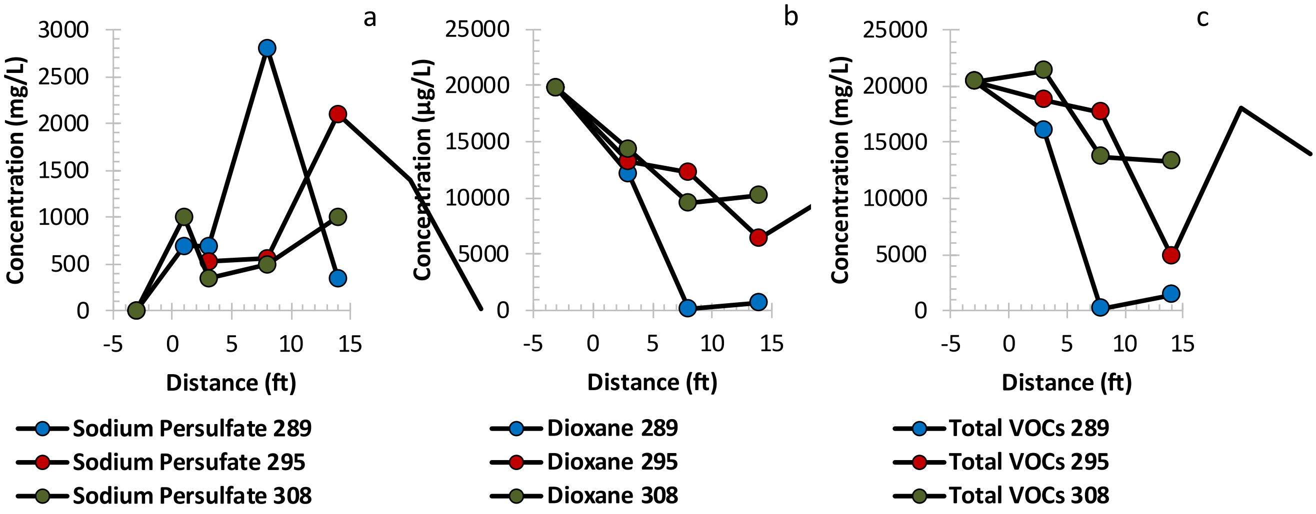


Figure 5.54. Individual VOC Concentrations from the 12.5-14.5 ft Interval Along the 289° Flow Path Downgradient of the Persulfate Cylinders.

Individual CVOCs were all reduced and the greatest reduction correlated to the maximum sodium persulfate concentration (**Figure 5.55**). Some rebound of TCE was observed 14 ft downgradient possibly because of back diffusion from the aquifer. 1,1-DCA was oxidized here, however it was poorly removed in the column study (**Figure 5.14**). The reason for this difference is uncertain but may be associated with natural activation by soil minerals (Ahmad 2008, Ahmad et al. 2010, Liu et al. 2014, Teel et al. 2011) and differences between the mineral composition of discrete sample used for the treatability study and those present in the subsurface flow path during the field demonstration.

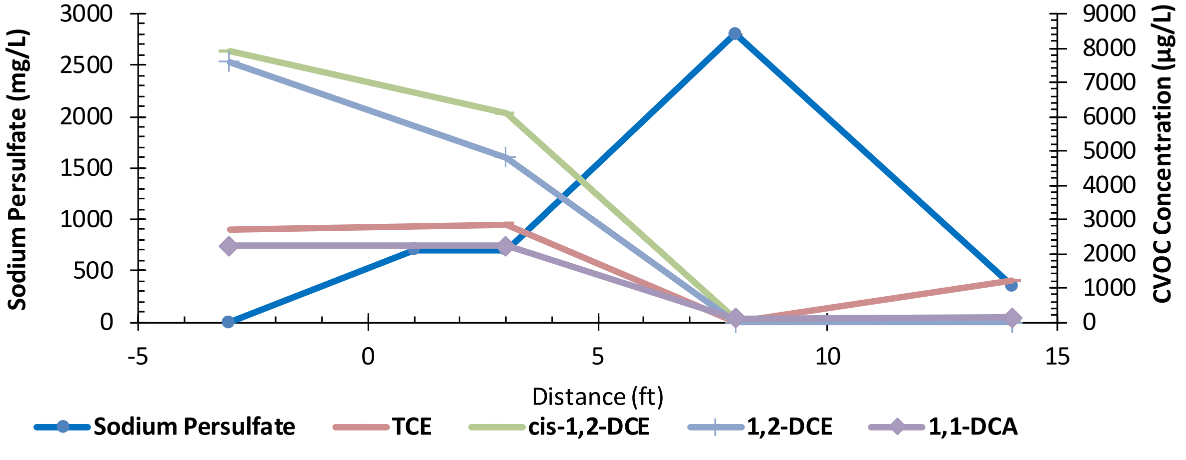


Figure 5.55. Individual CVOC Concentrations from the 12.5-14.5 ft Interval Along the 289° Flow Path Downgradient of the Persulfate Cylinders.

Geochemical data were consistent with sodium persulfate decomposition (**Figure 5.56**). Sulfate and oxidation-reduction potential increased and pH decreased in response to increased sodium persulfate concentrations. These geochemical parameters returned to their background values further downgradient suggesting that adverse secondary effects such as metals mobilization associated with depressed pH would likely be attenuated.

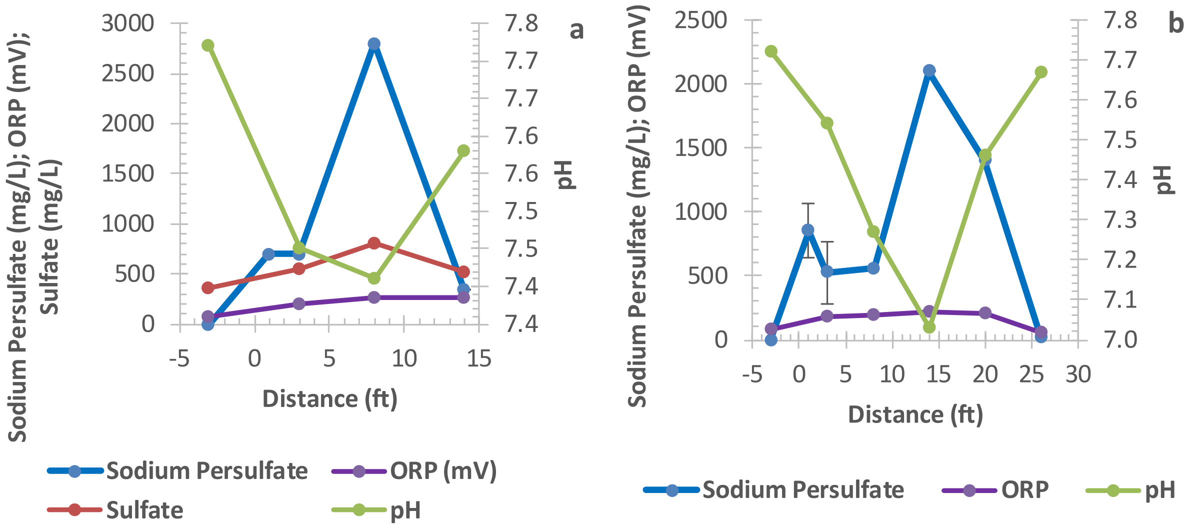


Figure 5.56. Geochemical Parameters from the 12.5-14.5 ft Interval Along the 289° (a) and 295° (b) Flow Paths Downgradient of the Persulfate Cylinders.

Samples collected from shallow borings along the 289° flow path also demonstrated CVOC removal even though sodium persulfate concentrations were substantially lower than in deep boring samples (**Figure 5.57**). Commensurately, the degree of CVOC reduction was less. Dioxane reduction was not quantifiable because upgradient concentrations in the shallow zone were low. The relatively lower persulfate concentrations in the shallow boring samples were attributed to density driven flow (**Figure 5.58**).

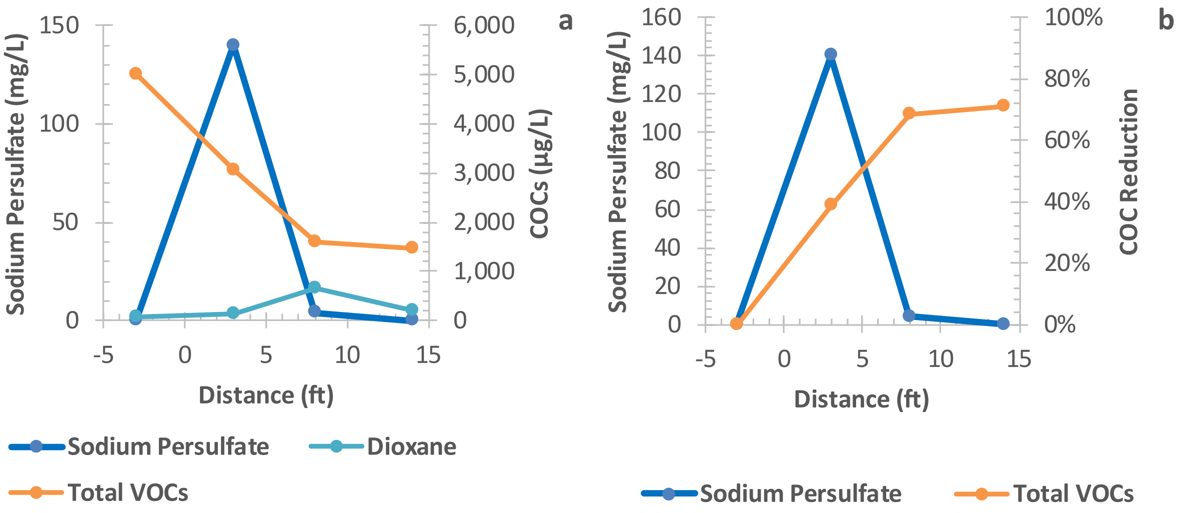


Figure 5.57. Total VOC (1,1-DCE, 1,1-DCA, cis-1,2-DCE and TCE) Concentrations (a), Percent Removals (b) and Persulfate Concentrations (a,b) from Hydropunch Groundwater Samples Along the 289° Flow Path Downgradient of the Persulfate Cylinders and From the Shallow Interval 2.5-4.5 ft Below the Water Table 119 Days After the Second Persulfate Cylinder Installation Event. Percent Removal for Dioxane Is Not Shown Because Upgradient Concentrations Were Negligible and Calculated Percent Removals Were Negative.

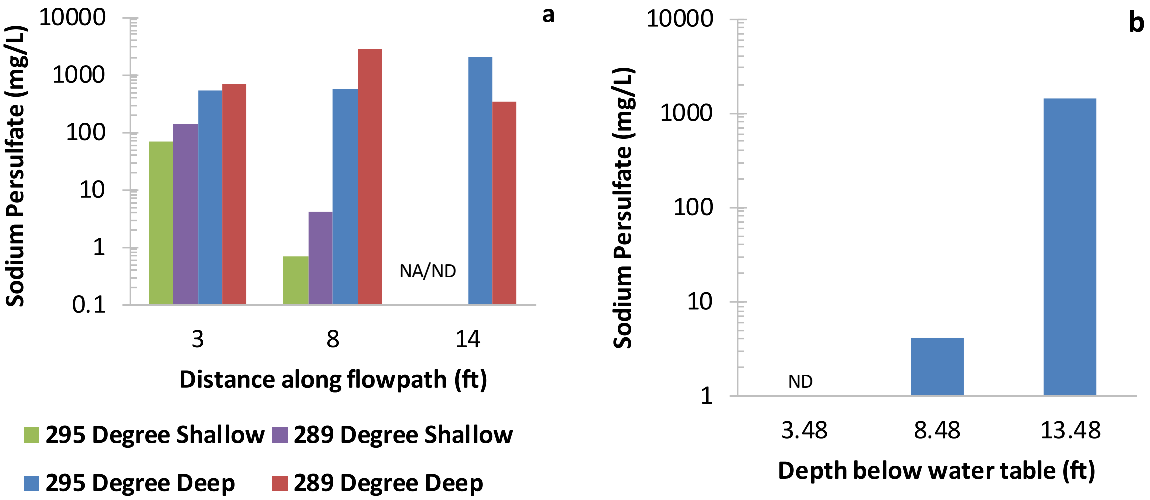


Figure 5.58. Sodium Persulfate Concentrations in Shallow and Deep Boring Samples Along 289° and 295° Flow Paths (a) and From Boring B20 Located 20 ft Downgradient of the Cylinders Along the 295° Flow Path (b).

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6.0 PERFORMANCE ASSESSMENT

6.1 QUANTITATIVE PERFORMANCE OBJECTIVE: TECHNOLOGY EFFECTIVENESS

The maximum dioxane and total CVOC destructions along the flow path were used to assess performance. The maximum destructions (99.3% and 99.0% for dioxane and total CVOCs, respectively) were observed in the deep sample located 8 ft downgradient along the main hydraulic flow path (**Figure 5.53**). The upgradient dioxane and total CVOC concentrations were 20,000 µg/L each. The downgradient dioxane concentration was 140 µg/L. Thus, the 90% minimum destruction criterion for dioxane was exceeded. Individual CVOCs were also reduced in concentration along the flow path (**Figure 5.55**). 1,1-DCE was reduced from 7,600 to < 33 µg/L (> 99.5% reduction; MCL = 7 µg/L); 1,1-DCA was reduced from 2,200 to 110 µg/L (95% reduction); cis-1,2-DCE was reduced from 7,900 to 75 µg/L (99.1% reduction; Federal MCL = 70 µg/L); and TCE was reduced from 2,700 to 15 µg/L (99.4% reduction; MCL = 5 µg/L).

The reductions in contaminant concentrations reported above were observed in deep aquifer samples. These samples are considered to be representative of the primary contaminant flow path at 40 ft bgs running along the top a silt aquitard (**Figures 5.3** and **5.49**). Greater specific conductivities and concentrations of sodium persulfate were observed in deeper samples (**Figures 5.43, 5.44, 5.45** and **5.58**). This path appears to have been density driven and induced by: 1) the density of sodium persulfate and 2) the low horizontal hydraulic gradient (**Figures 5.46** and **5.47**).

While sodium persulfate appears to have promoted density-driven flow, contaminant reductions were also observed in shallower portions of the aquifer (**Figure 5.57**). Total CVOCs were reduced by 71% 14 ft downgradient of the oxidant cylinders. The upgradient concentration of dioxane was 67 µg/L in the shallow sample compared to 20,000 µg/L in the deep sample and downgradient concentrations of dioxane in the shallow sample were greater than the upgradient concentration. Therefore, evaluation of dioxane removal in the shallow aquifer was not possible. The shallow aquifer would not be anticipated to be a major contributor to overall contaminant flux in the case of density driven flow. In this case, high contaminant destruction in the shallow aquifer would not be necessary for a remedial performance objective of contaminant mass flux reduction.

A permeable reactive barrier comprised of oxidant cylinders must be capable of contaminant destruction along the length of the barrier as well as between individual oxidant cylinders. The above results indicate that a simulated barrier comprised of two-cylinder boreholes was capable of exceeding the performance objective at a distance 8 ft downgradient. Contaminant removal was maintained at a level > 90% also at a distance 14 ft downgradient (**Figure 5.53**). However, the zone of contaminant destruction > 90% was narrow and less than the cylinder borehole spacing of 5 ft (**Figures 5.51** and **5.54**). This narrow lateral zone of influence may be attributable to diffusive influx of contaminants from groundwater cross-gradient to the main hydraulic flow path. Installation of a barrier containing more than two-cylinder boreholes and wider than 5 feet would be minimize diffusive influx. Nevertheless, contaminant bypass via advective transport through a “gap” between cylinder boreholes where the oxidant does not come into contact with the contaminant is an issue that must be considered during design. Modeling can be used to address this issue.

6.2 QUANTITATIVE PERFORMANCE OBJECTIVE: SUSTAINABILITY/ LONGEVITY

Sodium persulfate concentrations decreased in an exponential pattern over time with 42% remaining at the final sampling event (134 days) and 31% and 9% predicted to be remaining after 6 and 12 months, respectively (**Figure 5.42**). Thus, the treatability study observation that persulfate concentrations would remain relatively constant over time until the cylinders were spent (**Figure 5.17**) was not observed in the field demonstration. Dispersion and lack of a closed sulfate/persulfate mass balance (**Figure 5.48**) may have contributed to this difference. Nevertheless, the performance objective was not met based on this criterion.

On the other hand, contaminant concentrations in the borehole monitoring wells continued to decline throughout the 134-day sampling period resulting from oxidation by the released sodium persulfate (**Figures 5.39** to **5.41**). Dioxane removal steadily increased to 90% in the oxidant cylinder borehole monitoring wells by the time of the final sampling event thus meeting the performance objective (**Figures 5.39** and **5.41)**. Therefore, the decreasing oxidant concentrations did not adversely affect dioxane removal. CVOC removal increased only to 51% over the same time period. Previous treatability studies demonstrated the reaction rate of sodium persulfate with CVOCs was greater than that with dioxane. Thus, the 51% value may be an underestimate.

During the second oxidant cylinder deployment, dioxane and CVOC removals were ≥ 99% after 119 days further corroborating high contaminant destruction for extended time periods even when oxidant concentrations may be variable or declining (**Figure 5.53**). Thus, the criterion of contaminant destruction effectiveness being maintained for greater than 4 weeks was exceeded.

6.3 QUANTITATIVE PERFORMANCE OBJECTIVE: OXIDANT TRANSPORT AND DESTRUCTION

Initial investigations into sodium persulfate transport were complicated by density driven flow. HydraSleeve sampling techniques in monitoring wells were not capable of discretely sampling the deeper groundwater horizon overlaying the silt aquitard. HydroPunch sampling provided better contrast and demonstrated that sodium persulfate was transported at least 20 ft downgradient of the oxidant cylinders (**Figure 5.56**). Concentrations were variable but ultimately decreased along the flow path from a maximum concentration of 2,100 mg/L 14 ft downgradient to 21 mg/L 26 ft downgradient. This represents a 99% reduction in oxidant concentration. pH and ORP trends also indicate that groundwater downgradient of the oxidant returned to natural conditions (**Figure 5.56**).

6.4 QUANTITATIVE PERFORMANCE OBJECTIVE: TECHNOLOGY IMPLEMENTABILITY/ SECONDARY IMPACTS

pH decreased and ORP increased in response to the presence of sodium persulfate (**Figure 5.56**). Downgradient of the maximum sodium persulfate concentration, pH increased and ORP decreased to background values. Dissolved chromium (presumed to be hexavalent chromium) concentrations increased in the treatability column study to concentrations ranging from 200 to 300 µg/L (**Table 5.4**). Lead may have also been elevated but conflicting results from two different laboratories make this result uncertain. Concentrations of other hazardous metals were not elevated during the treatability study. Hexavalent chromium can be chemically or biologically reduced.

If hexavalent chromium concentrations in groundwater were observed during the field demonstration, it is possible that chemical or biological reduction could have occurred downgradient. The basis for this assertion is: 1) pH increased the baseline values and increased pH decreases metal solubility, and 2) ORP decreased to naturally reducing aquifer conditions that could reduce hexavalent chromium to less soluble trivalent chromium hydroxide.

6.5 QUALITATATIVE PERFORMANCE OBJECTIVE: TECHNOLOGY REPRODUCIBILITY

The relative percent deviation of the sodium persulfate concentrations in the cylinder borehole monitoring wells was 66±50% (**Figure 5.33**). The RPD ranged from 22 to 56% during the first 35 days of operation and then increased to 120% on day 134. The increase was associated with the sodium persulfate concentration in one of the cylinder wells decreasing to 700 mg/L while the concentration in the other well was 2,800 mg/L. Sodium persulfate concentrations also varied along flow paths that were adjacent to the main flow path (**Figure 5.54**). These variations may have been associated with variability of persulfate concentrations released from the cylinders and/or a narrow plume of persulfate-containing groundwater resulting from low dispersion. The sodium persulfate flux from the cylinders was reasonable when compared to treatability study results (**Table 5.9**). The observed variability may be inherent to the technology and can be exacerbated by aquifer heterogeneity. This variability will need to be addressed during design through use of multiple oxidant cylinders and care specification of cylinder spacing.

6.6 QUALITATIVE PERFORMANCE OBJECTIVE: ENGINEERING DESIGN TOOL UTILITY

The engineering design tool was not completed because of project constraints. See **Section 8** and **Appendix D** for additional information.

6.7 QUALITATIVE PERFORMANCE OBJECTIVE: DESIGN TOOL EASE OF USE

The engineering design tool was not completed because of project constraints. See **Section 8** and **Appendix D** for additional information.

6.8 QUALITATIVE PERFORMANCE OBJECTIVE: APPLICABILITY TO MULTIPLE SITE CONDITIONS

The engineering design tool was not completed because of project constraints. See **Section 8** and **Appendix D** for additional information.

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7.0 COST ASSESSMENT

The cost assessment includes presentation of the different cost components used in the cost model, an analysis of primary drivers for the technology, and a comparison of full-scale implementation of the technology at one theoretical site. Cost analysis was completed for one theoretical site under five different remedial scenarios. Details are provided in the subsequent sections.

7.1 COST MODEL

Various cost elements for implementation of the demonstrated technology are presented in **Table 7.1**. The major cost elements include bench-scale treatability/field pilot testing, drilling services, (IDW disposal, and costs for contractor oversight of the fieldwork. The presented costs are project-specific and may vary from site to site depending on physical (e.g., location), hydrogeological (e.g., hydraulic conductivity), and stratigraphic (e.g., lithology) characteristics. Costs presented include those required or recommended for implementing the demonstrated technology, on-site costs for monitoring well installation, groundwater sampling, and system O&M. Travel costs are not included, as they are site-specific. Overall, the cost model presented herein is intended to provide a representation of the primary cost elements to be considered, as well as the required time to implement the technologies at actual sites.

Table 7.1. Cost Model.

Cost element	Basis
Bench-scale treatability/field pilot testing	Previous projects
Drilling services	Previous projects
IDW disposal	Previous projects
Contractor oversight	Previous projects
O&M	Based on estimated project duration and discount factor
Treatment reagent	This project or previous projects
Project management	10% of all costs
Procurement, health and safety, coordination, QA/QC, auditing, and other miscellaneous activities	15% of all costs
Contingency	20% of all costs

7.2 COST DRIVERS

Several important cost drivers must be considered for implementing the demonstrated technology including target lithology and depth and site-specific hydrogeological characteristics, plume width, contaminant concentration, and O&M. Both site lithology and target treatment depth influence how the drilling will be performed at a given site. Although direct push may be appropriate for installing monitoring wells in select overburden materials in a cost-effective manner, it may not be suited for drilling cylinder wells. In addition, direct push is not applicable for sites with more consolidated materials and thus the use of more cost- and labor-intensive drilling technologies including hollow-stem auger, sonic or rotary techniques must be considered for installing both cylinder and monitoring wells. Lithology may also drive material costs as carbon-rich soils will exert a higher oxidant demand, rendering more frequent changing and resulting in higher material as well as O&M costs.

Similar to site-specific lithology, the target treatment depth interval affects the selection of the appropriate drilling technique.

In addition, vertical depth interval targeted for treatment influences the number of cylinder wells and oxidant cylinders required. Site-specific hydrogeological characteristics and contaminant profile may also affect implementation cost. Specifically, sites with high groundwater velocities and contaminant concentrations and therefore, high contaminant flux, may lead to greater numbers of oxidant cylinders resulting in potentially higher capital and O&M costs. On the other hand, sites with flat groundwater gradients may require pumping and reinjection to induce the necessary groundwater flow velocity and direction, resulting in higher capital and O&M costs. The plume width will directly impact the number of cylinders required to create a passive barrier to intercept the plume and therefore represents a direct cost driver of field implementation of the subject technology.

7.3 COST ANALYSIS

This section compares the capital, O&M, and overall project costs for implementing different remedial techniques for treating 1,4-dioxane and CVOCs at a theoretical site in a full-scale setting. Pertinent design parameters for the theoretical site are presented in **Table 7.2**. For simplicity, it is assumed that site lithology is primarily fine to coarse sand with a relatively high hydraulic conductivity and a low degree of heterogeneity. Hollow-stem auger drilling is assumed to be amenable to all cost scenarios and all IDW generated was assumed to be non-hazardous.

Table 7.2. Assumptions for Theoretical Site.

Parameters	Value
Lithology	Fine to coarse sand
Groundwater velocity	5 ft/day
Drilling technology	Hollow-stem auger
Plume length	400 ft
Plume width	100 ft
Treatment depth	20-40 ft bgs
1,4-dioxane concentration	10,000 µg/L
CVOCs	5,000 µg/L

The plume is assumed to be persistent and thus will require ongoing treatment for a period of 30 years. A discount factor of 7% was used for estimating lifecycle costs over the 30-year duration. Cost data used for this analysis were based on this or recently completed projects (e.g., drilling and persulfate cylinder costs), industry-standard estimates (e.g., trenching and installation of bentonite slurry walls) or vendor-provided estimates (e.g., capital and O&M costs of an AOP system). Remedial technologies being evaluated in this exercise include the following:

1. PRB with persulfate cylinders as demonstrated with cylinder changeouts being performed every 6 months for 30 years at different cylinder spacings of 1, 2.5, 5, and 10 feet.

2. PRB with persulfate cylinders as demonstrated with a cylinder spacing of 5 feet for 30 years with cylinder changeouts being performed every 3, 6, 12 or 18 months.
3. PRB using aqueous sodium persulfate injection with an injection spacing of 5 feet and reinjection performed every 30, 45, 60 or 90 days for 30 years.
4. F&G with persulfate cylinders as demonstrated with cylinder changeouts being performed every 6 months.
5. Pump and treat (P&T) using pump and treat using AOP and permitted discharge to surface water for 30 years.

A side-by-side comparison of the different scenarios being evaluated is presented in **Table 7.3**. Note the annual mass of sodium persulfate delivered varies in Scenarios 1 and 2 depending on the spacing (Scenario 1) or the changeout frequency (Scenario 2). In Scenario 3, the annual mass of sodium persulfate is intentionally kept constant to allow comparability to Scenarios 1c and 2b (which in fact are identical). This mass is also equal to the mass delivered in Scenario 4.

Table 7.3. Comparisons of Different Remedial Scenarios.

Scenario	Sub-scenario	Technology	Cylinder spacing/Radius of Influence	Changeout frequency/Reinjection frequency	Annual Mass $Na_2S_2O_8$ (pounds)
1	1a	PRB with cylinders	1 ft	Every 6 months	13,000
	1b		2.5 ft	Every 6 months	5,300
	1c		5 ft	Every 6 months	2,700
	1d		10 ft	Every 6 months	1,300
2	2a	PRB with cylinders	5 ft	Every 3 months	5,300
	2b		5 ft	Every 6 months	2,700
	2c		5 ft	Every 12 months	1,300
	2d		5 ft	Every 18 months	890
3	3a	Traditional ISCO	5 ft	Every 30 days	2,700
	3b		5 ft	Every 45 days	2,700
	3c		5 ft	Every 60 days	2,700
	3d		5 ft	Every 90 days	2,700
4	-	F&G with cylinders	NA	Every 6 months	2,700
5	-	AOP	10 ft	Constant	-

7.3.1 Scenario 1 – PRB with Slow-Release Oxidant Cylinders at Different Spacings

In this remedial scenario, it is assumed that persulfate cylinders will be deployed in 8-inch diameter boreholes that house 4-inch injection wells screened within the target vertical treatment interval ranging between 20 and 40 ft bgs. The cylinders will be installed in a single row at different spacings. Cylinder changeouts will be performed every 6 months for a total remedial timeframe of 30 years.

Estimated costs were developed for different cylinder spacing of 1, 2.5, 5, and 10 ft to facilitate assessment of cost sensitivity with regard to cylinder spacing. In all scenarios simulated herein, it is assumed that the natural groundwater gradient at the site is sufficient and thus a groundwater extraction/recirculation system will not be required. Monitoring wells will be installed upgradient and downgradient of the PRB every 100 feet to facilitate performance monitoring which will be performed on a biannual basis. The primary capital and O&M cost drivers for the four different scenarios simulated under Scenario 1 are presented in **Table 7.4**. Detailed cost estimates are provided in **Appendix I**.

Table 7.4. Cost Comparisons for Scenario 1.

Cost category	Cost element	Scenario 1a 1-ft spacing	Scenario 1b 2.5-ft spacing	Scenario 1c 5-ft spacing	Scenario 1d 10-ft spacing
Capital	Bench-scale treatability/field pilot testing	$200,000	$200,000	$200,000	$200,000
	Drilling	$416,000	$190,000	$113,000	$77,000
	IDW disposal	$82,000	$56,000	$47,000	$42,000
	ISCO reagent & injection system or other infrastructure	$170,000	$68,000	$34,000	$17,000
	Field oversight	$170,000	$80,000	$50,000	$35,000
	Project Management	$104,000	$59,000	$44,000	$37,000
	Project Procurement, Health and Safety, Coordination, QA/QC, Auditing, and Other Misc. Activities	$156,000	$89,000	$67,000	$56,000
	Contingency	$208,000	$119,000	$89,000	$74,000
	Total capital cost	**$1,506,000**	**$861,000**	**$644,000**	**$538,000**
O&M	Annual monitoring	$60,000	$60,000	$60,000	$60,000
	Annual changeout or reinjection or overall O&M	$425,000	$200,000	$125,000	$88,000
	Project Management	$48,500	$26,000	$19,000	$15,000
	Contingency	$97,000	$52,000	$37,000	$30,000
	Total annual O&M cost - First Year	$631,000	$338,000	$241,000	$192,000
	Total annual O&M cost - Remaining Years	$7,234,000	$3,878,000	$2,763,000	$2,204,000
	Total O&M	**$7,865,000**	**$4,216,000**	**$3,004,000**	**$2,396,000**
Overall project cost		**$9,371,000**	**$5,077,000**	**$3,648,000**	**$2,934,000**

The smaller spacing allowing for better capture of the flow-through groundwater plume results in the higher number of cylinder wells required, leading to not only higher drilling costs but also higher IDW disposal, contractor field oversight, and material costs. Additionally, the smaller cylinder spacing also resulted in higher O&M costs, especially with regard to the cost to change out the cylinders every 6 months. The relationship between cylinder spacing and capital as well as O&M and overall project cost is graphically depicted in **Figure 7.1.**

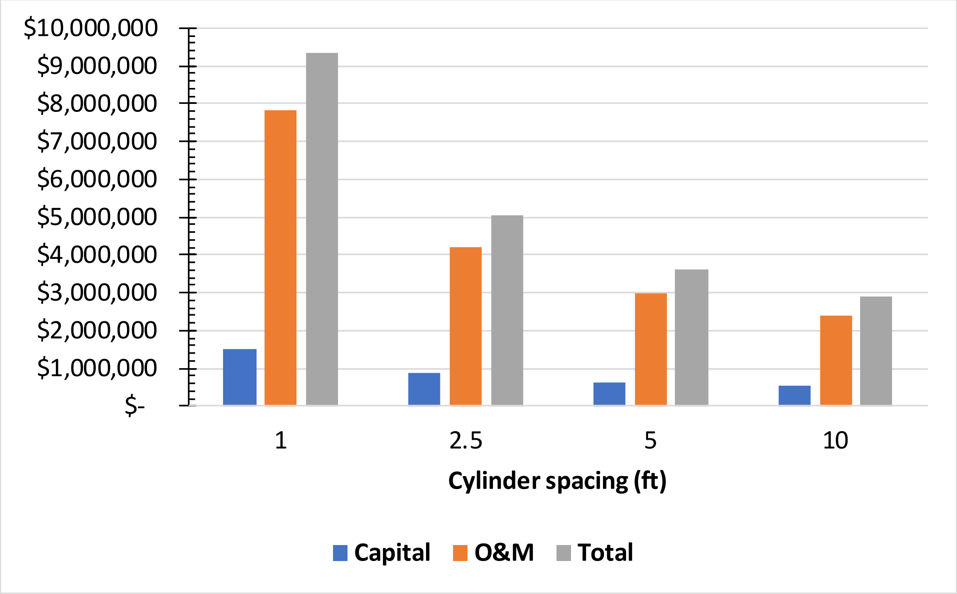

Figure 7.1. Relationship Between Cylinder Spacing and Capital, O&M, and Overall Project Cost.

7.3.2 Scenario 2 – PRB with Slow-Release Oxidant Cylinders with Changeout Frequencies

Similar to Scenario 1, it is assumed that, under Scenario 2, persulfate cylinders will be deployed in 8-inch diameter boreholes that house 4-inch injection wells screened within the target vertical treatment interval ranging between 20 and 40 ft bgs. Under this scenario, the cylinders will be installed in a single row at a 5-ft spacing. Estimated costs were developed for different cylinder changeout frequency of 3, 6, 12, and 18 months to facilitate assessment of cost sensitivity with regard to cylinder changeout frequency. Note that Scenario 2b is identical to Scenario 1c above – both have a cylinder spacing of 5 feet and a changeout frequency of 6 months. Monitoring wells will be installed upgradient and downgradient of the PRB every 100 feet to facilitate performance monitoring which will be performed on a biannual basis. The primary capital and O&M cost drivers for the four different scenarios simulated under Scenario 2 are presented in **Table 7.5**.

As expected, the capital cost is the same for all four simulations under Scenario 2. Therefore, cylinder changeout frequency is the primary cost driver; more frequent changeouts directly correspond to higher O&M and thus overall project cost. The relationship between cylinder changeout frequency and capital as well as O&M and overall project cost is graphically depicted in **Figure 7.2.**

Table 7.5. Cost Comparisons for Scenario 2.

Cost category	Cost element	Scenario 2a 3-month changeout	Scenario 2b 6-month changeout	Scenario 2c 12-month changeout	Scenario 2d 18-month changeout
Capital	Bench-scale treatability/field pilot testing	$200,000	$200,000	$200,000	$200,000
	Drilling	$113,000	$113,000	$113,000	$113,000
	IDW disposal	$47,000	$47,000	$47,000	$47,000
	ISCO reagent & injection system or other infrastructure	$34,000	$34,000	$34,000	$34,000
	Field oversight	$50,000	$50,000	$50,000	$50,000
	Project Management	$44,000	$44,000	$44,000	$44,000
	Project Procurement, Health and Safety, Coordination, QA/QC, Auditing, and Other Misc. Activities	$67,000	$67,000	$67,000	$67,000
	Contingency	$89,000	$89,000	$89,000	$89,000
	Total capital cost	**$644,000**	**$644,000**	**$644,000**	**$644,000**
O&M	Annual monitoring	$60,000	$60,000	$60,000	$60,000
	Annual changeout or reinjection or overall O&M	$250,000	$125,000	$63,000	$42,000
	Project Management	$31,000	$19,000	$12,000	$10,000
	Contingency	$62,000	$37,000	$25,000	$20,000
	Total annual O&M cost - First Year	$403,000	$241,000	$160,000	$132,000
	Total annual O&M cost - Remaining Years	$4,628,000	$2,763,000	$1,831,000	$1,520,000
	Total O&M	**$5,031,000**	**$3,004,000**	**$1,991,000**	**$1,652,000**
Overall project cost		**$5,675,000**	**$3,648,000**	**$2,635,000**	**$2,296,000**

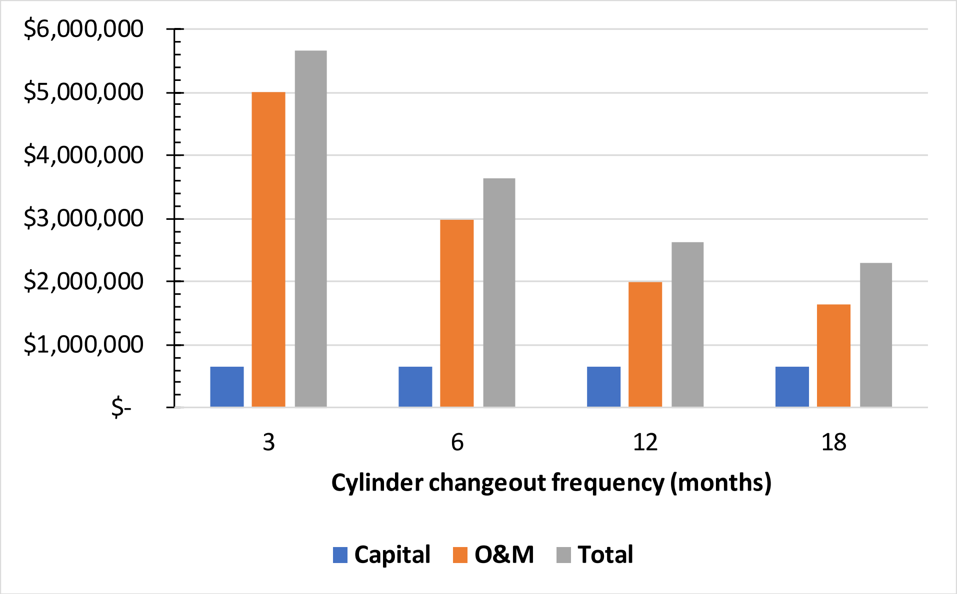

Figure 7.2. Relationship Between Cylinder Changeout Frequency and Capital, O&M, and Overall Project Cost.

7.3.3 Scenario 3 – PRB with Periodic Aqueous Sodium Persulfate Injection

In this remedial scenario, it is assumed that the unactivated persulfate will be used to facilitate treatment of groundwater in a PRB configuration. The persulfate solution will be introduced into the target treatment zone via permanent, 2-inch, Sch 40 PVC injection wells screened within 20 and 40 ft bgs. To provide comparability to Scenarios 1 and 2, the annual mass of sodium persulfate injected per year in Scenario 3 is identical to the annual mass of persulfate that would be released from the slow-release oxidant cylinders in Scenarios 1c and 2b. Note that cost estimation for this scenario was performed to allow for direct comparisons with Scenario 1c where PRB with persulfate cylinders are installed with a 5-ft spacing. Under this scenario, a single row of injection wells spaced 5 ft apart and injection rate of 5 gpm were assumed. Based on an assumed groundwater velocity of 5 ft/day and the plume length of 400 ft, the theoretical residence time of the injected persulfate was calculated to be 80 days. Therefore, reinjection frequencies of 30, 45, 60, and 90 days were assumed for this scenario to assess the sensitivity of reinjection requirements on the overall project cost. The primary capital and O&M cost drivers for Scenario 3 are presented in **Table 7.6**.

As expected, the capital cost is the very comparable among the four simulations under Scenario 3. The reinjection frequency is the primary cost driver with more frequent injection requirements directly correspond to higher O&M and thus overall project cost. The relationship between cylinder changeout frequency and capital as well as O&M and overall project cost is graphically depicted in **Figure 7.3.**

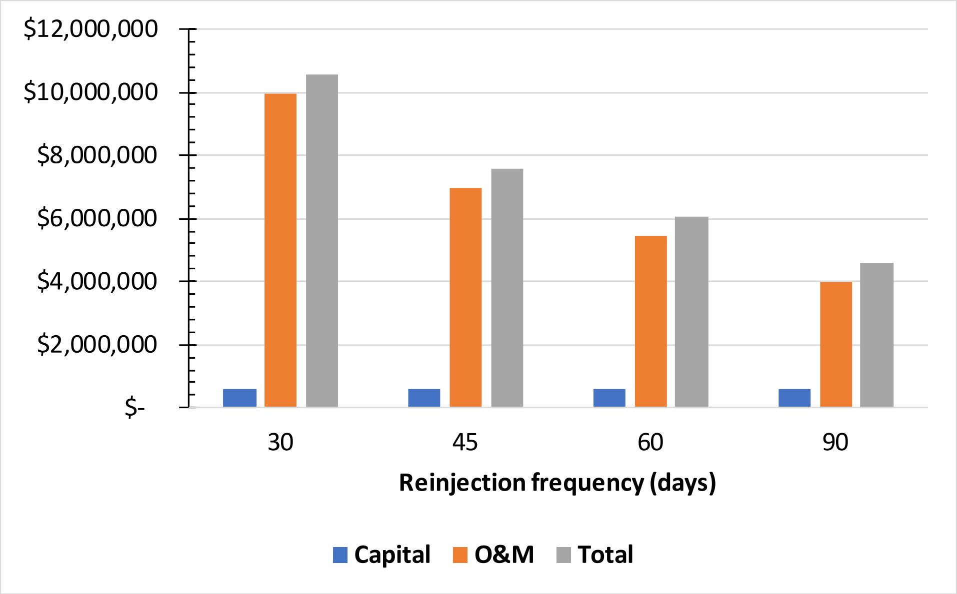

Figure 7.3. Relationship Between Traditional ISCO Reinjection Frequency and Capital, O&M, and Overall Project Cost.

Table 7.6. Cost Comparisons for Scenario 3.

Cost category	**Cost element**	**Scenario 3a 30-day reinjection**	**Scenario 3b 45-day reinjection**	**Scenario 3c 60-day reinjection**	**Scenario 3d 90-day reinjection**
Capital	Bench-scale treatability/field pilot testing	$200,000	$200,000	$200,000	$200,000
	Drilling	$107,000	$107,000	$107,000	$107,000
	IDW disposal	$30,000	$30,000	$30,000	$30,000
	ISCO reagent & injection system or other infrastructure	$19,000	$19,000	$19,000	$19,000
	Field oversight	$31,000	$31,000	$31,000	$31,000
	Project Management	$42,000	$42,000	$42,000	$42,000
	Project Procurement, Health and Safety, Coordination, QA/QC, Auditing, and Other Misc. Activities	$63,000	$63,000	$63,000	$63,000
	Contingency	$77,000	$77,000	$77,000	$77,000
	Total capital cost	**$569,000**	**$569,000**	**$569,000**	**$569,000**
O&M	Annual monitoring	$60,000	$60,000	$60,000	$60,000
	Annual changeout or reinjection or overall O&M	$557,000	$372,000	$279,000	$186,000
	Project Management	$62,000	$43,000	$34,000	$25,000
	Contingency	$124,000	$86,000	$68,000	$49,000
	Total annual O&M cost - First Year	$750,000	$525,000	$412,000	$299,000
	Total annual O&M cost - Remaining Years	$9,213,000	$6,441,000	$5,056,000	$3,670,000
	Total O&M	**$9,963,000**	**$6,966,000**	**$5,468,000**	**$3,969,000**
Overall project cost		**$10,532,000**	**$7,535,000**	**$6,037,000**	**$4,538,000**

7.3.4 Scenario 4

Scenario 4 was simulated to resemble Scenarios 1c and 2b. However, instead of persulfate cylinders installed in a 5-ft spacing, the PRB will be constructed in a F&G configuration where bentonite slurry walls are installed to route the contaminated groundwater through a barrier of persulfate cylinders (i.e., the gate). In this scenario, the length of the gate is 15 ft. However, the same number of cylinders required under Scenarios 1c and 2b is assumed. Persulfate cylinders were similarly assumed to be changed out every 6 months. Similar to other scenarios, monitoring wells will be installed upgradient and downgradient of barrier to facilitate performance monitoring which will be performed on a biannual basis. The remedial timeframe for this scenario is also assumed to be 30 years. The primary capital and O&M cost drivers for Scenario 4 are presented in **Table 7.7**.

Table 7.7. Cost Comparisons for Scenario 4.

Cost category	Cost element	Scenario 4 Cylinders in F&G
Capital	Bench-scale treatability/field pilot testing	$200,000
	Drilling	$113,000
	IDW disposal	$47,000
	ISCO reagent & injection system or other infrastructure[1]	$544,000
	Field oversight	$50,000
	Project Management	$99,000
	Project Procurement, Health and Safety, Coordination, QA/QC, Auditing, and Other Misc. Activities	$148,000
	Contingency	$191,000
	Total capital cost	**$1,392,000**
O&M	Annual monitoring	$60,000
	Annual changeout or reinjection or overall O&M	$125,000
	Project Management	$19,000
	Contingency	$37,000
	Total annual O&M cost - First Year	$241,000
	Total annual O&M cost - Remaining Years	$2,763,000
	Total O&M	**$3,004,000**
Overall cost		**$4,396,000**

[1] Includes F&G construction

7.3.5 Scenario 5

In this remedial scenario, it is assumed that a P&T system will be used for extraction of contaminated groundwater at the edge of the plume to prevent offsite contaminant migration. The P&T system consists of a series of extraction wells screened within the target treatment interval (20-40 ft bgs) and a piping conveyance system to transfer the extracted groundwater to an aboveground treatment system where AOP with ultraviolet (UV) lamps and hydrogen peroxide will be utilized for treatment. Treated water is then discharged to surface water under a state permit. Similar to other scenarios, monitoring wells will be installed upgradient and downgradient of the extraction wells to facilitate performance monitoring which will be performed on a biannual basis. The remedial timeframe for this scenario is assumed to be 30 years. Based on the groundwater velocity of 5 ft/day and a treatment area measuring 100 ft (plume width) and 20 ft (treatment thickness), the groundwater discharge was calculated to be approximately 52 gpm. Therefore, an AOP system capable of treating continuously 50 gpm was designed for costing purposes under this scenario. The primary capital and O&M cost drivers for Scenario 5 are presented in **Table 7.8**.

Table 7.8. Cost Comparisons for Scenario 5.

Cost category	Cost element	Scenario 5 - P&T & AOP
Capital	Bench-scale treatability/field pilot testing	$200,000
	Drilling	$38,000
	IDW disposal	$17,000
	AOP system, installation, and permitting	$320,000
	Field oversight	$31,000
	Project Management	$61,000
	Project Procurement, Health and Safety, Coordination, QA/QC, Auditing, and Other Misc. Activities	$91,000
	Contingency	$121,000
	Total capital cost	**$879,000**
O&M	Annual monitoring	$60,000
	Annual O&M including labor, maintenance, and chemicals	$172,000
	Project Management	$23,000
	Contingency	$46,000
	Total annual O&M cost - First Year	$282,000
	Total annual O&M cost - Remaining Years	$3,458,000
	Total O&M	**$3,740,000**
Overall cost		**$4,619,000**

7.3.6 Discussion

Injection or cylinder spacing and changeout/injection frequency are strong cost-drivers. As shown in **Figure 7.4**, installing persulfate cylinder in a passive PRB configuration may potentially result in significant cost saving over manual ISCO application over the duration of the remedy. Even at a cylinder spacing of 2.5 ft, the overall project cost utilizing PRB with persulfate cylinder is still less than that associated with manual ISCO injections at a reinjection frequency of 90 days. Use of slow-release oxidant cylinders provide a consistent flux of oxidant rather than a pulsed dose and is more cost-effective.

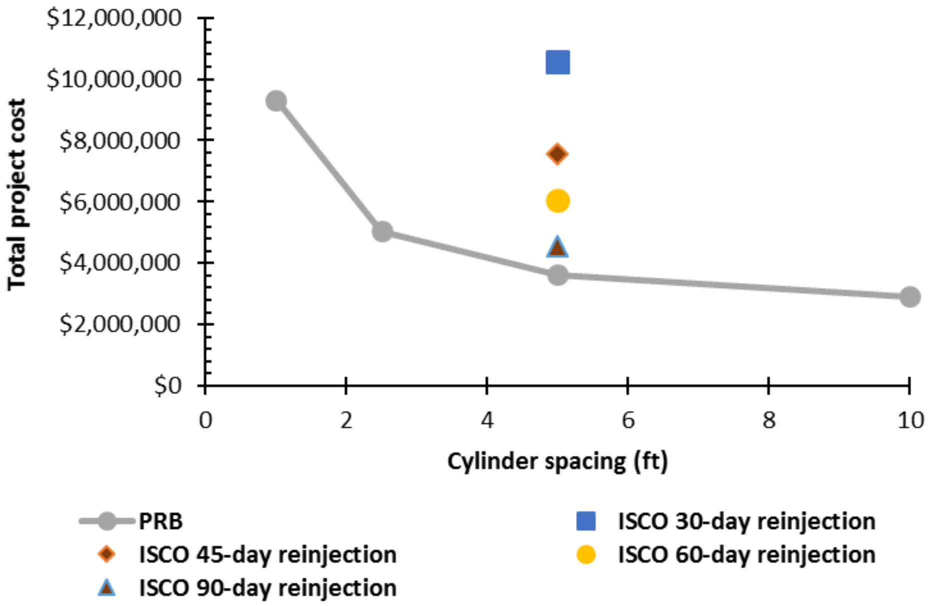

Figure 7.4. Overall Project Cost as a Function of Cylinder Spacing (PRB) and Reinjection Frequency (ISCO).

Similar to **Figure 7.4**, **Figure 7.5** showed the cost competitiveness of implementing the persulfate cylinder technology in a PRB configuring over manual ISCO injections. The overall project cost of PRB at the most aggressive changeout frequency of every 90 days is similar to that utilizing traditional ISCO at a reinjection frequency of every 90 days.

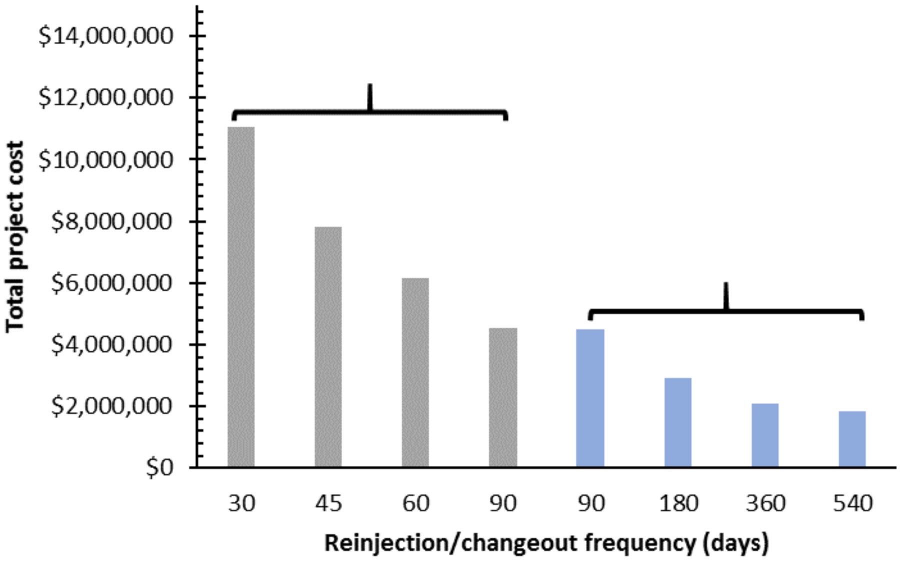

Figure 7.5. Overall Project Cost for Periodic Manual Oxidant Injections (ISCO) and Slow-release Oxidant Cylinders (PRB).

A comparison of the remedial scenarios 1c/2b, 3c, 4, and 5 was conducted. This comparison was based on demonstration results showing that a 5-ft spacing and a 6-month changeout frequency is reasonable for the sodium persulfate cylinders. Note that Scenarios 1c and 2b are the same. Scenario 3c involves manual injection of the same mass of sodium persulfate as Scenario 1c/2b as a comparative alternative to use of slow-release oxidant cylinders. Scenario 4 was simulated to provide a side-by-side comparison of F&G with PRB implementation of the cylinders. Scenario 5 was developed to compare P&T with AOP. A side-by-side cost comparison among these four scenarios is presented below in **Table 7.9**.

Table 7.9. Cost Comparisons Among Four Remedial Scenarios.

Cost category	Cost element	1c PRB with cylinders at 5-ft spacing	3c Traditional ISCO at 5-ft spacing; same persulfate mass per year	4 F&G with cylinders (same # as 1c)	5 AOP
Capital	Bench-scale treatability/field pilot testing	$200,000	$200,000	$200,000	$200,000
	Drilling	$113,000	$107,000	$113,000	$38,000
	IDW disposal	$47,000	$30,000	$47,000	$17,000
	ISCO reagent & injection system or other infrastructure	$34,000	$19,000	$544,000	$320,000
	Field oversight	$50,000	$31,000	$50,000	$31,000
	Project Management	$44,000	$42,000	$99,000	$61,000
	Project Procurement, Health and Safety, Coordination, QA/QC, Auditing, and Other Misc. Activities	$67,000	$63,000	$148,000	$91,000
	Contingency	$89,000	$77,000	$191,000	$121,000
	Total capital cost	**$644,000**	**$569,000**	**$1,392,000**	**$879,000**
O&M	Annual monitoring	$60,000	$60,000	$60,000	$60,000
	Annual changeout or reinjection or overall O&M	$125,000	$279,000	$125,000	$172,000
	Project Management	$19,000	$34,000	$19,000	$23,000
	Contingency	$37,000	$68,000	$37,000	$46,000
	Total annual O&M cost - First Year	$241,000	$412,000	$241,000	$282,000
	Total annual O&M cost - Remaining Years	$2,763,000	$5,056,000	$2,763,000	$3,458,000
	Total O&M	**$3,004,000**	**$5,468,000**	**$3,004,000**	**$3,740,000**
Overall cost		**$3,648,000**	**$6,037,000**	**$4,396,000**	**$4,619,000**

As shown in **Table 7.9**, highest capital costs are associated with Scenarios 4 and 5 (approximately $1.4 million and $880,000, respectively) where, while sharing the majority of the capital expenditures, additional costs are incurred for installation of a F&G system and an AOP system, respectively. Because of the same cylinder well/injection well spacing, the capital costs associated with Scenario 1c and 3c are very similar (between approximately $570,000 and $640,000), with the difference in cost primarily attributable to the drilling of 2-inch ID injection well versus 4-inch cylinder wells and corresponding IDW cost disposal. Because 2-inch ID injection wells were assumed to be sufficient for ISCO injection applications instead of the 4-inch ID cylinder wells used to deploy the persulfate cylinder, significant less IDW waste is generated in the former. While monitoring cost is the same among the four scenarios of interest, the difference in annual costs associated with cylinder changeout, reinjection, and labor/material results in the widely varied overall O&M cost. The total O&M cost over the 30-year duration of the project is the same for Scenarios 1c and 4 (approximately $3 million) because the same number of cylinders and changeout frequency are assumed.

The highest overall O&M cost is associated with the traditional ISCO approach at approximately $5.5 million because of the frequent and material- and labor-intensive reinjection requirements. AOP has the second highest overall O&M cost of approximately $3.7 million. The overall project cost is lowest with Scenario 1c utilizing persulfate cylinders in a passive PRB configuration ($3.7 million) followed by Scenario 4 utilizing persulfate cylinders in a F&G configuration ($4.4 million), Scenario 5 with AOP ($4.6 million), and Scenario 3c with traditional ISCO ($6 million).

Comparison of the overall project cost associated with the four scenarios of interest in this discussion is graphically depicted in **Figure 7.6**.

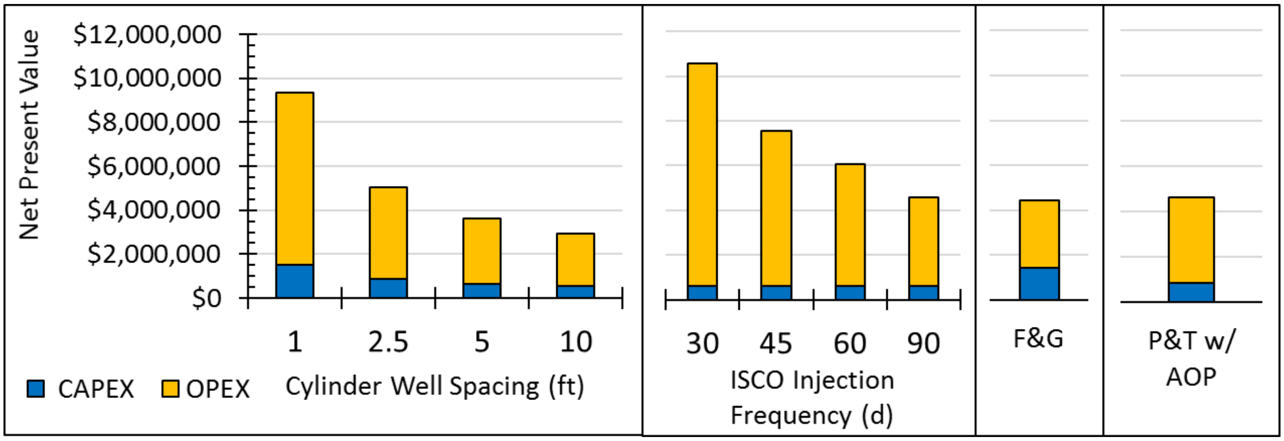

Figure 7.6. Comparison of the Overall Project Cost Among Scenario 1 with Slow-release Oxidant Cylinder PRB Changed Out Every 6 Months (a), Scenario 3 with Manual ISCO Injections on a 5-ft Spacing in a PRB (b), Scenario 4 with a Slow-release Oxidant Cylinder F&G System Changed Out Every 6 Months (c), and Scenario 5 with P&T plus AOP (d). CAPEX = Capital Expenditures and OPEX = Operating Expenditures.

A slow-release oxidant cylinder PRB changed out every 6 months (a) and a well spacing of ≥2.5 ft is more cost effective than manual ISCO injections (b). Note the same annual mass of sodium persulfate is released/injected in Scenarios 1c (**Figure 7.6a** with a 5-ft spacing) as in Scenario 3 (**Figure 7.6b**). Demonstration results indicated that a spacing of 5 ft is reasonable. The cylinder PRB with spacing of 5 ft is lower cost than an F&G having the same number of cylinders (**Figure 7.6c**). Depending on specific site characteristics, a F&G system could potentially be the lowest cost option. P&T with AOP (**Figure 7.6d**) has a greater cost than a cylinder PRB with 5-ft spacing **Figure 7.6a**) and also has the disadvantage of being an active remediation system compared to the passive slow-release oxidant PRB system. These results are specific to the hypothetical cost evaluation conducted but provide an example of how slow-release oxidant cylinder technology has good potential to be cost-competitive with alternative technologies used for long-term treatment of persistent groundwater plumes.

The above scenarios are hypothetical and were developed to illustrate the sensitivity of costs to cylinder spacing and changeout frequency. Several other site-specific factors must also be considered when developing cost estimates. These include: 1) the reaction rate(s) of the contaminant(s) of concern with the released oxidant, 2) the groundwater velocity, 3) the remedial action goal, and 4) the maximum distance along the flow path in which the remedial action goal must be met. In general, lower reaction rates, higher groundwater velocities, lower remedial action goals, and shorter flow path distances will require greater numbers of oxidant cylinders leading to greater costs. Greater natural oxidant demands will also lead to greater costs. The model developed in **Appendix D** can be used as a starting point when evaluating these factors.

Various engineering approaches can be envisioned to enhance lateral distribution of the released oxidant and in turn increase the spacing between oxidant cylinders. An example is groundwater mixing via constant or intermittent pumping at nearby locations. Depending on the site, installation of a mixing system and use of 5-ft cylinder spacing may be more cost effective than use of 2.5-ft cylinder spacing without mixing. However, the mass-based release rate of the oxidant must be sufficient to achieve the desired degree of contaminant destruction within the available flow path distance. Increasing the cylinder spacing from 2.5 to 5 ft will decrease the oxidant release rate by 50%. The engineer must determine whether this reduction in oxidant release rate is acceptable. Clearly there are several factors that must be considered when designing a system using slow-release oxidant cylinders and subsequently estimating lifecycle costs.

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8.0 IMPLEMENTATION ISSUES

A variety of end-use considerations are relevant when considering and implementing the persulfate cylinder technology for in situ treatment of 1,4-dioxane, CVOCs, and other contaminants as follows:

- Technology selection:
  - The intended use of slow-release oxidant cylinders is passive and long-term treatment of contaminated groundwater. This technology can be implemented in remediation wells or via direct push, used as a permeable reactive barrier or a grid, or in a reactive gate in an F&G system. Other technologies that should be considered are pump and treat and in situ bioremediation not to mention other potential technologies. The technology selection process conducted as part of a feasibility study will consider effectiveness, implementability, cost, and other factors.
  - The subject technology, because of its sustained and slow-release nature, can be very competitive compared to conventional ISCO applications via permanent injection wells. However, the most common applications are envisioned to be implementation of passive PRBs or funnel and gate systems for treatment of long, dilute plumes as an alternate to pump and treat.
  - Applicable contaminants include those that are capable of being oxidized by chemical oxidants that are released by the oxidant cylinders. Dioxane was demonstrated to be oxidized by unactivated persulfate at this site. It may or may not be oxidized at sufficient rates at other sites and engineering, treatability, or pilot studies should be conducted. Treatability studies should be conducted using site soil and groundwater.
  - The oxidant selection (i.e., persulfate, permanganate, or a mixture of persulfate and permanganate) should be based on the specific contaminants that are to be oxidized, the oxidant release rate, hydrogeological parameters such as groundwater velocity, and reaction rates. Formation of manganese dioxane crusts around permanganate-only cylinders will decrease the release rate and should be taken into account. In this study CVOCs were capable of being treated sufficiently in spite of the formation of a manganese dioxane crust.
  - Like other in situ techniques, the ultimate goal of utilizing the persulfate cylinders should be to treat the groundwater in an aquifer rather than groundwater in monitoring wells. Therefore, careful consideration should be made prior to deploying the oxidant cylinders in existing monitoring wells at a site because monitoring wells are designed and placed with the intent of monitoring and not remediation. The radius of influence of the cylinders has the potential to be small requiring close cylinder spacing. Existing monitoring wells are unlikely to be spaced appropriately with regard to slow-release oxidant cylinder technology. If oxidant cylinders are placed in monitoring wells, it is likely that groundwater in the monitoring well and only in the immediate vicinity of the monitoring wells will be treated. Groundwater that is not in the immediate vicinity of the monitoring wells is unlikely to be treated.

- Regulatory aspects:
  - Because of its reactive (i.e., oxidizing) nature, persulfate cylinders must be handled and shipped with care and in accordance with all local, state, and federal (i.e., DOT and International Air Transport Association [IATA]) regulations.

  - Upon receipt, the cylinders must be handled and stored in compliant with manufacturer-provided recommendations. Specifically, the cylinders must be stored at a dry and cool environment as they may be subject to degradation via exposure to elevated temperature, moisture and/or light. The cylinders should not be cut under any circumstances because of risk of fire.
  - Similar to conventional ISCO implementation utilizing persulfate, transient pH reduction and metal mobilization may be occurring within the target treatment zone as a result of the persulfate degradation and subsequent generation of sulfuric acid. However, it is also equally important to emphasize the transient nature of these geochemical changes. Specifically, geochemical changes within the treatment zone will likely revert to baseline conditions downgradient of the treatment zone.

- Design:
  - Cylinder spacing and changeout frequency can represent the primary cost drivers for implementing the subject technology. These design parameters can be determined using site-specific hydrogeological characteristics and modeling of oxidant dispersion.
  - The depth of the contaminant plume requiring treatment must also be considered. Because the cylinders are manufactured in 18-inch lengths, a cylinder holder assembly is required to allow for deployment of multiple cylinders encompassing the entire target treatment depth interval.
  - Density driven flow can result in downward migration of the oxidant and associated downward migration of groundwater and dissolved contaminants as observed in this study. At sites with a relatively flat gradient, an artificial gradient may be required to facilitate the appropriate groundwater transport as well as to prevent density-driven flow issues. Modeling and pilot-scale testing can be conducted to evaluate this potential issue.
  - Reaction rates of released oxidants with targeted contaminants as well as with NOD must be considered. Measurement of the second-order natural oxidant demand consumption rate using site soil and groundwater is recommended. Conducting a treatability study to determine reaction rates of the released oxidant with target contaminants in the presence of NOD is also recommended.
  - Cylinder deployment in a funnel and gate configuration may be appropriate for certain sites. The cylinders could be placed in wells in the gate or a customized cylinder holder could be used to lower multiple cylinders into a vault that comprises the gate.

- Procurement:
  - The oxidant cylinders can be purchased from Carus Corporation.
  - Equipment for suspending multiple cylinders in wells gates is not standardized and will engineering design and possible custom fabrication. The simplest approach is to use threaded hooks and eyes that are manually screwed into the ends of cylinders. In this way one or more cylinders can be linked together and suspended. The maximum number of cylinders that can be suspended without the hooks and eyes tearing out of the wax matrix must be evaluated. Other approaches were discussed in preceding sections in this report.

- Modeling and future work:

- An Excel-based design tool was developed to support conceptual design of site remediation using slow-release oxidant cylinders. The tool simulates oxidant release and its distribution with groundwater flow, along with contaminant destruction based on rates of oxidant release, groundwater movement, natural oxidant demand, and contaminant reaction with oxidant. Based on oxidant distribution and the size of the treatment zone, the tool determines the number of cylinders needed for treatment and the associated costs for purchasing, installing, and changing out the cylinders.
- A draft version of the tool was distributed to over 30 practitioners and site managers to solicit feedback on the form and function of the tool. The tool was then revised based on their feedback. Unfortunately, the tool, which was verified in the laboratory, could not be field-validated based on-site data collected, therefore it has not and will not be publicly released; however, Carus Corporation does use the tool to support their customers in determining the number and spacing of cylinders necessary for managing their sites.
- An advanced version of the tool is currently in progress that builds upon previous research (Yao et al. 2016). This tool uses numerical methods to solve and simulate oxidant release and reactive transport of oxidant and contaminant in 2-dimensions (in the direction of groundwater flow and lateral to groundwater flow). While the Excel-based tool simulates a single oxidant cylinder and presumes its behavior translates across the site uniformly (i.e., more cylinders behave exactly the same), the 2D tool can incorporate site heterogeneity and simulates multiple cylinders that can be spatially dispersed at user-defined points. Furthermore, the 2D tool calculates cylinder purchase, installation, and change-out costs similar to the Excel tool; however, the 2D tool will have additional functionality. The tool will have an optimization function to automatically spatially distribute cylinders to provide the least cost distribution that effectively treats the site. This work is currently in progress by Clarkson Mathematics Ph.D. candidate Jesse Clark-Stone. Completion is anticipated in 2018.

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APPENDIX B
TREATABILITY STUDY REPORT

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TREATABILITY STUDY REPORT

Sustained *In situ* Chemical Oxidation (ISCO) of 1,4-Dioxane Using Slow-Release Chemical Oxidant Cylinders

ESTCP Project ER-201324

August 4, 2014

Patrick Evans, Jennifer Smith, and Michael Lamar
CDM Smith

Pamela Dugan
Carus Chemical Corporation

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Clarkson University

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ACRONYMS

1,1-DCA	1,1-dichloroethane
1,2-DCA	1,2-dichloroethane
1,1-DCE	1,1-dichloroethene
cis-1,2- DCE	cis-1,2-dichloroethene
^{o}C	degrees Celsius
Ag	silver
As	arsenic
AWWA	American Water Works Association
Cr	chromium
$Cr(OH_3)$	chromium hydroxide
DI	de-ionized
DOT	Department of Transportation
EPA	U.S. Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
F&G	funnel and gate
ft bgs	feet below ground surface
g	gram
g/cm^3	grams per cubic centimeter
g/L	grams per liter
HRT	hydraulic residence time
HSA	hollow-stem auger
ID	inner diameter
IDW	investigation-derived waste
ISCO	*in situ* chemical oxidation
ITRC	Interstate Technology & Regulatory Council
kg	kilogram
KI	potassium iodide
$KMnO_4$	potassium permanganate
L	liter
MCL	maximum contaminant level
µg/L	microgram per liter
µm	micrometer
$mg\ cm^{-2}\ d^{-1}$	milligram per square centimeter per day
mg/kg	milligram per kilogram
mg/L	milligram per liter
mL	milliliter
mL/min	milliliter per minute
M	molar
mm	millimeter
$mM^{-1}\ d^{-1}$	per millimolar per day
Mn	manganese
MnO_2	manganese dioxide
$M^{-1}s^{-1}$	per molar per second
MS/MSD	matrix spike and matrix spike duplicate

N	normal
NA	not tested
$NaHCO_3$	sodium bicarbonate
$Na_2S_2O_8$	sodium persulfate
NAS	Naval Air Station
nM	nanometers
Ni	nickel
NOD	natural oxidant demand
O&M	operation and maintenance
Pb	lead
PRB	permeable reactive barrier
PVC	polyvinyl chloride
QA	quality assurance
QC	quality control
SEM	scanning electron microscopy
SR	sustained-release
SU	standard units
TCE	trichloroethene
VOA	volatile organic analysis
VOC	volatile organic compound
%	percent

1.0 INTRODUCTION

This report presents the results of a treatability study to evaluate use of slow release chemical oxidant chemicals to treat 1,4-dioxane and chlorinated volatile organic compounds (VOCs) in soil and groundwater at Naval Air Station (NAS) North Island in San Diego, California (the site).

1.1 BACKGROUND

Environmental Security Technology Certification Program (ESTCP) Project Number ER-201324 involves demonstration and validation of sustained in situ chemical oxidation (ISCO) of 1,4-dioxane using slow-release oxidant cylinders. This work plan describes a treatability study that will be conducted to collect design data for the field demonstration and kinetic data for modeling the processes. Following completion of the treatability study, the pilot-scale effort will be designed. The design and plan for the demonstration will be described in the Technology Demonstration Plan.

The technology concept involves use of slow-release chemical oxidant cylinders to treat large dilute plumes of 1,4-dioxane. Other contaminants, including chlorinated solvents, can also be treated using this technology. Permanganate or unactivated persulfate embedded in a slow-release paraffin wax formulation (i.e., cylinder) can be emplaced in existing monitoring wells, a funnel-and-gate (F&G), permeable reactive barrier (PRB), or using direct push technology. The slow-release oxidant cylinders are either 1.35 inches or 2.5 inches in diameter and 18 inches long. The cylinder dimensions will allow for easy emplacement with commonly available Geoprobe® tooling.

These oxidants diffuse into the groundwater and slowly oxidize dioxane. They are slowly consumed and persist sufficiently long enough – estimated to be on the order of years – to result in dioxane destruction. While not commonly known, dioxane can be oxidized by permanganate and unactivated persulfate as described below. Because of the flexibility in distribution methods, this technology can be used in the form of a permeable reactive zone or in a grid and can be used in multiple hydrogeologic environments. For large and dilute dioxane plumes, or sites with access restrictions, a PRB or F&G configuration is likely to be the best remediation approach (Interstate Technology & Regulatory Council [ITRC] 2011).

The fundamental advantage of slow-release forms of oxidants over traditional injection of liquid solutions is the ability to release the oxidant over a period of years, which will minimize rebound, treat large/dilute plumes, and minimize operation and maintenance (O&M) costs. The mechanism for release of the oxidant from the paraffin wax matrix is a dissolution-diffusion process (Lee and Schwartz 2007). Particles of potassium permanganate ($KMnO_4$) or sodium persulfate ($Na_2S_2O_8$) that become exposed at the surface of the cylinder rapidly dissolve, resulting in a large initial spike in oxidant flux. As the oxidant particles dissolve, the surface of the exposed particles retreats into the core of the cylinder, creating secondary porosity. The oxidant release rate from the cylinder becomes limited by the oxidant diffusion rate through the porous structure, eventually reaching a nearly steady state flux rate until the oxidant is consumed.

Selection of permanganate or persulfate slow-release cylinders for the demonstration will depend on a variety of factors, including natural oxidant demand (NOD) rate and extent, seepage velocity, oxidant release rates, contaminant degradation efficiency, cost, and potential secondary aquifer geochemistry effects. A number of researchers have demonstrated that activation of persulfate is not always necessary for a number of contaminants, including trichloroethene (TCE) and dioxane (Liang et al. 2008b; Liang et al. 2007; Felix-Navarro et al. 2007). Dioxane oxidation by unactivated persulfate is slower than by activated persulfate, which is advantageous for this technology because it results in greater amendment persistence. These relatively slow dioxane removal rates compared to typical oxidation strategies are favorable because contamination is often present in large dilute plumes. Oxidant kinetics were evaluated in this study and are discussed in detail in subsequent sections.

1.2 OBJECTIVES

ESTCP Project Number ER-201324 involves the demonstration and validation of slow release oxidant cylinders for 1,4-dioxane treatment. The three technical objectives of this demonstration/validation project were to:

1) Demonstrate the use of slow-release chemical oxidant cylinders for sustained in situ treatment of 1,4-dioxane
2) Demonstrate that the slow-release cylinder delivery vehicle can minimize potential secondary effects such as metals mobilization and permeability reduction
3) Produce engineering guidance in the form of a practical spreadsheet tool

Draft Technology Performance Objectives were presented in the Site Screening Memorandum (CDM Smith 2013a).

Treatability study performance objectives, data requirements, and success criteria related to these objectives are presented in Table 1.1

Table 1.1 Treatability Study Performance Objectives

Performance Objective	Data Requirements	Success Criteria
Quantitative Performance Objectives		
Technology effectiveness	1,4-dioxane and VOC concentrations in influent and effluent	• 90 percent (%) reduction in 1,4-dioxane concentration with unactivated persulfate or permanganate • 90% reduction of chlorinated VOC co-contaminants with unactivated persulfate or permanganate
Qualitative Performance Objectives		
Determine design criteria for the field demonstration	• Second order rate constants for dioxane and VOC oxidation with unactivated persulfate and permanganate with site soil and groundwater • Oxidant flux from the cylinders and influent and effluent oxidant and contaminant concentrations	• Develop quantitative relationships and criteria for contaminant flux, contaminant oxidation, natural oxidant demand, oxidant flux, and oxidant consumption. • Use these relationships to develop design criteria for oxidant flux, which ensure satisfactory contaminant oxidation without releasing excess oxidant.
Characterize secondary environmental impacts	Pre- and post-treatment pH, heavy metals, and hexavalent chromium in batch studies	• Quantify the potential for the listed secondary impacts to result in exceedances of California maximum contaminant levels (MCLs).
Characterize manganese dioxide deposition and fouling potential	Scanning electron microscopy	Determine the extent to which cylinder porosity is blocked by manganese dioxide.
Characterize frac fluid compatibility with slow release material	Chemical compatibility tests	Determine whether the material is capable of being suspended in the frac gel for a period of 8 hours.

2.0 MATERIALS AND METHODS

The treatability study methods are described below and were conducted in general accordance with the approved work plan (CDM Smith 2013b). Significant deviations are described in Section 2.5.

2.1 SITE SOIL AND GROUNDWATER COLLECTION

Groundwater and soil sampling from NAS North Island Operable Unit 11 (the site) was conducted by NOREAS, Inc. on December 5, 2013 as described below. A utility clearance and geophysical survey were performed by ULS Services Corporation on November 25, 2013 at the boring locations. No obstructions or utility mains/manholes were within the planned area for drilling. Cascade Drilling drilled two boreholes (B1 and B2) using hollow-stem auger (HSA) for soil sampling (see Figure 2.1) on December 5, 2013. The boreholes were advanced to 40 feet below ground surface (ft bgs), and soil samples were collected from approximately 25 to 40 ft bgs using a 2.5-inch inner diameter continuous barrel sampler. Boreholes were abandoned in accordance with the State of California Well Standards (California Department of Water Resources Bulletin 74-90, Part III). Fifty-five kilograms of soil were collected, and soil was handled to minimize disturbance (aeration) to the extent practicable and packed (compressed) in multiple 1-gallon plastic sealable bags. These individual bags were placed in labeled 5-gallon buckets and sealed with a lid, tape, and wrapped with plastic wrap.

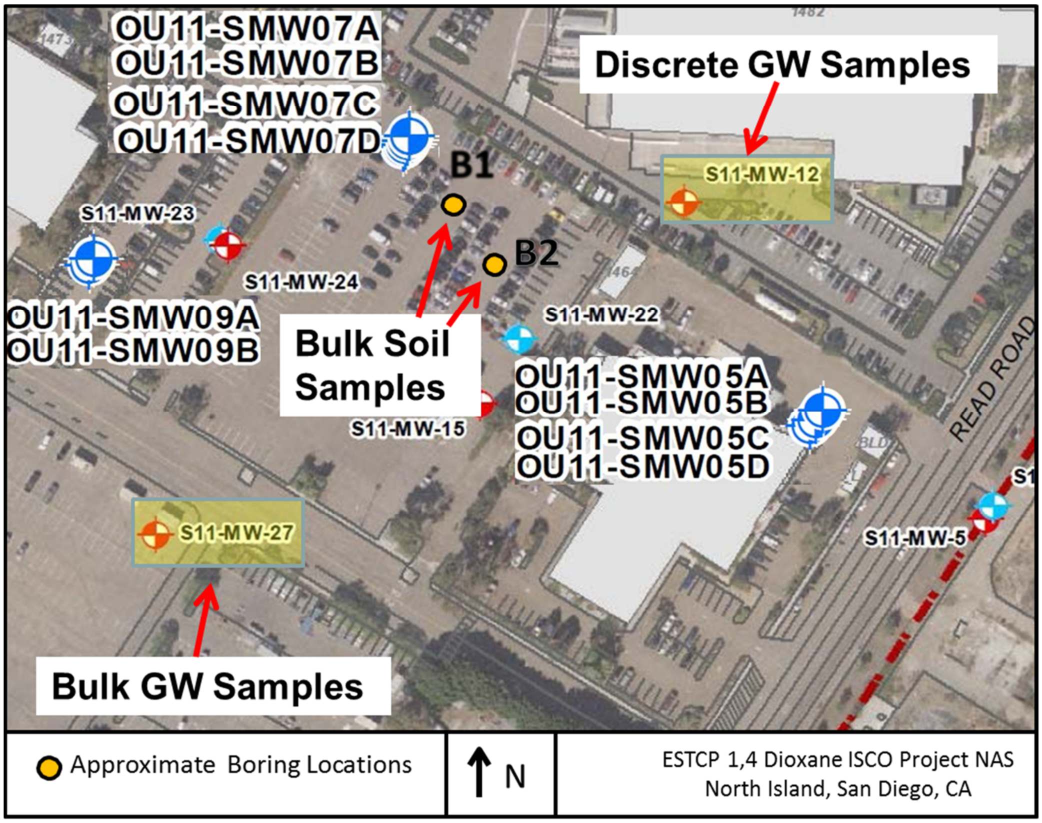

Figure 2.1 Site Plan Showing Soil and Groundwater Sampling Locations

A total of 345 liters of groundwater was collected from monitoring well S11-MU-27 (Figure 2.1) for the treatability study. Groundwater was collected using low flow sampling procedures, and water was collected once purge parameters (e.g., pH, conductivity, temperature, and turbidity) stabilized to ±0.1 standard units (SU) for pH, 3 percent for conductivity, and 10 percent for temperature and turbidity from three consecutive readings taken 3 to 5 minutes apart. Collected groundwater was placed into two labeled Department of Transportation (DOT)-approved 30-gallon poly drums. Groundwater from this well did not have appreciable levels of contamination based on historical data and was located within close proximity to the plume and the proposed demonstration area. This allowed tests to be conducted with relatively uncontaminated groundwater and with the same groundwater amended with specific site contaminants. In addition, Snap Samplers® (ProHydro, Inc.) were deployed at 29-31, 33-35, and 37-39 ft bgs in well S11-MW-12 to determine the relative distribution of contaminants over different stratigraphic units. Concentrations are reported in Table 2.1, indicating that contaminant concentrations were generally lowest in the shallowest groundwater horizon. Dioxane in particular had the greatest concentration in the deepest groundwater horizon. Bulk soil and groundwater were shipped by truck without refrigeration to Carus Corporation in LaSalle, Illinois on December 6, 2013 and were received on December 18, 2013. Soil from both borings was homogenized in the lab prior to testing.

Table 2.1 Groundwater Concentrations of Select Analytes in Well S11-MW-12

Analyte	Concentration (μg/L)		
	29-31 ft bgs	33-35 ft bgs	37-39 ft bgs
1,1-dichloroethane (DCA)	35	85	80
1,1-dichloroethene (1,1-DCE)	560 D	1,600 D	1,000 D
cis-1,2-dichloroethene (cis-1,2 DCE)	18	38	34
TCE	570 D	1,600 D	850 D
1,4-dioxane	53J	90	250

Notes: μg/L – micrograms per liter D – Diluted sample J – Estimated value

Investigation-derived waste (IDW) generated from development water and decontamination water was processed on site at NAS North Island's industrial water treatment plant. Solid IDW generated from drill cuttings was temporarily stored in five 55-gallon drums, characterized, and then disposed of off site by PCS Environmental Services on January 23, 2014.

2.2 BATCH AND COLUMN TESTS

2.2.1 Natural Oxidant Demand

To investigate the effect of soil oxidant demand due to the presence of naturally occurring organic matter and reduced metals, an NOD test was used to determine the background demand for the North Island site soil and groundwater. This testing was performed by Carus. A second-order rate NOD constant was estimated using procedures described previously (Siegrist et al. 2011; Cha et al. 2012; Borden et al. 2010). To determine the NOD rate, the soil was baked at 105 degrees Celsius (°C) for 24 hours then allowed to cool to room temperature. The soil was then blended and passed through a U.S. 10 sieve (2 millimeter [mm]). Glass reactors (240-milliliter [mL]) with Teflon®-lined caps were loaded with 50 grams (g) of soil and 100 mL of 0.05, 0.5, and 5 g/liter (L) $KMnO_4$ or $Na_2S_2O_8$ for an oxidant dosage of 0.1, 1.0, and 10 g/kilogram (kg) on a dry soil weight basis using a 1:2 soil to aqueous reagent ratio. The NOD samples were prepared and measured in triplicate. After adding the aqueous oxidant solution, the reaction vessels were inverted once to mix the soil and reagents. Residual potassium permanganate ($KMnO_4$) and sodium persulfate (NaS_2O_8) concentrations were determined over time. The demands were calculated on a dry weight basis. The second-order NOD rate constant was calculated using a spreadsheet tool described elsewhere (Borden et al. 2010). Spreadsheet tool output is included in the Appendix.

2.2.2 Batch Kinetics Tests

Batch reactor tests were conducted to estimate second-order reaction rate constants for 1,4-dioxane, TCE, cis-1,2-DCE, 1,1-DCE, and 1,1-DCA. These contaminants were selected based on historical groundwater detections at the site. CDM Smith and Carus both performed batch kinetics tests.

The tests were conducted either in 120-mL serum bottles with butyl rubber stoppers (dioxane tests only) or 40-mL volatile organics analysis (VOA) vials with Teflon®-lined septum caps. Initial proof-of-concept tests with dioxane only were conducted by CDM Smith. Subsequent tests with and without chlorinated VOCs and site soil were conducted by Carus. The tests with dioxane alone in de-ionized (DI) water conducted by CDM Smith and Carus were compared to assess inter-laboratory reproducibility. Studies in DI water without the presence of site soil contained 100-mL liquid in the serum bottles or 40-mL liquid in the VOA vials. Studies with site soil were conducted in VOA vials and contained 5 g of soil and 39 mL of liquid. These sample volumes allowed for a minimal amount of headspace in the VOA reactor vessel. Reactors were prepared by initially adding DI water, oxidant at various concentrations, and soil if required. The desired mixture of dioxane and chlorinated VOCs was then added to the vials, which were then capped, inverted to mix, and stored inverted at room temperature until the desired sampling time.

The CDM Smith proof-of-concept tests were conducted without replication, and the Carus tests were conducted in duplicate. In addition, both labs set up controls without oxidant. Samples were removed at various times and analyzed for residual oxidant and contaminants. Prior to analysis of the contaminants, the residual oxidant was quenched with ascorbic acid.

Calculation of first- and second-order rate constants was conducted as previously described (Waldemer and Tratnyek 2006; Felix-Navarro et al. 2007) and summarized below. The rate of 1,4 dioxane degradation can be expressed by the following equations:

$$\frac{-d[1,4\ dioxane]}{dt} = k_1[1,4\ dioxane] \tag{1}$$

$$k_1 = k_2[KMnO_4\ or\ Na_2S_2O_8] \tag{2}$$

Where k_1 is the pseudo first-order rate constant and k_2 is the second-order rate constant. A plot of the natural logarithm of the contaminant concentration versus time yields a straight line with a slope $-k_1$ provided the oxidant concentration does not appreciably change during the time period of analysis. The first-order rate constant is plotted against the "constant" oxidant concentrations to yield a slope equal to the second-order rate constant k_2.

As described in Section 3, chlorinated ethene concentrations in the presence of site soil were reduced by more than 99 percent by the first sampling time. Therefore, minimum rate constants for chlorinated ethene oxidation were calculated using the oxidant-free control sample as an estimate for the initial concentration and the measured chlorinated ethene concentration in the presence of oxidant at the initial sampling point (i.e., 2 hours). Measurement of rate constants with persulfate in the presence of soil and groundwater were conducted at a single oxidant concentration. Therefore, the second-order rate constant was calculated by dividing the estimate for the first-order rate constant by this oxidant concentration.

2.2.3 Column Tests

The two key processes affecting oxidant concentration and distribution using the slow-release oxidant technology are (1) oxidant release from the slow release cylinder matrix and (2) the reactive transport of oxidant through the aquifer material. One-dimensional column experiments were conducted by Carus to provide data to characterize oxidant release and evaluate contaminant degradation in the presence of site soil and groundwater. Column experiments were conducted using permanganate and persulfate slow-release cylinders in the presence of (1) clean sand and DI water; (2) site soil and groundwater; and (3) site soil and groundwater containing dioxane, TCE, cis-1,2-DCE, 1,1-DCE, and 1,1-DCA. The column studies conducted with sand and DI water or soil and uncontaminated groundwater were conducted in 4-inch inside diameter (ID) by 24-inch long polyvinyl chloride (PVC) pipes with PVC end caps (Figure 2.2). These columns were designated as the "control columns." Column studies conducted with site soil and groundwater containing site contaminants ("contaminant columns") were conducted in glass columns (4-inch ID x 24-inch length) with stainless steel end caps. For all columns, oxidant cylinders measuring 2.5 inches in diameter and 3 inches in length were emplaced 4 inches from the bottom of the columns, allowing for an 18-inch oxidant transport distance prior to reaching the effluent sampling port. Prior to packing the columns, the 3-inch pieces of slow-release oxidant cylinders were capped at the end with paraffin wax to ensure that oxidant diffusion occurred in the radial direction only. To pack the columns a 2-to-3-inch layer of the selected media was placed in the bottom of the column. DI water or site groundwater was then added to the columns to fully cover the porous media. The oxidant cylinder pieces were emplaced on their sides on top of the porous media so that column flow would be transverse to the cylinder axes as shown in Figure 2.3. Additional porous media were then added to cover the cylinder piece and fully wet-pack the columns. Peristaltic pumps were used to convey DI or groundwater to the columns. Syringe pumps were used to introduce a concentrated solution of dioxane, TCE, cis-1,2-DCE, 1,1-DCE, and 1,1-DCA to the groundwater prior to entry into the contaminant columns. The water flow rate was initially 0.15 milliliters per minute (mL/min) for an estimated hydraulic residence time of 5 days. The flow rates were decreased to 0.05 mL/min (15-day hydraulic residence time) on day 40 in the persulfate contaminant column and day 43 in the permanganate contaminant column. The flow rates were decreased in the DI control columns on day 34 and in the soil/groundwater control columns on day 36. The flow rates were decreased to increase residence time within the column to increase contaminant removal. Influent and effluent samples were collected regularly and analyzed for contaminants, residual oxidant, and pH as described below.

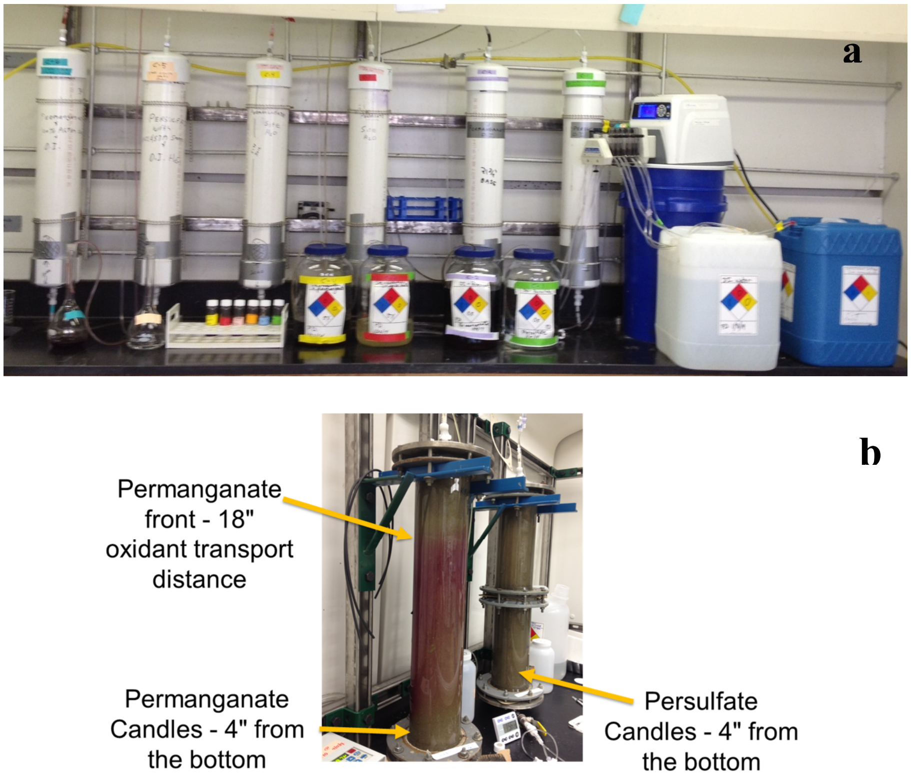

Figure 2.2 Setup for Control (a) and Contaminant (b) Columns

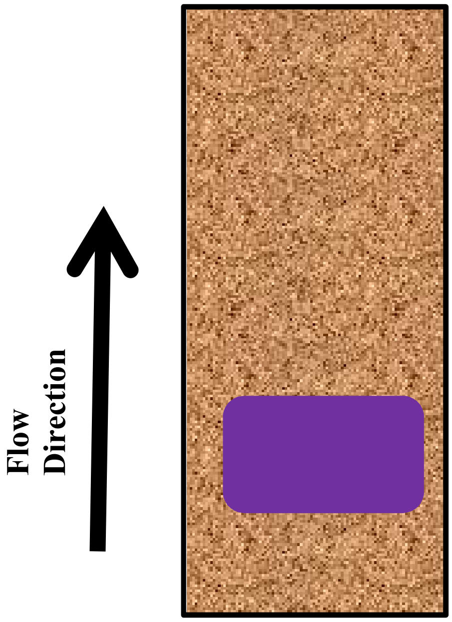

Figure 2.3 Slow-Release Cylinder Orientation in each Column

2.3 HYDRAULIC FRACTURING TESTS

To investigate the possibility of fracturing a form of the slow-release oxidant-based technology into subsurface porous media, Carus has developed small beads of sustained-release (SR) oxidant. The beads or "pastilles" are approximately 5 millimeters or less in diameter and are comprised of paraffin wax and oxidant that could serve as a sustained source of oxidant for dioxane and co-contaminant treatment (Figure 2.4).

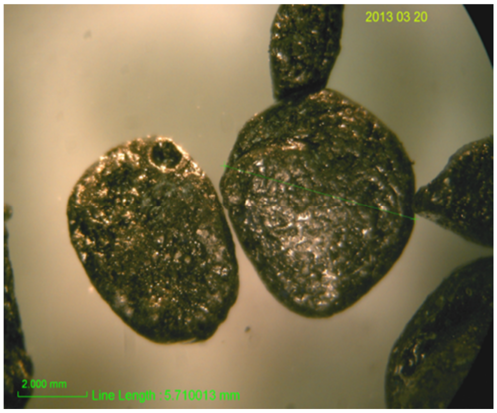

Figure 2.4 Photograph of Slow-Release Permanganate-Wax Pastilles

A chemical compatibility test was conducted by Frac Rite^{TM} (Calgary, Alberta, Canada) by mixing the SR pastilles with a polysaccharide gel (e.g., guar). The purpose of this test was to evaluate long-term settling or instability, which provides constraints for how slurry must be mixed prior to fracturing. The actual test is qualitative in nature and consisted of slowly mixing the pastilles with the gel in a kitchen blender for about 2 hours. During the first 30 minutes of blending, the mixture was visually inspected for chemical compatibility with the gel. The mixture was then poured into a beaker and allowed to remain in the beaker for up to 8 hours. The mixture was periodically inspected for settling or other indications of chemical incompatibility. After 8 hours, the non-Newtonian nature of the mixture was qualitatively assessed by slowly pouring the mixture into a second beaker. As the mixture was poured, the fluid was observed to determine whether it could be suspended in air and form a "lip." The length of the "lip" that was created was compared to the gel in the absence of the pastilles (i.e., the control) as an indicator of changes in viscosity of the non-Newtonian nature of the fluid. If the fluid could not be suspended and immediately poured into the beaker, then the gel was determined to be incompatible with the pastilles.

2.4 ANALYTICAL METHODS

Methods used for analysis of groundwater samples are listed in Table 2.2. In addition, cylinders were removed from the flow-through columns at the end of operations and extracted to estimate the mass of remaining oxidant. First, a representative sample of each cylinder cross-section was grated using a kitchen grater. The methods used for assaying the grated permanganate and persulfate cylinders were different. The permanganate cylinder assay was based on a standard method for permanganate (American Water Works Association [AWWA] 2010): 1 g of the grated sample was added to a 500-mL Erlenmeyer flask with 1.8 g of sodium oxalate, ~100 mL of DI water, and 25 mL of concentrated sulfuric acid. Sodium oxalate reduces permanganate to Mn^{2+} in an acidic environment. The sample was then heated above 80°C while stirring and then titrated with a 0.0316 normal (N) $KMnO_4$ solution until the solution turned a pale pink, indicating the endpoint. The following equation was used to determine the percent $KMnO_4$:

$$\%KMnO_4 = \frac{100[(0.4718S)-(31.606TN)]}{Ws} \qquad (2)$$

S= Sodium Oxalate weight, mg
T= Titration Volume, mL of 0.0316N $KMnO_4$ solution
N= Normality of $KMnO_4$ solution
Ws= Weight of sample, mg

For the persulfate cylinder assay analyses, a 1-g sample of grated cylinder was added to a glass reactor with 10-mL of hexane (~10 mL) in order to dissolve the paraffin wax. The glass reactor was allowed to agitate for 2 hours until all of the paraffin dissolved. DI water was then added to the glass reactor and agitated in order to allow persulfate to partition into the aqueous phase. A sample (~5 mL) was withdrawn from the reactor and placed in a fume hood to allow any residual hexane to evaporate. The aqueous sample was then analyzed for residual persulfate by iodometric titration method (Liang et al. 2008a).

Metals analyses were performed by Carus, and split samples were sent to OnSite Environmental to independently validate analytical results from Carus.

Table 2.2 Analytical Methods for Aqueous Samples

Analyte	Laboratory	Method
pH	CDM Smith, Carus	Standard Method 4500-H^+
1,4-dioxane	CDM Smith, Carus	Purge and trap sampling followed by gas chromatography with mass selected detection. U.S. Environmental Protection Agency (EPA) Method 5030 and EPA Method 522
Volatile organic compounds	Carus	Purge and trap sampling followed by gas chromatography with mass selected detection. EPA Method 5030 and EPA Method 8260B
Potassium permanganate	CDM Smith, Carus	Absorbance at 525 nanometers (nm). Standard Methods 4500-$KMnO_4$
Sodium persulfate	CDM Smith, Carus	Iodometric titration with sodium bicarbonate ($NaHCO_3$) and potassium iodide (KI) measurement of absorption at 352 nm or 400 nm (Liang et al. 2008a)
Dissolved metals	Carus OnSite Environmental	EPA Methods 200.7 [arsenic (As), total chromium (Cr), lead (Pb), nickel (Ni), manganaese (Mn), and silver (Ag)], and 213.2 (Cd) after 0.45 micormeter (µm) filtration EPA Method 200.8. (As, Cd, total Cr, Pb, Ni, and Ag) after 0.45 µm filtration

2.5 DEVIATIONS FROM THE WORK PLAN

Deviations from the work plan (CDM Smith 2013b) are as follows:

- Two-dimensional tank experiments were not conducted. One-dimensional column experiments were sufficient to obtain the necessary data.
- Hexavalent chromium was not quantified because of technical difficulties with the analytical method. However, a reasonable assumption is that, following chemical oxidation, dissolved chromium is in the hexavalent form (Chambers et al. 2000a; Chambers et al. 2000b).
- Scanning electron microscopy (SEM) of the spent cylinders was not conducted because of incompatibility issues of the semi-volatile wax with the instrument.
- Batch metals mobilization data were to be obtained by taking samples from the NOD reactors. While this was conducted, the data were not consistent and are therefore not reported. For further discussion see Section 2.6.

2.6 QUALITY ASSURANCE AND QUALITY CONTROL

Multiple experiments were used to evaluate data, including comparison to literature values. Laboratory instruments were calibrated in accordance with EPA methods, Carus Corporation Laboratory standard operating procedures, instrument manufacturer's recommendations, and/or internal quality assurance (QA) procedures. Reagents used were of the standards specified in the work plan. Data quality was generally good and acceptable for use. Split samples for metals analysis for the 1-D column experiment were sent to OnSite Environmental for comparison

(Table 3.3 in Section 3.6). Quality assurance and quality control results are summarized in the Appendix. Notable exceptions are identified below.

- Batch kinetics data for dioxane and chlorinated VOCs with permanganate in the presence of soil and groundwater were reported only for the test condition with approximately 1 milligram per liter (mg/L) initial contaminant concentrations. Data for other initial contaminant concentrations (i.e., 0.1, 0.5, and 5 mg/L) were excluded because the data sets either did not have enough non-detectable data points to generate a reliable curve or did not demonstrate an appreciable reduction in contaminant concentration.
- Batch kinetics data for dioxane and chlorinated VOCs with persulfate at 100, 500, and 1,000 mg/L in the presence of soil and groundwater were excluded because measurable changes in contaminant concentrations were not observed (e.g., concentrations were within 10 percent of starting conditions). This lack of removal was attributable to lower than expected reaction rates. The test was repeated with 10,000 mg/L persulfate and a single concentration of each contaminant.
- Batch kinetics metals mobilization data were not reported because several metals were detected in the persulfate control bottles that contained only DI water and sodium persulfate. For example, 2.4 to 5.2 mg/L of dissolved arsenic was detected in these controls. Mass balances on potassium in the permanganate reactors also did not close – there was greater potassium detected in the control reactors than in those with soil.
- Matrix spikes and matrix spike duplicates (MS/MSD) were not performed by Carus or CDM Smith laboratories. Analytical duplicates were not performed by Carus. A summary of QA/quality control (QC) results is available in the Appendix.

3.0 RESULTS AND DISCUSSION

3.1 SOIL NATURAL OXIDANT DEMAND

NOD measurements included the "fast" NOD, which is estimated as the 48-hour NOD and the second-order NOD rate constant. The 48-hour fast NOD concentrations for site soil with permanganate are shown in Figure 3.1. The NOD of site soil with permanganate increased with increasing permanganate dose and ranged from 0.089±0.0003 milligram per kilogram (mg/kg) to 0.41±0.02 mg/kg. The 48-hour fast NOD with persulfate was negligible.

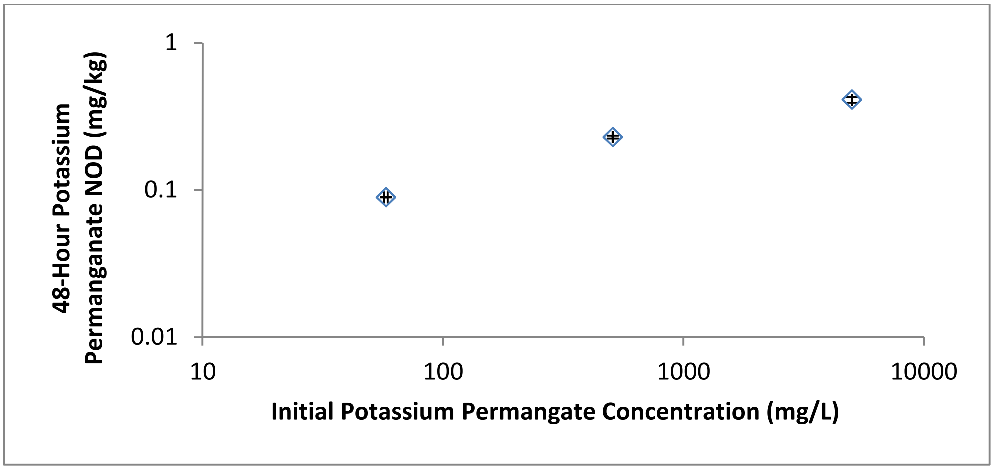

Figure 3.1 48-Hour Fast NOD of Site Soil with Potassium Permanganate

The second-order NOD rate constant for permanganate was determined using permanganate concentration-time data using software and methods that have been described previously (Siegrist et al. 2011; Borden et al. 2010). The second-order NOD rate constant for permanganate in the presence of site soil and groundwater was estimated to be 0.008 per millimolar per day (mM^{-1} d^{-1}) (see Appendix). The total NOD was estimated to be 0.8 g $KMnO_4$/kg.

No persulfate oxidant consumption was observed in the presence of site soil and groundwater after 48 hours, or up to 12 days (see Appendix), and therefore no rate constants were calculated.

3.2 BATCH KINETIC TEST RESULTS

3.2.1 Dioxane Oxidation in De-Ionized Water

Figure 3.2 shows the change in dioxane concentrations in de-ionized water upon exposure to various concentrations of permanganate conducted by CDM Smith. The linearity of the trends on this semilogarithmic graph indicates first-order kinetics. Negligible dioxane loss was observed in the control (i.e., no oxidant), and the greatest rate of removal was observed in the presence of the high permanganate concentration. The slopes of the curves in Figure 3.2 were used to estimate first-order rate constants.

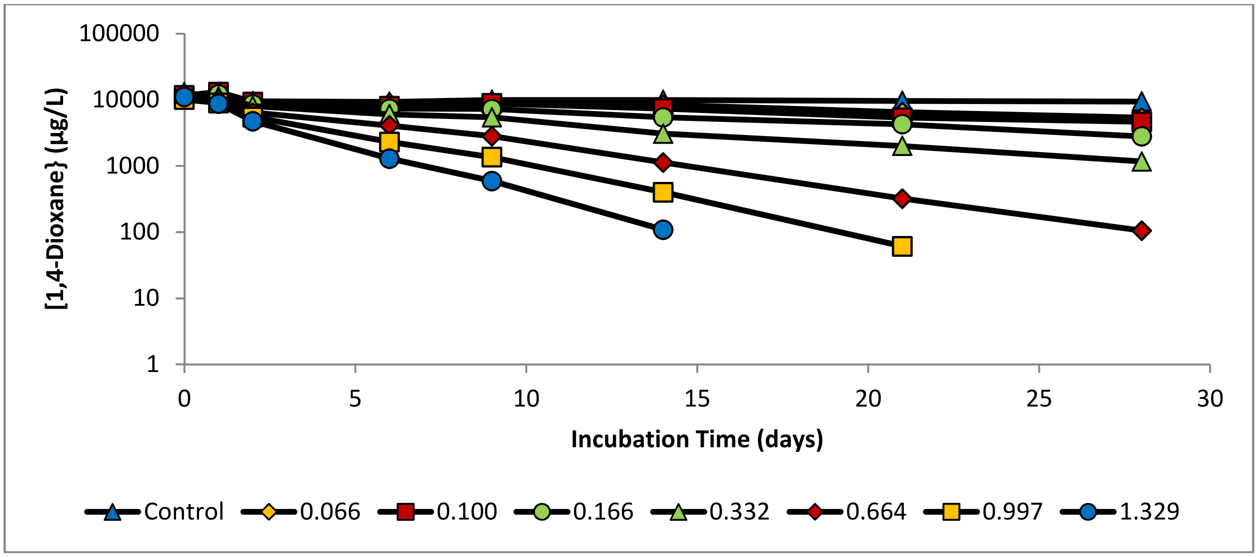

Figure 3.2 Dioxane Oxidation in De-ionized Water in the Presence of Various Concentrations (%) of Potassium Permanganate ($KMnO_4$)

These rate constants were then plotted as a function of the initial permanganate concentrations in Figure 3.3. The linearity ($r^2 = 0.999$) of the curve indicates that a second-order kinetic model was appropriate, and the second-order rate constant was estimated at 4.3×10^{-5} per molar per second ($M^{-1}\ s^{-1}$). Permanganate concentrations decreased during the tests an average of 5.6±1.4 percent, and the maximum decrease was 6.9 percent. Therefore, the assumption of relatively constant oxidant concentrations was valid, and use of initial oxidant concentrations in Figure 3.3 was appropriate. A separate test conducted under identical conditions by Carus yielded an average second-order rate constant of $3.3 \times 10^{-5}\ M^{-1}\ s^{-1}$. The relative percent difference between these two estimates is 53 percent. This variability of the two tests provides order-of-magnitude rate constant estimates that are sufficient for pilot study planning purposes.

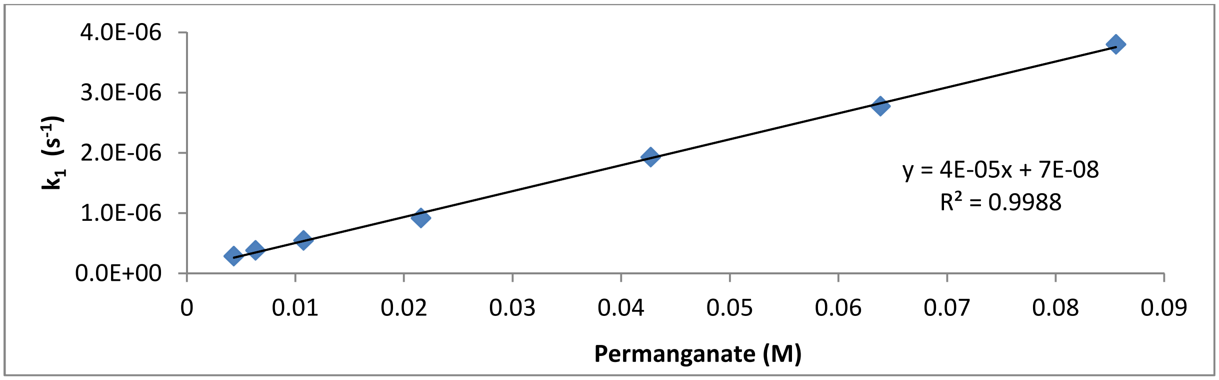

Figure 3.3 Relationship between First-Order Rate Constants for Dioxane Removal in DI Water and Initial Permanganate Concentration

Figure 3.4 shows the change in dioxane concentrations in de-ionized water upon exposure to various concentrations of persulfate conducted by CDM Smith. The nonlinearity of the trends on this semilogarithmic graph indicates non-first-order kinetics. The slopes of the curves – which are equal to the pseudo first-order rate constants – increase over time, suggesting some type of persulfate activation. However, no intentional activation of persulfate (e.g., hydrogen peroxide, iron or other metal ions, high pH, heat, etc.) was conducted. As with permanganate, negligible decrease of dioxane concentration was observed in the absence of oxidant, and the greatest rate was observed with the greatest concentration of persulfate. The average slopes of the curves in Figure 3.4 were used to estimate pseudo first-order rate constants. The r^2 values of these regressions ranged from 0.822 to 0.974.

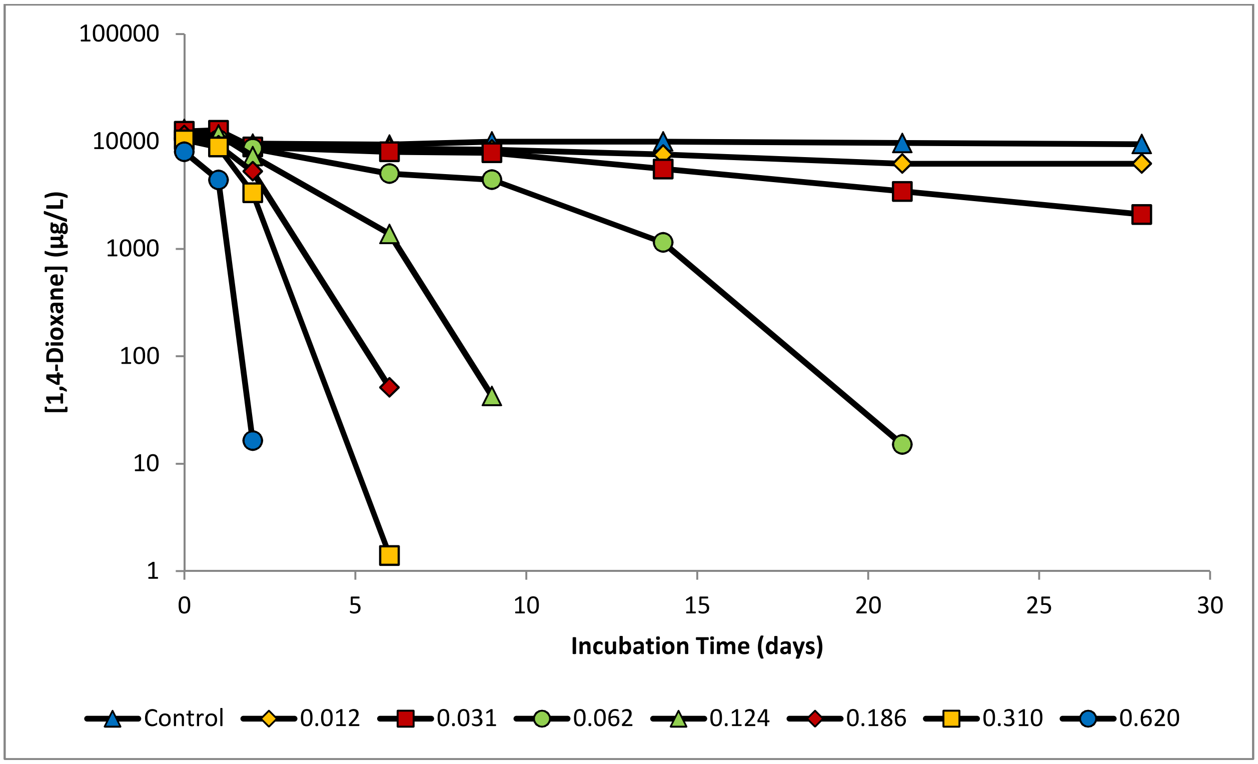

Figure 3.4 Dioxane Oxidation in De-ionized Water in the Presence of Various Concentrations (%) of Sodium Persulfate ($Na_2S_2O_8$)

These pseudo first-order rate constants were then plotted as a function of the initial persulfate concentrations in Figure 3.5. The linearity ($r^2 = 0.998$) of the curve indicates the reaction was apparently second-order with respect to the oxidant concentration. However, these data are not sufficient to inform the actual mechanism of oxidation. The pseudo second-order rate constant was estimated at $1.4 \times 10^{-3}\ M^{-1}\ s^{-1}$. This value is about 30-fold greater than that for permanganate. Persulfate concentrations began to decrease after approximately 5 days, with an average of 5.4±6.3 percent and a maximum decrease of 19 percent during the study. The 19 percent persulfate loss was associated with the test condition that contained 0.05 percent persulfate (0.0027 M). A separate test conducted under identical conditions by Carus yielded an estimate for the second-order rate constant of $1.2 \times 10^{-3}\ M^{-1}\ s^{-1}$. The relative percent difference between these two estimates is 24 percent and both were the same order of magnitude.

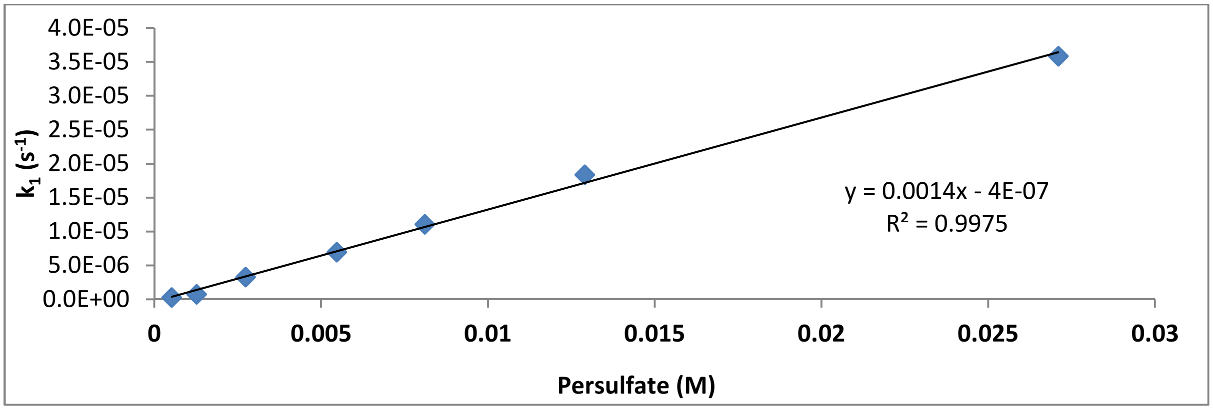

Figure 3.5 Relationship between First-Order Rate Constants for Dioxane Removal in DI Water and Initial Persulfate Concentration

3.2.2 Dioxane Oxidation in Site Soil and Groundwater

A second series of batch tests were conducted in the presence of site soil and groundwater. In addition, the tests were conducted with a mixture of dioxane, TCE, cis-1,2-DCE, 1,1-DCE, and 1,1-DCA. Figure 3.6 presents the result for dioxane and demonstrates increasing dioxane removal rates with increasing permanganate concentration. The curves generally followed first-order kinetics; however, the dioxane removal rate appeared to decline near the end of the study and especially with lower initial permanganate concentrations. Therefore, the 500-hour data points were not used to estimate first-order rate constants. The 10,000 mg/L and 5,000 mg/L starting doses of potassium permanganate were sufficient to reduce 1,4-dioxane by 90 percent.

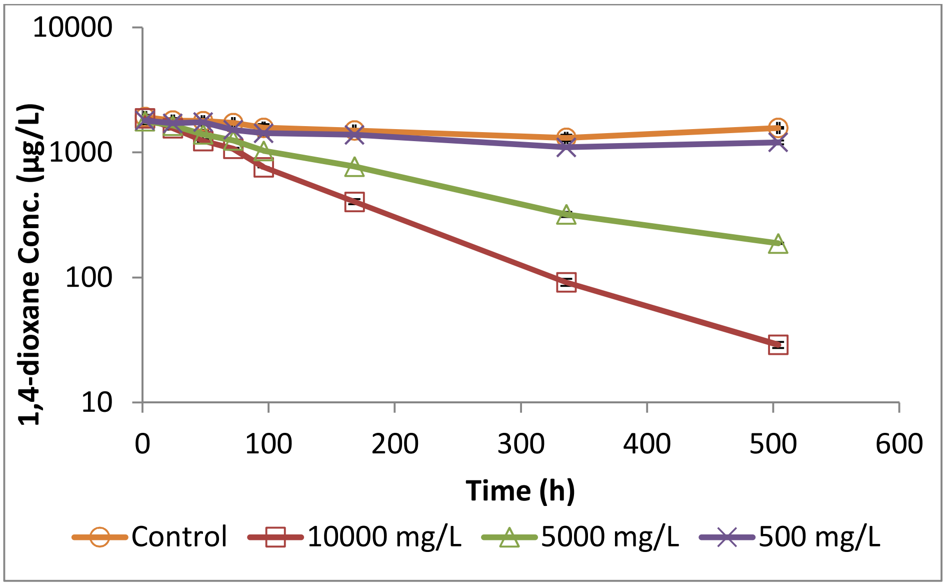

Figure 3.6 Dioxane Removal by Various Concentrations of Potassium Permanganate ($KMnO_4$) in the Presence of Soil and Groundwater, Error Bars Denote Standard Deviation on Duplicate Runs

The reason for the rate decline may have been attributable to soil oxidant demand and relatively greater losses of oxidant in test conditions having lower initial oxidant concentrations. Table 3.1 shows the percent loss of potassium permanganate at various initial doses.

Table 3.1 Site Soil and Groundwater Potassium Permanganate Kinetics Testing Results

Potassium Permanganate Dose (mg/L)	Condition	Percent Loss of Potassium Permanganate (%)
10,000	With contaminants	0.3
	Without contaminants	0.9
5,000	With contaminants	1.6
	Without contaminants	2.1
500	With contaminants	13
	Without contaminants	16

Figure 3.7 illustrates the relationship between the first-order rate constants for dioxane removal in the presence of soil, groundwater, and chlorinated VOCs and the initial potassium permanganate concentration. The estimate of the second-order rate constant is 3.4×10^{-5} M^{-1} s^{-1}, which is similar to the Carus estimate in de-ionized water (3.3×10^{-5} M^{-1} s^{-1}). These data indicate that the presence of soil, groundwater, and chlorinated VOCs did not affect the second-order rate constant for dioxane oxidation by permanganate. The data are also similar to previous research (Waldemer and Tratnyek 2006) where the second order rate constant in phosphate buffer was 4.19×10^{-5} M^{-1} s^{-1}.

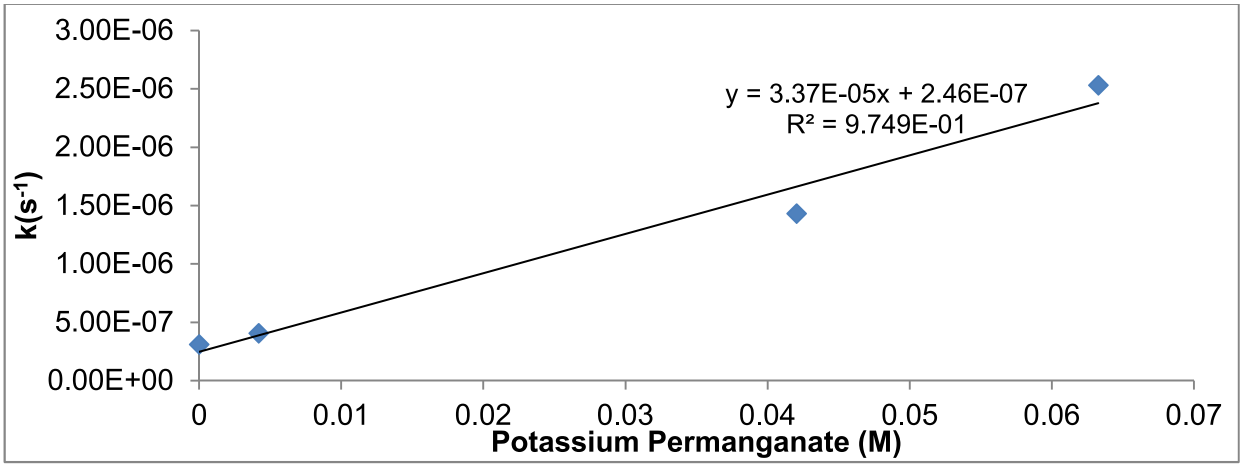

Figure 3.7 Relationship between First-Order Rate Constants for Dioxane Removal and Initial Permanganate Concentration in the Presence of Soil, Groundwater, and Chlorinated VOCs

Figure 3.8 illustrates the concentration trends of the chlorinated VOCs in soil and groundwater along with dioxane in the presence of various permanganate concentrations. The data indicate that chlorinated ethene concentrations were reduced by over 99 percent compared to the no-oxidant control at the first sampling time (2 hours). The sole chlorinated ethane (1,1-DCA) was not removed. These results are consistent with expected reactivity of permanganate (Waldemer and Tratnyek 2006). Permanganate is capable of oxidizing chlorinated ethenes containing carbon double bonds but not chlorinated ethanes. The rapid reactivity complicated estimation of rate constants, which is discussed below. Nevertheless, the data demonstrate that chlorinated ethenes were capable of being rapidly oxidized by permanganate in the presence of dioxane and site soil and groundwater.

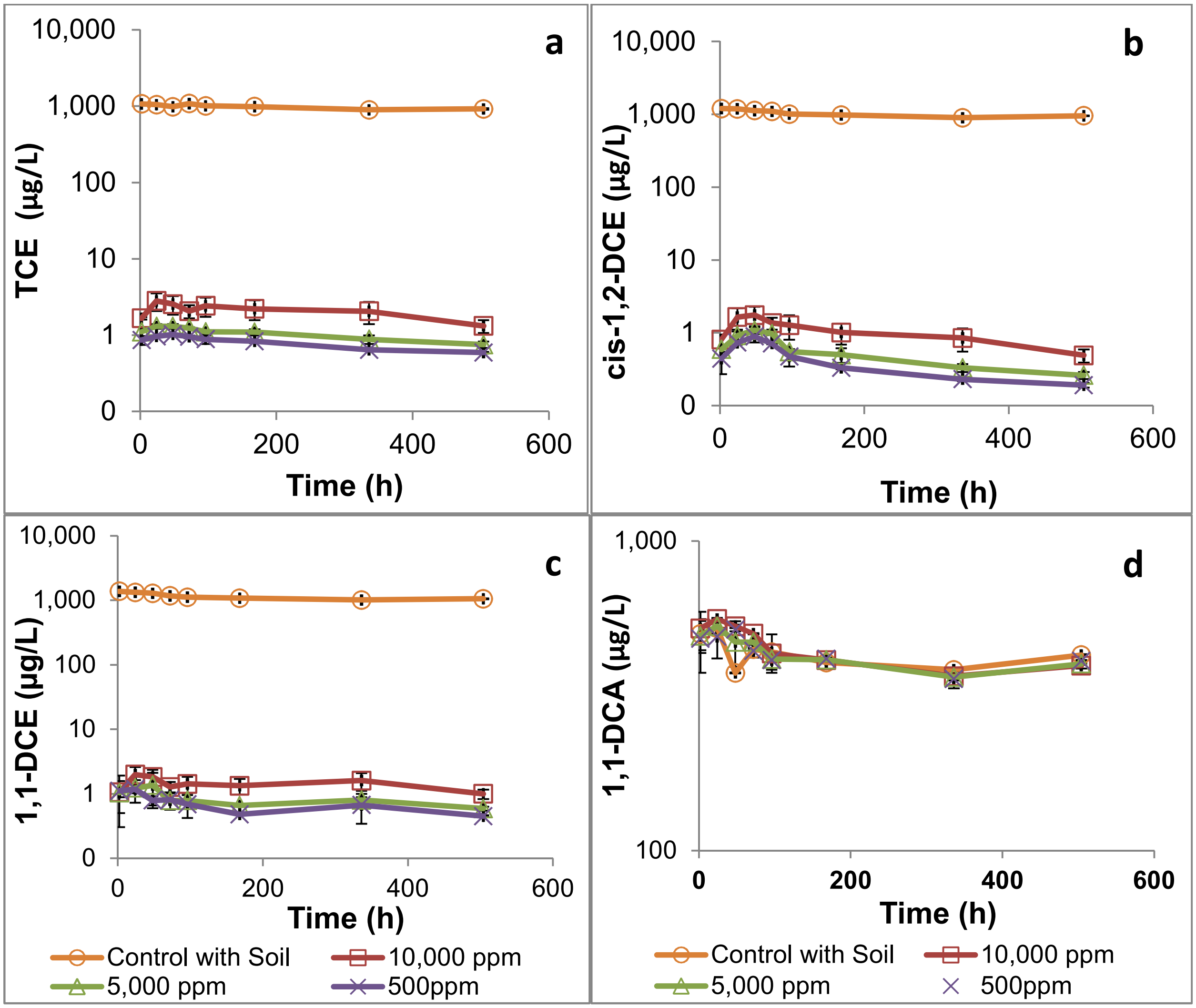

Figure 3.8 Potassium Permanganate ($KMnO_4$) Effect on Concentrations of TCE (a), cis-1,2-DCE (b), 1,1-DCE (c), and 1,1-DCA (d) in the Presence of Dioxane, Soil, and Groundwater, Error Bars Denote Standard Deviation on Duplicate Runs

Figure 3.9 illustrates the concentration trends of the chlorinated VOCs in soil and groundwater along with dioxane in the presence of 10,000 mg/L persulfate. Preliminary experiments conducted with lower persulfate concentrations (100 to 1,000 mg/L) did not result in reductions of dioxane or chlorinated VOCs within the testing duration of 14 days (data not shown). A second test with 10,000 mg/L persulfate was conducted and resulted in 90 percent or more removal of dioxane and chlorinated ethenes (Figure 3.9). 1,1-DCA was removed only by 22 percent, again indicating the relative recalcitrance of chlorinated ethanes. Non-first-order behavior was apparent with dioxane and chlorinated ethenes in the presence of soil and groundwater similar to that observed with dioxane in de-ionized water (Figure 3.4). Thus, some type of apparent persulfate activation was occurring in the presence of soil and groundwater as was observed in de-ionized water alone without chlorinated VOCs.

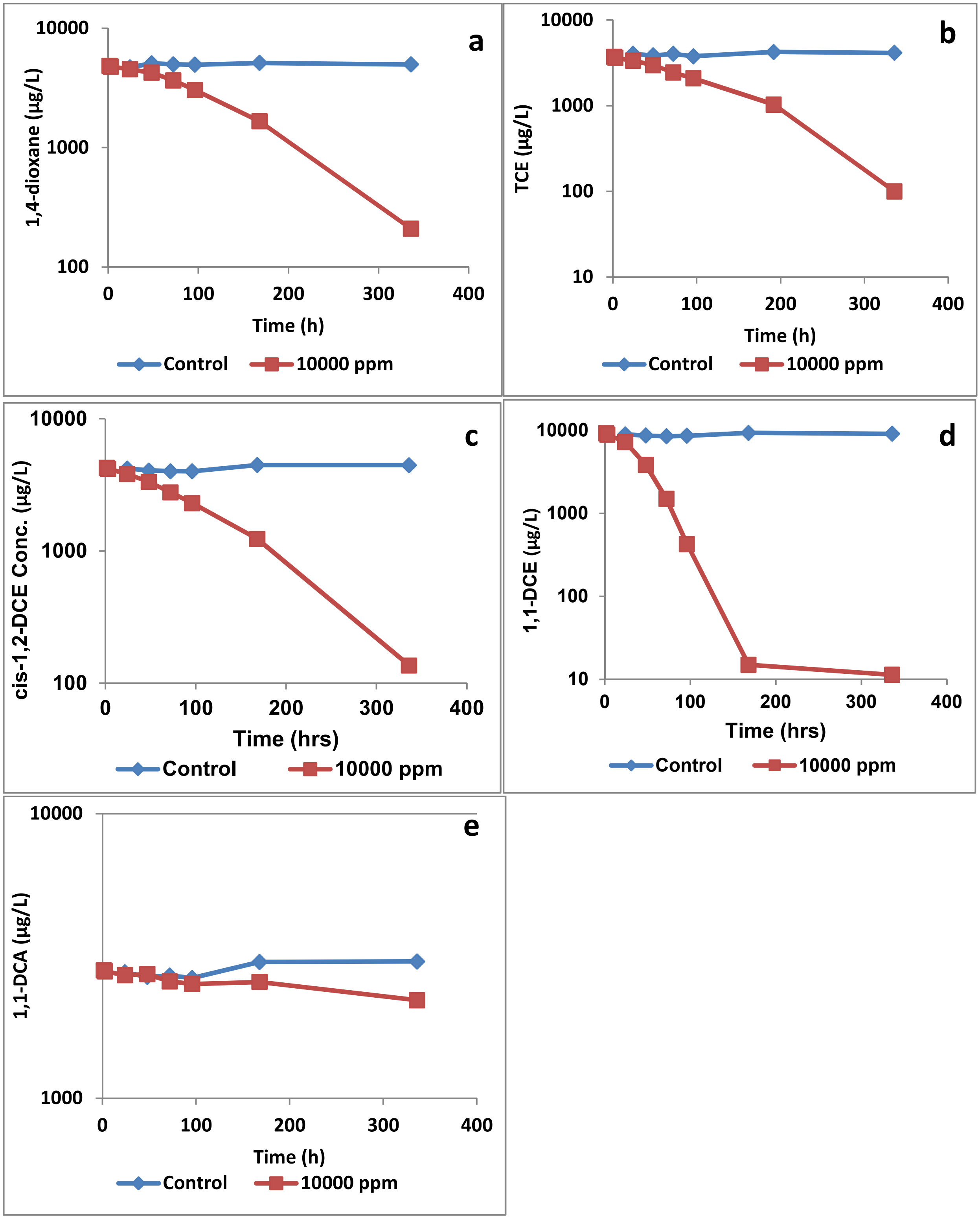

Figure 3.9 Persulfate Effect on Concentrations of Dioxane (a), TCE (b), cis-1,2-DCE (c), 1,1-DCE (d), and 1,1-DCA (e) in the Presence of Soil and Groundwater

Table 3.2 presents a compilation of pseudo second-order rate constants for all of the tests presented above. Second-order rate constants for dioxane oxidation with permanganate in de-ionized water or in soil and groundwater were similar to each other and within the range previously reported in the literature (Waldemer and Tratnyek 2006). These data corroborate the ability of permanganate to oxidize dioxane. Chlorinated ethene oxidation with permanganate in soil and groundwater was more rapid than dioxane oxidation, and accurate rate constants were not estimable. Minimum estimates for the rate constants were calculated and are consistent with literature values (Waldemer and Tratnyek 2006). 1,1-DCA was not oxidizable by permanganate as has been reported for other chlorinated alkanes (Waldemer and Tratnyek 2006).

Table 3.2 Estimated Pseudo Second-Order Rate Constants

Contaminant	Oxidant	Matrix	k_2 (M^{-1} s^{-1})	Reference
Dioxane	Permanganate	DI water	4.3×10^{-5}	This study (CDM Smith)
		DI water	2.5×10^{-5}	This study (Carus)
		Phosphate buffer	4.19×10^{-5}	(Waldemer and Tratnyek 2006)
		Soil and groundwater	2.7×10^{-5}	This study (Carus)
TCE		Soil and groundwater	> 0.24	This study (Carus)
		Phosphate buffer	0.46 to 0.76	(Waldemer and Tratnyek 2006)
cis-1,2-DCE		Soil and groundwater	> 0.26	This study (Carus)
		Phosphate buffer	0.69 to 0.71	(Waldemer and Tratnyek 2006)
1,1-DCE		Soil and groundwater	> 0.24	This study (Carus)
		Phosphate buffer	0.21 to 0.25	(Waldemer and Tratnyek 2006)
1,1-DCA		Soil and groundwater	No removal	This study (Carus)
1,2-dichloroethane (DCA)		Phosphate buffer	$< 1 \times 10^{-5}$	(Waldemer and Tratnyek 2006)
Dioxane	Persulfate	DI water	1.4×10^{-3}	This study (CDM Smith)
		DI water	1.1×10^{-3}	This study (Carus)
		DI water	1.7×10^{-3}	Estimated from (Felix-Navarro et al. 2007)
		Soil and groundwater	4.6×10^{-5}	This study (Carus)
TCE		Soil and groundwater	5.3×10^{-5}	This study (Carus)
		DI water	2.4×10^{-4}	Estimated from (Liang et al. 2007)
cis-1,2-DCE		Soil and groundwater	5.0×10^{-5}	This study (Carus)
1,1-DCE		Soil and groundwater	1.9×10^{-4}	This study (Carus)
1,1-DCA		Soil and groundwater	3.3×10^{-6}	This study (Carus)

The second-order rate constant for dioxane oxidation by persulfate in de-ionized water (1.2 to 1.4 $\times 10^{-3}$ M^{-1} s^{-1}) was similar to a value of 1.7×10^{-3} M^{-1} s^{-1} estimated using data reported in the literature (Felix-Navarro et al. 2007). Rate constants for dioxane oxidation with sodium persulfate in the presence of chlorinated VOCs, soil, and groundwater were 4.7 percent of those measured in de-ionized water and in the absence of chlorinated VOCs (5.7×10^{-5} versus 1.2×10^{-3} M^{-1} s^{-1}). Rate constants for oxidation of TCE and cis-1,2-DCE were similar to those for dioxane in the presence of soil and groundwater (i.e., 6×10^{-5} and 5×10^{-5} M^{-1} s^{-1}, respectively). Compared to the rate constants for TCE and cis-1,2-DCE, the rate constant for 1,1-DCE was about one order of magnitude greater, and the rate constant for 1,1-DCA was about one order of magnitude lower. A second-order rate constant for TCE in de-ionized water was not estimated, but data in the literature (Liang et al. 2007) were used to estimate a value of 2.4×10^{-4} M^{-1} s^{-1} for TCE, which is one order-of-magnitude greater than the value measured in soil and groundwater. These data suggest that the soil and/or groundwater inhibited oxidation of the organic compounds but did not completely prevent oxidation. The inhibition of persulfate oxidation by soil and groundwater resulted in the rate constants for dioxane oxidation with permanganate and persulfate being similar (3.4×10^{-5} versus 5.7×10^{-5} M^{-1} s^{-1}) in the presence of chlorinated VOCs, soil, and groundwater.

3.3 COLUMN TEST RESULTS

Figure 3.10 shows the removals of individual contaminants in the permanganate column study. Dioxane was not appreciably removed by permanganate even though removal was observed in the batch kinetics study. The chlorinated ethenes TCE, cis-1,2-DCE and 1,1-DCE were removed to non-detectable concentrations. 1,1-DCA was not removed, which is consistent with the batch kinetic study results. The observed second-order reactor rate constants were calculated from the influent and effluent contaminant concentrations, hydraulic residence time (HRT), and effluent oxidant concentration by the following equation:

$$k_{reactor} = \ln\left(\frac{[Influent]}{[Effluent]}\right)\left(\frac{1}{[Oxidant]}\right)\left(\frac{1}{HRT}\right) \tag{3}$$

The second-order reactor rate constant for dioxane removal from the reactor was estimated to be $1.1 \pm 0.6 \times 10^{-4}$ M^{-1} s^{-1} (see Appendix). This value is about one order-of-magnitude greater than that observed in the batch kinetics test, suggesting that kinetic limitations of dioxane oxidation did not occur in the column study. Rather, dioxane removal was low apparently because of low permanganate concentrations, which ranged from 260 to 2,100 mg/L. Minimum second-order reactor rate constants were estimated for the chlorinated ethenes because the effluent concentrations were less than the detection limit. These minimum reactor rate constants for TCE, cis-1,2-DCE, and 1,1-DCE were similar and estimated to be $2.2 \pm 0.6 \times 10^{-3}$ M^{-1} s^{-1} (see Appendix). The values are about two orders-of-magnitude lower than second-order rate constants estimated from the batch kinetic tests (see Table 3.1). Thus, the permanganate concentrations and residence time in this column were more than sufficient for chlorinated ethene oxidation. The second-order reactor rate constant for 1,1-DCA continually declined during the column test, and the final values were about 10^{-6} to 10^{-5} M^{-1} s^{-1} (see Appendix). This range of values is consistent with negligible removal and literature data for chlorinated ethanes (Table 3.1).

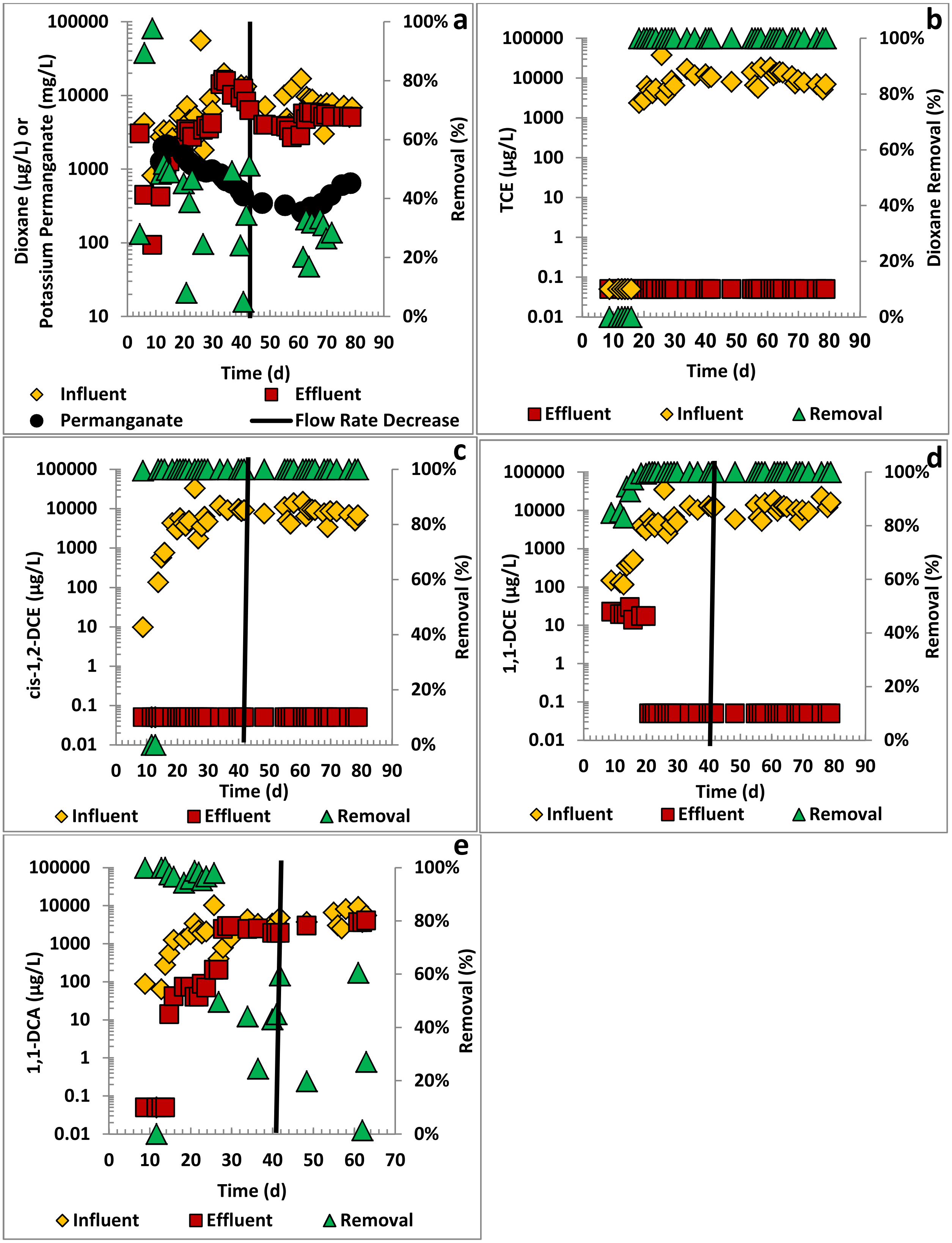

Figure 3.10 Removal of Dioxane (a), TCE (b), cis-1,2-DCE (c), 1,1-DCE (d), and 1,1-DCA (e) by Potassium Permanganate ($KMnO_4$) in the Column Study

Figure 3.11 shows the removals of individual contaminants in the persulfate column study. Initially, dioxane was not appreciably removed. The flow rate was decreased from 0.15 to 0.05 mL/min on day 40 to determine if dioxane removal could be increased. Dioxane removal did increase however the increase appears to have started about two days earlier. Nevertheless, dioxane removal continued to increase and effluent concentration decreased to less than 100 micrograms per liter (µg/L) on day 74 (> 99 percent removal). Persulfate concentrations increased gradually over time to 44,000 mg/L on day 89 when the study ended. The second-order reactor rate constant was estimated to be $2.2 \pm 0.9 \times 10^{-5}$ M^{-1} s^{-1}, which is similar to that the rated constant measured in the batch kinetics study in the presence of soil and groundwater (4.6×10^{-5} M^{-1} s^{-1}). Thus the apparent inhibition by soil and groundwater observed in the batch kinetic study was also observed in the column study. Still, dioxane was removed by over 99 percent. Steady state (i.e., after day 50) TCE, cis-1,2-DCE, and 1,1-DCE removals were also at or greater than 99 percent and reactor rate constants were 2.4 ± 1.0, 3.3 ± 1.2, and $3.9 \pm 1.5 \times 10^{-5}$ M^{-1} s^{-1}, respectively. The values for TCE and cis-1,2-DCE are similar to those for the batch kinetic study, but the value for 1,1-DCE is about one order-of-magnitude lower. The second-order reactor constant for 1,1-DCA was $4.8 \pm 3.2 \times 10^{-6}$ M^{-1} s^{-1} and consistent with the observed lack of appreciable removal in the column study.

Figure 3.12 illustrates the second-order reactor rate constant for dioxane oxidation by permanganate was generally greater than that by persulfate even though dioxane removal was greater with persulfate. Average second-order reactor rate constants were greater for permanganate than persulfate for dioxane and chlorinated VOCs as shown in Figure 3.13. The reason the rate constant for permanganate was greater than for persulfate is attributable to the relative different in oxidant concentrations. Permanganate ranged from 260 to 650 mg/L after flow rate was decreased whereas persulfate ranged from 15,000 to 42,000 mg/L (see Figure 3.14). Permanganate concentrations decreased steadily over time. However, about 20 days after the flow rate was decreased from 0.15 to 0.05 mL/min, the permanganate concentration started to increase. This increase was not sufficient to increase overall dioxane removal in the column.

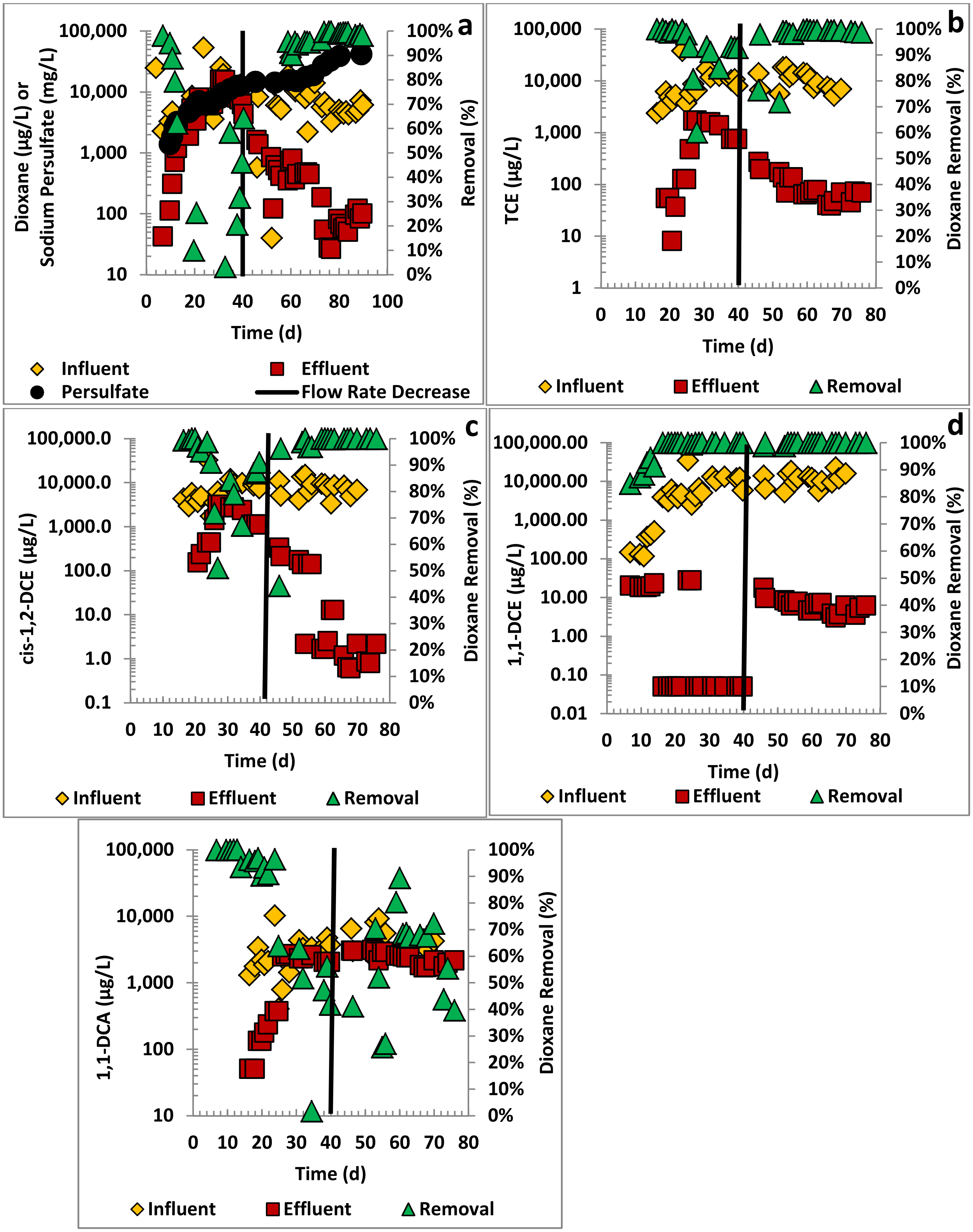

Figure 3.11 Removal of Dioxane (a), TCE (b), cis-1,2-DCE (c), 1,1-DCE (d), and 1,1-DCA (e) by Sodium Persulfate (Na2S2O8) in the Column Study

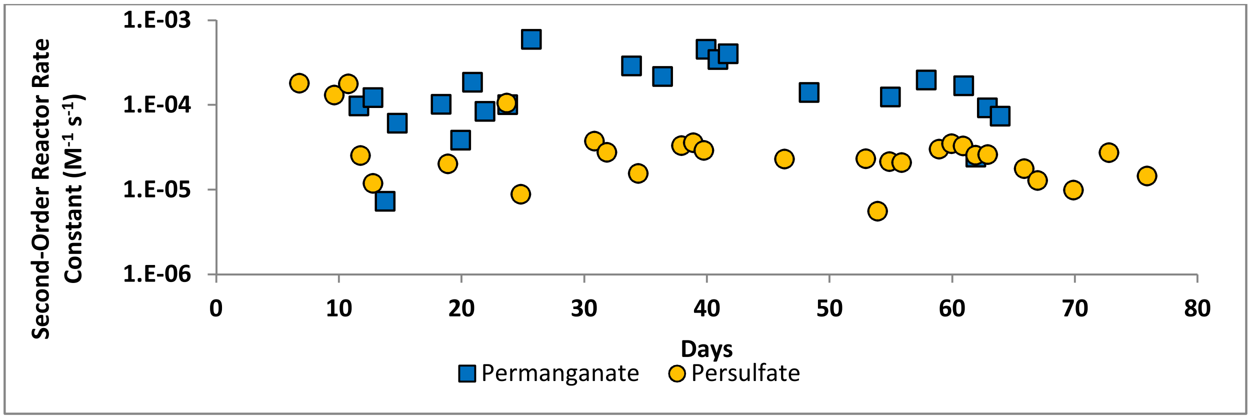

Figure 3.12 Comparison of Second-Order Reactor Rate Constants over Time for Dioxane with Permanganate and Persulfate

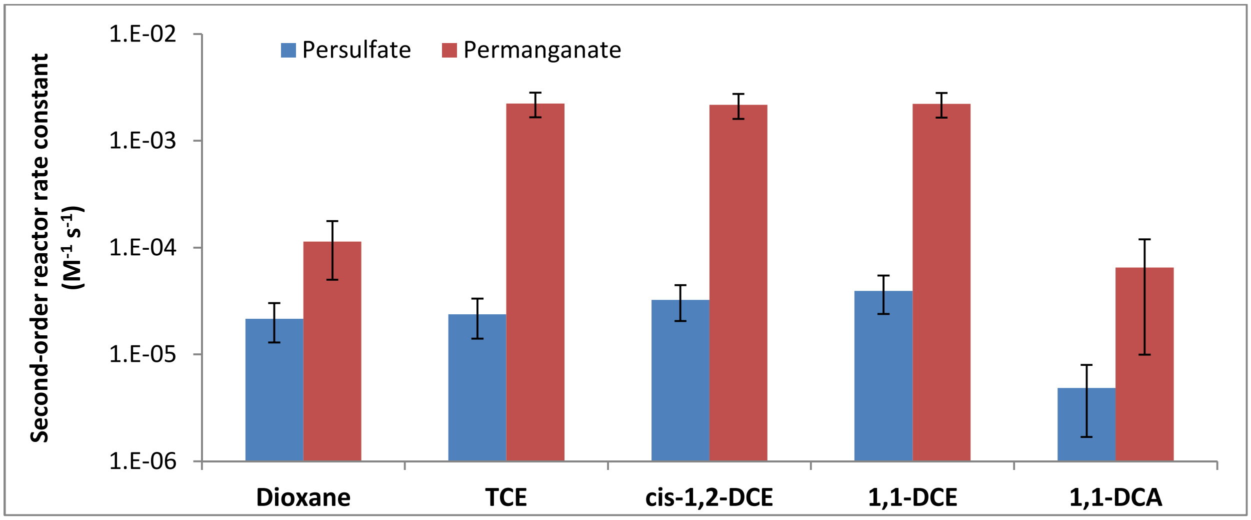

Figure 3.13 Comparison of Average Second-Order Reactor Rate Constants for Dioxane and Chlorinated VOCs with Permanganate and Persulfate

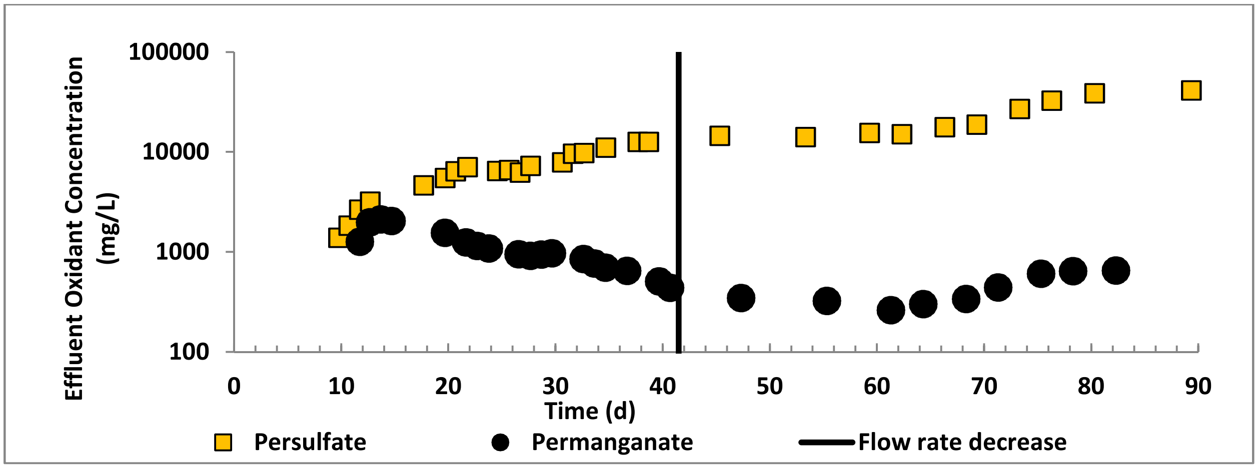

Figure 3.14 Comparison Column Effluent Oxidant Concentrations of Potassium Permanganate ($KMnO_4$) and Sodium Persulfate ($Na_2S_2O_8$)

3.4 OXIDANT RELEASE

The different oxidant concentrations in the column effluents was attributable to different oxidant release rates from the cylinders as shown in Figure 3.15. The final persulfate release rate was 15 milligrams per square centimeter per day (mg cm^{-2} d^{-1}). This release rate was similar to the release rate of 15 mg cm^{-2} d^{-1} estimated just before the flow rate was decreased. The persulfate release rates were greater than the final release rate estimated for permanganate (0.3 mg cm^{-2} d^{-1}). The oxidant release rates were initially similar as shown in Figure 3.15 but diverged after about 10 days of operation. Figure 3.15 also shows the cumulative percent mass of oxidant released (based on effluent concentrations) from each cylinder over time. Only 2.4 percent of the permanganate was released compared to 37 percent of the persulfate.

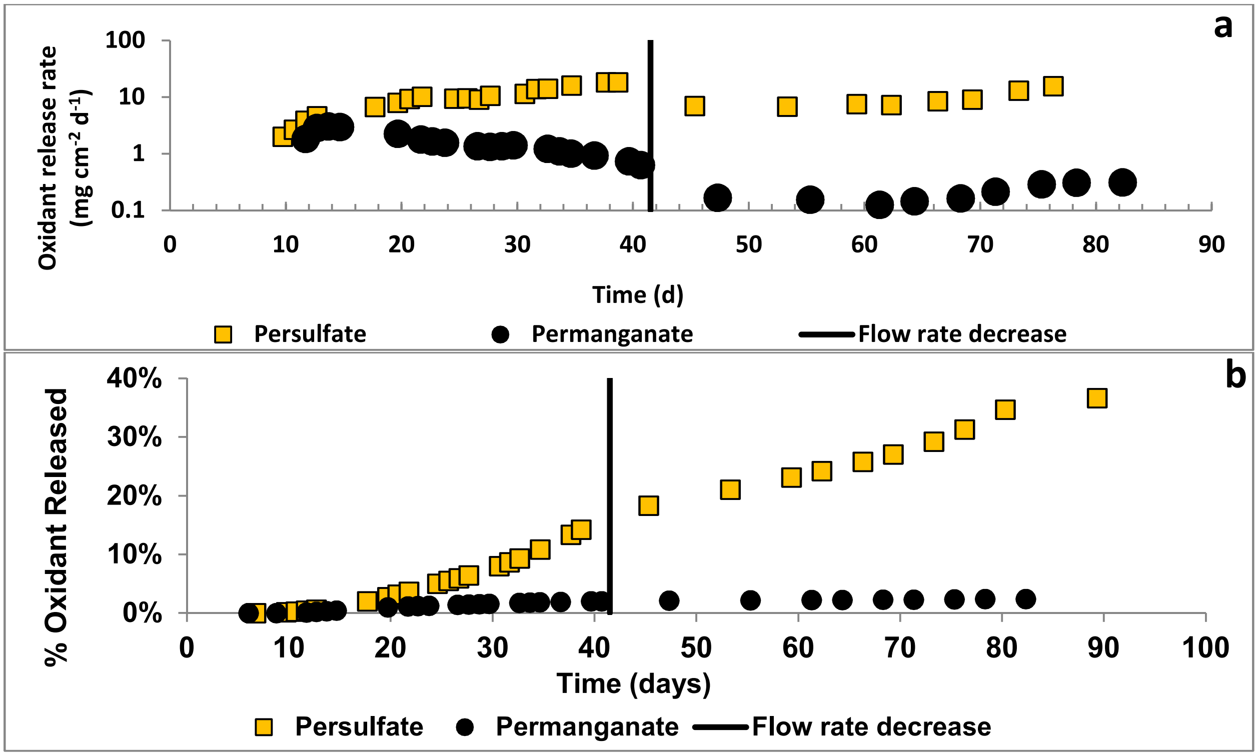

Figure 3.15 Oxidant Release Rates (a) and Percent Mass Released (b) from the Potassium Permanganate ($KMnO_4$) and Sodium Persulfate ($Na_2S_2O_8$) Cylinders in the Column Study

Further confirmation of the oxidant release was attempted by extracting the oxidants from the new and used cylinders. Analysis of new and used permanganate cylinders indicated the MnO_4 mass decreased from 620 mg to 610 mg for a 1 percent reduction. This value is about half the above estimate of 2.4 percent. Analysis of new and used persulfate cylinders indicated the S_2O_8 mass decreased from 660 mg to 140 mg for an 80 percent reduction. This value is about twice the above estimate. Thus, further work is needed to develop reliable estimates of oxidant loss from the cylinders. Such estimates are necessary to estimate cylinder lifetime. Nevertheless, the extraction data do confirm that relatively less oxidant remained in the persulfate cylinder compared to the permanganate cylinder.

Figures 3.16 and 3.17 show photographs of the cylinders at the conclusion of column operation. A rind, possibly manganese dioxide (MnO_2), is evident around the circumference of the permanganate cylinder. As noted in Section 2.5, SEM could not be used to verify the rind composition. This rind may have inhibited oxidant release from the cylinder, which resulted in the relatively low permanganate concentrations. The photographs of the persulfate cylinders show some staining but no clear evidence of a coating as was observed on the permanganate cylinder.

The temporal patterns of oxidant release from the cylinders were also qualitatively different as illustrated in Figure 3.18. Permanganate concentrations rapidly increased and then gradually decreased. The patterns were qualitatively similar in columns packed with sand and operated with DI water and in columns packed with soil and operated with both contaminated and uncontaminated groundwater. On the other hand, persulfate concentrations in all three column conditions increased gradually and did not decrease over the period of the study.

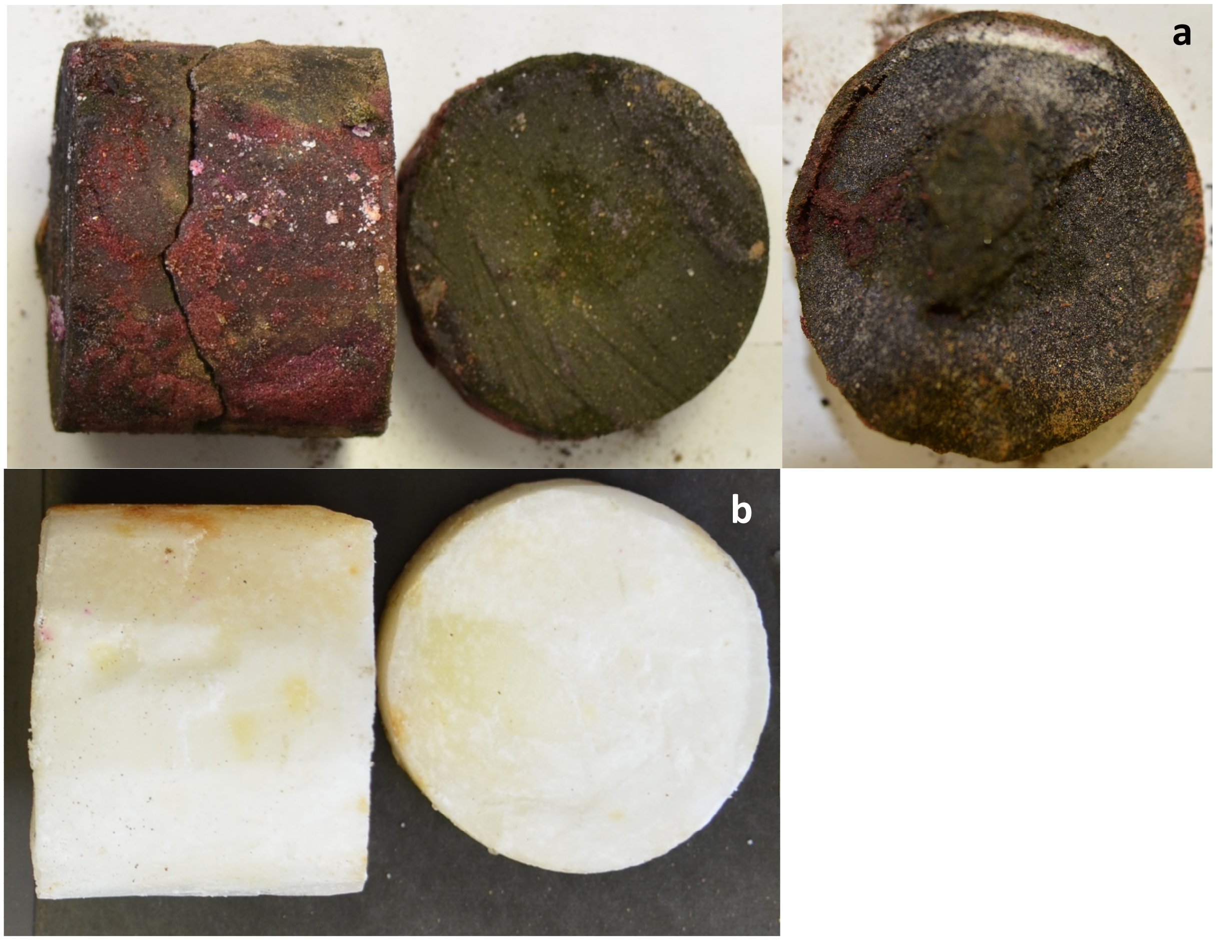

Figure 3.16 Photographs of Permanganate (a) and Persulfate (b) Column Cylinders at the Conclusion of the Study

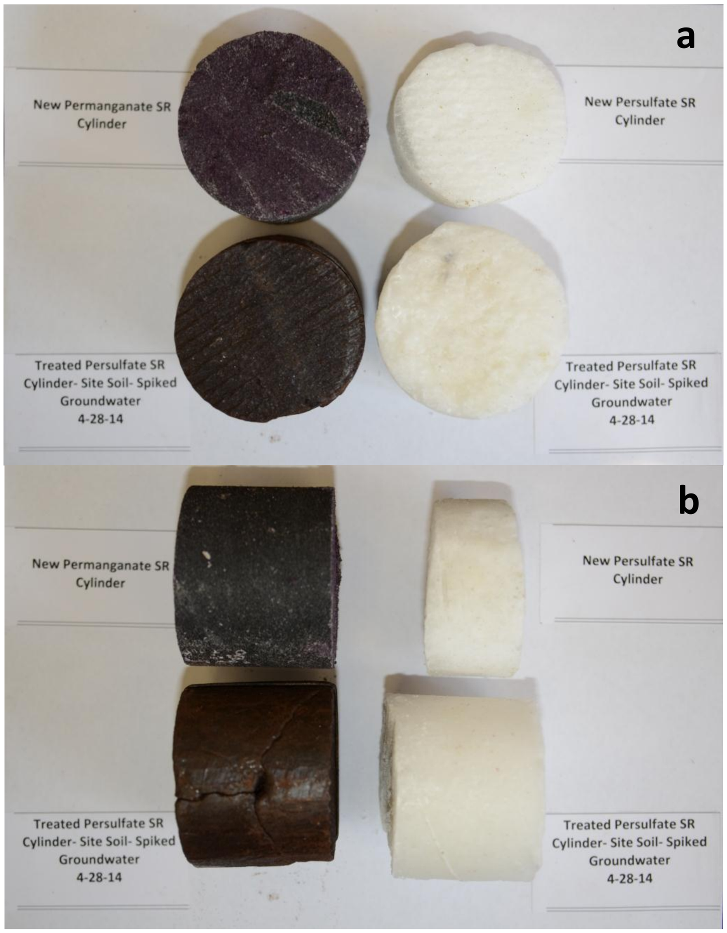

Figure 3.17 Photographs of Permanganate and Persulfate Column Cylinders at the Beginning and Conclusion of the Study – Cross Section (a) and Side View (b)

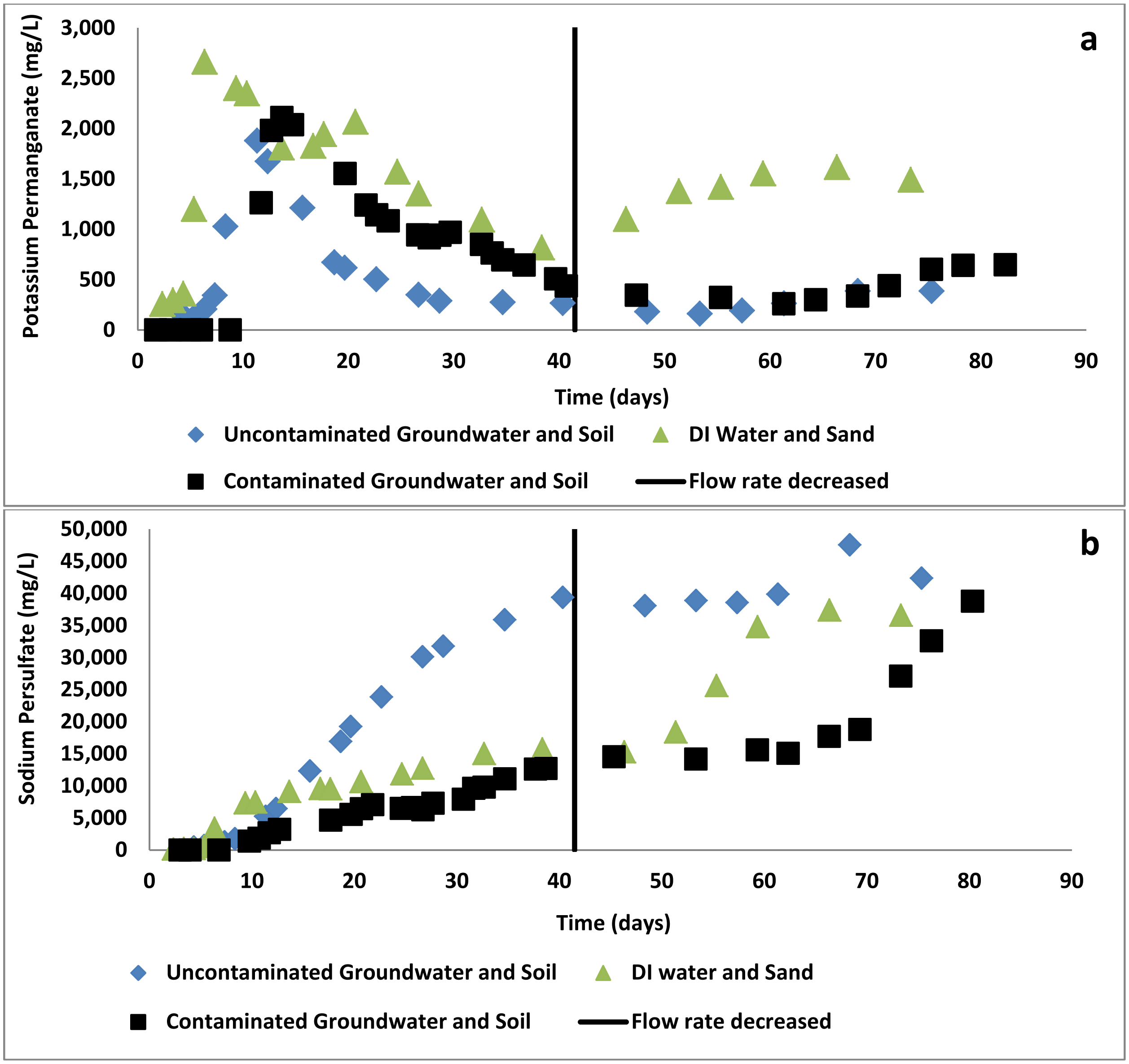

Figure 3.18 Oxidant Release Profiles for Potassium ($KMnO_4$) Permanganate (a) and Sodium Persulfate ($Na_2S_2O_8$) Cylinders (b) Based on Effluent Concentrations

3.5 POTENTIAL SECONDARY EFFECTS ON GROUNDWATER QUALITY

Secondary effects on groundwater quality, including pH and dissolved metals, were evaluated in the column study. Figure 3.19 shows the temporal changes in oxidant concentration and pH in the permanganate and persulfate column effluents. The pH in the permanganate column effluent remained near neutral. The pH in the persulfate column effluent was about 6 SU during the steady state period (i.e., after about day 50). However, the final pH was 4.6 SU. It is not known whether this low pH was representative or an anomaly. Nevertheless, persulfate decomposition is known to result in decreased pH. Hydrogen ions are generated per the following equation for sodium persulfate with dioxane:

$$C_4H_8O_2 + 6H_2O + 10\,Na_2S_2O_8 \rightarrow 4CO_2 + 20SO_4^{2-} + 20H^+ + 20Na^+ \qquad (4)$$

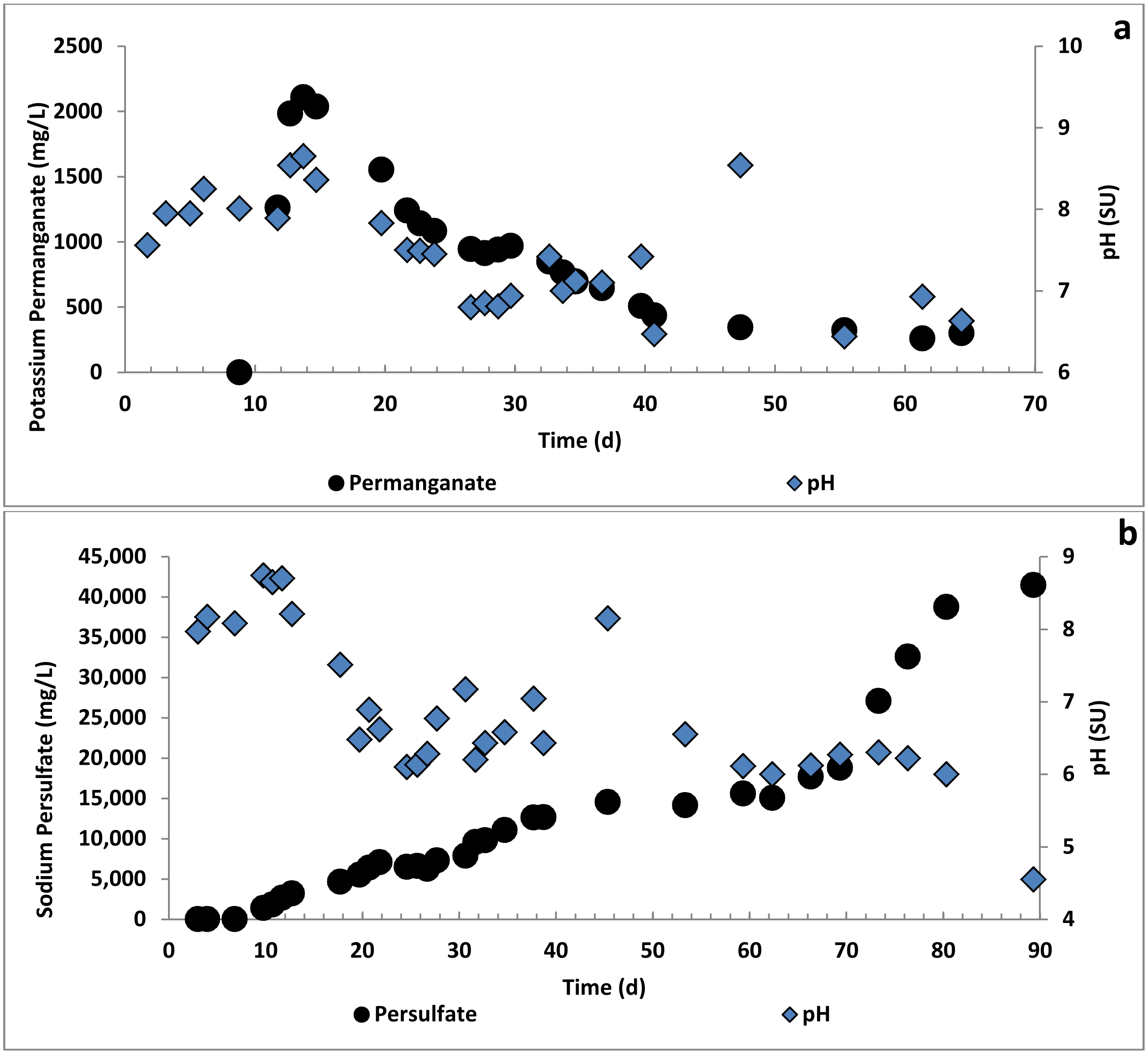

Figure 3.19 Effluent Oxidant Concentrations and pH in the Potassium Permanganate ($KMnO_4$) (a) and Sodium Persulfate ($Na_2S_2O_8$) (b) Columns

Dissolved metals were analyzed by Carus and an independent laboratory (OnSite Environmental). Table 3.3 shows the site groundwater contained non-detectable concentrations of dissolved metals with the possible exception of nickel, which was detected by Carus at 6.2 µg/L (less than the California MCL of 100 µg/L).

Arsenic was detected in the permanganate column by Carus but not OnSite. Neither lab observed arsenic in the persulfate column effluent. Thus, Carus arsenic results may be high estimates of the actual arsenic concentration. The California MCL for arsenic is 10 µg/L. Cadmium was not detected above the California MCL of 5 µg/L. Chromium was present at concentrations greater than the California MCL of 50 µg/L in both column effluents, and chromium was likely present in the hexavalent form, which has a California MCL of 10 µg/L. Hexavalent chromium is likely to be reduced to insoluble trivalent chromium hydroxide once groundwater migrates downgradient to reducing areas of the plume. Lead was not detected above the California MCL of 15 µg/L in the snapshot sampling of the column effluents. However, lead was detected above this regulatory limit periodically in both column effluents as evidenced by the average concentration results. Thus, lead release from the soil in the presence of the chemical oxidants may be transient. Mercury and silver were not detected. Nickel was not detected above the California MCL of 100 grams per liter (g/L) in the snapshot sampling of the column effluents but was periodically detected in the persulfate column effluent. Nickel was not detected above the California MCL in the permanganate column effluent.

Table 3.3 Filtered Metals Concentrations in Site Groundwater and Column Effluent Samples

	NAS North Island Groundwater		**Permanganate Column Effluent**				**Persulfate Column Effluent**			
Laboratory	**OnSite Env.**	**Carus**	**OnSite Env.**	**Carus**			**OnSite Env.**	**Carus**		
	Metal (µg/L)									
Sample Date	December 5, 2013		Day 90	Day 90	Day 2 to 89		Day 87	Day 97	Day 45 to 87	
					avg	stdev			avg	stdev
Arsenic	<3	<1	<3	**39**	**68**	**72**	<3	<1	1.0	0.0
Cadmium	<4	NA	<4	<0.1	0.1	0.0	<4	2	1.4	0.5
Chromium	<10	<2	**220**	**570**	**280**	**330**	**290**	**300**	**230**	**66**
Lead	<1	<1	<1	<1	9.6	**20**	5.5	<1	**49**	**35**
Mercury	<0.5	NA	<0.5	NA	NA	NA	<0.5	NA	NA	NA
Nickel	<20	6.2	<20	9.1	5.1	5.0	92	63.9	**120**	83
Silver	<10	NA	<10	NA	NA	NA	<10	NA	NA	NA

Notes: Concentrations greater than the California State MCL are denoted in bold.
NA = Not tested

3.6 HYDRAULIC FRACTURING

Hydraulic fracturing of the slow release oxidant material was evaluated with respect to material compatibility. Figure 2.4 shows a photomicrograph of the wax-permanganate “pastilles” that were about 5 mm in size and had a particle density of 1.54 grams per cubic centimeter (g/cm^3). Fracrite conducted a compatibility test that involved mixing the pastilles with an organic cross-linker (e.g., guar) and then conducting a pour test to qualitatively evaluate viscosity. Fracrite determined that permanganate oxidized the cross-linker, which prevented formation of suspension with suitable physical properties. The suspension was not stable at any time-point tested. In addition, it is unlikely that the pastille configuration would be practical because the slow-release lifetime is related to particle size – the smaller sized pastilles would probably not have desirable longevity. Therefore, further evaluation of this technology configuration was not conducted.

4.0 CONCLUSIONS

Unactivated persulfate was successfully demonstrated to oxidize dioxane and chlorinated ethenes (TCE, cis-1,2-DCE, and 1,1-DCE) in the presence of site soil and groundwater. Table 4.1 presents a summary of treatability study results compared to performance objectives. The chlorinated ethane 1,1-DCA was not oxidized with persulfate as expected. Oxidation was observed in batch reactors with dissolved persulfate and in continuous flow column studies with a slow-release persulfate cylinder. Over 99 percent removal was observed in the column study, which exceeds the project go-stop criterion of 90 percent. The pseudo second-order rate constant for dioxane removal in site soil and groundwater (4.6×10^{-5} M^{-1} s^{-1}) was less than that measured in DI water (1.1×10^{-3} M^{-1} s^{-1}). These data suggest some form of partial inhibition by site soil and groundwater. Dioxane removal did not follow first-order kinetics (i.e., the slope of the semi-logarithmic plot of concentration versus time was not linear, and the absolute value of the slope increased over time), suggesting some type of activation. This behavior was observed in DI water and in the presence of soil and groundwater. While intentional activation was not conducted (e.g., hydrogen peroxide, iron salts, heat, or high pH), activation may have occurred nevertheless. Dioxane oxidation by persulfate in the absence of an activator has been previously observed (Felix-Navarro et al. 2007). Considering the pseudo second-order rate constant was lower in the presence of soil and groundwater, we hypothesize that some property of the soil and groundwater may have partially inhibited the activation process which led to the lower oxidation rates. The measured pseudo second-order rate constant for TCE in the presence of site soil and groundwater (5.3×10^{-5} M^{-1} s^{-1}) was less than that calculated using previously published data (Liang et al. 2007) further suggesting some form of inhibition. Even though partial inhibition was observed, dioxane was removed by over 99 percent in the column with a steady-state second-order reactor rate constant of $2.2 \pm 0.9 \times 10^{-5}$ M^{-1} s^{-1}, which is similar to the rate constant measured in the batch kinetics study in the presence of soil and groundwater (4.6×10^{-5} M^{-1} s^{-1}). These data further substantiate the ability of unactivated persulfate to consistently oxidize persulfate in a continuous-flow system in the presence of site soil and groundwater.

Permanganate was capable of oxidizing dioxane and chlorinated ethenes in batch reactor studies. 1,1-DCA was not oxidized as expected. The column study demonstrated greater than 99 percent removal of chlorinated ethenes but little to no removal of dioxane. The reason for the low removal of dioxane was attributable to low permanganate concentrations rather than a kinetic inhibition per se – the second-order reactor rate constant for dioxane in the column $1.1 \pm 0.6 \times 10^{-4}$ M^{-1} s^{-1}) was actually greater than that measured in the batch reactors (2.7×10^{-5} M^{-1} s^{-1}) in the presence of site soil and groundwater. Low permanganate concentrations were attributed to site-specific chemistry.

In spite of similar second-order rate constants (i.e., measured in the batch reactors) for dioxane with permanganate and persulfate in the presence of site soil and groundwater, the persulfate column performed better than the permanganate column with respect to dioxane removal. The reason was the difference in oxidant release rate and thus oxidant concentrations. The permanganate release rate decreased over time in part because of the formation of a rind around the exterior surface of the cylinder. This rind inhibited mass transfer of permanganate from the cylinder into the groundwater. The persulfate cylinder did not develop such a rind, and release rates increased over time. Different release mechanisms for the oxidants may have also played a role; however, this was not explored in this study. The maximum release rate for the persulfate cylinder was 18 mg cm^{-2} d^{-1} and can be used for design of the field demonstration. Further work is ongoing to develop mathematic expressions for persulfate release from the persulfate cylinders over time.

Secondary effects on groundwater quality were observed in the column study. These included pH depression and elevated concentrations of certain heavy metals. In the persulfate column, pH was trending downward near the end of the study, and the final measured pH was 4.6. Dissolved metals were also observed in the persulfate column effluent. In particular, dissolved chromium, most likely in the hexavalent form, was present at concentrations in excess of the California MCL of 10 µg/L. Other metals, including lead and nickel may also have exceeded the MCLs at times; however, there is some uncertainty regarding the analytical data. Decreased pH, elevated metal concentrations, and formation of hexavalent chromium are typical observations during ISCO. Downgradient geochemical conditions, especially if they are reducing, can be expected to attenuate these secondary effects. For example, hexavalent chromium is easily reduced to trivalent chromium hydroxide [$Cr(OH)_3$] which precipitates. Natural soil alkalinity will buffer the acidity produced during persulfate decomposition. Other dissolved metals can be expected to precipitate as the pH increases. The actual attenuation of groundwater geochemistry was not evaluated and will need to be addressed during the field demonstration.

In summary, the treatability study demonstrated that slow-release persulfate cylinder technology without intentional activation is capable of treating site groundwater contaminants with the exception of 1,1-DCA. Field demonstration using slow-release persulfate cylinders is recommended as the next step in demonstration and validation of this technology. Slow-release permanganate cylinder technology was successful for treatment of chlorinated ethenes but not dioxane. Presumed MnO_2 deposition decreased permanganate release rates, which affected contaminant oxidation rates. This effect may be dependent on site-specific groundwater chemistry rather than a general technology limitation.

Table 4.1 Treatability Study Performance

Performance Objective	Success Criteria	Results
Technology Effectiveness	• 90% reduction in 1,4-dioxane concentration with unactivated persulfate or permanganate. • 90% reduction of chlorinated VOC co-contaminants with unactivated persulfate or permanganate.	• > 99% reduction with persulfate only, and nearly 30% reduction with permanganate. • > 99% reduction for chlorinated ethenes with persulfate and permanganate. No oxidation of 1,1-DCA.

Table 4.1 Treatability Study Performance

Performance Objective	Success Criteria	Results
Determine design criteria for the field demonstration	• Develop quantitative relationships and criteria for contaminant flux, contaminant oxidation, natural oxidant demand, oxidant flux, and oxidant consumption. • Use these relationships to develop design criteria for oxidant flux, which ensure satisfactory contaminant oxidation without releasing excess oxidant.	• Second-order rate constants for dioxane in site soil and groundwater with permanganate and persulfate were estimated to be 2.7×10^{-5} and 4.6×10^{-5} M^{-1} s^{-1}, respectively. Rate constants for chlorinated ethenes were equal to or greater than those for dioxane. • 1,1-DCA was not oxidized by either oxidant. • Persulfate, which will be used in the field demonstration, did not have detectable NOD or observable consumption. A maximum persulfate release rate from the 2.5-inch diameter cylinder was measured to be 18 mg cm^{-2} d^{-1}. Further work is being conducted to characterize oxidant release but may be modelled using a Gaussian distribution. • Permanganate will not be used for the field demonstration, but the NOD ranged from 0.089±0.0003 mg/kg to 0.41±0.02 mg/kg at higher doses. The 48-hour fast NOD with persulfate was negligible.

Table 4.1 Treatability Study Performance

Performance Objective	Success Criteria	Results
Characterize secondary environmental impacts	• Quantify the potential for the listed secondary impacts to result in exceedances of MCLs.	• pH decreased to less than 6.0 in the final sampling event for the persulfate column, suggesting that pH may decrease to less than 6.0 when deployed in the field. The pH is expected to increase downgradient of the oxidant area. • Dissolved arsenic was periodically detected in excess of the California MCL of 10 µg/L in the permanganate column effluent based on Carus analysis but was not detected in snapshot sampling by a certified laboratory. Lead was not in excess of the MCL in the persulfate column. • Dissolved chromium was in excess of the California MCL of 50 µg/L and likely in the CrVI form (California MCL of 10 µg/L). CrVI will likely attenuate downgradient of the chemical oxidant treatment area. • Dissolved lead was periodically detected in excess of the California MCL of 15 µg/L in the column effluent based on Carus analysis but was not detected in snapshot sampling by a certified laboratory. • Dissolved nickel was periodically in excess of the California MCL of 100 µg/L in the persulfate column based on Carus analysis but was not detected in snapshot sampling by a certified laboratory. • Dissolved cadmium, mercury, and silver were either not detected or detected at concentrations less than the California MCLs.
Characterize manganese dioxide deposition and fouling potential	Determine the extent to which cylinder porosity is blocked by manganese dioxide.	A rind presumably comprised of manganese dioxide coated the exterior surface of the permanganate cylinder and affected oxidant release rates. Chlorinated ethenes nevertheless were removed from the groundwater; dioxane was not removed appreciably.
Characterize frac fluid compatibility with slow release material	Determine whether the material is capable of being suspended in the frac gel for a period of 8 hours.	Limited testing of polysaccharide gel indicated incompatibility with the slow-release permanganate oxidant, and it was not able to remain suspended for a period of 8 hours.

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APPENDIX – SUPPORTING INFORMATION

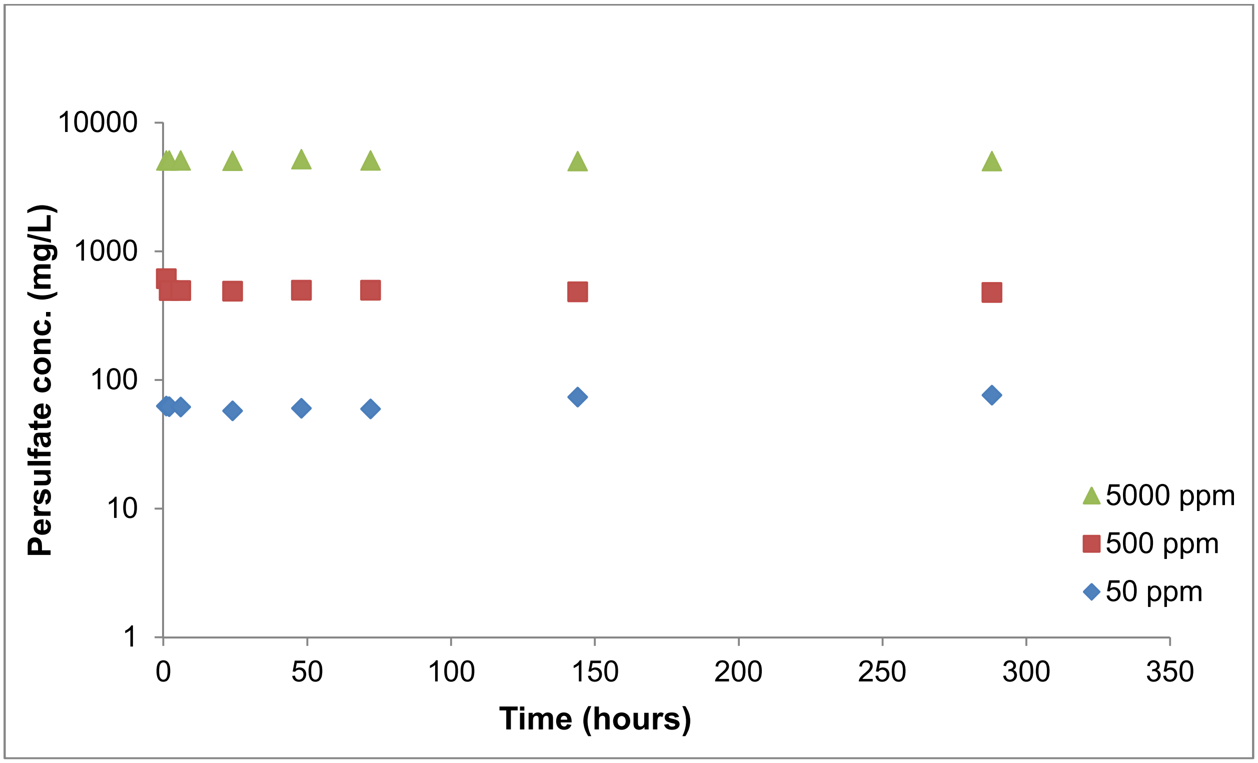


Figure A.1 NOD Experiment Persulfate Trends

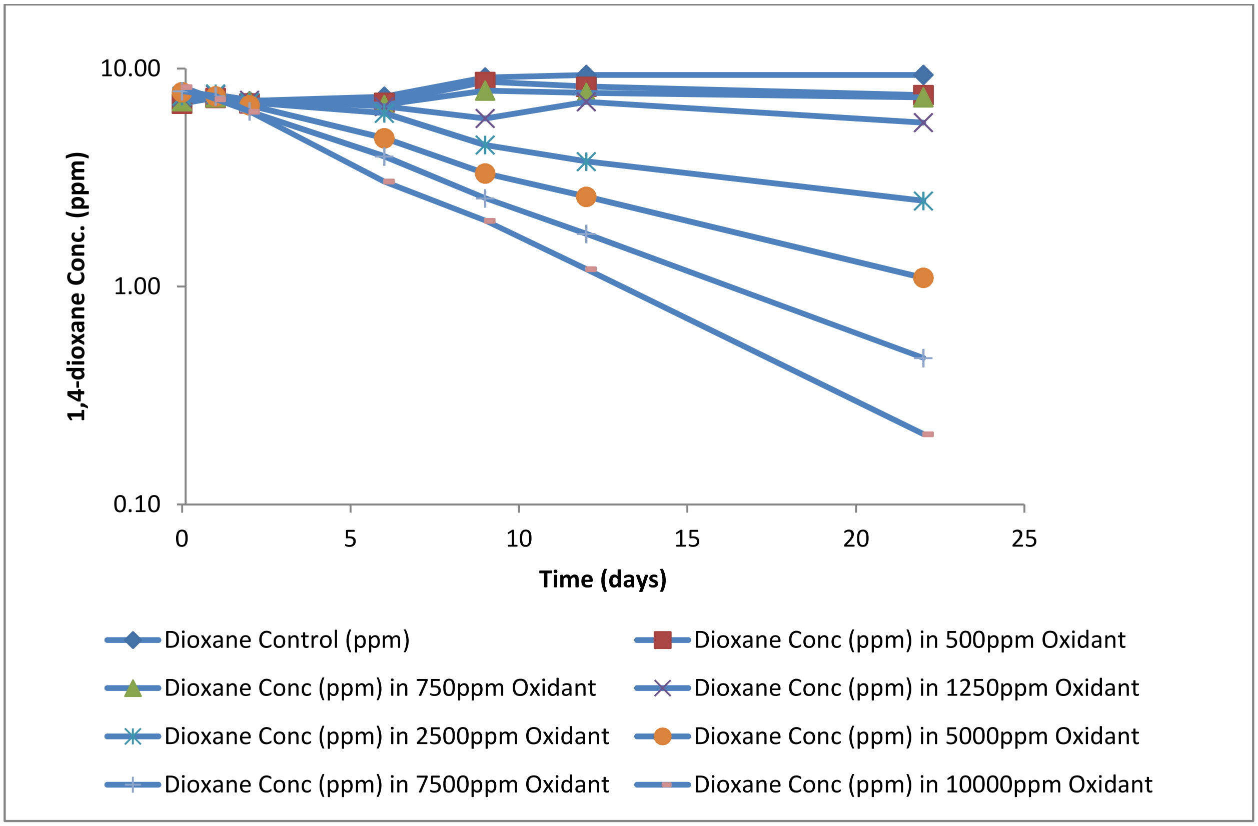


Figure A.2 Carus Results for Dioxane Oxidation by Permanganate in DI Water

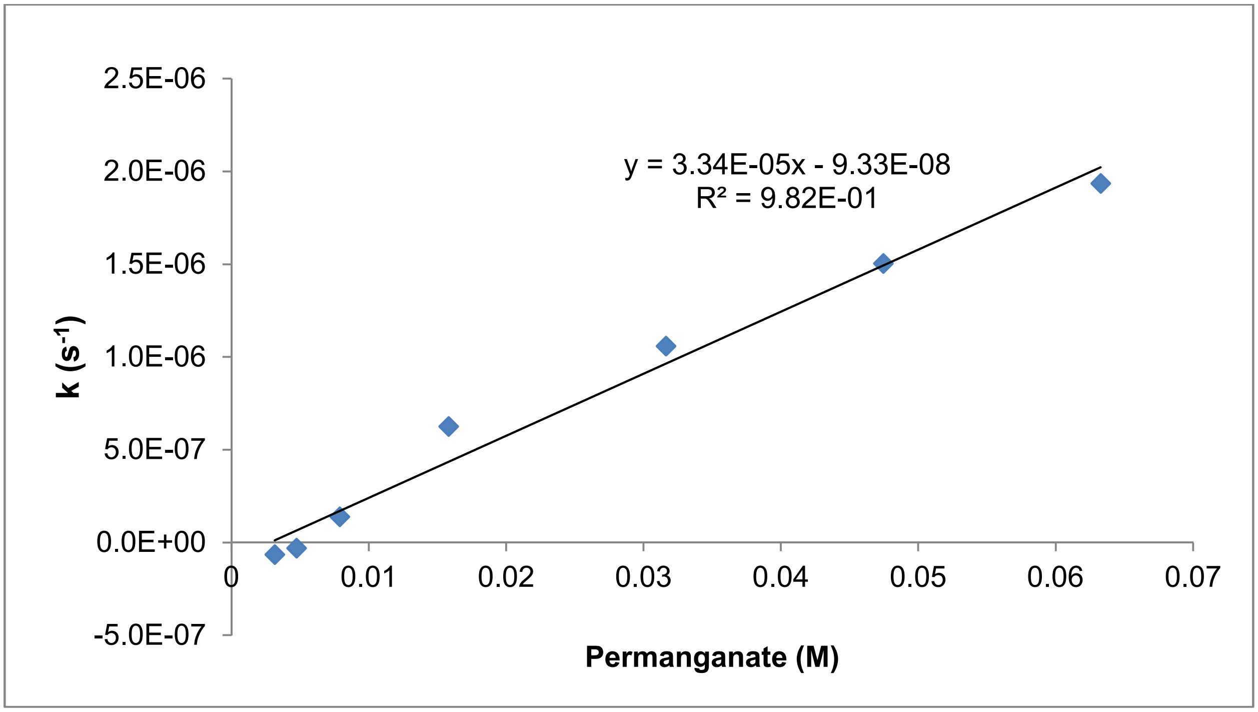


Figure A.3 Carus Estimate of Pseudo Second-Order Rate Constant for Dioxane Oxidation by Permanganate in DI Water

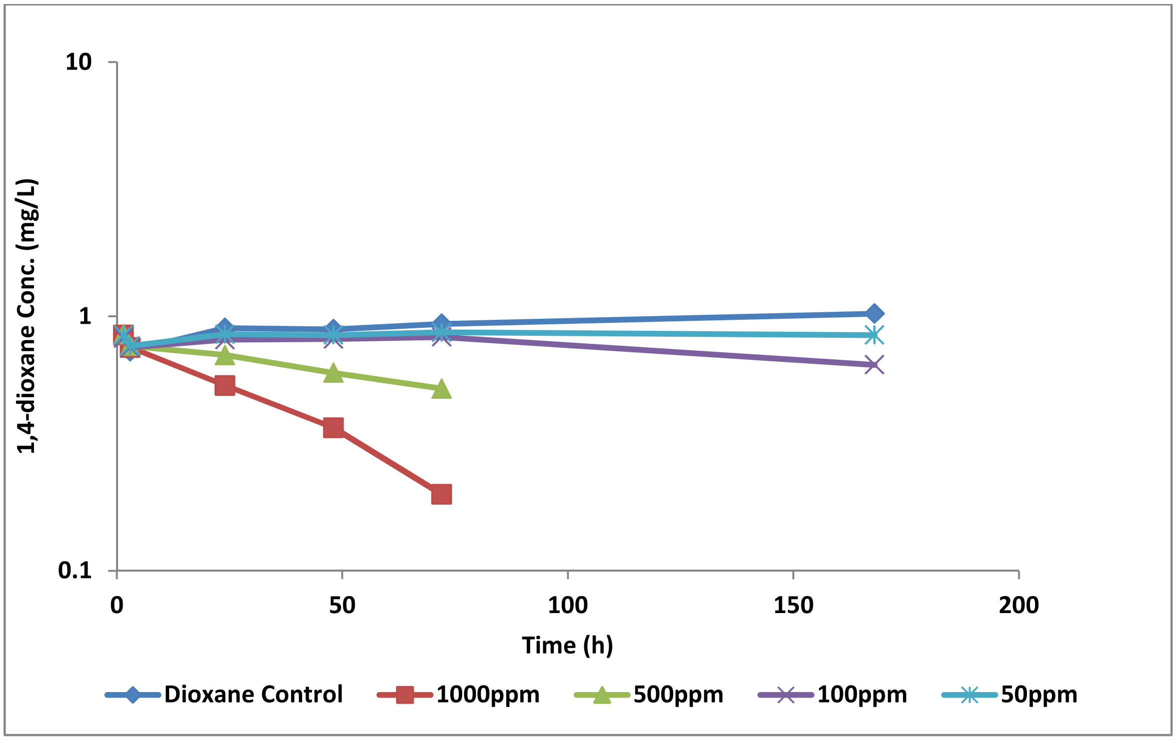


Figure A.4 Carus Results for Dioxane Oxidation by Persulfate in DI Water

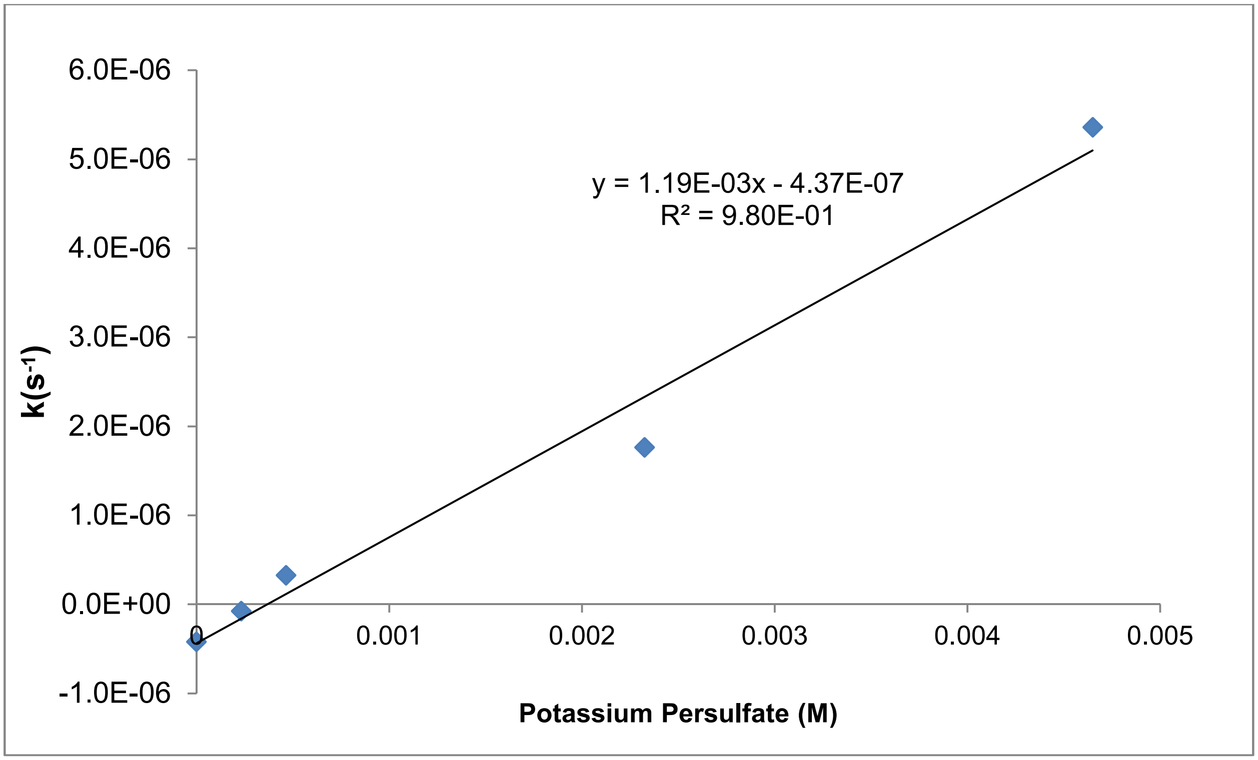


Figure A.5 Carus Estimate of Pseudo Second-Order Rate Constant for Dioxane Oxidation by Persulfate in DI Water

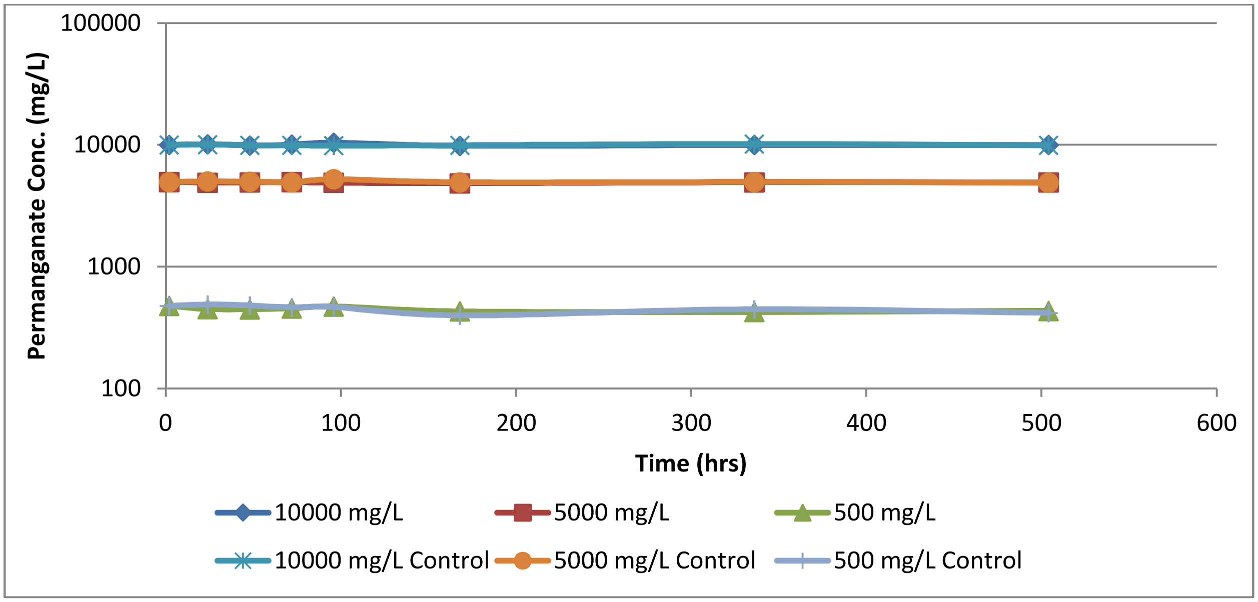


Figure A.6 Permanganate Concentration Trends in Carus Batch Kinetics Studies Conducted with ~1 mg/L Each Contaminant and In the Presence of Soil and Groundwater

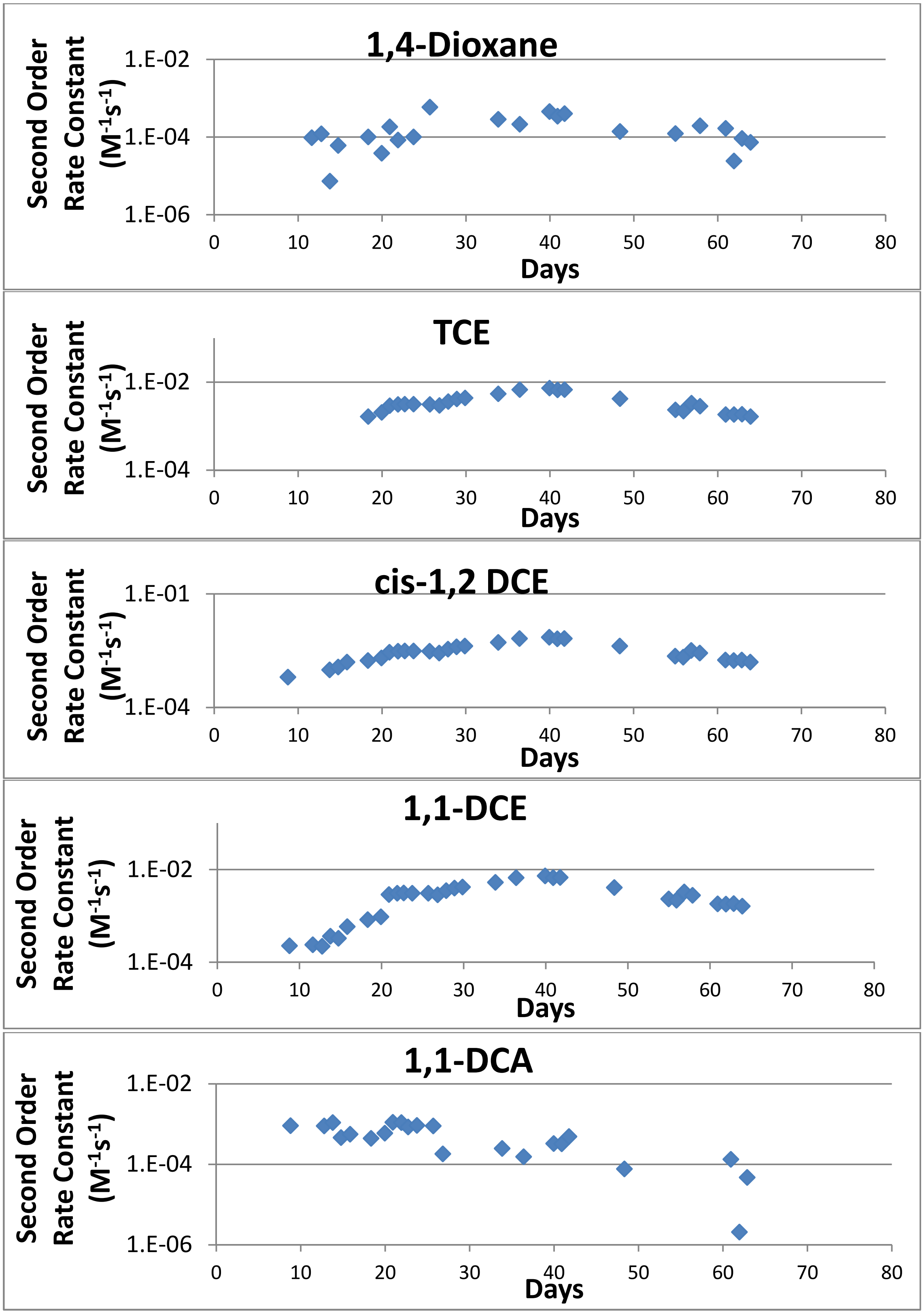


Figure A.7 Reactor Rate Constants for the Permanganate Column Study

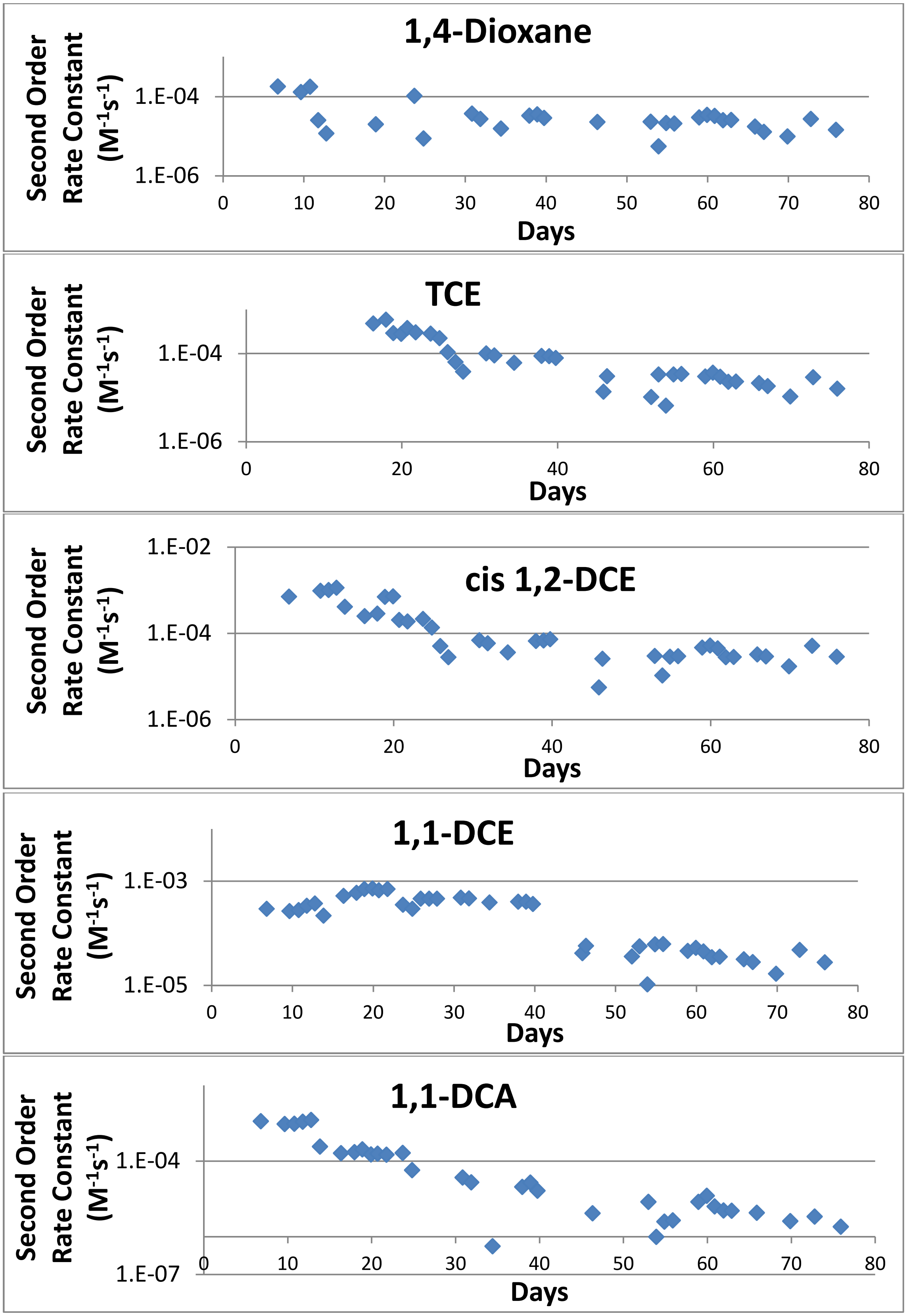
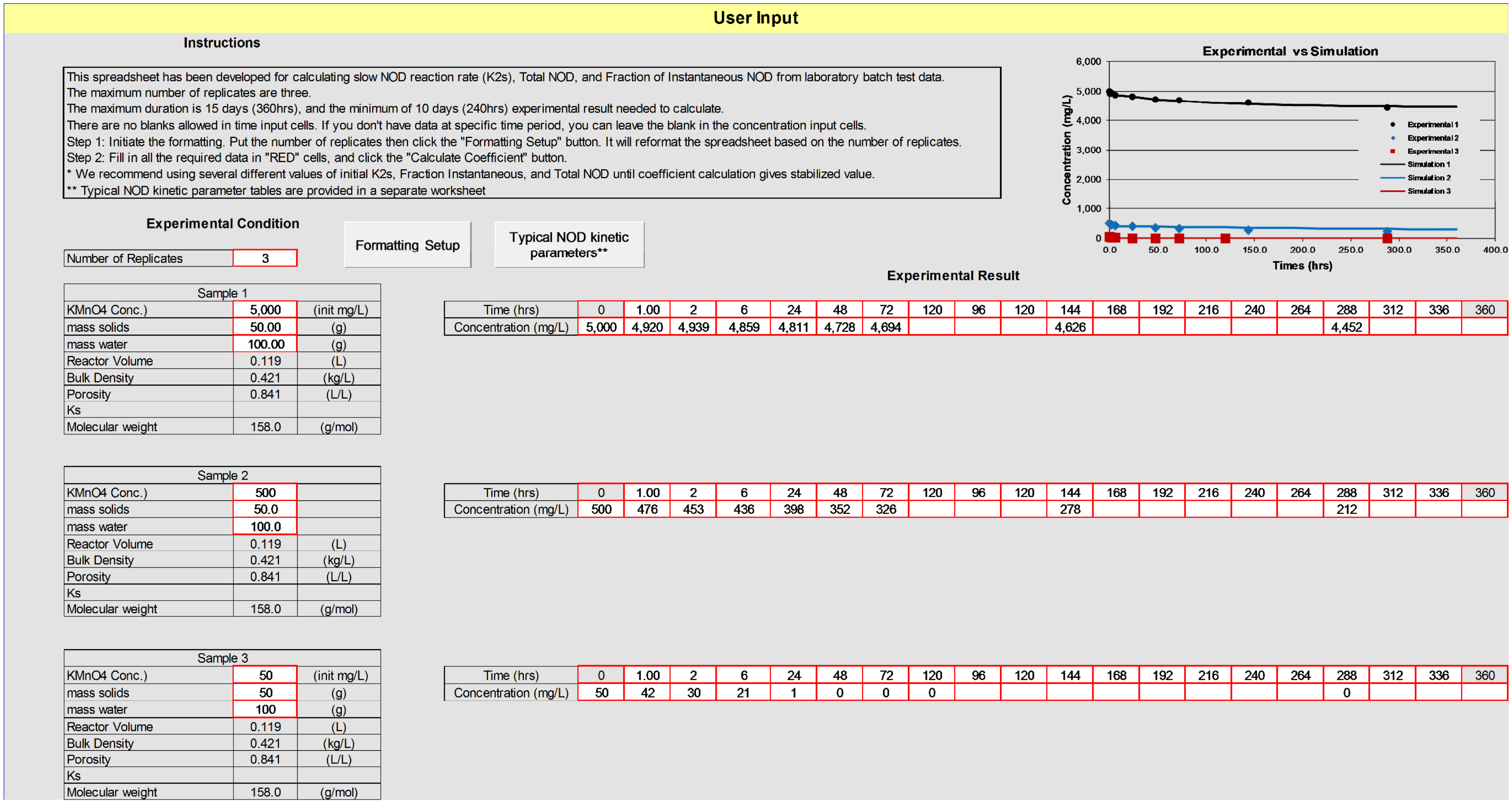


Figure A.8 Reactor Rate Constants for the Persulfate Column Study

CDISCO design tool output for permanganate NOD in the presence of site soil and groundwater



User Input

Instructions

This spreadsheet has been developed for calculating slow NOD reaction rate (K2s), Total NOD, and Fraction of Instantaneous NOD from laboratory batch test data.
The maximum number of replicates are three.
The maximum duration is 15 days (360hrs), and the minimum of 10 days (240hrs) experimental result needed to calculate.
There are no blanks allowed in time input cells. If you don't have data at specific time period, you can leave the blank in the concentration input cells.
Step 1: Initiate the formatting. Put the number of replicates then click the "Formatting Setup" button. It will reformat the spreadsheet based on the number of replicates.
Step 2: Fill in all the required data in "RED" cells, and click the "Calculate Coefficient" button.
* We recommend using several different values of initial K2s, Fraction Instantaneous, and Total NOD until coefficient calculation gives stabilized value.
** Typical NOD kinetic parameter tables are provided in a separate worksheet

Experimental Condition

Number of Replicates	3

Experimental Result

Sample 1		
KMnO4 Conc.)	5,000	(init mg/L)
mass solids	50.00	(g)
mass water	100.00	(g)
Reactor Volume	0.119	(L)
Bulk Density	0.421	(kg/L)
Porosity	0.841	(L/L)
Ks		
Molecular weight	158.0	(g/mol)

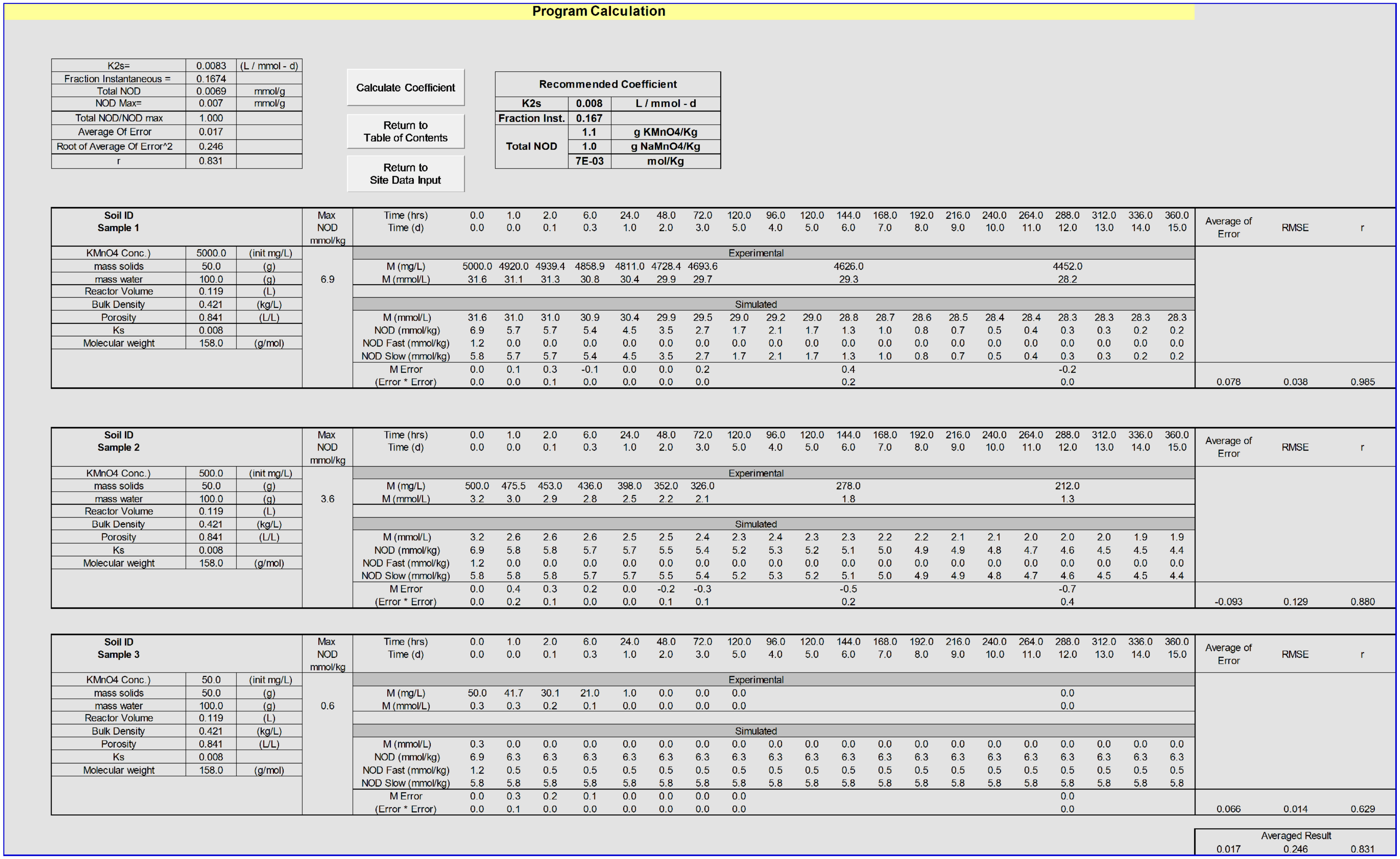
Time (hrs)	0	1.00	2	6	24	48	72	120	96	120	144	168	192	216	240	264	288	312	336	360
Concentration (mg/L)	5,000	4,920	4,939	4,859	4,811	4,728	4,694				4,626						4,452			

Sample 2		
KMnO4 Conc.)	500	
mass solids	50.0	
mass water	100.0	
Reactor Volume	0.119	(L)
Bulk Density	0.421	(kg/L)
Porosity	0.841	(L/L)
Ks		
Molecular weight	158.0	(g/mol)

Time (hrs)	0	1.00	2	6	24	48	72	120	96	120	144	168	192	216	240	264	288	312	336	360
Concentration (mg/L)	500	476	453	436	398	352	326				278						212			

Sample 3		
KMnO4 Conc.)	50	(init mg/L)
mass solids	50	(g)
mass water	100	(g)
Reactor Volume	0.119	(L)
Bulk Density	0.421	(kg/L)
Porosity	0.841	(L/L)
Ks		
Molecular weight	158.0	(g/mol)

Time (hrs)	0	1.00	2	6	24	48	72	120	96	120	144	168	192	216	240	264	288	312	336	360
Concentration (mg/L)	50	42	30	21	1	0	0	0									0			



Program Calculation

K2s=	0.0083	(L / mmol - d)
Fraction Instantaneous =	0.1674	
Total NOD	0.0069	mmol/g
NOD Max=	0.007	mmol/g
Total NOD/NOD max	1.000	
Average Of Error	0.017	
Root of Average Of Error^2	0.246	
r	0.831	

Recommended Coefficient		
K2s	**0.008**	**L / mmol - d**
Fraction Inst.	**0.167**	
Total NOD	**1.1**	**g KMnO4/Kg**
	1.0	**g NaMnO4/Kg**
	7E-03	**mol/Kg**

Soil ID Sample 1			Max NOD mmol/kg
KMnO4 Conc.)	5000.0	(init mg/L)	
mass solids	50.0	(g)	
mass water	100.0	(g)	6.9
Reactor Volume	0.119	(L)	
Bulk Density	0.421	(kg/L)	
Porosity	0.841	(L/L)	
Ks	0.008		
Molecular weight	158.0	(g/mol)	

Time (hrs)	0.0	1.0	2.0	6.0	24.0	48.0	72.0	120.0	96.0	120.0	144.0	168.0	192.0	216.0	240.0	264.0	288.0	312.0	336.0	360.0	Average of Error	RMSE	r
Time (d)	0.0	0.0	0.1	0.3	1.0	2.0	3.0	5.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0			
Experimental																							
M (mg/L)	5000.0	4920.0	4939.4	4858.9	4811.0	4728.4	4693.6				4626.0						4452.0						
M (mmol/L)	31.6	31.1	31.3	30.8	30.4	29.9	29.7				29.3						28.2						
Simulated																							
M (mmol/L)	31.6	31.0	31.0	30.9	30.4	29.9	29.5	29.0	29.2	29.0	28.8	28.7	28.6	28.5	28.4	28.4	28.3	28.3	28.3	28.3			
NOD (mmol/kg)	6.9	5.7	5.7	5.4	4.5	3.5	2.7	1.7	2.1	1.7	1.3	1.0	0.8	0.7	0.5	0.4	0.3	0.3	0.2	0.2			
NOD Fast (mmol/kg)	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0			
NOD Slow (mmol/kg)	5.8	5.7	5.7	5.4	4.5	3.5	2.7	1.7	2.1	1.7	1.3	1.0	0.8	0.7	0.5	0.4	0.3	0.3	0.2	0.2			
M Error	0.0	0.1	0.3	-0.1	0.0	0.0	0.2				0.4						-0.2						
(Error * Error)	0.0	0.0	0.1	0.0	0.0	0.0	0.0				0.2						0.0				0.078	0.038	0.985

Soil ID Sample 2			Max NOD mmol/kg
KMnO4 Conc.)	500.0	(init mg/L)	
mass solids	50.0	(g)	
mass water	100.0	(g)	3.6
Reactor Volume	0.119	(L)	
Bulk Density	0.421	(kg/L)	
Porosity	0.841	(L/L)	
Ks	0.008		
Molecular weight	158.0	(g/mol)	

Time (hrs)	0.0	1.0	2.0	6.0	24.0	48.0	72.0	120.0	96.0	120.0	144.0	168.0	192.0	216.0	240.0	264.0	288.0	312.0	336.0	360.0	Average of Error	RMSE	r
Time (d)	0.0	0.0	0.1	0.3	1.0	2.0	3.0	5.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0			
Experimental																							
M (mg/L)	500.0	475.5	453.0	436.0	398.0	352.0	326.0				278.0						212.0						
M (mmol/L)	3.2	3.0	2.9	2.8	2.5	2.2	2.1				1.8						1.3						
Simulated																							
M (mmol/L)	3.2	2.6	2.6	2.6	2.5	2.5	2.4	2.3	2.4	2.3	2.3	2.2	2.2	2.1	2.1	2.0	2.0	2.0	1.9	1.9			
NOD (mmol/kg)	6.9	5.8	5.8	5.7	5.7	5.5	5.4	5.2	5.3	5.2	5.1	5.0	4.9	4.9	4.8	4.7	4.6	4.5	4.5	4.4			
NOD Fast (mmol/kg)	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0			
NOD Slow (mmol/kg)	5.8	5.8	5.8	5.7	5.7	5.5	5.4	5.2	5.3	5.2	5.1	5.0	4.9	4.9	4.8	4.7	4.6	4.5	4.5	4.4			
M Error	0.0	0.4	0.3	0.2	0.0	-0.2	-0.3				-0.5						-0.7						
(Error * Error)	0.0	0.2	0.1	0.0	0.0	0.1	0.1				0.2						0.4				-0.093	0.129	0.880

Soil ID Sample 3			Max NOD mmol/kg
KMnO4 Conc.)	50.0	(init mg/L)	
mass solids	50.0	(g)	
mass water	100.0	(g)	0.6
Reactor Volume	0.119	(L)	
Bulk Density	0.421	(kg/L)	
Porosity	0.841	(L/L)	
Ks	0.008		
Molecular weight	158.0	(g/mol)	

Time (hrs)	0.0	1.0	2.0	6.0	24.0	48.0	72.0	120.0	96.0	120.0	144.0	168.0	192.0	216.0	240.0	264.0	288.0	312.0	336.0	360.0	Average of Error	RMSE	r
Time (d)	0.0	0.0	0.1	0.3	1.0	2.0	3.0	5.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0			
Experimental																							
M (mg/L)	50.0	41.7	30.1	21.0	1.0	0.0	0.0	0.0									0.0						
M (mmol/L)	0.3	0.3	0.2	0.1	0.0	0.0	0.0	0.0									0.0						
Simulated																							
M (mmol/L)	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0			
NOD (mmol/kg)	6.9	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3			
NOD Fast (mmol/kg)	1.2	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5			
NOD Slow (mmol/kg)	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8			
M Error	0.0	0.3	0.2	0.1	0.0	0.0	0.0	0.0									0.0						
(Error * Error)	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0									0.0				0.066	0.014	0.629

Averaged Result		
0.017	0.246	0.831

Quality Assurance/Quality Control (QA/QC) Supplemental Data

The treatability testing performed for this study was intended to provide multiple experiments to understand the oxidant kinetics and efficacy for removal of both dioxane and other chlorinated volatile organic compounds (VOCs). Natural oxidant demand (NOD) experiments were performed in triplicate, and kinetics experiments were performed in duplicate. Blanks and matrix spike/matrix spike duplicates (MS/MSDs) were performed by OnSite Environmental for the metals analyses and met all QA/QC requirements. CDM Smith performed blanks, check standards, and analytical replicates (Table A.1). All results met the QA requirements of the laboratory standard operating procedure (SOP) with the exception of the 1,4-dioxane duplicate sample, which exceeded the 40 percent limit for relative percent difference (RPD). While analytical replicates and MS/MSDs were not performed by Carus, data accuracy can be assessed through a combination of results from experimental replicates, blanks, check standards, and standard curves for specific analytes. Representative standard curves performed by Carus Corporation associated with NOD testing, kinetics testing, and 1-D column testing are included below for reference. Standard curves exceeded the 3 point requirement for calibration from the work plan. Analytical replicates were not collected for the 1-D column study because the low flow rates (0.05 milliliters per minute [mL/min] or 0.15 mL/min) required collection of a single sample over approximately 5 to 6 hours and thus analytical replication was not possible. Tables A.2 and A.3 and Figure A.8 summarize example QA/QC data collected by Carus during the study. Onsite Environmental performed MS/MSDs, method blanks, and analytical duplicates. All results met the laboratory QA standards. Copies of the analytical reports are available upon request.

Table A.1 Example Blanks, Replicates, and Standard Checks (Performed by CDM Smith)

Date	Sample ID	1,4-Dioxane (ppb)	1,4-Dioxane RPD (%)	Persulfate RPD (%)	Permanganate RPD (%)	1,4-Dioxane Recovery (%)
T=0 Day Sampling	PS-0.15	572.49	19%	1%	-	-
	Dup-PS-0.15	473.24				-
	PM-0.05	509.82	13%	-	0%	-
	Dup-PM-0.05	581.54				-
	blank	2.03	-	-	-	-
	blank	4.80	-	-	-	-
	blank	3.82	-	-	-	-
	blank	2.91	-	-	-	-
	blank	0.87	-	-	-	-
	blank	1.59	-	-	-	-
	blank	2.21	-	-	-	-
	blank	2.06	-	-	-	-
	500 ppb Std	432.98	-	-	-	87%
	500 ppb Std	414.23	-	-	-	83%
	500 ppb Std	399.81	-	-	-	80%
	500 ppb Std	406.21	-	-	-	81%

Date	Sample ID	1,4-Dioxane (ppb)	1,4-Dioxane RPD (%)	Persulfate RPD (%)	Permanganate RPD (%)	1,4-Dioxane Recovery (%)
T=1 Day Sampling	PS-0.50	219.34	44%	0%	-	-
	Dup-PS-0.50	140.55				-
	PM-0.25	558.62	11%	-	0%	-
	Dup-PM-0.25	622.44				-
	blank	0.83	-	-	-	-
	blank	0.75	-	-	-	-
	blank	0.89	-	-	-	-
	blank	1.30	-	-	-	-
	blank	1.04	-	-	-	-
	blank	2.16	-	-	-	-
	blank	0.64	-	-	-	-
	blank	1.46	-	-	-	-
	500 ppb Std	570.59	-	-	-	114%
	500 ppb Std	550.74	-	-	-	110%
	500 ppb Std	522.54	-	-	-	105%
	500 ppb Std	512.84	-	-	-	103%
T=2 Day Sampling	PS-0.025	443.21	10%	1%	-	-
	Dup-PS-0.025	401.31				-
	PM-1.00	237.16	0%	-	0%	-
	Dup-PM-1.00	237.77				-
	blank	1.22	-	-	-	-
	blank	0.71	-	-	-	-
	blank	1.41	-	-	-	-
	blank	1.03	-	-	-	-
	blank	2.26	-	-	-	-
	blank	1.03	-	-	-	-
	blank	1.79	-	-	-	-
	blank	0.76	-	-	-	-
	500 ppb Std	499.45	-	-	-	100%
	500 ppb Std	469.31	-	-	-	94%
	500 ppb Std	465.71	-	-	-	93%
	500 ppb Std	470.79	-	-	-	94%
T=6 Day Sampling	PS-0.01	428.44	13%	0%		-
	Dup-PS-0.01	376.70				-
	PM-0.125	366.60	13%		1%	-
	Dup-PM-0.125	323.02				-
	blank	0.58	-	-	-	-
	blank	1.13	-	-	-	-

Date	Sample ID	1,4-Dioxane (ppb)	1,4-Dioxane RPD (%)	Persulfate RPD (%)	Permanganate RPD (%)	1,4-Dioxane Recovery (%)
T=6 Day Sampling	blank	1.02	-	-	-	-
	blank	0.64	-	-	-	-
	blank	0.72	-	-	-	-
	blank	0.83	-	-	-	-
	blank	1.15	-	-	-	-
	blank	1.09	-	-	-	-
	500 ppb Std	469.29	-	-	-	94%
	500 ppb Std	439.65	-	-	-	88%
	500 ppb Std	444.14	-	-	-	89%
	500 ppb Std	444.31	-	-	-	89%
T=9 Day Sampling	PS-0.05	440.22	13%	5%	-	-
	Dup-PS-0.05	386.07				-
	PM-0.075	440.64	10%	-	2%	-
	Dup-PM-0.075	399.24				-
	blank	1.11	-	-	-	-
	blank	0.63	-	-	-	-
	blank	0.59	-	-	-	-
	blank	0.89	-	-	-	-
	blank	0.52	-	-	-	-
	blank	1.05	-	-	-	-
	blank	0.67	-	-	-	-
	blank	1.14	-	-	-	-
	500 ppb Std	539.80	-	-	-	108%
	Check Std	577.37	-	-	-	115%
	500 ppb Std	557.99	-	-	-	112%
	500 ppb Std	502.84	-	-	-	101%
T=14 Day Sampling	PS-0.01	376.67	3%	3%	-	-
	Dup-PS-0.01	389.66				-
	PM-0.50	281.50	6%	-	1%	-
	Dup-PM-0.50	264.03				-
	blank	0.39	-	-	-	-
	blank	0.00	-	-	-	-
	blank	0.46	-	-	-	-
	blank	0.43	-	-	-	-
	blank	0.60	-	-	-	-
	blank	0.00	-	-	-	-
	blank	0.39	-	-	-	-
	blank	0.43	-	-	-	-

Date	Sample ID	1,4-Dioxane (ppb)	1,4-Dioxane RPD (%)	Persulfate RPD (%)	Permanganate RPD (%)	1,4-Dioxane Recovery (%)
T=14 Day Sampling	500 ppb Std	527.67	-	-	-	106%
	500 ppb Std	563.24	-	-	-	113%
	500 ppb Std	565.95	-	-	-	113%
	500 ppb Std	501.11	-	-	-	100%
T=21 Day Sampling	PS-0.025	342.01	10%	0%	-	-
	Dup-PS-0.025	310.51				-
	PM-0.075	267.73	4%	-	1%	-
	Dup-PM-0.075	258.40				-
	blank	0.61	-	-	-	-
	blank	1.23	-	-	-	-
	blank	0.58	-	-	-	-
	blank	1.75	-	-	-	-
	blank	0.33	-	-	-	-
	blank	0.65	-	-	-	-
	500 ppb Std	462.24	-	-	-	92%
	500 ppb Std	459.05	-	-	-	92%
	500 ppb Std	458.54	-	-	-	92%
T=28 Day Sampling	PS-0.01	620.33	13%	6%	-	-
	Dup-PS-0.01	543.71				-
	PM-0.25	583.83	1%	-	1%	-
	Dup-PM-0.25	575.66				-
	blank	1.72	-	-	-	-
	blank	0.65	-	-	-	-
	blank	1.06	-	-	-	-
	blank	0.00	-	-	-	-
	blank	0.42	-	-	-	-
	blank	1.43	-	-	-	-
	500 ppb Std	471.79	-	-	-	94%
	500 ppb Std	472.00	-	-	-	94%
	500 ppb Std	481.43	-	-	-	96%

Notes: ppb parts per billion RPD relative percent difference
- Not applicable for this sample/sample pair

Table A.2 Example Calibration Curve r^2 Values (performed by Carus Corporation)

Analyte	Range	Calibration Curve R^2 Value
Dioxane	High Low Low	0.9980 1.0000 0.9995
TCE	Low Low	0.9990 0.9988
1,1-DCE	Low Low	0.9982 0.9990
cis-1,2-DCE	Low Low	0.9986 0.9988
1,1-DCA	Low Low	1.0000 0. 9949

Note: High range had concentrations on the order of milligrams per liter (mg/L) and low range was on the order of micrograms per liter (µg/L).

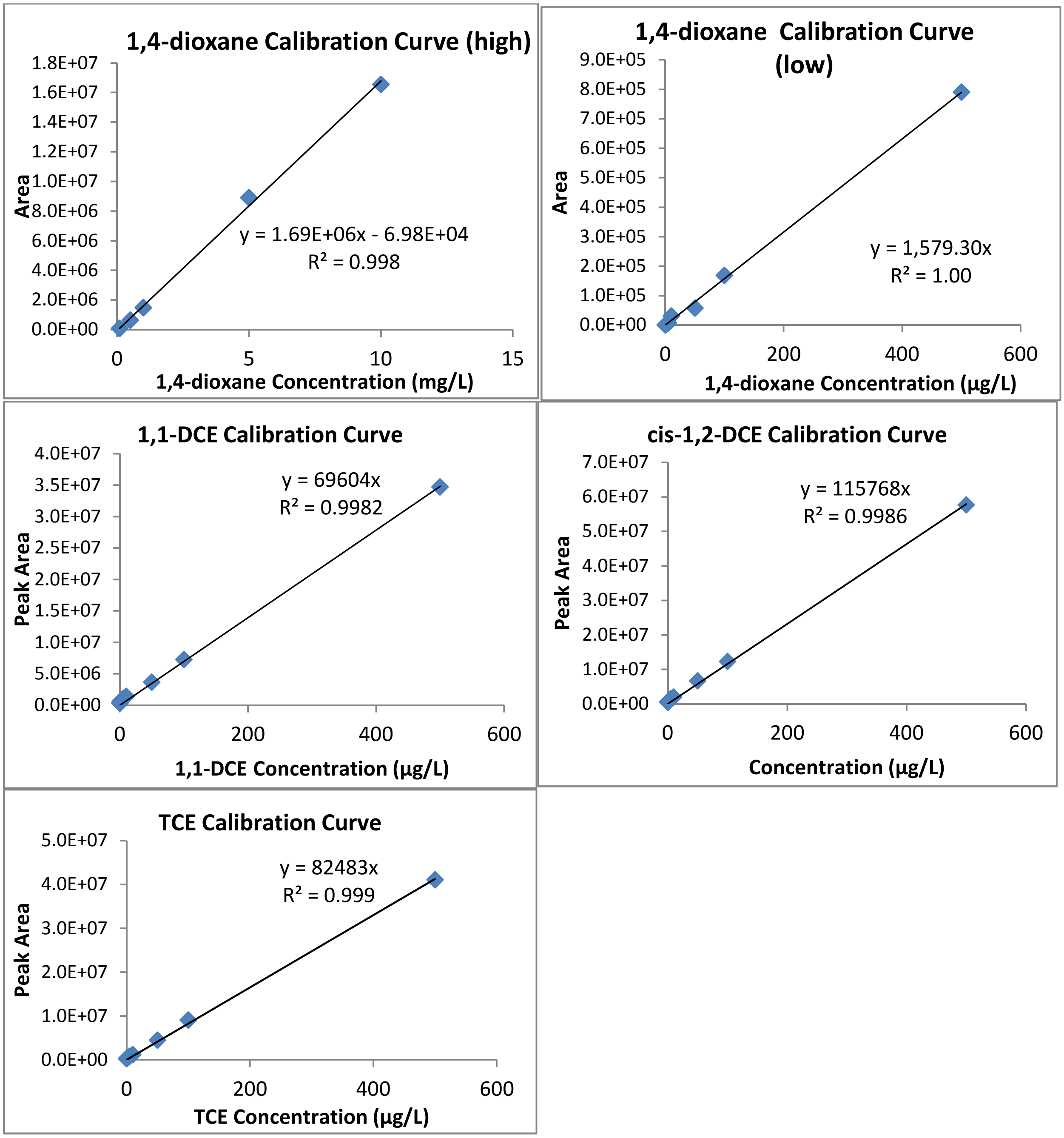


Figure A.9 Example Calibration Curves (Performed by Carus Corporation)

Table A.3 Example Blanks and Standard Checks (Performed by Carus Corporation)

Permanganate Kinetics Tests

Date	Standard	1,4-dioxane		TCE		1,1-DCA		cis-1,2 DCE		1,1-DCE	
		Actual	% Error	Actual	% Error	Actual	% Error	Actual	% Error	Actual	% Error
12/13/13	Blank	0.04	-	-	-	-	-	-	-	-	-
	5	4.32	14	-	-	-	-	-	-	-	-
	5	4.42	12	-	-	-	-	-	-	-	-
	0.1	0.11	10	-	-	-	-	-	-	-	-
	0.1	0.11	10	-	-	-	-	-	-	-	-
	0.1	0.11	11	-	-	-	-	-	-	-	-
12/16/13	Blank	0.04	-	-	-	-	-	-	-	-	-
	0.1	0.08	17	-	-	-	-	-	-	-	-
	0.1	0.09	8	-	-	-	-	-	-	-	-
	5	3.90	22	-	-	-	-	-	-	-	-
2/21/14	Blank	0.15	-	0.93	-	0.07	-	0.40	-	0.42	-
	Blank	5.18	-	41.0	-	0.34	-	0.83	-	3.43	-
	50	82.4	65	99.2	98	1.95	96	106	111	139.7	179
2/25/14	Blank	0.00	-	0.54	-	0.04	-	0.27	-	0.35	-
	Blank	0.85	-	1.10	-	0.07	-	0.55	-	0.88	-
	50	72.0	44	78.4	57	0.82	98	93.7	87	121.7	143
2/28/14	Blank	0.66	-	1.13	-	0.20	-	0.67	-	0.85	-
	Blank	0.53	-	0.89	-	0.02	-	0.60	-	0.57	-
	50	67.9	36	89.7	79	25.2	50	62.0	24	94.9	90
3/5/14	Blank	0.14	-	0.39	-	0.08	-	0.19	-	0.20	-
	Blank	0.55	-	0.90	-	0.06	-	0.35	-	0.60	-
	50	58.7	17	79.9	60	33.4	33	55.2	10	86.9	74
3/10/14	Blank	0.44	-	1.88	-	0.36	-	1.04	-	1.48	-
	Blank	0.00	-	0.46	-	0.11	-	0.22	-	0.31	-
	50	69.7	39	87.1	74	39.2	22	60.9	22	95.5	91

Persulfate Kinetics Test

Date	Standard	1,4-dioxane		TCE		1,1-DCA		cis-1,2 DCE		1,1-DCE	
		Actual	% Error	Actual	% Error	Actual	% Error	Actual	% Error	Actual	% Error
10/23/13	Blank	0.06	-	-	-	-	-	-	-	-	-
	Blank	0.05	-	-	-	-	-	-	-	-	-
	0.1	0.11	15	-	-	-	-	-	-	-	-
	0.1	0.11	10	-	-	-	-	-	-	-	-
	5	4.68	6	-	-	-	-	-	-	-	-
	5	4.69	92	-	-	-	-	-	-	-	-
10/24/13	Blank	0.04	-	-	-	-	-	-	-	-	-
	Blank	N.D.	-	-	-	-	-	-	-	-	-
	0.1	0.11	9	-	-	-	-	-	-	-	-

		1,4-dioxane		TCE		1,1-DCA		cis-1,2 DCE		1,1-DCE	
Date	Standard	Actual	% Error	Actual	% Error	Actual	% Error	Actual	% Error	Actual	% Error
	5	4.28	14	-	-	-	-	-	-	-	-
10/25/13	Blank	N.D.	-	-	-	-	-	-	-	-	-
	Blank	N.D.	-	-	-	-	-	-	-	-	-
	0.1	0.11	8	-	-	-	-	-	-	-	-
	5	4.99	0	-	-	-	-	-	-	-	-
10/28/13	Blank	N.D.	-	-	-	-	-	-	-	-	-
	Blank	N.D.	-	-	-	-	-	-	-	-	-
	0.1	0.11	13	-	-	-	-	-	-	-	-
	5	5.34	7	-	-	-	-	-	-	-	-
10/30/13	Blank	N.D.	-	-	-	-	-	-	-	-	-
	Blank	N.D.	-	-	-	-	-	-	-	-	-
	0.1	0.11	12	-	-	-	-	-	-	-	-
	5	5.24	5	-	-	-	-	-	-	-	-
1/29/14	Blank	N.D.	-	5.43	-	N.D.	-	1.35	-	2.70	-
	Blank	3.38	-	6.23	-	N.D.	-	1.77	-	3.41	-
2/3/14	Blank	N.D.	-	5.54	-	1.80	-	1.54	-	2.79	-
	Blank	3.25	-	5.66	-	1.77	-	1.58	-	2.95	-
2/6/14	Blank	N.D.	-	5.93	-	1.77	-	1.63	-	3.07	-
	Blank	3.24	-	6.00	-	1.78	-	1.64	-	3.21	-
2/7/14	Blank	N.D.	-	5.86	-	1.77	-	1.64	-	3.02	-
	Blank	3.20	-	5.85	-	1.75	-	1.58	-	3.09	-
2/10/14	Blank	-	-	5.89	-	1.76	-	1.55	-	2.90	-
	Blank	2.93	-	6.20	-	1.74	-	1.59	-	3.02	-
	50	37.3	25	38.5	23	1.90	96	53.5	7	59.0	18
2/12/14	Blank	2.84	-	5.89	-	1.77	-	1.70	-	3.06	-
	Blank	4.14	-	6.20	-	1.78	-	1.78	-	3.21	-
	50	28.8	42	38.5	23	2.54	95	41.1	18	48.3	3
2/14/14	Blank	2.62	-	5.66	-	1.74	-	1.56	-	2.94	-
	Blank	3.96	-	6.27	-	1.79	-	1.77	-	3.16	-

Note: - indicates data were either not collected or calculated N.D. – below detection

APPENDIX C
TECHNOLOGY DEMONSTRATION PLAN

FINAL TECHNOLOGY DEMONSTRATION PLAN

Sustained *In Situ* Chemical Oxidation (ISCO) of 1,4-Dioxane Using Slow Release Chemical Oxidant Cylinders

ESTCP Project Number ER-201324

September 2015

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ACRONYMS

%	percent
/kg	per kilogram
µg/L	microgram per liter
AF	Air Force
AFB	Air Force Base
AOP	advanced oxidation process
bgs	below ground surface
CA	California
cis-1,2-DCE	cis-1,2-dichloroethene
cm/s	centimeter per second
deg C	degree Celcius
dioxane	1,4-dioxane
DNAPL	dense non-aqueous phase liquid
DOC	dissolved organic carbon
DoD	Department of Defense
DPT	direct push technology
ERPIMS	Environmental Restoration Program Information Management System
F&G	funnel and gate
Fe-EDTA	iron chelated complex
ft	foot/feet
ft/d	foot/feet per day
ft/ft	foot/feet per foot
ft^2	square foot
g/kg	gram per kilogram
HDPE	High-density polyethylene
ID	inside diameter
ISCO	*in situ* chemical oxidation
$KMnO_4$	potassium permanganate
MCL	maximum contaminant level
mg/day	milligram per day
mg/L	milligram per liter
MnO_2	manganese dioxide
MRL	minimum reporting level
NAS	Naval Air Station
NI	North Island
NIRIS	Naval Installation Restoration Information Solution
NOD	natural oxidant demand
O&M	operation and maintenance
ORP	oxidation-reduction potential
OU	operable unit
PCE	tetrachloroethene

PRB	permeable reactive barrier
RPM	remedial project manager
RWQCB	Regional Water Quality Control Board
SOD	soil oxidant demand (also referred to as NOD)
SU	standard unit
TCA	1,1,1-trichloroethane
TCE	trichloroethene
UCMR	Unregulated Contaminant Monitoring Regulation
US	United States
USAF	United States Air Force
USEPA	United States Environmental Protection Agency
VOC	volatile organic compound

1.0 INTRODUCTION

ESTCP Project Number ER-201324 involves demonstration and validation of sustained *in situ* chemical oxidation (ISCO) of 1,4-dioxane (dioxane) using slow-release oxidant cylinders. This demonstration includes two phases: Phase I – Laboratory treatability study and engineering design tool development and Phase II – Field demonstration of permeable cylinder barrier. A complete discussion of Phase I activities was provided in the *ER-201324 Treatability Study Work Plan* (CDM Smith, 2013) and *ER 201324 Treatability Study Report* (CDM Smith, 2014). This Demonstration Plan describes the activities that will be performed during Phase II, along with a summary of results obtained from Phase I.

1.1 BACKGROUND

Dioxane is increasingly recognized as a challenging contaminant at sites where 1,1,1-trichlorethane (TCA) was released to soil and groundwater. In 1985, 90 percent (%) of all United States (US) production of dioxane was used to stabilize TCA. At that time, there were about 25,000 vapor degreasers in operation, which consumed about 165 million pounds of TCA per year. A Navy query of the Naval Installation Restoration Information Solution (NIRIS) indicated that over 200 sites have detected dioxane above 3 micrograms per liter (µg/L). In addition, based on a query of United States Air Force (USAF) Environmental Restoration Program Information Management System (ERPIMS), dioxane has been observed in 17.4% of the monitoring wells with records for trichloroethene (TCE) and/or TCA. In fact, 64.4% of all dioxane detections were collocated with TCE with the presence of TCA (Anderson et al. 2012).

Once released into groundwater, dioxane can migrate more rapidly than volatile organic compounds (VOCs) due to its miscibility with water, low affinity for sorption to soil organic matter, and resistance to biodegradation and abiotic breakdown (Mohr et al. 2010). Plumes of dioxane often occupy a substantially larger footprint than VOCs. Dioxane also has the capacity to diffuse into and occupy the large pore volumes in silts and clays due to its high solubility and molecular charge distribution that favors invasion of clays by breaking the tightly held mono-layer of water on clay surfaces (Zhang et al. 1990; Mazurkiewicz and Tomasik 2006; Payne et al. 2008; Mohr et al. 2010). As with VOCs, a significant mass of dioxane may reside in fine-grained deposits, slowly diffusing back into the aquifer sustaining large and dilute plumes (Payne et al. 2008).

Dioxane is not easily treated. *Ex situ* advanced oxidation processes (AOPs) are the most developed approach for dioxane treatment (USEPA 2006). Because of high operation and maintenance (O&M) costs associated with AOPs, successful deployment of *in situ* approaches would grant remedial project managers (RPMs) a far more flexible and cost effective remedial approach. As an example, natural attenuation of dioxane is being evaluated at the Air Force (AF) Plant 44. While evidence of dioxane-oxidizing bacteria exists, site data show rates are insufficient to contain the plume (Mora et al. 2011). Previous research indicates the major reason is these bacteria have low specific growth rates, low cell yields, and high half-saturation constants (Evans et al. 2007; Parales et al. 1994; Mahendra and Alvarez-Cohen 2006; Adamus et al. 1995). Cometabolism via propane sparging is a promising approach but may result in high O&M costs and safety issues for continued treatment of large dilute plumes. Traditional ISCO is also not a solution to large dilute plumes because the reactants are relatively short-lived (Siegrist et al. 2011). Slow-release chemical oxidant cylinders, described further in subsequent sections, match the contaminant destruction rate to the contaminant transport rate with a sustainable, simple, and low O&M approach. Using innovative oxidation chemistries in concert with innovative deployment strategies, cost-effective treatment of large and dilute dioxane plumes is possible.

This field demonstration will utilize slow-release chemical oxidant cylinders to treat a plume containing dioxane and chlorinated ethenes. Unactivated persulfate embedded in a slow-release paraffin wax formulation will be emplaced in two 4-inched wells which are housed inside 18-inch diameter boreholes backfilled with sand to induce groundwater flow convergence and partially simulate a funnel and gate. The slow-release oxidant cylinders to be used in this demonstration are 2.5 inches in diameter and 18 inches long. The cylinder dimensions will allow for easy emplacement of multiples in series inside the 4-inch diameter wells. Monitoring will be performed upgradient, within, and downgradient of the treatment area. Groundwater analysis will include dioxane, VOCs, dissolved metals, hexavalent chromium, bromate, sulfate, chloride, pH, and conductivity.

1.2 OBJECTIVE OF THE DEMONSTRATION

The overall objective of this project is to demonstrate the use of slow-release chemical oxidants to destroy dioxane in groundwater *in situ*. Because dioxane is highly miscible in water, has a low Henry's Law constant, and has a low octanol/water partitioning coefficient; it often forms long, relatively low concentration groundwater plumes. Therefore, the use of slow-release technology can be advantageous to treat dioxane plumes in a variety of barrier-type applications as they slowly migrate from the original source.

The technical objectives of this demonstration/validation project are:

- Demonstrate the use of slow-release chemical oxidant cylinders for sustained *in situ* treatment of dioxane and chlorinated solvents.
- Demonstrate the use of unactivated persulfate in the slow-release cylinders to couple the oxidant release rate, the contaminant transport rate, and the contaminant destruction rate.
- Demonstrate that the slow-release cylinder delivery vehicle can minimize potential secondary effects such as metals mobilization.
- Produce engineering guidance in the form of a practical spreadsheet tool.

1.3 REGULATORY DRIVERS

In September 2013, the United States Environmental Protection Agency (USEPA) published the *Toxicological Review of 1,4-Dioxane* (USEPA 2013). In this review, USEPA revised the $1x10^{-6}$ cancer risk assessment level for dioxane to 0.35 µg/L from 3.0 µg/L. As a result, the proposed minimum reporting level (MRL) for dioxane as part of the *Unregulated Contaminant Monitoring Regulation (UCMR 3) for Public Water Systems* (Federal Register, 2012) was reduced to 0.07 µg/L. Some states including California and Massachusetts have already lowered their advisory drinking water thresholds and New Hampshire, Washington, and other states have lowered their provisional cleanup levels and lab method reporting limit requirements (USEPA 2013). New-found dioxane contamination will likely influence decisions regarding Department of Defense

(DoD) monitoring and cleanup. Although no federal drinking water standards have been established to date, USEPA has established an "action level" of 3 µg/L for dioxane and it is currently listed on the contaminant candidate list (CCL3) (Federal Register, 2014).

The DoD has hundreds of sites contaminated with chlorinated solvents, which represents a large remediation liability (Parsons 2004). Dioxane in particular can form large dilute dissolved-phase plumes that may extend for miles down gradient of source areas and may persist long after source areas have been removed. While these large plumes may contain relatively low concentrations of dioxane (e.g., less than 100 µg/L), sites with concentrations greater than the health-based drinking water standards continue to involve active remediation. These plumes present significant challenges to the DoD as they can be costly to contain and clean up (SERDP 2007).

2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

Figure 2.1. Slow-release cylinder

The technology concept involves use of slow-release chemical oxidant cylinders shown in **Figure 2.1** to treat large dilute plumes of dioxane. Chemical oxidant (e.g., sodium persulfate) embedded in a slow-release wax formulation "cylinder" can be emplaced in existing monitoring wells, a F&G configuration (described further below), permeable reactive barrier (PRB), or directly installed into boreholes using direct push technology (DPT). The oxidant/paraffin mixtures have been designed to allow oxidant to gradually diffuse into the groundwater and slowly oxidize dioxane. They are slowly consumed and persist sufficiently long enough – estimated to be on the order of years – to result in dioxane destruction as a dilute plume migrates through the treatment zone created by these cylinders. Dioxane can be oxidized by permanganate and unactivated persulfate as described below. Because of the flexibility in distribution methods, this technology can be used in the form of a permeable reactive zone or in a grid, and can be used in multiple hydrogeologic environments. For large and dilute dioxane plumes, or sites with access restrictions, a PRB or F&G configuration is likely to be the best remediation approach.

The fundamental advantage of slow-release forms of oxidants over traditional injection of liquid solutions is the ability to release the oxidant over a period of years which will minimize rebound, treat large/dilute plumes, and minimize O&M costs. The mechanism for release of the oxidant from the paraffin wax matrix is a dissolution-diffusion process (Lee and Schwartz 2007a). In the case of potassium permanganate ($KMnO_4$), oxidant particles exposed at the surface of the cylinder rapidly dissolve, resulting in a large spike in permanganate flux. As the $KMnO_4$ particles dissolve, the surface of the exposed particles retreats into the core of the cylinder creating secondary porosity. The $KMnO_4$ release rate from the cylinder becomes limited by the $KMnO_4$ diffusion rate through the porous structure, eventually reaching a nearly steady state flux rate until the oxidant is consumed. Additionally, the slow-release oxidant can effectively treat the dioxane as it slowly diffuses from less mobile pore spaces into groundwater. A similar mechanism occurs with sodium persulfate.

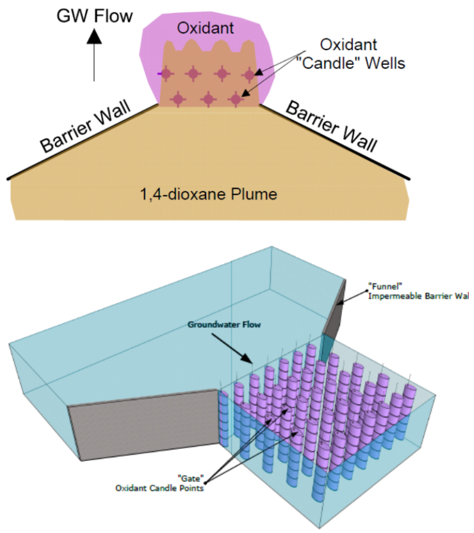


Figure 2.2. Funnel and gate concept

Work during the treatability study (Phase 1) showed that unactivated persulfate can destroy dioxane more efficiently than permanganate (Nguyen et al. 2012). Selection of the correct oxidant depends on a variety of site-specific factors including natural oxidant demand (NOD), oxidant release rates, contaminant degradation efficiency, cost, and potential secondary aquifer geochemistry effects. Dioxane oxidation by unactivated persulfate is slower than by activated persulfate which is advantageous for this technology because it results in greater oxidant persistence. These relatively slow dioxane removal rates compared to typical oxidation strategies are favorable because contamination is often present in large dilute plumes.

Funnel and Gate (F&G) Concept

The F&G concept is a variation of a permeable reactive barrier (ITRC 2011). The principle is based on use of sheet pile or impermeable materials (e.g., grout) to create an impermeable barrier to groundwater flow and then to include openings in this barrier (i.e., gates) through which water flows as shown in **Figure 2.2**. Hydraulic modeling is critical to ensure groundwater does not flow around, under, or over the impermeable funnel. Various processes (e.g., air sparging) or materials (e.g., chemical oxidants) can be included in these gates. In the case of the technology described in this proposal, slow-release chemical oxidants would be emplaced in the gates. Emplacement technologies for amendments in gates has been described (ITRC 2011).

This barrier can be envisioned as part of a PRB or the gate of an F&G. The F&G approach is ideal in many ways because it is a passive method to control the velocity – a key cylinder installation design parameter. The funnel can be designed to achieve a groundwater velocity that will result in an optimized target oxidant concentration tailored to site contaminants, their concentrations, and the NOD.

Alternative methods can be conceived including fracturing, augering, and removable flow-through cassettes. Some of these approaches have been described previously for other amendments (ITRC 2011). As described below, the gate can be modified to promote mixing through use of baffles, water circulation, and pneumatic mixing.

Figure 2.3. Cylinder Holder

For this demonstration, 18-inch diameter boreholes backfilled with a material of significantly higher conductivity than those of the surrounding will be used to simulate a mini F&G configuration. Oxidant cylinders measuring 2.5 inches in diameter by 18 inches in length will be emplaced inside two 4-inch diameter wells inside the 18-inch diameter boreholes to treat the entire depth of aquifer contamination. **Figure 2.3** shows an example of a cylinder holder that can be used to emplaced oxidant cylinders inside the wells.

Cylinder Spacing

Close cylinder spacing (e.g., less than 1 foot) may be necessary if the only means of oxidant mixing with the aquifer is dispersion. Use of close cylinder spacing to intercept a large plume may not be cost-effective. Use of a F&G is a good approach to mitigate the issues associated with close cylinder spacing. By funneling groundwater into a gate, cylinders can be spaced closely and still be cost-effective. The reason is the width of the gate is much less than the width of the plume that is being intercepted. Additional approaches include: 1) providing baffles in the gate, and 2) providing means for mixing within the gate. Baffles can create a serpentine flow pattern that can greatly enhance mixing. Active mixing either by

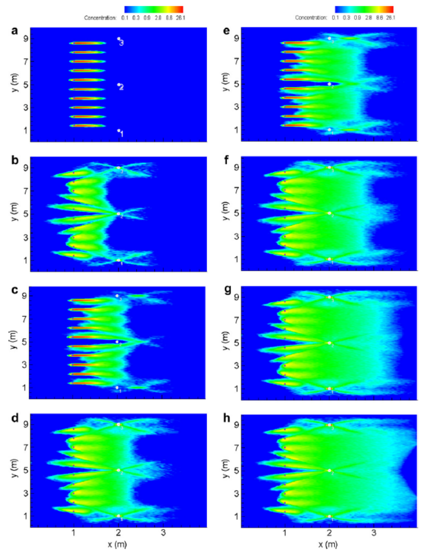


Figure 2.4. Distribution and mixing of the oxidant promoted by periodic pumping (Lee et al. 2008).

pumping or gas sparging can also be used to promote mixing. Researchers at The Ohio State University conducted modeling simulations to investigate a semi-passive approach of intermittent pumping down-gradient from a row of slow-release permanganate cylinders to enhance mixing and lateral dispersion as shown in **Figure 2.4** (Lee et al. 2008). On the left side, a lack of lateral dispersion is occurring which would reduce cylinder treatment efficiency and could require close spacing. With wider cylinder spacing ways to provide in zone mixing may be needed. This was accomplished in their studies with well-based mixing and zero net injection/withdrawal pumping that facilitated lateral spreading and reagent mixing as illustrated on the right side of **Figure 2.4**. Pneumatic circulators can also be used but the risk of VOC volatilization would need to be considered (Christenson 2011). Pneumatic circulators have been used in the Cozad, Nebraska cylinder field site (Christenson et al. 2012). Modeling is often performed to assess the potential impact of these gate modifications (i.e., baffling, pumping, or pneumatic mixing) on cylinder spacing. Nevertheless, it is estimated the cylinder spacing can be increased by a factor of 3 to 10 with these approaches.

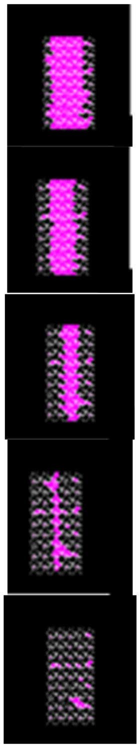


Figure 2.5. Time series progression of oxidant release from a cylinder.

<u>Longevity</u>

The longevity of slow-release oxidant cylinders will be a function of a number of parameters including: oxidant flux, cylinder diameter, ground water velocity, hydraulic conductivity, and soil oxidant demand. Dissolution rates from slow-release oxidants is characterized by an initial flush followed by slower and sustained first order release (Kang et al. 2004; Lee and Schwartz 2007b). Oxidant release from the paraffin wax matrix occurs through the processes of dissolution and diffusion. The release of permanganate from a slow-release permanganate cylinder is illustrated schematically in **Figure 2.5**. As permanganate solids dissolve and void spaces are created. Newly created void spaces expose new permanganate solids for dissolution and diffusion. This process occurs radially starting at the outer circumference of the cylinder progressing to the cylinder "core". This is why there is an initial spike of permanganate immediately upon emplacement and a significantly slower permanganate release rate at later times. The release rates will also vary as a function of the cylinder diameter or geometry of the slow release oxidant. **Figure 2.6** provides a comparative illustration of slow-release permanganate cylinders prior to exposure to flowing

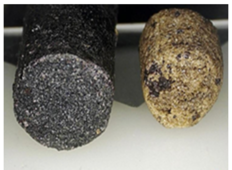


Figure 2.6. New and spent cylinders

water and an expended permanganate cylinder.

Figure 2.7 illustrates the high initial flux that occurs when flow is started followed by slow and sustained-release over 80 days of tank operation. Longevity increases significantly as cylinder diameter increases (e.g., from the straw-sized cylinder to the full-scale 2.5-inch diameter cylinder as shown in **Figure 2.8.** Data were simulated using a modification of a published model (Lee et al. 2008) by adjusting the effective diffusion coefficient of the slow-release system. In this

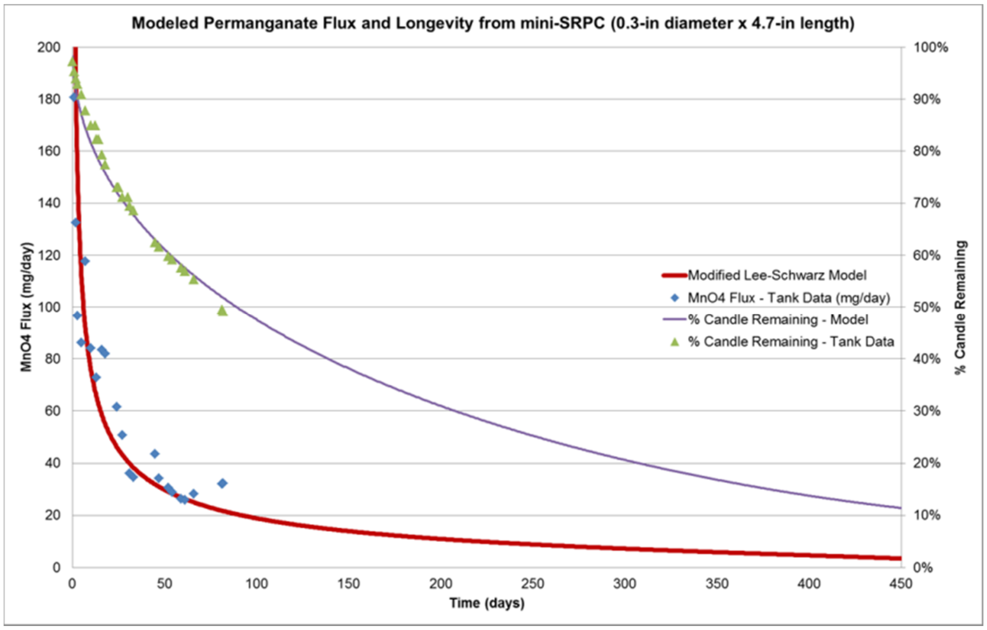


Figure 2.7. A modified existing oxidant release model (Lee et al. 2008)

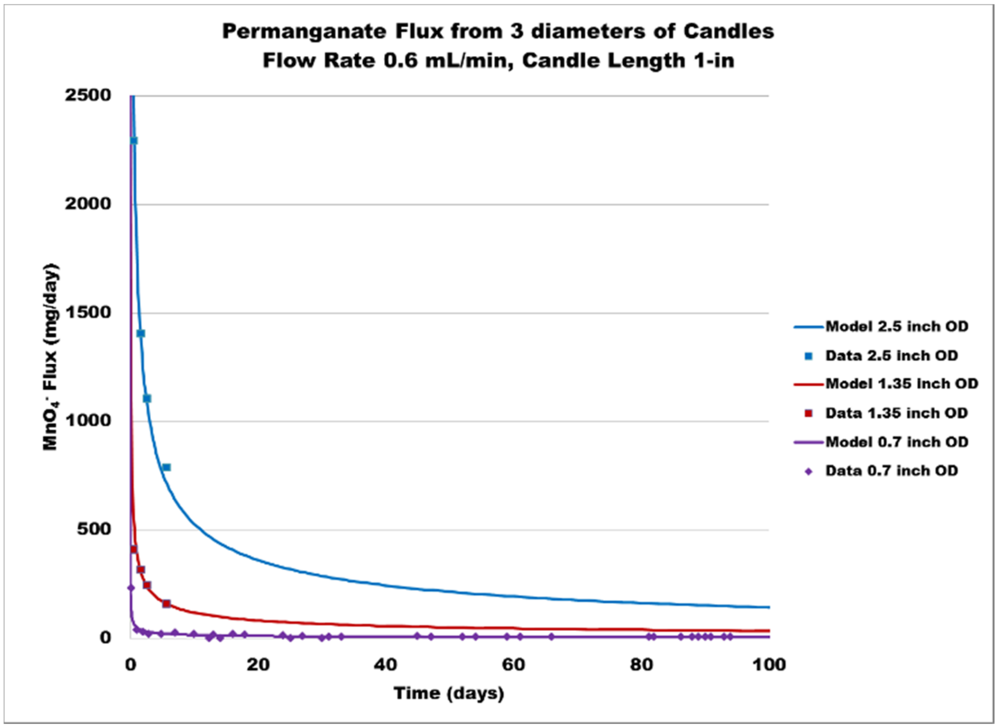


Figure 2.8. Cylinder Diameter vs. Longevity

experiment, approximately 50% of the total permanganate in the mini-cylinder was released with the average permanganate flux in the effluent ranging from 25 to 30 milligrams per day over a 30 day period. These data suggest good predictability of the model and reasonable cylinder longevity.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Substantial advantages of sustained ISCO of dioxane using slow-release chemical oxidant cylinders include:

- This technology provides an *in situ* application to treat large dilute plumes of dioxane – something that does not currently exist
- This technology is also applicable to a multitude of co-contaminants such as tetrachloroethene (PCE), TCE, etc.
- Sustained ISCO is implementable in a variety of configurations with different oxidants
- This flexible and adjustable technology can be configured to match the rate of oxidant release to the mass flux of dioxane and solvents and control cylinder replacement frequency
- It can be used in heterogeneous aquifers
- The technology mitigates rebound problems with ISCO
- It does not require injection of gases for cometabolic biodegradation
- *In situ* application is a sustainable application, which significantly reduces energy usage and overall costs
- The technology does not depend on biodegradation that we have shown to have drawbacks (Evans et al. 2007; Adamus et al. 1995).
- Excellent health and safety profile
- Can be deployed at active sites with minimal infrastructure required for deployment and monitoring

Limitations of sustained ISCO of dioxane using slow release chemical oxidant cylinders currently include:

- Mobilization of metals such as hexavalent chromium or bromate due to the oxidative conditions of both permanganate and persulfate or the low pH conditions that can result from persulfate reactions (Crimi and Siegrist 2003; Tsitonaki et al. 2010). These risks are minimized in the cylinder configuration because of the lower concentration of oxidant involved in the reaction.
- Potential for low transverse dispersion of oxidants may require tight spacing between cylinders perpendicular to migration direction. The use of paraffin/oxidant “walls” in a F&G-style system could be used to overcome this limitation.

- Generation of oxidation byproduct such as manganese dioxide (in the case of permanganate) or iron hydroxides may lead to decrease in oxidant release rate or, possibly, preferential flow due to plugging within the reactive zones.

This demonstration will benefit the DoD by demonstrating and validating a novel technology for remediation of an emerging contaminant, dioxane. The demonstration will increase the understanding of potential *in situ* applications to treat dioxane in groundwater, especially in cases where the other VOCs have been adequately treated using an ex situ method. The increased understanding of this technology will add to the portfolio of sustainable treatment methods that are economical and effective for large dioxane plumes. Additionally, this demonstration will expand our understanding of designing, implementing, optimizing, and evaluating engineering design tool for treatment of dioxane. Finally, the demonstration will promote the use and acceptance of an innovative and sustainable remediation technology.

3.0 PERFORMANCE OBJECTIVES

Performance objectives for the demonstration are presented in **Table 3.1**. A description of each performance objective, specific data requirements, and success criteria are detailed below.

3.1 PERFORMANCE OBJECTIVE: TECHNOLOGY EFFECTIVENESS

This objective is focused on demonstrating the ability to destroy dioxane and chlorinated ethenes (TCE, cis-1,2-DCE, 1,1-DCE, and vinyl chloride) in the reactive zone.

3.1.1 Data Requirements

Concentrations of dioxane and chlorinated ethenes in groundwater will be measured in monitoring wells located up-gradient, within, and down-gradient of the treatment zone.

3.1.2 Success Criteria

Treatment of dioxane will be considered successful if a minimum of 90 percent reduction is documented from the up-gradient to the furthest down-gradient monitoring well, or if the concentration in the down-gradient monitoring well is less than 3 µg/L. Chlorinated ethene treatment will be considered successful if there is a 90 percent reduction on a molar basis from up-gradient to down-gradient of the treatment zone.

3.2 PERFORMANCE OBJECTIVE: SUSTAINABILITY/LONGEVITY

This objective is focused on demonstrating the ability to consistently distribute the oxidant in the reactive zone and to meet the above Technology Effectiveness objective for a minimum period of time.

3.2.1 Data Requirements

Dioxane, chlorinated ethene, and oxidant concentrations will be measured in monitoring wells up-gradient, within, and down-gradient of the treatment zone.

3.2.2 Success Criteria

Once detected in each monitoring well, oxidant concentrations are observed to remain constant or increase over time during one year demonstration period. Also, 90% contaminant destruction is maintained for at least 4 weeks once achieved.

3.3 PERFORMANCE OBJECTIVE: OXIDANT TRANSPORT AND DESTRUCTION

This objective is focused on demonstrating that oxidants will not be transported significantly past the reactive zone.

3.3.1 Data Requirements

Oxidant concentrations will be measured in monitoring wells up-gradient, within, and down-gradient of the treatment zone.

3.3.2 Success Criteria

Success criteria for this objective are either non-detectable oxidant concentrations in the down-gradient monitoring well or concentration trends demonstrating oxidant destruction along the flow path.

3.4 PERFORMANCE OBJECTIVE: TECHNOLOGY IMPLEMENTABILITY/ SECONDARY IMPACTS

This objective is focused on demonstrating that secondary groundwater quality impacts are either acceptable or transient.

3.4.1 Data Requirements

Data will be collected to evaluate if oxidant cylinder deployment results in secondary changes in aquifer properties. Persulfate can lower pH and thus mobilize metals from soils. Data to be collected include: filtered metals (i.e., As, Ba, Be, Cd, Cr, Cu, Hg, Pb, Tl, Se, and U) concentrations in monitoring wells. Filtered chromium concentrations will be assumed to be equivalent to hexavalent chromium. pH, ORP, and persulfate will be measured to assist in data interpretation.

3.4.2 Success Criteria

The goal of this performance objective is to determine if any secondary impacts to the aquifer result from the oxidant cylinder deployment. Success criteria are based on filtered metals and bromate concentrations. Groundwater concentrations in the furthest down-gradient monitoring well should be less than background (upgradient) concentrations for metals with primary drinking water MCLs and for hexavalent chromium (measured as dissolved chromium) and bromate. As persulfate decomposition is known to decrease pH via production of sulfuric acid, monitoring of the contaminant concentrations along the flow path will also be used to assess success. The site aquifer is naturally reducing and will also have some pH neutralization capacity. Oxidation products including bromate and hexavalent chromium may be produced and subsequently reduced down-gradient of the reactive zone containing persulfate. Elevated metals concentrations may decrease down-gradient of the reactive zone because the aquifer may naturally neutralize acid generated during persulfate decomposition. Therefore, pH, ORP, and persulfate concentrations will be used to assess potential for attenuation of secondary effects.

Table 3.1. Performance Objectives

	Performance Objective	Data Requirements	Success Criteria
Quantitative Performance Objectives	Technology Effectiveness	1,4-Dioxane and chlorinated ethene concentrations	90% reduction in 1,4- dioxane concentration or concentration reduced to < 3 µg/L
			90% reduction of chlorinated ethene co-contaminants
	Sustainability/ Longevity	Oxidant and contaminant concentrations along flow path	Rate of oxidant concentration change at any given location ≥ 0 mg/L/d over 1 year
			90% contaminant removal is sustained for at least 4 weeks
	Oxidant Transport and Destruction	Oxidant concentrations along flow path	Oxidant consumed to below detection at final down-gradient monitoring point or trends support its destruction along the flow path
	Technology Implementability/ Secondary Impacts	pH, ORP, persulfate, filtered metals (As, Ba, Be, Cd, Cr, Cu, Hg, Pb, Se, Tl, and U), and bromate.	Filtered metals and bromate below background (upgradient well concentration) in the final down-gradient monitoring point or demonstrated decrease in concentration along flow path. pH, ORP, and persulfate concentrations will be used to evaluate attenuation trends.

Table 3.1 (cont). Performance Objectives

	Performance Objective	Data Requirements	Success Criteria
Qualitative Performance Objectives	Technology Reproducibility	Oxidant concentrations in cylinder boreholes and seepage velocity estimated using a chloride tracer test	Oxidant concentrations over time will be compared and relative percent different will be calculated to characterize reproducibility. Persulfate flux will be calculated and compared to treatability test results.
	Engineering Design Tool Utility	Simulations based on site data including 1,4-dioxane and chlorinated ethene concentrations, oxidant concentrations, and seepage velocity (using chloride tracer)	Reasonable prediction of oxidant release rate and contaminant destruction with the engineering design tool
	Design Tool Ease of Use	User feedback	Accessible by typical anticipated users (e.g. engineers and scientists)
	Applicability to Multiple Site Conditions	Compare design requirements for different plume and soil characteristics	Engineering tool can be applied to multiple site conditions (e.g. hydraulic conductivity, soil oxidant demand, 1,4-dioxane concentrations)

****Notes***:

- µg/L: microgram per liter
- As: arsenic
- Ba: barium
- Be: beryllium
- Cd: cadmium
- Cr: chromium
- Hg: mercury
- mg/L/d: milligram per liter per day
- Pb: lead
- ORP: oxidation-reduction potential
- Se: selenium
- Tl: thallium
- U: uranium

3.5 PERFORMANCE OBJECTIVE: TECHNOLOGY REPRODUCIBILITY

Two replicate cylinder installations will be used to characterize reproducibility in this qualitative performance objective.

3.5.1 Data Requirements

Data to be collected to evaluate the reproducibility of the technology used in the demonstration include oxidant concentrations within the two boreholes containing the oxidant cylinders. Seepage velocity will also be determined using a chloride tracer test.

3.5.2 Success Criteria

The criterion for the technical reproducibility is the successful comparison oxidant release in the two replicate boreholes. The relative percent difference of oxidant concentrations within the two boreholes will be calculated. The seepage velocity will be used in combination with the persulfate concentrations to calculate the persulfate flux from each cylinder. The estimated fluxes will be compared to values measured during the treatability test.

3.6 PERFORMANCE OBJECTIVE: ENGINEERING DESIGN TOOL UTILITY

This performance objective involves qualitative assessment of the ability of the design tool to predict oxidant cylinder performance.

3.6.1 Data Requirements

Data to be collected to evaluate the performance of the engineering design tool utility including dioxane and chlorinated ethene concentrations, groundwater seepage velocity, and oxidant concentrations.

3.6.2 Success Criteria

Success criteria for the engineering design tool utility are a reasonable prediction of cylinder release rates and contaminant distributions over time. The design tool utility predictions will be compared to field data collected before, during, and after the field demonstration. Multiple lines of evidence will be used to assess reasonableness.

3.7 PERFORMANCE OBJECTIVE: DESIGN TOOL EASE OF USE

This qualitative objective will involve beta testing of the design tool.

3.7.1 Data Requirements

The design tool will be distributed to select users to test the usability of the tool.

3.7.2 Success Criteria

User feedback will be used to evaluate the usability of the design tool and to determine if changes to the design tool are required.

3.8 PERFORMANCE OBJECTIVE: APPLICABILITY TO MULTIPLE SITE CONDITIONS

This objective will involve a virtual design of cylinder installation at hypothetical or real sites.

3.8.1 Data Requirements

Once the engineering design tool utility has been validated, site characteristics from different sites will be used to evaluate the applicability of oxidant cylinders under varied site conditions (minimum 2 additional site conditions).

3.8.2 Success Criteria

The success criteria for this objective include clear, understandable design tool utility output of cylinder requirements. An engineering evaluation will be performed following output of the utility to determine if oxidant cylinder deployment can be utilized at the given site based on data outputs (cylinder depth, spacing, longevity, etc.).

4.0 SITE DESCRIPTION

4.1 SITE SELECTION

Five sites were evaluated in detail: North Island NAS Naval Air Station (NAS), Air Force Plant 3, Arnold NAS, Tinker Air Force Base (AFB), and Whidbey Island NAS. Technical screening and evaluation was conducted as detailed in Site Screening Memorandum for this Demonstration. As described in the Site Selection Memorandum (CDM Smith, 2013a), the majority of threshold criteria were met at North Island NAS (NAS NI) and either not enough information was available or fewer threshold criteria were met for the other potential sites. Because of this, North Island NAS was recommended and approved for use in this Demonstration.

4.2 SITE LOCATION AND HISTORY

Operable Unit 11 (OU11) of NAS NI (**Figure 4.1**) was selected for this demonstration project as a number of threshold and other criteria requirements were met. The area proposed for the demonstration is shown in **Figure 4.2**. The only condition not met was the depth to groundwater as less than 20 feet. The average groundwater elevation is at approximately 22 to 25 ft below ground surface (bgs), which is not an issue for implementation of this project considering other criteria have been met. One other criteria critical to success of this demonstration is the groundwater flow rate. The seepage velocity at NAS NI is historically around 0.1 feet per day (ft/d). However, because the gradient is generally flat and groundwater flow directions can vary, an induced gradient will be used for this demonstration, as discussed further below.

Figure 4.1. NAS North Island Location Map

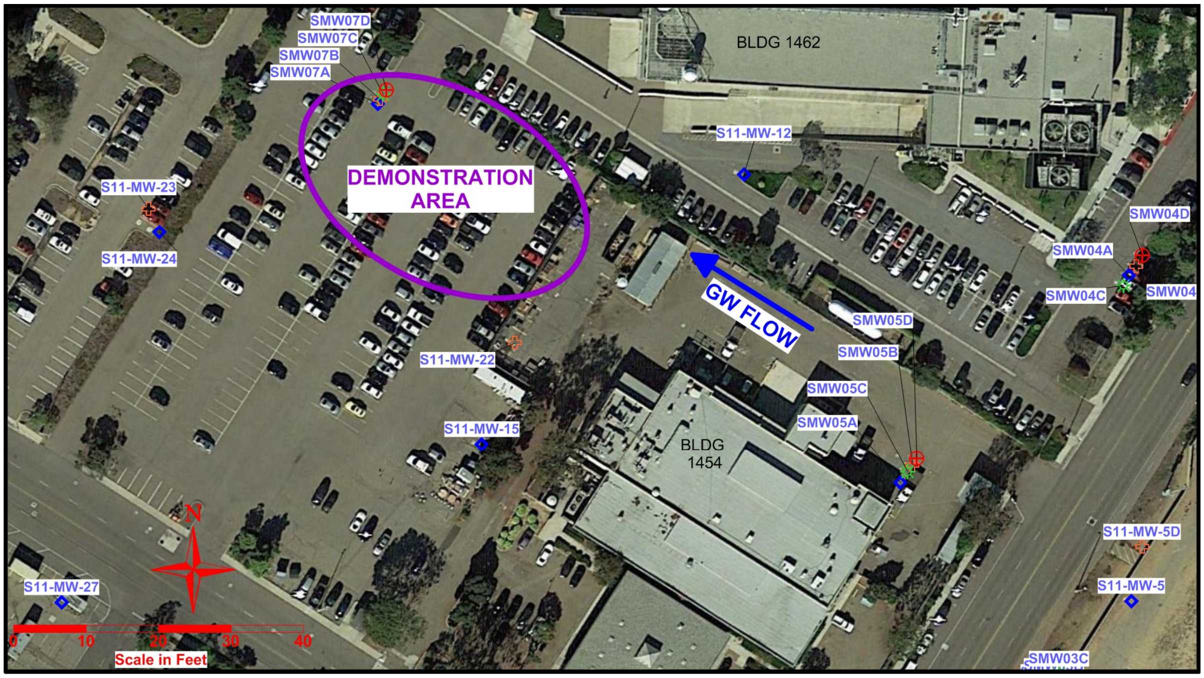


Figure 4.2. Proposed Demonstration Area – NAS NI OU11

4.2.1 OU11 Hydrogeology

Groundwater flow direction in the proposed demonstration area is to the northwest with a flow rate ranging from 0.9 to 1.2 ft/d and a hydraulic gradient of approximately 0.00037 ft/ft (Accord MACTEC 2013). The groundwater is comprised of a lens-shaped layer of freshwater on top of saltwater. The thickness of the freshwater body varies throughout the site. NAS North Island is part of the Coronado hydrologic basin (Unit No. 10.10), which is designated as a non-beneficial use aquifer by the San Diego Regional Water Quality Control Board (CA RWQCB 1994). Lithology at OU11 includes a thick sequence of fine to very fine sand and silty sand to a depth of approximately 40 feet bgs. Below these layers are several fine-grained layers of silt and clay. The geology at the site is comprised of the Bay Point Formation and primarily consists of marine, fossiliferous, loosely consolidated, fine- to medium-grained sand (Kennedy 1975). The primary fine-grained lithologic layers at the site are called the A silt and the B, B1, and C clays, which occur at approximately 40, 80, 100, and 115 feet bgs, respectively. Identified thicknesses of these fine-grained layers are 1 to 5 feet thick for the A silt, 5 to 15 feet thick for the B clay, and about 20 to 40 feet thick for the C clay (BAI 2008).

4.2.2 OU11 Groundwater Chemistry

Based on OU11 groundwater quality data collected in 2012 (Accord MACTEC 2013), dioxane concentrations are as high as 6,500 μg/L upgradient of the demonstration area (OU11-SMW05A). Similarly, the dioxane concentration was 6,000 μg/L in OU11-SMW07A on the downgradient portion of the demonstration area. TCE, cis-1,2-DCE, 1,1-DCE, 1,1-DCA, vinyl chloride and hexavalent chromium are co-contaminants at the site. 2012 TCE concentrations within the proposed demonstration area were 9,200 µg/L in OU11-SMW05A and 3,500 µg/L in OU11-SMW07A. Other VOC concentrations (cis-1,2-DCE, 1,1-DCE, 1,1-DCA, and vinyl chloride were generally similar to TCE (350-6,400 µg/L) except vinyl chloride, which was detected at 39 µg/L in OU11-SMW07A. Hexavalent chromium concentrations were below detection within the proposed demonstration area, but further up-gradient in the source area concentrations were as high as 218 µg/L in monitoring well S11-MW-9 (not shown on Figure 4.2). The estimated dioxane extent in groundwater is shown in **Figure 4.3.**

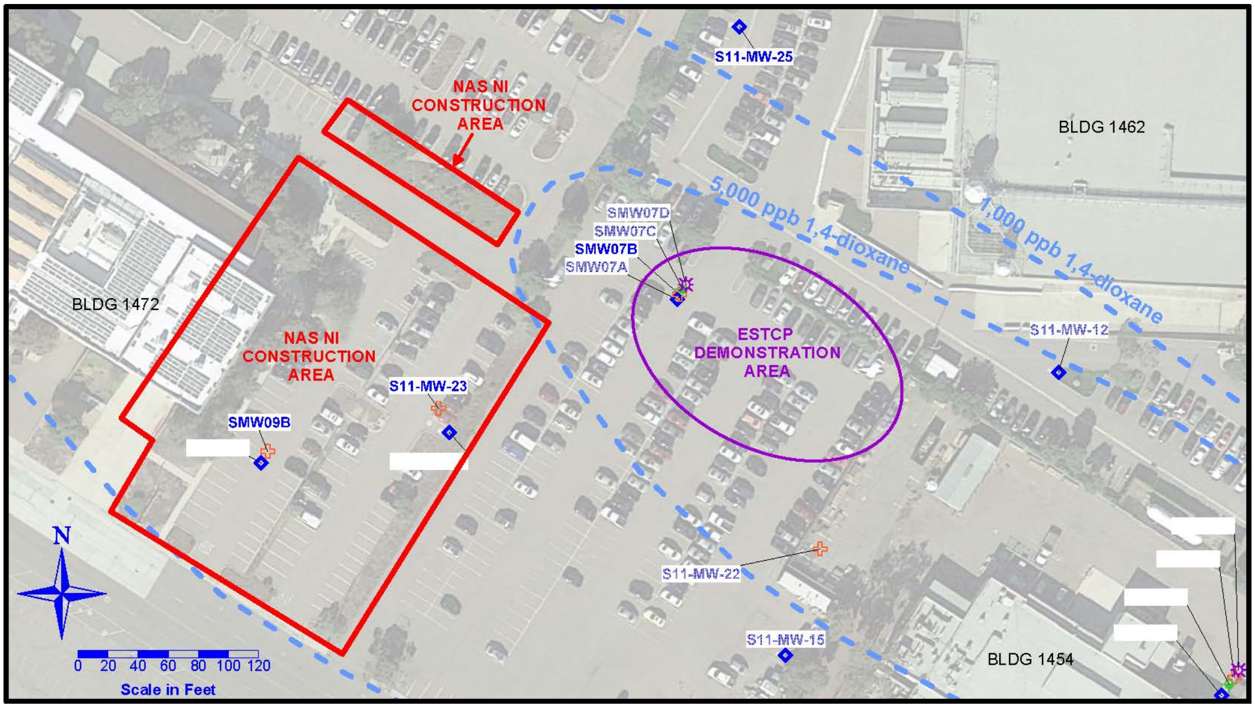


Figure 4.3 – Estimated 1,4-Dioxane Groundwater Concentration Contours

4.2.3 OU20 ISCO Pilot Study

A pilot-scale ISCO treatability study was conducted at nearby OU20 which is located approximately 2,000 feet northwest of OU11 (Shaw 2007). Among other tests, NOD testing was conducted at a concentration of 30,000 mg/L sodium persulfate at 22 (unactivated) Degrees Celcius (deg C). The estimated NOD for unactivated persulfate at 22 Deg C was 2.3 g persulfate/kg wet soil. Higher demand was observed at 60 Deg C, at 40.2 g persulfate/kg wet soil. The 22 deg C sample (unactivated) correlates well with the demonstration design, and the reported 2.3 g persulfate/kg wet soil NOD result indicates that there will likely be some natural oxidation occuring. However, during the field implementation of unactivated persulfate, the 90 day NOD demand rate ranged from 0.0001 to 0.00016 liters per millimol-day (L/mmol/d) based on persulfate concentration trends in PMW-6, PMW-8, and PIW-2 (Shaw 2007). The calculated second-order NOD demand rates are provided in **Table 4.1**. Overall, these pilot test results demonstrated that unactivated persulfate has the potential to be used for effective *in situ* treatment of site contaminants with minimal secondary effects.

Table 4.1 - Estimated second-order NOD rate coefficient based on OU20 Pilot Study Results (Shaw 2007)

PMW-6								
Time d	$Na_2S_2O_8$ mg/L	$Na_2S_2O_8$ mg/kg	NOD mg/kg	Residual NOD mg/kg	ln (NODr)	k 1/d	$Na_2S_2O_8$ mM	K L/mmol/d
7	54740	6440	0	7000	8.85	0.023604	230	0.000103
19	32400	3812	2628	4372	8.38			
30	17374	2044	4396	2604	7.86			
60	6960	819	5621	1379	7.23	**Density**	**1.7**	**kg/L**
90	3270	385	6055	945	6.85	**Porosity**	**0.2**	
		TNOD	**7000**					

PMW-8								
Time d	$Na_2S_2O_8$ mg/L	$Na_2S_2O_8$ mg/kg	NOD mg/kg	Residual NOD mg/kg	ln (NODr)	k 1/d	$Na_2S_2O_8$ mM	K L/mmol/d
7	40460	4760	0	7000	8.85	0.026513	170	0.000156
19	19300	2271	4169	2831	7.95			
30	9401	1106	5334	1666	7.42			
60	357	42	6398	602	6.4	**Density**	**1.7**	**kg/L**
90	1490	175	6265	735	6.6	**Porosity**	**0.2**	
		TNOD	**7000**					

PIW-2								
Time d	$Na_2S_2O_8$ mg/L	$Na_2S_2O_8$ mg/kg	NOD mg/kg	Residual NOD mg/kg	ln (NODr)	k 1/d	$Na_2S_2O_8$ mM	K L/mmol/d
7	55335	6510	0	7000	8.85	0.024261	232.5	0.000104
30	22610	2660	3780	3220	8.08			
60	1610	189	6251	749	6.62			
90	5000	588	5852	1148	7.05	**Density**	**1.7**	**kg/L**
			TNOD	**7000**		**Porosity**	**0.2**	

d-days
$Na_2S_2O_8$ - Sodium persulfate
mg/L - milligrams per liter
NOD - natural oxidant demand
mg/kg - milligrams per kilogram
TNOD -Total NOD

ln - natural log
k - $Na_2S_2O_8$ oxidation rate (per day)
mM - milimolar (milimoles per liter)
K - NOD rate coefficient
L/mmol/d - Liters per millimoles per day
kg/L - kilograms per liter

5.0 TEST DESIGN

This demonstration is being conducted in two phases. Phase I includes the treatability study using site soils and groundwater and development of the oxidant release design tool. Phase II includes the field demonstration of the oxidant cylinders. Phase I was completed in 2014, and results from Phase I were used to develop the field demonstration design. This section provides a brief summary of Phase I activities, followed by the field demonstration details including conceptual design (including results of predictive models), baseline characterization activities, demonstration design and layout, field testing, sampling plan, and data analysis.

5.1 SUMMARY OF PHASE I ACTIVITIES

5.1.1 Treatability Study Summary

This section summarizes the treatability study work performed to evaluate the effectiveness of oxidant cylinders for destruction of dioxane and to determine the most appropriate oxidant for use at OU11. A complete summary of the treatability study is provided in the *ER 201324 Treatability Study Report* (CDM Smith, 2014).

NOD, batch kinetic tests, and column tests were performed during the treatability study with soil and groundwater collected from OU11 – locations of soil and groundwater collected are provided in **Figure 5.1**. Overall, unactivated persulfate was successfully demonstrated to oxidize dioxane and chlorinated ethenes (TCE, cis-1,2-DCE, and 1,1-DCE) in the presence of site soil and groundwater. During the field mobilization to collect groundwater and soil for the treatability study, discrete groundwater samples were collected from S11-MW-12 using Snap Samplers^{TM} at three depth intervals. It should be noted that S11-MW-12 is off the centerline of the plume, which is from the OU11-SMW-05 well cluster to the OU11-SMW-07 cluster. Relevant results from this discrete vertical profile are provided in **Table 5.1**. The results from the stratified sampling indicate that the contaminant concentrations are higher in the deeper portion of the aquifer, although detectable concentrations are present in the upper portions as well.

A summary of treatability study results are provided in **Table 5.2**. The main findings of treatability study that are pertinent to this technology demonstration are as follows:

- Permanganate, one of the two chemical oxidants being considered for the demonstration plan, was highly effective for TCE, cis-1,2-DCE, and 1,1-DCE destruction but less effective for dioxane destruction.
- Unactivated persulfate was highly effective for both TCE, cis-1,2-DCE, 1,1-DCE, and dioxane destruction at the same oxidant concentrations.
- The oxidants were not capable of destroying the chlorinated ethane 1,1-DCA as expected.
- The oxidant demand of site-specific soil for permanganate was high in comparison to that of persulfate.
- The use of permanganate resulted in significant manganese oxide deposition that partially blocked oxidant release from the oxidant cylinder. No such issue was observed when persulfate was used.

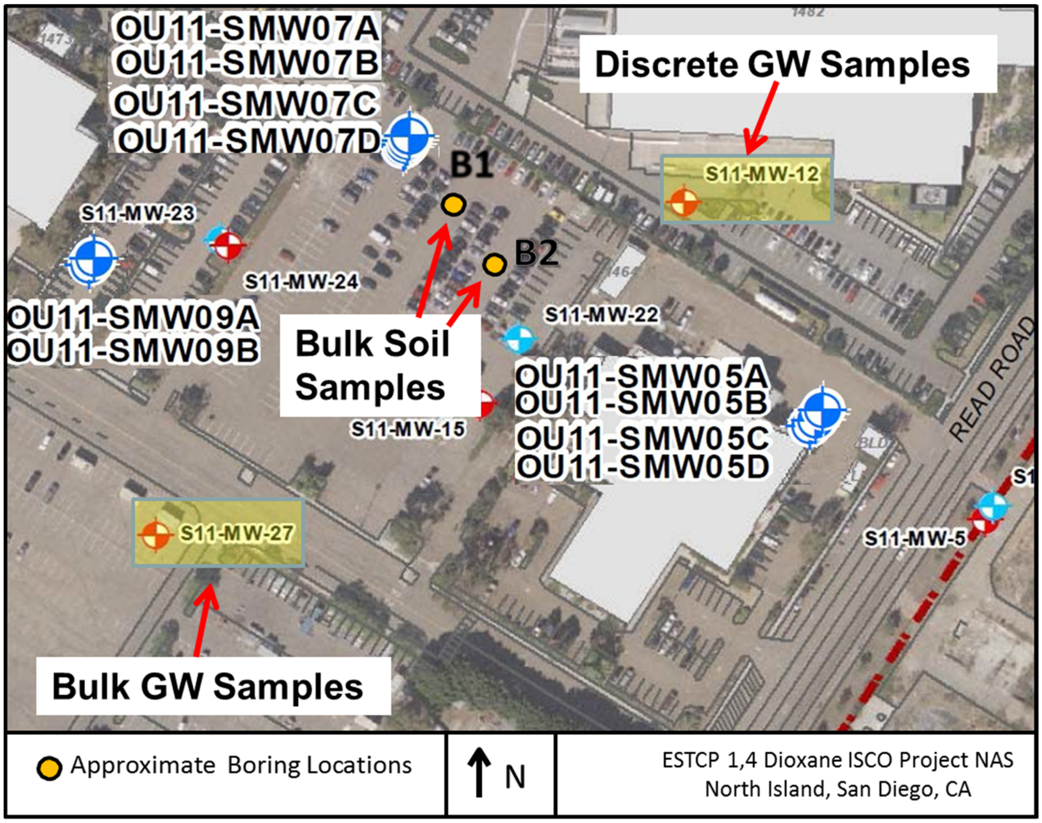


Figure 5.1 Treatability Study Field Sampling Locations

Table 5.1 Groundwater concentrations of select analytes in well S11-MW-12

Analyte	**Concentration (µg/L)**		
	29-31 ft bgs	33-35 ft bgs	37-39 ft bgs
1,1-DCA	35	85	80
1,1-DCE	560 D	1,600 D	1,000 D
cis-1,2 DCE	18	38	34
TCE	570 D	1,600 D	850 D
1,4-dioxane	53J	90	250

*_**Notes**_:

- µg/L: microgram per liter
- 1,1-DCA: 1,1-dichloroethane
- 1,1-DCE: 1,1-dichloroethene
- bgs: below ground surface
- TCE: trichloroethene
- cis-1,2-DCE: cis-1,2-dichloroethene
- D: diluted sample
- ft: foot
- J: estimated value

In summary, the treatability study demonstrated that slow-release persulfate cylinder technology without intentional activation is capable of treating site groundwater contaminants with the exception of 1,1-DCA. Based on these findings, unactivated persulfate was selected for the technology demonstration.

Table 5.2. Treatability Study Performance

Performance Objective	Success Criteria	Results
Technology Effectiveness	* 90% reduction in 1,4-dioxane concentration with unactivated persulfate or permanganate. * 90% reduction of chlorinated VOC co-contaminants with unactivated persulfate or permanganate.	**Performance Goal was achieved** * > 99% reduction with persulfate only, and nearly 30% reduction with permanganate. * > 99% reduction for chlorinated ethenes with persulfate and permanganate. No oxidation of 1,1-DCA.
Determine design criteria for the field demonstration	* Develop quantitative relationships and criteria for contaminant flux, contaminant oxidation, natural oxidant demand, oxidant flux, and oxidant consumption. * Use these relationships to develop design criteria for oxidant flux, which ensure satisfactory contaminant oxidation without releasing excess oxidant.	**Performance Goal was achieved** * Second-order rate constants for dioxane in site soil and groundwater with permanganate and persulfate were estimated to be 2.7×10^{-5} and 4.6×10^{-5} M^{-1} s^{-1}, respectively. Rate constants for chlorinated ethenes were equal to or greater than those for dioxane. * 1,1-DCA was not oxidized by either oxidant. * Persulfate, which will be used in the field demonstration, did not have detectable NOD or observable consumption. A maximum persulfate release rate from the 2.5-inch diameter cylinder was measured to be 18 mg cm^{-2} d^{-1}. Further work is being conducted to characterize oxidant release but may be modelled using a Gaussian distribution.
Characterize secondary environmental impacts	* Quantify the potential for the listed secondary impacts to result in exceedances of background concentrations.	**Performance Goal was achieved** * pH decreased to less than 6.0 in the final sampling event for the persulfate column, suggesting that pH may decrease to less than 6.0 when deployed in the field. The pH is expected to increase downgradient of the oxidant area. * Dissolved arsenic was periodically detected in excess of the California MCL of 10 µg/L in the permanganate column effluent based on Carus analysis but was not detected in snapshot sampling by a certified laboratory. Lead was not in excess of the MCL in the persulfate column. * Dissolved chromium was in excess of 50 µg/L and likely in the CrVI form. CrVI will likely attenuate downgradient of the chemical oxidant treatment area. * Dissolved lead was periodically detected in excess of 15 µg/L in the column effluent based on Carus analysis but was not detected in snapshot sampling by a certified laboratory. * Dissolved nickel was periodically in excess of 100 µg/L in the persulfate column based on Carus analysis but was not detected in snapshot sampling by a certified laboratory. * Dissolved cadmium, mercury, and silver were either not detected or detected at concentrations less than the California MCLs.

Table 5.2 (cont.). Treatability Study Performance

Performance Objective	Success Criteria	Results
Characterize manganese dioxide deposition and fouling potential	* Determine the extent to which cylinder porosity is blocked by manganese dioxide.	**Performance Goal was achieved** * A rind presumably comprised of manganese dioxide coated the exterior surface of the permanganate cylinder and affected oxidant release rates. * Chlorinated ethenes nevertheless were removed from the groundwater; dioxane was not removed appreciably.
Characterize frac fluid compatibility with slow release material	* Determine whether the material is capable of being suspended in the frac gel for a period of 8 hours.	**Performance Goal was achieved** *Limited testing of polysaccharide gel indicated incompatibility with the slow-release permanganate oxidant, and it was not able to remain suspended for a period of 8 hours.

*<u>***Notes***</u>:

- %: percent
- µg/L: microgram per liter
- 1,1-DCA: 1,1-dichloroethane
- cm: centimeter
- d: day
- M: molar (moles per liter)
- MCL: maximum contaminant level
- mg: milligram
- NOD: natural oxidant demand
- s: second

5.1.2 Oxidant Release Design Tool

Concurrent to the treatability study, a slow release oxidant cylinder conceptual design tool was developed to capture the oxidant release processes and predict oxidant distribution and treatment in the subsurface. The draft *ER 201324 Design Tool Technical Report* (Clarkson University, 2015) provides a detailed description of this report. In general, it couples oxidant release with oxidant transport to predict subsurface oxidant concentration spatially and temporally, incorporating oxidant demand and contaminant reactions. It also predicts contaminant destruction as a result of reaction with released oxidant. It was built in Microsoft Excel using analytical solutions to mathematical models to allow for ease of use and access. The conceptual design tool is not meant to be used as an all-encompassing predictor of ISCO performance. It is intended help to predict the distance that oxidant will travel in the subsurface, the concentration of the oxidant that will be present down-gradient of the oxidant source, and the resulting degradation of contaminant.

Once both the treatability study and design tool were completed, the field demonstration design was initiated using information gathered during Phase I work.

5.2 PHASE II - CONCEPTUAL EXPERIMENTAL DESIGN

The general and detailed design layouts of the technology demonstration are illustrated in **Figures 5.2** and **5.3**, respectively. Upgradient cylinder wells containing the oxidant cylinders will simulate a small-scale funnel and gate design. Due to the flat gradient observed at the site, a recirculation system consisted of a downgradient extraction well and a reinjection well will be constructed to facilitate better hydraulic control. A series of upgradient and downgradient monitoring wells will be used to aid performance monitoring, evaluation, and optimization. A number of important design parameters pertinent to the demonstration layouts were obtained using numerical groundwater modeling and an engineering design tool. Numerical groundwater modeling was used to aid estimating the natural versus induced groundwater extraction rate, groundwater seepage velocity, groundwater transverse dispersion, oxidant transport, and contaminant transport. In addition, the numerical groundwater modeling results indicated that application of an artificial gradient does not result in significant downgradient migration of the dioxane plume. A detailed summary of the numerical modeling is provided in **Appendix A.**

Outputs from the numerical model were then used to construct the engineering design tool and to ultimately determine the appropriate well spacing, anticipated contaminant destruction, and oxidant longevity. Specifically, under the conditions created by inducing the gradient, the tool provided estimates of when the oxidant cylinder would need to be changed out (6 months) and the distance from the cylinders at which 90% dioxane removal would occur (37 feet after 7 months). The two major assumptions that were made for the design tool were the unactivated persulfate NOD (estimated to be 0.0001 L $mmol^{-1}$ d^{-1} based on OU20 pilot study results [**Table 4.1**]) and the dispersion factor used in the spreadsheet tool. This factor is dimensionless and ranges from 0 to 1. When a value of 0 is selected, no dispersion occurs and the persulfate is released into a cross sectional area with a width of 2.5 inches (i.e., the cylinder diameter). When a value of 1 is selected, the persulfate is dispersed across the distance between the centerpoints of the two cylinder boreholes (i.e., 5 feet). A value of 1 was assumed for the design based on results from dispersion modeling (**Appendix A)**. The results from the design tool are provided in

Appendix B. Once the objective output was predicted (90% dioxane removal), 75%, 99%, and 99.9% removal distances were also calculated to determine the appropriate locations of additional monitoring wells (5, 10, and 20 feet from cylinders for 80, 95, and >99% removal, respectively). Additionally, one monitoring well will be installed five feet upgradient from the cylinder locations.

Additional design considerations included the potential impact of naturally occurring iron in the aquifer during this demonstration. Data collected as recently as 2012 from well S11-MW-12 (approximately 140 feet upgradient from demonstration area) indicate ferrous iron is approximately 1.1 mg/L. Although recent monitoring did not include total iron, data collected before 2004 indicated that total iron was generally less than 0.05 mg/L. Based on these data it is anticipated that the amount of iron mass available in the groundwater will not be sufficient to cause iron fouling in the cylinder boreholes. Iron fouling calculations were performed assuming a conservative mass (five times observed ferrous iron concentration) of iron was precipitated for the entire demonstration period. These calculations performed using MathCad® (**Appendix C**) show that with an 18-inch borehole and pea gravel used to backfill the borehole, over 1,000 days is likely required before significant fouling may occur. Groundwater concentrations did not exceed 0.5 mg/L for any metals in the three nearby wells S11-MW-12, S11-MW-05A, and S11-MW-07A. Therefore, it is also unlikely that precipitation of other metals will result in significant fouling or that dissolved concentrations of other metals will activate persulfate oxidation.

Additionally, if enough iron is present in the subsurface, persulfate can be iron (II) EDTA-activated, which would provide site-specific benefits to this demonstration that may not be observed in other sites. However, iron (II) EDTA-activated persulfate oxidation generally requires orders of magnitude higher concentrations of dissolved iron (150 – 600 mg/L) than have generally been observed in the aquifer near the demonstration area. Therefore, it is also unlikely that iron activation will be a significant factor in persulfate oxidation during this demonstration. Other dissolved metals have similarly low concentrations in nearby wells.

Despite the indication that natural conditions appear unlikely to cause clogging or activation of persulfate, metals monitoring will still be performed. Dissolved metals, including field analysis ferrous iron (via Hach Method 8146) will be performed during baseline activities and periodically throughout the demonstration to evaluate if the naturally occurring iron in the aquifer may result in iron fouling of the cylinder boreholes and the downgradient extraction/reinjection wells. Discussion of monitoring is provided in **Section 5.6.**

A cross-sectional view of the demonstration well network is provided in **Figure 5.4**. As shown in this cross section, the demonstration will be performed in the 15-20 foot water table above a semi-confining unit located approximately 40 feet bgs. This treatment thickness is within the depth interval where dioxane and other contaminants are observed.

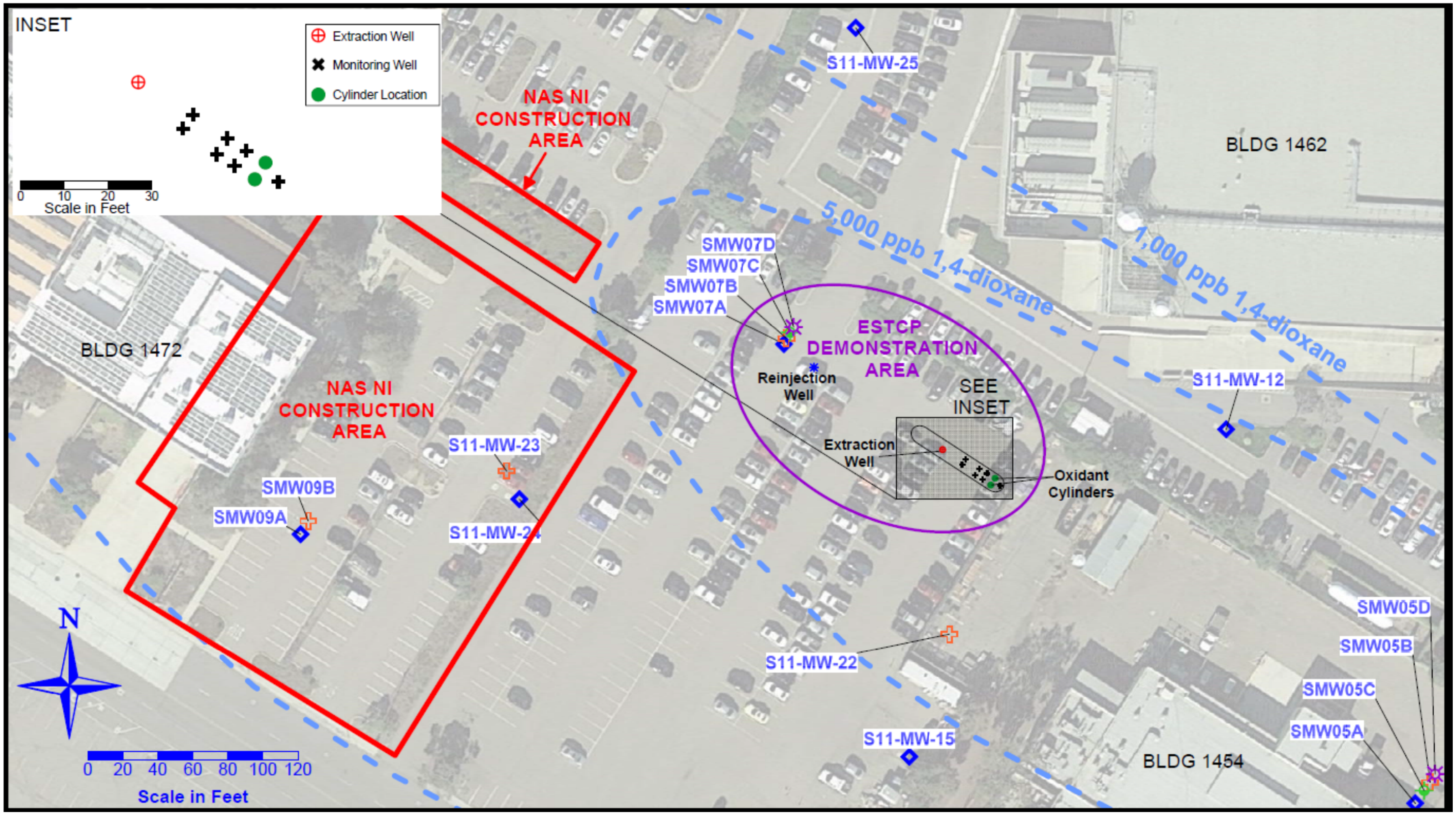


Figure 5.2. Demonstration Layout

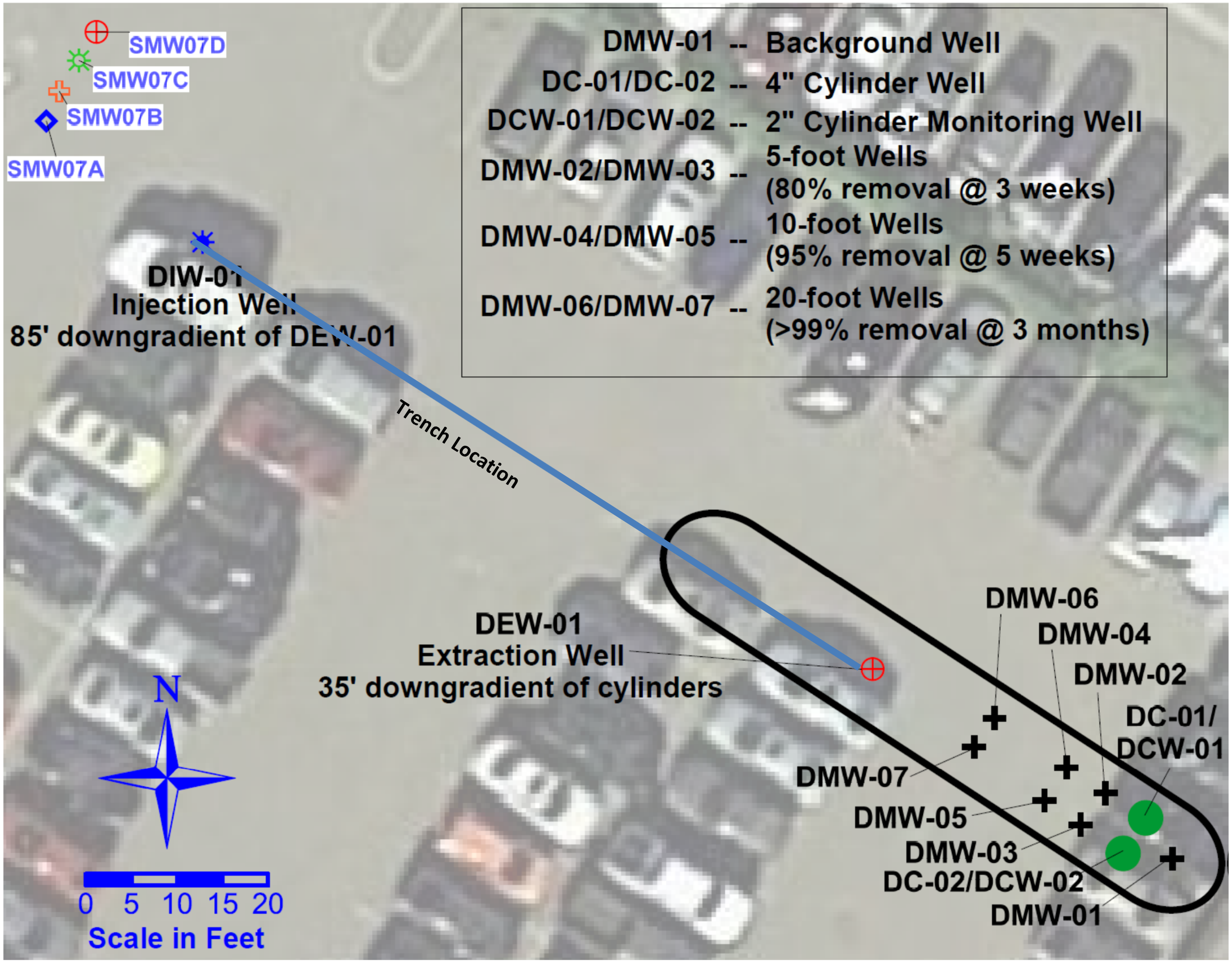


Figure 5.3. Detailed Demonstration Layout w/ Tool-Estimated Removal Distances and Times

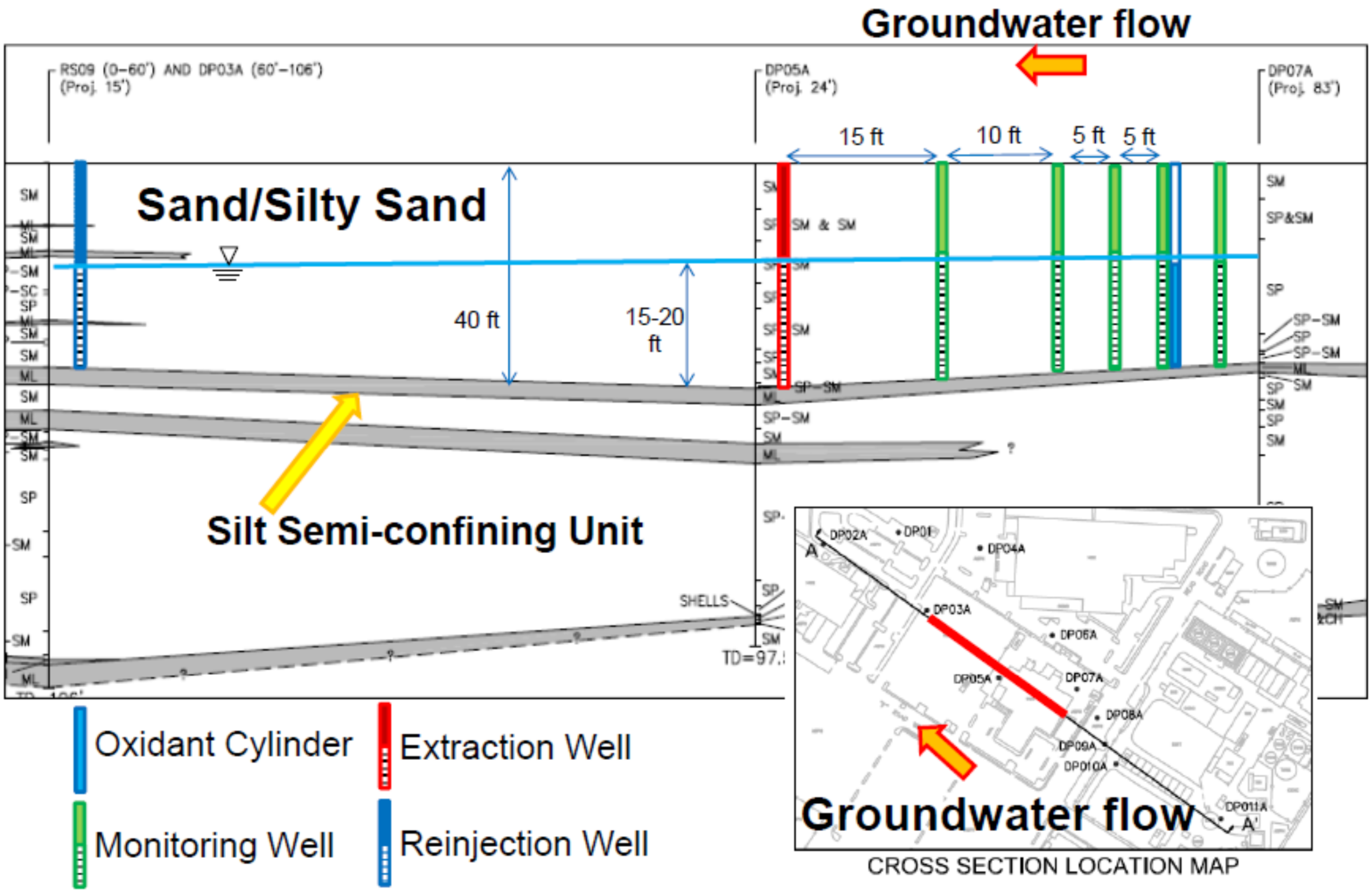


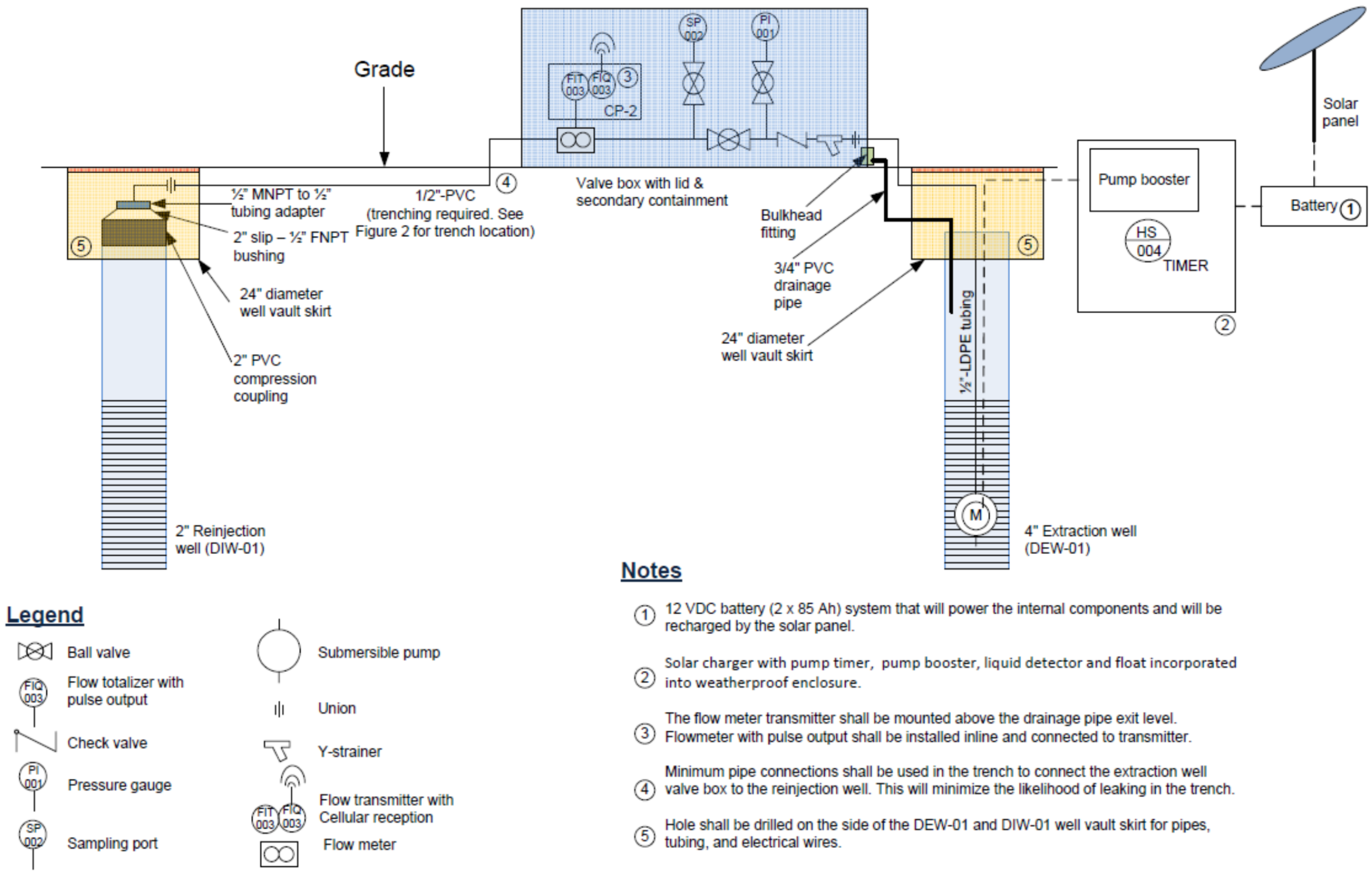
Figure 5.4. Cross-Sectional View of the Demonstration Well Network

5.3 BASELINE CHARACTERIZATION ACTIVITIES

A number of baseline characterization activities have been and will be performed prior to the start of the demonstration system. Specifically, detailed laboratory studies involving site-specific soil and groundwater had been initiated to demonstrate the potential of the chemical oxidation technology to effectively destroy dioxane and co-contaminants under laboratory settings, to determine which oxidant to use in field demonstration, to determine potential secondary groundwater effects and appropriate mitigation options, and to produce a spreadsheet design tool applicable for designing and optimizing the demonstration system. This Phase I work was summarized in **Section 5.1**. In addition to these aforementioned laboratory testing activities, baseline sampling will be conducted following well installation and development. Because baseline sampling will include only groundwater, the discussion for baseline characterization is included in the sampling plan (**Section 5.6**). No soil samples will be collected except for characterization for investigation-derived waste (IDW).

5.4 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

As discussed in **Section 5.1**, the demonstration system is designed to simulate the use of persulfate to treat groundwater contaminated with dioxane in an induced groundwater gradient. The system consists of two boreholes/ wells containing the persulfate cylinders, one upgradient and eight downgradient monitoring wells, an extraction well, and a reinjection well as shown previously in **Figure 5.2** through **Figure 5.4**. A solar panel equipped with battery packs will be used to provide power to the recirculation system. Specifically, a submersible pump housed inside a 4-inch diameter extraction well will be used to extract groundwater and promote a controlled hydraulic system. To achieve the design extraction rate of 0.35 gallon per minute (gpm) the submersible pump will cycle operating at approximately 1.5-1.75 gpm for four to six hours per day. The extracted water will then be injected to the down-gradient reinjection well. A simplified piping and instrumentation diagram (P&ID) and instrumentation and control (I&C) drawing for the pilot system are presented in **Figure 5.5** while the solar panel layout is presented in **Figure 5.6**. Details associated with the various process equipment, process controls, installation, commissioning, operations and maintenance (O&M), decommissioning, and inspections and documentations are discussed below.



Notes

① 12 VDC battery (2 x 85 Ah) system that will power the internal components and will be recharged by the solar panel.

② Solar charger with pump timer, pump booster, liquid detector and float incorporated into weatherproof enclosure.

③ The flow meter transmitter shall be mounted above the drainage pipe exit level. Flowmeter with pulse output shall be installed inline and connected to transmitter.

④ Minimum pipe connections shall be used in the trench to connect the extraction well valve box to the reinjection well. This will minimize the likelihood of leaking in the trench.

⑤ Hole shall be drilled on the side of the DEW-01 and DIW-01 well vault skirt for pipes, tubing, and electrical wires.

Figure 5.5. Piping and Instrumentation Diagram and Instrumentation and Control Diagram

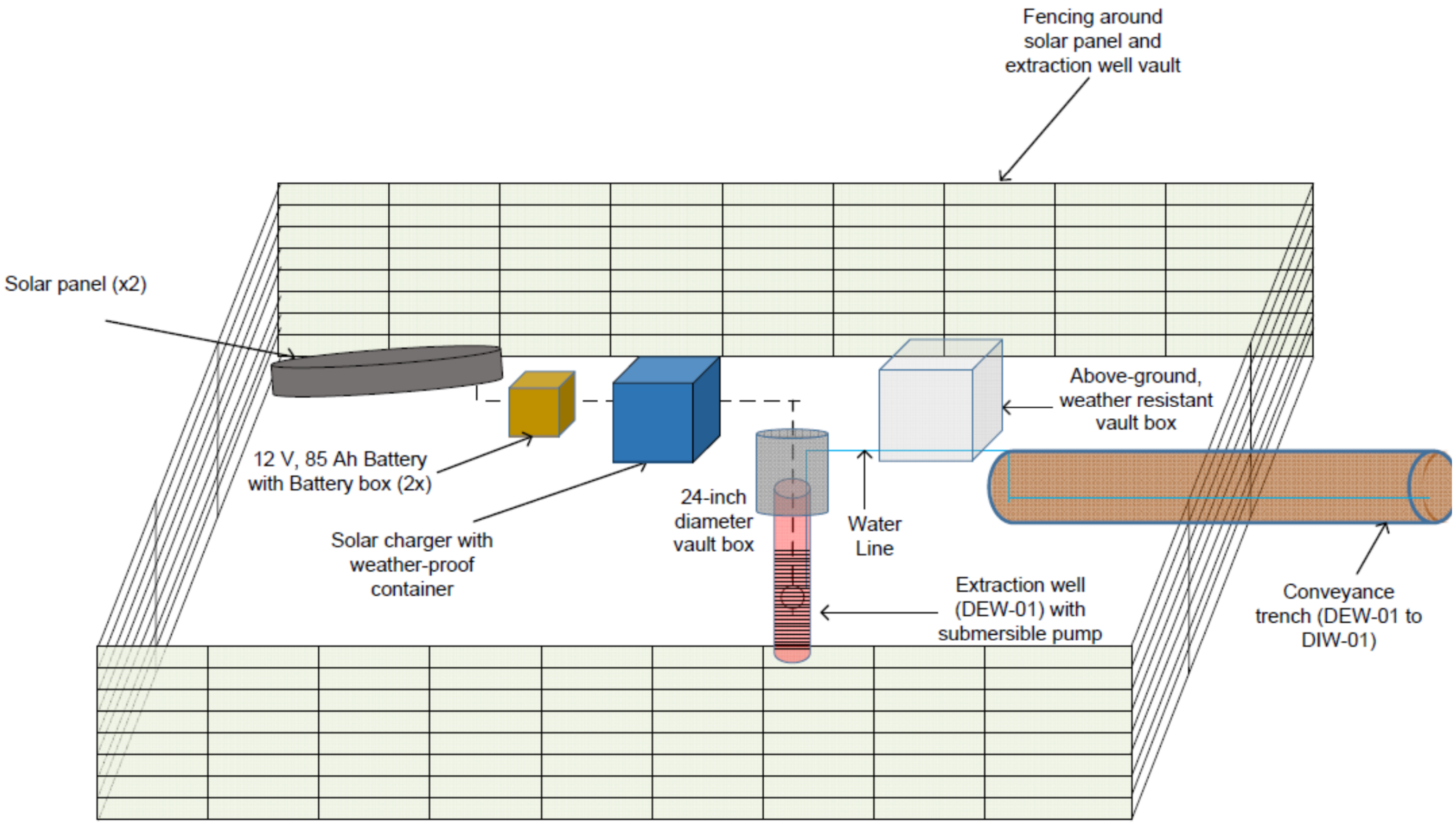


Figure 5.6. Solar Panel Layout

5.4.1 Process Equipment

The main process equipment required for this technology demonstration is described as follows:

Extraction and reinjection well
A groundwater extraction well (DEW-01) and a disposal re-injection well (DIW-01) will be installed to 40 ft bgs. The extraction well will be located approximately 35 feet down-gradient of the cylinder wells and the reinjection well will be located approximately 85 feet down-gradient from the extraction well, as shown in **Figure 5.3**.

The extraction and disposal re-injection wells will be installed using hollow stem auger (HSA) drilling, and will be constructed through the augers to avoid the natural collapse of native material around the well. The extraction well will be constructed using 4-inch diameter, schedule 40 polyvinyl chloride (PVC) casing with the screen set at approximately 20 to 40 feet bgs. The construction diagram for the extraction well is shown in **Figure 5.7**. The reinjection well will be installed in the same manner except it will be constructed using 2-inch diameter materials, as shown in **Figure 5.8**. Both of the well screens will be constructed with factory slotted, 0.020-inch openings, and fitted with a PVC bottom cap. A graded sand filter pack consisting of clean, 10-20 size silica sand (or equivalent) will be installed from the bottom of the hole to 2 feet above the top of the well screen. A seal will be installed above the filter pack using bentonite pellets or chips. The bentonite seal will be a minimum of 2 feet thick and will be hydrated in place with potable water. The seal will be overlain by a bentonite/cement grout that will extend to within 4 feet of the ground surface. The reinjection and extraction well surface completions will be completed within a 2-foot diameter by 2-foot deep concrete valve box. The top of casing will terminate at approximately 3 feet bgs to allow for the installation of subsurface well head components. **Table 5.3** provides construction details for the proposed extraction and disposal wells.

An electric submersible groundwater extraction pump will be installed in the extraction well, controlled by a pump charger. The pump will be hung from the surface using braided polyethylene rope. A check valve will be fitted on top of the pump, and water will be conveyed to the surface through 1/2-inch schedule 80 PVC piping. Water will be conveyed from the extraction to the reinjection well through 1/2-inch diameter schedule 80 PVC pipe buried in a trench at a minimum depth of 24 inches bgs. The current understanding of site lithology indicates that the reinjection well will likely be able to receive a relatively high injection rate before developing any wellhead pressure. In addition, since the extraction pump will only be operated approximately 20% of the time at 1.5-1.75 gpm, it is highly unlikely that over-pressurization at the extraction well will be encountered. Therefore, a pressure switch for the extraction pump is not warranted; instead, a pressure indicator will be used for visual pressure monitoring during scheduled site visits. A remote water meter reading system will be installed to record the volume of groundwater extraction/reinjection.

Groundwater drawdown at the extraction well will be monitored carefully during well development. While it is unlikely that significant groundwater drawdown will be observed upon extraction (based on available site lithology data), the solar charger system will be equipped with a low-level switch. If the water level is observed to decreased during initial operation, the level switch will be installed to shut off the extraction pump when groundwater level falls below a certain level was in taken into consideration.

Cylinder wells

A mini funnel and gate concept will be used to construct the two cylinder wells (DC-01 and DC-02). Specifically, each 4-inch inside-diameter oxidant cylinder well will be constructed using schedule 40 PVC, factory-slotted with 0.020-inch openings, fitted with a PVC bottom cap, and screened from 20 to 40 ft bgs will be housed inside an 18-inch borehole backfilled with pea gravel to 40 ft bgs to create a zone of groundwater convergence/divergence due to the contrast in hydraulic conductivity with the surrounding aquifer (See Appendix B). In addition, 2-inch monitoring wells will be installed within each 18-inch borehole, since multi-level monitoring will not be possible within the 4-inch wells. The 2-inch wells will also be constructed of schedule 40 PVC, factory-slotted with 0.020-inch openings, fitted with a PVC bottom cap, and screened from 20 to 40 ft bgs. The construction well diagram for the cylinder wells is shown in **Figure 5.9**. Once the wells have been developed, baseline groundwater samples have been collected, and the tracer has been added (**Section 5.4.4**), 2.5-inch oxidant cylinders housed in series in an oxidant compatible plastic cylinder holder shown in **Figure 2.3** will then be lowered into the screened interval of the 4-inch cylinder wells. The cylinders will be installed using a tripod. Because the oxidant cylinder density can decrease to below the specific gravity of water as oxidant is released, the top of the cylinder setup will be configured such that it can be connected to rigid 1-inch PVC piping. The 1-inch PVC piping will be installed between the top of the cylinders to the top of the well so that the cylinders will not rise as their density decreases. A cable will also be connected from the top of the cylinder series and suspended from the top of the well. A description of this cylinder installation is shown in **Figure 5.10**.

Monitoring wells

A series of monitoring wells (DMW-01 through DMW-07) located 5 feet upgradient and 5, 10, and 20 feet downgradient of the cylinder wells will be installed via HSA drilling to facilitate performance monitoring (**Figure 5.4)**. Specifically, each monitoring well will be constructed of 2-inch diameter, schedule 40 PVC, factory-slotted with 0.020-inch openings, fitted with a PVC bottom cap, and screened from 20 to 40 ft bgs. Well construction details are provided in **Figure 5.9**. In addition, one 2-inch monitoring well will also be installed within each 18-inch borehole which contains the oxidant cylinders, as shown in **Figure 5.11**.

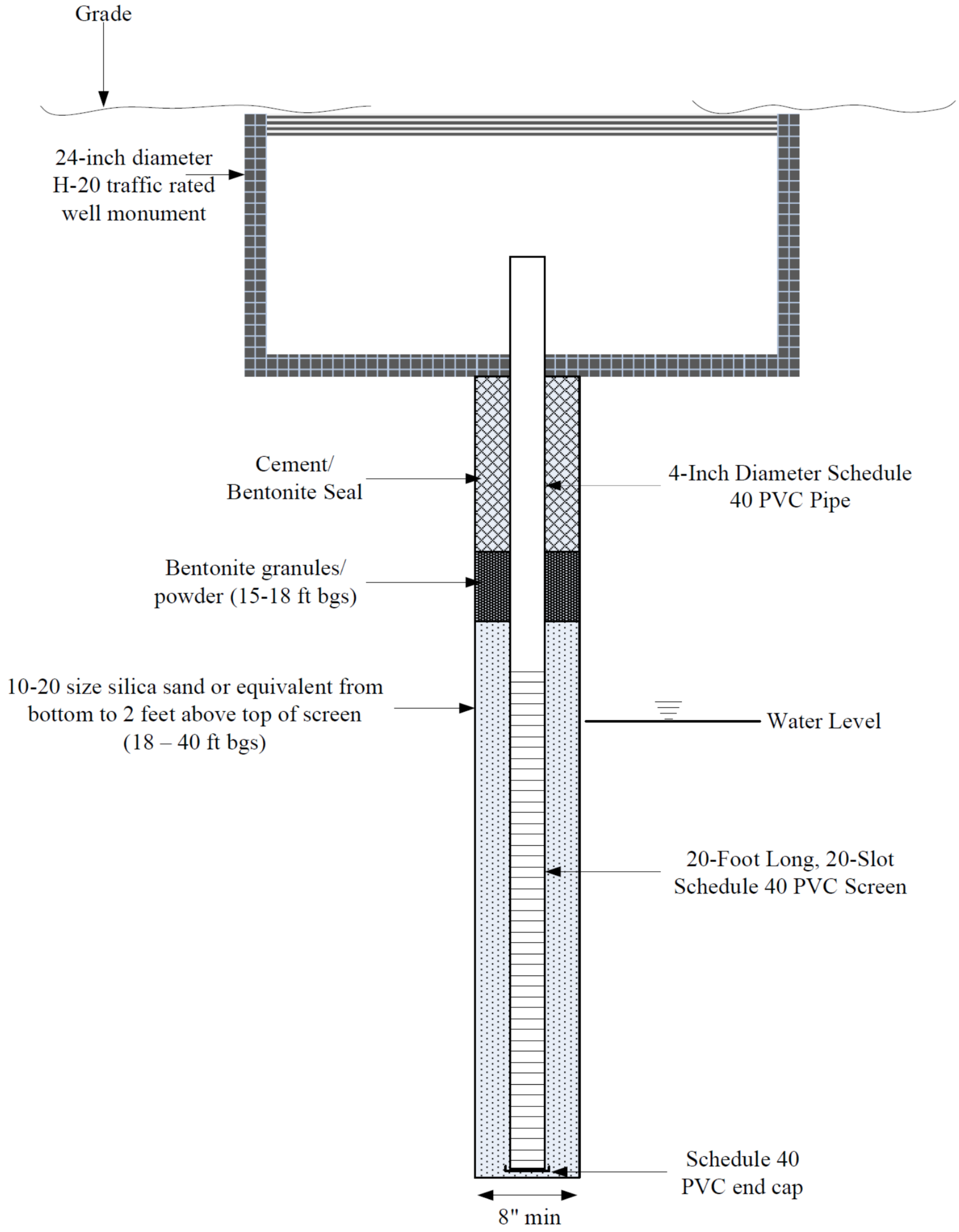


Figure 5.7. Extraction Well Construction Diagram (not to scale)

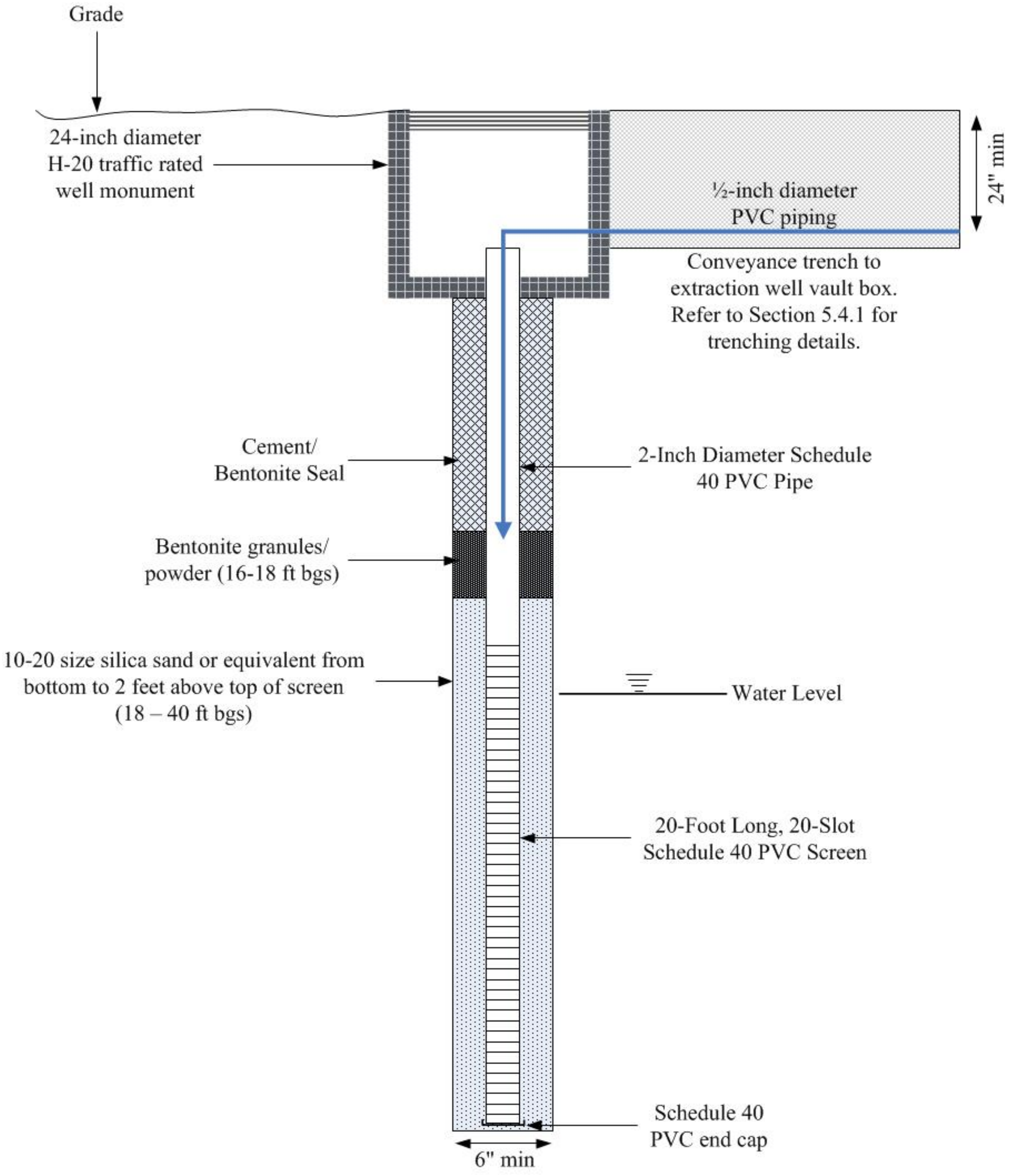


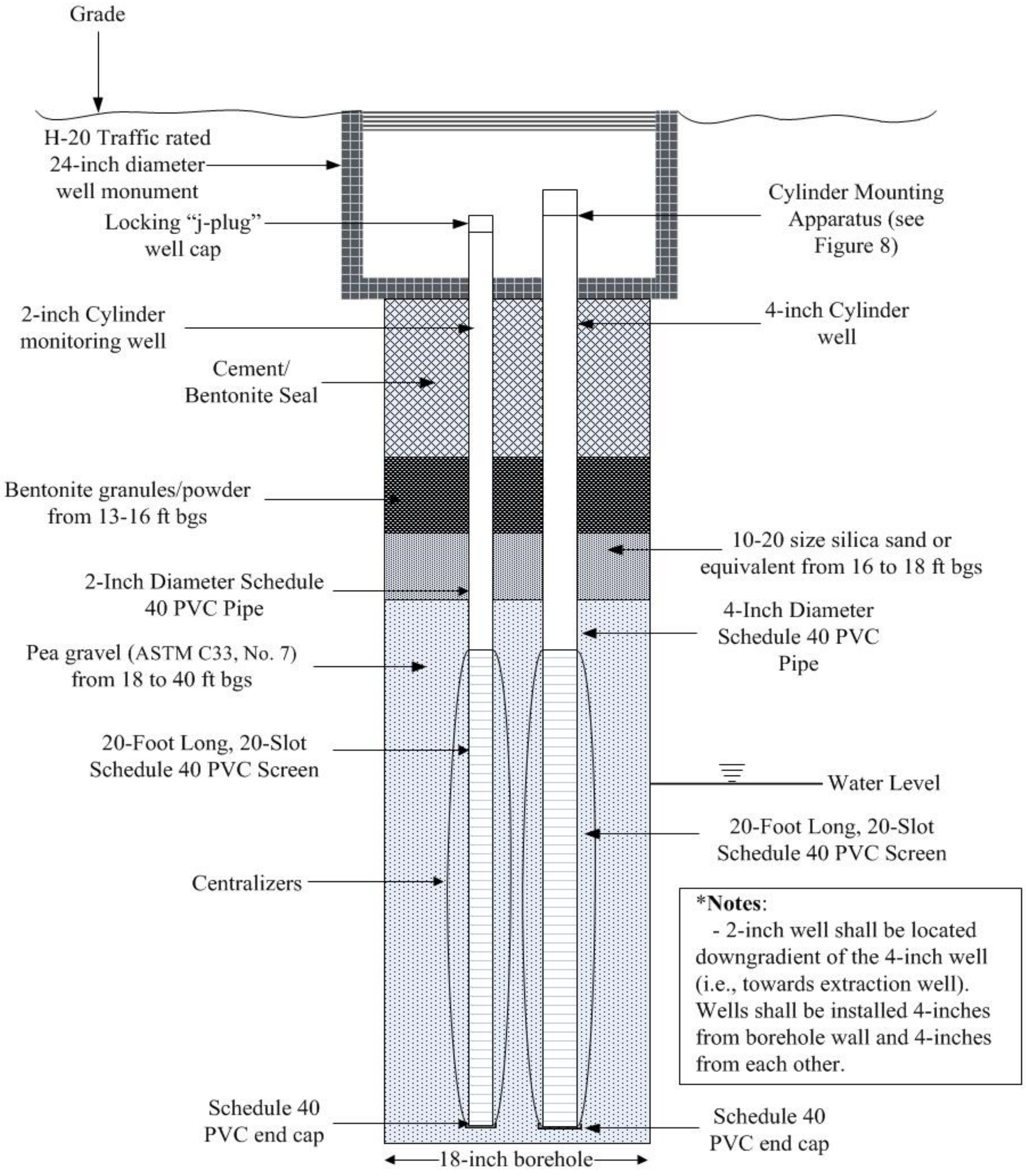
Figure 5.8. Reinjection Well Construction Diagram (not to scale)

Table 5.3. Well Construction Details

Well ID	Description	Borehole Diameter (inches)	Well Diameter (inches)	Total Depth (ft bgs)	Screened Interval (ft bgs)	Length of Riser (ft)	Well Material	Screen Size
DMW-01	Upgradient monitoring well	6	2	40	20-40	20	Sch 40 PVC	20-slot
DC-01[1]	Cylinder oxidant well	18	4	40	20-40	20	Sch 40 PVC	20-slot
DC-02[2]	Cylinder oxidant well	18	4	40	20-40	20	Sch 40 PVC	20-slot
DCW-01[1]	Cylinder monitoring well	18	2	40	20-40	20	Sch 40 PVC	20-slot
DCW-02[2]	Cylinder monitoring well	18	2	40	20-40	20	Sch 40 PVC	20-slot
DMW-02	Downgradient monitoring well	6	2	40	20-40	20	Sch 40 PVC	20-slot
DMW-03	Downgradient monitoring well	6	2	40	20-40	20	Sch 40 PVC	20-slot
DMW-04	Downgradient monitoring well	6	2	40	20-40	20	Sch 40 PVC	20-slot
DMW-05	Downgradient monitoring well	6	2	40	20-40	20	Sch 40 PVC	20-slot
DMW-06	Downgradient monitoring well	6	2	40	20-40	20	Sch 40 PVC	20-slot
DMW-07	Downgradient monitoring well	6	2	40	20-40	20	Sch 40 PVC	20-slot
DEW-01	Extraction well	10	4	40	20-40	20	Sch 40 PVC	20-slot
DIW-01	Reinjection well	6	2	40	20-40	20	Sch 40 PVC	20-slot

****Notes***:

- [1]: 4-inch cylinder well and 2-inch monitoring well installed within the same 18-inch borehole.
- [2]: 4-inch cylinder well and 2-inch monitoring well installed within the same 18-inch borehole.
- bgs: below ground surface
- CW: monitoring well inside oxidant borehole (co-located with oxidant well)
- DC: oxidant cylinder well
- EW: extraction well
- ft: feet
- IW: reinjection well
- MW: monitoring well



*Notes:
- 2-inch well shall be located downgradient of the 4-inch well (i.e., towards extraction well). Wells shall be installed 4-inches from borehole wall and 4-inches from each other.

Figure 5.9. Cylinder Borehole Construction Diagram (not to scale)

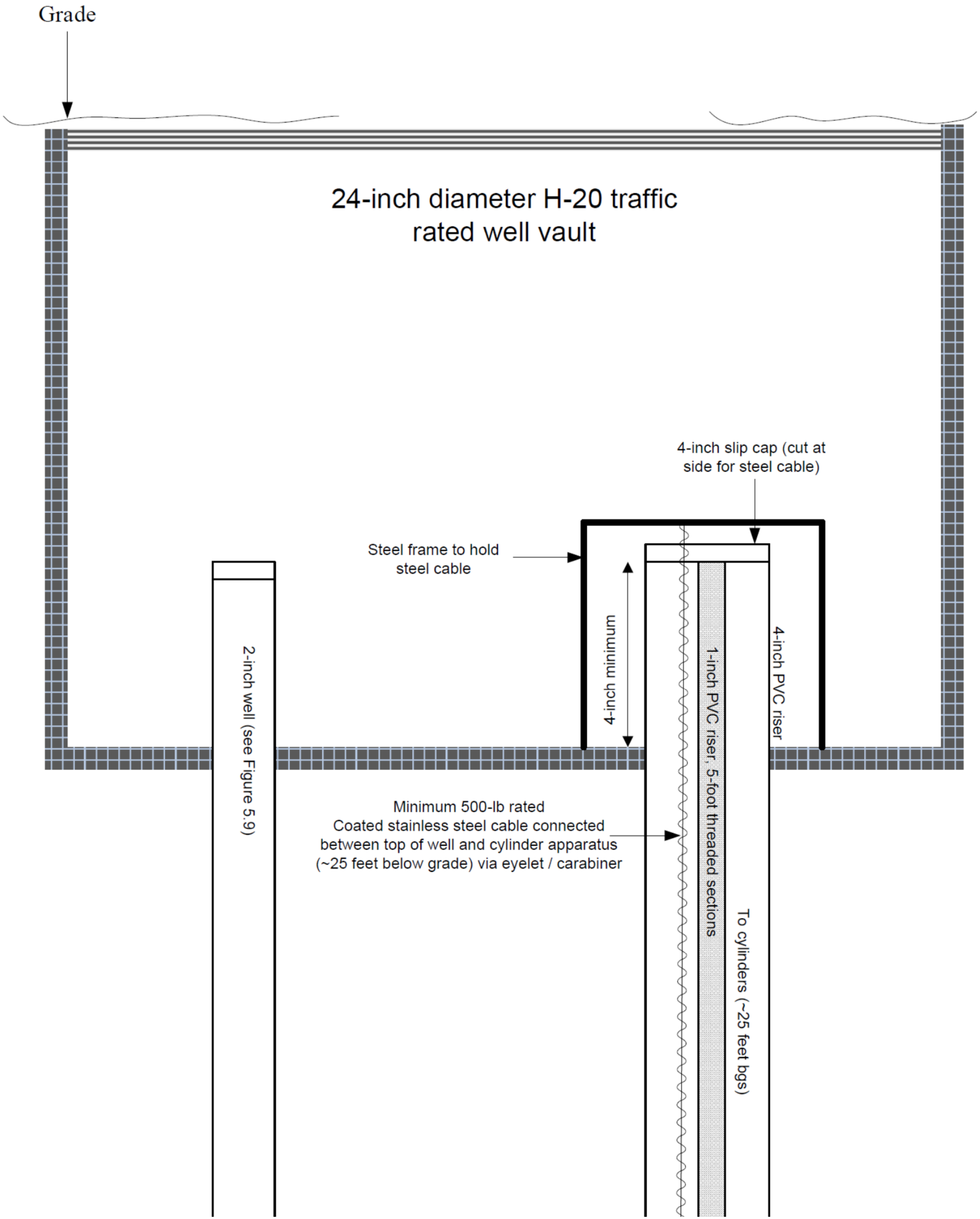


Figure 5.10. Cylinder Vault Construction Detail

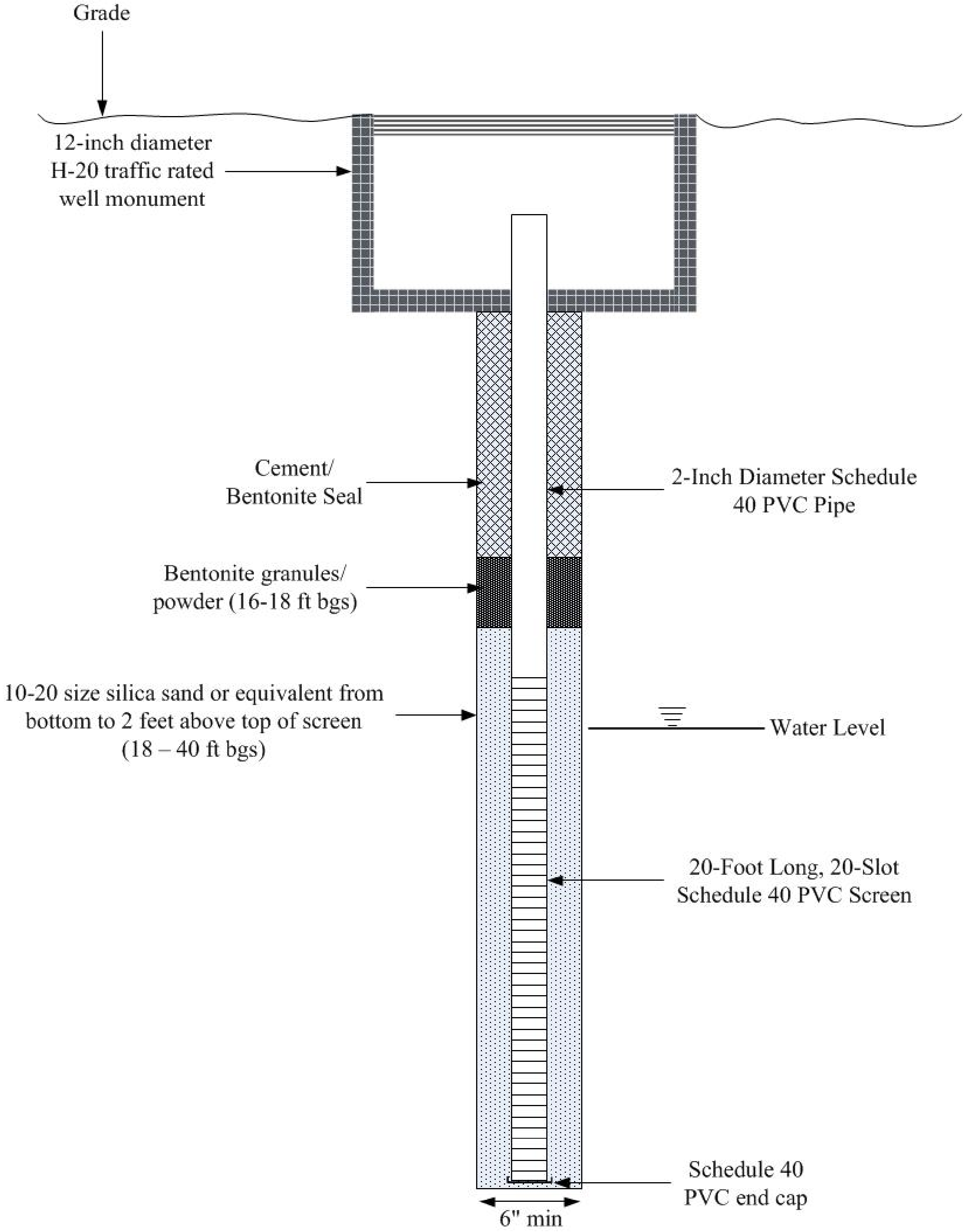


Figure 5.11. Monitoring Well Construction Diagram (not to scale)

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Conveyance Trenching

Approximately 85 to 100 feet of conveyance trenching will be installed between the vault box connected to the extraction well and the reinjection well as shown in **Figure 5.3** and **Figure 5.5**. The trench will be installed as described below.

- Minimum 24 inches between ground surface and pipe
- Minimum 3 inches of bedding sand emplaced on either side of and below pipe
- Minimum 6 inches of bedding sand emplaced above pipe
- Conveyance pipe must be schedule 80 PVC
- Minimum 18 inches of 1.5 concrete sack slurry above bedding sand to bottom of asphalt
- Asphalt patch to restore parking lot to pre-existing condition, as approved by site facility.
- The trench will not be backfilled until Startup activities (**Section 5.5.1**) are completed.
- Bedding sand used will have the following characteristics:
  - 100% will pass ¾-inch sieve
  - No more than 15% will pass the No. 8 sieve
- All IDW generated will be stored separately from drilling IDW in a roll-off container for disposal to a municipal landfill.

Solar Panel

A solar panel kit and battery pack capable of powering the system continuously for one year will be installed as the sole energy source for the demonstration system. Assuming an estimated total of 200 W for all electrical appliances running 20-25% of the time and a minimum sun-hours for the winter of 4.29 for site location, the total wattage requirement of the solar panel was calculated to be 222 Watts (W). Assuming 3 days of backup power for cloudy/rainy days and 50 degrees Fahrenheit as the lowest temperature the battery pack will experience, and a 50 percent battery discharge to optimize battery life, it was calculated that two-250 W solar panels and two 12-volt, 85 Amp-hour batteries will sufficiently power the entire demonstration system. All calculations were performed using the online calculator at *www.sunsoglobal.com/calculator.html#* and are shown in **Appendix C**. A list of equipment is presented in **Table 5.4**.

5.4.2 Process Control

The demonstration system will include controls to facilitate remote transmission of daily totalizer reading, to protect the extraction pump from pumping dry, to allow for precise adjustment of the extraction rate, and to allow for the designed periodic operation of the pump. Specifically, a water meter transmitter equipped with cellular signal connection modem will be installed to facilitate remote retrieval of daily totalizer reading via the internet. If necessary, a low level float switch will be installed inside the extraction well such that the pump will be turned off when the groundwater level inside the well falls below 35 ft bgs and thus provides a protective measure against pumping dry in the highly unlikely of significant drawdown is encountered. A pump controller will be used in tandem with the extraction pump to allow for precise adjustment of the extraction rate. A timer will be used to allow for periodic operation of the extraction at the designed frequency of 20-25% of the time.

Table 5.4. Proposed Demonstration System Construction Equipment

Description	**Manufacturer**	**Part number**	**Qty**	**Comments**	**Dimensions**	**Link**
Downhole Extraction pump	Proactive	Abyss 220ft	1	Max power consumption 90W at 12V; max amp output: 8A	Fits standard 4-inch well. Connects to 3/8" or 1/2" ID LDPE tubing	http://www.gopronow.biz/pumps-a-accessories-plastic-a-stainless/plastic-pumps-standard/abyss-dtw-220ft
80 Amp Solar Charger	Proactive		1	Self-contained solar charger with up to 8 on/off cycles per day	-	http://www.gopronow.biz/power-supplies-batteries/solar-chargers/solar-charger-80-amp
Cold-water flow meter	Dwyer	WMT2-A-C-01	1	Pulse output 0.1 gpm	5/8" male fittings	https://www.dwyer-inst.com/Product/Flow/WaterMeters/SeriesWMT2#specs
Y-strainer	McMaster-Carr	1090N11	1	To protect flow meter	1/2" female NPT connection	http://www.mcmaster.com/#wye-strainers/=vkvj8t
Y-strainer replacement screen	McMaster-Carr	1090N21	5	For O&M	-	
Remote water meter reading system	Flows.com	RRS-1PC-050-R/1P-CC	1	Self powered and equipped with cellular modem and annual subscription of $360/year	-	http://flows.com/remote-water-meter-reading-system/

Table 5.4 (cont). Proposed Demonstration System Construction Equipment

Description	Manufacturer	Part number	Qty	Comments	Dimensions	Link
24V, 250W Solar panel	Amerisolar	AS-6P30-250	2	Assuming 4-6 hrs of operation/day, total wattage of 200 for all appliances, 100% dependence on solar energy, and 4.29 hours of peak sun/day, the online calculator shows a minimum system size of 222 W. The system selected has a total wattage of 250W.	Panel = 65.04 × 39.37 × 1.5 inches; 48.4 lbs	https://www.solarblvd.com/product_info.php?cPath=1_270&products_id=3027 http://www.sunsoglobal.com/calculator.html#
Solar Battery	VMAX	SLR-85	2	12V, 85 Ahr deep cycle battery	L=10.2" W=6.6" H=8.2", 55 lbs	http://www.gopronow.biz/power-supplies-batteries/batteries-chargers/85-amp-battery
Battery box	TBD	TBD	2	Big enough for battery; reference Figure 5.6	-	-

5.4.3 System Installation

Well installation and development in accordance to CDM Smith's SOPs - as shown in the Quality Assurance Project Plan (QAPP) (**Appendix D) -** will comprise the first main component of system installation. Subsequently, other main components of system installation will be executed including:

- Installation of a 24-inch diameter vault in the extraction well – traffic rated for parking lot
- Installation of approximately 85' of 1/2" schedule 80 PVC water conveyance line – with connection between extraction well and injection well.
- Installation and electrical connection of pump, water meter, solar charger (with pump booster and timer), and valves. The solar charger comes with a control box that will be installed off of the ground surface.
- Installation of water meter transmitter and cellular signal connection. Transmitter will be connected to water meter. Transmitter will be stored in transmitter manufacturer-provided weatherproof container.
- Installation of two 250 W solar panels and connection to two 85 ampere hour (Ah) battery in series. Battery to be stored in outdoor-rated battery housing and on a surface elevated off of the ground.
- Installation of fencing around extraction well, solar charger panel, solar panel, and battery, with pedestrian access gate and lock.

Upon completion, testing, and troubleshooting of aforementioned components, the recirculation system will be operated for approximately one week to identify and resolve any issues. After the system has been operated under normal conditions for one week without issues, tracer additions and oxidant cylinder deployment will be performed at the cylinder wells. The tracer solution (described below) will first be prepared then added into the cylinder wells. Subsequently, a surge block will be used to facilitate uniform distribution of such solution into the surrounding formation. A series of oxidant cylinders (approximately 14 per well) housed in cylinder holders illustrated in **Figure 2.3** will be put together and be lowered into the cylinder wells. A cable will be tied to each set of holders and secured inside the cylinder well vaults to allow for easy retrieval, inspection, and replacement of the persulfate cylinders. In addition, 1-inch PVC pipe will be connected between the top of the cylinder setup and the top of the well. The use of the 1-inch PVC pipe is to restrict the cylinders from floating as the density decreases during oxidant release.

5.4.4 Tracer Study

A chloride tracer (sodium chloride) will be added concurrently with the deployment of the persulfate oxidant cylinders to measure seepage velocity. Specifically, a 10,000-mg/L chloride pulse surrounding each cylinder well will be created by homogenizing approximately 4 kilograms of sodium chloride in 15 gallons of deionized water. Such concentration was designed to correspond to chloride concentrations that are significantly higher than background concentrations. Historically, the average historical chloride concentration at monitoring wells located in close proximity to the proposed demonstration area is approximately 250 mg/L. The slug of tracer added in the cylinder wells will result in chloride concentrations ranging between approximately 300 and 1,500 mg/L at down-gradient monitoring wells, which is sufficient to determine tracer breakthrough analytically. Detailed calculations are provided in **Appendix C**.

One data-logging conductivity probe will be installed in one of the 5-foot downgradient monitoring wells (DMW-02) for continuous measurement of tracer and water level. The probe will be installed at approximately 36 feet bgs, which correlates to the standard groundwater monitoring interval of 32.5-40 feet bgs. This continuous conductivity measurement will be useful to adjust extraction flow rates and/or monitoring periods, if necessary. Once breakthrough occurs in DMW-02, the probe will be moved to the 20-foot down-gradient well (DMW-06) to monitor tracer as it moves through the demonstration area. In addition, groundwater sampling and analysis for chloride in all wells will be conducted as described in Section 5.6.

5.4.5 Soil and Water Management and Site Restoration

Any residuals that are generated during drilling and during the technology demonstration will be handled and disposed in an appropriate manner. Residuals that are expected to be generated from this work include water during drilling, well development, and equipment decontamination; purge water from sampling; drill cuttings; field test kit wastes, sampling equipment decontamination wastes; and personal protective equipment (PPE).

Water generated during the demonstration will be stored temporarily in a storage tank and then disposed of in the onsite treatment system or sent to an appropriate disposal facility, depending on water characterization results. Soil generated during well installation will be stored in a covered bin onsite. Previous characterization data collected from the OU11 treatability study field effort will be used to dispose of soil.

5.4.6 Operations and Maintenance

The demonstration system has been designed to require minimal oversight and maintenance. In fact, the groundwater extraction pump and the remote water reading system are the only pieces of mechanical equipment in the design. O&M activities will primarily include replacement of the extraction pump if necessary (pump lifetime is 3,000 hours), replacement of oxidant cylinders after about 6 months based on expected lifetime (Appendix B), periodic cleaning of system components, verifying and recording system parameters (e.g., pressure and flow rates), downloading of data from the conductivity meter, and visual inspection of the system for leaks. Inspection and cleaning of the demonstration system will follow the O&M schedule outlined in **Table 5.5**.

Table 5.5. Operations and Maintenance Schedule

Frequency	**Inspect Extraction Pump**	**Pump and Oxidant Changeout**	**Verify Flow Totalizer**	**Visual Check for Leaks and General Cleaning**	**Site Conditions**
Installation	X		X	X	X
Weekly (for 4 weeks post-installation)			X	X	X
Performance Monitoring Events*	X		X	X	X
Six Months Post-Installation		X			

*__*Notes*__:

- *: as shown in Table 5.11-12

5.4.7 Decommissioning

The demonstration system will be decommissioned at the conclusion of the technology demonstration. Decommissioning will include the following:

- The extraction pump will be turned off and the extraction pump and piping for the extraction and re-injection wells will be removed.
- All instrumentation and pumps will be disassembled, cleaned, and provided to CDM Smith.
- The groundwater extraction well, the disposal reinjection well, the cylinder wells, and monitoring wells, if desired by Navy SWDIV, will be abandoned by a driller licensed in the State of California in accordance with applicable regulations.
- A licensed electrician will remove electrical service from the site.
- A construction contractor will excavate and remove all piping and remaining wiring from the equipment shed and conveyance trenches. Fencing will be removed and disposed of by the construction contractor.
- Any areas disturbed by decommissioning activities will be graded, re-seeded, and/or repaved as necessary.

All decommissioning activities will be supervised and documented by the site personnel.

5.4.8 Inspections and Documentation

The CDM Smith field representative or a CDM Smith subcontractor will supervise all onsite construction activities. Field inspections will be performed to verify that all work is in conformance with the design drawings and equipment manufacturer-provided specifications. Inspection of construction activities will include the following:

- Each phase of construction is completed properly including installation of cylinder, monitoring, reinjection and extraction wells, the extraction pump, and circulation piping;
- Solar panel and extraction pump equipment and accessories are operating safely and within manufacturer-provided specifications;
- Leak and pressure testing is performed to ensure the integrity of the circulation system;
- Health and safety monitoring is performed; and
- As-built records for the demonstration system are prepared.

These inspection activities will ensure that the demonstration system is installed in accordance with this demonstration plan and the statement of work (SOW) and that all reporting requirements can be met.

Field documentation will consist of inspection reports, design and specification clarifications or modifications, photographic records, observation and testing data sheets, as-built documentation, and a brief daily oversight report. All phases of construction will be documented with photographs taken by project personnel. All photographs will be identified by location, date, and time.

The construction manager will maintain a set of project drawings for the purpose of noting any changes. Changes will be noted in red ink or pencil and referenced to approved change orders, if necessary. Copies of all change orders, notes, sketches, and memoranda will be available for reference in the project field office. As-built drawings will be available for review in the project field office at all times.

A final oversight summary report will be prepared after construction of the system. This report will include a description of the construction activities, copies of field reports, boring logs, and as-built drawings. In addition, the report will include any additional recommendations for operation and maintenance of the oxidant cylinder and recirculation system.

5.4.9 Health and Safety

A health and safety plan (HASP) specific to CDM Smith activities at the NAS NI is provided in **Appendix E** of this Plan. CDM Smith plans to use subcontractors to perform the majority of the field work including construction, operations and maintenance, and sampling. At this time the subcontractor has not been identified. The subcontractor will be responsible for preparing a site-specific HASP that meets NAS NI and CDM Smith requirements. This HASP will be prepared and submitted separately from this Technology Demonstration Plan. The HASP will require an Accident Prevention Plan (APP), which will also need approval by CDM Smith and NAS NI.

5.5 FIELD TESTING

This section describes details associated with system startup and normal operation activities.

5.5.1 System Start-up

A series of tests will be conducted prior to startup to confirm the integrity of the recirculation system. Testing of the extraction pump, water meter recording system, piping, and fittings is performed to expose defective materials or possible leaks and serves as a final validation of the integrity of the demonstration system. Leak testing will be conducted after any system failures or modifications to the system configuration. Testing will be conducted in specific portions of the recirculation system as shown below.

Timer relay and flow controls

The extraction pump's timer relay and flow controls will be tested using the following procedure:

- The ball valve inside the reinjection well vault will be completely open to allow for transfer of groundwater from the extraction to the reinjection well.
- The extraction rate will be measured by pumping 5 gallons into a graduated bucket at least 3 times. The graduation on the side of the 5-gallon bucket will be used to confirm the extraction flow rate for at least 5 cycles.
- The extraction pump's timer relay will be programmed for a time-weighted average of 0.35 gpm, i.e., if the pump flow rate is 1.75 gpm then the timer will be set to run for 36 minutes every 180 minutes. A maximum of eight on/off cycles per day are possible with the control switch.
- The tubing union inside the reinjection well vault will be disconnected to allow for transfer of the extracted groundwater into a 5-gallon graduated bucket.
- A timer will be used to confirm the accuracy and precision of the timer relay, i.e., groundwater flows for 36 minutes every 180 minutes, for at least 5 cycles.
- The acceptable accuracy for this test is ± 10% of desired cycle ratio. If such criterion is not met, the appropriate equipment vendors will be contacted for customer support and troubleshooting. A third party timer relay will be obtained if necessary.

Water Meter Recording System

Concurrent to the aforementioned test, the remote water meter recording system will be tested using the following additional procedure:

- Verify the pulse output for the flow meter is set to send a pulse every 0.1 gallons based on manufacturer specifications.
- The hourly totalizer reading will be obtained via the internet and will be confirmed by comparing against the actual volume of groundwater transferred into the 5-gallon bucket.
- Continue testing the system for at least 5 cycles.
- The acceptable accuracy for this test is ± 10% of the totalizer reading. If such criterion is not met, the recirculation system will be checked again for leaks and the appropriate equipment vendors will be contacted for customer support and troubleshooting.

Leak Testing

Following completion of the above-mentioned tests, the recirculation system will be tested for leaks prior to startup of operations.

The recirculation system shall be tested for leaks prior to startup of operations using hydrostatic pressure testing. The integrity of the piping and any leaks in the fittings between the extraction and injection well will need to be confirmed by performing pneumatic leak testing. Specifically, the test should be performed as follows:

- Test medium. The medium utilized to perform pneumatic pressure testing shall be clean dry air or an inert gas.
- Test Pressure. After initial expansion at 4 pounds per square inch (psi) the test pressure shall be dropped to 3.5 psi. Pressure gauges should have increments of 0.1 psi or less.
- Test duration. The test duration shall be no less than 2 hours. The allowable maximum pressure drop (following the expansion phase at 4 psi) to indicate acceptance of the pipe, shall be 1 psi for the test duration.
- Testing procedures. The section between union in the Valve Box and the union in the injection well skirt. One end shall be capped with a test assembly (half of a union with a short section of PVC pipe and cap) and the other shall be terminated with a second test piece (half of a union, and a PVC tee: one connection for the gauge, and one for injecting compressed air). In accordance with the attached test method an air compressor shall be used to slowly increase the pressure of the test medium to the pressure specified for the test.
- Pressure test connections. The pressure test assembly shall have two openings. The first opening shall be used to introduce air inside the pipe. The second opening shall be used to connect the pressure gauge to the test manifold.
- Testing will not be considered complete until performance metrics noted above are attained.

Following pneumatic testing, the ball valve inside the reinjection vault will be closed partially so that the pressure is greater than 30 psi in the line. The pump will be allowed to run for at least 2 hours at 30 psi to determine of any leaks develop in fittings in either vault. If leaks occur, the affected fittings will be adjusted and the leak test will be performed again. All leak testing will be performed prior to filling in the trench.

5.5.2 Normal Operations

Under normal operating conditions, it is envisioned that the extraction pump will be programmed to remain on for approximately one-fifth of the time – assumed to be on for 36 minutes / off for 144 minutes (180 minute cycle). The actual on/off time will be determined by field personnel such that:

- The pump will not be turned on and off too often (no more than 8 times per day) as it can adversely affect its longevity.
- The pump will not be operated for more than 1 hour per each on cycle to ensure its longevity and that of the battery pack.

Valves will be adjusted for a normal operating extraction rate of 1.5-1.75 gpm and a timer-adjusted rate of 0.35 gpm.

The totalizer reading will be retrieved remotely on a daily basis and be compared against the anticipated value. If the relative percent difference between such values exceeds 30%, a site visit will be scheduled to determine corrective actions, if any.

5.6 SAMPLING PLAN

This section describes the various aspects of the sampling plan, which is designed to facilitate remedial performance monitoring. Sampling will be performed at select existing monitoring wells, new monitoring wells, and cylinder wells. Sampling collection will follow CDM Smith's Technical Standard Operating Procedures (SOP) for collection and handling and manufacturer-provided SOPs as provided in the QAPP (**Appendix D**). Groundwater elevation data will also be collected to monitor the hydraulic impacts of the extraction well. System parameters including the reinjection pressure and manual totalizer readings will also be recorded during each scheduled site visit.

5.6.1 Quality Assurance and Quality Control (QA/QC)

The container and preservative requirements are shown in **Table 5.6** while analytical detection limits are presented in **Tables 5.7** through **5.10**. Quality assurance sampling will include trip blanks, field duplicates, and temperature blanks. Field duplicates will be collected at a frequency of 5 percent. Each cooler will contain a temperature blank and each cooler containing VOC/dioxane samples will have a trip blank. Calibration of field equipment will be conducted at the beginning of each day prior to sampling. Calibration of analytical equipment will follow the quality procedures detailed in **Appendix D**. Details on QA/QC protocols and procedures including sample handling, calibration, sample documentation, and decontamination are described in further detail in **Appendix D**.

Table 5.6. Analytical Requirements

Analyte	Analytical Methods	Minimum Sample Volume	Container (number, size, and type)	Preservative Requirements	Holding Time
VOCs	SW 846 EPA 8260B	120 mL	4 x 40-mL vials with Teflon-lined septum	Preserve with HCl to pH <2; Cool to 4°C; no headspace; no bubbles. For dioxane, preserve with ascorbic acid.	14 days
1,4-dioxane	SW 846 EPA 8260 SIM				
Dissolved metals	SW 846 EPA 6010C	100 mL	1-250-mL polyethylene bottle	Filter; Preserve with HNO3; pH <2; Cool to 4 °C	14 days
Mercury	SW 846 EPA 7470A				
Bromate	EPA 300.1	100 mL	1-250-mL polyethylene bottle	Cool to 4°C	48 hours for bromate, 28 days for chloride, and sulfate
Sulfate					
Chloride					
pH	Multiparameter water quality meter	50 mL	NA	Analyzed immediately	NA
Conductivity			NA	Analyzed immediately	NA
Temperature			NA	Analyzed immediately	NA
ORP			NA	Analyzed immediately	NA
Ferrous iron	HACH ferrous iron AccuVac® Ampoules		NA	Analyzed immediately	NA
Persulfate	Chemetrics kit K-7870		NA	Analyzed immediately	NA

****Notes***:

- VOCs: volatile organic compounds
- EPA: Environmental Protection Agency
- HCl: hydrochloric acid
- °C: degree Celsius
- ORP: oxidation-reduction potential
- mL: milliliter

Table 5.7. Analytical Reference Limits for EPA Method 8260B / 8260 SIM

VOC	CAS Number	Analytical Method		Achievable Laboratory Limits	
		MDL (µg/L)	RLs (µg/L)	MDLs (µg/L)	EQLs (µg/L)
1,1,1-Trichloroethane	71-55-6	0.04	NP	0.25	1
1,1,2,2-Tetrachloroethane	79-34-5	0.2	NP	0.1	0.5
1,1,2-Trichloroethane	79-00-5	0.08	NP	0.25	1
1,1-Dichloroethane	75-34-3	0.03	NP	0.25	1
1,1-Dichloroethylene	75-35-4	0.2	NP	0.25	1
1,2,4-Trichlorobenzene	120-82-1	0.2	NP	0.5	2
1,2-Dichlorobenzene	95-50-1	0.05	NP	0.25	1
1,2-Dichloroethane	107-06-2	0.02	NP	0.25	1
1,2-Dichloropropane	78-87-5	0.02	NP	0.25	1
1,3-Dichlorobenzene	541-73-1	0.05	NP	0.25	1
1,4-Dichlorobenzene	106-46-7	0.04	NP	0.25	1
1,2,4-Trimethylbenzene	95-63-6	0.13	NP	0.25	1
1,3,5-Trimethylbenzene	108-67-8	0.05	NP	0.25	1
2-Butanone	78-93-3	NP	NP	2.5	10
2-Hexanone	591-78-6	NP	NP	1.25	5
4-Methyl-2-Pentanone	108-10-1	NP	NP	0.25	5
Acetone	67-64-1	NP	NP	2.5	10
Benzene	71-43-2	0.03	NP	0.25	1
Bromodichloromethane	75-27-4	0.03	NP	0.25	1
Bromoform	75-25-2	0.2	NP	0.25	1
Bromomethane	74-83-9	NP	NP	0.5	2
Carbon disulfide	75-15-0	NP	NP	0.25	1
Carbon tetrachloride	56-23-5	0.02	NP	0.25	1
Chlorobenzene	108-90-7	0.03	NP	0.25	1
Chloroethane	75-00-3	NP	NP	0.5	2
Chloroform	67-66-3	0.04	NP	0.25	1
Chloromethane	74-87-3	0.05	NP	0.25	1
cis-1,2-Dichloroethylene	156-59-2	0.06	NP	0.25	1
cis-1,3-Dichloropropene	10061-01-5	NP	NP	0.5	1
Dibromochloromethane	75-25-2	0.07	NP	0.25	1
Ethylbenzene	100-41-4	0.03	NP	0.25	1
Naphthalene	91-20-3	0.04	NP	0.5	2
Methylene chloride	75-09-2	NP	NP	0.5	2
m, p-xylene	136777-61-2	0.13	NP	0.5	2
Methyl tertiary butyl ether	1634-04-4	0.13	NP	0.25	1
o-xylene	95-47-6	0.11	NP	0.25	1
Styrene	100-42-5	0.27	NP	25	1

Table 5.7 (cont). Analytical Reference Limits for EPA Method 8260B / 8260 SIM

VOC	CAS Number	Analytical Method		Achievable Laboratory Limits	
		MDL (µg/L)	RLs (µg/L)	MDLs (µg/L)	EQLs (µg/L)
Tetrachloroethylene	127-18-4	0.05	NP	0.25	1
Toluene	108-88-3	0.08	NP	0.25	1
trans-1,2-Dichloroethylene	156-60-5	NP	NP	0.25	1
trans-1,3-Dichloropropene	10061-02-6	NP	NP	0.25	1
Trichloroethylene	79-01-6	NP	NP	0.25	1
Vinyl chloride	75-01-4	NP	NP	0.15	0.5
Trichlorofluoromethane	75-69-4	NP	NP	0.5	2
1,4-dioxane**	123-91-1	NP	NP	0.25	1

<u>Notes</u>:

- **8260 SIM
- *project-specific
- µg/L: microgram per liter
- NP: not published
- NA: not available
- RL: reporting limit
- CAS: chemical abstract service
- EQL: estimated quantitation limit
- MDL: method detection limit

Table 5.8. Analytical Reference Limits for EPA Method 6010C

Analyte	CAS Number	Analytical Method		Achievable Laboratory Limits	
		MDL (µg/L)	RLs (µg/L)	MDLs (µg/L)	EQLs (µg/L)
Arsenic	7440-38-2	35	NP	5	10
Barium	7440-39-3	0.87	NP	10	10
Beryllium	7440-41-7	0.18	NP	1	5
Cadmium	7440-43-9	2.3	NP	2	5
Chromium	7440-47-3	4.7	NP	2.5	5
Copper	7440-50-8	3.6	NP	5	5
Lead	7439-92-1	28	NP	2.5	3
Selenium	7782-49-2	50	NP	5	10
Thallium	7440-28-0	27	NP	1	10
Uranium	7440-61-1	0.33	NP	0.67	NA

*<u>***Notes***</u>:

- µg/L: microgram per liter
- CAS: chemical abstract service
- EQL: estimated quantitation limit
- MDL: method detection limit
- NA: not available
- NP: not published
- RL: reporting limit

Table 5.9. Analytical Reference Limits for EPA Method 7470A

Analyte	CAS Number	Analytical Method		Achievable Laboratory Limits	
		MDL (µg/L)	RLs (µg/L)	MDLs (µg/L)	EQLs (µg/L)
Mercury	7439-97-6	0.2	NP	0.1	NA

*<u>***Notes***</u>:

- µg/L: microgram per liter
- CAS: chemical abstract service
- EQL: estimated quantitation limit
- MDL: method detection limit
- RL: reporting limit
- NA: not available
- NP: not published

Table 5.10. Analytical Reference Limits for EPA Method 300.1

Analyte	**CAS Number**	**Analytical Method**		**Achievable Laboratory Limits**
		MDL (µg/L)	RLs (µg/L)	MDLs (µg/L)
Bromate	15541-45-4	1.3	NP	2.5
Sulfate	18785-72-3	20	NP	330
Chloride	16887-00-6	20	NP	170

****Notes***:

- µg/L: microgram per liter
- CAS: chemical abstract service
- EQL: estimated quantitation limit
- MDL: method detection limit
- NA: not available
- NP: not published
- RL: reporting limit

5.6.2 Water Sampling

Rationale

A number of analytes will be collected to facilitate evaluating the remedial performance of the demonstration system. The rationale for each selected analyte is presented below:

- Dioxane and VOCs: samples collected in up-gradient, cylinder, and down-gradient wells will be used to determine VOC removal effectiveness and efficiency.
- Dissolved metals: persulfate decomposition increases the oxidation state of the aquifer and generates sulfuric acid that can reduce the aquifer pH. Such changes in groundwater pH and oxidation state can lead to increases in dissolved metals concentrations. Therefore, dissolved metals samples will be collected in up-gradient, cylinder, and down-gradient wells to access the impacts of persulfate on groundwater quality in the aquifer.
- Bromate: bromide may be oxidized to the carcinogenic bromate in the presence of persulfate and therefore will be monitored to assess groundwater quality.
- Sulfate: sulfate is the byproduct of persulfate degradation and will be monitored to evaluate persulfate distribution and longevity in the aquifer.
- Chloride: chloride will be used as a tracer to facilitate evaluation of groundwater seepage velocity and oxidant transport in the aquifer.

Field parameters including persulfate, ferrous iron, oxidation-reduction potential (ORP), pH, temperature, and conductivity will be collected concurrently with collection of aforementioned analytes. Groundwater levels will also be measured prior to the start of each performance monitoring event. The rationale for measuring such parameter is as follows:

- Persulfate: persulfate will be measured using a field kit as a direct measure of the residual oxidant in the demonstration area.
- Ferrous iron: ferrous iron will be measured using a field kit to evaluate the potential impact of iron to foul the wells and to activate persulfate oxidation.
- ORP: ORP measures an aqueous system’s capacity to either release or accept electrons from chemical reactions. This will be used as a general parameter to evaluate effects of persulfate in the reactive zone and re-establishment of reducing conditions and associated natural attenuation down-gradient of the reactive zone.
- pH: pH is a general groundwater quality parameter that is easy to measure and can be used to evaluate potential adverse impacts of the persulfate oxidant on the aquifer. pH will also be monitored to evaluate if increased sulfuric acid concentrations (from persulfate) are causing increased acidity in the aquifer.
- Conductivity: similar to pH, conductivity can be used to evaluate oxidant and tracer transport and distribution within the aquifer.
- Groundwater level: water levels will be measure to evaluate the impact of the artificial hydraulic gradient induced by the extraction well.

Monitoring Well Design

The monitoring well network will consist of one new up-gradient monitoring well (DMW-01), two new monitoring wells in the cylinder boreholes (DCW-01 and DCW-02), and six new down-gradient monitoring wells (DMW-02 through DMW-07). One existing monitoring well (SMW-

07A), which is screened between 34.5 and 39.5 ft bgs, will be used as a downgradient monitoring location. The screen intervals associated with other aforementioned wells are presented in **Table 5.3**.

Sampling Protocol

No-purge (passive) groundwater sampling via HydraSleeve® deployment will be used to collect all groundwater samples directly within the well screens. The Hydrasleeve™ sampler was chosen because stratified sampling will be required at this site to measure how well the persulfate mixes in the aquifer as it migrates between the cylinder wells and the extraction well. Because large sample volumes (and different sample container types) will be required, the HydraSleeve™ was considered over Snap Sampler™ for stratified sampling. As described in more detail in **Appendix F,** this disposable groundwater sampler offers a cost-effective and easy-to-use method to collect formation-quality groundwater samples equivalent to those collected using low-flow purging and sampling. Multiple Hydrasleeves® can be deployed in series along a single suspense line or tether to enable vertical contaminant characterization. Additionally, the HydraSleeves® can be recovered immediately with minimal equilibration time, within a few hours or can be left in a well for an indefinite period of time within concern. Therefore, multiple HydraSleeves® can be deployed in a well concurrently and be retrieved periodically during different performance monitoring events. It is anticipated that standard 1-Liter HydraSleeves with a maximum sample volume of 1.3 liter will be used to collect groundwater samples.

Sampling Schedule

Two types of groundwater sampling activities will be executed to facilitate performance monitoring during this technology demonstration. In the standard sampling as shown in **Table 5.11**, Hydrasleeves® will be deployed at approximately 32.5 to 40 ft bgs at different sampling frequencies based on distance from the cylinders. It should be noted that even though the monitoring wells are screened between 20 and 40 ft bgs, historical water level data in the vicinity of the proposed demonstration area indicate that the water level is often around 25 ft bgs. Therefore, the effective monitoring interval is likely between 25 and 40 ft bgs. Monitoring wells which are located closer to the cylinder wells and therefore are anticipated to achieve target remedial objectives sooner will be monitored more frequently at the beginning of system operations. On the contrary, monitoring wells located further away from the cylinder wells will be monitored less frequently at the beginning of system operations but will be monitored for longer periods of time. In addition to this standard sampling schedule, a stratified sampling program will be executed to characterize vertical contaminant distribution in the anticipated flow path from one of the two cylinders (i.e., approximately half of the downgradient monitoring wells). Specifically, in select wells and at select monitoring events, Hydrasleeves® will be deployed at approximately 25 to 32.5 ft bgs as shown in **Table 5.12**. With exception of the monitoring wells within the cylinder boreholes and monitoring wells 5 feet downgradient, stratified sampling will not commence at select monitoring points until oxidant/tracer breakthrough has been observed at such locations. Therefore, the stratified sampling schedule shown in **Table 5.12** may be subject to change based on analytical results of previous standard sampling events. It should also be noted that not all analytes will be collected during the stratified sampling events. In fact, only the contaminants of concern (i.e., VOCs and dioxane) and the inorganic anions (i.e., tracer – chloride, persulfate, oxidant breakdown product – sulfate) will be collected during such events. The one exception to the sampling program is existing well

OU11-SMW-07A – which has a designated pump installed. This well will be sampled using standard low-flow purge methods using the designated pump.

Table 5.11. Monitoring Schedule for Standard Sampling

Analyte	**Upgradient Well**	**Cylinder Wells**	**Downgradient Wells**				
	DMW-01	DCW-01/02	DMW-02/03	DMW-04/05	DMW-06/07	DEW-01	SMW-07A**
Distance from cylinder wells (ft)	-5	0	5	10	20	35	~ 150
VOCs	B	B	B	B	C	D	E
1,4-dioxane	B	B	B	B	C	D	E
Dissolved metals	B	B	B	B	C	D	E
Bromate	B	B	B	B	C	D	E
Sulfate	B	B	B	B	C	D	E
Chloride	B	B	B	B	C	D	E
Ferrous Iron*	A	A	A	A	A	A	A
Persulfate*	-	B	B	B	C	D	E
ORP, pH, conductivity, temperature, groundwater level*	B	B	B	B	C	D	E

Notes:

- ** SMW-07A is screened between 34.5 and 39.5 ft bgs
- * field analysis
- A: Hydrasleeve collected at 32.5-40 ft bgs at t = 0, 12 months
- B: Hydrasleeve collected at 32.5-40 ft bgs at t = 0, 2 weeks, 1, 3, 7, 12 months
- C: Hydrasleeve collected at 32.5-40 ft bgs at t = 0, 1, 3, 7, 12 months
- D: Sample collected via sample port at t = 0, 3, 7, 12 months
- DCW: cylinder monitoring well
- DMW: monitoring well
- E: Sample collected with low-flow purging at t = 0, 7, 12 months
- ft: foot
- ORP: oxidation-reduction potential
- VOCs: volatile organic compounds

Table 5.12. Monitoring Schedule for Stratification Sampling

	Upgradient Well	**Cylinder Wells**	**Downgradient Wells**		
	DMW-01	DCW-01/02	DMW-02/03	DMW-04/05	DMW-06/07
Distance from cylinder wells (ft)	-5	0	5	10	20
VOCs	-	A	A	B	B
1,4-dioxane	-	A	A	B	B
Dissolved Metals	-	-	-	-	-
Bromate	-	-	-	-	-
Sulfate	-	A	A	B	B
Chloride	-	A	A	B	B
Ferrous Iron*	-	C	C	C	C
Persulfate*	-	A	A	B	B
ORP, pH, conductivity*	-	A	A	B	B

Notes:

- * field analysis
- A: Hydrasleeve collected at 25-32.5 ft bgs at tentatively t = 0, 1, 3, 12 months
- B: Hydrasleeve collected at 25-32.5 ft bgs at tentatively t = 0, 3, 7, 12 months
- C: Hydrasleeve collected at 25-32.5 ft bgs at t = 0 months (baseline), 12 months (demonstration end)
- DCW: cylinder monitoring well
- DMW: monitoring well
- ft: foot
- ORP: oxidation-reduction potential
- VOCs: volatile organic compounds

"-": not sampled

5.7 DATA ANALYSIS

Field forms will be stored in the project file and data will be entered into Microsoft Excel as an electronic database. Analytical results will also be incorporated into such database for data tracking, validation, and analysis. Statistical analysis involving summary statistics such as average, maximum, and minimum values and trend analysis of temporal data using Microsoft Excel and Minitab, if necessary, will be performed. The demonstration system will be operated for one year, during which time concentrations of the contaminants of concern, oxidants, tracer, and other analytes pertinent to groundwater quality will be obtained over time and at different distances from the cylinder wells. VOCs and dioxane data will be used to evaluate the effectiveness as well as the sustainability/longevity of the persulfate cylinders. Persulfate, sulfate, and chloride data will be used to evaluate oxidant transport and distribution. pH, dissolved metals, and bromate data will be used to assess the secondary impacts of the demonstrated technology. Collectively, the demonstration will provide actual field data that can be used to compare and update the existing design spreadsheet tool. Within the one year of operation, system optimization may be warranted in which case operating parameters such as extraction rate and cycling frequency will be altered to access the impacts on performance. Statistical analysis may be used to determine if such impacts are statistically significant. In addition, data analysis involving trend analysis and linear correlation between design, operating, and performance data will be performed.

6.0 COST ASSESSMENT

6.1 COST REPORTING

Table 6.1 presents an outline of costs that will be developed for a full-scale system. The general approach to obtaining these costs will be to first develop a design basis using demonstration data. Specifically, demonstration construction, installation, and operations and maintenance performance data and costs will be used to as the basis for estimating full-scale costs.

Table 6.1. Cost Tracking

Cost element	Type
Treatability Study	Soil NOD testing
	Rate constant estimates
	Oxidant selection
Baseline Characterization	Groundwater sampling and analysis
Design	Modeling
	Engineering design
	Permitting
Material Cost	Oxidant cylinders
Installation	Geophysical survey/Utility locate
	Surveyor
	Driller/well installation
	Funnel and gate installation
Waste Disposal	IDW disposal
Operations and Maintenance Costs	Oxidant cylinder reinstallation
	Driller
Long-term Monitoring	Groundwater sampling and analysis

****Notes***:

- IDW: investigation-derived waste
- NOD: natural oxidant demand

6.2 COST ANALYSIS

6.2.1 Cost Comparison

Cost data and parameters controlling cost collected during the demonstration will be applied to a full-scale system. These would include factors such as hydraulic conductivity, oxidant distribution and longevity, pH adjustment needs, and impacts of the oxidation technology on groundwater quality of the aquifer. Costs for full-scale application of ISCO using slow-release persulfate cylinders will be compared to other conventional technologies including AOPs, cometabolism via propane sparging, and traditional ISCO. Example design parameters are shown in **Table 6.2**, which may be altered to meet the cost basis criteria. The assessment will assume similar treatment areas and water quality between the different technologies for comparison.

Table 6.2. Technology Cost Comparison

Technology in Comparison	Design Parameter	Project Duration (years)
AOPs	Contaminant concentration	30
	Oxidant dosage	
	Hydraulic conductivity	
Cometabolism via propane sparging	Well spacing	30
	Injection rate, frequency, and dosage	
	Propane consumption	
Traditional ISCO	Contaminant concentration	30
	Natural oxidant demand	
	Hydraulic conductivity	
	Injection dosage and frequency	
	Number of wells/well spacing	

****Notes***:

- AOP: advanced oxidation process
- ISCO: *in situ* chemical oxidation

6.2.2 Cost Basis

Equipment Capital Cost

The equipment capital cost will be based on a full-scale operation of dioxane oxidation using slow-release oxidant cylinders. CDM Smith will provide a budgetary equipment capital cost after the demonstration study is completed. The cost of the other ancillary equipment will be based on budgetary cost for appropriate vendors.

Engineering Design Cost

The preliminary and final design cost of a full-scale treatment system will be based on the equipment design. The electrical, instrumentation, civil, mechanical, and structural design will be based on the information CDM Smith provides on the power requirements, preliminary piping and instrumentation diagrams (P&ID), equipment sizes including all necessary ancillary equipment. The engineering design will be based on complying with the local codes, city, and agency requirements.

Construction/Installation Cost

The construction/installation cost estimate will be prepared by CDM Smith. For the purpose of this plan, it will be assumed that the site owner will provide necessary power lines up to the boundary of the site for full-scale operations. The construction cost will include installation of the all equipment and materials located within the treatment system and all necessary permits. It will be assumed that there is ample space for installation of the full-scale system.

Operations & Maintenance

Power and oxidant cost will be a significant factor to the O&M cost as well as equipment maintenance, repair, and replacement. The results of the demonstration study will provide the basis for estimating the O&M costs of the full scale system. Another factor that will affect the O&M cost is the ease of maintenance. For the purpose of the preliminary cost estimate, an assumption will be made after the demonstration study is completed on the man hours/week required to operate and maintain the treatment system.

6.2.3 Cost Drivers

The expected cost drivers for the treatment system are the capital cost for equipment, materials, construction, and O&M. Primary O&M cost drivers are anticipated to include labor and general system maintenance activities.

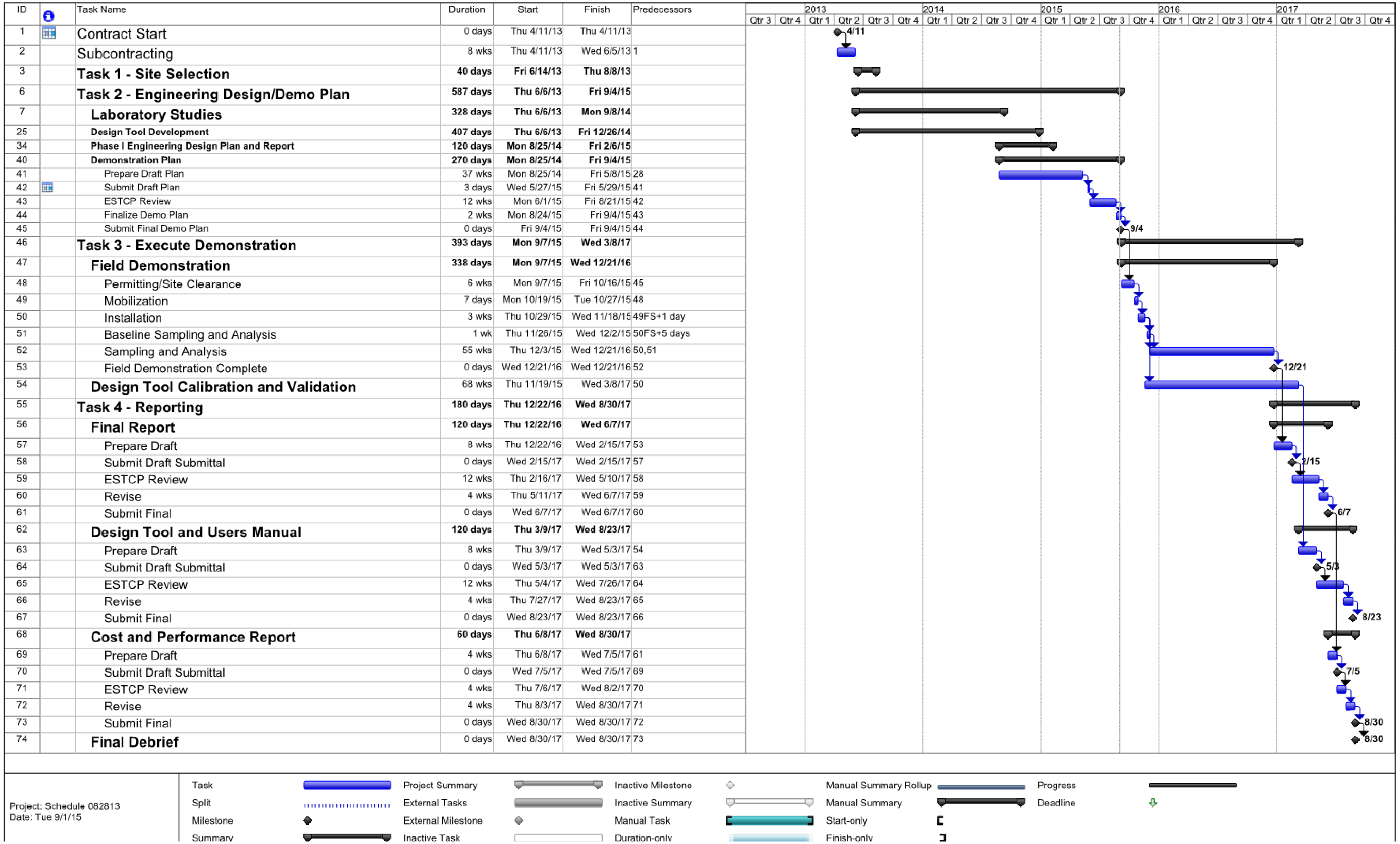
6.2.4 Life Cycle Costs

The life cycle costs will be based on a 30-year operating life of the treatment system. The costs will take into account the capital, construction, energy consumption, and O&M costs. A 5 percent interest rate will be assumed in calculating the life cycle costs. Information gathered during the demonstration study including energy, chemical throughput and maintenance activities will be used to calculate the expected life cycle costs of the full scale treatment system.

7.0 SCHEDULE OF ACTIVITIES

The tentative schedule of the technology demonstration described in this plan is graphically depicted in **Figure 7.1**.

Figure 7.1. Demonstration Schedule

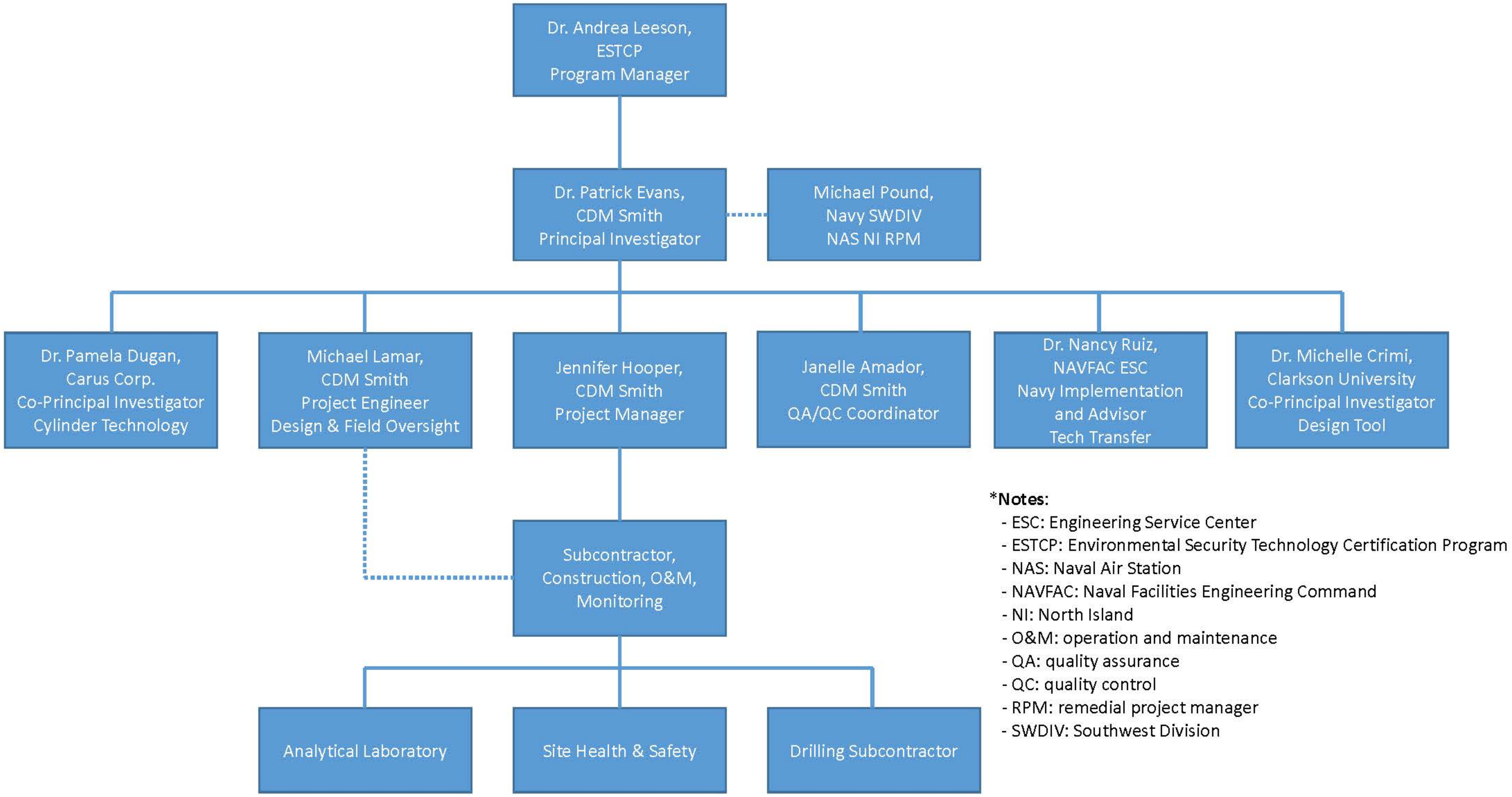


ID	ℹ	Task Name	Duration	Start	Finish	Predecessors
1	▦	Contract Start	0 days	Thu 4/11/13	Thu 4/11/13	
2		Subcontracting	8 wks	Thu 4/11/13	Wed 6/5/13	1
3		**Task 1 - Site Selection**	**40 days**	**Fri 6/14/13**	**Thu 8/8/13**	
6		**Task 2 - Engineering Design/Demo Plan**	**587 days**	**Thu 6/6/13**	**Fri 9/4/15**	
7		**Laboratory Studies**	**328 days**	**Thu 6/6/13**	**Mon 9/8/14**	
25		**Design Tool Development**	**407 days**	**Thu 6/6/13**	**Fri 12/26/14**	
34		**Phase I Engineering Design Plan and Report**	**120 days**	**Mon 8/25/14**	**Fri 2/6/15**	
40		**Demonstration Plan**	**270 days**	**Mon 8/25/14**	**Fri 9/4/15**	
41		Prepare Draft Plan	37 wks	Mon 8/25/14	Fri 5/8/15	28
42	▦	Submit Draft Plan	3 days	Wed 5/27/15	Fri 5/29/15	41
43		ESTCP Review	12 wks	Mon 6/1/15	Fri 8/21/15	42
44		Finalize Demo Plan	2 wks	Mon 8/24/15	Fri 9/4/15	43
45		Submit Final Demo Plan	0 days	Fri 9/4/15	Fri 9/4/15	44
46		**Task 3 - Execute Demonstration**	**393 days**	**Mon 9/7/15**	**Wed 3/8/17**	
47		**Field Demonstration**	**338 days**	**Mon 9/7/15**	**Wed 12/21/16**	
48		Permitting/Site Clearance	6 wks	Mon 9/7/15	Fri 10/16/15	45
49		Mobilization	7 days	Mon 10/19/15	Tue 10/27/15	48
50		Installation	3 wks	Thu 10/29/15	Wed 11/18/15	49FS+1 day
51		Baseline Sampling and Analysis	1 wk	Thu 11/26/15	Wed 12/2/15	50FS+5 days
52		Sampling and Analysis	55 wks	Thu 12/3/15	Wed 12/21/16	50,51
53		Field Demonstration Complete	0 days	Wed 12/21/16	Wed 12/21/16	52
54		**Design Tool Calibration and Validation**	68 wks	Thu 11/19/15	Wed 3/8/17	50
55		**Task 4 - Reporting**	**180 days**	**Thu 12/22/16**	**Wed 8/30/17**	
56		**Final Report**	**120 days**	**Thu 12/22/16**	**Wed 6/7/17**	
57		Prepare Draft	8 wks	Thu 12/22/16	Wed 2/15/17	53
58		Submit Draft Submittal	0 days	Wed 2/15/17	Wed 2/15/17	57
59		ESTCP Review	12 wks	Thu 2/16/17	Wed 5/10/17	58
60		Revise	4 wks	Thu 5/11/17	Wed 6/7/17	59
61		Submit Final	0 days	Wed 6/7/17	Wed 6/7/17	60
62		**Design Tool and Users Manual**	**120 days**	**Thu 3/9/17**	**Wed 8/23/17**	
63		Prepare Draft	8 wks	Thu 3/9/17	Wed 5/3/17	54
64		Submit Draft Submittal	0 days	Wed 5/3/17	Wed 5/3/17	63
65		ESTCP Review	12 wks	Thu 5/4/17	Wed 7/26/17	64
66		Revise	4 wks	Thu 7/27/17	Wed 8/23/17	65
67		Submit Final	0 days	Wed 8/23/17	Wed 8/23/17	66
68		**Cost and Performance Report**	**60 days**	**Thu 6/8/17**	**Wed 8/30/17**	
69		Prepare Draft	4 wks	Thu 6/8/17	Wed 7/5/17	61
70		Submit Draft Submittal	0 days	Wed 7/5/17	Wed 7/5/17	69
71		ESTCP Review	4 wks	Thu 7/6/17	Wed 8/2/17	70
72		Revise	4 wks	Thu 8/3/17	Wed 8/30/17	71
73		Submit Final	0 days	Wed 8/30/17	Wed 8/30/17	72
74		**Final Debrief**	0 days	Wed 8/30/17	Wed 8/30/17	73

Project: Schedule 082813
Date: Tue 9/1/15

8.0 MANAGEMENT AND STAFFING

The organizational chart is illustrated in **Figure 8.1.** The project Principal Investigator is Dr. Patrick Evans. He will be supported by Mr. Mike Lamar, PE for design, planning, installation and commissioning, and reporting.



***Notes:**
- ESC: Engineering Service Center
- ESTCP: Environmental Security Technology Certification Program
- NAS: Naval Air Station
- NAVFAC: Naval Facilities Engineering Command
- NI: North Island
- O&M: operation and maintenance
- QA: quality assurance
- QC: quality control
- RPM: remedial project manager
- SWDIV: Southwest Division

Figure 8.1. Organizational Chart

9.0 REFERENCES

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APPENDICES

Appendix A	**Hydraulic Modeling Details**
Appendix B	**Oxidant Release Design Tool Details**
Appendix C	**Design Calculations**
Appendix D	**Quality Assurance Project Plan**
Appendix E	**CDM Smith Site Health and Safety Plan**
Appendix F	**HydraSleeve^{TM} Standard Operating Procedure**
Appendix G	**Points of Contact**

Appendix A

Hydraulic Modeling Details

APPENDIX A

Summary of Modeling Analysis

Introduction

A deterministic numerical model describing the groundwater flow and solute transport processes at the proposed pilot testing location at Naval Air Station North Island was developed to assist in design of the test. The objectives of the modeling were:

- Assess spacing of the cylinder treatment wells, gradient control well, monitoring wells and reinjection well
- Estimate transport times from the cylinder treatment wells
- Assess effective treatment radius and dispersion from the cylinder treatment wells

The modeling was conducted using industry standard model codes, including MODFLOW-2005 for groundwater flow, MODPATH for particle tracking evaluations and MT3DMS for solute transport simulations. Initial evaluations assessed the potential for use of closed form analytical solutions, however, no appropriate methods were found, so use of numerical models was selected. No calibration of the models was done during the assessment.

Since one of the objectives of the pilot testing is to provide an analog of a passive treatment system, the approach included an extraction well pumping at a minimal rate to develop a controlled flow field to reduce uncertainty in placement of monitoring wells. The cylinder treatment wells are located upgradient of the extraction well, with an injection well placed downgradient of the pumping wells for disposal of the extracted water.

Parameter Estimates

The modeling that was conducted was deterministic in nature, where a simple model grid with uniform hydraulic properties and variable dispersion properties was defined based on estimates from the site and professional judgment. The hydraulic conductivity was estimated from single borehole slug tests in the vicinity of the test site. Water levels at monitoring wells near the site were used to estimate the hydraulic gradient. Well logs indicate that a sand unit has a saturated thickness of about 15 feet and comprises the aquifer in this area. The effective porosity was conservatively estimated based on the lithology. Dispersivity, which describes the longitudinal and transverse spreading of a solute as it migrates in the aquifer, was estimated based on empirical relationships reported in the literature (Figure A-1). Figure A-2 shows the model zonation of the dispersivity parameter that approximates this function in a stepwise manner. This approach was implemented to account for the increased spreading of the solute in the aquifer during migration from the cylinder treatment well. A summary of the parameters used in the modeling is provided in Table A1.

A uniform model grid consisting of a single layer with grid cells .5 * .5 feet. The model domain included 320,000 cells over the 400 * 200 ft area. The use of a single model layer assumes full mixing occurs in the vertical dimension, which is expected, since the cylinder well fully penetrates the aquifer. The same computational grid is used in MODPATH and in MT3DMS. A uniform hydraulic gradient was imposed on the system by setting constant head boundaries at the top and bottom of the grid. Figure A-3 shows the model grid relative to the cylinder well convergence-divergence zone locations, pumping well and injection well. Individual grid cells are not shown due to their small size. The small grid cells were selected to allow definition of the solute spreading.

A cylinder well was modeled using a highly detailed grid to represent the impact of the borehole and well structure on the local groundwater flow. The presence of the highly permeable well structure, consisting of the boring with its filter pack and screen creates a converging flow field in the upgradient direction with subsequent divergence downgradient of the well structure. Figure A-4 shows the results of the simulation, indicating an estimated width of the zone containing the persulfate zone at 27 inches immediately downgradient of the cylinder treatment well.

The release rate of persulfate from the cylinders was used to calculate the concentration in this source zone for the remainder of the modeling. The mass release rate from each of the persulfate cylinders was 91 gm/day, resulting in a concentration of 3,818 mg/L in the zone immediately downgradient of the cylinder treatment wells under the effect of pumping a downgradient well, and approximately 10,250 mg/L for the case with no pumping. This was simulated in the model by setting a constant concentration boundary to represent each of the cylinder treatment wells, with the width of the constant concentration zone set at the estimated divergence width. The extent of the 5,000 µg/L 1,4-Dioxane plume was defined in the model based on site data and this concentration was maintained with a constant concentration boundary at the upgradient model boundary (Figure A-5). Water recovered at the extraction well and reinjected downgradient was assumed to remain at 5,000 µg/L to allow a conservative assessment of the potential for spreading the existing plume due to early operation of the pilot testing program. After arrival of the persulfate at the pumping well, concentrations of 1,4-Dioxane will decrease.

Model Results

Simulations were conducted for two scenarios, a passive scenario where two cylinder treatment wells are installed and the resulting persulfate zone will drift with the ambient groundwater flow, and an active scenario where an extraction well pumping at a low rate is used to control the flow direction.

Passive Scenario

The passive scenario relies on the existing groundwater flow to distribute the persulfate in the area downgradient of the cylinder treatment wells. The approximation of dispersion, with increasing dispersion with distance from the treatment wells was incorporated into the simulation. Figure A-6 shows the simulated distribution of persulfate after one year, assuming a constant release rate at the cylinder treatment wells. The concentration in groundwater will decrease as the persulfate disperses with transport downgradient. Figure A-7 shows the distribution of the 5,000 mg/L persulfate contour at 3 month intervals for the passive simulation. Figure A-8 shows the simulated concentration along a flow line directly downgradient from a cylinder treatment well as a function of time. The core of the persulfate treatment zone remains relatively narrow, so placement of monitoring wells is difficult, since the local groundwater flow direction is difficult to predict.

Active Scenario

The active scenario incorporates two cylinder treatment wells, an extraction well located 35 feet downgradient, pumping at 0.35 gpm, and an injection well 120 feet downgradient of the cylinder treatment wells. The spacing of the wells was designed to allow arrival of the persulfate front at the extraction well within less than a year, while the injection well is located sufficiently downgradient to minimize the impact on the flow field between the cylinder treatment wells and the extraction well. Figure A-9 shows the simulated steady state water table in the pilot test area under the active scenario. Figure A-10 shows the extent of the capture zone at the extraction well after one year. Figure A-11 shows the extent of the injected water after one year. The particle travel time from the cylinder treatment well to the extraction well is about 3 months, not including the effects of dispersion. Figure A-12 shows the simulated concentration of persulfate at the extraction well, which includes the impact of capture of groundwater outside the persulfate treatment zone. Figure A-13 shows the simulated persulfate concentration at 3 month intervals in the area between the treatment wells and the extraction well, which indicates that concentrations are at a near steady-state condition after about 90 days. The concentration over time at distances of 10, 20, and 30 feet downgradient of the cylinder well is shown on figure A-14. Particle tracks at the assumed perimeter of the existing 5,000 µg/L 1,4-Dioxane plume were compared for baseline conditions and operation of the pilot system. Figure A-15 shows the simulation results, which indicate minor difference in the flow direction as a result of the pilot project on the 5,000 µg/L extent.

Table A1 - Model Parameters.

Parameter	**Modeled Value**
Hydraulic Conductivity	17.24 ft/day
Longitudinal Dispersivity	Varies from near 0 to 5 feet.
Transverse Dispersivity	.03*longitudinal dispersivity
Porosity	0.1
Specific storativity	1e-6
Depth to Water	20 ft bgs
Hydraulic Gradient (Natural)	0.00054
Groundwater Velocity (Natural)	0.1 ft/day
Extraction and reinjection well screened interval	25 to 40 ft bgs
Lithology	Sand
Treatment zone thickness	15 feet – there is a semi-confining silt layer at 40 ft bgs

Model Appendix Figures

Figure A-1 – Relationship of Dispersivity to Transport Distance

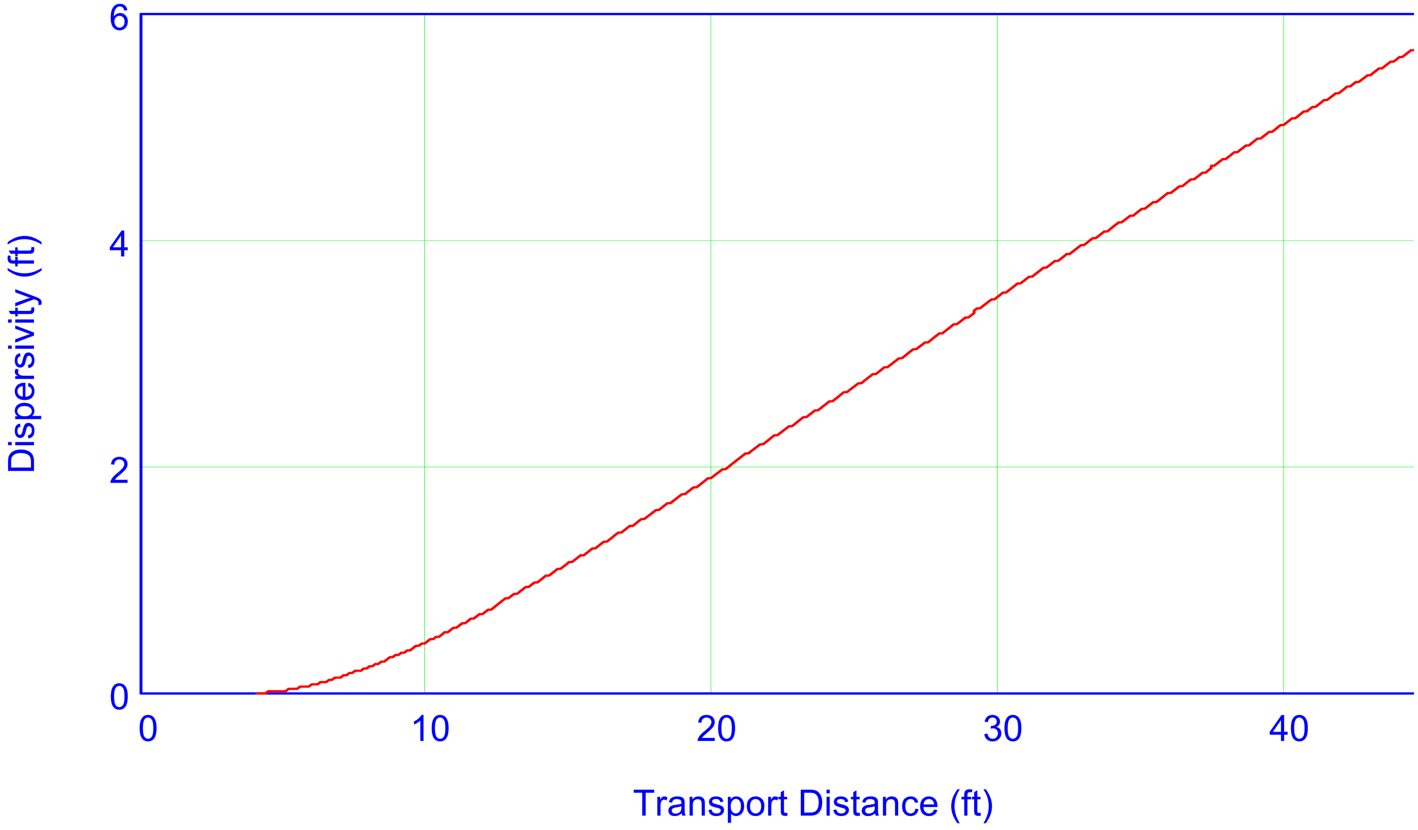


Figure A-2 - Dispersivity Zones

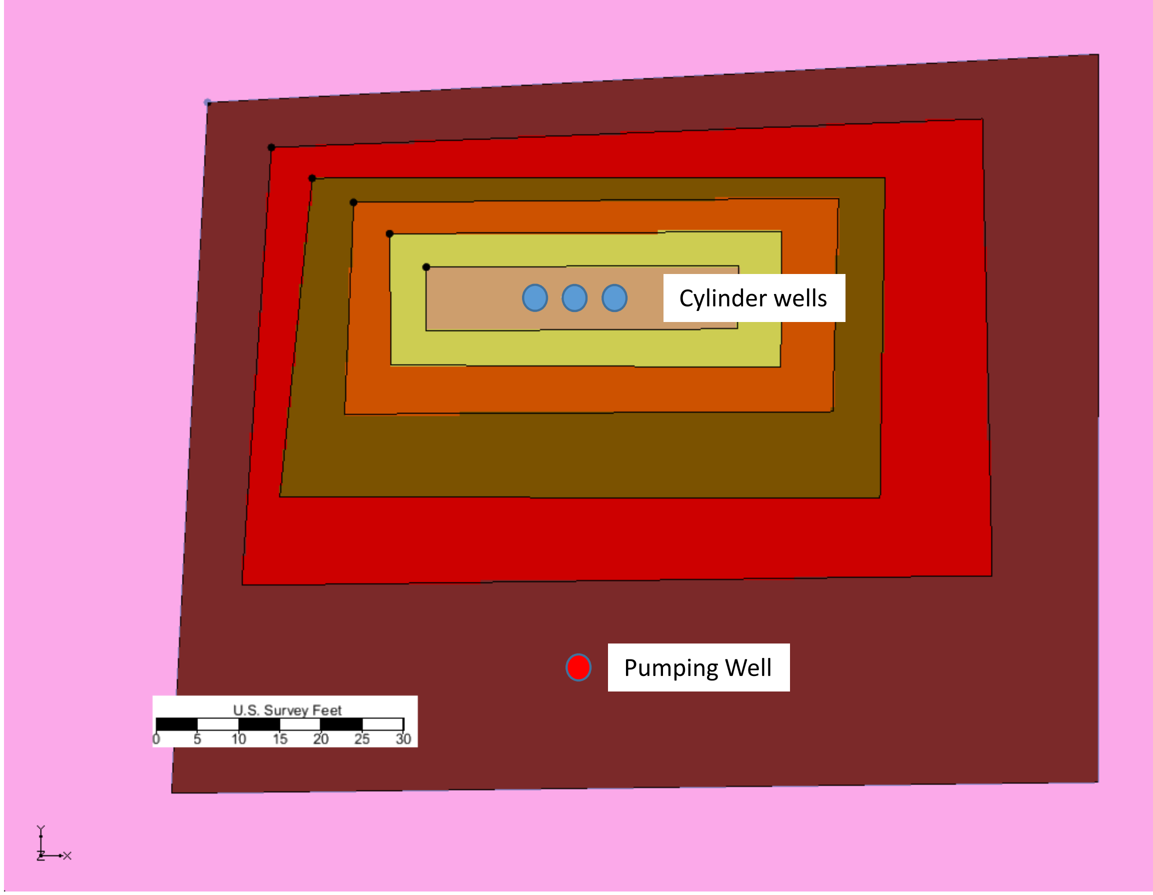


Figure A-3 – Model Grid Location

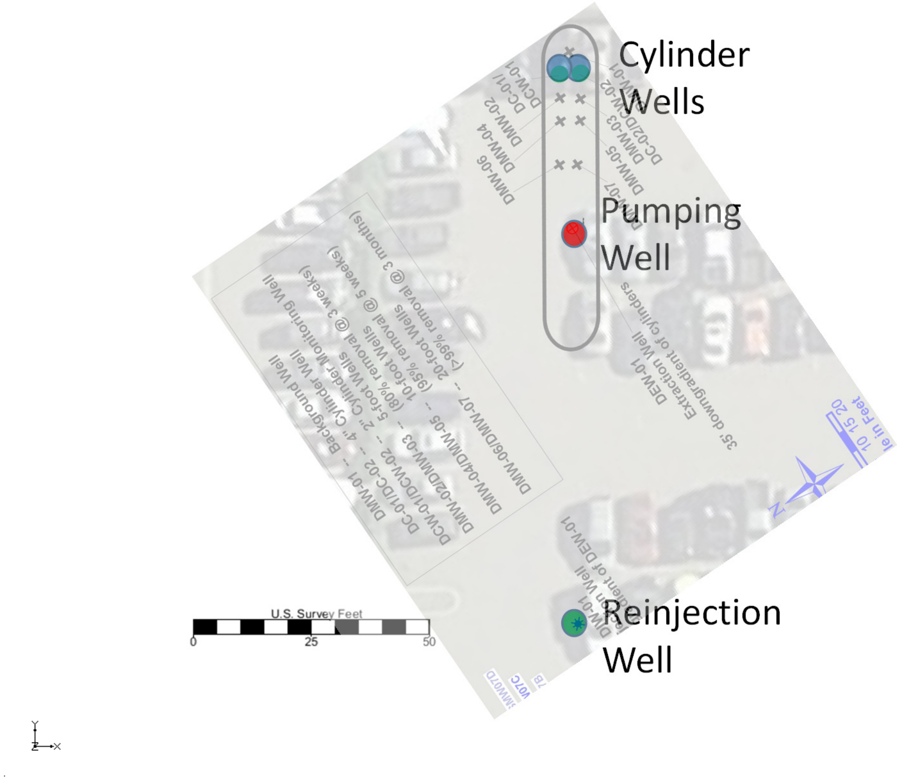


Figure A-4 – Well Structure Convergence-Divergence Zone

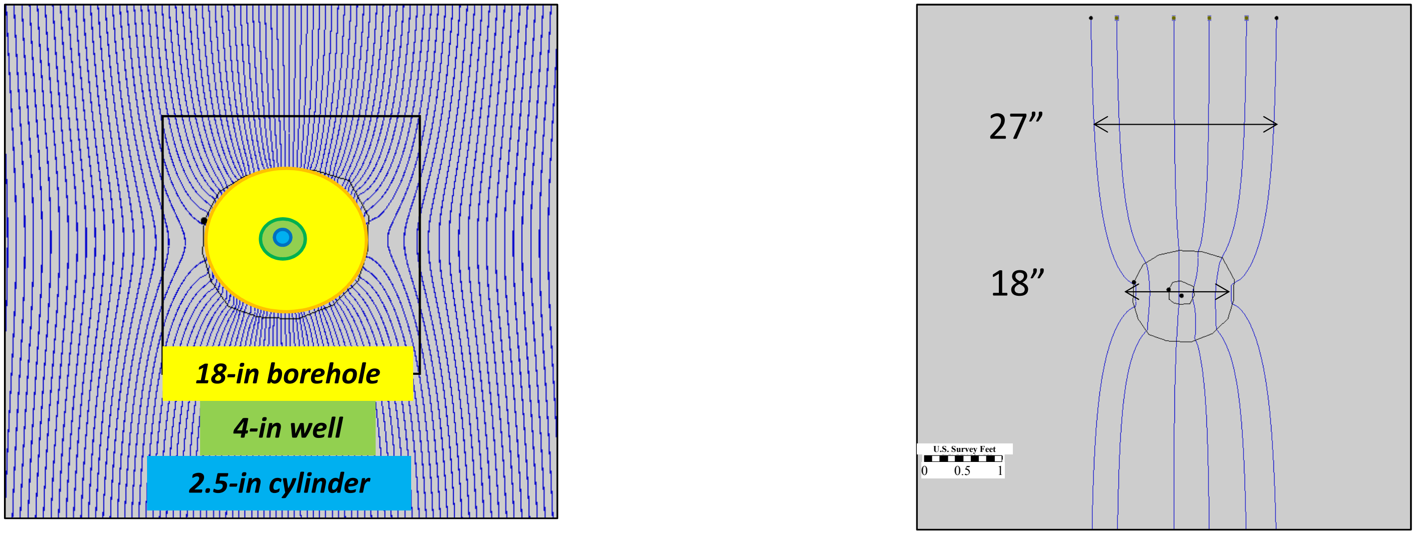


Figure A-5 – Extent of 5,000 µg/L 1,4-Dioxane Plume Assumed in Model

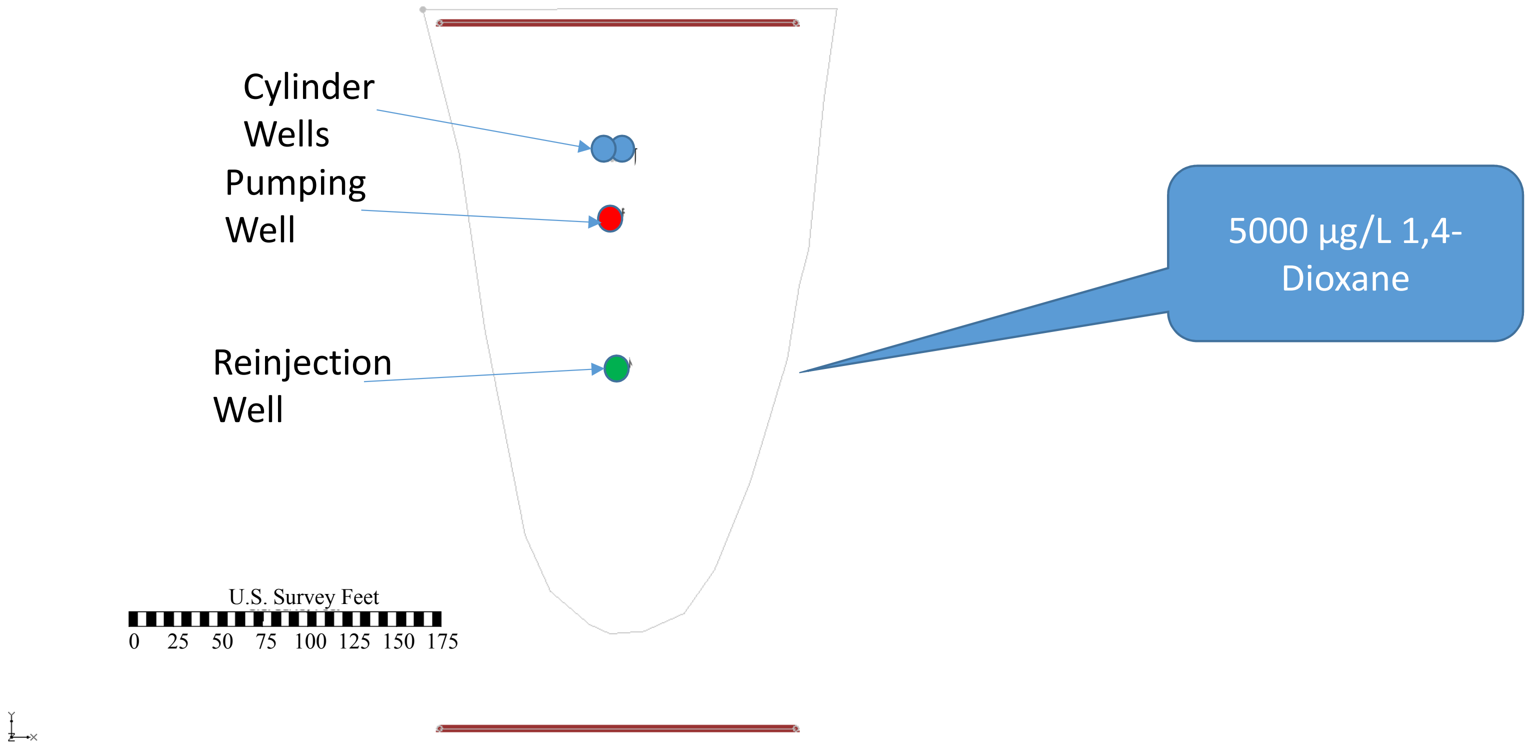


Figure A-6 – Simulated Persulfate Concentration at One Year- Passive Scenario

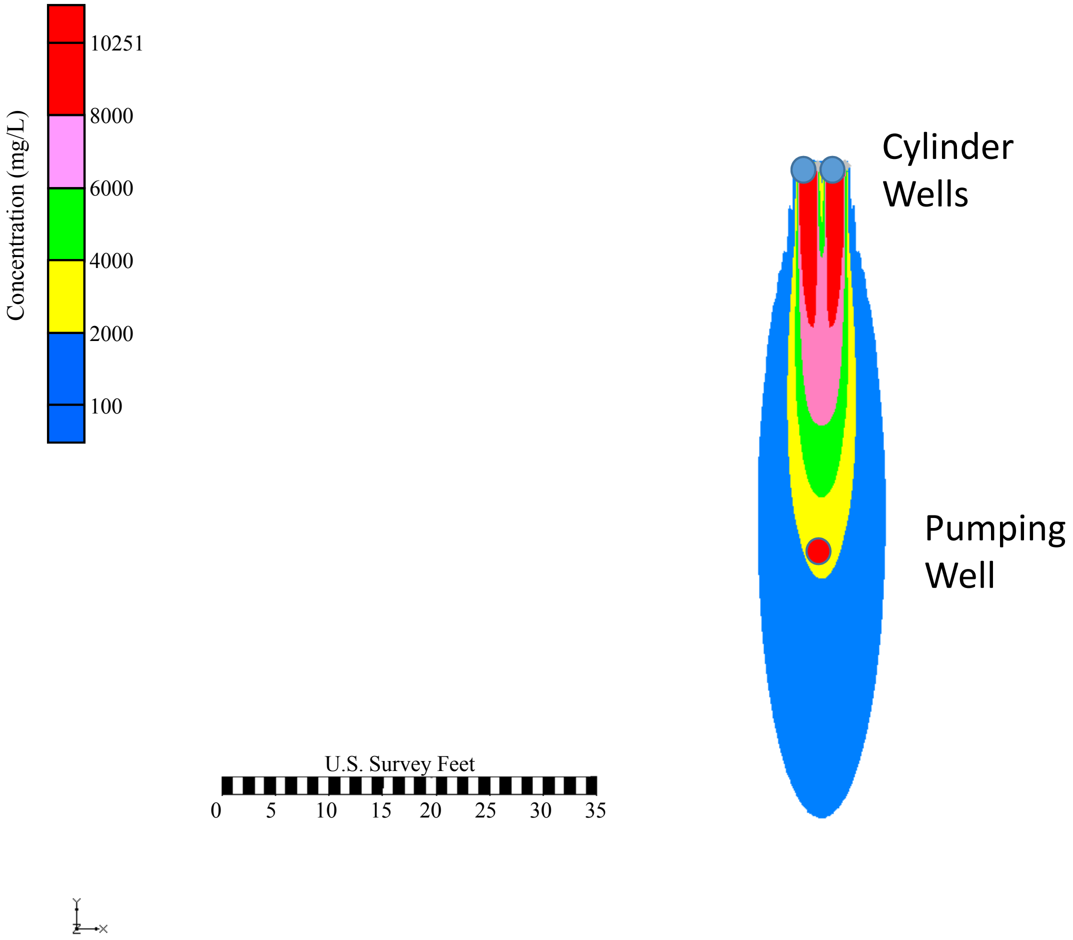


Figure A-7 – Simulated Persulfate Migration – Passive Scenario

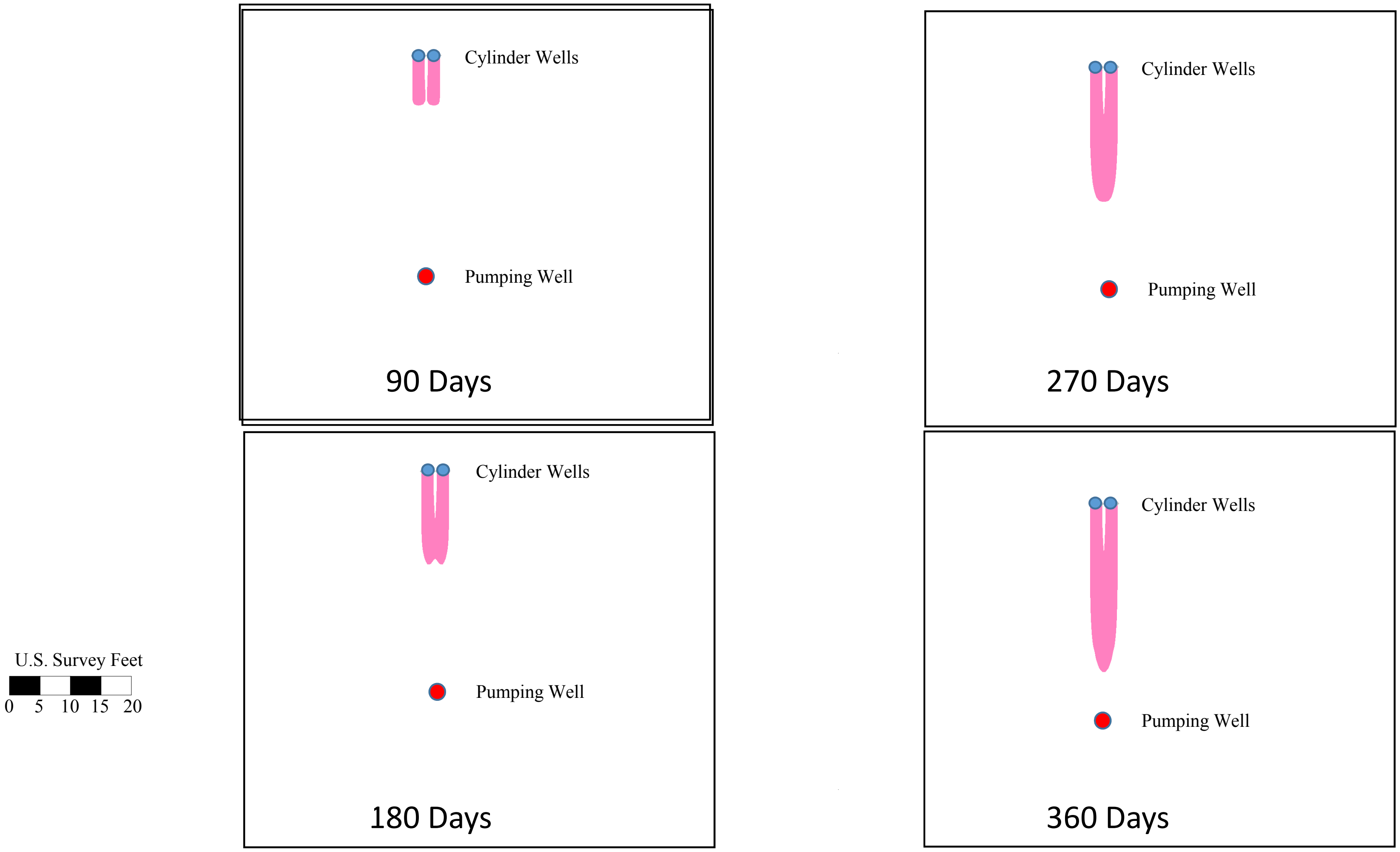


Figure A-8 - Concentration along flow pathline from source - Passive Scenario

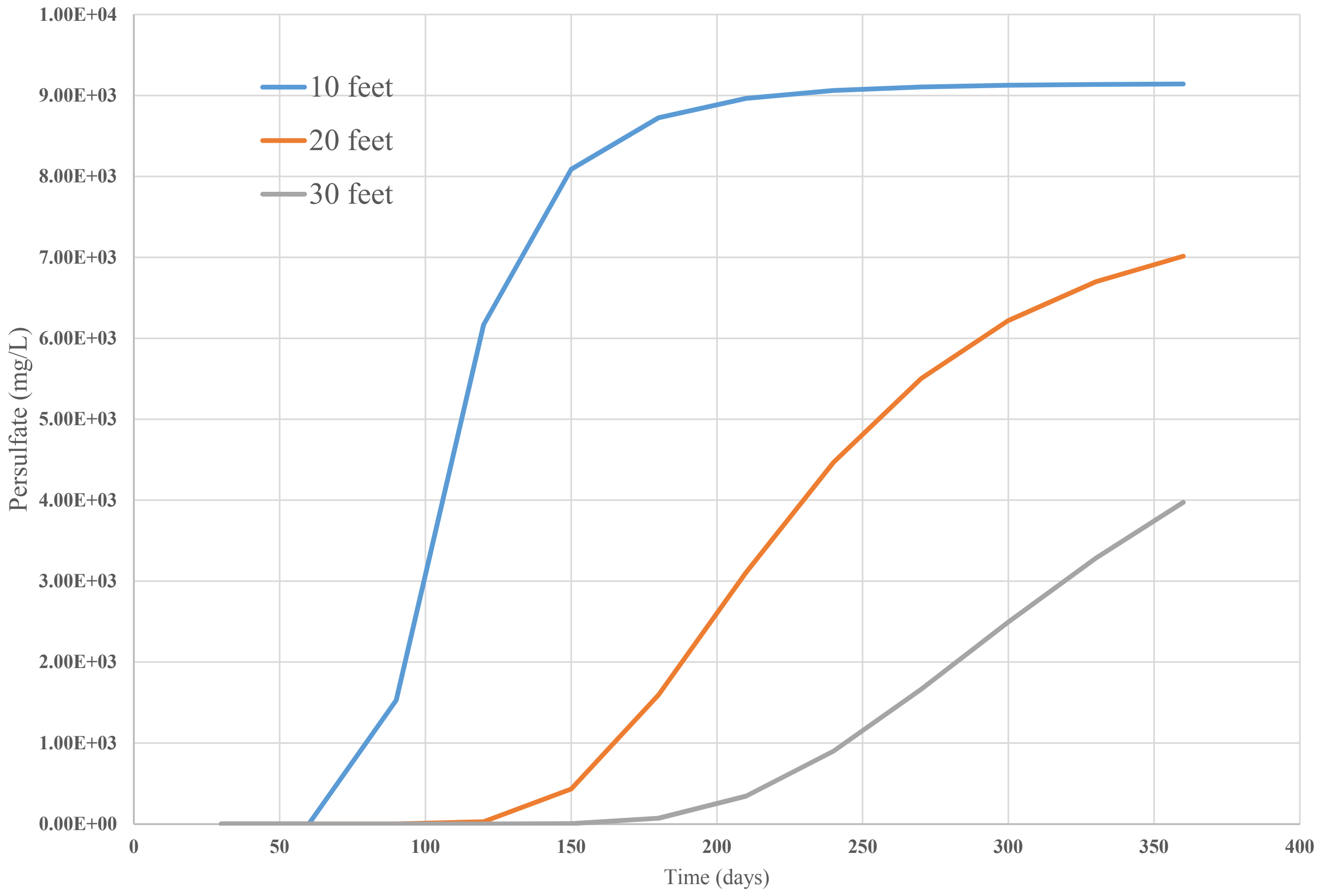


Figure A-9 - Simulated Steady-State Head

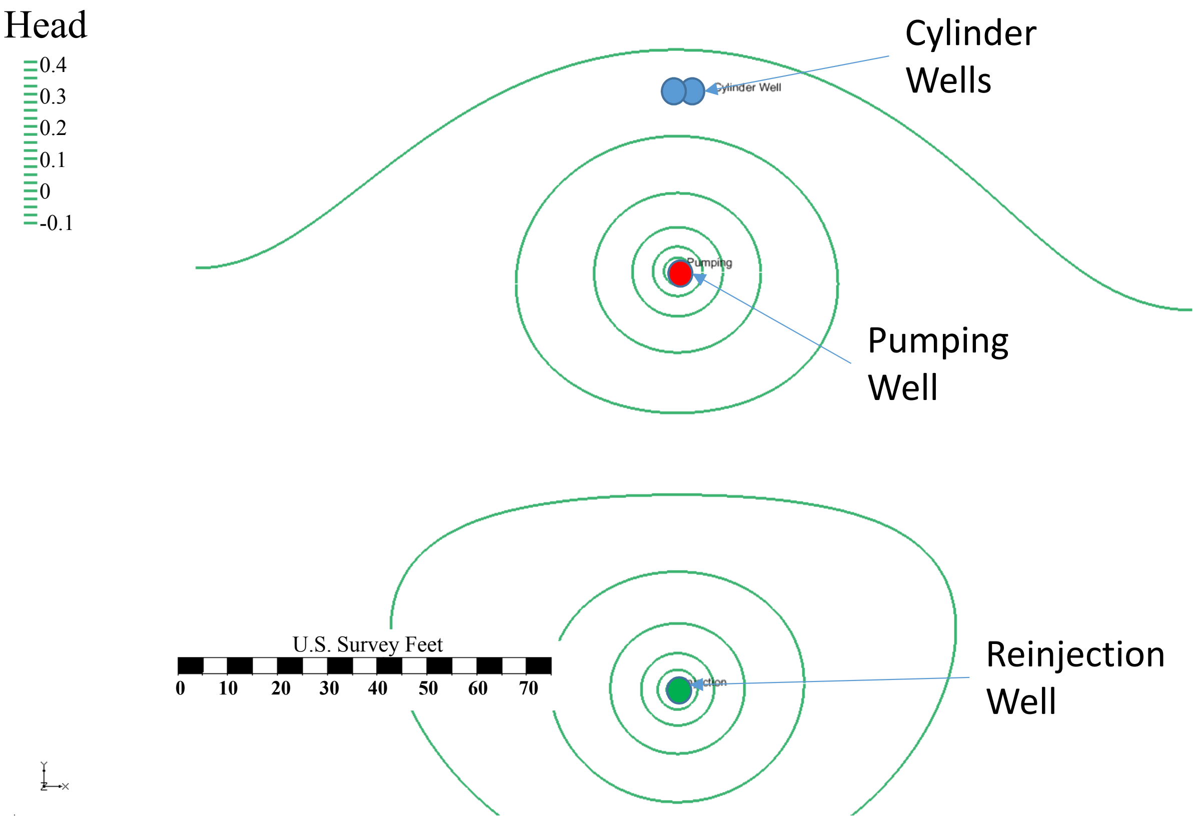


Figure A-10 - One year capture zone at pumping well

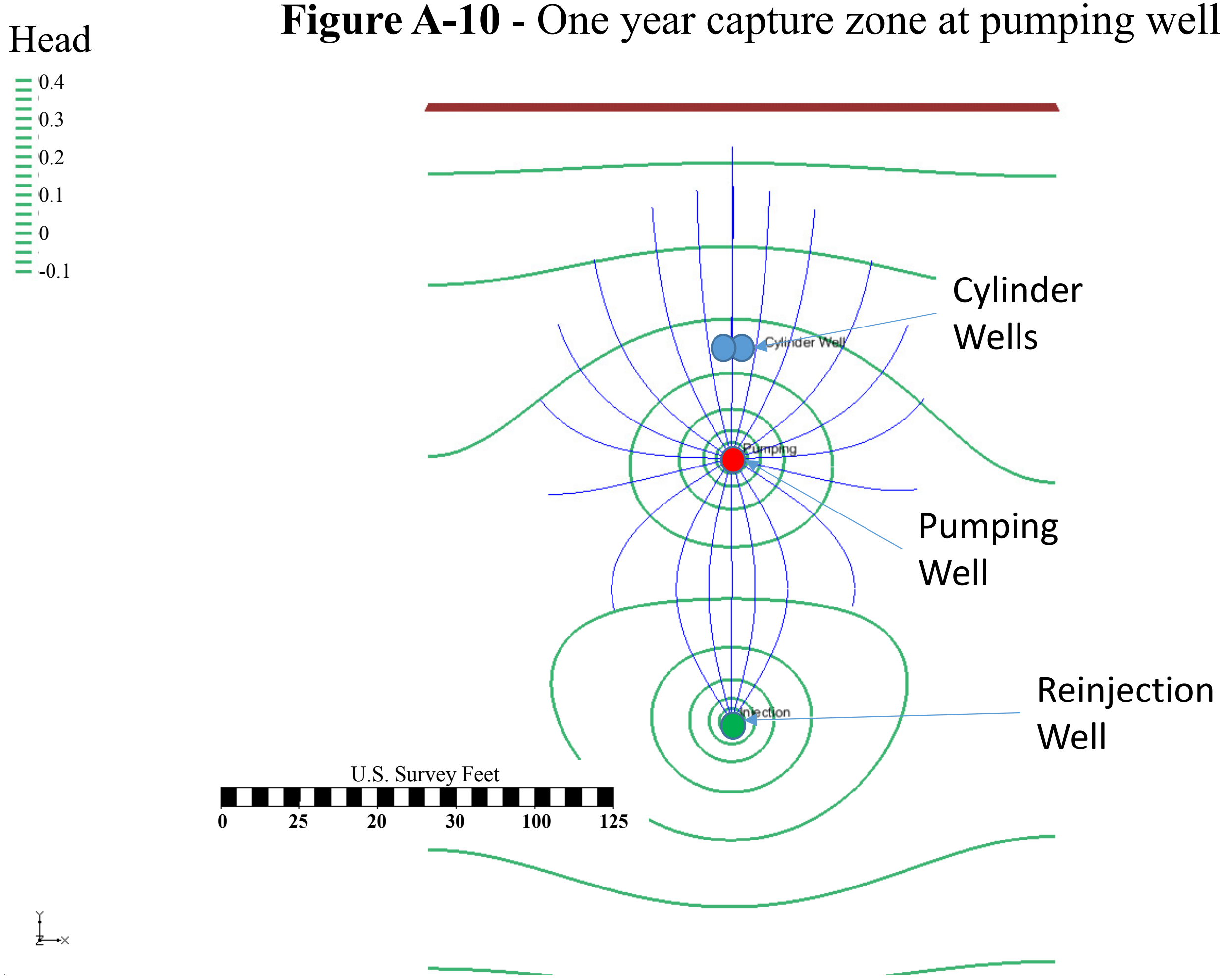


Figure A-11 - One year travel time – Injection well

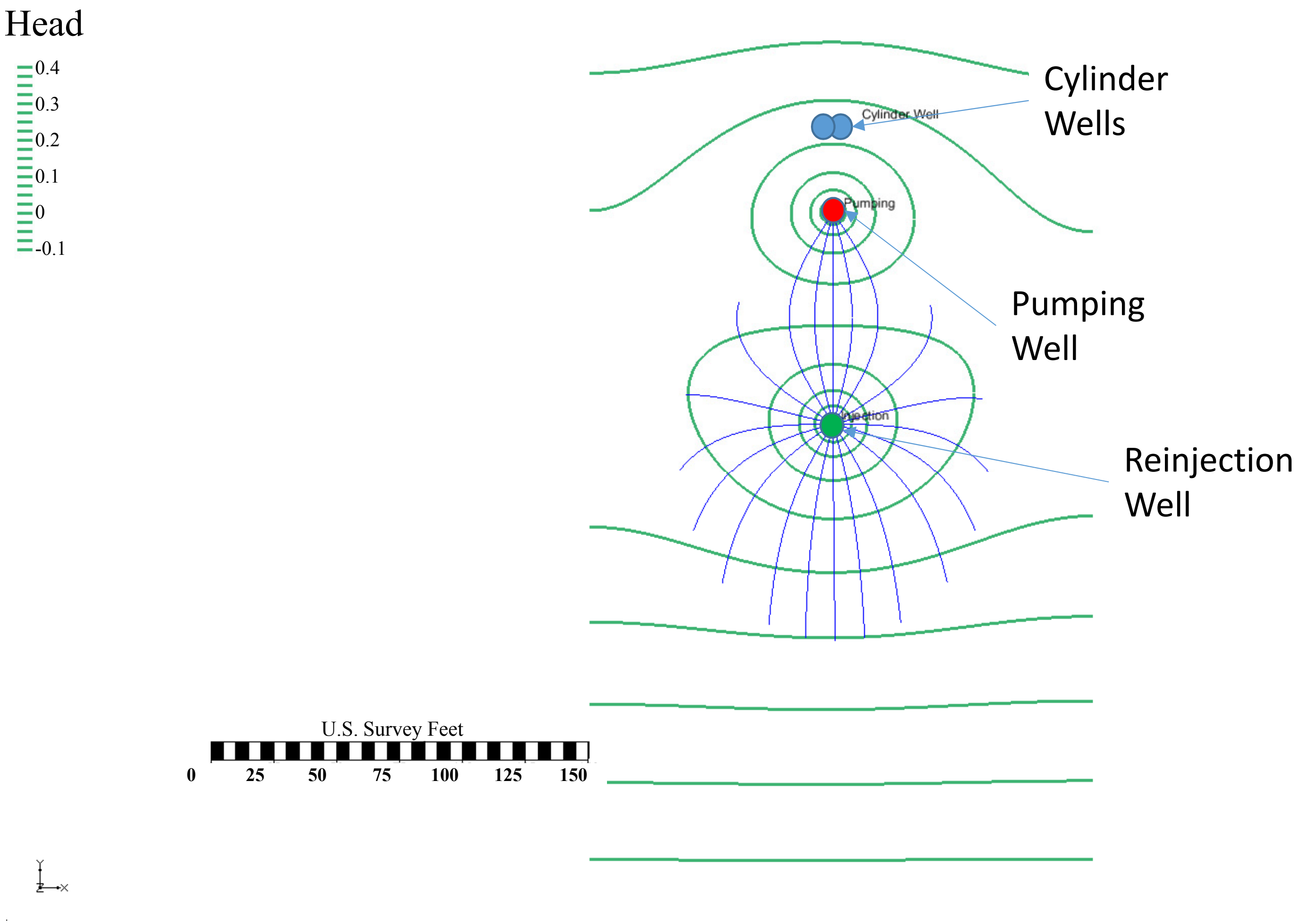


Figure A-12 - Simulated Persulfate Concentration at Pumping and Injection Wells

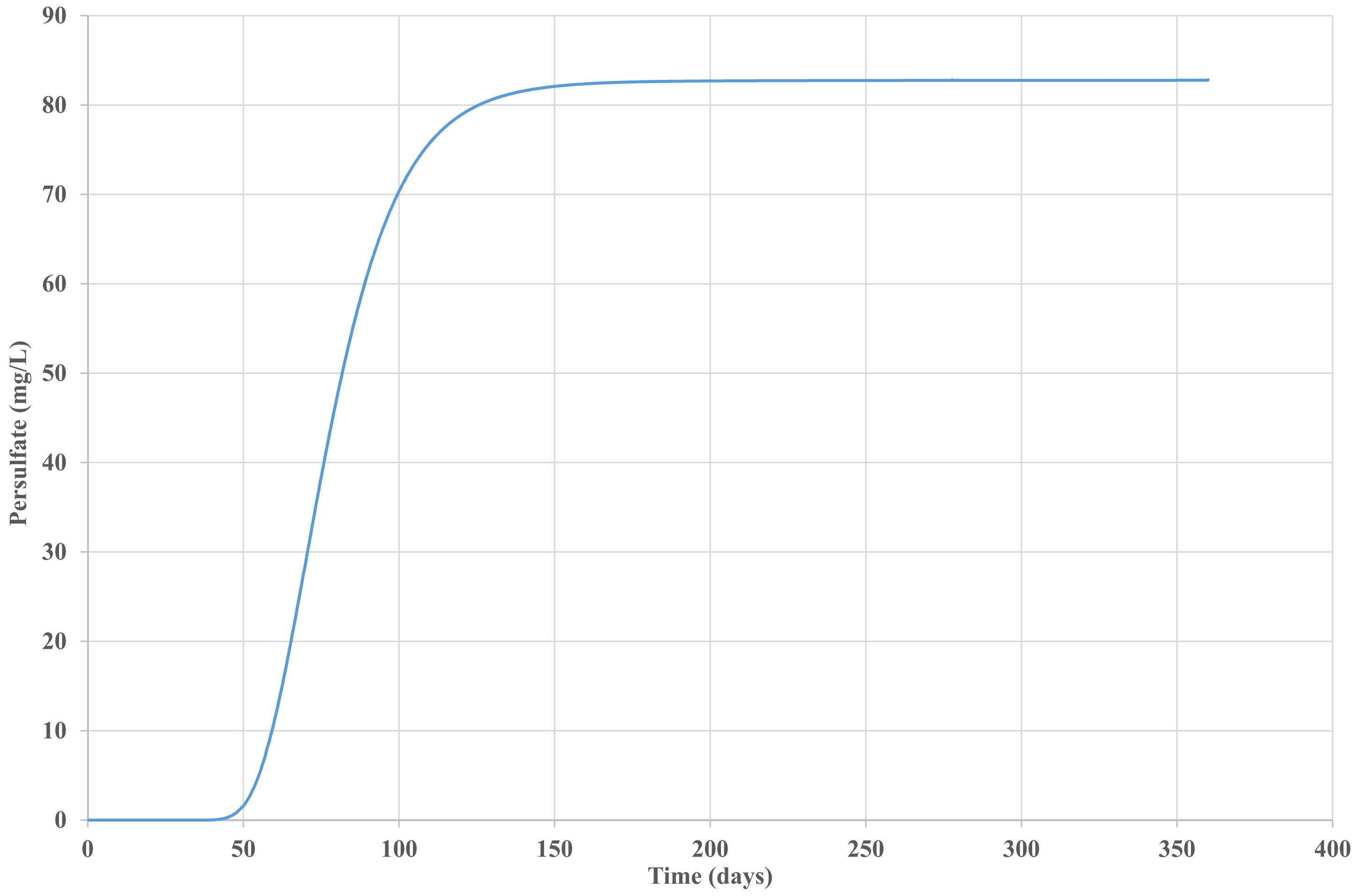


Figure A-13 – Distribution of Persulfate – Active Scenario

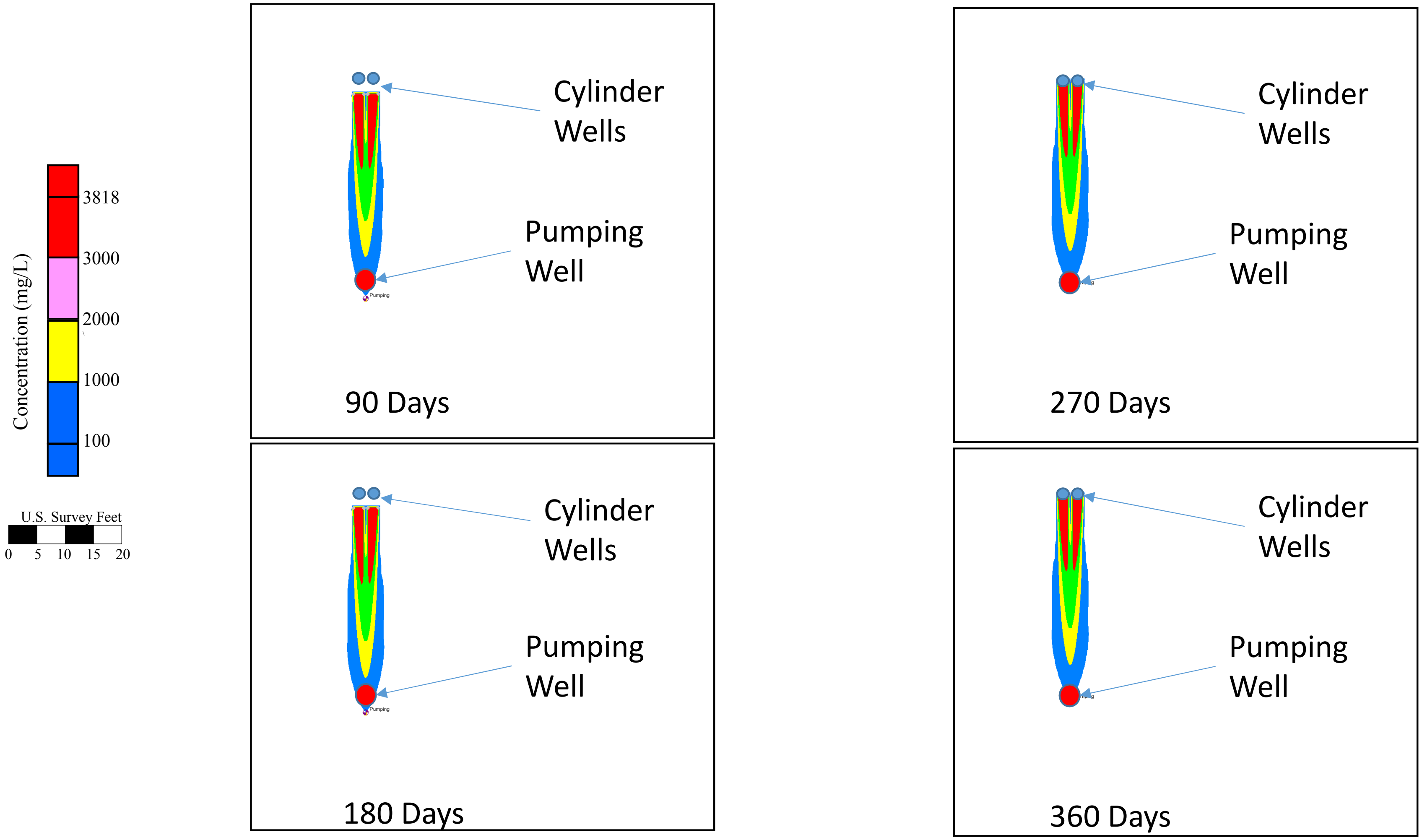


Figure A-14 - Concentration along flow pathline from source - Active Scenario

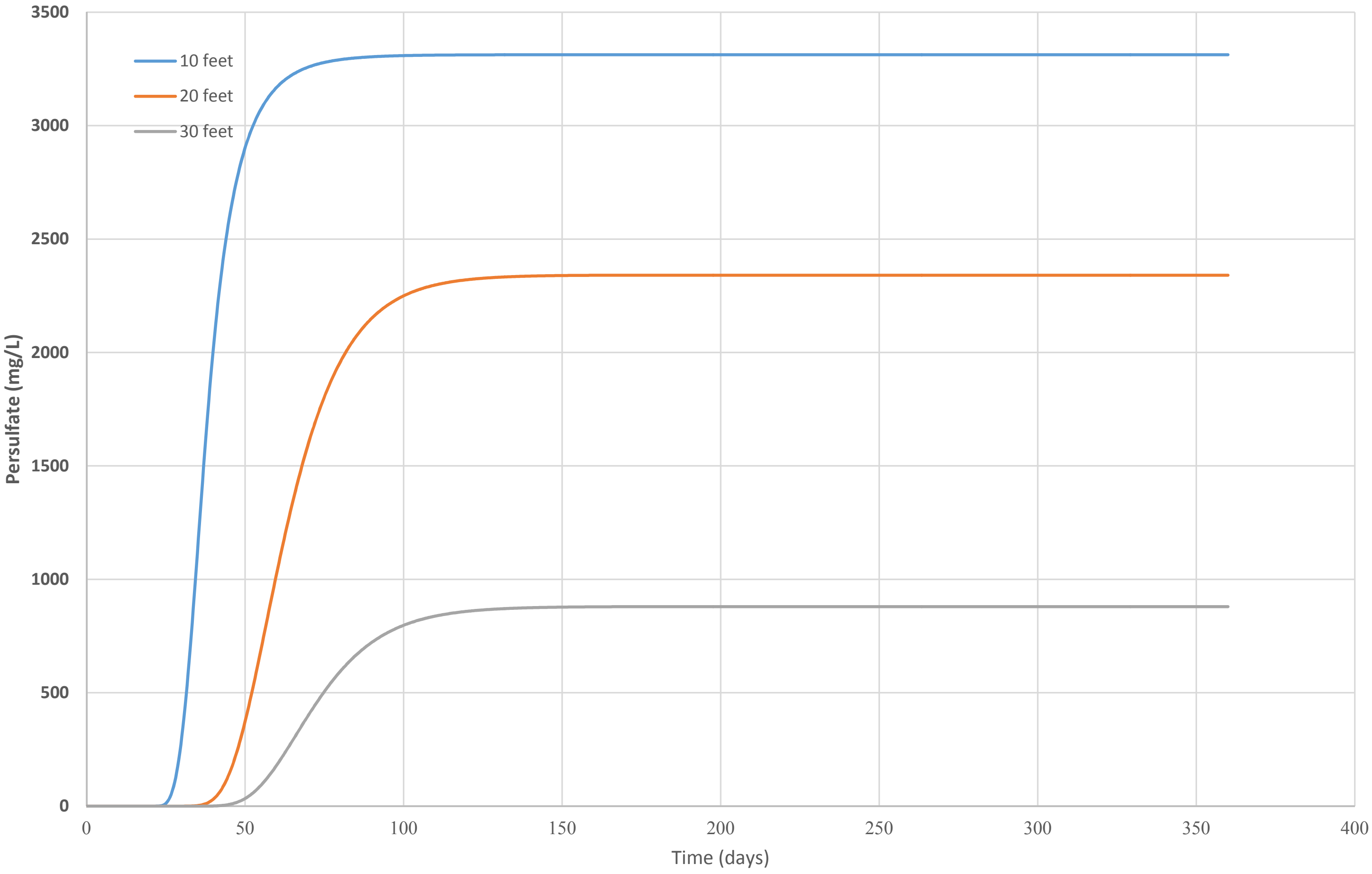
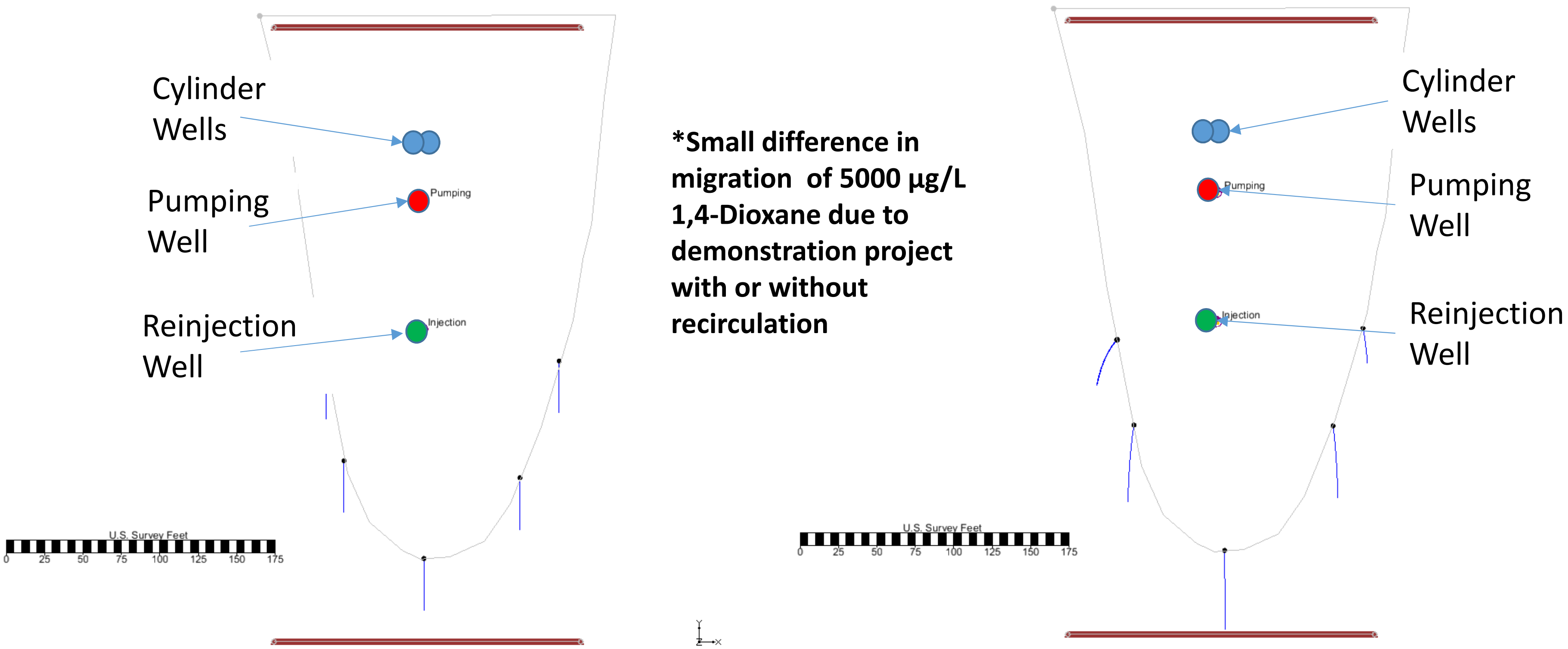


Figure A-15 - Comparison of Particle Path for One Year with and without the injection



***Small difference in migration of 5000 µg/L 1,4-Dioxane due to demonstration project with or without recirculation**

No injection

With Injection

Appendix B

Oxidant Release Design Tool Details

GREEN cells = user must enter or choose values
YELLOW cells = output relevant to system design

Oxidant Release	Value	
Cylinder Diameter (inches)	2.50	
Release Rate per cylinder area (mg/cm^2-d)	10	Based on experimental data; value ranges 10-20
Release Rate (mg/d)	9114	
Change out time (days)	185	Time when all oxidant has been released, with 0.9 safety factor

Site Characteristics	Value	
Contaminant	1,4 Dioxane	
Contaminant concentration (µg/L)	6000	
Contaminant 2nd order reaction rate (L/mmol-d)	3.97E-03	From literature or from treatability tests; Values measured in limited treatability tests wit
Hydraulic gradient	0.00145	
Hydraulic conductivity (cm/s)	0.006138333	
Hydraulic conductivity (cm/d)	530.352	
Porosity	0.1	
Groundwater seepage velocity (cm/d)	7.69E+00	
Estimated dispersion factor: **NOTE - unless engineering design promotes dispersion, value entered should be zero**	1.00	Enter value ranging from 0 (no dispersion) to 1 (persulfate is completely distributed betwe
Natural oxidant demand rate - 2nd order (L/mmol-d)	0.0001	From treatability tests; guidance: 0.001 = low rate, 0.01 = moderate rate, 0.1 = high rate;

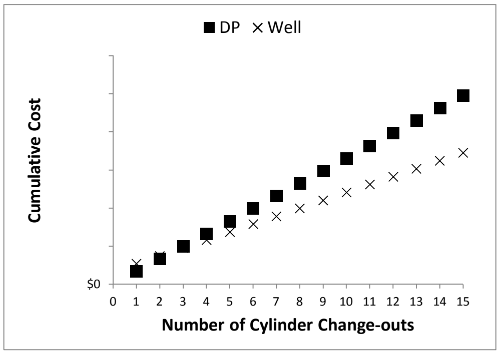
Contamination	Value	
Top of contaminated zone (feet bgs)	25	
Bottom of contaminated zone (feet bgs)	40	
Width of contamination or reactive-zone (feet)	2.25	Perpendicular to flow of groundwater
Length of contamination or reactive-zone (feet)	40	Parallel to flow of groundwater
Volume of contamined zone (cubic feet)	1350	

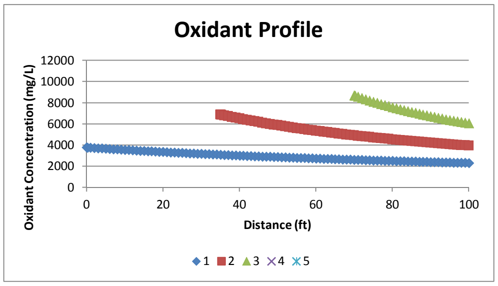
Treatment Goal	Contaminant % Reduction	Select from dropdown menu
EPA MCLs (µg/L)	6.1	N/A will appear if "other" contaminant is selected in Cell C11
Specific Contaminant % Reduction	75	Enter value between 0-100
Other specified final concentration (µg/L)	1000	
Desired final concentration (µg/L)	1500	N/A will appear if "other" contaminant is selected in Cell C11 AND "EPA MCL or Recomme

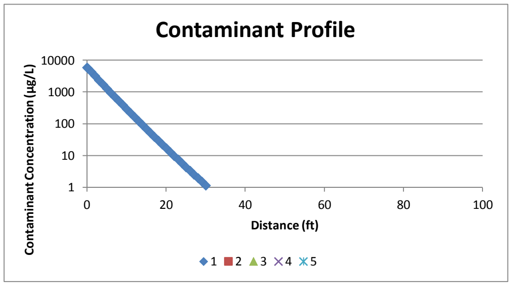
Design Specifications	Value	
Desired distance by which goal is to be achieved (ft)	35	Must be whole numbers ≤ 1000
Travel time to reach target distance from first row of cylinders (days)	139	
Travel time to reach target distance from first row of cylinders (years)	0.4	
Number of rows of cylinders to test (in direction of flow)	1	Select from dropdown menu; Up to 25 rows can be selected and evaluate
Distance between rows (ft)	35	Rows are assumed to be equally spaced
Travel time between rows (days)	139	

Design Parameters	Value	
Time to reach target concentration (days)	16	
Distance from first row of cylinders where target is reached (ft)	4	
Does calculated distance where target is reached meet goal?	YES	If response is NO, select a greater number of cylinders
Number of cylinder changouts to achieve goal at target distance	0	"N/A" (not applicable) will display if goal is not met with selected # rows
Number of cylinders in direction of flow	1	
Maximum number of cylinders perpendicular to flow	11	Provided to guide spacing selection below; assumes no oxidant dispersion
Desired spacing between cylinders, on center (ft)	2.25	Minimum = 0.11 ft for 1.35" cylinders or 0.21 for 2.5" cylinders; engineering features to pr
Number of cylinders perpendicular to flow	1	Values << the value provided in Cell C56 should only be used if system is engineered to pr
Number of cylinders with depth	10	
Total number of cylinders	10	

Cost	Value	**PROCEED to the "Cost Calculations" tab to enter cost data; select oxidant first**
Direct Push		
Total installation fixed costs ($)	$21,480	
Total installation daily costs ($)	$5,750	
Number of direct push points that can be made per day	5	
Number of days per installation (days)	2	
Total cost per installation and per change-out ($)	$32,980	
Wells		
Installation		
Well-drilling fixed costs ($)	$45,480	
Well-installation daily costs ($)	$1,300	
Number of wells that can be installed per day	2	
Number of days per installation (days)	1	
Total cost to install wells ($)	$53,280	
Change-out		
Number of wells that can be changed-out per day	30	
Number of days per change-out (days)	1	
Change-out fixed costs ($)	$17,980	
Change-out daily costs($)	$2,800	
Total costs per subsequent change-out ($)	$20,780	







Appendix B.1
75% Removal Estimate

GREEN cells = user must enter or choose values	
YELLOW cells = output relevant to system design	

Oxidant Release	Value	
Cylinder Diameter (inches)	2.50	
Release Rate per cylinder area (mg/cm^2-d)	10	Based on experimental data; value ranges 10-20
Release Rate (mg/d)	9114	
Change out time (days)	185	Time when all oxidant has been released, with 0.9 safety factor

Site Characteristics	Value	
Contaminant	1,4 Dioxane	
Contaminant concentration (µg/L)	6000	
Contaminant 2nd order reaction rate (L/mmol-d)	3.97E-03	From literature or from treatability tests; Values measured in limited treatability tests with
Hydraulic gradient	0.00145	
Hydraulic conductivity (cm/s)	0.006138333	
Hydraulic conductivity (cm/d)	530.352	
Porosity	0.1	
Groundwater seepage velocity (cm/d)	7.69E+00	
Estimated dispersion factor: **NOTE - unless engineering design promotes dispersion, value entered should be zero**	1.00	Enter value ranging from 0 (no dispersion) to 1 (persulfate is completely distributed betwe
Natural oxidant demand rate - 2nd order (L/mmol-d)	0.0001	From treatability tests; guidance: 0.001 = low rate, 0.01 = moderate rate, 0.1 = high rate; n

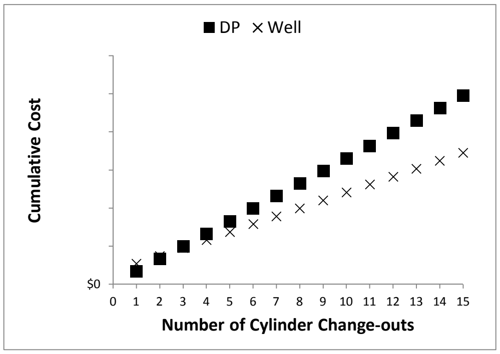
Contamination	Value	
Top of contaminated zone (feet bgs)	25	
Bottom of contaminated zone (feet bgs)	40	
Width of contamination or reactive-zone (feet)	2.25	Perpendicular to flow of groundwater
Length of contamination or reactive-zone (feet)	40	Parallel to flow of groundwater
Volume of contamined zone (cubic feet)	1350	

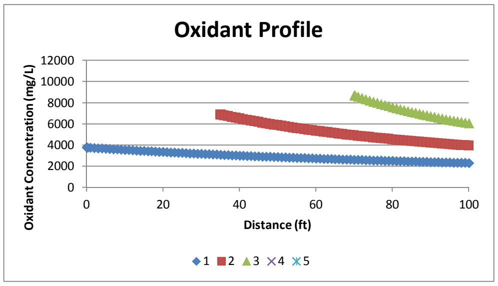
Treatment Goal	Contaminant % Reduction	Select from dropdown menu
EPA MCLs (µg/L)	6.1	N/A will appear if "other" contaminant is selected in Cell C11
Specific Contaminant % Reduction	90	Enter value between 0-100
Other specified final concentration (µg/L)	1000	
Desired final concentration (µg/L)	600	N/A will appear if "other" contaminant is selected in Cell C11 AND "EPA MCL or Recomme

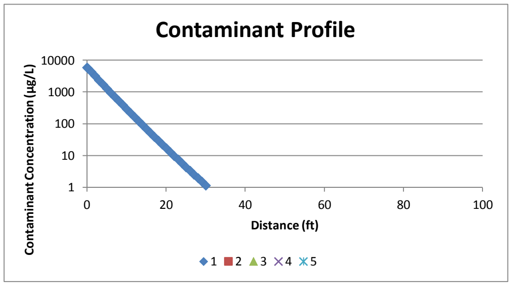
Design Specifications	Value	
Desired distance by which goal is to be achieved (ft)	35	Must be whole numbers ≤ 1000
Travel time to reach target distance from first row of cylinders (days)	139	
Travel time to reach target distance from first row of cylinders (years)	0.4	
Number of rows of cylinders to test (in direction of flow)	1	Select from dropdown menu; Up to 25 rows can be selected and evaluated
Distance between rows (ft)	35	Rows are assumed to be equally spaced
Travel time between rows (days)	139	

Design Parameters	Value	
Time to reach target concentration (days)	28	
Distance from first row of cylinders where target is reached (ft)	7	
Does calculated distance where target is reached meet goal?	YES	If response is NO, select a greater number of cylinders
Number of cylinder changouts to achieve goal at target distance	0	"N/A" (not applicable) will display if goal is not met with selected # rows
Number of cylinders in direction of flow	1	
Maximum number of cylinders perpendicular to flow	11	Provided to guide spacing selection below; assumes no oxidant dispersion
Desired spacing between cylinders, on center (ft)	2.25	Minimum = 0.11 ft for 1.35" cylinders or 0.21 for 2.5" cylinders; engineering features to pr
Number of cylinders perpendicular to flow	1	Values << the value provided in Cell C56 should only be used if system is engineered to pro
Number of cylinders with depth	10	
Total number of cylinders	10	

Cost	Value	**PROCEED to the "Cost Calculations" tab to enter cost data; select oxidant first**
Direct Push		
Total installation fixed costs ($)	$21,480	
Total installation daily costs ($)	$5,750	
Number of direct push points that can be made per day	5	
Number of days per installation (days)	2	
Total cost per installation and per change-out ($)	$32,980	
Wells		
Installation		
Well-drilling fixed costs ($)	$45,480	
Well-installation daily costs ($)	$1,300	
Number of wells that can be installed per day	2	
Number of days per installation (days)	1	
Total cost to install wells ($)	$53,280	
Change-out		
Number of wells that can be changed-out per day	30	
Number of days per change-out (days)	1	
Change-out fixed costs ($)	$17,980	
Change-out daily costs($)	$2,800	
Total costs per subsequent change-out ($)	$20,780	







Appendix B.2

90% Removal Estimate

GREEN cells = user must enter or choose values

YELLOW cells = output relevant to system design

Oxidant Release	Value	
Cylinder Diameter (inches)	2.50	
Release Rate per cylinder area (mg/cm^2-d)	10	Based on experimental data; value ranges 10-20
Release Rate (mg/d)	9114	
Change out time (days)	185	Time when all oxidant has been released, with 0.9 safety factor

Site Characteristics	Value	
Contaminant	1,4 Dioxane	
Contaminant concentration (µg/L)	6000	
Contaminant 2nd order reaction rate (L/mmol-d)	3.97E-03	From literature or from treatability tests; Values measured in limited treatability tests witl
Hydraulic gradient	0.00145	
Hydraulic conductivity (cm/s)	0.006138333	
Hydraulic conductivity (cm/d)	530.352	
Porosity	0.1	
Groundwater seepage velocity (cm/d)	7.69E+00	
Estimated dispersion factor: **NOTE - unless engineering design promotes dispersion, value entered should be zero**	1.00	Enter value ranging from 0 (no dispersion) to 1 (persulfate is completely distributed betwe
Natural oxidant demand rate - 2nd order (L/mmol-d)	0.0001	From treatability tests; guidance: 0.001 = low rate, 0.01 = moderate rate, 0.1 = high rate; n

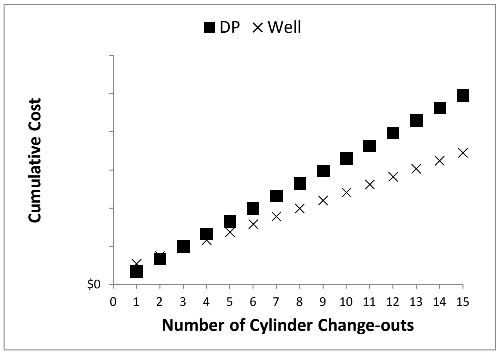
Contamination	Value	
Top of contaminated zone (feet bgs)	25	
Bottom of contaminated zone (feet bgs)	40	
Width of contamination or reactive-zone (feet)	2.25	Perpendicular to flow of groundwater
Length of contamination or reactive-zone (feet)	40	Parallel to flow of groundwater
Volume of contamined zone (cubic feet)	1350	

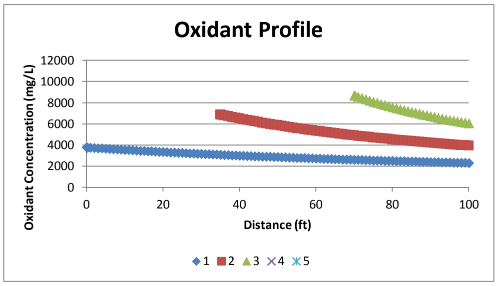
Treatment Goal	Contaminant % Reduction	Select from dropdown menu
EPA MCLs (µg/L)	6.1	N/A will appear if "other" contaminant is selected in Cell C11
Specific Contaminant % Reduction	99	Enter value between 0-100
Other specified final concentration (µg/L)	1000	
Desired final concentration (µg/L)	60	N/A will appear if "other" contaminant is selected in Cell C11 AND "EPA MCL or Recommer

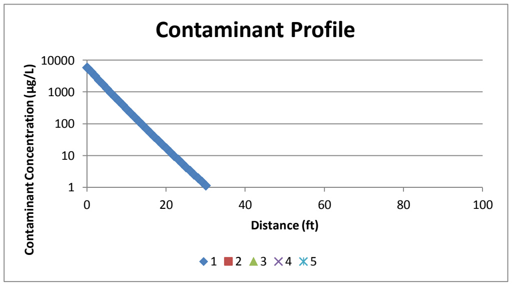
Design Specifications	Value	
Desired distance by which goal is to be achieved (ft)	35	Must be whole numbers ≤ 1000
Travel time to reach target distance from first row of cylinders (days)	139	
Travel time to reach target distance from first row of cylinders (years)	0.4	
Number of rows of cylinders to test (in direction of flow)	1	Select from dropdown menu; Up to 25 rows can be selected and evaluatec
Distance between rows (ft)	35	Rows are assumed to be equally spaced
Travel time between rows (days)	139	

Design Parameters	Value	
Time to reach target concentration (days)	59	
Distance from first row of cylinders where target is reached (ft)	15	
Does calculated distance where target is reached meet goal?	YES	If response is NO, select a greater number of cylinders
Number of cylinder changouts to achieve goal at target distance	0	"N/A" (not applicable) will display if goal is not met with selected # rows
Number of cylinders in direction of flow	1	
Maximum number of cylinders perpendicular to flow	11	Provided to guide spacing selection below; assumes no oxidant dispersion
Desired spacing between cylinders, on center (ft)	2.25	Minimum = 0.11 ft for 1.35" cylinders or 0.21 for 2.5" cylinders; engineering features to pr
Number of cylinders perpendicular to flow	1	Values << the value provided in Cell C56 should only be used if system is engineered to prc
Number of cylinders with depth	10	
Total number of cylinders	10	

Cost	Value	**PROCEED to the "Cost Calculations" tab to enter cost data; select oxidant first**
Direct Push		
Total installation fixed costs ($)	$21,480	
Total installation daily costs ($)	$5,750	
Number of direct push points that can be made per day	5	
Number of days per installation (days)	2	
Total cost per installation and per change-out ($)	$32,980	
Wells		
Installation		
Well-drilling fixed costs ($)	$45,480	
Well-installation daily costs ($)	$1,300	
Number of wells that can be installed per day	2	
Number of days per installation (days)	1	
Total cost to install wells ($)	$53,280	
Change-out		
Number of wells that can be changed-out per day	30	
Number of days per change-out (days)	1	
Change-out fixed costs ($)	$17,980	
Change-out daily costs($)	$2,800	
Total costs per subsequent change-out ($)	$20,780	







Appendix B.3

99% Removal Estimate

GREEN cells = user must enter or choose values
YELLOW cells = output relevant to system design

Oxidant Release	Value	
Cylinder Diameter (inches)	2.50	
Release Rate per cylinder area (mg/cm^2-d)	10	Based on experimental data; value ranges 10-20
Release Rate (mg/d)	9114	
Change out time (days)	185	Time when all oxidant has been released, with 0.9 safety factor

Site Characteristics	Value	
Contaminant	1,4 Dioxane	
Contaminant concentration (µg/L)	6000	
Contaminant 2nd order reaction rate (L/mmol-d)	3.97E-03	From literature or from treatability tests; Values measured in limited treatability tests wit
Hydraulic gradient	0.00145	
Hydraulic conductivity (cm/s)	0.006138333	
Hydraulic conductivity (cm/d)	530.352	
Porosity	0.1	
Groundwater seepage velocity (cm/d)	7.69E+00	
Estimated dispersion factor: **NOTE - unless engineering design promotes dispersion, value entered should be zero**	1.00	Enter value ranging from 0 (no dispersion) to 1 (persulfate is completely distributed betwe
Natural oxidant demand rate - 2nd order (L/mmol-d)	0.0001	From treatability tests; guidance: 0.001 = low rate, 0.01 = moderate rate, 0.1 = high rate;

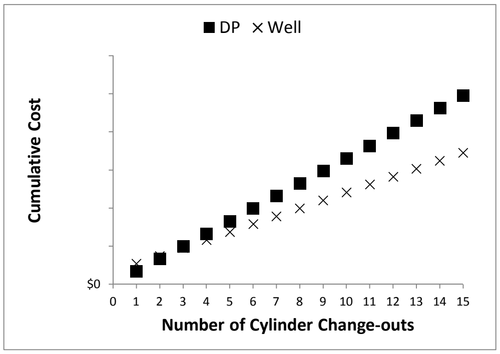
Contamination	Value	
Top of contaminated zone (feet bgs)	25	
Bottom of contaminated zone (feet bgs)	40	
Width of contamination or reactive-zone (feet)	2.25	Perpendicular to flow of groundwater
Length of contamination or reactive-zone (feet)	40	Parallel to flow of groundwater
Volume of contamined zone (cubic feet)	1350	

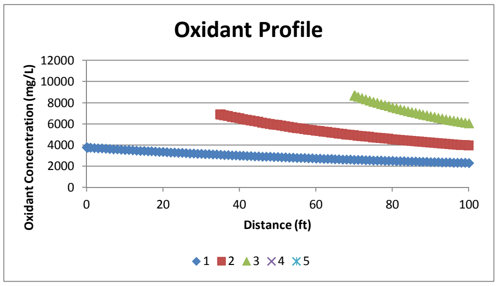
Treatment Goal	Contaminant % Reduction	Select from dropdown menu
EPA MCLs (µg/L)	6.1	N/A will appear if "other" contaminant is selected in Cell C11
Specific Contaminant % Reduction	99.9	Enter value between 0-100
Other specified final concentration (µg/L)	1000	
Desired final concentration (µg/L)	6	N/A will appear if "other" contaminant is selected in Cell C11 AND "EPA MCL or Recomme

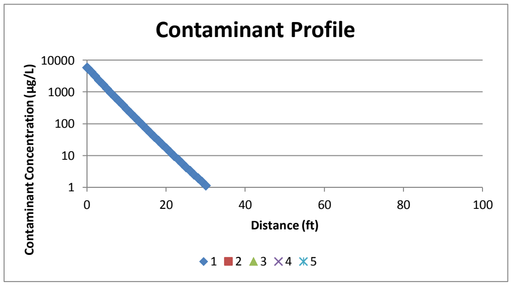
Design Specifications	Value	
Desired distance by which goal is to be achieved (ft)	35	Must be whole numbers ≤ 1000
Travel time to reach target distance from first row of cylinders (days)	139	
Travel time to reach target distance from first row of cylinders (years)	0.4	
Number of rows of cylinders to test (in direction of flow)	1	Select from dropdown menu; Up to 25 rows can be selected and evaluate
Distance between rows (ft)	35	Rows are assumed to be equally spaced
Travel time between rows (days)	139	

Design Parameters	Value	
Time to reach target concentration (days)	91	
Distance from first row of cylinders where target is reached (ft)	23	
Does calculated distance where target is reached meet goal?	YES	If response is NO, select a greater number of cylinders
Number of cylinder changouts to achieve goal at target distance	0	"N/A" (not applicable) will display if goal is not met with selected # rows
Number of cylinders in direction of flow	1	
Maximum number of cylinders perpendicular to flow	11	Provided to guide spacing selection below; assumes no oxidant dispersion
Desired spacing between cylinders, on center (ft)	2.25	Minimum = 0.11 ft for 1.35" cylinders or 0.21 for 2.5" cylinders; engineering features to pr
Number of cylinders perpendicular to flow	1	Values << the value provided in Cell C56 should only be used if system is engineered to pr
Number of cylinders with depth	10	
Total number of cylinders	10	

Cost	Value	**PROCEED to the "Cost Calculations" tab to enter cost data; select oxidant first**
Direct Push		
Total installation fixed costs ($)	$21,480	
Total installation daily costs ($)	$5,750	
Number of direct push points that can be made per day	5	
Number of days per installation (days)	2	
Total cost per installation and per change-out ($)	$32,980	
Wells		
Installation		
Well-drilling fixed costs ($)	$45,480	
Well-installation daily costs ($)	$1,300	
Number of wells that can be installed per day	2	
Number of days per installation (days)	1	
Total cost to install wells ($)	$53,280	
Change-out		
Number of wells that can be changed-out per day	30	
Number of days per change-out (days)	1	
Change-out fixed costs ($)	$17,980	
Change-out daily costs($)	$2,800	
Total costs per subsequent change-out ($)	$20,780	







Appendix B.4
99.9% Removal Estimate

Appendix C

Design Calculations

Appendix C-1

Tracer Calculations

✌
Client: ESTCP
Project:________________
Detail: Check analytical calculation for a strip source

Job #:____________________
CHK By/Date:_____________
RVW By/Date:_____________

Calc By: M J Smith
Date: 10/17/2014
Calc #:_________________

Tracer Test Design

1.0 Purpose/Objective

Calculate inlet tracer concentration to ensure it is detectable above the 500 mg/L chloride background. Use analytical solution for a strip source in uniform flow field

2.0 Procedure

TWRI 3-B7

$$A(x,y,Y_1,Y_2,t)=\frac{x}{4\sqrt{\pi D_x}}\exp\left(\frac{Vx}{2D_x}\right)\int_0^t \tau^{-\frac{3}{2}}$$

$$\exp\left[\frac{-x^2}{4D_x\tau}-\frac{V^2\tau}{4D_x}\right]\cdot\left\{\operatorname{erfc}\left[\frac{Y_1-y}{2\sqrt{D_y\tau}}\right]\right.$$

$$\left.-\operatorname{erfc}\left[\frac{Y_2-y}{2\sqrt{D_y\tau}}\right]\right\}d\tau,$$

x, y coordinates of the point to calculate concentration

Y1 , Y2 coordinates of the strip source

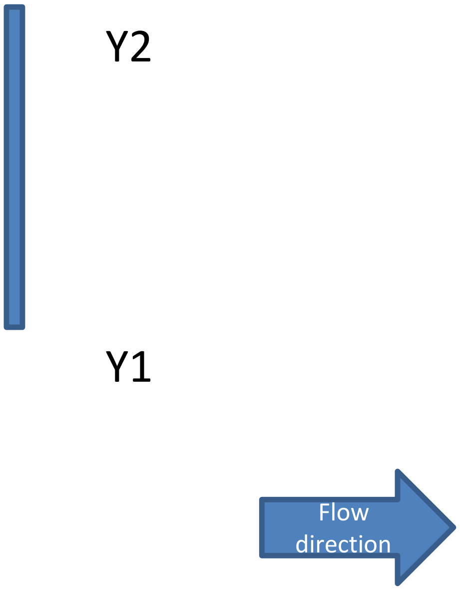
t time at which concentration is calculated since release started

Dx dispersion in x longitudinal direction (αL * v)
Dy dispersion in y transverse direction (αt * v)
v particle velocity (darcy velocity/effective porosity)
τ integration dummy variable

if velocities are extremely low, then diffusion must also be included in the dispersion term.

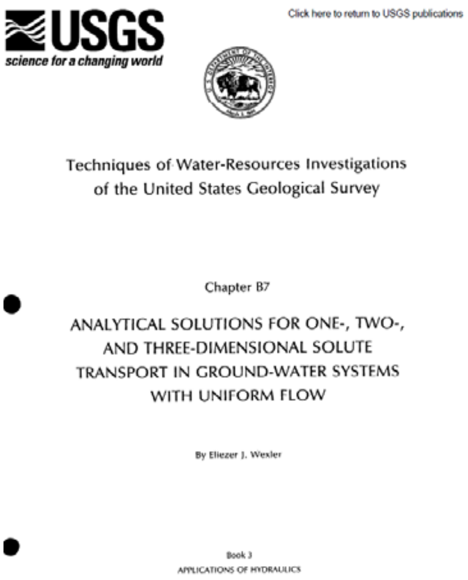
This is an closed form analytical solution for a strip source located at the left boundary of a flow domain, with constant groundwater velocity. The width of the source is specified by the Y coordinate defining the endpoints of the strip source. The strip source is located at coordinate X = 0.

Strip source with constant concentration



3.0 References/Data Sources

Source of solution is:



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Techniques of Water-Resources Investigations
of the United States Geological Survey

Chapter B7

ANALYTICAL SOLUTIONS FOR ONE-, TWO-,
AND THREE-DIMENSIONAL SOLUTE
TRANSPORT IN GROUND-WATER SYSTEMS
WITH UNIFORM FLOW

By Eliezer J. Wexler

Book 3
APPLICATIONS OF HYDRAULICS

For dispersivity calculation:

Xu, M, and Eckstein, Y., 1995, Use of Weighted Least-Squares Method in Evaluation of hte Relationship between Dispersivity and Field Scale, Ground Water, Vol. 33, No. 6, pp 905 - 908

Following is a plot from the paper showing the data and various relationships. Equation 12b is the best description and is widely used in the literature.

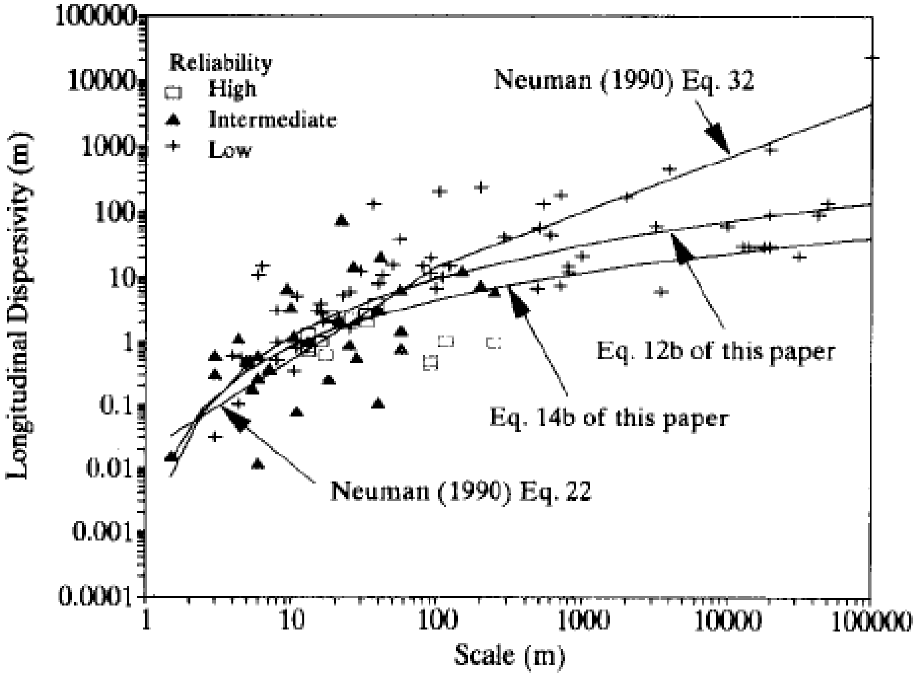


Fig. 1. Comparison of different regressions.

Equation 12b from paper (note this is units specific to meters)

$$\alpha_L = 1.20\,(\log_{10} L)^{2.958} \qquad \text{for 1:1:1 scheme} \qquad (12b)$$

4.0 Assumptions

This solution assume uniform flow in a homogenous 2-D aquifer of infinite lateral extent. A constant concentration source is present at the inflow boundary, with flow parallel to the X coordinate axis.

5.0 Calculations

Define the variables

Assume worst case dispersivity

Use midpoint of 40-ft maximum plume length

$$\text{Mid\_Plume\_length} := 20 \cdot \text{ft}$$

Longitudinal Dispersivity

$$\alpha_L := 1.2 \cdot \text{m} \cdot \left(\log\left(\frac{\text{Mid\_Plume\_length}}{\text{m}} \right)^{2.958} \right) = 1.9243 \cdot \text{ft}$$

Transverse dispersivity $\alpha_T := 0.12 \cdot \text{ft}$

Hydraulic conductivity $k := 17.43 \cdot \frac{\text{ft}}{\text{day}}$

Hydraulic gradient $i := .000714$

Effective porosity $\theta_e := 0.1$

Particle velocity $v := \frac{k \cdot i}{\theta_e} = 0.1245 \cdot \frac{\text{ft}}{\text{day}}$

Diffusion coefficient - inorganic chemical (HCO3 as surrogate) $Dd := 11.8 \cdot 10^{-6} \cdot \frac{\text{cm}^2}{\text{sec}}$

Longitudinal Dispersion Coefficient

$$D_L := \alpha_L \cdot v + Dd$$

Transverse Dispersion Coefficient

$$D_T := \alpha_T \cdot v + Dd$$

monitor location $x := 25 \cdot \text{ft}$ $y := 25 \cdot \text{ft}$

time for calculation $t := 10 \cdot \text{day}$

location of source on boundary $Y1 := 24 \cdot \text{ft}$ $Y2 := (Y1) + 27 \cdot \text{in}$

$C_i := 10000 \cdot \frac{\text{mg}}{\text{L}}$

Analytical solution function (allow specification of time and location of calculation point, remaining variable defined above)

$$\text{conc}(x, y, t) := C_i \cdot \frac{x}{4 \cdot \sqrt{\pi \cdot D_L}} \cdot e^{\frac{v \cdot x}{2 \cdot D_L}} \cdot \int_0^t \tau^{\frac{-3}{2}} \cdot e^{\left(\frac{-x^2}{4 \cdot D_L \cdot \tau} - \frac{v^2 \cdot \tau}{4 \cdot D_L}\right)} \cdot \left(\text{erfc}\left(\frac{Y1 - y}{2 \cdot \sqrt{D_T \cdot \tau}}\right) - \text{erfc}\left(\frac{Y2 - y}{2 \cdot \sqrt{D_T \cdot \tau}}\right)\right) d\tau$$

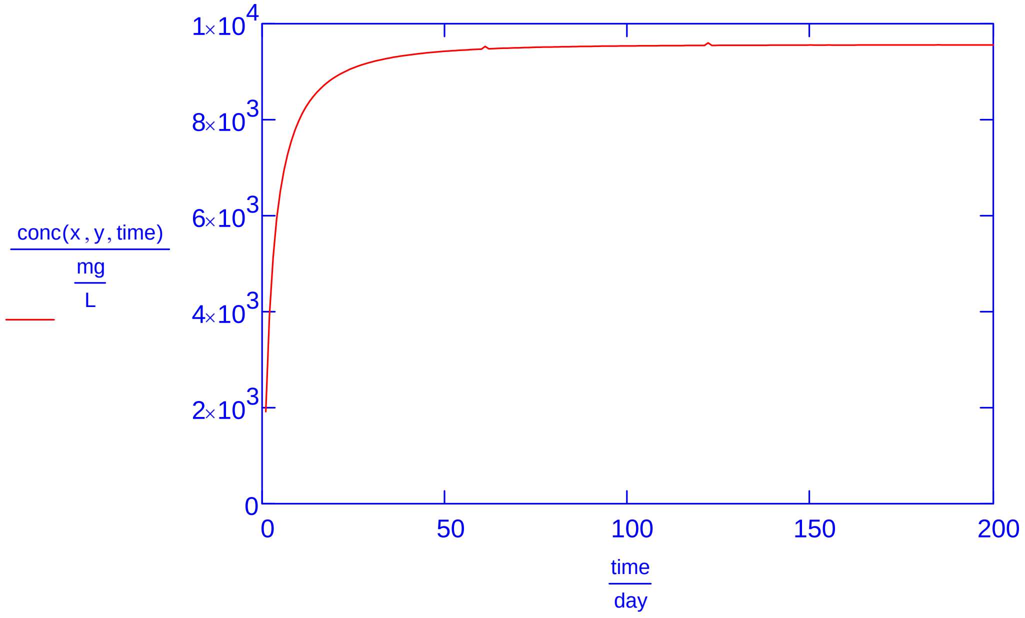
Example - calculate concentration at a single point and single time 1 foot downgradient of the center of the source

$x := 1 \cdot \text{ft}$ $y := 25 \cdot \text{ft}$ $\text{time} := 10 \cdot \text{day}$

$\text{conc}(x, y, \text{time}) = 7972.5121 \cdot \frac{\text{mg}}{\text{L}}$

Plot of concentration vs. time:

$\text{time} := 1 \cdot \text{day}, 2 \cdot \text{day} .. 200 \cdot \text{day}$



Superposition solution to assess a pulse tracer placment

Assume that a pulse of 10000 mg/L is placed in the cylinder well, mixes with the regional inflow and proceeds downgradient. Simplify to assume piston flow and assume no density driven flow component.

calculate volume of well, gravel pack pore space.

$\text{saturated\_thickness} := 20 \cdot \text{ft}$

$\text{diameter\_boring} := 18 \cdot \text{in}$

$\text{diameter\_casing} := 4 \cdot \text{in}$

$\text{porosity\_pack} := .3$

volume of gravel pack porosity

$$\text{vol\_pack} := \left[\left(\frac{\text{diameter\_boring}}{2}\right)^2 - \left(\frac{\text{diameter\_casing}}{2}\right)^2\right] \cdot \pi \cdot \text{porosity\_pack} \cdot \text{saturated\_thickness}$$

$\text{vol\_pack} = 75.3982\,\text{gal}$

$$\mathrm{vol\_casing} := \left(\frac{\mathrm{diameter\_casing}}{2}\right)^2 \cdot \pi \cdot \mathrm{saturated\_thickness}$$

$$\mathrm{volume\_est} := \mathrm{vol\_pack} + \mathrm{vol\_casing} = 88.4542\,\mathrm{gal}$$

assume that sufficient tracer is added to bring up concentration in the well and pack to bring this volume of water up to 1000 mg/L, and that the tracer is mixed in the well by surging in order to distribute into the pack.

$$\mathrm{tracer\_initial} := 10000 \cdot \frac{\mathrm{mg}}{\mathrm{L}}$$

$$\mathrm{mass\_tracer} := \mathrm{volume\_est} \cdot \mathrm{tracer\_initial} = 3.3484 \cdot \mathrm{kg}$$

The tracer mass is as chloride. Calculate the mass as sodium chloride

$$\mathrm{FW\_chloride} := 35.5\,\frac{\mathrm{gm}}{\mathrm{mol}}$$

$$\mathrm{FW\_NaCl} := (23 + 35.5)\frac{\mathrm{gm}}{\mathrm{mol}}$$

$$\mathrm{mass\_NaCl} := \mathrm{mass\_tracer} \cdot \frac{\mathrm{FW\_NaCl}}{\mathrm{FW\_chloride}} = 5.5177 \cdot \mathrm{kg}$$

Sodium chloride solubility in water is 359 g/L according to Wikipedia

Calculate volume of water needed to ensure NaCl concentration is not greater than 20% of solubility

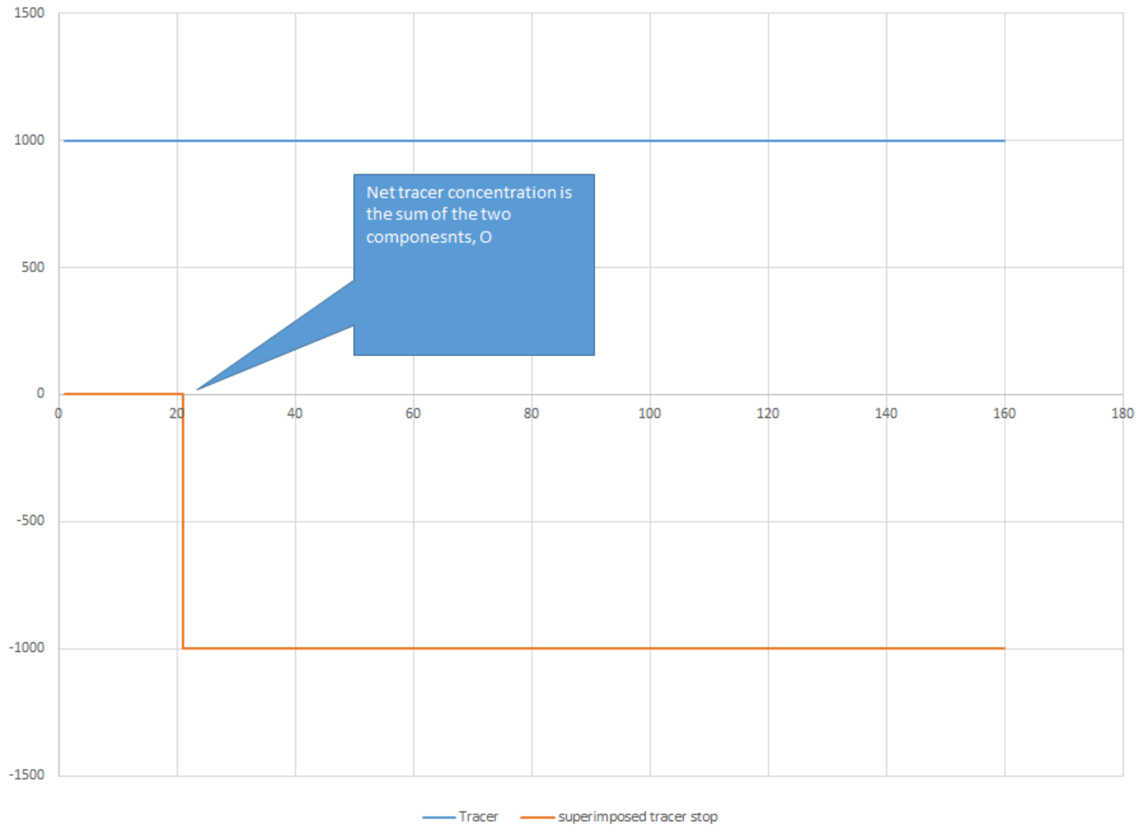
$$\mathrm{V\_water} := \frac{\mathrm{mass\_NaCl}}{\left(0.2 \cdot 359\,\frac{\mathrm{gm}}{\mathrm{L}}\right)} = 20.3012\,\mathrm{gal}$$

use the regional flow rate under the 0.1gpm scenario to estimate flushing time under piston flow assumption

$$\mathrm{flow\_rate} := 0.002878 \cdot \mathrm{gpm}$$

$$\mathrm{Time\_displace} := \frac{\mathrm{volume\_est}}{\mathrm{flow\_rate}} = 21.3435 \cdot \mathrm{day}$$

use a duration of tracer of 21 days as a simplifying assumption in superposition. The cessation of tracer is simulated by assuming a value equal in magnitude and opposite in sign is injected starting at the calculated displacment time, while at the same time assuming the tracer continues. This is conceptually illustrated in the following (old graph based on 1000 mg/L tracer scenario)



Set up to evaluate tracer at different distances

$\text{time} := 1 \cdot \text{day}, 2 \cdot \text{day} .. 365 \cdot \text{day}$

$i := 1 .. 365$

$\text{conc\_step}_i := \text{conc}(10 \cdot \text{ft}, 25 \cdot \text{ft}, i \cdot \text{day})$

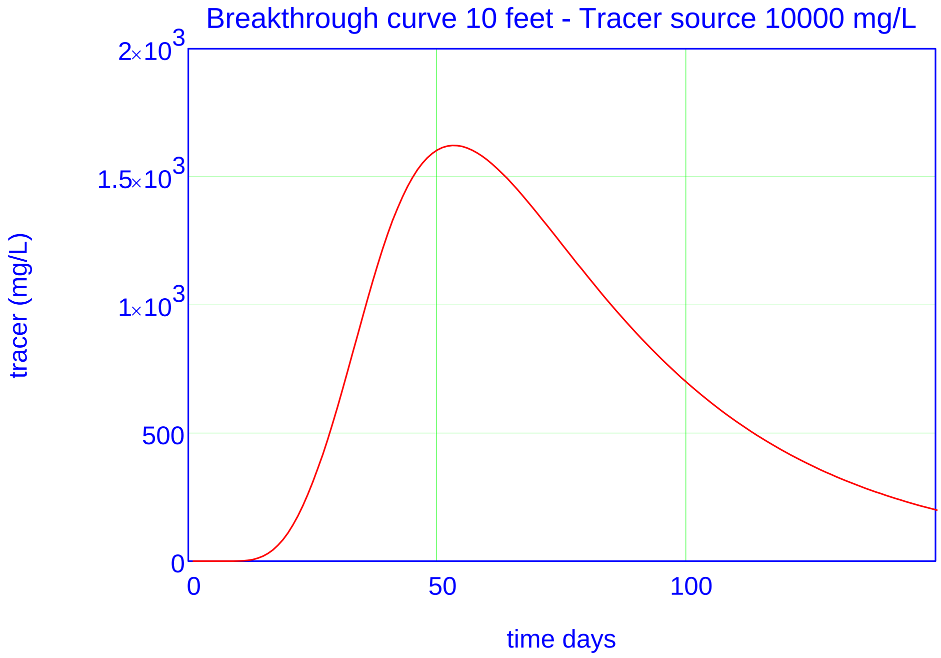
initialize

$conc\_super_i := 0 \cdot \frac{mg}{L}$

$j := 21 .. 365$

$conc\_super_j := conc[10 \cdot ft, 25 \cdot ft, (j - 21) \cdot day]$

$conc\_result_i := conc\_step_i - conc\_super_i$



$time := 1 \cdot day, 2 \cdot day .. 365 \cdot day$

$i := 1 .. 365$

$conc\_step_i := conc(20 \cdot ft, 25 \cdot ft, i \cdot day)$

initialize

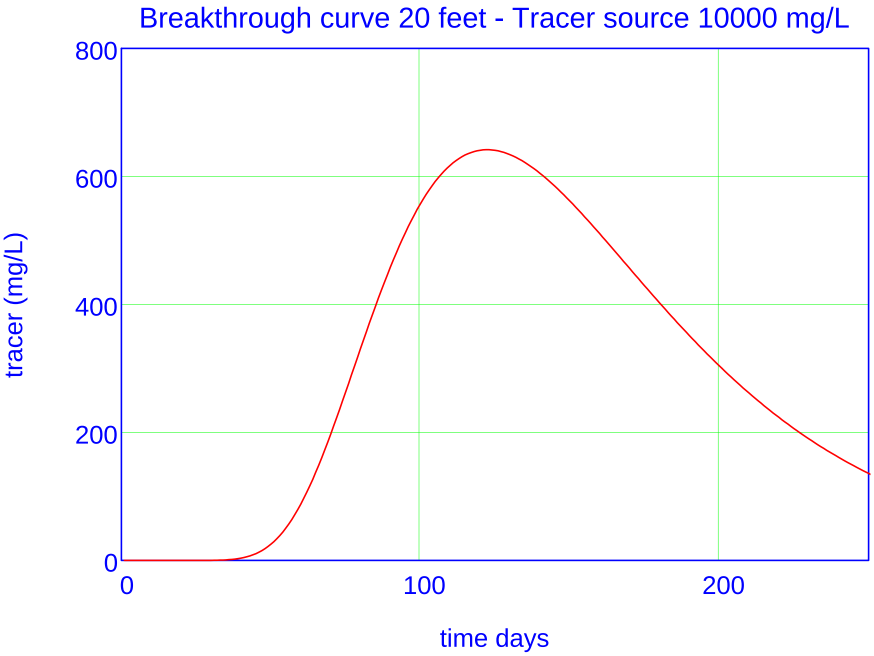
Client: ESTCP
Project:________________
Detail: Check analytical calculation for a strip source

$conc\_super_i := 0 \cdot \frac{mg}{L}$

$j := 21 .. 365$

$conc\_super_j := conc\left[20 \cdot ft, 25 \cdot ft, (j - 21) \cdot day\right]$

$conc\_result_i := conc\_step_i - conc\_super_i$



$time := 1 \cdot day, 2 \cdot day .. 365 \cdot day$

$i := 1 .. 365$

$conc\_step_i := conc(30 \cdot ft, 25 \cdot ft, i \cdot day)$

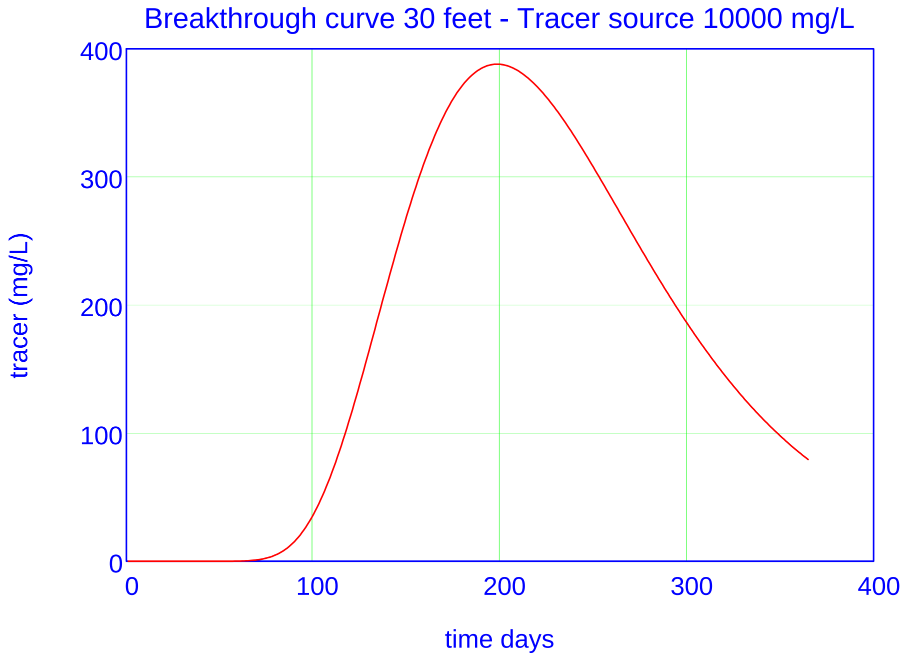
initialize

$conc\_super_i := 0 \cdot \frac{mg}{L}$

$j := 21 .. 365$

$conc\_super_j := conc\left[30 \cdot ft, 25 \cdot ft, (j - 21) \cdot day\right]$

$conc\_result_i := conc\_step_i - conc\_super_i$



$time := 1 \cdot day, 2 \cdot day .. 365 \cdot day$

$i := 1 .. 365$

$conc\_step_i := conc(40 \cdot ft, 25 \cdot ft, i \cdot day)$

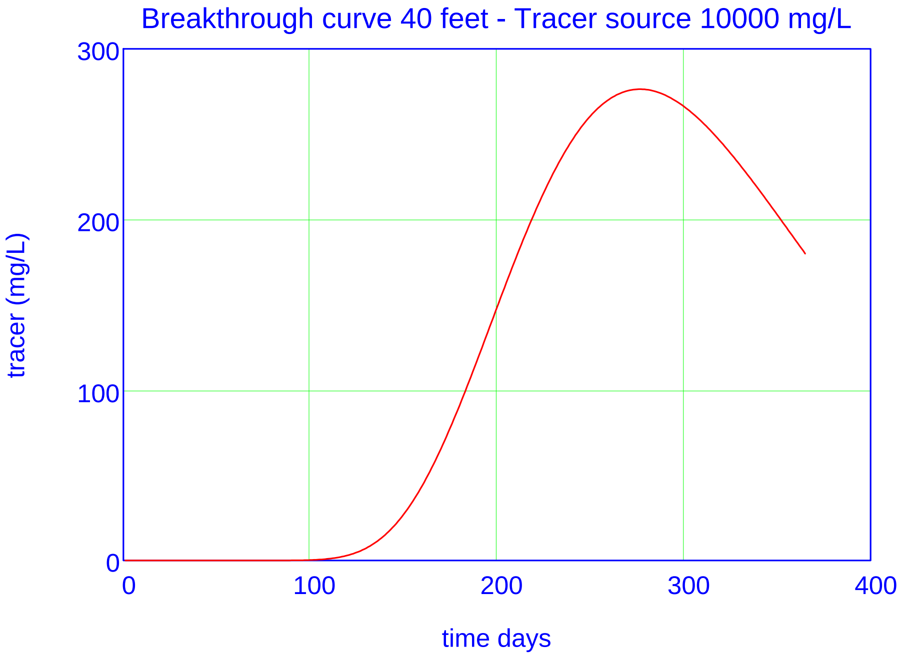
initialize

$conc\_super_i := 0 \cdot \frac{mg}{L}$

$j := 21 .. 365$

$conc\_super_j := conc\left[40 \cdot ft, 25 \cdot ft, (j - 21) \cdot day\right]$

$conc\_result_i := conc\_step_i - conc\_super_i$



Background chloride is 500 mg/L so this will be fine

Appendix C-2

Iron Fouling Calculations

Iron Fouling Calculations

1.0 Purpose/Objective

Determine potential iron fouling of extraction well due to oxididation of naturally occurring iron following installation of oxidant (persulfate) cylinders in locations 50 feet upgradient of extraction well.

2.0 Procedure

Calculate amount of iron sludge that will be produced as a function of void volume.
Calculate potential for iron sludge filling the pea gravel void space.

3.0 References/Data Sources

Liu, D.H.F, and B.G. Liptak. 1997. Environmental Engineers' Handbook. Second Edition. CRC Press. p. 904.

Perry's Chemical Engineers' Handbook. Eighth Edition. 2008. McGraw-Hill. New York.

Onda, K., H. Takeuchi, and Y. Okumoto. 1968. Mass transfer coefficients between gas and liquid phases in packed columns. J. Chem. Engin. Japan. 1(1):56-62.

4.0 Assumptions

Pea gravel is assumed to be spheres with a diameter of 0.5 in
Diameter of borehole with pea gravel section for infiltration is 18 in
Width of pea gravel section for infiltration is 18 in

5.0 Calculations

Input data section (specify the units)

Ground water flow rate is the estimated flow rate through the cell at 0.1 gpm

$$\text{Groundwater\_Flow\_Rate} := 0.10\,\frac{\text{gal}}{\text{min}} = 0.00000631\,\frac{\text{m}^3}{\text{s}}$$

Water viscosity μ

$$\mu\_L := 0.01\,\frac{\text{gm}}{\text{cm} \bullet \text{s}}$$

Water density ρ

$\rho\_L := 1\,\frac{gm}{cm^{3}}$

Pea gravel diameter d_p

$d\_p := 0.5\,in = 0.0127\,m$

Calculate potential for iron fouling of cylinder well. Assume that entire saturated annular space in borehole is available for iron deposition. Based on a ferrous iron concentration observed in monitoring well S11-MW-12 (1.15 mg/L), the total iron concentration is assumed to be 5 times this amount (5.75 mg/L). The minimum depth for to water during injection is assumed to be 20 feet below ground surface (bgs). The static depth to water is approximately 25 feet bgs. Since the well is 40 feet bgs, this means the static water column is 15 feet and the pumping water column is 20 feet. Assume the cylinder well is a 4-inch well with an 18-inch borehole.

$Iron := 5.75\,\frac{mg}{l}$

$Iron\ \ Mass\ \ Rate := Iron \bullet Groundwater\_Flow\_Rate = 3.6276865 \times 10^{-8}\,\frac{kg}{s}$

$Well\_Diameter := \frac{1}{3}\,ft$

$Borehole\_Diameter := 1.5\,ft$

$Min\_Infiltration\_Depth := 15\,ft$

$Normal\_Infiltration\_Depth := 20\,ft$

$$Min\_Pea\_Gravel\_Volume := \left[\left[\pi\left(\frac{Borehole\_Diameter}{2}\right)^{2}\right] - \left[\pi \bullet \left(\frac{Well\_Diameter}{2}\right)^{2}\right]\right] \bullet Min\_Infiltration\_Depth = 713.5333\,L$$

$$Normal\_Pea\_Gravel\_Volume := \left[\left[\pi\left(\frac{Borehole\_Diameter}{2}\right)^{2}\right] - \left[\pi \bullet \left(\frac{Well\_Diameter}{2}\right)^{2}\right]\right] \bullet Normal\_Infiltration\_Depth = 951.3777\,L$$

Assume 30% void volume

$Min\_Void\_volume := 30\% \bullet Min\_Pea\_Gravel\_Volume = 214.06\,L$

$Normal\_Void\_volume := 30\% \bullet Normal\_Pea\_Gravel\_Volume = 285.4133\,L$

Assume iron is oxidized to FeOOH which is present in the sludge coating the pea gravel at a concentration of 10% wt/vol. This is based on reported dry solids content of 10 to 15% in iron coagulant sludges (Liu and Liptak, 1997). Assume sludge density is 1.5 g/ml.

$FW\_Fe := 56\,\frac{gm}{mol}$

$FW\_FeOOH := (56 + 2 \bullet 16 + 1 \bullet 1)\,\frac{gm}{mol}$

$$\rho\_sludge := 1.5\,\frac{gm}{mL}$$

$$Iron\_Sludge\_Volume\_Rate := \frac{Iron\_Mass\_Rate \cdot FW\_FeOOH}{FW\_Fe \cdot \rho\_sludge \cdot 10\%} = 3.8436 \times 10^{-10}\,\frac{m^3}{s}$$

Calculate time to fill void volume

$$Min\_Time := \frac{Min\_Void\_volume}{Iron\_Sludge\_Volume\_Rate} = 5.5692 \times 10^{8}\,s$$

$$Min\_Time = 6445.8664 \cdot day$$

$$Normal\_Time := \frac{Normal\_Void\_volume}{Iron\_Sludge\_Volume\_Rate} = 7.4256 \times 10^{8}\,s$$

$$Normal\_Time = 8594.4885 \cdot day$$

6.0 Conclusions/Results

Based on the ambient iron concentration observed in the aquifer, it does not appear that fouling will occur within the one year demonstration period. It will take over 2.5 years for significant fouling to occur based on the calculations performed.

Appendix C-3

Pump Sizing Calculations

Performed by SH Date 11/19/2014
Checked by ML Date 5/28/2015

Extraction Well Detail for: **DEW-01** @ 1.65 gpm

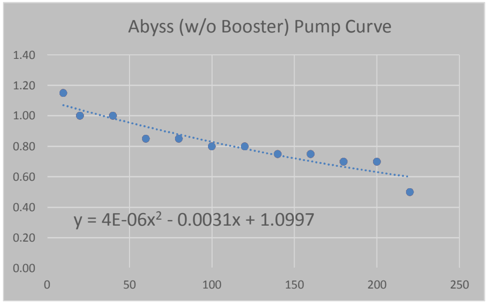
21% Cycle Frequency for 0.35 gpm
5.1 # Hours/Day Operation @ 0.35 gpm

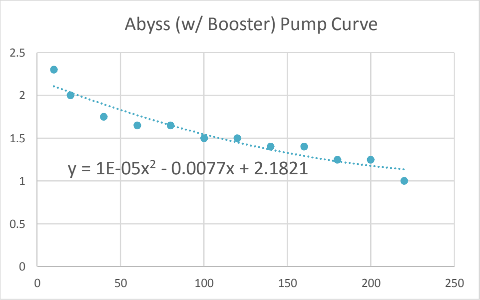
TDH Required 69.1 ft

Assumptions:
Specific Roughness (ft): 5.00E-06
Kinematic viscosity (ft2/sec): 0.000013
Hazen Williams roughness coefficient: 140

		Flow (gpm)	Pipe ID (in)	Velocity (fps)	Re	f	Length (ft)	Fitting K	QTY	Head Loss (pipe) by Hazaen Williams (ft)	Head Loss (pipe) by Darcy Weisbach (ft)	Head Loss (fitting) Scale Velocity Head by K (ft)	Head Loss (Equipment) (ft)	
From DEW-01 to DIW-01														
Riser		1.65	0.5	2.70	8.64E+03	0.03245	40.0			3.2918	3.51924		35	Required Static Lift, assume water level to be 25 feet bgs and assume pump placement at 15 feet below WL.
DEW-01 Vault														
Decreaser		1.65	0.5	2.70				0.0	1			0.0000000		
Flow Meter		1.65	0.5	2.70					0				5	Estimated Losses (worst case)
Increaser		1.65	0.5	2.70				0.0	0			0.0000000		
Standard Elbow 90°		1.65	0.5	2.70				0.81	4			0.3656980		
Through Tee		1.65	0.5	2.70				0.54	1			0.0609497		
Swing Check Valve		1.65	0.5	2.70				2.7	1			0.3047483		
Ball Valve		1.65	0.5	2.70				0.08	2			0.0180592		
Total Pipe in Vault		1.65	0.5	2.70	8.64E+03	0.03245	5			0.411472	0.43991			Conservative
Increaser		1.65	0.5	2.70				0.0	1			0.0000000		
Pipe to DIW-01														
Pipe		1.65	0.5	2.70	8.64E+03	0.03245	150			12.3442	13.197			
Standard Elbow 90°		1.65	0.5	2.70				0.81	3			0.2742735		
Decreaser		1.65	0.5	2.70				0.0	1			0.0000000		
DIW-01 Vault														
Total pipe in vault		1.65	0.5	2.70	8.64E+03	0.03245	5			0.4115	0.440			
Ball Valve		1.65	0.5	2.70				0.08	2			0.0180592		
Standard Elbow 90°		1.65	2	0.17				0.57	1			0.0002513		

	Total Losses (Frictional and Static)	57.5	ft
	Total Losses (Frictional and Static)	24.9	psi
Safety	Residual Total Dynamic Head Desired After Losses	5.0	psi
	Total Dynamic Head Required for Pump	29.9	psi
	Total Dynamic Head Required for Pump	69.1	ft





Without Booster Pumping Depth (DTW)	Gallons Per Minute	With Abyss® Booster Pumping Depth (DTW)	Gallons Per Minute
10	1.15	10	2.3
20	1.00	20	2
40	1.00	40	1.75
60	0.85	60	1.65
80	0.85	80	1.65
100	0.80	100	1.5
120	0.80	120	1.5
140	0.75	140	1.4
160	0.75	160	1.4
180	0.70	180	1.25
200	0.70	200	1.25
220	0.50	220	1
230	END OF WIRE	230	END OF WIRE

Well	**DEW-01**	
PUMP SELECTED:	http://www.gopronow.biz/pumps-a-accessories-plastic-a-stainless/plastic-pumps-standard/abyss-dtw-220ft	
	gpm	
DESIGN FLOW	**1.65**	**69.1 FT TDH**

Appendix C-4

Solar Panel System Calculations

To use this form, simply list all of your appliance that use electricity. These are items like Refrigerator, Range, computer, stereo, lights etc..

For each appliance, enter the number of that appliance that you own (**Qty**), the power is uses (**Watts**) and the number of hours a day (**Hrs/Day**) you use the item. We have a provided a list of common appliance and their power consumption at the bottom of the page.

Load Calculator

Use this form if you don't know what your power consumption (kilowatt-hours) is.

Name: ESTCP Dioxane Date 5/29/2015

	Appliance*	Qty	Watts (Volts x Amps)	Hrs/Day	Watt Hrs/Day
1	Abyss w/ Booster	1	72	6	432
2	Miscellaneous	1	20	2	40
3					0
4					0
5					0
6					0
7					0
8					0
9					0
10					0
11					0
12					0
13					0
14					0
15					0
16					0
17					0
18					0
19					0
20					0

Total Watt Hrs Per Day: **472**

Total Kilowatt Hrs Per Month (30 Days): **14**

(write down this value and enter it into Step 1 of solar panel sizing calculator)

* Help! I'm not sure of the wattage of my appliances.

Select the appliances from this drop down menu. To the right will appear typical wattage values for the appliance you selected. However, for the most accurate information look on your appliance to find its wattage rating (or it amperage rating and then multiply that by its voltage to approximate its wattage).

Stereo ▼ **10-30** **Watts**

| **Solar Panels** | Charge Controller | Battery Bank | Load Calculator |

Welcome to the Alternative Energy Store Calculator. This calculator is designed to help you size a system for off-grid use.

Start by filling out the first tab, titled **Solar Panels**. This tab will calculate how many Solar Panels you need, based upon you load(how much electricity you consume).
Once you've completed this tab, move on to the other tabs labeled **Charge Controller** & **Battery Bank**.

Solar Panel Array Sizing

Determine the size of the solar panel array you will need.

Step 1:

How many kilowatt-hours (kwh) does your home/location use per month?

(This value is usually printed on your electric bill. If you don't have a bill, or don't know your consumption, click on 'load calculator' at the top of this page to go through the steps to determine this value.)

15 kilowatt-hours per month

Step 2:

You need to determine the minimum number of sun hrs per day during the winter.
Select the State-City Closest to your location (currently only US states are provided)

CA-La Jolla ▼

4.29 Minimum sun-hours for the winter times

or

0 Manually enter the minimum sun-hours for your location.

Step 3:

The total wattage of Solar Panels that you need is:

152 Watts, or 0.16 kilowatts

This value takes into account losses due to system inefficiencies.

0.15

Step 4:

How many solar panels do you need? That depends on the panel you choose.
Select the wattage of the panel your interested in, and see the results below:

240 ▼

240

These solar panels are 240 watts each.

So you will need 1 of them, which makes a total wattage of 240 watts.

1

| **Solar Panels** | Charge Controller | Battery Bank | Load Calculator |

Battery Bank Sizing

This calculator will help you size the battery bank for your system.

Step 1

Wattage of solar panel array: **240** Watts

Step 2

How many days of backup power do you want in case of cloudy/rainy days?

3

Step 3

What is the lowest temperature your battery bank will experience?

65 Degrees Fahrenheit

Results

You need a battery bank that has a capacity of 65 amp hrs at 24V

65 Amp Hrs

Select a battery amperage: 85 ▼

Select a battery voltage: 12 ▼

Amp-Hour capacity of this battery is:	85 amp-hrs
Voltage of this battery:	12 volts
Batteries per row (in series)	2
Number of rows in parallel	1

Total number of these batteries you will need: **2**

Total Amp-Hours of this Battery Bank is: **85** **Amps-Hours**

*All calculations assume only a 50% discharge to your batteries to optimize battery life.

Appendix D

Quality Assurance Project Plan

Final Quality Assurance Project Plan for the Sustained In Situ Chemical Oxidation (ISCO) of 1,4-Dioxane Using Slow Release Chemical Oxidant Cylinders
ESTCP Project Number ER-201324

May 2015

Revision 0

Reviewed by: ________________________ Date: 5/29/15

Patrick Evans, PhD.
Principal Investigator

Reviewed by: ________________________ Date: 5/29/15

Janelle Amador, CHMM
Quality Assurance Coordinator

Contents

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Acronyms

%	percent
%R	percent recovery
µg/L	microgram per liter
AFCEE	Air Force Center for Engineering and the Environment
CDM Smith	CDM Smith Inc.
CERCLA	Comprehensive Environmental Response Compensation and Liability Act
DQO	data quality objective
EPA	U.S. Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
IDW	investigation derived waste
ISCO	*in situ* chemical oxidation
mg/L	milligrams per liter
mV	millivolt
NA	not available/applicable
NAS	Naval Air Station
NI	North Island
O&M	operation and maintenance
ORP	oxidation reduction potential
PI	principal investigator
PM	project manager
PQL	practical quantitation limit
QA	quality assurance
QAPP	quality assurance project plan
QC	quality control
RPD	relative percent difference
SIM	single ion mode
SOP	standard operating procedure
SW	solid waste
VOC	volatile organic compound
mg/L/d	milligram per liter per day
MCL	maximum contaminant level

1.0 Purpose and Scope of the Plan

The purpose of this Quality Assurance Project Plan (QAPP) is to collect data of known and defensible quality as determined by adherence to quality assurance (QA) and quality control (QC) requirements detailed within this document. The QAPP presents the organization, functional activities, and specific QA/QC activities associated with the implementation of the Demonstration Plan. All QA/QC procedures will be performed in accordance with applicable professional technical standards.

This QAPP addresses *in situ* chemical oxidation (ISCO) of 1,4-dioxane using slow-release oxidant cylinders at the Operable Unit 11 (OU11) at the North Island (NI) Naval Air Station (NAS) located in San Diego, California. This QAPP was developed in accordance with U.S. Environmental Protection Agency (EPA) Guidance for Quality Assurance Project Plans EPA QA/G5 (EPA 2002), Environmental Security Technology Certification Program (ESTCP) Demonstration Plan Guidance for Environmental Restoration Projects dated July 2010, and CDM Smith's Quality Assurance Manual, Revision 20 (CDM Smith 2012). A discussion on the regulatory drivers associated with the project is presented in **Section 1.3** of the Demonstration Plan. Additional details on the objectives of the technology demonstration are presented in **Section 3** of the Demonstration Plan. Background and historical information associated with the demonstration site are provided in **Section 4** of the Demonstration Plan. Major activities to be conducted during this technology demonstration include system installation, operation and maintenance (O&M), groundwater monitoring, and demobilization. A CDM Smith Subcontractor will perform all field activities outlined during system installation and groundwater monitoring while a CDM Smith representative will oversee select activities during installation, O&M, and demobilization. A brief description of each of the aforementioned demonstration activities is provided below.

1.1 System Installation

Major components of the demonstration system including two cylinder wells, monitoring wells, an extraction well, and a reinjection well will be installed during this initial phase of the project. Specifically, a submersible pump will be installed inside the extraction well to induce an artificial hydraulic gradient within the demonstration cell. Additionally, a solar panel equipped with battery packs will be installed to provide power to the recirculation system and to facilitate remote monitoring and instrumentation controls. Details pertinent to the various process equipment, process controls, and other aspects of system installation activities such as trenching and fencing are discussed in **Section 5** of the Demonstration Plan.

1.2 System Operations & Maintenance

Upon completion of all system installation activities, equipment testing and system startup will ensue. Specifically, process control equipment including the pump timer relay and flow controller, and the remote water meter system will be tested to verify their functionality and accuracy. Details associated with these testing procedures are provided in **Section 5** of the Demonstration Plan. Once all equipment testing activities are completed, the demonstration system will be operated under normal design conditions specified in **Section 5** of the Demonstration Plan. Periodic O&M activities including a one-time change-out of the extraction pump and oxidant cylinders after 6 months, periodic cleaning of system components, verifying and recording system parameters (e.g., pressure and flow rates), general site conditions, and visual inspection of the system for leaks will be performed as part of this phase of the demonstration project.

1.3 Groundwater Monitoring

A groundwater monitoring program will be implemented as part of this technology demonstration. A number of analytes will be collected to facilitate evaluating the remedial performance of the demonstration system. The rationale for each selected analyte is presented below:

- Volatile organic compounds (VOCs): samples collected in upgradient and downgradient wells will be used to determine VOC removal effectiveness and efficiency.
- 1,4-dioxane: similar to VOCs, dioxane samples collected in upgradient and downgradient wells will be used to determine the dioxane removal effectiveness and efficiency
- Dissolved metals: persulfate degradation generates sulfuric acid that can reduce the aquifer pH. Such changes in groundwater pH can lead to increases in dissolved metals concentrations. Therefore, dissolved metals samples will be collected in upgradient and downgradient wells to access the impacts of persulfate on groundwater quality in the aquifer.
- Bromate: naturally-occurring bromide in groundwater can be oxidized to the more toxic form bromate in the presence of persulfate and therefore will be monitored to access groundwater quality.
- Sulfate: sulfate is the byproduct of persulfate degradation and will be monitored to evaluate persulfate distribution and longevity in the aquifer.
- Chloride: chloride will be used as a tracer to facilitate evaluation of oxidant travel time, distribution, and longevity in the aquifer.

Field parameters including pH and conductivity will be collected concurrently with collection of aforementioned groundwater analytes. Groundwater levels will also be measured prior to the start of each performance monitoring event. The rationale for measuring such parameter is as follows:

- pH: pH is a general groundwater quality parameter that is easy to measure and can be used to evaluate potential adverse impacts of the persulfate oxidant on the aquifer.
- Conductivity: conductivity can be used to evaluate oxidant and tracer transport and distribution within the aquifer.
- Oxidation-reduction potential (ORP): additions of an ISCO oxidant such as persulfate will result in changes in the aquifer ORP. Such parameter will be monitored to evaluate oxidant transport, impacts on secondary groundwater quality, and down-gradient re-establishment of reducing conditions which can attenuation bromate and hexavalent chromium via chemical or biological reduction.
- Ferrous iron: under oxidizing conditions, ferrous iron dissolved in groundwater can be oxidized into iron precipitate and can potentially cause iron fouling. Therefore, ferrous iron will be monitored at the onset of system operations to evaluate the potential of iron fouling.
- Persulfate: the oxidant of interest will be monitored to evaluate oxidant transport and longevity.

- Groundwater level: water levels will be measured to evaluate the impact of the artificial hydraulic gradient induced by the extraction well.

1.4 Demobilization

Upon completion of the project, the demonstration system will be decommissioned. Activities to be performed during this phase include removal of the extraction pump and all conveyance piping, abandonment of all cylinder, extraction, reinjection, and monitoring wells (if desired by NAS NI), removal of all electrical service and equipment from the Site, and site restoration.

2.0 Quality Assurance Responsibilities

The specific individuals participating in the project and their roles are presented in **Section 8** of the Demonstration Plan. The specific QA and management responsibilities of key project personnel are described below.

2.1 CDM Smith Principal Investigator

Patrick Evans, CDM Smith's Principal Investigator (PI), will have the ultimate responsibility for all aspects of this project, including implementation of the QA program as defined in this QAPP and in the Demonstration Plan. He will ensure proper adherence to the QA program. He is also responsible for managing and executing the technical aspects of this project.

2.2 CDM Smith Project Manager

Jennifer Hooper, CDM Smith's Project Manager (PM), is responsible for scheduling, budgeting, and procurement. She has overall responsibility for implementation of the QA program. She has final responsibility to make sure that the requirements of the contract are disseminated to the project team and into project plans and ultimately implemented. This includes Planning, Design, Work Planning, Contracting, Construction, Operations and Testing and Project Closeout. The project manager will be responsible for the overall performance of field operations and testing and will ensure that they are conducted in accordance with approved work plans and procedures, including this QAPP. The project manager is responsible for ensuring that proper reviews are performed on reports and documents in accordance with the CDM Smith QA program.

2.3 CDM Smith Quality Assurance Coordinator

The CDM Smith QA Coordinator is Laura Splichal. The QA Coordinator is responsible for establishing the QA policy and practices for the project. This includes reviewing this QAPP and procedures, ensuring management and independent assessments are scheduled and performed and ensuring that acceptance testing is performed and that equipment is calibrated on a routine basis. The QA Officer will remain independent of the data generating activities.

2.4 CDM Smith Technical Team

CDM Smith technical staff will be used to oversee field activities, procure and direct subcontractors, gather and analyze data, and prepare various task reports and support materials. The designated technical team members are experienced professionals who possess the degree of specialization and technical competence required to perform the required work effectively and efficiently. The field team lead will coordinate field activities for adherence to procedures outlined in this QAPP on a routine basis. The technical task lead for data analysis and interpretation will coordinate data acquisition and validation and check that data quality indicators are met. The technical team will adhere to QA requirements under direction of the project manager.

2.5 CDM Smith Subcontractor's Field Staff Team

CDM Smith will hire Subcontractor's to carry out the majority of field activities. Experienced professionals who possess the degree of specialization, technical competence required, and proper certifications to perform the required work effectively and efficiently will be hired as

Subcontractor's to CDM Smith. The Subcontractor will adhere to QA requirements under direction of CDM Smith's Technical Team.

2.6 Laboratory Project Manager/Project Chemist

The responsibilities of the laboratory PM are to initiate and maintain the services of the contract, ensure all resources of the laboratory are available on an as-required basis and to review final analytical data and reports.

2.7 Laboratory Operations Manager

The laboratory operations manager shall have complete authority for the production capabilities of the laboratory. Each laboratory under subcontract to CDM Smith and performs work for this project will have their own Operations Manager. The responsibilities of the laboratory operations manager are:

- Coordinates laboratory analyses;
- Supervises in-house chain-of-custody procedures;
- Schedules sample analyses;
- Oversees data review;
- Oversees preparation of analytical reports; and
- Approves final analytical reports.

2.8 Laboratory Quality Assurance Officer

The laboratory QA Officer is responsible for the laboratory QA/QC in accordance with the requirements of this QAPP and in conjunction with the laboratory's established QA Program. The responsibilities of the laboratory QA officer are:

- Implements the lab QA/QC program
- Supervises laboratory quality assurance;
- Supervises QA/QC documentation;
- Conducts detailed data review;
- Decides laboratory corrective actions, if required;
- Processing laboratory non-conformance reports;
- Provides technical representation of laboratory QA procedures; and
- Prepares laboratory Standard Operation Procedures.

2.9 Laboratory Sample Custodian

The responsibilities of the laboratory sample custodian are:

- Receives and inspects the incoming sample containers;
- Records the condition of the incoming sample containers;
- Signs appropriate documents;
- Verifies chain-of-custody and its correctness;
- Notifies laboratory manager and laboratory supervisor of sample receipt and inspection;
- Control and safekeeping of all samples received by the laboratory; and
- Assigns a unique identification number and customer number, and enters each number into the sample receiving log.

2.10 Laboratory Data Manager

The responsibilities of the laboratory Data Manager are:

- Support and maintenance of the laboratory database;
- Initiate and create compatible electronic data; and
- Serve as the single point-of-contact for transmission of electronic data deliverables and corrections of versions with problems

The Principal Investigator and Project Manager have primary responsibility for project quality and will interface with the analytical laboratory. Independent quality assurance will be provided by the Laboratory Project Manager and Laboratory QA Officer prior to the release of the data to CDM Smith.

3.0 Data Quality Objectives

The data quality objective (DQO) process is a series of planning steps designed to ensure that data of known and appropriate quality are obtained to support decisions. The process uses qualitative and quantitative statements intended to clarify study objectives; define appropriate data types; determine appropriate conditions from which to collect the data; and specify acceptable levels of decision errors. The outputs of each step are then used as inputs in designing the sampling plan.

EPA DQO guidance recommends a seven-step process be used to implement the process to design both qualitative and quantitative sampling and analysis plans. This demonstration will use both qualitative and quantitative analysis of influent and effluent groundwater monitoring results to determine progress toward the performance objectives identified in **Table 3-1** of the Demonstration Plan. The steps of the DQO process are listed below:

Step 1: State the problem, including identifying the data users, the planning team, the primary decision maker, resources and deadlines

Step 2: Identify the decision to be made, including the principal study question(s), alternative actions that could result from resolution of the principal study questions, and formulate and prioritize decision statements

Step 3: Identify inputs to the decision, including required data types and sources, action levels, and analytical methods

Step 4: Define study boundaries, including spatial and temporal aspects

Step 5: Develop a decision rule, including (where appropriate) specifying the statistical parameter that characterizes the population, and (where appropriate) action levels for the statistical tests

Step 6: Specify limits on decision errors

Step 7: Design the data collection program, which will be implemented through this demonstration project.

3.1 State the Problem

This level of the analysis summarizes the problem requiring new data, and identifies resources available to resolve the problem. The overall problem to be investigated is to demonstrate the technology effectiveness, sustainability/longevity, oxidant transport and destruction, technology implementability/secondary impacts, technology reproducibility, engineering design tool utility and ease of use, and applicability to multiple site conditions associated with the use of *in situ* slow-release persulfate cylinders.

3.2 Identify the Decision

This step identifies the decisions that must be made based on results of influent and effluent monitoring as well as who will use the data. The immediate data users will be CDM Smith scientists and engineers analyzing trends to make operational adjustments and to assess overall performance. Ultimate data users include site owners and other scientists and engineers who will apply the technology at other sites; and regulatory agency personnel who must evaluate site-specific applicability of the technology. Additional data users include Department of Defense Remedial Project Managers, Department of Defense contractors, private industry, and the general public.

The decisions that are of qualitative objectives and relevant to this demonstration are:

1. Determine whether the demonstrated technology is capable of destroying dioxane and chlorinated ethenes in the reactive zone (performance objective 1).
2. Determine whether the demonstrated technology is capable of consistently distributing the oxidant in the reactive zone and meeting the aforementioned technology effectiveness for a minimal period of time (performance objective 2).
3. Determine whether the demonstrated technology will result in significant oxidant transport past the reactive zone (performance objective 3).
4. Determine whether the demonstrated technology will result in acceptable or transient secondary groundwater quality impacts (performance objective 4).

3.3 Identify Inputs to the Decisions

This step identifies information required to make the decision including specific types, quality, and quantity needed to support decisions. This stage of analysis must ensure that sufficient data of the required types, and of a quality appropriate for the data uses, are obtained. Results of this stage are typically used to define quality levels to be applied to the entire data collection effort, from sampling through analysis and data validation. Specifying unnecessarily stringent data quality costs the project time and money; while specifying insufficiently stringent data quality may result in failure to meet project objectives.

The EPA defines data quality levels as “screening” or “definitive.” Screening data are generated using rapid, less precise analytical methods with less rigorous sample preparation. Screening data both identify and quantify analytes, although quantification may be relatively imprecise. Screening data are adequate for some performance monitoring of groundwater parameters via calibrated instruments such as pH and conductivity.

Definitive data are generated using rigorous analytical methods such as approved EPA or other well established and documented test methods. Definitive data both identify and quantify analytes with relatively high precision and accuracy, and are typically used for compliance monitoring and to confirm screening data. Definitive data will be generated for groundwater contaminants of concern including dioxane and VOCs as well as other analytes of interest such as chloride and sulfate. Definitive analytical methods produce tangible hardcopy, or electronic format, raw data (e.g. chromatograms, spectra, and digital readout values). Data not obtained and/or reported in these formats are documented in logbooks.

Inputs to the decisions stated previously, including data required, data uses, and minimum data quality levels, are summarized in **Table 3-1.** Requirements for decision input data, including analytical methods and practical quantitation limits are summarized in **Table 3-2**.

Table 3-1. Decision Inputs

Decision	**Data Required**	**Data Use**	**Minimum Data Quality Level Required**
Determine whether the demonstrated technology is capable of destroying dioxane and chlorinated ethenes in the reactive zone	Pre-, during, and post-treatment dioxane and VOC concentrations in groundwater	Concentrations of these analytes of interest will be monitored at select monitoring points to evaluate technology effectiveness	Definitive
Determine whether the demonstrated technology is capable of consistently distributing the oxidant in the reactive zone and meeting the aforementioned technology effectiveness for a minimal period of time	Dioxane, chlorinated ethene, and oxidant concentrations in upgradient monitoring wells and downgradient treatment zone	Concentrations of these analyte of interest will be used to evaluate the oxidant transport, distribution, and longevity in the reactive zone as well as the ability to achieve removal effectiveness for a minimal period of time	Definitive (dioxane and chlorinated ethenes) and Screening (persulfate)
Determine whether the demonstrated technology will result in significant oxidant transport past the reactive zone	Oxidant concentrations in upgradient monitoring wells, within, and downgradient of the treatment zone	Oxidant concentrations will be used to evaluate the extent of transport	Screening
Determine whether the demonstrated technology will result in acceptable or transient secondary groundwater quality impacts	Metals, bromate, pH, ORP, and persulfate concentrations at select monitoring points within the demonstration cell	Changes in concentrations or value of these analytes will be used to evaluate secondary groundwater quality impacts as a result of this demonstrated technology	Definitive (metals and bromate) and Screening (pH, ORP, persulfate)

Table 3-2. Acceptable Practical Quantitation Limits for Field and Laboratory Analyses

Analyte	Analytical Method	Practical Quantitation Limit
Offsite Laboratory Analysis		
VOCs	SW 846 EPA 8260B	0.5-1 µg/L
1,4-dioxane	SW 846 EPA 8260SIM	1 µg/L
Dissolved metals	SW 846 EPA 6010C	5 µg/L
Mercury	SW 846 EPA 7470A	0.5 µg/L
Bromate	EPA 300.1	5 µg/L
Sulfate	EPA 300.1	2.5 µg/L
Chloride	EPA 300.1	500 µg/L
Field/Test Kit Measurements		
pH	Multi-parameter water quality meter	0.1 standard unit
Conductivity		NA
Temperature		0.1 degree Celsius
ORP		0.1 mV
Ferrous Iron	HACH ferrous iron AccuVac® Ampoules	0.03 mg/L
Persulfate	Chemetrics kit K-7870	0.35 mg/L

µg/L: microgram per liter
mg/L: milligram per liter
mV: millivolt
NA: not applicable
EPA: United States Environmental Protection Agency
ORP: oxidation-reduction potential
VOC: volatile organic compound

3.4 Define Study Boundaries

The Demonstration will be conducted at the OU11 of the NI NAS. The anticipated duration of the technology demonstration is estimated to be one year beginning in the spring/summer of 2015.

3.5 Develop a Decision Rule

Decision rules should contain four main elements including:

- The *parameter of interest* (e.g., a descriptive measure that specifies the characteristic or attribute that the decision maker would like to know about a statistical population)
- The *scale of decision making* (i.e., the smallest, most appropriate subset of the data for which separate decisions will be made)
- The *action level* a measurement threshold value of the parameter of interest that provides the criterion for choosing among alternative actions (e.g., a regulatory standard or other risk-based level)
- The *alternative actions*, which are the actions that the decision maker would take depending on the true value of the parameter of interest.

Decision Rule 1: If 90 percent (%) reduction in 1,4-dioxane concentration or a 1,4-dioxane concentration of less than 3 µg/L is achieved ***and*** if 90% reduction in chlorinated ethene concentration or chlorinated ethene concentrations are achieved, the demonstrated technology will be considered to be effective with respect to contaminant destruction. Otherwise, operating data will be reviewed and operational parameters may be adjusted, if applicable, to determine the cause(s).

Decision Rule 2: If the rate of oxidant concentration change at any given monitoring location is equal to or greater than 0 milligram per liter per day (mg/L/d) ***and*** 90% contaminant removal is sustained for 4 weeks of operation, the demonstrated technology will be considered capable of consistently distributing the oxidant in the reactive zone and meeting the technology effectiveness for aforementioned operational period. Otherwise, operating data will be reviewed and operational parameters may be adjusted, if applicable, to determine the cause(s).

Decision Rule 3: If the oxidant is consumed below its detection limit at the most downgradient monitoring location ***or*** other lines of evidence support its destruction along the flow path, it will be determined that the demonstrated technology will not result in significant oxidant transport past the reactive zone.

Decision Rule 4: If dissolved metal concentrations are below their respective MCLs at the most downgradient monitoring location ***or*** if dissolved metal concentrations demonstrate a decreasing trend along the flow path, the demonstrated technology will be considered having minimal impacts on groundwater secondary quality. Other parameters such as pH, ORP, and persulfate concentrations will be used to evaluate attenuation trends.

3.6 Specify Limits on Decision Errors

Because this is a research demonstration, an explicit definition of limits on decision errors is not necessary or appropriate. The weight of evidence of several groups of parameters will be considered as described in the previous section.

3.7 Design Data Collection Program

The final step in the DQO process is to design a program to collect data cost-effectively that will meet the DQOs. This program is described in Section 5.6 of the Technology Demonstration Plan.

4.0 Calibration Procedures, Quality Control Checks, and Corrective Action

The purpose of this section is threefold:

- Provide the specific maintenance/calibration procedures for equipment related to the collection of data either in the field or through laboratory analysis of samples.
- Provide specific quality control checks to determine if an analytical operation is in control or if the sample matrix has an effect on the data being generated.
- Provide a corrective action process for general field issues and laboratory analyses.

4.1 Calibration Procedures

4.1.1 Laboratory Equipment Calibration

Initial and continuing calibration procedures for laboratory instruments are found in each laboratory's QA Manual. Calibration for analyses performed by offsite laboratories are defined by the analytical methods. Data reduction and validation for the laboratory data and for the final reporting are described in the laboratory's QA Manual.

4.1.2 Field Instrumentation and Test Kits

Air monitoring instrumentation will be used to provide data concerning health and safety considerations. Water quality meters will be used to provide field parameters for groundwater samples. All field instrumentation will be calibrated in accordance with manufacturers' recommendations. Documentation of the results from each calibration will be maintained in the field manager's logbook and on equipment calibration log forms. Any equipment maintenance that is performed or field calibrations will also be recorded.

4.2 Quality Control Checks

4.2.1 Field Sample Collection

QA/QC samples are analyzed to provide site-specific, field-originated information regarding the homogeneity of the sample matrix and the consistency of the sampling effort. These samples are collected concurrently with the primary environmental samples and will equally represent the medium at a given time and location. QA/QC samples to be collected and used for the demonstration are:

- Field duplicates
- Matrix Spike/Matrix Spike Duplicates

Field Duplicates

These samples will be collected by the sampling team for analysis by the off-site laboratory. The purpose of these samples is to provide site-specific, field-originated information regarding the homogeneity of the sample matrix and the consistency of the sampling effort. Additionally, field duplicates provide an assessment of precision including sampling and handling error. Field duplicates will be collected at a frequency of 10 percent of the total field samples (i.e., 1 QC sample per 10 field samples).These samples are collected concurrently with the primary environmental samples and will equally represent the medium at a given time and location.

Matrix Spike/Matrix Spike Duplicates

Matrix spike/matrix spike duplicate samples assess the laboratory accuracy and the matrix effects (if any) on the outcome of laboratory analysis. Matrix spike and matrix spike duplicates will be collected at a frequency of 5 percent (i.e., 1 matrix spike/matrix spike duplicate per 20 field samples). Extra volume for each matrix spike/matrix spike duplicate sample will be specified by the analytical laboratory, but generally is double sample volume.

4.2.2 Laboratory Analysis

To ensure the production of analytical data of known and documented quality, laboratories associated with this demonstration will implement method required QA and QC checks. Subcontracted laboratories will have a written QA program that provides rules and guidelines to ensure the reliability and validity of work conducted at the laboratory. Compliance with the QA program is coordinated and monitored by the laboratory's QA department, which is independent of the operating departments. All laboratory procedures will be documented in writing as standard operating procedures, which will be edited and controlled by the QA department. Internal QC measures for analysis will be conducted with their standard operating procedures and the individual method requirements specified.

4.3 Corrective Action

4.3.1 General Field Issues

All nonconformance situations noted during the demonstration will be documented and acted upon. The person identifying the nonconformance is responsible for notifying the CDM Smith Principal Investigator and Project Manager, and initiating a corrective action request. The corrective action request is submitted to the QA Officer who determines if the nonconformance is a significant condition adverse to quality and assigns personnel responsible for developing and implementing the corrective action plan. Implementation of corrective action will be confirmed in writing and noted in reports generated describing the demonstration results.

For unexpected situations encountered during field activities where changes to operating systems are necessary to implement, a field change request will be completed by oversight personnel that will make the change and will be approved by the project manager. All variances from existing operating procedures, field sampling, quality assurance requirements, and/or health and safety plans will be documented on a field change request form.

4.3.2 Laboratory Analyses

Each laboratory QA plan shall provide systematic procedures to identify laboratory related out-of-control situations and corrective actions. Corrective actions shall be implemented to resolve problems and restore malfunctioning analytical systems. Laboratory personnel shall have received QA training and will be aware that corrective actions are necessary when QC data are outside warning or control windows for precision and accuracy, blanks contain target analytes above acceptable levels and must be investigated, undesirable trends are detected in spike recoveries or RPDs between duplicates, there are unusual changes in practical quantitation limits, deficiencies are detected by internal audits, external audits, or from performance evaluation sample results.

Corrective action procedures are generally handled by the analyst who reviews the preparation or extraction procedure for possible errors, checks instrument calibration, spike, and calibration mixes, instrument sensitivity, etc. If the problem persists or cannot be identified, the matter is referred to the Laboratory Supervisor, Manager, and/or QA Department. Once resolved, full documentation of the corrective action procedure is filed with project records and the QA Department, and the information is summarized within case narratives.

5.0 Demonstration Procedures

Demonstration plans are discussed in **Section 1** of this QAPP and **Section 5** of the Demonstration Plan.

5.1 Field Equipment

The field equipment for this project includes meters for measurement of flow, depth to water, pressure, pH, ORP, temperature, and conductivity. Specific preventative maintenance procedures to be followed for field equipment are those recommended by the manufacturer. Where appropriate, new batteries will be purchased and kept with the field equipment to facilitate immediate replacement in the field as necessary.

5.2 Equipment Maintenance

Instruments used for field measurements will be calibrated on the day field measurements are collected. Instruments installed as part of the amendment system (e.g. pressure gauges and totalizers) will be calibrated per manufacturer's specifications. CDM Smith subcontractors will monitor and maintain the extraction well and recirculation system as needed.

5.3 Laboratory Instruments

Laboratory instruments will be maintained according to laboratory standard operating procedures (SOPs). Preventive maintenance procedures are described in the laboratory QA manuals.

5.4 Sampling and Analysis

The sampling and analysis program for this Demonstration was developed based on the objectives discussed in Section 3 and the design discussed in **Section 5** of the Technology Demonstration Plan. A summary of the process monitoring parameters including a sampling and analysis schedule is provided in **Section 5** of the Technology Demonstration Plan.

The primary objective of sample collection is to monitor, control and evaluate the performance of the *in situ* slow-release oxidant cylinders. CDM Smith SOPs to be implemented during sample collection include 1-2 Sample Custody, 1-4 Subsurface Sampling, 1-6 Groundwater Level Measurement, 1-12 Low-Stress Low-Flow Groundwater Sampling, 1-13 Drum Sampling (for Investigation Derived Waste (IDW) management), 2-1 Packaging and Shipping Environmental Samples, 2-2 Guide to Handling of IDW, 3-5 Lithologic Logging, 3-6 Underground Facility Location, 4-1 Field Logbook Content and Control, 4-2 Photographic Documentation of Field Activities, 4-3 Well Development and Purging, 4-4 Design and Installation of Monitoring Wells in Aquifers, 4-5 Field Equipment Decontamination, 4-10 Borehole Well Decommissioning, and 5-1 Control of Measurement and Test Equipment.

Groundwater Sampling

The following general procedure will be used to collect groundwater samples for field and on-site analysis.

- Groundwater samples will be collected using procedures described in **Section 5** of the Technology Demonstration Plan

- Sample container and preservation requirements are presented in **Table 5-1** of the Demonstration Plan. Sample containers will be completely filled with groundwater.

- Each sample will be labeled with the appropriate sample identification and other information discussed in **Section 9** of this QAPP below.

- The sample containers will then be placed on ice or inside a refrigerator to maintain the temperature at 4 degrees Celsius prior to being analyzed in the field and/or shipped to the laboratory on ice.

6.0 Calculation of Data Quality Indicators

The following subsections list the parameters that will be assessed and the criteria used to review and validate data objectively and consistently. The practical quantitation limits (PQLs) for the individual parameters for both field and laboratory analyses have been outlined in **Table 3-2**. Additional performance objectives and criteria are provided in **Table 3-1** of the Demonstration Plan.

6.1 Accuracy

Accuracy of laboratory results will be assessed using the analytical results of method-defined surrogates, laboratory control samples, matrix spikes, and calibration standards. The percent recovery (%R) will be calculated using the following equation:

$$\%R = \frac{A - B}{C} \times 100$$

where:
A = Analyte concentration determined experimentally in the spiked sample.
B = Analyte concentration determined by a separate analysis of the unspiked sample.
C = concentration of spiked analyte.

The only samples to be sent to an offsite laboratory that require matrix spikes are dioxane, VOCs, dissolved metals, bromate, sulfate, and chloride. The accuracy goal for these samples is a percent recovery of 70-130%. Matrix spikes will be conducted as part of the laboratory QAQC program. Trip blanks will be included for dioxane and VOC samples to assess whether contamination during sample handling occurred. The accuracy goal for method-defined surrogates, laboratory control samples and calibration standards are defined by the laboratory in their quality assurance plan and standard operating procedure methods.

6.2 Precision

Precision will be assessed by calculating RPD between the field duplicate samples and laboratory duplicate samples. The RPD will be calculated for each pair of duplicates using the following equation:

$$\%RPD = \frac{S - D}{(S + D)/2} \times 100$$

where:
S = First sample value
D = Second sample value (duplicate value)

The precision goal for this project for sample pairs whose values are both greater than 10X the PQL limit is an RPD $\leq$ 35%. For sample pairs that have one or both values less than 10X the PQL, the precision goal is RPD $\leq$ 50%. Sample pairs that have one or both values that are less than the PQL will not have RPDs calculated. If the precision goals are not met for a given sampling round, the project manager and field team leader will perform a review of sample collection and handling procedures. For analyses performed in the field, the analytical procedure will also be reviewed.

6.3 Completeness

Completeness of data will be assessed as the percentage amount of valid/usable data (i.e., meeting precision, accuracy requirements, and requirements discussed in previous sections) compared to the total amount of expected data using the following equation:

$$\%Completeness = \frac{Valid\ Data\ Obtained}{Total\ Data\ Planned} \times 100$$

The completeness goal for this project is 90% of all planned samples, as defined in the Demonstration Plan. Completeness will be tracked both for individual sampling rounds and cumulatively over the course of the demonstration.

6.4 Representativeness

Representativeness expresses the degree to which data accurately and precisely represent a characteristic of a population and parameter variations at a sampling point, a process condition, or an environmental condition. Representativeness is a qualitative parameter that is dependent on the proper design of the sampling program and proper laboratory protocol. The sampling program is described in Section 5.5 of the Demonstration Plan.

Representativeness of the data will be assessed by the CDM Smith Project Manager and the QA Officer through review and comparison of the applicable data (field and laboratory duplicates, spikes, blanks) and by verifying that the sampling and analysis plan/design set forth in the Demonstration Plan was followed for all data generated during the project activities.

6.5 Comparability

Comparability expresses the confidence with which one data set can be compared with another. The extent of comparability between existing and planned analytical data depends in part on the similarity of sampling and analytical methods. The procedures used to obtain the planned analytical data, as documented in the QAPP and Demonstration Plan, are expected to provide comparable data for these project activities.

7.0 Performance and System Audits

Field audits, laboratory audits, and self-assessments may be conducted to verify that sampling and analysis are performed in accordance with the procedures established in the Demonstration Plan and this QAPP. This section discusses the scope and frequency of each activity.

7.1 Field Audits

Internal audits of field activities (sampling and measurements) will be conducted by the CDM Smith QA Coordinator, QA-trained field auditor, Principal Investigator, or designated field team lead. The audits will include examination of field sampling records, field instrument operating records, sample collection, handling and packaging, chain-of-custody records, and the maintenance of QA procedures. These internal audits will be performed to make sure field work is in compliance with established procedures. It is currently anticipated that one field audit will be performed – during the baseline sampling event of the demonstration.

If nonconformances are found, then the QA Officer working with the Project Manager and Principal Investigator will be responsible for ensuring that corrective actions are initiated by:

- Documenting them in an audit report to be added to the project file;
- Evaluating all reported nonconformances;
- Controlling additional work on nonconforming items;
- Determining disposition or action to be taken;
- Reviewing corrective action requests and corrective actions taken; and
- Ensuring corrective action requests are included in the final site documentation in project files.

If appropriate, the QA Officer will verify that no additional work that is dependent on the nonconforming activity is performed until the corrective actions are completed.

Corrective action for field measurements may include:

- Repeat the measurement to check the error;
- Check for all proper adjustments for ambient conditions such as temperature;
- Check the batteries;
- Recalibrate;
- Check the calibration;
- Replace the instrument or measurement devices; and
- Stop work (if necessary).

At this time it is not anticipated that external audits of the field activities will be needed. If the internal audits determine that deficiencies exist that require an outside organization or agent to resolve, external audits will be conducted by an independent subcontractor.

7.2 Laboratory Audits

CDM Smith is responsible for conducting laboratory pre-qualification evaluations consisting of the review of QA plans and the costs of various laboratories. A contingency laboratory may be contracted to perform general chemistry analyses, if necessary.

Internal laboratory system audits will be performed by the Laboratory QA Officer on at least an annual basis and will include an examination of laboratory documentation on sample receiving, sample log-in, sample storage, chain-of-custody procedures, sample preparation and analysis, and instrument operating records, as described in the laboratory QA Manual.

7.3 Self Assessments

CDM Smith will perform a self-assessment of the project files near the conclusion of the demonstration. This self-assessment will serve to ensure that documents have undergone appropriate review cycles. It also provides a check on records retention and management.

8.0 Quality Assurance Reports

8.1 ESTCP Quarterly Reports

The CDM Smith project manager will prepare ESTCP-required quarterly reports. These reports will update accomplishments on the demonstration and briefly describe any concerns that may affect technical or financial progress of the demonstration. These will be submitted using the web-based ESTCP reporting system. The Principal Investigator will also update ESTCP on progress and any issues affecting the project during annual in-progress review meetings.

8.2 Audit Reports

Laboratory audits will be written and maintained by the individual laboratory. These will be reviewed by CDM Smith as needed during the demonstration.

9.0 Data Management

Data management requirements are an essential part of the demonstration. The data management requirements included in this section outline procedures necessary to document, track, and manage field and laboratory data generated during the course of the field activities. The purpose of this section is to identify:

- Data management personnel and responsibilities
- Field, laboratory, and development data to be recorded and maintained
- Data coding requirements
- Data to be included on progress and site investigation reports

This section provides format requirements for presenting raw data, tabulated data, and summary data of field and laboratory analyses.

9.1 Management and Organization

9.1.1 CDM Smith Project Manager

The CDM Smith Project Manager will be responsible for checking that all field and laboratory information is collected and recorded accurately. The Project Manager will also be responsible for approving any changes in or deviations from the reporting of data, including data validation. Furthermore, the Project Manager will be responsible for performing inspections related to the generation, collection, and storage of data by laboratories.

9.1.2 CDM Smith Field Team Leader

The CDM Smith Field Team Leader or subcontractor will be responsible for maintaining and recording information and data required in the field logbook. In addition, the Field Team Leader will be responsible for checking that laboratory data are accounted for and accurately reflect field sampling and chain-of-custody information.

9.1.3 CDM Smith Technical Task Lead for Data Analysis and Interpretation

The Technical Task Lead for Data Analysis and Interpretation will be responsible for data entry, management, and evaluation. The Technical Task Lead will maintain project data in spreadsheets or databases as appropriate. The Technical Task Lead will also work with the Principal Investigator to form interpretations of demonstration plan data. The Technical Task Lead for Data Analysis and Interpretation will be responsible for maintaining trend charts and cumulative data tables. The Technical Task Lead for Data Analysis and Interpretation will work with the Technical Task Lead for Planning and Reporting as needed in order to produce the required project reports.

9.1.4 Laboratory Project Manager

Multiple laboratories may be contracted to analyze environmental samples collected during the demonstration. These laboratories will each provide a Laboratory Project Manager responsible for ensuring that all laboratory data submitted are recorded, documented, and presented in the proper formats.

9.1.5 CDM Smith QA Coordinator

The CDM Smith QA Coordinator is responsible for data management efforts related to detecting and correcting errors, and data loss prevention.

9.2 Documentation and Records

Data, photographs, field logs, and calibration logs generated during the course of the investigation will be included as part of the project file. After completing the demonstration, data and reports will be maintained by CDM Smith.

9.2.1 Recording of Field Data

Field logbooks will be maintained by CDM Smith in accordance with CDM Smith's SOP 4-1 *Field Logbook Content and Control*. Separate field sheets may also be used to record field data. The front cover of each logbook will be labeled with the following information:

- Person or organization to whom the book is assigned
- Book number
- Project name, number
- Start date
- End date

Logbook entries will contain accurate and detailed documentation of daily project activities. Because the information contained in these logbooks forms a basis for subsequent reports, the field logbook will include the information specified below:

- Site identification
- Location of sampling points
- Description of sampling points
- References to any photographs
- Sample identification numbers
- Number of samples taken
- Date and time of sample collection
- Reference to sample location map
- Number of QA samples taken (e.g., duplicates)
- Collector's name
- Field observations
- Sample distribution (e.g., onsite laboratory, offsite laboratory)
- Field measurements made (e.g., pH, temperature, ORP, conductivity).

Any changes required to field logbook entries will not obscure the original entry. Changes will be made by striking a single line through the information to be changed and initialing and dating the change.

The Field Team Leader will perform quarterly reviews of field logbooks to check that data entries are being performed as specified above and in accordance with the CDM Smith standard operating procedure for field logbook content and control.

9.2.2 Recording of Laboratory Data

Particular procedures related to the management of data received from the laboratory will be recorded. These forms will not be included as part of the field logbook but will be maintained as part of the project files. The Laboratory Manager will be responsible for storing information and data recorded by the laboratory and related to the investigation. This information may include:

- Chain-of-custody forms
- Internal laboratory performance audits
- Raw data printouts
- Tabulated data printouts
- Laboratory QA/QC data

In addition, these data will be stored in a manner that protects their integrity.

For documentation purposes, each environmental sample or measurement will have the following applicable record details:

- A unique sample or field-measurement identification number
- Sample or field-measurement location
- Date sample or field measurement was taken
- Sample or field-measurement type
- Sample or field-measurement raw data
- Laboratory analysis qualifier
- Property or analysis measured
- Result of analysis (e.g., concentration)

9.2.3 Documentation of Sample Collection

Sample collection will be documented as described previously in Sections 9.2.1 and 9.2.2. The following information will be recorded, as applicable:

- Custody and document control
- Chain-of-custody from field to laboratory
- Laboratory custody through designated laboratory-sample custodian
- Sample designation number(s)
- Identity of sampler
- Date of sample collection, shipping, and laboratory analysis
- Physical data elements
- Sampling date and time
- Sampling location and description
- Sample collection technique
- Field preparation techniques (e.g., filtering)
- A description of the sampling methodology used
- Field preservation technique

9.2.4 Analytical Database

The primary objective for developing an analytical database is to ensure that a detailed record of data collection, analysis, verification, and reporting is maintained. In particular, environmental sampling data will be stored in an Excel database to facilitate data evaluation, statistical analyses, and reporting. CDM Smith will manage all field sampling and laboratory analytical data, which will be maintained in the project files.

9.2.5 Tabular Displays

Tabular displays will be used in the final report to present laboratory data, as appropriate. These displays may include:

- Unsorted (raw) data
- Data reduced for statistical analysis
- Sorted data by constituent monitored
- Other summarized data

9.2.6 Recording of Development Data

Development data are identified as those data or information developed using raw field or laboratory results (e.g., test kits, meter readings). Such data will be included in the final report and will be prepared in a clear, concise manner using graphical displays as appropriate.

9.3 Data Validation and Usability

Laboratory results will be reviewed for compliance with project objectives. Data validation and evaluation are discussed in the following sections.

9.3.1 Validation and Verification Methods

CDM Smith will evaluate analytical results to determine if they meet the expected performance criteria detailed in **Tables 3-1, 5-1 and 5-2** of the Demonstration Plan and Section 3 of this QAPP. For each sample delivery group, CDM Smith will review the data to flag any obvious discrepancies and compare the data with the expected performance metrics. Data quality reviews will include the evaluation of holding times, blanks, laboratory control samples, surrogate recoveries, internal standards, calibration checks, dilutions and laboratory case narratives.

9.3.2 Data Reporting

The analytical laboratory will provide all project data in both hardcopy and electronic format. The laboratory will also be required to confirm sample receipt and log-in information. The laboratory will return a copy of the completed chain-of-custody and confirmation of the laboratory's analytical log-in to CDM Smith within 24 hours of sample receipt.

The laboratory is required to retain a full copy of the analytical data and QC documentation. Such retained documentation will include all hard copies and electronic storage media. Deficiencies in data deliverables will be corrected through direct communication with the laboratory. All significant data discrepancies noted during the validation process will be documented.

Data assessment will be based on the criteria that the sample was properly collected and handled in accordance with the Demonstration Plan and QAPP. An evaluation of data accuracy, precision, and completeness, based on the criteria presented in this QAPP, will be performed by the data validator. This data quality assessment will indicate that the data are: (1) usable as a quantitative concentration, (2) usable with caution as an estimated concentration, or (3) unusable due to excessive out-of-control QC results. The demonstration study report will include a quality assurance section that will include an explanation of any deviations, the extent objectives were met, the usability of the data collected, and if data precision and accuracy were met.

9.3.3 Data Turnaround Time Requirements

The standard turnaround times for most analytical deliverables is 14 days from the time of receipt by the laboratory; however, CDM Smith may request accelerated turnaround times. Advance notification will be provided to the laboratory prior to decreasing the turnaround time. The laboratory will store samples for a minimum of 90 days prior to appropriate disposal. The laboratory will dispose of samples in accordance with all applicable regulatory requirements.

10.0 Data Storage and Archiving Procedures

The documents outlined below shall be maintained in Bellevue, Washington by CDM Smith in project files. The following documents shall be placed in the project file:

- Copy of the Demonstration Plan;
- Copy of the Health and Safety Plan;
- Copy of this QAPP;
- Original chain-of-custody records and field logs;
- Laboratory data (including electronic data deliverables);
- Copies of the Receipt of Sample Forms;
- Original records obtained during the demonstration;
- Complete copy of the analytical data and memoranda transmitting analytical data;
- Official correspondence received by or issued by ESTCP or sub-consultants to ESTCP, relating to the demonstration;
- Photographs associated with the project; and
- Reports (interim and final).

All records and documents that relate in any way to the site shall be preserved and retained for a minimum of ten years after the work has been completed. The CDM Smith Project Manager will review the files at the conclusion of the project to ensure that they are complete.

Electronic documents generated through the demonstration will be retained on CDM Smith’s document control system ProjectWise. This server is backed up daily, minimizing the potential for data loss. The most current version of each document will be maintained on the server and working copies will be placed in a file marked as superseded. The Principal Investigator will be the point-of-contact to obtain copies of records from the project file.

11.0 References

CDM Smith. 2012. CDM Federal Programs Corporation. Quality Assurance Manual. Revision 20. January.

Environmental Protection Agency (EPA). 2002. Guidance for Quality Assurance Project Plans. EPA QA/G-5. EPA/240/R-02/009. December.

Environmental Security Technology Certification Program (ESTCP). 2010. Demonstration Plan Guidance, Environmental Restoration Projects. July.

Attachment 1 CDM Smith Standard Operating Procedures

1-2	Sample Custody
1-4	Subsurface Soil Sampling
1-6	Groundwater Level Measurement
1-12	Low-Stress Low-Flow Groundwater Sampling
1-13	Drum Sampling
2-1	Packaging and Shipping Environmental Samples
2-2	Guide to Handling Investigation-Derived Waste
3-5	Lithologic Logging
3-6	Underground Facility Location
4-1	Field Logbook Content and Control
4-2	Photographic Documentation of Field Activities
4-3	Well Development and Purging
4-4	Design and Installation of Monitoring Wells in Aquifers
4-5	Field Equipment Decontamination
4-10	Borehole Well Decommissioning
5-1	Control of Measurement and Test Equipment

Appendix E

CDM Smith Site Health and Safety Plan

HEALTH AND SAFETY PLAN FORM

CDM Smith Health and Safety Program

This document is for the exclusive use of CDM Smith and its subcontractors

CDM Smith

PROJECT DOCUMENT #:

PROJECT NAME Sustained In Situ Chemical Oxidation (ISCO) of 1,4-Dioxane Using Slow Release Chemical Oxidant Cylinders

PROJECT# 9998-103347

REGION West

SITE ADDRESS Read Rd
Coronado, CA 92118
Lat./Long: 32.702654 -117.205114

CLIENT ORGANIZATION ESTCP

CLIENT CONTACT Andrea Leeson

CLIENT CONTACT PHONE # 703-696-2118

( ) AMENDMENT TO EXISTING APPROVED H&SP?

( ) H&SP AMENDMENT NUMBER? ____

( ) DATE OF PREVIOUS H&SP APPROVAL ____

OBJECTIVES OF FIELD WORK:
(e.g. collect surface soil samples):

Oversight of demonstration activities that will be performed by a CDM Smith subcontractor. CDM Smith personnel will not perform any actual work. The subcontractor will perform the work in accordance with their NI NAS approved HASP.

SITE TYPE: *Check as many as applicable*

Active	(X)	Landfill	( )	Unknown	( )
Inactive	( )	Uncontrolled	( )	Military	(x)
Secure	(X)	Industrial	( )	Active Parking Lot	(x)
Unsecure	( )	Recovery	( )	Construction activities	(x)
Enclosed space	( )	Well Field	(x)	Traffic	(x)

All requirements described in the **CDM Health and Safety Manual** are incorporated in this health and safety plan by reference.

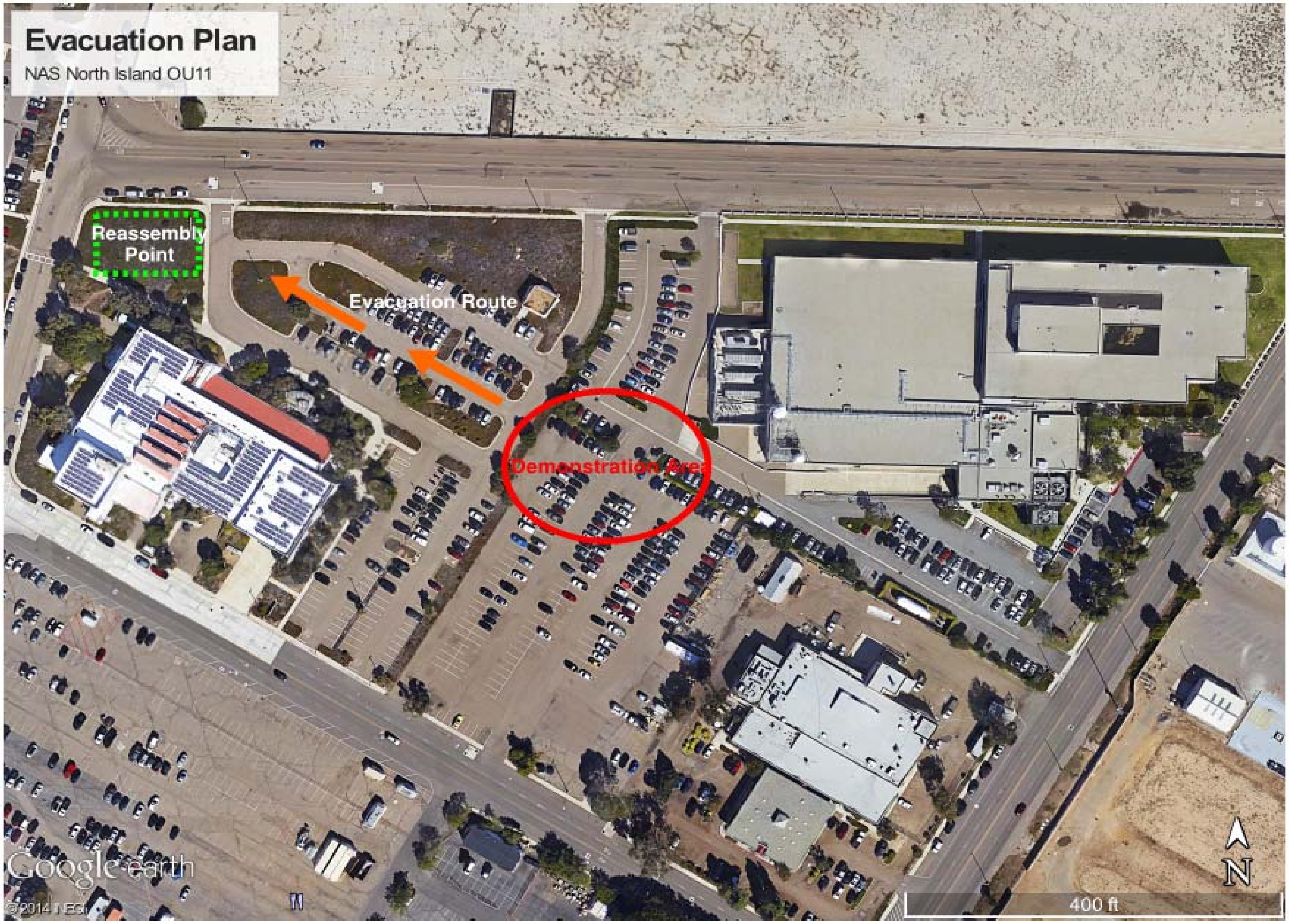
PERSONNEL AND RESPONSIBILITIES

NAMES OF WORK CREW MEMBERS	**Company / Division / Office**	**Current Training & Medical?**	**Project or Site Responsibilities**	**Tasks On Site?**
Jennifer Hooper	CDM Smith/FSG/BLV	--	Project Manager	1-2-3-4-5-6
Patrick Evans	CDM Smith/ERD/BLV	HAZWOPER	Site Engineer	**1-2-3**-4-5-6
Mike Lamar	CDM Smith/ERD/DEN	HAZWOPER	Health & Safety Coordinator	**1-2-3**-4-5-6
Dung Nguyen	CDM Smith/ERD/DEN	HAZWOPER	2nd Health & Safety Coordinator	**1-2-3**-4-5-6
Steve Holmes	CDM Smith/ERD/BLV	HAZWOPER	2nd Health & Safety Coordinator	**1-2-3**-4-5-6
TBD	TBD		Subcontractor	1-2-3-4-5-6

BACKGROUND REVIEW: (X) Complete ( ) Incomplete

HEALTH AND SAFETY PLAN FORM	*This document is for the exclusive*	**CDM Smith**
CDM Smith Health and Safety Program	*use of CDM Smith and its subcontractors*	**PROJECT DOCUMENT #:**

SITE MAP: *Show Exclusion, Contamination Reduction, and Support Zones. Indicate Evacuation and Reassembly Points*



HEALTH AND SAFETY PLAN FORM *This document is for the exclusive* **CDM Smith**
CDM Smith Health and Safety Program *use of CDM Smith and its subcontractors* **PROJECT DOCUMENT #:**

HISTORY: *Summarize conditions that relate to hazard. Include citizen complaints, spills, previous investigations or agency actions, known injuries, etc.*

Operable Unit (OU) 11 at NAS North Island is an active Department of Defense site. Primary contaminants of concern are VOCs including TCE and 1,4-dioxane, resulting from past releases of chlorinated solvents. Recent groundwater concentrations have been detected of 210,000 ug/L for TCE and 6,500 ug/L for 1,4-dioxane. Other groundwater contaminants include cis-1,2-DCE, 1,1-DCE, and 1,1-DCA.

WASTE TYPES: ( ) Liquid ( ) Solid ( ) Sludge ( ) Gas (X) Unknown ( ) Other, specify:

WASTE CHARACTERISTICS: *Check as many as applicable.*

(x) Corrosive	(x) Flammable	( ) Radioactive
( ) Toxic	(x) Volatile	( ) Reactive
( ) Inert Gas	( ) Unknown	
( ) Other:		

WORK ZONES:

Exclusion: Within 1.5 times the mast height of any drill rig, 10 feet from heavy equipment or trench.

Contamination Reduction: Immediately outside of the exclusion zone where equipment will be decontaminated

Support Zone: All other areas outside of the Exclusion and Contamination Reduction zones

HAZARDS OF CONCERN: *Check as many as applicable.*

( ) Heat Stress	CDM Smith Guideline	(X) Noise	CDM Smith Guideline
( ) Cold Stress	CDM Smith Guideline	(X) Inorganic Chemicals	
( ) Explosive/Flammable		(X) Organic Chemicals	
( ) Oxygen Deficient		(X) Motorized Traffic	
( ) Radiological		(X) Heavy Machinery	
(X) Active parking lot	Traffic	(X) Slips & Falls	CDM Smith Guideline
( ) Other:			
( ) Other:			

FACILITY'S PAST AND PRESENT DISPOSAL METHODS AND PRACTICES:

This plan incorporates CDM Smith's procedure for: *(Click on the relevant topics to download the hazard guideline. Delete irrelevant topics.)*

Housekeeping	Traffic and Work Zone Safety	Working Safely Around Drill Rigs
Manual Material Handling	Excavations	Hazardous Waste Site Controls
Electrical Safety	Tools and Power Equipment	Decontamination at Hazardous Waste Sites
Lock Out/Tag Out	Working Around Heavy Equipment	
	Hazardous Waste Site Decontamination	

HEALTH AND SAFETY PLAN FORM *This document is for the exclusive use of CDM Smith and its subcontractors* **CDM Smith**
CDM Smith Health and Safety Program **PROJECT DOCUMENT #:**

DESCRIPTION AND FEATURES: *Include principal operations and unusual features (containers, buildings, dikes, power lines, hillslopes, rivers, etc.)*

The technology demonstration will be performed in a portion of an active parking lot within Operable Unit 11 of the North Island Naval Air Station as shown on Page 2.

SURROUNDING POPULATION: (X) Residential (X) Industrial ( ) Commercial (X) Rural ( ) Urban OTHER:

HAZARDOUS MATERIAL SUMMARY: ***Highlight or bold waste types and estimate amounts by category.***

CHEMICALS:	**SOLIDS:**	**SLUDGES:**	**SOLVENTS:**	**OILS:**	**OTHER:**
Amount/Units:	*Amount/Units:*	*Amount/Units:*	*Amount/Units:*	*Amount/Units:*	*Amount/Units:*
Acids	Flyash	Paints	Ketones	Oily Wastes	Laboratory
Pickling Liquors	Mill or Mine Tailings	Pigments	Aromatics	Gasoline	Pharmaceutical
Caustics	Asbestos	Metals Sludges	**Hydrocarbons**	Diesel Oil	Hospital
Pesticides	Ferrous Smelter	POTW Sludge	Alcohols	Lubricants	Radiological
Dyes or Inks	Non-Ferrous Smelter	Distillation Bottoms	**Halogenated (chlorinated solvents, historical)**	Polynuclear Aromatics	Municipal
Cyanides	Metals	Aluminum	Esters	PCBs	**Construction**
Phenols	Dioxins		Ethers	Heating Oil	**Possible Munitions (historical activities)**
Halogens					
Persulfate - Oxidizer	Other - *specify*	Other - *specify*	Other - *specify*	Other - *specify*	Other - *specify*
Persulfate - Corrosive			**1,4-Dioxane**		
Persulfate - Flammable			**Trichloroethene**		
			Cis-1,2-dichloroethene		
			1,1-dichloroethene		
			1,1-dichloroethane		

HEALTH AND SAFETY PLAN FORM
CDM Smith Health and Safety Program

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CDM Smith
PROJECT DOCUMENT #:

KNOWN CONTAMINANTS	HIGHEST OBSERVED CONCENTRATION	PEL/TLV *ppm or mg/m3 (specify)*	IDLH *ppm or mg/m3 (specify)*	Warning Concentration *(in ppm)*	SYMPTOMS & EFFECTS OF ACUTE EXPOSURE	PHOTO IONIZATION POTENTIAL
1,4-Dioxane	**6.5 ppm in GW**	100 ppm	500 ppm	2.7 ppm *(mild, ether-like odor)*	Eye/skin/nose/throat irritation, cough, sore throat, shortness of breath, dizziness, headache, drowsiness, abdominal pain	9.13
Trichloroethylene	**210 ppm in GW**	50 ppm	1,000 ppm	82 ppm	Vertigo, visual disturbance, headache, drowsiness, cancer	9.45
Cis-1,2-dichloroethene	**6 ppm in GW**	200 ppm	1,000 ppm	0.08 ppm	Irritation eyes, respiratory system; central nervous system depression	9.65
1,1-dichloroethene	**6.4 ppm in GW**	NA	NA	500 ppm	Irritation eyes, skin, throat; dizziness, headache, nausea, dyspnea (breathing difficulty); liver, kidney disturbance; pneumonitis; [potential occupational carcinogen]	10.00
1,1-dichloroethane	**3.2 ppm in GW**	100 ppm	4,000 ppm	120 ppm	Irritation skin; central nervous system depression; liver, kidney, lung damage	11.06
Persulfate	**10,000 ppm in GW**	NA	NA	NA	Corrosive	NA

NA = Not Available **NE = None Established** **U = Unknown**

Verify your access to an MSDS for each chemical you will use at the site.

S = Soil
A = Air
SW = Surface Water
GW = Ground Water
T = Tailings
SL = Sludge
W = Waste
D = Drums
TK = Tanks
L = Lagoons
SD = Sediment
OFF = Off-Site

HEALTH AND SAFETY PLAN FORM *This document is for the exclusive use of CDM Smith and its subcontractors* **CDM Smith**

CDM Smith Health and Safety Program **PROJECT DOCUMENT #:**

SPECIFIC TASK DESCRIPTIONS	Disturbing the Waste?	TASK - SPECIFIC HAZARDS	HAZARD & SCHEDULE
1 Oversight of all activities described in the demonstration plan	**Intrusive**	None	**Low Hazard**
2	**Pick from the list**		**Pick from the list**
3	**Pick from the list**		**Pick from the list**
4	**Pick from the list**		**Pick from the list**
5	**Pick from the list**		**Pick from the list**
6	**Pick from the list**		**Pick from the list**

SPECIALIZED TRAINING REQUIRED: None	**SPECIAL MEDICAL SURVEILLANCE REQUIREMENTS:** **None**

OVERALL HAZARD EVALUATION: ( ) High ( ) Medium (X) Low ( ) Unknowr *(Where tasks have different hazards, evaluate each.)*

JUSTIFICATION: Risk of exposure is medium due to working with contaminated groundwater and soil. O&M activities will present an exposure to electrical systems, etc.

FIRE/EXPLOSION POTENTIAL: ( ) High ( ) Medium (X) Low ( ) Unknown

HEALTH AND SAFETY PLAN FORM
CDM Smith Health and Safety Program

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CDM Smith
PROJECT DOCUMENT #:

PROTECTIVE EQUIPMENT: *Specify by task. Indicate type and/or material, as necessary. Group tasks if possible. Use copies of this sheet if needed.*

BLOCK A

TASKS: **1** - 2 - 3 - 4 - 5 - 6 - 7 - 8 - 9 - 10
LEVEL: A - B - C - **D**
(x) Primary ( ) Contingency

Respiratory: (x) Not needed
( ) SCBA, Airline:
( ) APR:
( ) Cartridge:
( ) Escape Mask:
( ) Other:

Head and Eye: ( ) Not needed
(x) Safety Glasses:
( ) Face Shield:
( ) Goggles:
(x) Hard Hat: overhead hazards
( ) Other:

Boots: ( ) Not needed
(x) Steel-Toe ( ) Steel Shank
( ) Rubber ( ) Leather
( ) Overboots:

Prot. Clothing: ( ) Not needed
( ) Encapsulated Suit:
( ) Splash Suit
( ) Apron:
( ) Tyvek Coverall or
( ) Saranex Coverall
( ) Cloth Coverall:
(x) Long sleeves, pants

Gloves: ( ) Not needed
( ) Undergloves:
(x) Gloves: Nitrile
( ) Overgloves:

Other: specify below
(x) Traffic control
(x) Comply with H&S Manual page 16.4-9 for electrical work
(x) Hearing Protection
(x) Sun Screen

BLOCK B

TASKS: **1** - 2 - 3 - 4 - 5 - 6 - 7 - 8 - 9 - 10
LEVEL: A - B - C - D - Modified
(x) Primary (x) Contingency

Respiratory: (x) Not needed
( ) SCBA, Airline:
( ) APR
( ) Car
( ) Esca
( ) Oth

Head and Eye: ( ) Not needed
( ) Safety Glasses:
( ) Face Shield:
( ) Goggles:
( ) Hard Hat:
( ) Oth

Boo N eed
( )) Shar
(ber ner
( ) Overboots: Latex

Prot. Clothing: ( ) Not needed
( ) Encapsulated Suit:
( ) Sp Suit
( ) Apron:
) Ty C r
) Sa x C all
C Cov
( ) Other: Long sleeves, pants

Gloves: ( ) Not needed
( ) Undergloves:
( ) Gloves: Nitrile
( ) Overgloves:

he ecify bel
) Tick Spr
. D Wate
( ) Hearing Protection
( ) Sun Screen

Exit Area

I

TASKS: 1 - 2 - 3 - 4 - 5 - 6 - 7 - 8 - 9 - 10
LEVEL: A - B - C - D - Modified
( ) Primary ( ) Contingency

Respiratory: ( ) Not needed
( ) SCBA, Airline:
( ) APR:
( ) Cartridge:
( ) Escape Mask:
( ) Other:

Head and Eye: ( ) Not needed
( ) Safety Glasses:
( ) Face Shield:
( ) Goggles:
( ) Hard Hat:
( ) Other:

Boots: ( ) Not needed
( ) Steel-Toe ( ) Steel Shar
( ) Rubber ( ) Leather
( ) Overboots:

Prot. Clothing: ( ) Not needed
( ) Encapsulated Suit:
( ) Splash Suit
( ) Apron:
( ) Tyvek Coverall
( ) Saranex Coverall
( ) Cloth Coverall:
( ) Other:

Gloves: ( ) Not needed
( ) Undergloves:
( ) Gloves:
( ) Overgloves:

Other: specify below
( ) Tick Spray
( ) Flotation Device
( ) Hearing Protection
( ) Sun Screen

K D

TASKS: 1 - 2 - 3 - 4 - 5 - 6 - 7 - 8 - 9 - 10
LEVEL: A - B - C - D - Modified
( ) Primary ( ) Contingency

Respiratory: ( ) Not needed
( ) SCBA, Airline:
( ) APR:
( ) Cartridge:
( ) Escape Mask:
( ) Other:

Head and Eye: ( ) Not needed
( ) Safety Glasses:
( ) Face Shield:
( ) Goggles:
( ) Hard Hat:
( ) Other:

Boots: ( ) Not needed
( ) Steel-Toe ( ) Steel Shank
( ) Rubber ( ) Leather
( ) Overboots:

Prot. Clothing: ( ) Not needed
( ) Encapsulated Suit:
( ) Splash Suit
( ) Apron:
( ) Tyvek Coverall
( ) Saranex Coverall
( ) Cloth Coverall:
( ) Other:

Gloves: ( ) Not needed
( ) Undergloves:
( ) Gloves:
( ) Overgloves:

Other: specify below
( ) Tick Spray
( ) Flotation Device
( ) Hearing Protection
( ) Sun Screen

This health and safety plan form constitutes hazard analysis per 29 CFR 1910.132

HEALTH AND SAFETY PLAN FORM		*This document is for the exclusive*		**CDM Smith**
CDM Smith Health and Safety Program		*use of CDM Smith and its subcontractors*		**PROJECT DOCUMENT #:**
MONITORING EQUIPMENT:		*Specify by task. Indicate type as necessary. Attach additional sheets if needed.*		
INSTRUMENT	**TASK**	**ACTION GUIDELINES**		**COMMENTS**
Combustible		0-10% LEL	*No explosion hazard*	(x) Not Needed
Gas Indicator	1-2-3-4-5-6-7-8	10-25% LEL	*Potential explosion hazard; notify SHSC*	
		>25% LEL	*Explosion hazard; interrupt task/evacuate*	
		21.0% O2	*Oxygen normal*	
		<21.0% O2	*Oxygen deficient; notify SHSC*	
		<19.5% O2	*Interrupt task/evacuate*	
Radiation		3 x Background:	*Notify HSM*	(x) Not Needed
Survey Meter	1-2-3-4-5-6-7-8	>2mR/hr:	*Establish REZ*	
Photoionization **Detector** 10.6 eV Lamp Type: OVM	*Specify:* **1**-2-3-4-5-6-7-8	0-1 ppm : Level D > 1 ppm sustained in breathing zone: Exit Area If oversight personnel notices unusual odors or irritation of the eyes or throat, they will leave the area.		( ) Not Needed Monitor breathing zone continuously. Compare action levels to time-averaged breathing zone measurements.
Flame Ionization **Detector** Type____________	*Specify:* 1-2-3-4-5-6-7-8			(x) Not Needed
Gas Meter Type H_2S________ Type____________	*Specify:* 1-2-3-4-5-6-7-8			(x) Not Needed
Respirable **Dust Monitor** Type____________ Type____________	*Specify:* **1**-2-3-4-5-6-7-8			( ) Not Needed Direct subcontractor to perform visible dust using engineering controls such as applying water if necessary.
Other Type____________ Type____________	*Specify:* 1-2-3-4-5-6-7-8			(x) Not Needed
Other Type____________ Type____________	*Specify:* 1-2-3-4-5-6-7-8			(x) Not Needed

HEALTH AND SAFETY PLAN FORM *This document is for the exclusive* **CDM Smith**
CDM Smith Health and Safety Program *use of CDM Smith and its subcon* **PROJECT DOCUMENT #:**

DECONTAMINATION PROCEDURES

ATTACH SITE MAP INDICATING EXCLUSION, DECONTAMINATION, & SUPPORT ZONES AS PAGE TWO

Personnel Decontamination *Summarize below or attach diagram;*	**Sampling Equipment Decontamination** *Summarize below or attach diagram;*	**Heavy Equipment Decontamination** *Summarize below or attach diagram;*
Not applicable	Not applicable	Not applicable
( ) Not Needed	( ) Not Needed	( ) Not Needed
Containment and Disposal Method	**Containment and Disposal Method**	**Containment and Disposal Method**
Not applicable	Not applicable	Not applicable

HAZARDOUS MATERIALS TO BE BROUGHT ONSITE

Preservatives		*Decontamination*		*Calibration*	
(X) Hydrochloric Acid	( ) Zinc Acetate	(X) Alconox ™	( ) Hexane	(X) 100 ppm isobutylene	( ) Hydrogen Sulfide
(X) Nitric Acid	( ) Ascorbic Acid	( ) Liquinox ™	( ) Isopropanol	( ) Methane	( ) Carbon Monoxide
( ) Sulfuric Acid	( ) Acetic Acid	( ) Acetone	( ) Nitric Acid	( ) Pentane	(X) pH Standards
( ) Sodium Hydroxide	( ) Other:	( ) Methanol	( ) Other:	( ) Hyrogen	(X) Conductivity Std
		( ) Mineral Spirits		( ) Propane	( ) Other:

HEALTH AND SAFETY PLAN FORM

CDM Smith Health and Safety Program

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CDM Smith

PROJECT DOCUMENT #:

EMERGENCY CONTACTS	
Water Supply	
EPA Release Report #:	800 / 424 - 8802
CDM 24-Hour Emergency #:	FSG 406 / 293 - 1547
Facility Management	
Other (specify)	
CHEMTREC Emergency #:	800 / 424 - 9300

SAFETY NARRATIVE: *Summarize below*

CDM Smith will only perform oversight of activities described in the demonstration plan.

HEALTH AND SAFETY PLAN APPROVALS (H&S Mgr must sign each plan)

Prepared by ____________ Date ____________

HSC Signature ____________ Date ____________

HSM Signature ____________ Date May 29, 2015

EMERGENCY CONTACTS	**NAME**	**PHONE**
Health and Safety Manager	Joe Leslie	760 / 947 - 4898
Site Safety Coordinator	Patrick Evans	425-519-8300
Client Contact	Andrea Leeson	703-696-2118
Other *(specify)*		
Environmental Agency		
State Spill Number	California	(800) 852-7550
Fire Department (Station 1 Building 792)		(619) 545-6682
Police Department (Force Protection, Building 2001)		(619) 545-7418
State Police		911
Health Department		
Poison Control Center	Nationwide	800 / 222 - 1222
Occupational Physician	Dr. Jerry Berke	800 / 350 - 4511

MEDICAL EMERGENCY		**PHONE**
Hospital Name:	Sharp Coronado Hospital	619 522-3600
Hospital Address	250 Prospect Place, Coronado, CA 92118	
Name of Contact at Hospital:		
Name of 24-Hour Ambulance:		

Route to Hospital:

1. Head north on Read Rd toward McCain W Blvd.
2. Turn right onto McCain W Blvd.
3. Turn left onto Read Rd.
4. Continue straight onto 4th St.
5. Turn right onto Quentin Roosevelt Blvd.
6. At the traffic circle, take the 2nd exit onto McCain Blvd/4th St.
7. Continue onto McCain Blvd/4th St.
8. Turn left toward Third St.
9. Slight right at 3rd St/Pomona Ave.
10. Slight right onto Third St.
11. Turn left onto Prospect Pl., Hospital is on the left.

Distance to Hospital 1.6 miles

HEALTH AND SAFETY PLAN SIGNATURE FORM

CDM Smith Health and Safety Plan

All site personnel must sign this form indicating receipt of the H&SP. Keep this original on site. It becomes part of the permanent project files. Send a copy to the Health and Safety Manager (HSM).

SITE NAME/NUMBER: Sustained In Situ Chemical Oxidation (ISCO) of 1,4-Dioxane Using Slow Release Chemical Oxidant Cylinders

DIVISION/LOCATION: ____________________

CERTIFICATION:

I understand, and agree to comply with, the provisions of the above referenced H&SP for work activities on this project. I agree to report any injuries, illnesses or exposure incidents to the site Health and Safety Coordinator (SHSC). I agree to inform the SHSC about any drugs (legal and illegal) that I take within three days of site work.

PRINTED NAME	SIGNATURE	DATE

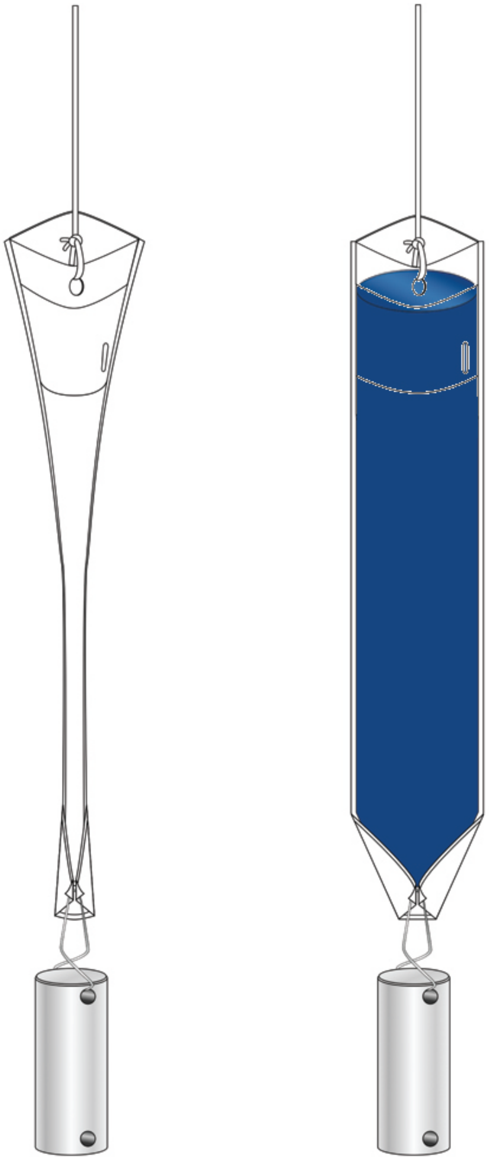
Appendix F

HydraSleeve^{TM} Standard Operating Procedure

HYDRASleeve™

Simple by Design US Patent No. 6,481,300; No. 6,837,120 others pending

Standard Operating Procedure:
Sampling Ground Water with a HydraSleeve



This Guide should be used in addition to field manuals appropriate to sampling device (i.e., HydraSleeve or Super Sleeve).

Find the appropriate field manual on the HydraSleeve website at http://www.hydrasleeve.com.

For more information about the HydraSleeve, or if you have questions, contact:
GeoInsight, 2007 Glass Road, Las Cruces, NM 88005, 1-800-996-2225,
info@hydrasleeve.com.

Table of Contents

Introduction

The HydraSleeve is classified as a no-purge (passive) grab sampling device, meaning that it is used to collect ground-water samples directly from the screened interval of a well without having to purge the well prior to sample collection. When it is used as described in this Standard Operating Procedure (SOP), the HydraSleeve causes no drawdown in the well (until the sample is withdrawn from the water column) and only minimal disturbance of the water column, because it has a very thin cross section and it displaces very little water (<100 ml) during deployment in the well. The HydraSleeve collects a sample from within the screen only, and it excludes water from any other part of the water column in the well through the use of a self-sealing check valve at the top of the sampler. It is a single-use (disposable) sampler that is not intended for reuse, so there are no decontamination requirements for the sampler itself.

The use of no-purge sampling as a means of collecting representative ground-water samples depends on the natural movement of ground water (under ambient hydraulic head) from the formation adjacent to the well screen through the screen. Robin and Gillham (1987) demonstrated the existence of a dynamic equilibrium between the water in a formation and the water in a well screen installed in that formation, which results in formation-quality water being available in the well screen for sampling at all times. No-purge sampling devices like the HydraSleeve collect this formation-quality water as the sample, under undisturbed (non-pumping) natural flow conditions. Samples collected in this manner generally provide more conservative (i.e., higher concentration) values than samples collected using well-volume purging, and values equivalent to samples collected using low-flow purging and sampling (Parsons, 2005).

Applications of the HydraSleeve

The HydraSleeve can be used to collect representative samples of ground water for all analytes (volatile organic compounds [VOCs], semi-volatile organic compounds [SVOCs], common metals, trace metals, major cations and anions, dissolved gases, total dissolved solids, radionuclides, pesticides, PCBs, explosive compounds, and all other analytical parameters). Designs are available to collect samples from wells from 1” inside diameter and larger. The HydraSleeve can collect samples from wells of any yield, but it is especially well-suited to collecting samples from low-yield wells, where other sampling methods can’t be used reliably because their use results in dewatering of the well screen and alteration of sample chemistry (McAlary and Barker, 1987).

The HydraSleeve can collect samples from wells of any depth, and it can be used for single-event sampling or long-term ground-water monitoring programs. Because of its thin cross section and flexible construction, it can be used in narrow, constricted or damaged wells where rigid sampling devices may not fit. Using multiple HydraSleeves deployed in series along a single suspension line or tether, it is also possible to conduct in-well vertical profiling in wells in which contaminant concentrations are thought to be stratified.

As with all groundwater sampling devices, HydraSleeves should not be used to collect groundwater samples from wells in which separate (non-aqueous) phase hydrocarbons (i.e., gasoline, diesel fuel or jet fuel) are present because of the possibility of incorporating some of the separate-phase hydrocarbon into the sample.

Description of the HydraSleeve

The HydraSleeve (Figure 1) consists of the following basic components:

- A suspension line or tether (A.), attached to the spring clip or directly to the top of the sleeve to deploy the device into and recover the device from the well. Tethers with depth indicators marked in 1-foot intervals are available from the manufacturer.
- A long, flexible, 4-mil thick lay-flat polyethylene sample sleeve (C.) sealed at the bottom (this is the sample chamber), which comes in different sizes, as discussed below with a self-sealing reed-type flexible polyethylene check valve built into the top of the sleeve (B.) to prevent water from entering or exiting the sampler except during sample acquisition.
- A reusable stainless-steel weight with clip (D.), which is attached to the bottom of the sleeve to carry it down the well to its intended depth in the water column. Bottom weights available from the manufacturer are 0.75" OD and are available in three sizes: 5 oz. (2.5" long); 8 oz. (4" long); and 16 oz. (8" long). In lieu of a bottom weight, an optional top weight may be attached to the top of the HydraSleeve to carry it to depth and to compress it at the bottom of the well (not shown in Figure 1);
- A discharge tube that is used to puncture the HydraSleeve after it is recovered from the well so the sample can be decanted into sample bottles (not shown).
- Just above the self-sealing check valve at the top of the sleeve are two holes which provide attachment points for the spring clip and/or suspension line or tether. At the bottom of the sample sleeve are two holes which provide attachment points for the weight clip and weight.

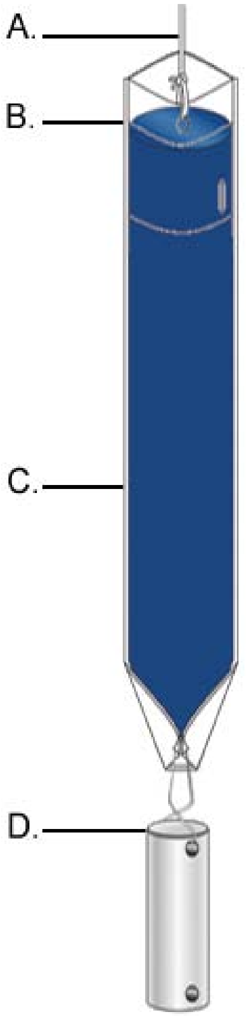


Figure 1. HydraSleeve components.

Note: The sample sleeve and the discharge tube are designed for one-time use and are disposable. The spring clip, weight and weight clip may be reused after thorough cleaning. Suspension cord is generally disposed after one use although, if it is dedicated to the well, it may be reused at the discretion of the sampling personnel.

Selecting the HydraSleeve Size to Meet Site-Specific Sampling Objectives

It is important to understand that each HydraSleeve is able to collect a finite volume of sample because, after the HydraSleeve is deployed, you only get one chance to collect an undisturbed sample. Thus, the volume of sample required to meet your site-specific sampling and analytical requirements will dictate the size of HydraSleeve you need to meet these requirements.

The volume of sample collected by the HydraSleeve varies with the diameter and length of the HydraSleeve. Dimensions and volumes of available HydraSleeve models are detailed in Table 1.

Table 1. Dimensions and volumes of HydraSleeve models.

Diameter	Volume	Length	Lay-Flat Width	Filled Dia.
2-Inch HydraSleeves				
Standard 625-ml HydraSleeve	625 ml	< 30”	2.5”	1.4”
Standard 1-Liter HydraSleeve	1 Liter	38”	3”	1.9”
1-Liter HydraSleeve SS	1 Liter	36”	3”	1.9”
2-Liter HydraSleeve SS	2 Liters	60”	3”	1.9”
4-Inch HydraSleeves				
Standard 1.6-Liter HydraSleeve	1.6 Liters	30”	3.8”	2.3”
Custom 2-Liter HydraSleeve	2 Liters	36”	4”	2.7”

HydraSleeves can be custom-fabricated by the manufacturer in varying diameters and lengths to meet specific volume requirements. HydraSleeves can also be deployed in series (i.e., multiple HydraSleeves attached to one tether) to collect additional sample to meet specific volume requirements, as described below.

If you have questions regarding the availability of sufficient volume of sample to satisfy laboratory requirements for analysis, it is recommended that you contact the laboratory to discuss the minimum volumes needed for each suite of analytes. Laboratories often require only 10% to 25% of the volume they specify to complete analysis for specific suites of analytes, so they can often work with much smaller sample volumes that can easily be supplied by a HydraSleeve.

HydraSleeve Deployment

Information Required Before Deploying a HydraSleeve

Before installing a HydraSleeve in any well, you will need to know the following:

- The inside diameter of the well
- The length of the well screen
- The water level in the well
- The position of the well screen in the well
- The total depth of the well

The inside diameter of the well is used to determine the appropriate HydraSleeve diameter for use in the well. The other information is used to determine the proper placement of the HydraSleeve in the well to collect a representative sample from the screen (see HydraSleeve Placement, below), and to determine the appropriate length of tether to attach to the HydraSleeve to deploy it at the appropriate position in the well.

Most of this information (with the exception of the water level) should be available from the well log; if not, it will have to be collected by some other means. The inside diameter of the well can be measured at the top of the well casing, and the total depth of the well can be measured by sounding the bottom of the well with a weighted tape. The position and length of the well screen may have to be determined using a down-hole camera if a well log is not available. The water level in the well can be measured using any commonly available water-level gauge.

HydraSleeve Placement

The HydraSleeve is designed to collect a sample directly from the well screen, and it fills by pulling it up through the screen a distance equivalent to 1 to 1.5 times its length. This upward motion causes the top check valve to open, which allows the device to fill. To optimize sample recovery, it is recommended that the HydraSleeve be placed in the well so that the bottom weight rests on the bottom of the well and the top of the HydraSleeve is as close to the bottom of the well screen as possible. This should allow the sampler to fill before the top of the device reaches the top of the screen as it is pulled up through the water column, and ensure that only water from the screen is collected as the sample. In short-screen wells, or wells with a short water column, it may be necessary to use a top-weight on the HydraSleeve to compress it in the bottom of the well so that, when it is recovered, it has room to fill before it reaches the top of the screen.

Example

2” ID PVC well, 50’ total depth, 10’ screen at the bottom of the well, with water level above the screen (the entire screen contains water).

Correct Placement (figure 2): Using a standard HydraSleeve for a 2” well (2.6” flat width/1.5” filled OD x 30” long, 650 ml volume), deploy the sampler so the weight (an 8 oz., 4”-long weight with a 2”-long clip) rests at the bottom of the well. The top of the sleeve is thus set at about 36” above the bottom of the well. When the sampler is recovered, it will be pulled upward approximately 30” to 45” before it is filled; therefore, it is full (and the top check valve closes) at approximately 66” (5 ½ feet) to 81” (6 ¾ feet) above the bottom of the well, which is well before the sampler reaches the top of the screen. In this example, only water from the screen is collected as a sample.

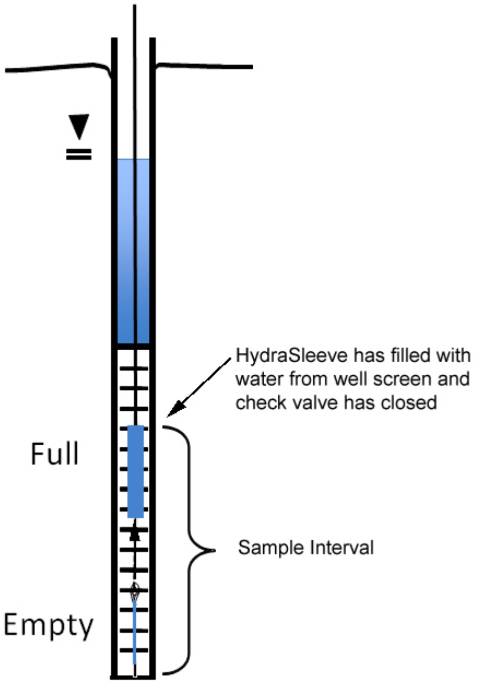


Figure 2. Correct placement of HydraSleeve.

Incorrect Placement (figure 3): If the well screen in this example was only 5' long, and the HydraSleeve was placed as above, it would not fill before the top of the device reached the top of the well screen, so the sample would include water from above the screen, which may not have the same chemistry.

The solution? Deploy the HydraSleeve with a top weight, so that it is collapsed to within 6" to 9" of the bottom of the well. When the HydraSleeve is recovered, it will fill within 39" (3 ¼ feet) to 54" (4 ½ feet) above the bottom of the well, or just before the sampler reaches the top of the screen, so it collects only water from the screen as the sample.

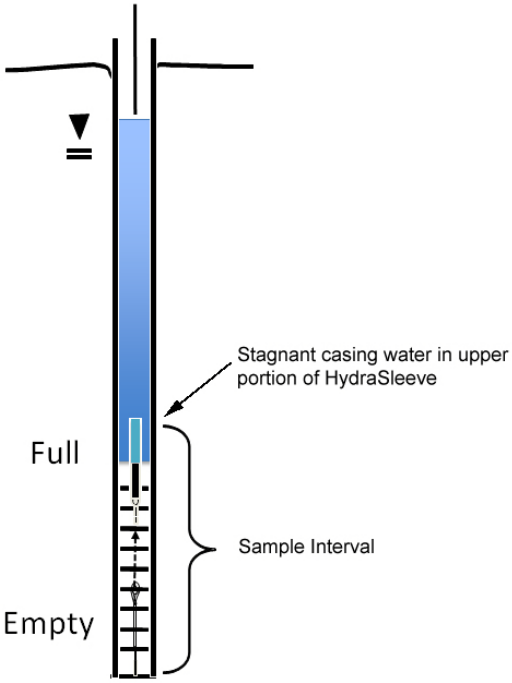


Figure 3. Incorrect placement of HydraSleeve.

This example illustrates one of many types of HydraSleeve placements. More complex placements are discussed in a later section.

Procedures for Sampling with the HydraSleeve

Collecting a ground-water sample with a HydraSleeve is a simple one-person operation.

Note: Before deploying the HydraSleeve in the well, collect the depth-to-water measurement that you will use to determine the preferred position of the HydraSleeve in the well. This measurement may also be used with measurements from other wells to create a ground-water contour map. If necessary, also measure the depth to the bottom of the well to verify actual well depth to confirm your decision on placement of the HydraSleeve in the water column.

Measure the correct amount of tether needed to suspend the HydraSleeve in the well so that the weight will rest on the bottom of the well (or at your preferred position in the well). Make sure to account for the need to leave a few feet of tether at the top of the well to allow recovery of the sleeve

Note: Always wear sterile gloves when handling and discharging the HydraSleeve.

I. Assembling the HydraSleeve

1. Remove the HydraSleeve from its packaging, unfold it, and hold it by its top.
2. Crimp the top of the HydraSleeve by folding the hard polyethylene reinforcing strips at the holes.
3. Attach the spring clip to the holes to ensure that the top will remain open until the sampler is retrieved.
4. Attach the tether to the spring clip by tying a knot in the tether.

Note: Alternatively, attach the tether to one (NOT both) of the holes at the top of the Hydrasleeve by tying a knot in the tether.

5. Fold the flaps with the two holes at the bottom of the HydraSleeve together and slide the weight clip through the holes.
6. Attach a weight to the bottom of the weight clip to ensure that the HydraSleeve will descend to the bottom of the well.

II. Deploying the HydraSleeve

1. Using the tether, carefully lower the HydraSleeve to the bottom of the well, or to your preferred depth in the water column

   During installation, hydrostatic pressure in the water column will keep the self-sealing check valve at the top of the HydraSleeve closed, and ensure that it retains its flat, empty profile for an indefinite period prior to recovery.

Note: Make sure that it is not pulled upward at any time during its descent. If the HydraSleeve is pulled upward at a rate greater than 0.5'/second at any time prior to recovery, the top check valve will open and water will enter the HydraSleeve prematurely.

2. Secure the tether at the top of the well by placing the well cap on the top of the well casing and over the tether.

Note: Alternatively, you can tie the tether to a hook on the bottom of the well cap (you will need to leave a few inches of slack in the line to avoid pulling the sampler up as the cap is removed at the next sampling event).

III. Equilibrating the Well

The equilibration time is the time it takes for conditions in the water column (primarily flow dynamics and contaminant distribution) to restabilize after vertical mixing occurs (caused by installation of a sampling device in the well).

- Situation: The HydraSleeve is deployed for the first time or for only one time in a well

  The HydraSleeve is very thin in cross section and displaces very little water (<100 ml) during deployment so, unlike most other sampling devices, it does not disturb the water column to the point at which long equilibration times are necessary to ensure recovery of a representative sample.

  In most cases, the HydraSleeve can be recovered immediately (with no equilibration time) or within a few hours. In regulatory jurisdictions that impose specific requirements for equilibration times prior to recovery of no-purge sampling devices, these requirements should be followed.

- Situation: The HydraSleeve is being deployed for recovery during a future sampling event

  In periodic (i.e., quarterly or semi-annual) sampling programs, the sampler for the current sampling event can be recovered and a new sampler (for the next sampling event) deployed immediately thereafter, so the new sampler remains in the well until the next sampling event.

Thus, a long equilibration time is ensured and, at the next sampling event, the sampler can be recovered immediately. This means that separate mobilizations, to deploy and then to recover the sampler, are not required. HydraSleeves can be left in a well for an indefinite period of time without concern.

IV. HydraSleeve Recovery and Sample Collection

1. Hold on to the tether while removing the well cap.
2. Secure the tether at the top of the well while maintaining tension on the tether (but without pulling the tether upwards)
3. Measure the water level in the well.
4. In one smooth motion, pull the tether up between 30” to 45” (36” to 54” for the longer HydraSleeve) at a rate of about 1’ per second (or faster).

   The motion will open the top check valve and allow the HydraSleeve to fill (it should fill in about 1 to 1.5 times the length of the HydraSleeve). This is analogous to coring the water column in the well from the bottom up.

   When the HydraSleeve is full, the top check valve will close. You should begin to feel the weight of the HydraSleeve on the tether and it will begin to displace water. The closed check valve prevents loss of sample and entry of water from zones above the well screen as the HydraSleeve is recovered.
5. Continue pulling the tether upward until the HydraSleeve is at the top of the well.
6. Decant and discard the small volume of water trapped in the Hydrasleeve above the check valve by turning the sleeve over.

V. Sample Collection

Note: Sample collection should be done immediately after the HydraSleeve has been brought to the surface to preserve sample integrity.

1. Remove the discharge tube from its sleeve.
2. Hold the HydraSleeve at the check valve.
3. Puncture the HydraSleeve just below the check valve with the pointed end of the discharge tube
4. Discharge water from the HydraSleeve into your sample containers.

Control the discharge from the HydraSleeve by either raising the bottom of the sleeve, by squeezing it like a tube of toothpaste, or both.

5. Continue filling sample containers until all are full.

Measurement of Field Indicator Parameters

Field indicator parameter measurement is generally done during well purging and sampling to confirm when parameters are stable and sampling can begin. Because no-purge sampling does not require purging, field indicator parameter measurement is not necessary for the purpose of confirming when purging is complete.

If field indicator parameter measurement is required to meet a specific non-purging regulatory requirement, it can be done by taking measurements from water within a HydraSleeve that is not used for collecting a sample to submit for laboratory analysis (i.e., a second HydraSleeve installed in conjunction with the primary sample collection HydraSleeve [see Multiple Sampler Deployment below]).

Alternate Deployment Strategies

Deployment in Wells with Limited Water Columns

For wells in which only a limited water column exists to be sampled, the HydraSleeve can be deployed with an optional top weight instead of a bottom weight, which collapses the HydraSleeve to a very short (approximately 6” to 9”) length, and allows the HydraSleeve to fill in a water column only 36” to 45” in height.

Multiple Sampler Deployment

Multiple sampler deployment in a single well screen can accomplish two purposes:

- It can collect additional sample volume to satisfy site or laboratory-specific sample volume requirements.
- It can accommodate the need for collecting field indicator parameter measurements.
- It can be used to collect samples from multiple intervals in the screen to allow identification of possible contaminant stratification.

It is possible to use up to 3 standard 30" HydraSleeves deployed in series along a single tether to collect samples from a 10' long well screen without collecting water from the interval above the screen.

The samplers must be attached to the tether at both the top and bottom of the sleeve. Attach the tether at the top with a stainless-steel clip (available from the manufacturer). Attach the tether at the bottom using a cable tie. The samplers must be attached as follows (figure 4):

- The first (attached to the tether as described above, with the weight at the bottom) at the bottom of the screen
- The second attached immediately above the first
- The third (attached the same as the second) immediately above the second

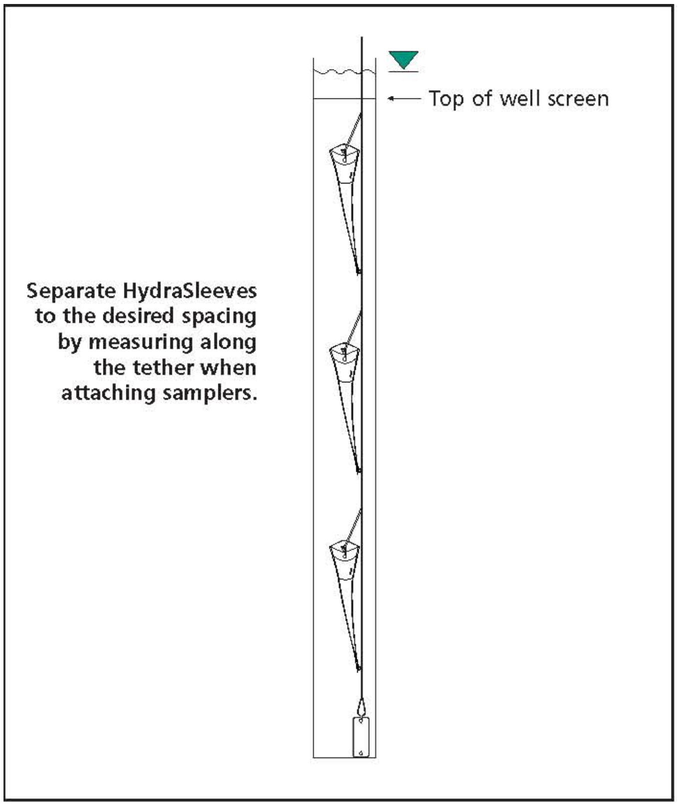


Figure 4. Multiple HydraSleeve deployment.

Alternately, the first sampler can be attached to the tether as described above, a second attached to the bottom of the first using a short length of tether (in place of the weight), and the third attached to the bottom of the second in the same manner, with the weight attached to the bottom of the third sampler (figure 5).

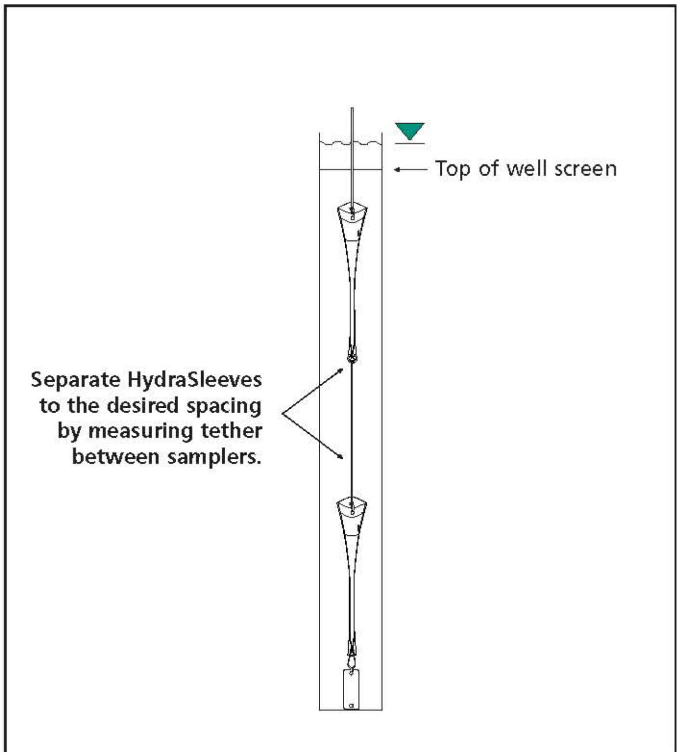


Figure 5. Alternative method for deploying multiple HydraSleeves.

In either case, when attaching multiple HydraSleeves in series, more weight may be required to hold the samplers in place in the well than would be required with a single sampler. Recovery of multiple samplers and collection of samples is done in the same manner as for single sampler deployments.

Post-Sampling Activities

The recovered HydraSleeve and the sample discharge tubing should be disposed as per the solid waste management plan for the site. To prepare for the next sampling event, a new HydraSleeve can be deployed in the well (as described previously) and left in the well until the next sampling event, at which time it can be recovered.

The weight and weight clip can be reused on this sampler after they have been thoroughly cleaned as per the site equipment decontamination plan. The tether may be dedicated to the well and reused or discarded at the discretion of sampling personnel.

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Appendix G

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Points of Contact

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APPENDIX D
DESIGN TOOL TECHNICAL REPORT

DRAFT
DESIGN TOOL TECHNICAL REPORT

Sustained *In situ* Chemical Oxidation (ISCO) of 1,4-Dioxane Using Slow-Release Chemical Oxidant Cylinders

ESTCP Project ER-201324

January 14, 2015

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Acronyms and Symbols

A	Amount of available MnO_4^- per unit volume (g/cm^3)
$\hat{A}$	Initial concentration of the solute in the matrix
C	Species (oxidant) concentration in groundwater (mg/L)
$\check{C}$	Concentration of source (mg/L)
C_0	Contaminant concentration in the source well (mg/L)
C_r	Concentration ratio
C_s	Solubility of $KMnO_4$ (g/cm^3)
C_x	Species concentration in a down gradient well along the plume centerline at a distance *x* (mg/L)
CDISCO	Conceptual Design for ISCO
D	Diffusivity of the solute through the matrix
D_e	Effective diffusion coefficient (cm^2/sec)
D_{et}	Diffusion coefficient at time t
D_x, D_y, D_z	Dispersion coefficients for the x, y, z dimensions (ft^2/day), respectively
E_L	Dispersion coefficient
h	Height of cylinder (cm)
H	Partitioning coefficient for $KMnO_4$ in the solid phase
ISCO	*In situ* chemical oxidation
$\hat{j}$	Release constant unique to the SRPC
k	Source decay constant
k_1	1st order NOD rate
K_s	Decay rate
L	Dispersive distance
n	Diffusional exponent
NOD	Natural oxidant demand
NRMSE	Normalized room mean square error
q_s	Flow rate of source (ft^3/day)
Q	Fraction of permanganate released at time t
Q'	Mass of permanganate released (g)
Q_{rr}	Release rate of permanganate (mg/day)
Q_f	Groundwater flow rate (L/day)

r	Radius of cylinder at time t (cm) (effective radius)
ř	Radius of the microcapsules
ŕ	Radius of the core
r_o	Initial radius of cylinder at $t = 0$ (cm)
R	Retardation (=1 for permanganate)
R_n	Reactions
RMSE	Root mean square error
S	Solubility of the solute in the matrix
SR	Slow release
t	Time
T	Tortuosity
Ť	Thickness of the shell
v	Groundwater seepage velocity (ft/day)
V_w	Volume of water
x	Downgradient distance
X	Time of interest (days), a known value
$x^{'}$	Centerline distance between down gradient reference point and source (ft)
y	Unit weight of the particles (gcm^{-3})
Y_s	Width (ft)
Z_s	Depth (ft)
α_x, α_y, and α_z	Longitudinal, transverse, and vertical dispersivity (ft), respectively
λ	Degradation rate constant (1/day), $\lambda = 0.693/t_{1/2}$ (where $t_{1/2}$ is the degradation half-life of the compound)

1.0 INTRODUCTION

To support the demonstration, validation, and technology transfer of slow release oxidant cylinders, an open-source conceptual design tool has been developed. Once oxidant cylinders are inserted in the subsurface, oxidant release and distribution are entirely passive processes. Oxidant is released to the surface of the cylinder resulting in a concentration at the surface of the cylinder. The oxidant is then carried in the direction of groundwater flow, at the same velocity as the groundwater, while simultaneously reacting with subsurface reduced species exerting natural oxidant demand (NOD) and contaminants. The conceptual design tool was developed to capture these processes and to simulate cylinder release rate, natural oxidant demand, reaction of oxidation with contaminant, and the resulting oxidant and contaminant distributions over time.

The design tool will be available for future users of the cylinder approach. Development of the tool was based on theoretical equations for oxidant release and reaction, and it was calibrated using results of the treatability laboratory evaluations conducted in support of the technology field demonstration/validation. The current version of the tool is a first draft and has been used to support the design of the field demonstration. The data collected during the demonstration will be used to validate, recalibrate, and finalize the design tool. In the meantime, the tool will be distributed to a select group of users, including DoD representatives, for beta testing. Feedback will be used to revise the tool as needed.

The tool was built in Microsoft Excel using analytical solutions to mathematical models to allow for ease of use and access. It is not meant to be used as an all-encompassing predictor of ISCO performance. It is intended help to predict the distance that oxidant will travel in the subsurface, the concentration of the oxidant that will be present downgradient of the oxidant source, and the resulting degradation of contaminant.

2.0 TOOL DEVELOPMENT

2.1 Permanganate Release

Upon initial contact with water, the granules of permanganate at the surface of slow release oxidant cylinders rapidly dissolve. This instant dissolution results in an initially high flux of oxidant mass and results in an early ‘spike’ or ‘pulse’ of oxidant (Lee and Schwartz 2007a). Eventually, the surface of the granules that is exposed to the water retreats into the center of the cylinder. As the permanganate retreats inward, the paraffin wax skeleton or matrix is left behind in the original shape and size of the cylinder and a secondary porosity is formed by the wax skeleton (Lee and Schwartz 2007a; Kang et al. 2004). **Figure 1** below depicts the different stages of permanganate release from a cylinder. Over time more permanganate (purple) will dissolve causing the surface of the solid permanganate to retreat further into the cylinder wax matrix (black). This creates a longer diffusive pathway for the remaining permanganate and consequently further slowing the oxidant release rate. As permanganate is released the rigid polymer matrix maintains its original shape and dimensions. **Figure 2** shows an example of a permanganate cylinder before and after is it is used. From the used cylinder shown in **Figure 2**, it is evident that the wax matrix is left behind as permanganate is released.

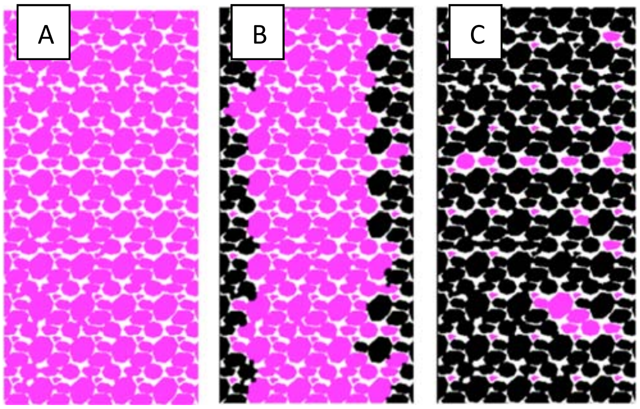


Figure 1. Schematic representation of permanganate release; a. Early-stage Release, b. Mid-stage Release, c. Late-stage Release

Figure 2. Photos of slow release permanganate cylinders. Left: Unused cylinder; Right: Used cylinder showing wax skeleton.

Permanganate dissolves and then diffuses through the inner cylinder porosity to the surface of the cylinder; therefore diffusion dictates the release rate of the remaining permanganate. The second phase of permanganate release is a diffusion-dissolution process. Previous literature indicates that highly water-soluble substances generally exhibit biphasic release patterns (Becirevic and Begic, 1994). Much of the slow release permanganate cylinder literature is in agreement; characterizing two phases to their dissolution; an initially large mass flux, followed by a sustained release which gradually slows as time goes (Kang et al., 2004; Lee and Schwartz, 2007a; Christenson et al., 2012).

Researchers have conducted bench scale experimental studies in order to predict the longevity of various types of slow release oxidants, primarily with permanganate. The bench scale experiments done by Ross et al. (2005) determined that slow release permanganate microcapsules had the capability to release permanganate from 3 to 80 days, with 27 days being the average time. A similar study was carried out by Kang et al. (2004) in which a time of 1.6 months, 19.3 years, and 472 years was estimated for 90% of permanganate release to occur, for paraffin wax to permanganate mass ratios of 1:1, 2:1, and 5:1, respectively. In a study conducted by Lee and Schwartz (2007a) 2.5 inch diameter permanganate cylinders were pre washed to remove surface permanganate (about 2.8 grams) and then tested in bench scale column and proof-of-concept flow tank experiments with 5 cm and 10 cm long cylinder sections respectively.

Initially permanganate concentrations were 56.6 mg/L and then decreased to 14.3 during the first 48 hours. After a 20 day long column study about 5.1 g of permanganate was released from a 5 cm cylinder section. Short-term experimental results and subsequent modeling of long-term slow release permanganate cylinder behavior from Lee and Schwartz (2007a) indicated that slow release permanganate cylinders (SRPCs) have the potential to release permanganate for 810 days or about 2.2 years. Christenson et al. (2012) also conducted longevity tests using various sizes of SRPC disks. In this study it was predicted that only about 20% of the total permanganate would be released from a 5.1 cm diameter 1.27 cm length cylinder section after 2 years (Christenson et al., 2012), which indicates a long lifespan for a slow release permanganate cylinder.

Persulfate release, based on experimental studies, is initially similar to that of permanganate in that there is initial release as a high concentration spike from the outer perimeter of the cylinder; however, thereafter, release is steady until complete (Kambhu et al., 2012).

2.1.1 Overview of Permanganate Release Models

There have been two main forms of kinetic models proposed to describe the slow release of permanganate from various formulations – exponential decay forms and power function forms. Kang et al., (2004) tested several models including zero order kinetics, the Sinclair Peppas Equation, modified first order kinetics and a modified hyperbola model. Of these models, release experiments were found to most closely match the Sinclair and Peppas model ($R^2 = 0.974$), which follows the general trend of a power function and is shown below in Equation 1.

$$Q = \hat{j}t^{n} \qquad [1]$$

Where:

Q= fraction of permanganate released at time t
ĵ = release constant unique to the cylinder
n= diffusional exponent

Kang et al. (2004) describe permanganate release from spherical granules, however. SRPCs are of cylindrical form and the geometry does not quite match that of the SRPCs.

More commonly used release models follow first order exponential decay trends (Ross et al., 2005; Lee and Schwartz 2007a, 2007b). A first order exponentially decaying model fits the theory of a dissolving source which is retreating further into the matrix and encounters an increasing diffusive distance (Higuchi, 1963). Ross et al., (2005) used two exponential decay models and an empirical function to characterize permanganate release. The first decay model was based on a model described by Desai et al., (1965) and Kydonieus, (1980). This model assumes that (1) a pseudo steady state exists; (2) permanganate particles are small compared to the average distance of diffusion; (3) the diffusion coefficient of the matrix is constant; and (4) a perfect sink condition exists in the media. This model is shown in Equation 2.

$$t = \frac{\hat{A}\check{r}^2}{2SD}\left[1 - \left(\frac{C_r}{C_{r,max}}^{2/3}\right) - \frac{2}{3}\left(\frac{C_r}{C_{r,max}}\right)\right] \qquad [2]$$

Where:

S = solubility of the solute in the matrix

C_r = concentration ratio
D = diffusivity of the solute through the matrix
Â = initial concentration of the solute in the matrix
ř = radius of the microcapsules

Another function that was used by Ross et al. (2005) assumes one-dimensional diffusion occurring from a core containing a saturated solution of permanganate through a shell with a diffusivity of D and into water with a concentration of C_w. This function is shown in Equation 3.

$$C_w = C_{sat}\left(1 - e^{-\left(\frac{3DHW}{\check{T}\acute{r}yV_w}\right)t}\right) \quad [3]$$

Where:

H = partitioning coefficient for $KMnO_4$ in the solid phase
W = initial mass of $KMnO_4$ in the solid phase
t = time
Ť = thickness of the shell
ŕ = radius of the core
y = unit weight of the particles (gcm^{-3})
V_w = volume of water
C_{sat} = 63.8 g L^{-1} at 20°c for $KMnO_4$ (Weast, 1987)

An empirical function, shown in Equation 4, was also used by Ross et al. (2005) to characterize release of the permanganate from microcapsules.

$$C_r = \frac{C_{r,max}t}{t_{0.5}+t} \quad [4]$$

Where:

$T_{0.5}$ = time required to release half of $C_{r,max}$

These models used by Ross et al. (2005) also describe release of permanganate from spheres, which do not fit with the cylindrical geometry of a SRPC. A spherical shape would overestimate the release because it has a larger surface area than a cylinder.

Lee and Schwartz (2007a,b) utilize a model to simulate permanganate release from SRPCs that captures the release of a solid via diffusion from a finite-height controlled release matrix of cylindrical form, described by an analytical model that was developed by Roseman and Higuchi (1970). This model was derived for a non-porous, solid agent matrix system that assumes: a pseudo steady state ($A>>C_s$); a constant diffusion coefficient; a perfect sink condition (i.e. release in flowing water); homogeneous initial agent distribution; no matrix degradation or swelling and that diffusion is the rate limiting step (Roseman and Higuchi, 1970). A full derivation of the analytical model can be found in Roseman and Higuchi (1970). The critical parts of the analytical model are presented in Equations 5-9 below.

The differential Equation being utilized is:

$$\frac{dQ'}{dt} = -2\pi hD_e r\frac{dC}{dr} \quad [5]$$

Where the boundary conditions are:

$$C = 0, \qquad t > 0, \qquad r = r_o, \qquad h = h_o \quad [6]$$

And the initial conditions are:

$$C = C_s, \qquad t = 0, \qquad r = 0, \qquad h = 0 \quad [7]$$

The solution to Equation 1 for the given boundary and initial conditions is:

$$\frac{r^2}{2}\ln\frac{r}{r_o} + \frac{1}{4}({r_o}^2 - r^2) = \frac{C_s D_e t}{A} \quad [8]$$

Where:

$$Q' = \pi h A({r_o}^2 - r^2) \quad [9]$$

And where:

A = amount of available MnO_4^- per unit volume (g/cm^3)
C_s = Solubility of K MnO_4^- (g/cm^3)
Q' = quantity of permanganate released (g)
De = effective diffusion coefficient (cm^2/sec)
t = time (sec)
h = height of cylinder (cm)
r = radius of cylinder at time t (cm) (effective radius)
r_o = initial radius of cylinder at t = 0 (cm)

This model follows an exponential decay trend and represents release from an object with a shrinking cylindrical core which has been experimentally validated (Roseman and Higuchi, 1970). Initially high release rates followed by a decrease in release rate were observed throughout experimentation, holding true to results reported in previous literature (Kang et al., 2004; Lee and Schwartz 2007a; Christenson et al., 2012). The model operates under 5 key assumptions.

1. The rate-limiting step is the oxidant diffusion from the matrix, not oxidant dissolution.
2. A pseudo steady state condition exists.
3. A >> C_s , the concentration in the matrix is much greater than the solubility concentration
4. The Diffusion Coefficient is constant.
5. The Diffusion process occurs through the matrix phase rather than through pores of channels within the matrix.

The Roseman and Higuchi model (1970) selected, used, and described by Lee and Schwartz (2007a,b) is a better fit to the physical processes of the slow release oxidant cylinders than the aforementioned models and was selected for use in the design tool. A limitation of this model, however, is it does not incorporate inner cylinder tortuosity effects. As the oxidant is released over time, the path through which remaining oxidant must diffuse becomes more tortuous, requiring adjustment to the effective diffusion coefficient over time.

2.1.2 Fit and Adaptation of Oxidant Release Model

Figure 3 shows oxidant release data from slow release cylinders generated by Carus Corporation in comparison to the Lee and Schwartz (2007a) release model for two cylinder sizes. **Figure 3** was made generated using Equations 8 and 9. Root mean square error (RMSE) and normalized RMSE (NRMSE) values were calculated to compare the laboratory concentration data to the model predicted concentrations for a 1 inch cylinder, at a flow rate of 0.5 mL/day, the same flow rate used in Carus' laboratory testing. The 1.35" cylinder size had a RMSE of 173.9 mg/L and a NRMSE value of 0.45. The 2.5" cylinder size had RMSE of 567.5 mg/L and a NRMSE of 0.22. The exponential decay trend of the model holds true to the theory of a biphasic release scheme.

The analytical solution to the chosen release model presented in Equations 8 and 9 above is similar to the theory of the shrinking core model in which the core or source size decreases over time. However, an importance difference is the fact that as the effective radius gets smaller over time the initial radius of the wax skeleton stays the same. This means that any oxidant released from the effective radius still must travel though the paraffin wax matrix to the surface of the cylinder. A key variable in controlling the oxidant release from the inner cylinder is the diffusion coefficient. Since diffusion of oxidant is the rate-limiting step of the cylinder release process, it is important to understand this parameter. The diffusion of oxidant to the surface of the cylinder will depend on the matrix that the oxidant is suspended in within the cylinder. For example, a larger amount of wax will likely decrease the diffusion coefficient, making it more difficult for oxidant to travel through the inner cylinder. Therefore, the ratio of oxidant to paraffin wax will play an important role in influencing the release characteristics of the cylinder. Lee and Schwartz (2007a) used short-term release data to estimate a D_e value of 8.61×10^{-7} cm^2s^{-1} for a permanganate cylinder with dimensions 2.5cm x 5 cm. Lee and Schwartz (2007b) used modeling and simulation techniques to determine that as the D_e decreases, so will the permanganate release rate.

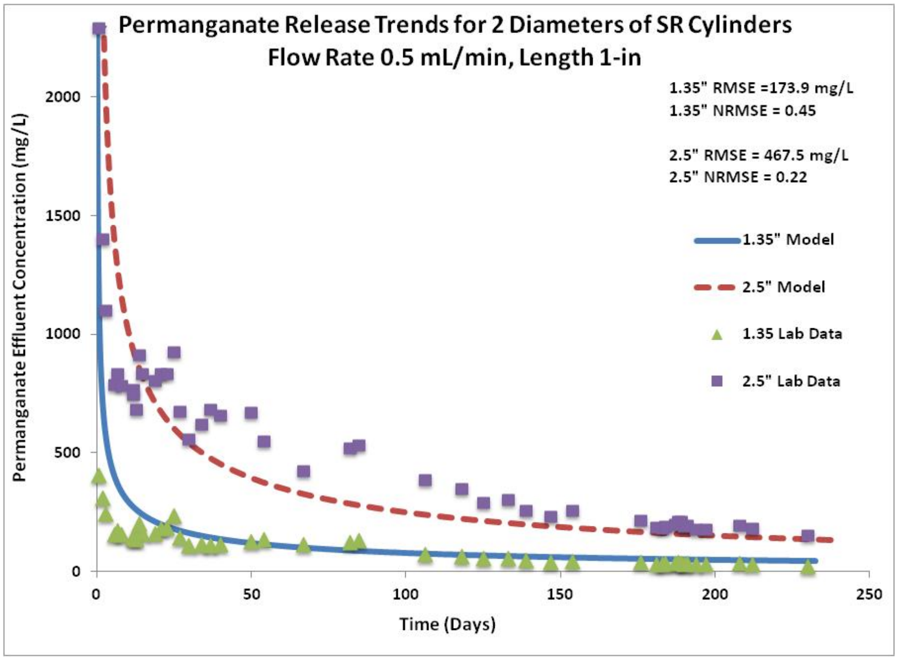


Figure 3. Carus Corporation data compared to the Lee and Schwartz (2007a) model.

Carus laboratory data indicated that permanganate cylinders did not follow a monolithic diffusion pattern and therefore the effect of inner cylinder tortuosity (T) on oxidant release rates must be taken into account. **Figure 4** indicates that the tortuous distance is longer than the linear distance, which is theoretically justified because as permanganate is consumed, the oxidant located further from the perimeter of the cylinder has a more tortuous path to the exterior.

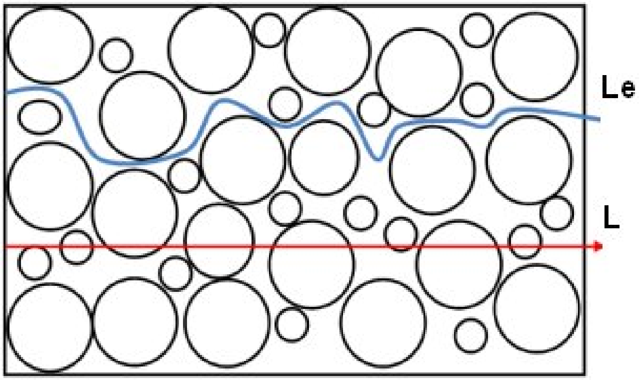


Figure 4. Effect of tortuosity where L is the linear distance and L_e is the tortuous distance where the circles represent the solid was matrix and the space around the circles represents the void space through which the permanganate must diffuse.

As time goes on and r shrinks, the T will increase thereby decreasing D_e. In order to do this logistically, D_e is altered as the cylinder radius (r) decreases. New values of T and D_e are calculated and used for each time step (Equations 10 and 11). The new D_e is then used in the permanganate release equation. Equation 10 was empirically derived in Carus laboratory experiments.

Inner cylinder tortuosity is calculated by:

$$T = 1.4^{(r_o - r)} \quad [10]$$

Where T= Tortuosity

And D_e is calculated by:

$$D_{et} = \frac{D_{e\,(t-1)}}{T} \quad [11]$$

Where D_{et} = diffusion coefficient at time t

The change in diffusion coefficient over time as a function of shrinking cylinder radius is captured by integrating Equations 8-11, resulting in the calculation of Q' (Equation 9), the cumulative amount of oxidant released in grams, the mass of oxidant remaining in grams, the mass released for each time step in grams, the oxidant release rate in mg/day (Q_{rr}), and finally the concentration of oxidant being released at each time. The release rate of oxidant, Q_{rr}, is calculated as follows:

$$Q_{rr} = \frac{mass\ released}{time} \times 1000 \quad [12]$$

Where:

Q_{rr} = release rate of permanganate (mg/day)
Mass released has units of mg
Time has units of days

The concentration of permanganate (mg/L) directly on the surface of the cylinder at each time step is calculated as follows:

$$C = \frac{Q_{rr}}{Q_f} \quad [13]$$

Where:

Q_f = groundwater flow rate (L/day)

The concentration of oxidant that results is the concentration in the groundwater at the surface of the cylinder. This concentration value is then used as an input to the transport model.

2.2 Persulfate Release

As previously mentioned, a difference between permanganate and persulfate release is that persulfate release is steady after the initial surge – the change in release rate over time is not pronounced like it is for permanganate.

Laboratory release studies were conducted at both Carus Corporation and CDM Smith in support of tool development (reported in the ER-201324 Treatability Study Report). Results of both sets of experiments indicate the steady release rate is approximately 10-20 mg/cm^2-day for both cylinder sizes. This values is substituted as the Qrr value in equation 13 and the concentration of persulfate at the point of release is determined accordingly.

2.3 Oxidant Transport

The fundamental equation for solute transport through a saturated soil is a partial differential known as the Advection-Dispersion-Equation (ADE) (Equation 14).

$$\frac{\partial C}{\partial t} = D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} + D_z \frac{\partial^2 C}{\partial z^2} - v \frac{\partial C}{\partial x} \quad [14]$$

Where:

C - species (oxidant) concentration in groundwater (mg/L)
t - time (days)
v - groundwater seepage velocity (ft/day)
D_x, D_y, D_z - dispersion coefficients for the x, y, z dimensions (ft^2/day)

The ADE follows the assumptions that the porous media is homogeneous, isotropic, and that groundwater flow conditions follow Darcy's Law. The addition of two terms to the ADE gives the general reactive transport equation, show in Equation 15.

$$\frac{\partial C}{\partial t} = D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} + D_z \frac{\partial^2 C}{\partial z^2} - v \frac{\partial C}{\partial x} + q_s C_s^k + \sum R_n \qquad [15]$$

Where:

C - species (oxidant) concentration in groundwater (mg/L)
t - time (days)
v - groundwater seepage velocity (ft/day)
D_x, D_y, D_z - dispersion coefficients for the x, y, z dimensions (ft^2/day)
q_s – flow rate of source (ft^3/day)
$\hat{C}_s$ = Concentration of the source
k – source decay constant
R_n – reactions

There are numerous analytical solutions to the ADE used in different programs and tools to simulate transport. One approach for transport estimates and analyses used by a commonly employed tool in the remediation field, REMChlor (Falta et al., 2007), is a basic 1-dimensional advective transport model that includes a first order decay function. The model does not include diffusion or dispersion of the solute. A full derivation of the analytical model that was used was done by and Falta et al. (2005), and can be seen in the REMChlor user guide. The critical parts of the analytical model are presented below in Equations 16-20.

The advective front moves at a constant velocity of v/R, so that at any location of x the advective front will pass location x at a time of t=Rx/v. The solute concentration ahead of the front is always zero. Without degradation, the concentration at any location behind the advective front is determined from the time of solute release, $t_{release}$. If the total time is equal to t, then the parcel of water at the location (x,t) was released from the source at a time of:

$$t_{release} = t - \frac{Rx}{v} \qquad [16]$$

And the concentration at that (x, t) point would be:

$$C(x,t) = C(t_{release})|_{x=0} \qquad [17]$$

To include a plume degradation process a parcel of water would be moved downstream without any mixing, similar to a batch reactor. The reaction would start at time t=0 with an initial condition of:

$$C(t_{release})|_{x=0} \qquad [18]$$

and it would react for a period of time equal to the travel time to position x which is t=Rx/v. If the solute was undergoing a first order decay reaction, for example, representing decay due to natural oxidant demand (NOD), it would have a decay rate constant, k; and the equivalent batch reaction of:

$$R\frac{dC}{dt} = -kC \;\; with \; C|_{t=0} = \; C(t_{release})|_{x=0} \qquad [19]$$

At location (x,t) behind the advective front, the oxidant concentration is

$$C(x,t) = C\left(t - \frac{Rx}{v}\right)\Big|_{x=0} \exp\left(\frac{-k_1 x}{v}\right) \quad [20]$$

Where,

x = downgradient distance
R = retardation (=1 for permanganate)
k_1 = 1st order NOD rate
All other variables previously defined.

Initially, it was thought that advection and dispersion would be important means of oxidant transport. During the evaluation of various transport models calculations were carried out to provide an estimate of how influential dispersion would be to the overall transport distance. Equation 21 (Logan, 1999) was used to calculate the dispersive distance, which was then compared to the advective distance.

$$L = 4\sqrt{2E_L t} \quad [21]$$

Where:

L = dispersive distance
E_L = dispersion coefficient
t = time

The dispersive distance was calculated using Equation 21 over time and the advective distance was calculated by multiplying the velocity and time. The dispersion coefficient is equal to ½ of the velocity. These two values were then compared and it was determined that over long periods of time the forward dispersive distance was negligible compared to the forward advective distance. After 3 years, a longer than expected time for a cylinder to be active on site, the longitudinal dispersive distance was only 1.8% of the advective distance traveled. Therefore, it is justifiable to use a transport equation that neglects dispersion and only simulates advective transport for the design tool.

This model (Equation 20) assumes:

1. Dispersion is negligible because it was mathematically determined to be negligible under the time and distance scales of interest to the treatment design.
2. R = 1, if there were to be a retardation factor then the reacting solutes and the groundwater must be assumed to have a single R.
3. Aquifer media is homogeneous.
4. Flow past the cylinder continues linearly and is not refracted by the cylinder itself.
5. 2nd order rate of NOD, which is transformed as a pseudo 1st order rate based on the oxidant concentration at the cylinder surface in order to be compatible with the model.
6. Soil NOD is constant and that soil NOD demand never decreases. In reality soil NOD will decrease over time, so the tool will over predict consumption over time and provide a somewhat conservative prediction.
7. Assumptions of Darcy's Law apply:

a. There is a pressure gradient over a distance, if not, no flow occurs
b. Flow will occur from high pressure towards low pressure (opposite the direction of increasing gradient)
c. The greater the pressure gradient (through the same formation material), the greater the discharge rate
d. The discharge rate of fluid will often be different through different formation materials (or even through the same material, in a different direction) even if the same pressure gradient exists in both cases.

The cylinder release model given by Lee and Schwartz (2007a) generates oxidant release rates and concentration directly at the surface of the cylinder (x=0) over time, which are then used in Equation 20 for calculation of the model's term:

$$C\left(t - \frac{Rx}{v}\right)\Big|_{x=0}$$

2.4 Linear Interpolation of Concentration Values

The design tool spreadsheet calculations result in values that are not integer values and therefore would not match up with the $t_{release}$ term of the transport model shown above in Equation 16, or the user specified time of interest, which will be a whole number. For example, if a user is interested in an oxidant concentration in 2 years, or 730 days, the tool must be able to interpret this input to provide a value, even if the calculated time point is not an exact match. Therefore, the tool needed to be able to provide concentrations for any point in time. Using Equation 9, Q' is calculated for a range of changes in radii (r) as the permanganate in the cylinder "shrinks" over time (t). A change in r corresponds with a given change in time according to Equation 8. Thus, all concentrations released from the cylinder are for very specific times, often not an integer value. To overcome this challenge linear interpolation is used to calculate oxidant concentrations at desired integer input values. Equation 22 is the standard linear interpolation equation where x is time and y is the concentration of oxidant at that corresponding cylinder time.

$$y = y_o + (y_1 - y_o)\frac{x - x_o}{x_1 - x_o} \quad [22]$$

Where:

X = the time of interest (days), a known value
Y = the concentration at the time of interest (mg/L), an unknown value
(X_0, Y_0) = the first known coordinate (cylinder time (days), concentration (mg/L)
(X_1, Y_1) = the second known coordinate (cylinder time (days), concentration (mg/L)

The built-in Microsoft Excel Match and Offset functions were used in conjunction with the Forecast function perform linear interpolation. The linearly interpolated concentration values are then used as direct inputs to the following term in the transport model:

$$C\left(t - \frac{Rx}{v}\right)\Big|_{x=0}$$

This term facilitates the coupling of the oxidant release and oxidant transport functions.

2.5 Natural Oxidant Demand

The design tool takes into account subsurface natural oxidant demand (NOD) reactions, which are expected to occur at most field sites. In the Conceptual Design for ISCO (CDISCO) user's guide, Borden et al., (2010) outline several different models for permanganate consumption by NOD. While there is no general consensus on the best model for simulating this reaction, some conclusions have been made. They are (1) NOD is usually composed of different components; (2) some components react quickly on the scale of minutes to hours; (3) some components react slowly on the scale of days to months; and (4) the effective NOD is a function of oxidant concentration with higher concentrations resulting in higher effective NOD. From the model evaluations performed for the CDISCO tool, it was shown that the 2nd order models provided a relatively good fit to the data. Therefore the 2nd order model after instantaneous reaction is an acceptable approach for simulating NOD reactions.

This design tool's transport equation, however, incorporates a first-order reaction term, not a second order reaction term. Using the second order rate constant, a pseudo first order rate can be calculated by multiplying by the concentration of permanganate of interest as shown in Equation 23:

$$K_{1,NOD} = [oxidant] * K_{2,NOD} \qquad [23]$$

Where,

K_2 = 2nd order NOD rate

The design tool requires the user to provide a 2nd order NOD rate value, which is typically determined through laboratory soil NOD tests or estimated based on soil parameters. Typical values for permanganate range from 0.001 to 0.1 L/mmol-day, and typical values for persulfate are assumed to be similar. This rate constant is then used to calculate a pseudo 1st order NOD rate (k_1). Because the amount of oxidant released from the cylinder changes over time as the cylinder radius shrinks, the concentration will change as well. Thus the pseudo first order rate from Equation 20 is also calculated over time with the changing release concentration. This results in the tool having a greater accuracy than which would result from using a single first order NOD value throughout all tool calculations.

2.6 Contaminant Destruction

The design tool captures the 2nd order reaction between oxidant and contaminant:

$$\frac{d[C]}{dt} = -k_2[oxidant][C] \qquad [24]$$

Here, k_2 is the 2nd order reaction rate constant. C represents the contaminant concentration. The tool is programmed with k_2 values for common contaminants, which the user selects by dropdown menu. To calculate C, the tool refers to calculated values of oxidant concentration at the surface of the cylinder over time (Eqn. 13), to recognize that the rate of contaminant destruction will decrease over time as the amount of oxidant available (concentration at cylinder face) decreases over time. The tool then calculates a pseudo first order rate constant (k_1) as described for the NOD reactions (Eqn. 25). The contaminant concentration is calculated using the same approach as the oxidant concentration (Eqn. 20, where C now = contaminant) using the calculated k_1 values. To simplify the calculation and have it amenable to Excel's capabilities, it is assumed that there is no change in oxidant due to the contaminant during the small time steps for which the contaminant concentration is calculated.

$$K_{1,contaminant} = [oxidant] * K_{2,contaminant} \qquad [25]$$

Figure 5 presents a schematic representation of how oxidant and contaminant concentrations are calculated over time. The initial oxidant concentration for the first time step for which oxidant concentration is calculated is the concentration determined at the face of the cylinder. This concentration is then "picked up" by groundwater, moving downgradient, and reacting via NOD over time/distance. The extent of NOD is assumed constant. The outcome is a smooth profile of oxidant concentration over time and space as a function of the rate of NOD. The contaminant concentration calculations are a bit more complex because the oxidant concentration changes over time/distance due to NOD, and this change must be reflected in the contaminant calculations while still maintaining computational simplicity. The initial contaminant concentration (entered by a user) reacts with the initial oxidant concentration at the face of the cylinder. The contaminant moves with groundwater and reacts via first order kinetics, where k_1 is calculated by the known k_2 and the known oxidant concentration (Eqn. 23). The oxidant concentration changes not only with the change over time of what is available at the face of the cylinder, but also due to its NOD reaction. To reflect this change, the contaminant concentration is calculated for small time steps where the oxidant concentration is assumed constant during that time step. However, at the beginning of the next time step, a new initial oxidant concentration is used in the calculation to calculate a new k_1 based on the oxidant concentration at that same time (**Figure 5)**. The outcome is a profile of contaminant concentration vs. time/distance that is not quite smooth because of the "jumps" in the initial oxidant concentration at each time step.

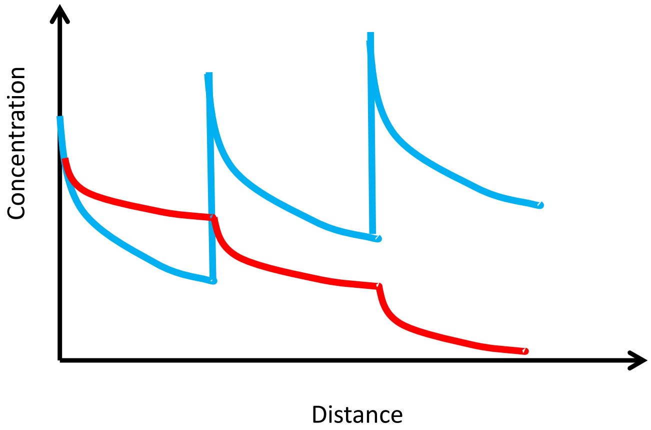


Figure 5. Representation of oxidant (blue) and contaminant (red) concentration calculations over distance from cylinder emplacement.

3.0 TOOL ORGANIZATION

There are three tabs in the tool's Excel file which are shown to the tool user, and several hidden tabs (to prevent modification) in which the calculations are performed. The first tab is the "User's Guide". The second is the "User Interface". The third is the "Cost Calculations". The hidden tabs include all of calculations used to estimate oxidant release, contaminant and oxidant reactive transport, cylinder spacing, number of cylinders, cylinder change-out time, and cost.

3.1 User's Guide

The first tab is the "User's Guide" tab, which contains instructions and guidance for user input in the remaining sections of the tool. The guide presents useful guidance and instructions for using the tool incorporated into 7 different sections, which correspond to sections in the User Interface described in more detail in **Section 3.2**:

1. Oxidant Release
2. Site Characteristics
3. Contaminated Volume
4. Treatment Goal
5. Design Specifications
6. Design Parameters
7. Cost

3.2 User Interface

The second tab is the "user interface" tab. Cells highlighted in green indicate that the user must enter or select information in these cells. Cells highlighted in yellow indicate that the cell provides useful output or design information for the user.

3.2.1 User Input

Below, the sections of the User Interface are described along with snapshots from the tool with values filled in for an example site. This section describes the data the user must enter or select, along with calculated values (any cells not highlighted in yellow or green). Output, or the yellow highlighted cells, is descried in Section 3.2.2. The tool includes embedded guidance for selecting or entering values in a column in the Excel file directly to the right of the "value" column.

1. **Oxidant Release**
    a. User input
        a. The cylinder size of interest
        b. The oxidant release rate per cylinder area with ranges provided as guidance based on lab tests (mg/cm^2-d)
    b. Calculated values
        a. Release rate (mg/d) – release rate per cylinder area x area of cylinder based on size selected

Oxidant Release	Value
Cylinder Diameter (inches)	2.50
Release Rate per cylinder area (mg/cm^2-d)	10
Release Rate (mg/d)	9114
Change out time (days)	185

2. Site Characteristics

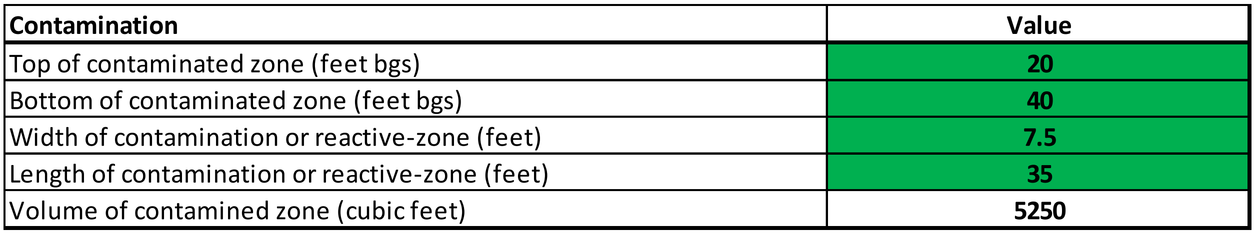
a. Contaminant type, concentration, and reaction rate
b. Site hydraulic conductivity, porosity, and hydraulic gradient – the groundwater seepage velocity = hydraulic conductivity x hydraulic gradient / porosity.
c. The groundwater flow across a single cylinder is calculated by the tool as the seepage velocity x cylinder area (height x diameter).
d. The estimated dispersion factor – a user can estimate a dispersion factor, which is indicative of the influence of any engineering design features' influence on dispersion or flow. Example design features include flow focusing, flow funneling, or other type of mixing that will either increase flow or effectively dilute oxidant concentration by the "disperson factor". A user enters a value ranging from 0 (no dispersion) to 1 (oxidant is completely distributed between cylinders spaced apart orthogonal to flow).
e. Adjusted flow – calculated as the dispersion factor x the flow across a single cylinder adjusted for spacing. The adjustment for spacing is calculated as the spacing between cylinder (which user enters in the Design Parameters section described below) divided by the cylinder diameter, then multiplied by the flow across a single cylinder.
f. The natural oxidant demand rate – the user sure determine this value experimentally using site soil and groundwater; however, guidance is also provided to test low, moderate, or high values of NOD.

Site Characteristics	Value
Contaminant	1,4 Dioxane
Contaminant concentration (ug/L)	6000
Contaminant 2nd order reaction rate (L/mmol-d)	3.97E-03
Hydraulic gradient	0.00055
Hydraulic conductivity (cm/s)	0.0061
Porosity	0.1
Groundwater seepage velocity (cm/d)	2.90E+00
GW flow across single cylinder (L/d)	0.84
Estimated dispersion factor: **NOTE - unless engineering design promotes dispersion, value entered should be zero**	0.50
Adjusted flow (adjusted for dispersion factor) (L/d)	10.09
Natural oxidant demand rate - 2nd order (L/mmol-d)	0

3. Contaminated Volume - length, width, depth of contamination

a. The top and bottom of the contaminated zone (depth of contamination)
b. The width of contamination or the targeted reactive zone

c. The length of contamination or the targeted distance for treatment
d. The tool calculates the total volume of the contaminated or targeted treatment zone based on the dimensions input by the user.



Contamination	**Value**
Top of contaminated zone (feet bgs)	**20**
Bottom of contaminated zone (feet bgs)	**40**
Width of contamination or reactive-zone (feet)	**7.5**
Length of contamination or reactive-zone (feet)	**35**
Volume of contamined zone (cubic feet)	**5250**

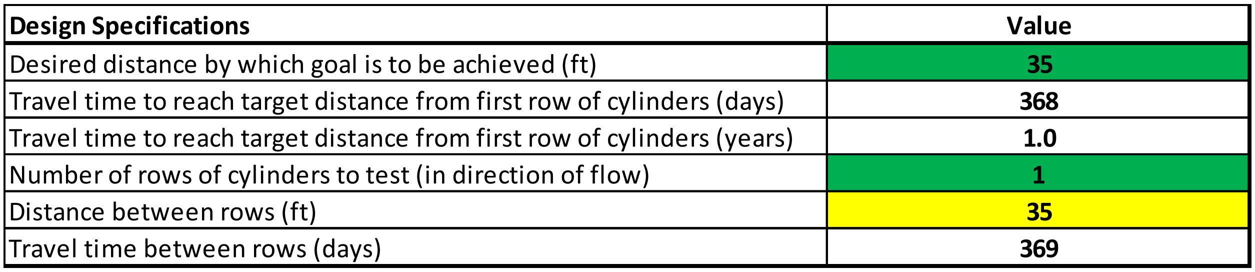
4. Treatment Goal – selected from a drop down menu

a. EPA maximum contaminant levels – the tool will autofill the MCL for contaminant selected in the Site Characteristic Section
b. A specific % concentration reduction
c. A specific target concentration
d. The desired final concentration will fill in based on the treatment goal selected by the user

Treatment Goal	**Contaminant % Reduction**
EPA MCLs (ug/L)	**6.1**
Specific Contaminant % Reduction	**90**
Other specified final concentration (ug/L)	**1000**
Desired final concentration (ug/L)	**600**

5. Design Specifications

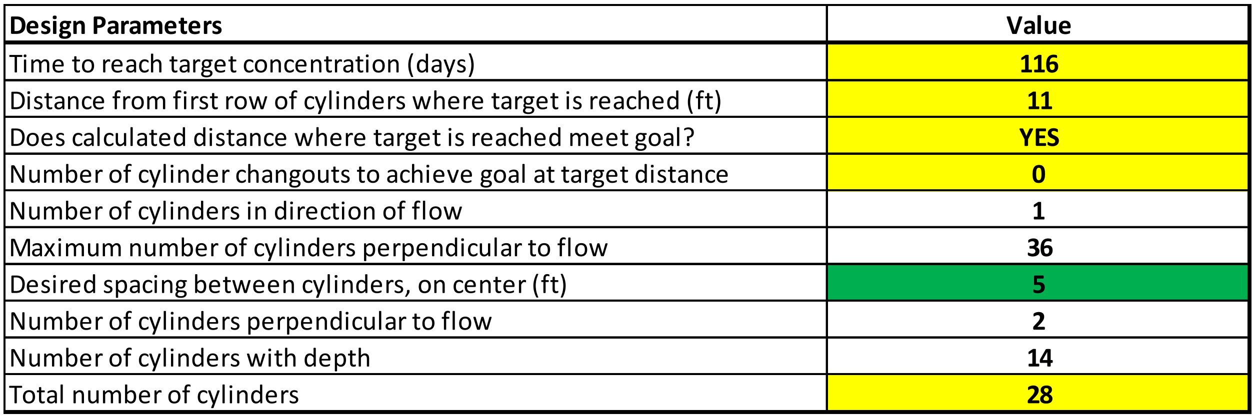
a. The desired distance by which the goal is to be achieved
b. The tool calculates the time to reach this target distance based on the seepage velocity in both days and years.
c. The number of rows of cylinders, in the direction of flow, for the tool to evaluate (the user iterates this value until the tool indicates the goal is achieved within the specified target distance in the next section, Design Parameters).
d. The tool calculates the travel time between rows based on the seepage velocity.



Design Specifications	**Value**
Desired distance by which goal is to be achieved (ft)	**35**
Travel time to reach target distance from first row of cylinders (days)	**368**
Travel time to reach target distance from first row of cylinders (years)	**1.0**
Number of rows of cylinders to test (in direction of flow)	**1**
Distance between rows (ft)	**35**
Travel time between rows (days)	**369**

6. **Design Parameters**

a. The tool fills the number of cylinders in direction of groundwater flow based on the user-selected value in the Design Specifications Section.
b. The tool calculates the maximum number of cylinders perpendicular to flow as the width of contamination divided by the cylinder diameter. This calculation assumes the cylinders are spaced directly side-by-side in the direction orthogonal to flow and serves as a frame of reference.
c. Desired spacing between cylinders perpendicular to flow – entered by the user (the user is cautioned in the associated guidance that engineering features will be needed to promote dispersion or mixing of oxidant with increasing distance between cylinders in a row).
d. The tool calculates the number of cylinders perpendicular to flow as the width of contamination divided by the user-entered spacing between cylinders. A large discrepancy between this value and the maximum number of cylinders perpendicular to flow warns the user that they will need to add engineering features to promote dispersion or mixing between the spaced cylinders.
e. The tool calculates the number of cylinders with depth as the total depth of contamination divided by the 18 inch cylinder length.



Design Parameters	**Value**
Time to reach target concentration (days)	**116**
Distance from first row of cylinders where target is reached (ft)	**11**
Does calculated distance where target is reached meet goal?	**YES**
Number of cylinder changouts to achieve goal at target distance	**0**
Number of cylinders in direction of flow	**1**
Maximum number of cylinders perpendicular to flow	**36**
Desired spacing between cylinders, on center (ft)	**5**
Number of cylinders perpendicular to flow	**2**
Number of cylinders with depth	**14**
Total number of cylinders	**28**

7. **Cost Factors**

a. Fixed and daily costs for well installation or direct push installation of cylinders (taken from the Cost Calculations tab of the tool described in Section 3.3).
b. The user enters a site-specific number of direct push points that can be made or wells that can be installed, or changed out after initial installation, per day, based on site geology.

Cost	Value
Direct Push	
Total installation fixed costs ($)	**$23,300**
Total installation daily costs ($)	**$5,750**
Number of direct push points that can be made per day	**10**
Number of days per installation (days)	**1**
Total cost per installation and per change-out ($)	**$29,050**
Wells	
Installation	
Well-drilling fixed costs ($)	**$39,300**
Well-installation daily costs ($)	**$1,300**
Number of wells that can be installed per day	**5**
Number of days per installation (days)	**1**
Total cost to install wells ($)	**$44,500**
Change-out	
Number of wells that can be changed-out per day	**30**
Number of days per change-out (days)	**1**
Change-out fixed costs ($)	**$19,800**
Change-out daily costs($)	**$2,800**
Total costs per subsequent change-out ($)	**$22,600**

3.2.2 Tool Output

The key design parameters the tool determines include (1) the cylinder change out time, (2) distance between rows of cylinders, (3) a determination if the number of rows of cylinders in the direction of groundwater flow will achieve the target concentration at a specified target distance, (4) time it takes to reach the target concentration, (5) the distance at which target concentration is met, (5) the total number of cylinders needed for site treatment per change out, and (6) the cost for direct push or well installation and change out of cylinders.

The cylinder change out time, found in the Oxidant Release section of the User Interface, is a function of the size of the cylinder selected for site treatment and the release rate of oxidant from the cylinder. The change out time is equal to the mass of cylinder contained in the selected size cylinder divided by the release rate. A safety factor of 0.9 is multiplied this value to assure there is not a lapse in release of oxidant at the site.

The design tool calculates the distance between the rows of cylinders simply as the target distance by which the goal is to be achieved divided by the number of rows of cylinders the user selects to test. This is found in the "Design Specification" section of the tool.

The majority of useful tool output if found in the "Design Parameters" section of the tool. In this section, the tool indicates whether the goal concentration is met within the user-specified distance of interest. The user is instructed to iterate the number of cylinder rows until treatment goal is met. If the user selected more rows than necessary for treatment, the tool will indicate "fewer rows will meet goal". If the user selects fewer rows than necessary for treatment, the tool will indicate "goal not met". The total number of cylinders needed for treatment is also found in the Design Parameters section. This is simply the number of cylinders specified in the direction orthogonal to flow, times the number of rows in the direction of groundwater flow, times the number of cylinders needed to span the contaminated depth (each cylinder is 18" long).

The estimated cost for direct push or well installation, including the cumulative cost per change out (**Figure 6**) is found in the Cost section of the user interface. Based on current (2014) average fixed and daily costs for direct push cylinder installation and for well installation, the tool calculates total costs for each approach per installation. The costs per for direct push are the same (in 2014 dollars) for each mobilization. For well installation, the initial costs are high, but the cost per mobilization thereafter is lower because heavy equipment and drilling is not required after initial installation.

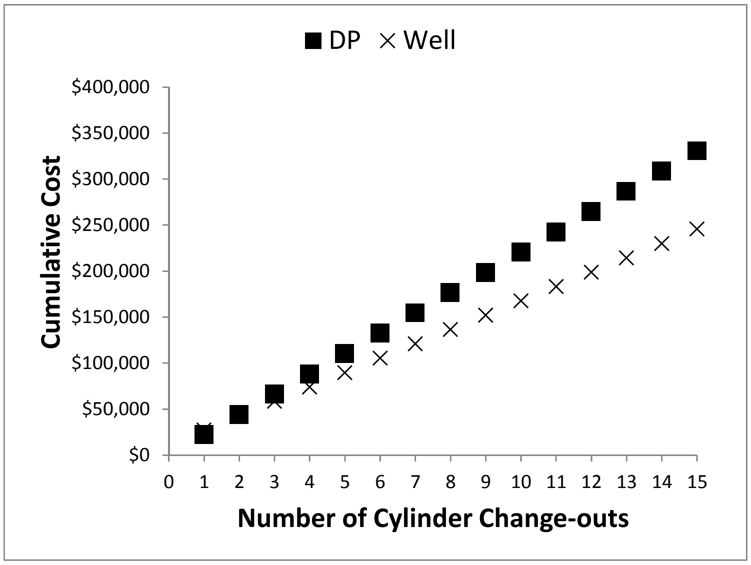


Figure 6. Cost per change out for direct push (DP) or well installation and change-out of cylinders per number of change-outs using example site data and contractor/subcontractor costs.

3.3 Cost Calculations

The third tab is the "cost calculations" tab, where the user can enter cost details for the tool to calculate fixed and daily costs associated with direct push or well installation and change out. The detailed calculations performed in this section of the tool are reported in the User Interface's Cost section, as described above. Details the user enters in this tab for primary contractors and subcontractors include:

- Number of laborers on site per day
- Mobilization costs
- Hourly labor costs
- Hours billed per day
- Per diem rates
- Equipment rental costs

4.0 TOOL AND TECHNOLOGY LIMITATIONS

4.1 Limitations of the Design Tool

One inherent limitation of the 1-D design tool is that the design tool is built using analytical solutions to equations, which are generally less accurate than numerical solutions. This approach was necessary to make the tool user friendly, computationally fast, and available in Excel.

It should be noted that there are some limitations to the tool output. The tool calculates a matrix of output values (oxidant concentration) for each size of cylinder based on a user selected time and distance. However, because the tool is based on an analytical solution, not a numerical solution, not every downgradient distance could be represented in this tool; only discrete values could be entered. The distance values that are used in the tool are representative of typical distances that a user would be interested and include 0.25, 0.5, 0.75, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, and 20 ft. Likewise, the time points are also restricted to every other day resulting in even day values (e.g. 0, 2, 4, 6 days etc.) up to the predicted longevity. The tool's output combinations are limited in order to keep the computations fast.

Another important limitation to the conceptual design tool is the assumption that the NOD remains constant over time. In reality the NOD will with decrease as the NOD is satisfied, which will leave more oxidant available for contaminant destruction. NOD has been found to have two distinct reaction periods, an initial instantaneous reaction, followed by a prolonged slow reaction period (Cha et al., 2012; Mumford et al., 2005). It has been shown that the instantaneous NOD accounts for less of the ultimate NOD than the slow reactions, meaning that the ultimate NOD may not be satisfied for some time, although the demand may not be as high as during the instantaneous reactions (Xu and Thomson, 2008). For the design tool, because the NOD is assumed to be constant over time, the resulting oxidant concentrations are likely to be underestimations of the actual concentration value at that time and location. For the design tool this limitation was accepted because it is far better to underestimate a concentration than to overestimate it.

Additional limitations of the design tool include: (1) the tool does not include passive solute transport due to dispersion or diffusion, and (2) the tool does not include oxidant consumption due to contaminant reaction. The tool does allow for adjustment of oxidant concentration due to engineering features that promote mixing and dispersion, and they are based on professional judgment. These are minor limitations that have been previously explained and is has been shown that they do not significantly hinder design tool, but they should be kept in mind when using the tool to make decisions about a remediation site.

4.2 Limitations of Slow Release Oxidant Cylinders

While slow release cylinders are a versatile remediation technology, they are not applicable to all types of sites. The applicability analysis demonstrated that certain types of field conditions may not be amenable to using the cylinders. For example, at sites with very low or very high velocities, the cylinders may not be able to produce concentrations that are high enough for successful contaminant destruction. At sites with very high NOD rates the oxidant may be unproductively consumed causing it to deplete too fast resulting in low concentrations.

There are some feasible design approaches that can be used to overcome some of the site related limitations. For example, **Figure 7** shows a funnel-and-gate system that could be implemented at a site where groundwater velocities are not in a favorable range. This would allow practitioners to control the groundwater velocity and direct the flow through the gate and through the cylinder placement area.

Figure 8 shows a "two for one" injection scheme. In this type of implementation configuration the site is pretreated with liquid oxidant followed and then cylinders are inserted into the injection wells. This design approach would help to overcome limitations at a site where the NOD rate is very high. The pretreatment with liquid oxidant would satisfy the initial oxidant demand and then the cylinders would provide oxidant to the site over the long term to facilitate contaminant destruction.

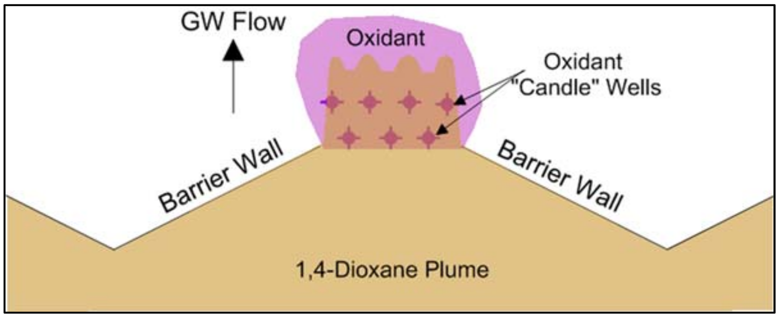


Figure 7. Funnel and gate implementation configuration

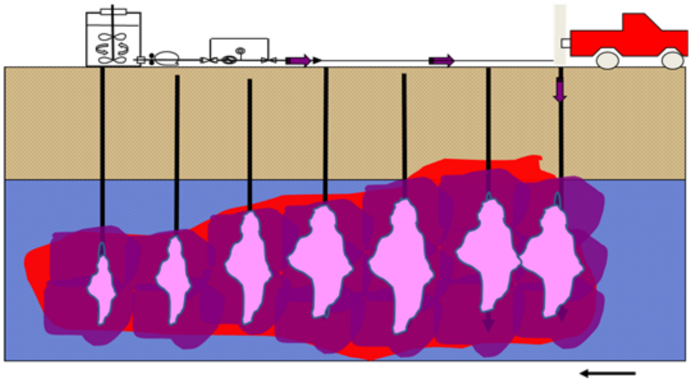


Figure 8. Two-for-one injection implementation configuration

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APPENDIX E
QA/QC EVALUATION

					Concentration															
Sample type	Well ID	Bottom sampling depth interval (ft bgs)	Distance from cylinder well (ft)	DATE SAMPLED	1,1,2-TRICHLOROETHANE	1,1-DICHLOROETHANE	1,1-DICHLOROETHENE	1,2-DICHLOROBENZENE	1,2-DICHLOROETHANE	1,4-DIOXANE	BENZENE	CHLORIDE-CL	CHLOROFORM	CIS-1,2-DICHLOROETHENE	SULFATE	TETRACHLOROETHENE	TOLUENE	TRANS-1,2-DICHLOROETHENE	TRICHLOROETHENE	VINYL CHLORIDE
					UG/L	UG/L	UG/L	UG/L	UG/L	UG/L	UG/L	MG/L	UG/L	UG/L	MG/L	UG/L	UG/L	UG/L	UG/L	UG/L
Field duplicate	DMW-01	40	-10	1/20/2016	83	4100	11000	12	55	29000	1.6	386	40	16000	285	51	4.7	23	2700	550
Field sample	DMW-01	40	-10	1/20/2016	81	4100	11000	11	55	26000	1.7	364	40	16000	240	54	4.7	23	2800	530
Field duplicate	DMW-01	40	-10	2/9/2016	16	476	1217	3	14	8734	1	268	15	907	217	24	1	8	796	122
Field sample	DMW-01	40	-10	2/9/2016	17	487	1217	3	14	9950	1	297	15	907	227	23	1	8	785	122
Field duplicate	DCW-01	32.5	1	12/21/2015	29	1300	3600	2.5	22	9700	0.62	264	13	5000	245	17	0.42	6.8	2000	150
Field sample	DCW-01	32.5	1	12/21/2015	28	570	790	2.7	19	10000	0.72	285	14	1000	272	18	0.49	6.7	690	140
Field duplicate	DEW-01	40	35	12/21/2015	51	2200	6500	7.1	31	17000	1.1	380	23	8800	243	39	1.5	7.2	3300	240
Field sample	DEW-01	40	35	12/21/2015	48	1700	2800	7.1	0	18000	1.1	491	23	3700	280	40	1.6	6.9	2300	230

					RPD (%)															
Sample type	Well ID	Bottom sampling depth interval (ft bgs)	Distance from cylinder well (ft)	DATE SAMPLED	1,1,2-TRICHLOROETHANE	1,1-DICHLOROETHANE	1,1-DICHLOROETHENE	1,2-DICHLOROBENZENE	1,2-DICHLOROETHANE	1,4-DIOXANE	BENZENE	CHLORIDE-CL	CHLOROFORM	CIS-1,2-DICHLOROETHENE	SULFATE	TETRACHLOROETHENE	TOLUENE	TRANS-1,2-DICHLOROETHENE	TRICHLOROETHENE	VINYL CHLORIDE
Field duplicate	DMW-01	40	-10	1/20/2016	2%	0%	0%	9%	0%	11%	6%	6%	0%	0%	17%	6%	0%	0%	4%	4%
Field sample	DMW-01	40	-10	1/20/2016																
Field duplicate	DMW-01	40	-10	2/9/2016	6%	2%	0%	0%	0%	13%	0%	10%	0%	0%	5%	4%	0%	0%	1%	0%
Field sample	DMW-01	40	-10	2/9/2016																
Field duplicate	DCW-01	32.5	1	12/21/2015	4%	78%	128%	8%	15%	3%	15%	8%	7%	133%	10%	6%	15%	1%	97%	7%
Field sample	DCW-01	32.5	1	12/21/2015																
Field duplicate	DEW-01	40	35	12/21/2015	6%	26%	80%	0%	200%	6%	0%	25%	0%	82%	14%	3%	6%	4%	36%	4%
Field sample	DEW-01	40	35	12/21/2015																
				Average	***5%***	***27%***	***52%***	***4%***	***54%***	***8%***	***5%***	***12%***	***2%***	***54%***	***12%***	***5%***	***5%***	***1%***	***35%***	***4%***

Appendix E-1. QA/QC Evaluation - Duplicate Samples

CLIENT SAMPLE ID	Well ID	Sample type	LAB SAMPLE ID	ANALYTICAL METHOD CODE	PREP METHOD CODE	DATE SAMPLED	DATE ANALYZED	MATRIX	CAS NUMBER	PARAMETER NAME	RESULT	Result2	Result2 (RL)	QUALIFIER	QualCode	UNITS	DETECTION LIMIT	REPORTING LIMIT	DILUTION FACTOR	LAB NAME
HGA002WBBLK	HGA002WBBLK	Blank	HGA002W	SW7470A	METHOD		1/6/2016	WA	7439-97-6	MERCURY	ND	0	1	U	1	UG/L	0.1	0.5	1	EMXT
ICL061WBBLK	ICL061WBBLK	Blank	ICL061WB	E300.0	NONE		12/23/2015	WA	16887-00-	CHLORIDE-CL	ND	0	0	U	1	MG/L	0.1	0.2	1	EMXT
ICL063WBBLK	ICL063WBBLK	Blank	ICL063WB	E300.0	NONE		12/23/2015	WA	16887-00-	CHLORIDE-CL	ND	0	0	U	1	MG/L	0.1	0.2	1	EMXT
ICL063WBBLK	ICL063WBBLK	Blank	ICL063WB	E300.0	NONE		12/23/2015	WA	14808-79-	SULFATE	ND	0	1	U	1	MG/L	0.25	0.5	1	EMXT
ICL065WBBLK	ICL065WBBLK	Blank	ICL065WB	E300.0	NONE		12/24/2015	WA	16887-00-	CHLORIDE-CL	ND	0	0	U	1	MG/L	0.1	0.2	1	EMXT
ICL065WBBLK	ICL065WBBLK	Blank	ICL065WB	E300.0	NONE		12/24/2015	WA	14808-79-	SULFATE	ND	0	1	U	1	MG/L	0.25	0.5	1	EMXT
ILA001WBBLK	ILA001WBBLK	Blank	ILA001WB	E300.0M	NONE		1/5/2016	WA	15541-45-	BROMATE	ND	0	10	U	1	UG/L	5	10	1	EMXT
IML041WBBLK	IML041WBBLK	Blank	IML041WB	SW6020A	FLDFLT		1/5/2016	WA	7440-38-2	ARSENIC	ND	0	0	U	1	MG/L	0.0002	0.001	1	EMXT
IML041WBBLK	IML041WBBLK	Blank	IML041WB	SW6020A	FLDFLT		1/5/2016	WA	7440-39-3	BARIUM	ND	0	0	U	1	MG/L	0.0005	0.001	1	EMXT
IML041WBBLK	IML041WBBLK	Blank	IML041WB	SW6020A	FLDFLT		1/5/2016	WA	7440-41-7	BERYLLIUM	ND	0	0	U	1	MG/L	0.0001	0.001	1	EMXT
IML041WBBLK	IML041WBBLK	Blank	IML041WB	SW6020A	FLDFLT		1/5/2016	WA	7440-43-9	CADMIUM	ND	0	0	U	1	MG/L	0.0002	0.001	1	EMXT
IML041WBBLK	IML041WBBLK	Blank	IML041WB	SW6020A	FLDFLT		1/5/2016	WA	7440-47-3	CHROMIUM	ND	0	0	U	1	MG/L	0.0002	0.001	1	EMXT
IML041WBBLK	IML041WBBLK	Blank	IML041WB	SW6020A	FLDFLT		1/5/2016	WA	7440-50-8	COPPER	ND	0	0	U	1	MG/L	0.0005	0.001	1	EMXT
IML041WBBLK	IML041WBBLK	Blank	IML041WB	SW6020A	FLDFLT		1/5/2016	WA	7439-92-1	LEAD	ND	0	0	U	1	MG/L	0.0001	0.001	1	EMXT
IML041WBBLK	IML041WBBLK	Blank	IML041WB	SW6020A	FLDFLT		1/5/2016	WA	7782-49-2	SELENIUM	ND	0	0	U	1	MG/L	0.0003	0.001	1	EMXT
IML041WBBLK	IML041WBBLK	Blank	IML041WB	SW6020A	FLDFLT		1/5/2016	WA	7440-28-0	THALLIUM	ND	0	0	U	1	MG/L	0.0002	0.001	1	EMXT
IML041WBBLK	IML041WBBLK	Blank	IML041WB	SW6020A	FLDFLT		1/5/2016	WA	7439-89-6	IRON	ND	0	0	U	1	MG/L	0.01	0.1	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	71-55-6	1,1,1-TRICHLOROETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	79-34-5	1,1,2,2-TETRACHLOROETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	79-00-5	1,1,2-TRICHLOROETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	75-34-3	1,1-DICHLOROETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	75-35-4	1,1-DICHLOROETHENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	120-82-1	1,2,4-TRICHLOROBENZENE	ND	0	1	U	1	UG/L	0.3	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	95-63-6	1,2,4-TRIMETHYLBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	95-50-1	1,2-DICHLOROBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	107-06-2	1,2-DICHLOROETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	78-87-5	1,2-DICHLOROPROPANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	108-67-8	1,3,5-TRIMETHYLBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	541-73-1	1,3-DICHLOROBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	106-46-7	1,4-DICHLOROBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	78-93-3	2-BUTANONE	ND	0	10	U	1	UG/L	4	10	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	591-78-6	2-HEXANONE	ND	0	5	U	1	UG/L	4	5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	67-64-1	ACETONE	ND	0	10	U	1	UG/L	5	10	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	71-43-2	BENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	75-27-4	BROMODICHLOROMETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	75-25-2	BROMOFORM	ND	0	1	U	1	UG/L	0.3	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	74-83-9	BROMOMETHANE	ND	0	1	U	1	UG/L	0.3	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	75-15-0	CARBON DISULFIDE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	56-23-5	CARBON TETRACHLORIDE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	108-90-7	CHLOROBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	75-00-3	CHLOROETHANE	ND	0	1	U	1	UG/L	0.3	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	67-66-3	CHLOROFORM	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	74-87-3	CHLOROMETHANE	ND	0	1	U	1	UG/L	0.3	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	156-59-2	CIS-1,2-DICHLOROETHENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	10061-01-	CIS-1,3-DICHLOROPROPENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	124-48-1	DIBROMOCHLOROMETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	100-41-4	ETHYLBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	136777-61	M,P-XYLENES	ND	0	1	U	1	UG/L	0.4	1	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	108-10-1	MIBK	ND	0	5	U	1	UG/L	4	5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	75-09-2	METHYLENE CHLORIDE	ND	0	1	U	1	UG/L	0.5	1	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	1634-04-4	MTBE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	91-20-3	NAPHTHALENE	ND	0	1	U	1	UG/L	0.5	1	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	95-47-6	O-XYLENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	100-42-5	STYRENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	127-18-4	TETRACHLOROETHENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	108-88-3	TOLUENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	156-60-5	TRANS-1,2-DICHLOROETHENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	10061-02-	TRANS-1,3-DICHLOROPROPENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	79-01-6	TRICHLOROETHENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	75-69-4	TRICHLOROFLUOROMETHANE	ND	0	1	U	1	UG/L	0.3	0.5	1	EMXT
QCTB-12212015	QCTB-12212015	Blank	L192-12	SW8260B	SW5030B	12/21/2015	12/30/2015	WA	75-01-4	VINYL CHLORIDE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	71-55-6	1,1,1-TRICHLOROETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	79-34-5	1,1,2,2-TETRACHLOROETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	79-00-5	1,1,2-TRICHLOROETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	75-34-3	1,1-DICHLOROETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	75-35-4	1,1-DICHLOROETHENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	120-82-1	1,2,4-TRICHLOROBENZENE	ND	0	1	U	1	UG/L	0.3	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	95-63-6	1,2,4-TRIMETHYLBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	95-50-1	1,2-DICHLOROBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	107-06-2	1,2-DICHLOROETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	78-87-5	1,2-DICHLOROPROPANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	108-67-8	1,3,5-TRIMETHYLBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	541-73-1	1,3-DICHLOROBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	106-46-7	1,4-DICHLOROBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	78-93-3	2-BUTANONE	ND	0	10	U	1	UG/L	4	10	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	591-78-6	2-HEXANONE	ND	0	5	U	1	UG/L	4	5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	67-64-1	ACETONE	ND	0	10	U	1	UG/L	5	10	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	71-43-2	BENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	75-27-4	BROMODICHLOROMETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	75-25-2	BROMOFORM	ND	0	1	U	1	UG/L	0.3	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	74-83-9	BROMOMETHANE	ND	0	1	U	1	UG/L	0.3	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	75-15-0	CARBON DISULFIDE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	56-23-5	CARBON TETRACHLORIDE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	108-90-7	CHLOROBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	75-00-3	CHLOROETHANE	ND	0	1	U	1	UG/L	0.3	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	67-66-3	CHLOROFORM	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	74-87-3	CHLOROMETHANE	ND	0	1	U	1	UG/L	0.3	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	156-59-2	CIS-1,2-DICHLOROETHENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	10061-01-	CIS-1,3-DICHLOROPROPENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	124-48-1	DIBROMOCHLOROMETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	100-41-4	ETHYLBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	136777-61	M,P-XYLENES	ND	0	1	U	1	UG/L	0.4	1	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	108-10-1	MIBK	ND	0	5	U	1	UG/L	4	5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	75-09-2	METHYLENE CHLORIDE	ND	0	1	U	1	UG/L	0.5	1	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	1634-04-4	MTBE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	91-20-3	NAPHTHALENE	ND	0	1	U	1	UG/L	0.5	1	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	95-47-6	O-XYLENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	100-42-5	STYRENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	127-18-4	TETRACHLOROETHENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	108-88-3	TOLUENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	156-60-5	TRANS-1,2-DICHLOROETHENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	10061-02-	TRANS-1,3-DICHLOROPROPENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	79-01-6	TRICHLOROETHENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	75-69-4	TRICHLOROFLUOROMETHANE	ND	0	1	U	1	UG/L	0.3	0.5	1	EMXT
VO06A01QBLK	VO06A01QBLK	Blank	VO06A01Q	SW8260B	SW5030B		1/4/2016	WA	75-01-4	VINYL CHLORIDE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L18BBLK	VO06L18BBLK	Blank	VO06L18B	SW8260B	SW5030B		12/29/2015	WA	123-91-1	1,4-DIOXANE	ND	0	1	U	1	UG/L	0.5	1	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	71-55-6	1,1,1-TRICHLOROETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	79-34-5	1,1,2,2-TETRACHLOROETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	79-00-5	1,1,2-TRICHLOROETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	75-34-3	1,1-DICHLOROETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	75-35-4	1,1-DICHLOROETHENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	120-82-1	1,2,4-TRICHLOROBENZENE	ND	0	1	U	1	UG/L	0.3	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	95-63-6	1,2,4-TRIMETHYLBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT

CLIENT SAMPLE ID	Well ID	Sample type	LAB SAMPLE ID	ANALYTICAL METHOD CODE	PREP METHOD CODE	DATE SAMPLED	DATE ANALYZED	MATRIX	CAS NUMBER	PARAMETER NAME	RESULT	Result2	Result2 (RL)	QUALIFIER	QualCode	UNITS	DETECTION LIMIT	REPORTING LIMIT	DILUTION FACTOR	LAB NAME
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	95-50-1	1,2-DICHLOROBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	107-06-2	1,2-DICHLOROETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	78-87-5	1,2-DICHLOROPROPANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	108-67-8	1,3,5-TRIMETHYLBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	541-73-1	1,3-DICHLOROBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	106-46-7	1,4-DICHLOROBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	78-93-3	2-BUTANONE	ND	0	10	U	1	UG/L	4	10	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	591-78-6	2-HEXANONE	ND	0	5	U	1	UG/L	4	5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	67-64-1	ACETONE	ND	0	10	U	1	UG/L	5	10	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	71-43-2	BENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	75-27-4	BROMODICHLOROMETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	75-25-2	BROMOFORM	ND	0	1	U	1	UG/L	0.3	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	74-83-9	BROMOMETHANE	ND	0	1	U	1	UG/L	0.3	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	75-15-0	CARBON DISULFIDE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	56-23-5	CARBON TETRACHLORIDE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	108-90-7	CHLOROBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	75-00-3	CHLOROETHANE	ND	0	1	U	1	UG/L	0.3	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	67-66-3	CHLOROFORM	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	74-87-3	CHLOROMETHANE	ND	0	1	U	1	UG/L	0.3	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	156-59-2	CIS-1,2-DICHLOROETHENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	10061-01-	CIS-1,3-DICHLOROPROPENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	124-48-1	DIBROMOCHLOROMETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	100-41-4	ETHYLBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	136777-61	M,P-XYLENES	ND	0	1	U	1	UG/L	0.4	1	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	108-10-1	MIBK	ND	0	5	U	1	UG/L	4	5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	75-09-2	METHYLENE CHLORIDE	ND	0	1	U	1	UG/L	0.5	1	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	1634-04-4	MTBE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	91-20-3	NAPHTHALENE	ND	0	1	U	1	UG/L	0.5	1	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	95-47-6	O-XYLENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	100-42-5	STYRENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	127-18-4	TETRACHLOROETHENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	108-88-3	TOLUENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	156-60-5	TRANS-1,2-DICHLOROETHENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	10061-02-	TRANS-1,3-DICHLOROPROPENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	79-01-6	TRICHLOROETHENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	75-69-4	TRICHLOROFLUOROMETHANE	ND	0	1	U	1	UG/L	0.3	0.5	1	EMXT
VO06L19BBLK	VO06L19BBLK	Blank	VO06L19B	SW8260B	SW5030B		12/30/2015	WA	75-01-4	VINYL CHLORIDE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	71-55-6	1,1,1-TRICHLOROETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	79-34-5	1,1,2,2-TETRACHLOROETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	79-00-5	1,1,2-TRICHLOROETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	75-34-3	1,1-DICHLOROETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	75-35-4	1,1-DICHLOROETHENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	120-82-1	1,2,4-TRICHLOROBENZENE	ND	0	1	U	1	UG/L	0.3	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	95-63-6	1,2,4-TRIMETHYLBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	95-50-1	1,2-DICHLOROBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	107-06-2	1,2-DICHLOROETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	78-87-5	1,2-DICHLOROPROPANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	108-67-8	1,3,5-TRIMETHYLBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	541-73-1	1,3-DICHLOROBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	106-46-7	1,4-DICHLOROBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	78-93-3	2-BUTANONE	ND	0	10	U	1	UG/L	4	10	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	591-78-6	2-HEXANONE	ND	0	5	U	1	UG/L	4	5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	67-64-1	ACETONE	ND	0	10	U	1	UG/L	5	10	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	71-43-2	BENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	75-27-4	BROMODICHLOROMETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	75-25-2	BROMOFORM	ND	0	1	U	1	UG/L	0.3	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	74-83-9	BROMOMETHANE	ND	0	1	U	1	UG/L	0.3	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	75-15-0	CARBON DISULFIDE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	56-23-5	CARBON TETRACHLORIDE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	108-90-7	CHLOROBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	75-00-3	CHLOROETHANE	ND	0	1	U	1	UG/L	0.3	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	67-66-3	CHLOROFORM	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	74-87-3	CHLOROMETHANE	ND	0	1	U	1	UG/L	0.3	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	156-59-2	CIS-1,2-DICHLOROETHENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	10061-01-	CIS-1,3-DICHLOROPROPENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	124-48-1	DIBROMOCHLOROMETHANE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	100-41-4	ETHYLBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	136777-61	M,P-XYLENES	ND	0	1	U	1	UG/L	0.4	1	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	108-10-1	MIBK	ND	0	5	U	1	UG/L	4	5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	75-09-2	METHYLENE CHLORIDE	ND	0	1	U	1	UG/L	0.5	1	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	1634-04-4	MTBE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	91-20-3	NAPHTHALENE	ND	0	1	U	1	UG/L	0.5	1	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	95-47-6	O-XYLENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	100-42-5	STYRENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	127-18-4	TETRACHLOROETHENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	108-88-3	TOLUENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	156-60-5	TRANS-1,2-DICHLOROETHENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	10061-02-	TRANS-1,3-DICHLOROPROPENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	79-01-6	TRICHLOROETHENE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	75-69-4	TRICHLOROFLUOROMETHANE	ND	0	1	U	1	UG/L	0.3	0.5	1	EMXT
VO67L19BBLK	VO67L19BBLK	Blank	VO67L19B	SW8260B	SW5030B		12/30/2015	WA	75-01-4	VINYL CHLORIDE	ND	0	1	U	1	UG/L	0.2	0.5	1	EMXT
MBLK1W		Blank	ICA041WB	E300.0	NONE	1/21/2016	1/21/2016	WATER	16887-00-	CHLORIDE-CL	ND	0	0.10	U	1	mg/L	0.1	0.1	1	EMAX
MBLK1W		Blank	ICA041WB	E300.0	NONE	1/21/2016	1/21/2016	WATER	14808-79-	SULFATE	ND	0	0.25	U	1	mg/L	0.25	0.25	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	71-55-6	1,1,1-TRICHLOROETHANE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	79-34-5	1,1,2,2-TETRACHLOROETHANE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	79-00-5	1,1,2-TRICHLOROETHANE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	75-34-3	1,1-DICHLOROETHANE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	75-35-4	1,1-DICHLOROETHENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	120-82-1	1,2,4-TRICHLOROBENZENE	ND	0	0.30	U	1	ug/L	0.3	0.3	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	95-63-6	1,2,4-TRIMETHYLBENZENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	95-50-1	1,2-DICHLOROBENZENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	107-06-2	1,2-DICHLOROETHANE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	78-87-5	1,2-DICHLOROPROPANE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	108-67-8	1,3,5-TRIMETHYLBENZENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	541-73-1	1,3-DICHLOROBENZENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	106-46-7	1,4-DICHLOROBENZENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	78-93-3	2-BUTANONE	ND	0	4.00	U	1	ug/L	4	4	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	591-78-6	2-HEXANONE	ND	0	4.00	U	1	ug/L	4	4	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	67-64-1	ACETONE	ND	0	5.00	U	1	ug/L	5	5	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	71-43-2	BENZENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	75-27-4	BROMODICHLOROMETHANE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	75-25-2	BROMOFORM	ND	0	0.30	U	1	ug/L	0.3	0.3	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	74-83-9	BROMOMETHANE	ND	0	0.30	U	1	ug/L	0.3	0.3	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	75-15-0	CARBON DISULFIDE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	56-23-5	CARBON TETRACHLORIDE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	108-90-7	CHLOROBENZENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	75-00-3	CHLOROETHANE	ND	0	0.30	U	1	ug/L	0.3	0.3	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	67-66-3	CHLOROFORM	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	74-87-3	CHLOROMETHANE	ND	0	0.30	U	1	ug/L	0.3	0.3	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	156-59-2	CIS-1,2-DICHLOROETHENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	10061-01-	CIS-1,3-DICHLOROPROPENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	124-48-1	DIBROMOCHLOROMETHANE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16B	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	100-41-4	ETHYLBENZENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX

CLIENT SAMPLE ID	Well ID	Sample type	LAB SAMPLE ID	ANALYTICAL METHOD CODE	PREP METHOD CODE	DATE SAMPLED	DATE ANALYZED	MATRIX	CAS NUMBER	PARAMETER NAME	RESULT	Result2	Result2 (RL)	QUALIFIER	QualCode	UNITS	DETECTION LIMIT	REPORTING LIMIT	DILUTION FACTOR	LAB NAME
MBLK1W		Blank	VO05A16E	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	136777-61	M,P-XYLENES	ND	0	0.40	U	1	ug/L	0.4	0.4	1	EMAX
MBLK1W		Blank	VO05A16E	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	108-10-1	MIBK	ND	0	4.00	U	1	ug/L	4	4	1	EMAX
MBLK1W		Blank	VO05A16E	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	75-09-2	METHYLENE CHLORIDE	ND	0	0.50	U	1	ug/L	0.5	0.5	1	EMAX
MBLK1W		Blank	VO05A16E	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	1634-04-4	MTBE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16E	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	91-20-3	NAPHTHALENE	ND	0	0.50	U	1	ug/L	0.5	0.5	1	EMAX
MBLK1W		Blank	VO05A16E	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	95-47-6	O-XYLENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16E	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	100-42-5	STYRENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16E	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	127-18-4	TETRACHLOROETHENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16E	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	108-88-3	TOLUENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16E	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	156-60-5	TRANS-1,2-DICHLOROETHENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16E	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	10061-02-	TRANS-1,3-DICHLOROPROPENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16E	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	79-01-6	TRICHLOROETHENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO05A16E	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	75-69-4	TRICHLOROFLUOROMETHANE	ND	0	0.30	U	1	ug/L	0.3	0.3	1	EMAX
MBLK1W		Blank	VO05A16E	SW8260B	SW5030B	1/26/2016	1/26/2016	WATER	75-01-4	VINYL CHLORIDE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK1W		Blank	VO06A18E	SW8260B	SW5030B	1/22/2016	1/22/2016	WATER	123-91-1	1,4-DIOXANE	ND	0	0.50	U	1	ug/L	0.5	0.5	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	71-55-6	1,1,1-TRICHLOROETHANE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	79-34-5	1,1,2,2-TETRACHLOROETHANE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	79-00-5	1,1,2-TRICHLOROETHANE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	75-34-3	1,1-DICHLOROETHANE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	75-35-4	1,1-DICHLOROETHENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	120-82-1	1,2,4-TRICHLOROBENZENE	ND	0	0.30	U	1	ug/L	0.3	0.3	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	95-63-6	1,2,4-TRIMETHYLBENZENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	95-50-1	1,2-DICHLOROBENZENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	107-06-2	1,2-DICHLOROETHANE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	78-87-5	1,2-DICHLOROPROPANE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	108-67-8	1,3,5-TRIMETHYLBENZENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	541-73-1	1,3-DICHLOROBENZENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	106-46-7	1,4-DICHLOROBENZENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	78-93-3	2-BUTANONE	ND	0	4.00	U	1	ug/L	4	4	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	591-78-6	2-HEXANONE	ND	0	4.00	U	1	ug/L	4	4	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	67-64-1	ACETONE	ND	0	5.00	U	1	ug/L	5	5	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	71-43-2	BENZENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	75-27-4	BROMODICHLOROMETHANE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	75-25-2	BROMOFORM	ND	0	0.30	U	1	ug/L	0.3	0.3	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	74-83-9	BROMOMETHANE	ND	0	0.30	U	1	ug/L	0.3	0.3	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	75-15-0	CARBON DISULFIDE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	56-23-5	CARBON TETRACHLORIDE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	108-90-7	CHLOROBENZENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	75-00-3	CHLOROETHANE	ND	0	0.30	U	1	ug/L	0.3	0.3	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	67-66-3	CHLOROFORM	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	74-87-3	CHLOROMETHANE	ND	0	0.30	U	1	ug/L	0.3	0.3	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	156-59-2	CIS-1,2-DICHLOROETHENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	10061-01-	CIS-1,3-DICHLOROPROPENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	124-48-1	DIBROMOCHLOROMETHANE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	100-41-4	ETHYLBENZENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	136777-61	M,P-XYLENES	ND	0	0.40	U	1	ug/L	0.4	0.4	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	108-10-1	MIBK	ND	0	4.00	U	1	ug/L	4	4	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	75-09-2	METHYLENE CHLORIDE	ND	0	0.50	U	1	ug/L	0.5	0.5	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	1634-04-4	MTBE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	91-20-3	NAPHTHALENE	ND	0	0.50	U	1	ug/L	0.5	0.5	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	95-47-6	O-XYLENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	100-42-5	STYRENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	127-18-4	TETRACHLOROETHENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	108-88-3	TOLUENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	156-60-5	TRANS-1,2-DICHLOROETHENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	10061-02-	TRANS-1,3-DICHLOROPROPENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	79-01-6	TRICHLOROETHENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	75-69-4	TRICHLOROFLUOROMETHANE	ND	0	0.30	U	1	ug/L	0.3	0.3	1	EMAX
MBLK2W		Blank	VO05A18E	SW8260B	SW5030B	1/28/2016	1/28/2016	WATER	75-01-4	VINYL CHLORIDE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	71-55-6	1,1,1-TRICHLOROETHANE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	79-34-5	1,1,2,2-TETRACHLOROETHANE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	79-00-5	1,1,2-TRICHLOROETHANE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	75-34-3	1,1-DICHLOROETHANE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	75-35-4	1,1-DICHLOROETHENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	120-82-1	1,2,4-TRICHLOROBENZENE	ND	0	0.30	U	1	ug/L	0.3	0.3	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	95-63-6	1,2,4-TRIMETHYLBENZENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	95-50-1	1,2-DICHLOROBENZENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	107-06-2	1,2-DICHLOROETHANE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	78-87-5	1,2-DICHLOROPROPANE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	108-67-8	1,3,5-TRIMETHYLBENZENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	541-73-1	1,3-DICHLOROBENZENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	106-46-7	1,4-DICHLOROBENZENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	78-93-3	2-BUTANONE	ND	0	4.00	U	1	ug/L	4	4	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	591-78-6	2-HEXANONE	ND	0	4.00	U	1	ug/L	4	4	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	67-64-1	ACETONE	ND	0	5.00	U	1	ug/L	5	5	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	71-43-2	BENZENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	75-27-4	BROMODICHLOROMETHANE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	75-25-2	BROMOFORM	ND	0	0.30	U	1	ug/L	0.3	0.3	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	74-83-9	BROMOMETHANE	ND	0	0.30	U	1	ug/L	0.3	0.3	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	75-15-0	CARBON DISULFIDE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	56-23-5	CARBON TETRACHLORIDE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	108-90-7	CHLOROBENZENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	75-00-3	CHLOROETHANE	ND	0	0.30	U	1	ug/L	0.3	0.3	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	67-66-3	CHLOROFORM	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	74-87-3	CHLOROMETHANE	ND	0	0.30	U	1	ug/L	0.3	0.3	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	156-59-2	CIS-1,2-DICHLOROETHENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	10061-01-	CIS-1,3-DICHLOROPROPENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	124-48-1	DIBROMOCHLOROMETHANE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	100-41-4	ETHYLBENZENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	136777-61	M,P-XYLENES	ND	0	0.40	U	1	ug/L	0.4	0.4	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	108-10-1	MIBK	ND	0	4.00	U	1	ug/L	4	4	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	75-09-2	METHYLENE CHLORIDE	ND	0	0.50	U	1	ug/L	0.5	0.5	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	1634-04-4	MTBE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	91-20-3	NAPHTHALENE	ND	0	0.50	U	1	ug/L	0.5	0.5	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	95-47-6	O-XYLENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	100-42-5	STYRENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	127-18-4	TETRACHLOROETHENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	108-88-3	TOLUENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	156-60-5	TRANS-1,2-DICHLOROETHENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	10061-02-	TRANS-1,3-DICHLOROPROPENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	79-01-6	TRICHLOROETHENE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	75-69-4	TRICHLOROFLUOROMETHANE	ND	0	0.30	U	1	ug/L	0.3	0.3	1	EMAX
QCTB-01202016		Blank	A187-08	SW8260B	SW5030B	1/20/2016	1/28/2016	WATER	75-01-4	VINYL CHLORIDE	ND	0	0.20	U	1	ug/L	0.2	0.2	1	EMAX
ICB015WBBLK		Blank	ICB015WE	E300.0	NONE		2/11/2016	WATER	16887-00-	CHLORIDE-CL	ND	0	0.20	U	1	MG/L	0.1	0.2	EMXT	
ICB015WBBLK		Blank	ICB015WE	E300.0	NONE		2/11/2016	WATER	14808-79-	SULFATE	ND	0	0.50	U	1	MG/L	0.25	0.5	EMXT	
ICB017WBBLK		Blank	ICB017WE	E300.0	NONE		2/11/2016	WATER	16887-00-	CHLORIDE-CL	ND	0	0.20	U	1	MG/L	0.1	0.2	EMXT	
ICB017WBBLK		Blank	ICB017WE	E300.0	NONE		2/11/2016	WATER	14808-79-	SULFATE	ND	0	0.50	U	1	MG/L	0.25	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	71-55-6	1,1,1-TRICHLOROETHANE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	79-34-5	1,1,2,2-TETRACHLOROETHANE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	79-00-5	1,1,2-TRICHLOROETHANE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	75-34-3	1,1-DICHLOROETHANE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	75-35-4	1,1-DICHLOROETHENE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	120-82-1	1,2,4-TRICHLOROBENZENE	ND	0	1	U	1	UG/L	0.3	0.5	EMXT	

CLIENT SAMPLE ID	Well ID	Sample type	LAB SAMPLE ID	ANALYTICAL METHOD CODE	PREP METHOD CODE	DATE SAMPLED	DATE ANALYZED	MATRIX	CAS NUMBER	PARAMETER NAME	RESULT	Result2	Result2 (RL)	QUALIFIER	QualCode	UNITS	DETECTION LIMIT	REPORTING LIMIT	DILUTION FACTOR	LAB NAME
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	95-63-6	1,2,4-TRIMETHYLBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	95-50-1	1,2-DICHLOROBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	107-06-2	1,2-DICHLOROETHANE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	78-87-5	1,2-DICHLOROPROPANE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	108-67-8	1,3,5-TRIMETHYLBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	541-73-1	1,3-DICHLOROBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	106-46-7	1,4-DICHLOROBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	78-93-3	2-BUTANONE	ND	0	10	U	1	UG/L	4	10	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	591-78-6	2-HEXANONE	ND	0	5	U	1	UG/L	4	5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	67-64-1	ACETONE	ND	0	10	U	1	UG/L	5	10	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	71-43-2	BENZENE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	75-27-4	BROMODICHLOROMETHANE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	75-25-2	BROMOFORM	ND	0	1	U	1	UG/L	0.3	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	74-83-9	BROMOMETHANE	ND	0	1	U	1	UG/L	0.3	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	75-15-0	CARBON DISULFIDE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	56-23-5	CARBON TETRACHLORIDE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	108-90-7	CHLOROBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	75-00-3	CHLOROETHANE	ND	0	1	U	1	UG/L	0.3	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	67-66-3	CHLOROFORM	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	74-87-3	CHLOROMETHANE	ND	0	1	U	1	UG/L	0.3	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	156-59-2	CIS-1,2-DICHLOROETHENE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	10061-01-	CIS-1,3-DICHLOROPROPENE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	124-48-1	DIBROMOCHLOROMETHANE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	100-41-4	ETHYLBENZENE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	136777-61	M,P-XYLENES	ND	0	1	U	1	UG/L	0.4	1	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	108-10-1	MIBK	ND	0	5	U	1	UG/L	4	5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	75-09-2	METHYLENE CHLORIDE	ND	0	1	U	1	UG/L	0.5	1	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	1634-04-4	MTBE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	91-20-3	NAPHTHALENE	ND	0	1	U	1	UG/L	0.5	1	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	95-47-6	O-XYLENE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	100-42-5	STYRENE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	127-18-4	TETRACHLOROETHENE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	156-60-5	TRANS-1,2-DICHLOROETHENE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	10061-02-	TRANS-1,3-DICHLOROPROPENE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	79-01-6	TRICHLOROETHENE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	75-69-4	TRICHLOROFLUOROMETHANE	ND	0	1	U	1	UG/L	0.3	0.5	EMXT	
QCTB-02092016		Blank	B076-13	SW8260B	SW5030B	2/9/2016	2/16/2016	WATER	75-01-4	VINYL CHLORIDE	ND	0	1	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	71-55-6	1,1,1-TRICHLOROETHANE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	79-34-5	1,1,2,2-TETRACHLOROETHANE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	79-00-5	1,1,2-TRICHLOROETHANE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	75-34-3	1,1-DICHLOROETHANE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	75-35-4	1,1-DICHLOROETHENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	120-82-1	1,2,4-TRICHLOROBENZENE	ND	0	0.50	U	1	UG/L	0.3	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	95-63-6	1,2,4-TRIMETHYLBENZENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	95-50-1	1,2-DICHLOROBENZENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	107-06-2	1,2-DICHLOROETHANE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	78-87-5	1,2-DICHLOROPROPANE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	108-67-8	1,3,5-TRIMETHYLBENZENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	541-73-1	1,3-DICHLOROBENZENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	106-46-7	1,4-DICHLOROBENZENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	78-93-3	2-BUTANONE	ND	0	10.00	U	1	UG/L	4	10	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	591-78-6	2-HEXANONE	ND	0	5.00	U	1	UG/L	4	5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	67-64-1	ACETONE	ND	0	10.00	U	1	UG/L	5	10	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	71-43-2	BENZENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	75-27-4	BROMODICHLOROMETHANE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	75-25-2	BROMOFORM	ND	0	0.50	U	1	UG/L	0.3	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	74-83-9	BROMOMETHANE	ND	0	0.50	U	1	UG/L	0.3	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	75-15-0	CARBON DISULFIDE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	56-23-5	CARBON TETRACHLORIDE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	108-90-7	CHLOROBENZENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	75-00-3	CHLOROETHANE	ND	0	0.50	U	1	UG/L	0.3	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	67-66-3	CHLOROFORM	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	74-87-3	CHLOROMETHANE	ND	0	0.50	U	1	UG/L	0.3	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	156-59-2	CIS-1,2-DICHLOROETHENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	10061-01-	CIS-1,3-DICHLOROPROPENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	124-48-1	DIBROMOCHLOROMETHANE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	100-41-4	ETHYLBENZENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	136777-61	M,P-XYLENES	ND	0	1.00	U	1	UG/L	0.4	1	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	108-10-1	MIBK	ND	0	5.00	U	1	UG/L	4	5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	75-09-2	METHYLENE CHLORIDE	ND	0	1.00	U	1	UG/L	0.5	1	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	1634-04-4	MTBE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	91-20-3	NAPHTHALENE	ND	0	1.00	U	1	UG/L	0.5	1	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	95-47-6	O-XYLENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	100-42-5	STYRENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	127-18-4	TETRACHLOROETHENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	108-88-3	TOLUENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	156-60-5	TRANS-1,2-DICHLOROETHENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	10061-02-	TRANS-1,3-DICHLOROPROPENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	79-01-6	TRICHLOROETHENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	75-69-4	TRICHLOROFLUOROMETHANE	ND	0	0.50	U	1	UG/L	0.3	0.5	EMXT	
VO06B11BBLK		Blank	VO06B11E	SW8260B	SW5030B		2/11/2016	WATER	75-01-4	VINYL CHLORIDE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B12BBLK		Blank	VO06B12E	SW8260B	SW5030B		2/12/2016	WATER	123-91-1	1,4-DIOXANE	ND	0	1.00	U	1	UG/L	0.5	1	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	71-55-6	1,1,1-TRICHLOROETHANE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	79-34-5	1,1,2,2-TETRACHLOROETHANE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	79-00-5	1,1,2-TRICHLOROETHANE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	75-34-3	1,1-DICHLOROETHANE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	75-35-4	1,1-DICHLOROETHENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	120-82-1	1,2,4-TRICHLOROBENZENE	ND	0	0.50	U	1	UG/L	0.3	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	95-63-6	1,2,4-TRIMETHYLBENZENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	95-50-1	1,2-DICHLOROBENZENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	107-06-2	1,2-DICHLOROETHANE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	78-87-5	1,2-DICHLOROPROPANE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	108-67-8	1,3,5-TRIMETHYLBENZENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	541-73-1	1,3-DICHLOROBENZENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	106-46-7	1,4-DICHLOROBENZENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	78-93-3	2-BUTANONE	ND	0	10.00	U	1	UG/L	4	10	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	591-78-6	2-HEXANONE	ND	0	5.00	U	1	UG/L	4	5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	67-64-1	ACETONE	ND	0	10.00	U	1	UG/L	5	10	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	71-43-2	BENZENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	75-27-4	BROMODICHLOROMETHANE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	75-25-2	BROMOFORM	ND	0	0.50	U	1	UG/L	0.3	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	74-83-9	BROMOMETHANE	ND	0	0.50	U	1	UG/L	0.3	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	75-15-0	CARBON DISULFIDE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	56-23-5	CARBON TETRACHLORIDE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	108-90-7	CHLOROBENZENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	75-00-3	CHLOROETHANE	ND	0	0.50	U	1	UG/L	0.3	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	67-66-3	CHLOROFORM	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	74-87-3	CHLOROMETHANE	ND	0	0.50	U	1	UG/L	0.3	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	156-59-2	CIS-1,2-DICHLOROETHENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	10061-01-	CIS-1,3-DICHLOROPROPENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	124-48-1	DIBROMOCHLOROMETHANE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	100-41-4	ETHYLBENZENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13E	SW8260B	SW5030B		2/16/2016	WATER	136777-61	M,P-XYLENES	ND	0	1.00	U	1	UG/L	0.4	1	EMXT	

CLIENT SAMPLE ID	Well ID	Sample type	LAB SAMPLE ID	ANALYTICAL METHOD CODE	PREP METHOD CODE	DATE SAMPLED	DATE ANALYZED	MATRIX	CAS NUMBER	PARAMETER NAME	RESULT	Result2	Result2 (RL)	QUALIFIER	QualCode	UNITS	DETECTION LIMIT	REPORTING LIMIT	DILUTION FACTOR	LAB NAME
VO06B13BBLK		Blank	VO06B13B	SW8260B	SW5030B		2/16/2016	WATER	108-10-1	MIBK	ND	0	5.00	U	1	UG/L	4	5	EMXT	
VO06B13BBLK		Blank	VO06B13B	SW8260B	SW5030B		2/16/2016	WATER	75-09-2	METHYLENE CHLORIDE	ND	0	1.00	U	1	UG/L	0.5	1	EMXT	
VO06B13BBLK		Blank	VO06B13B	SW8260B	SW5030B		2/16/2016	WATER	1634-04-4	MTBE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13B	SW8260B	SW5030B		2/16/2016	WATER	91-20-3	NAPHTHALENE	ND	0	1.00	U	1	UG/L	0.5	1	EMXT	
VO06B13BBLK		Blank	VO06B13B	SW8260B	SW5030B		2/16/2016	WATER	95-47-6	O-XYLENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13B	SW8260B	SW5030B		2/16/2016	WATER	100-42-5	STYRENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13B	SW8260B	SW5030B		2/16/2016	WATER	127-18-4	TETRACHLOROETHENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13B	SW8260B	SW5030B		2/16/2016	WATER	108-88-3	TOLUENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13B	SW8260B	SW5030B		2/16/2016	WATER	156-60-5	TRANS-1,2-DICHLOROETHENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13B	SW8260B	SW5030B		2/16/2016	WATER	10061-02-	TRANS-1,3-DICHLOROPROPENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13B	SW8260B	SW5030B		2/16/2016	WATER	79-01-6	TRICHLOROETHENE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13B	SW8260B	SW5030B		2/16/2016	WATER	75-69-4	TRICHLOROFLUOROMETHANE	ND	0	0.50	U	1	UG/L	0.3	0.5	EMXT	
VO06B13BBLK		Blank	VO06B13B	SW8260B	SW5030B		2/16/2016	WATER	75-01-4	VINYL CHLORIDE	ND	0	0.50	U	1	UG/L	0.2	0.5	EMXT	

	1,1,1-TRICHLOROETHANE	1,1,2,2-TETRACHLOROETHANE	1,1,2-TRICHLOROETHANE	1,1-DICHLOROETHANE	1,1-DICHLOROETHENE	1,2,4-TRICHLOROBENZENE	1,2,4-TRIMETHYLBENZENE	1,2-DICHLOROBENZENE	1,2-DICHLOROETHANE	1,2-DICHLOROETHANE-D4	1,2-DICHLOROPROPANE	1,3,5-TRIMETHYLBENZENE	1,3-DICHLOROBENZENE	1,4-DICHLOROBENZENE	1,4-DIOXANE	2-BUTANONE	2-HEXANONE	4-BROMOFLUOROBENZENE	ACETONE	ARSENIC
	71-55-6	79-34-5	79-00-5	75-34-3	75-35-4	120-82-1	95-63-6	95-50-1	107-06-2	17060-07-0	78-87-5	108-67-8	541-73-1	106-46-7	123-91-1	78-93-3	591-78-6	460-00-4	67-64-1	7440-38-2
	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent
HGA002WCLCSD	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
HGA002WLLCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ICL061WCLCSD	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ICL061WLLCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ICL063WCLCSD	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ICL063WLLCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ICL065WCLCSD	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ICL065WLLCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ILA001WCLCSD	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ILA001WLLCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
IML041WCLCSD	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	95
IML041WLLCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	94
VO06A01LLCS	94	112	115	100	87	97	90	104	96	95	105	95	102	99	-	112	104	96	111	-
VO06A01YLCSD	87	119	118	98	81	92	88	102	90	94	102	90	97	97	-	117	111	97	113	-
VO06L18CLCSD	-	-	-	-	-	-	-	-	-	73	-	-	-	-	101	-	-	-	-	-
VO06L18LLCS	-	-	-	-	-	-	-	-	-	84	-	-	-	-	105	-	-	-	-	-
VO06L19CLCSD	85	109	117	96	81	97	90	104	87	89	99	92	99	98	-	107	109	94	101	-
VO06L19LLCS	89	117	121	98	85	98	90	106	94	97	102	89	99	100	-	119	119	94	115	-
VO67L19CLCSD	108	93	100	91	91	92	89	92	108	105	90	87	90	89	-	100	90	86	93	-
VO67L19LLCS	108	94	102	92	92	93	93	95	105	101	91	92	93	93	-	103	89	86	93	-

	BARIUM	BENZENE	BERYLLIUM	BROMATE	BROMODICHLOROMETHANE	BROMOFORM	BROMOMETHANE	CADMIUM	CARBON DISULFIDE	CARBON DISULFIDE	CARBON TETRACHLORIDE	CHLORIDE-CL	CHLOROBENZENE	CHLOROETHANE	CHLOROFORM	CHLOROMETHANE	CHROMIUM	CIS-1,2-DICHLOROETHENE	CIS-1,3-DICHLOROPROPENE	COPPER
	7440-39-3	71-43-2	7440-41-7	15541-45-4	75-27-4	75-25-2	74-83-9	7440-43-9	75-15-0	75-15-0	56-23-5	16887-00-6	108-90-7	75-00-3	67-66-3	74-87-3	7440-47-3	156-59-2	10061-01-5	7440-50-8
	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent
HGA002WCLCSD	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
HGA002WLLCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ICL061WCLCSD	-	-	-	-	-	-	-	-	-	-	-	99	-	-	-	-	-	-	-	-
ICL061WLLCS	-	-	-	-	-	-	-	-	-	-	-	96	-	-	-	-	-	-	-	-
ICL063WCLCSD	-	-	-	-	-	-	-	-	-	-	-	99	-	-	-	-	-	-	-	-
ICL063WLLCS	-	-	-	-	-	-	-	-	-	-	-	97	-	-	-	-	-	-	-	-
ICL065WCLCSD	-	-	-	-	-	-	-	-	-	-	-	98	-	-	-	-	-	-	-	-
ICL065WLLCS	-	-	-	-	-	-	-	-	-	-	-	101	-	-	-	-	-	-	-	-
ILA001WCLCSD	-	-	-	102	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ILA001WLLCS	-	-	-	102	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
IML041WCLCSD	99	-	96	-	-	-	-	99	-	-	-	-	-	-	-	-	98	-	-	100
IML041WLLCS	100	-	95	-	-	-	-	99	-	-	-	-	-	-	-	-	99	-	-	101
VO06A01LLCS	-	105	-	-	104	104	99	-	84	-	89	-	102	100	100	108	-	98	103	-
VO06A01YLCSD	-	101	-	-	99	104	92	-	81	-	82	-	102	89	93	96	-	94	97	-
VO06L18CLCSD	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VO06L18LLCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VO06L19CLCSD	-	100	-	-	95	100	95	-	86	-	82	-	103	96	90	104	-	93	95	-
VO06L19LLCS	-	104	-	-	100	107	95	-	83	-	84	-	104	92	93	101	-	96	101	-
VO67L19CLCSD	-	90	-	-	103	103	99	-	87	-	106	-	95	98	100	81	-	91	98	-
VO67L19LLCS	-	91	-	-	103	106	99	-	85	-	108	-	97	98	101	82	-	93	99	-

	DIBROMOCHLOROMETHANE	DIBROMOFLUOROMETHANE	ETHYLBENZENE	IRON	LEAD	M,P-XYLENES	MERCURY	METHYLENE CHLORIDE	MIBK	MTBE	NAPHTHALENE	O-XYLENE	SELENIUM	STYRENE	SULFATE	TETRACHLOROETHENE	THALLIUM	TOLUENE	TOLUENE-D8	TRANS-1,2-DICHLOROETHENE
	124-48-1	1868-53-7	100-41-4	7439-89-6	7439-92-1	136777-61-2	7439-97-6	75-09-2	108-10-1	1634-04-4	91-20-3	95-47-6	7782-49-2	100-42-5	14808-79-8	127-18-4	7440-28-0	108-88-3	2037-26-5	156-60-5
	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent
HGA002WCLCSD	-	-	-	-	-	-	105	-	-	-	-	-	-	-	-	-	-	-	-	-
HGA002WLLCS	-	-	-	-	-	-	106	-	-	-	-	-	-	-	-	-	-	-	-	-
ICL061WCLCSD	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ICL061WLLCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ICL063WCLCSD	-	-	-	-	-	-	-	-	-	-	-	-	-	-	102	-	-	-	-	-
ICL063WLLCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	100	-	-	-	-	-
ICL065WCLCSD	-	-	-	-	-	-	-	-	-	-	-	-	-	-	103	-	-	-	-	-
ICL065WLLCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	110	-	-	-	-	-
ILA001WCLCSD	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ILA001WLLCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
IML041WCLCSD	-	-	-	106	105	-	-	-	-	-	-	-	100	-	-	-	104	-	-	-
IML041WLLCS	-	-	-	107	106	-	-	-	-	-	-	-	100	-	-	-	104	-	-	-
VO06A01LLCS	104	106	96	-	-	95	-	86	110	98	97	98	-	102	-	102	-	93	99	87
VO06A01YLCSD	103	103	93	-	-	92	-	86	113	95	95	96	-	100	-	100	-	93	101	82
VO06L18CLCSD	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VO06L18LLCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VO06L19CLCSD	98	98	93	-	-	94	-	85	107	90	97	97	-	98	-	104	-	96	104	83
VO06L19LLCS	107	103	96	-	-	95	-	88	119	100	102	96	-	102	-	103	-	96	103	88
VO67L19CLCSD	109	101	95	-	-	96	-	85	87	106	87	96	-	93	-	95	-	95	94	85
VO67L19LLCS	111	99	100	-	-	100	-	84	84	106	87	100	-	98	-	99	-	98	94	86

	TRANS-1,3-DICHLOROPROPENE	TRICHLOROETHENE	TRICHLOROFLUOROMETHANE	VINYL CHLORIDE
	10061-02-6	79-01-6	75-69-4	75-01-4
	Percent	Percent	Percent	Percent
HGA002WCLCSD	-	-	-	-
HGA002WLLCS	-	-	-	-
ICL061WCLCSD	-	-	-	-
ICL061WLLCS	-	-	-	-
ICL063WCLCSD	-	-	-	-
ICL063WLLCS	-	-	-	-
ICL065WCLCSD	-	-	-	-
ICL065WLLCS	-	-	-	-
ILA001WCLCSD	-	-	-	-
ILA001WLLCS	-	-	-	-
IML041WCLCSD	-	-	-	-
IML041WLLCS	-	-	-	-
VO06A01LLCS	93	105	88	92
VO06A01YLCSD	93	101	79	82
VO06L18CLCSD	-	-	-	-
VO06L18LLCS	-	-	-	-
VO06L19CLCSD	93	100	80	90
VO06L19LLCS	100	104	79	86
VO67L19CLCSD	107	89	126	100
VO67L19LLCS	108	91	121	99

Well ID	Bottom sampling depth interval (ft bgs)	Distance from cylinder well (ft)	DATE SAMPLED	1,1,1-TRICHLOROETHANE	1,1,2,2-TETRACHLOROETHANE	1,1,2-TRICHLOROETHANE	1,2,4-TRICHLOROBENZENE	1,2,4-TRIMETHYLBENZENE	1,2-DICHLOROBENZENE	1,2-DICHLOROETHANE	1,2-DICHLOROETHANE-D4	1,2-DICHLOROPROPANE	1,3,5-TRIMETHYLBENZENE	1,3-DICHLOROBENZENE
				71-55-6	79-34-5	79-00-5	120-82-1	95-63-6	95-50-1	107-06-2	17060-07-0	78-87-5	108-67-8	541-73-1
				PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT
DMW-01	40	-10	1/20/2016	-	-	-	-	-	-	-	-	-	-	-
DMW-01	40	-10	2/9/2016	-	-	-	-	-	-	-	-	-	-	-
SMW-07A	40	150	12/21/2015	93	113	112	92	92	106	84	98	105	93	101

Well ID	Bottom sampling depth interval (ft bgs)	Distance from cylinder well (ft)	DATE SAMPLED	1,4-DICHLOROBENZENE	1,4-DIOXANE	2-BUTANONE	2-HEXANONE	4-BROMOFLUOROBENZENE	ACETONE	ARSENIC	BARIUM	BENZENE	BERYLLIUM	BROMATE
				106-46-7	123-91-1	78-93-3	591-78-6	460-00-4	67-64-1	7440-38-2	7440-39-3	71-43-2	7440-41-7	15541-45-4
				PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT
DMW-01	40	-10	1/20/2016	-	-	-	-	-	-	-	-	-	-	-
DMW-01	40	-10	2/9/2016	-	-	-	-	-	-	-	-	-	-	-
SMW-07A	40	150	12/21/2015	100	101	108	104	96	101	96	99	104	97	103

Well ID	Bottom sampling depth interval (ft bgs)	Distance from cylinder well (ft)	DATE SAMPLED	BROMODICHLOROMETHANE	BROMOFORM	BROMOMETHANE	CADMIUM	CARBON DISULFIDE	CARBON TETRACHLORIDE	CHLORIDE-CL	CHLORIDE-CL	CHLOROBENZENE	CHLOROETHANE	CHLOROFORM
				75-27-4	75-25-2	74-83-9	7440-43-9	75-15-0	56-23-5	16887-00-6	16887-00-6	108-90-7	75-00-3	67-66-3
				PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	%	PERCENT	PERCENT	PERCENT
DMW-01	40	-10	1/20/2016	-	-	-	-	-	-	-	96	-	-	-
DMW-01	40	-10	2/9/2016	-	-	-	-	-	-	94	-	-	-	-
SMW-07A	40	150	12/21/2015	102	101	99	92	90	90	108	-	106	104	91

Well ID	Bottom sampling depth interval (ft bgs)	Distance from cylinder well (ft)	DATE SAMPLED	CHLOROMETHANE	CHROMIUM	CIS-1,3-DICHLOROPROPENE	COPPER	DIBROMOCHLOROMETHANE	DIBROMOFLUOROMETHANE	ETHYLBENZENE	IRON	LEAD	M,P-XYLENES	MERCURY
				74-87-3	7440-47-3	10061-01-5	7440-50-8	124-48-1	1868-53-7	100-41-4	7439-89-6	7439-92-1	136777-61-2	7439-97-6
				PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT
DMW-01	40	-10	1/20/2016	-	-	-	-	-	-	-	-	-	-	-
DMW-01	40	-10	2/9/2016	-	-	-	-	-	-	-	-	-	-	-
SMW-07A	40	150	12/21/2015	121	95	99	91	102	101	98	100	99	98	84

Well ID	Bottom sampling depth interval (ft bgs)	Distance from cylinder well (ft)	DATE SAMPLED	METHYLENE CHLORIDE	MIBK	MTBE	NAPHTHALENE	O-XYLENE	SELENIUM	STYRENE	SULFATE	SULFATE	TETRACHLOROETHENE	THALLIUM
				75-09-2	108-10-1	1634-04-4	91-20-3	95-47-6	7782-49-2	100-42-5	14808-79-8	14808-79-8	127-18-4	7440-28-0
				PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	%	PERCENT	PERCENT
DMW-01	40	-10	1/20/2016	-	-	-	-	-	-	-	-	100	-	-
DMW-01	40	-10	2/9/2016	-	-	-	-	-	-	-	104	-	-	-
SMW-07A	40	150	12/21/2015	87	100	93	95	99	98	98	118	-	91	98

Well ID	Bottom sampling depth interval (ft bgs)	Distance from cylinder well (ft)	DATE SAMPLED	TOLUENE	TOLUENE-D8	TRANS-1,2-DICHLOROETHENE	TRANS-1,3-DICHLOROPROPENE	TRICHLOROFLUOROMETHANE	VINYL CHLORIDE
				108-88-3	2037-26-5	156-60-5	10061-02-6	75-69-4	75-01-4
				PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT
DMW-01	40	-10	1/20/2016	-	-	-	-	-	-
DMW-01	40	-10	2/9/2016	-	-	-	-	-	-
SMW-07A	40	150	12/21/2015	101	104	86	94	89	35

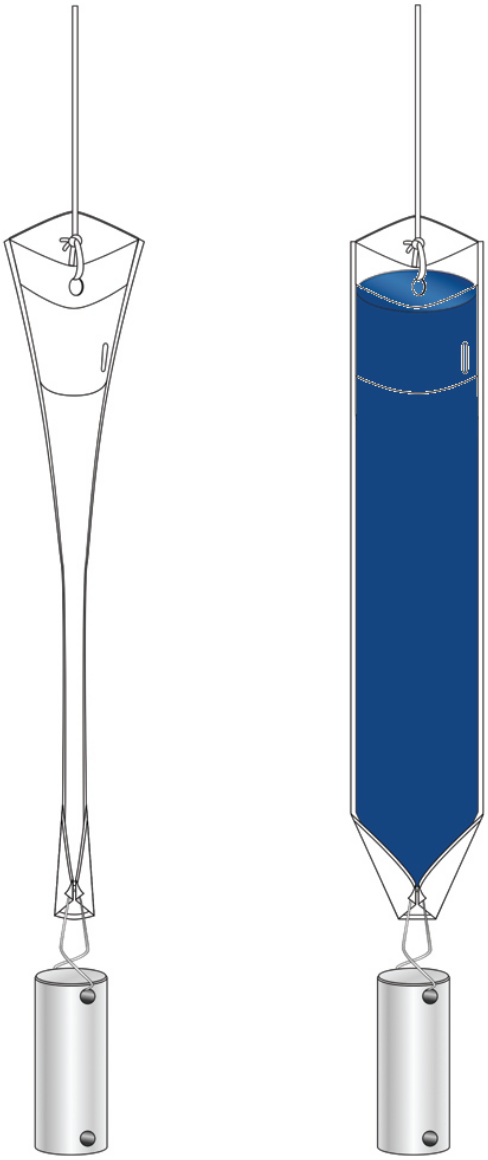
APPENDIX F
STANDARD OPERATING PROCEDURES

HydraSleeve^{TM} Standard Operating Procedure

HYDRASleeve™

Simple by Design US Patent No. 6,481,300; No. 6,837,120 others pending

Standard Operating Procedure:
Sampling Ground Water with a HydraSleeve



This Guide should be used in addition to field manuals appropriate to sampling device (i.e., HydraSleeve or Super Sleeve).

Find the appropriate field manual on the HydraSleeve website at http://www.hydrasleeve.com.

For more information about the HydraSleeve, or if you have questions, contact:
GeoInsight, 2007 Glass Road, Las Cruces, NM 88005, 1-800-996-2225,
info@hydrasleeve.com.

Table of Contents

Introduction

The HydraSleeve is classified as a no-purge (passive) grab sampling device, meaning that it is used to collect ground-water samples directly from the screened interval of a well without having to purge the well prior to sample collection. When it is used as described in this Standard Operating Procedure (SOP), the HydraSleeve causes no drawdown in the well (until the sample is withdrawn from the water column) and only minimal disturbance of the water column, because it has a very thin cross section and it displaces very little water (<100 ml) during deployment in the well. The HydraSleeve collects a sample from within the screen only, and it excludes water from any other part of the water column in the well through the use of a self-sealing check valve at the top of the sampler. It is a single-use (disposable) sampler that is not intended for reuse, so there are no decontamination requirements for the sampler itself.

The use of no-purge sampling as a means of collecting representative ground-water samples depends on the natural movement of ground water (under ambient hydraulic head) from the formation adjacent to the well screen through the screen. Robin and Gillham (1987) demonstrated the existence of a dynamic equilibrium between the water in a formation and the water in a well screen installed in that formation, which results in formation-quality water being available in the well screen for sampling at all times. No-purge sampling devices like the HydraSleeve collect this formation-quality water as the sample, under undisturbed (non-pumping) natural flow conditions. Samples collected in this manner generally provide more conservative (i.e., higher concentration) values than samples collected using well-volume purging, and values equivalent to samples collected using low-flow purging and sampling (Parsons, 2005).

Applications of the HydraSleeve

The HydraSleeve can be used to collect representative samples of ground water for all analytes (volatile organic compounds [VOCs], semi-volatile organic compounds [SVOCs], common metals, trace metals, major cations and anions, dissolved gases, total dissolved solids, radionuclides, pesticides, PCBs, explosive compounds, and all other analytical parameters). Designs are available to collect samples from wells from 1” inside diameter and larger. The HydraSleeve can collect samples from wells of any yield, but it is especially well-suited to collecting samples from low-yield wells, where other sampling methods can’t be used reliably because their use results in dewatering of the well screen and alteration of sample chemistry (McAlary and Barker, 1987).

The HydraSleeve can collect samples from wells of any depth, and it can be used for single-event sampling or long-term ground-water monitoring programs. Because of its thin cross section and flexible construction, it can be used in narrow, constricted or damaged wells where rigid sampling devices may not fit. Using multiple HydraSleeves deployed in series along a single suspension line or tether, it is also possible to conduct in-well vertical profiling in wells in which contaminant concentrations are thought to be stratified.

As with all groundwater sampling devices, HydraSleeves should not be used to collect groundwater samples from wells in which separate (non-aqueous) phase hydrocarbons (i.e., gasoline, diesel fuel or jet fuel) are present because of the possibility of incorporating some of the separate-phase hydrocarbon into the sample.

Description of the HydraSleeve

The HydraSleeve (Figure 1) consists of the following basic components:

- A suspension line or tether (A.), attached to the spring clip or directly to the top of the sleeve to deploy the device into and recover the device from the well. Tethers with depth indicators marked in 1-foot intervals are available from the manufacturer.
- A long, flexible, 4-mil thick lay-flat polyethylene sample sleeve (C.) sealed at the bottom (this is the sample chamber), which comes in different sizes, as discussed below with a self-sealing reed-type flexible polyethylene check valve built into the top of the sleeve (B.) to prevent water from entering or exiting the sampler except during sample acquisition.
- A reusable stainless-steel weight with clip (D.), which is attached to the bottom of the sleeve to carry it down the well to its intended depth in the water column. Bottom weights available from the manufacturer are 0.75” OD and are available in three sizes: 5 oz. (2.5” long); 8 oz. (4” long); and 16 oz. (8” long). In lieu of a bottom weight, an optional top weight may be attached to the top of the HydraSleeve to carry it to depth and to compress it at the bottom of the well (not shown in Figure 1);
- A discharge tube that is used to puncture the HydraSleeve after it is recovered from the well so the sample can be decanted into sample bottles (not shown).
- Just above the self-sealing check valve at the top of the sleeve are two holes which provide attachment points for the spring clip and/or suspension line or tether. At the bottom of the sample sleeve are two holes which provide attachment points for the weight clip and weight.

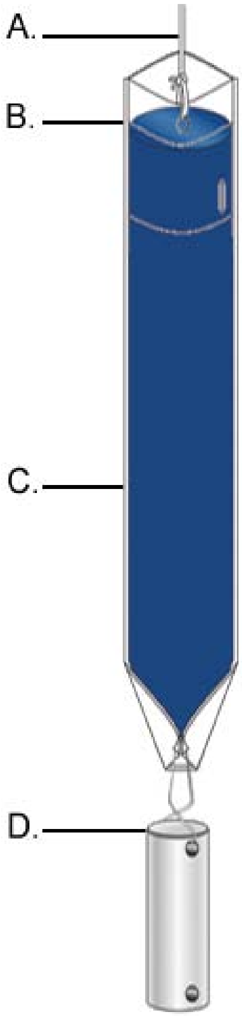


Figure 1. HydraSleeve components.

> **Note:** The sample sleeve and the discharge tube are designed for one-time use and are disposable. The spring clip, weight and weight clip may be reused after thorough cleaning. Suspension cord is generally disposed after one use although, if it is dedicated to the well, it may be reused at the discretion of the sampling personnel.

Selecting the HydraSleeve Size to Meet Site-Specific Sampling Objectives

It is important to understand that each HydraSleeve is able to collect a finite volume of sample because, after the HydraSleeve is deployed, you only get one chance to collect an undisturbed sample. Thus, the volume of sample required to meet your site-specific sampling and analytical requirements will dictate the size of HydraSleeve you need to meet these requirements.

The volume of sample collected by the HydraSleeve varies with the diameter and length of the HydraSleeve. Dimensions and volumes of available HydraSleeve models are detailed in Table 1.

Table 1. Dimensions and volumes of HydraSleeve models.

Diameter	Volume	Length	Lay-Flat Width	Filled Dia.
2-Inch HydraSleeves				
Standard 625-ml HydraSleeve	625 ml	< 30”	2.5”	1.4”
Standard 1-Liter HydraSleeve	1 Liter	38”	3”	1.9”
1-Liter HydraSleeve SS	1 Liter	36”	3”	1.9”
2-Liter HydraSleeve SS	2 Liters	60”	3”	1.9”
4-Inch HydraSleeves				
Standard 1.6-Liter HydraSleeve	1.6 Liters	30”	3.8”	2.3”
Custom 2-Liter HydraSleeve	2 Liters	36”	4”	2.7”

HydraSleeves can be custom-fabricated by the manufacturer in varying diameters and lengths to meet specific volume requirements. HydraSleeves can also be deployed in series (i.e., multiple HydraSleeves attached to one tether) to collect additional sample to meet specific volume requirements, as described below.

If you have questions regarding the availability of sufficient volume of sample to satisfy laboratory requirements for analysis, it is recommended that you contact the laboratory to discuss the minimum volumes needed for each suite of analytes. Laboratories often require only 10% to 25% of the volume they specify to complete analysis for specific suites of analytes, so they can often work with much smaller sample volumes that can easily be supplied by a HydraSleeve.

HydraSleeve Deployment

Information Required Before Deploying a HydraSleeve

Before installing a HydraSleeve in any well, you will need to know the following:

- The inside diameter of the well
- The length of the well screen
- The water level in the well
- The position of the well screen in the well
- The total depth of the well

The inside diameter of the well is used to determine the appropriate HydraSleeve diameter for use in the well. The other information is used to determine the proper placement of the HydraSleeve in the well to collect a representative sample from the screen (see HydraSleeve Placement, below), and to determine the appropriate length of tether to attach to the HydraSleeve to deploy it at the appropriate position in the well.

Most of this information (with the exception of the water level) should be available from the well log; if not, it will have to be collected by some other means. The inside diameter of the well can be measured at the top of the well casing, and the total depth of the well can be measured by sounding the bottom of the well with a weighted tape. The position and length of the well screen may have to be determined using a down-hole camera if a well log is not available. The water level in the well can be measured using any commonly available water-level gauge.

HydraSleeve Placement

The HydraSleeve is designed to collect a sample directly from the well screen, and it fills by pulling it up through the screen a distance equivalent to 1 to 1.5 times its length. This upward motion causes the top check valve to open, which allows the device to fill. To optimize sample recovery, it is recommended that the HydraSleeve be placed in the well so that the bottom weight rests on the bottom of the well and the top of the HydraSleeve is as close to the bottom of the well screen as possible. This should allow the sampler to fill before the top of the device reaches the top of the screen as it is pulled up through the water column, and ensure that only water from the screen is collected as the sample. In short-screen wells, or wells with a short water column, it may be necessary to use a top-weight on the HydraSleeve to compress it in the bottom of the well so that, when it is recovered, it has room to fill before it reaches the top of the screen.

Example

2” ID PVC well, 50’ total depth, 10’ screen at the bottom of the well, with water level above the screen (the entire screen contains water).

Correct Placement (figure 2): Using a standard HydraSleeve for a 2” well (2.6” flat width/1.5” filled OD x 30” long, 650 ml volume), deploy the sampler so the weight (an 8 oz., 4”-long weight with a 2”-long clip) rests at the bottom of the well. The top of the sleeve is thus set at about 36” above the bottom of the well. When the sampler is recovered, it will be pulled upward approximately 30” to 45” before it is filled; therefore, it is full (and the top check valve closes) at approximately 66” (5 ½ feet) to 81” (6 ¾ feet) above the bottom of the well, which is well before the sampler reaches the top of the screen. In this example, only water from the screen is collected as a sample.

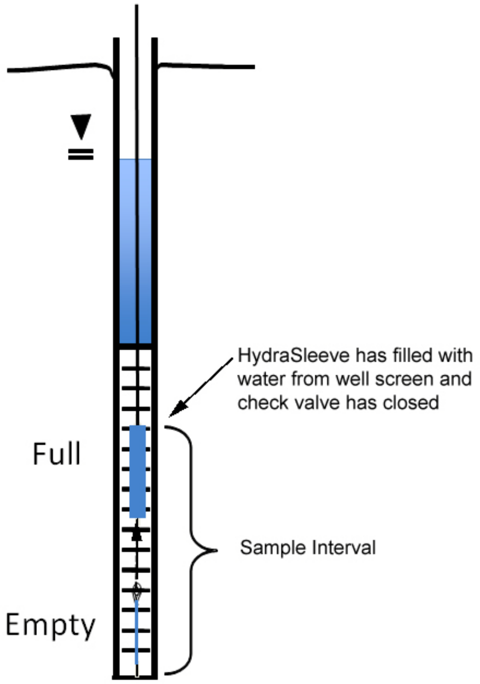


Figure 2. Correct placement of HydraSleeve.

Incorrect Placement (figure 3): If the well screen in this example was only 5' long, and the HydraSleeve was placed as above, it would not fill before the top of the device reached the top of the well screen, so the sample would include water from above the screen, which may not have the same chemistry.

The solution? Deploy the HydraSleeve with a top weight, so that it is collapsed to within 6" to 9" of the bottom of the well. When the HydraSleeve is recovered, it will fill within 39" (3 ¼ feet) to 54" (4 ½ feet) above the bottom of the well, or just before the sampler reaches the top of the screen, so it collects only water from the screen as the sample.

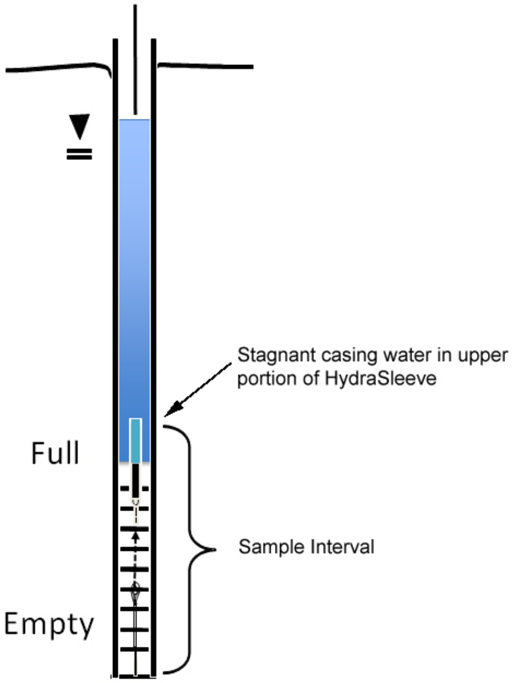


Figure 3. Incorrect placement of HydraSleeve.

This example illustrates one of many types of HydraSleeve placements. More complex placements are discussed in a later section.

Procedures for Sampling with the HydraSleeve

Collecting a ground-water sample with a HydraSleeve is a simple one-person operation.

Note: Before deploying the HydraSleeve in the well, collect the depth-to-water measurement that you will use to determine the preferred position of the HydraSleeve in the well. This measurement may also be used with measurements from other wells to create a ground-water contour map. If necessary, also measure the depth to the bottom of the well to verify actual well depth to confirm your decision on placement of the HydraSleeve in the water column.

Measure the correct amount of tether needed to suspend the HydraSleeve in the well so that the weight will rest on the bottom of the well (or at your preferred position in the well). Make sure to account for the need to leave a few feet of tether at the top of the well to allow recovery of the sleeve

Note: Always wear sterile gloves when handling and discharging the HydraSleeve.

I. Assembling the HydraSleeve

1. Remove the HydraSleeve from its packaging, unfold it, and hold it by its top.
2. Crimp the top of the HydraSleeve by folding the hard polyethylene reinforcing strips at the holes.
3. Attach the spring clip to the holes to ensure that the top will remain open until the sampler is retrieved.
4. Attach the tether to the spring clip by tying a knot in the tether.

Note: Alternatively, attach the tether to one (NOT both) of the holes at the top of the Hydrasleeve by tying a knot in the tether.

5. Fold the flaps with the two holes at the bottom of the HydraSleeve together and slide the weight clip through the holes.
6. Attach a weight to the bottom of the weight clip to ensure that the HydraSleeve will descend to the bottom of the well.

II. Deploying the HydraSleeve

1. Using the tether, carefully lower the HydraSleeve to the bottom of the well, or to your preferred depth in the water column

   During installation, hydrostatic pressure in the water column will keep the self-sealing check valve at the top of the HydraSleeve closed, and ensure that it retains its flat, empty profile for an indefinite period prior to recovery.

Note: Make sure that it is not pulled upward at any time during its descent. If the HydraSleeve is pulled upward at a rate greater than 0.5'/second at any time prior to recovery, the top check valve will open and water will enter the HydraSleeve prematurely.

2. Secure the tether at the top of the well by placing the well cap on the top of the well casing and over the tether.

Note: Alternatively, you can tie the tether to a hook on the bottom of the well cap (you will need to leave a few inches of slack in the line to avoid pulling the sampler up as the cap is removed at the next sampling event).

III. Equilibrating the Well

The equilibration time is the time it takes for conditions in the water column (primarily flow dynamics and contaminant distribution) to restabilize after vertical mixing occurs (caused by installation of a sampling device in the well).

- Situation: The HydraSleeve is deployed for the first time or for only one time in a well

  The HydraSleeve is very thin in cross section and displaces very little water (<100 ml) during deployment so, unlike most other sampling devices, it does not disturb the water column to the point at which long equilibration times are necessary to ensure recovery of a representative sample.

  In most cases, the HydraSleeve can be recovered immediately (with no equilibration time) or within a few hours. In regulatory jurisdictions that impose specific requirements for equilibration times prior to recovery of no-purge sampling devices, these requirements should be followed.

- Situation: The HydraSleeve is being deployed for recovery during a future sampling event

  In periodic (i.e., quarterly or semi-annual) sampling programs, the sampler for the current sampling event can be recovered and a new sampler (for the next sampling event) deployed immediately thereafter, so the new sampler remains in the well until the next sampling event.

Thus, a long equilibration time is ensured and, at the next sampling event, the sampler can be recovered immediately. This means that separate mobilizations, to deploy and then to recover the sampler, are not required. HydraSleeves can be left in a well for an indefinite period of time without concern.

IV. HydraSleeve Recovery and Sample Collection

1. Hold on to the tether while removing the well cap.

2. Secure the tether at the top of the well while maintaining tension on the tether (but without pulling the tether upwards)

3. Measure the water level in the well.

4. In one smooth motion, pull the tether up between 30” to 45” (36” to 54” for the longer HydraSleeve) at a rate of about 1’ per second (or faster).

   The motion will open the top check valve and allow the HydraSleeve to fill (it should fill in about 1 to 1.5 times the length of the HydraSleeve). This is analogous to coring the water column in the well from the bottom up.

   When the HydraSleeve is full, the top check valve will close. You should begin to feel the weight of the HydraSleeve on the tether and it will begin to displace water. The closed check valve prevents loss of sample and entry of water from zones above the well screen as the HydraSleeve is recovered.

5. Continue pulling the tether upward until the HydraSleeve is at the top of the well.

6. Decant and discard the small volume of water trapped in the Hydrasleeve above the check valve by turning the sleeve over.

V. Sample Collection

Note: Sample collection should be done immediately after the HydraSleeve has been brought to the surface to preserve sample integrity.

1. Remove the discharge tube from its sleeve.

2. Hold the HydraSleeve at the check valve.

3. Puncture the HydraSleeve just below the check valve with the pointed end of the discharge tube

4. Discharge water from the HydraSleeve into your sample containers.

Control the discharge from the HydraSleeve by either raising the bottom of the sleeve, by squeezing it like a tube of toothpaste, or both.

5. Continue filling sample containers until all are full.

Measurement of Field Indicator Parameters

Field indicator parameter measurement is generally done during well purging and sampling to confirm when parameters are stable and sampling can begin. Because no-purge sampling does not require purging, field indicator parameter measurement is not necessary for the purpose of confirming when purging is complete.

If field indicator parameter measurement is required to meet a specific non-purging regulatory requirement, it can be done by taking measurements from water within a HydraSleeve that is not used for collecting a sample to submit for laboratory analysis (i.e., a second HydraSleeve installed in conjunction with the primary sample collection HydraSleeve [see Multiple Sampler Deployment below]).

Alternate Deployment Strategies

Deployment in Wells with Limited Water Columns

For wells in which only a limited water column exists to be sampled, the HydraSleeve can be deployed with an optional top weight instead of a bottom weight, which collapses the HydraSleeve to a very short (approximately 6” to 9”) length, and allows the HydraSleeve to fill in a water column only 36” to 45” in height.

Multiple Sampler Deployment

Multiple sampler deployment in a single well screen can accomplish two purposes:

- It can collect additional sample volume to satisfy site or laboratory-specific sample volume requirements.
- It can accommodate the need for collecting field indicator parameter measurements.
- It can be used to collect samples from multiple intervals in the screen to allow identification of possible contaminant stratification.

It is possible to use up to 3 standard 30” HydraSleeves deployed in series along a single tether to collect samples from a 10’ long well screen without collecting water from the interval above the screen.

The samplers must be attached to the tether at both the top and bottom of the sleeve. Attach the tether at the top with a stainless-steel clip (available from the manufacturer). Attach the tether at the bottom using a cable tie. The samplers must be attached as follows (figure 4):

- The first (attached to the tether as described above, with the weight at the bottom) at the bottom of the screen

- The second attached immediately above the first

- The third (attached the same as the second) immediately above the second

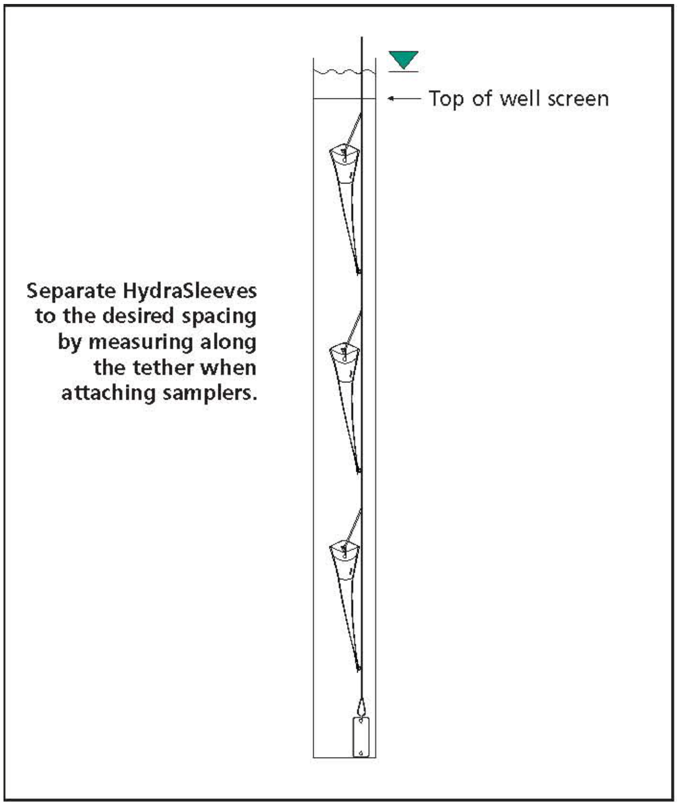


Figure 4. Multiple HydraSleeve deployment.

Alternately, the first sampler can be attached to the tether as described above, a second attached to the bottom of the first using a short length of tether (in place of the weight), and the third attached to the bottom of the second in the same manner, with the weight attached to the bottom of the third sampler (figure 5).

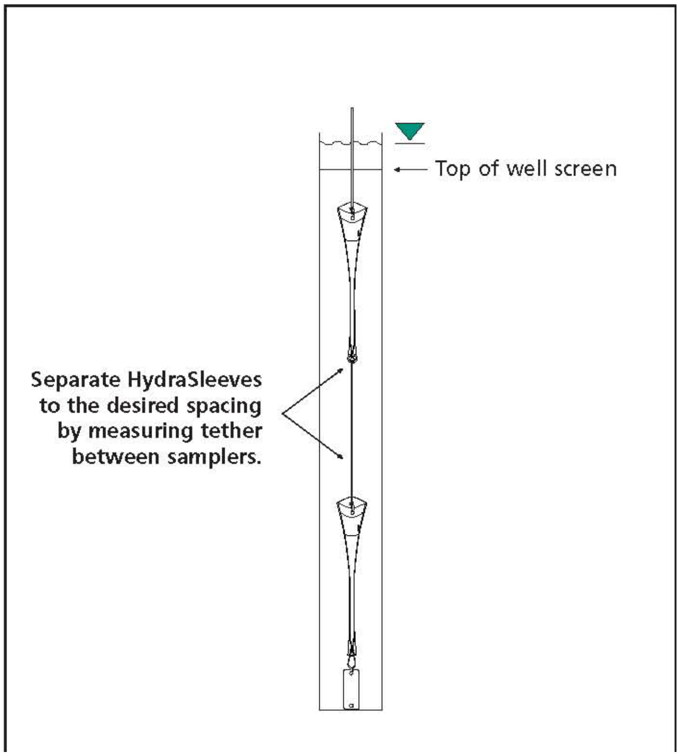


Figure 5. Alternative method for deploying multiple HydraSleeves.

In either case, when attaching multiple HydraSleeves in series, more weight may be required to hold the samplers in place in the well than would be required with a single sampler. Recovery of multiple samplers and collection of samples is done in the same manner as for single sampler deployments.

Post-Sampling Activities

The recovered HydraSleeve and the sample discharge tubing should be disposed as per the solid waste management plan for the site. To prepare for the next sampling event, a new HydraSleeve can be deployed in the well (as described previously) and left in the well until the next sampling event, at which time it can be recovered.

The weight and weight clip can be reused on this sampler after they have been thoroughly cleaned as per the site equipment decontamination plan. The tether may be dedicated to the well and reused or discarded at the discretion of sampling personnel.

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APPENDIX G
CPT REPORT

GREGG DRILLING & TESTING, INC.
GEOTECHNICAL AND ENVIRONMENTAL INVESTIGATION SERVICES

6/12/2017

NOREAS
Attn: Jason Schen

Subject: CPT Site Investigation
OU-11
San Diego, California
GREGG Project Number: 17-0581SH

Dear Mr. Schen:

The following report presents the results of GREGG Drilling & Testing's Cone Penetration Test investigation for the above referenced site. The following testing services were performed:

1	Cone Penetration Tests	(CPTU)	☒
2	Pore Pressure Dissipation Tests	(PPD)	☐
3	Seismic Cone Penetration Tests	(SCPTU)	☐
4	UVOST Laser Induced Fluorescence	(UVOST)	☐
5	Groundwater Sampling	(GWS)	☒
6	Soil Sampling	(SS)	☐
7	Vapor Sampling	(VS)	☐
8	Pressuremeter Testing	(PMT)	☐
9	Vane Shear Testing	(VST)	☐
10	Dilatometer Testing	(DMT)	☐

A list of reference papers providing additional background on the specific tests conducted is provided in the bibliography following the text of the report. If you would like a copy of any of these publications or should you have any questions or comments regarding the contents of this report, please do not hesitate to contact our office at (562) 427-6899.

Sincerely,
GREGG Drilling & Testing, Inc.

Peter Robertson
Technical Director, Gregg Drilling & Testing, Inc.

Cone Penetration Test Sounding Summary

-Table 1-

CPT Sounding Identification	Date	Termination Depth (feet)	Depth of Groundwater Samples (feet)	Depth of Soil Samples (feet)	Depth of Pore Pressure Dissipation Tests (feet)
CPT-1	6/5/17	45	-	-	-
CPT-2	6/8/17	45	-	-	-
CPT-3	6/8/17	45	-	-	-
CPT-4	6/8/17	45	-	-	-
CPT-5	6/8/17	45	-	-	-
CPT-6	6/8/17	45	-	-	-
B-1	6/5/17	39	29, 39	-	-
B-2	6/5/17	39	29, 39	-	-
B-3	6/5/17	39	29, 39	-	-
B-4	6/5/17	39	29, 39	-	-
B-5	6/6/17	39	29, 39	-	-
B-6	6/6/17	39	29, 39	-	-
B-7	6/6/17	39	29, 39	-	-
B-8	6/6/17	39	29, 39	-	-
B-9	6/6/17	39	29, 39	-	-
B-10	6/6/17	39	29, 39	-	-
B-11	6/6/17	39	29, 39	-	-
B-12	6/7/17	39	29, 39	-	-
B-13	6/7/17	39	29, 39	-	-
B-14	6/7/17	39	29, 39	-	-
B-15	6/7/17	39	29, 39	-	-
B-16	6/7/17	39	29, 39	-	-
B-17	6/7/17	39	29, 39	-	-
B-18	6/7/17	39	29, 39	-	-
B-19	6/7/17	39	29, 39	-	-
B-20	6/7/17	39	29, 39	-	-
B-21	6/7/17	39	29, 39	-	-

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Zemo, D.A., T.A. Delfino, J.D. Gallinatti, V.A. Baker and L.R. Hilpert, “Field Comparison of Analytical Results from Discrete-Depth Groundwater Samplers” BAT EnviroProbe and QED HydroPunch, Sixth national Outdoor Action Conference, Las Vegas, Nevada Proceedings, 1992, pp 299-312.

Copies of ASTM Standards are available through www.astm.org

Cone Penetration Testing Procedure (CPT)

Gregg Drilling carries out all Cone Penetration Tests (CPT) using an integrated electronic cone system, *Figure CPT*.

The cone takes measurements of tip resistance (q_c), sleeve resistance (f_s), and penetration pore water pressure (u_2). Measurements are taken at either 2.5 or 5 cm intervals during penetration to provide a nearly continuous profile. CPT data reduction and basic interpretation is performed in real time facilitating on-site decision making. The above mentioned parameters are stored electronically for further analysis and reference. All CPT soundings are performed in accordance with revised ASTM standards (D 5778-12).

The 5mm thick porous plastic filter element is located directly behind the cone tip in the u_2 location. A new saturated filter element is used on each sounding to measure both penetration pore pressures as well as measurements during a dissipation test (*PPDT*). Prior to each test, the filter element is fully saturated with oil under vacuum pressure to improve accuracy.

When the sounding is completed, the test hole is backfilled according to client specifications. If grouting is used, the procedure generally consists of pushing a hollow tremie pipe with a "knock out" plug to the termination depth of the CPT hole. Grout is then pumped under pressure as the tremie pipe is pulled from the hole. Disruption or further contamination to the site is therefore minimized.

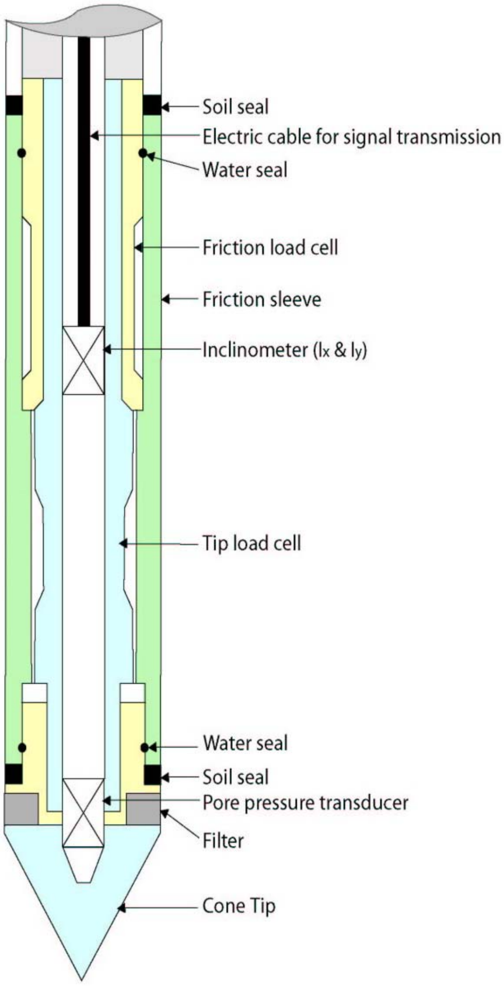


Figure CPT

Gregg 15cm^2 Standard Cone Specifications

Dimensions	
Cone base area	15 cm^2
Sleeve surface area	225 cm^2
Cone net area ratio	0.80
Specifications	
Cone load cell	
Full scale range	180 kN (20 tons)
Overload capacity	150%
Full scale tip stress	120 MPa (1,200 tsf)
Repeatability	120 kPa (1.2 tsf)
Sleeve load cell	
Full scale range	31 kN (3.5 tons)
Overload capacity	150%
Full scale sleeve stress	1,400 kPa (15 tsf)
Repeatability	1.4 kPa (0.015 tsf)
Pore pressure transducer	
Full scale range	7,000 kPa (1,000 psi)
Overload capacity	150%
Repeatability	7 kPa (1 psi)

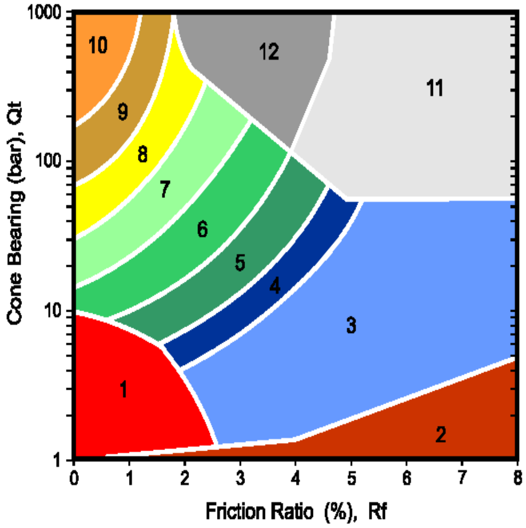
Note: The repeatability during field use will depend somewhat on ground conditions, abrasion, maintenance and zero load stability.

Cone Penetration Test Data & Interpretation

The Cone Penetration Test (CPT) data collected are presented in graphical and electronic form in the report. The plots include interpreted Soil Behavior Type (SBT) based on the charts described by Robertson (1990). Typical plots display SBT based on the non-normalized charts of Robertson et al (1986). For CPT soundings deeper than 30m, we recommend the use of the normalized charts of Robertson (1990) which can be displayed as SBTn, upon request. The report also includes spreadsheet output of computer calculations of basic interpretation in terms of SBT and SBTn and various geotechnical parameters using current published correlations based on the comprehensive review by Lunne, Robertson and Powell (1997), as well as recent updates by Professor Robertson (Guide to Cone Penetration Testing, 2015). The interpretations are presented only as a guide for geotechnical use and should be carefully reviewed. Gregg Drilling & Testing Inc. does not warranty the correctness or the applicability of any of the geotechnical parameters interpreted by the software and does not assume any liability for use of the results in any design or review. The user should be fully aware of the techniques and limitations of any method used in the software. Some interpretation methods require input of the groundwater level to calculate vertical effective stress. An estimate of the in-situ groundwater level has been made based on field observations and/or CPT results, but should be verified by the user.

A summary of locations and depths is available in Table 1. Note that all penetration depths referenced in the data are with respect to the existing ground surface.

Note that it is not always possible to clearly identify a soil type based solely on q_t, f_s, and u_2. In these situations, experience, judgment, and an assessment of the pore pressure dissipation data should be used to infer the correct soil behavior type.



ZONE		SBT	
1		🟥	Sensitive, fine grained
2		🟫	Organic materials
3		🟦	Clay
4		🟦	Silty clay to clay
5		🟩	Clayey silt to silty clay
6		🟩	Sandy silt to clayey silt
7		🟨	Silty sand to sandy silt
8		🟨	Sand to silty sand
9		🟫	Sand
10		🟧	Gravely sand to sand
11		⬜	Very stiff fine grained*
12		⬛	Sand to clayey sand*

*over consolidated or cemented

Figure SBT (After Robertson et al., 1986) – Note: Colors may vary slightly compared to plots

Cone Penetration Test (CPT) Interpretation

Gregg uses a proprietary CPT interpretation and plotting software. The software takes the CPT data and performs basic interpretation in terms of soil behavior type (SBT) and various geotechnical parameters using current published empirical correlations based on the comprehensive review by Lunne, Robertson and Powell (1997). The interpretation is presented in tabular format using MS Excel. The interpretations are presented only as a guide for geotechnical use and should be carefully reviewed. Gregg does not warranty the correctness or the applicability of any of the geotechnical parameters interpreted by the software and does not assume any liability for any use of the results in any design or review. The user should be fully aware of the techniques and limitations of any method used in the software.

The following provides a summary of the methods used for the interpretation. Many of the empirical correlations to estimate geotechnical parameters have constants that have a range of values depending on soil type, geologic origin and other factors. The software uses 'default' values that have been selected to provide, in general, conservatively low estimates of the various geotechnical parameters.

Input:

1 Units for display (Imperial or metric) (atm. pressure, p_a = 0.96 tsf or 0.1 MPa)
2 Depth interval to average results (ft or m). Data are collected at either 0.02 or 0.05m and can be averaged every 1, 3 or 5 intervals.
3 Elevation of ground surface (ft or m)
4 Depth to water table, z_w (ft or m) – input required
5 Net area ratio for cone, a (default to 0.80)
6 Relative Density constant, C_{Dr} (default to 350)
7 Young's modulus number for sands, α (default to 5)
8 Small strain shear modulus number
    a. for sands, S_G (default to 180 for SBT_n 5, 6, 7)
    b. for clays, C_G (default to 50 for SBT_n 1, 2, 3 & 4)
9 Undrained shear strength cone factor for clays, N_{kt} (default to 15)
10 Over Consolidation ratio number, k_{ocr} (default to 0.3)
11 Unit weight of water, (default to γ_w = 62.4 lb/ft^3 or 9.81 kN/m^3)

Column

1 Depth, z, (m) – CPT data is collected in meters
2 Depth (ft)
3 Cone resistance, q_c (tsf or MPa)
4 Sleeve resistance, f_s (tsf or MPa)
5 Penetration pore pressure, u (psi or MPa), measured behind the cone (i.e. u_2)
6 Other – any additional data
7 Total cone resistance, q_t (tsf or MPa) $q_t = q_c + u\,(1-a)$

8	Friction Ratio, R_f (%)	$R_f = (f_s/q_t) \times 100\%$
9	Soil Behavior Type (non-normalized), SBT	see note
10	Unit weight, γ (pcf or kN/m^3)	based on SBT, see note
11	Total overburden stress, σ_v (tsf)	$\sigma_{vo} = \sigma z$
12	In-situ pore pressure, u_o (tsf)	$u_o = \gamma_w (z - z_w)$
13	Effective overburden stress, σ'_{vo} (tsf)	$\sigma'_{vo} = \sigma_{vo} - u_o$
14	Normalized cone resistance, Q_{t1}	$Q_{t1} = (q_t - \sigma_{vo}) / \sigma'_{vo}$
15	Normalized friction ratio, F_r (%)	$F_r = f_s / (q_t - \sigma_{vo}) \times 100\%$
16	Normalized Pore Pressure ratio, B_q	$B_q = u - u_o / (q_t - \sigma_{vo})$
17	Soil Behavior Type (normalized), SBT_n	see note
18	SBT_n Index, I_c	see note
19	Normalized Cone resistance, Q_{tn} (n varies with I_c)	see note
20	Estimated permeability, k_{SBT} (cm/sec or ft/sec)	see note
21	Equivalent SPT N_{60}, blows/ft	see note
22	Equivalent SPT $(N_1)_{60}$ blows/ft	see note
23	Estimated Relative Density, D_r, (%)	see note
24	Estimated Friction Angle, ϕ', (degrees)	see note
25	Estimated Young's modulus, E_s (tsf)	see note
26	Estimated small strain Shear modulus, Go (tsf)	see note
27	Estimated Undrained shear strength, s_u (tsf)	see note
28	Estimated Undrained strength ratio	s_u/σ_v'
29	Estimated Over Consolidation ratio, OCR	see note

Notes:

1 Soil Behavior Type (non-normalized), SBT (Lunne et al., 1997 and table below)

2 Unit weight, γ either constant at 119 pcf or based on Non-normalized SBT (Lunne et al., 1997 and table below)

3 Soil Behavior Type (Normalized), SBT_n Lunne et al. (1997)

4 SBT_n Index, I_c $I_c = ((3.47 - \log Q_{t1})^2 + (\log F_r + 1.22)^2)^{0.5}$

5 Normalized Cone resistance, Q_{tn} (n varies with Ic)

$Q_{tn} = ((q_t - \sigma_{vo})/pa)\ (pa/(\sigma'_{vo})^n$ and recalculate I_c, then iterate:

When $I_c < 1.64$, $n = 0.5$ (clean sand)
When $I_c > 3.30$, $n = 1.0$ (clays)
When $1.64 < I_c < 3.30$, $n = (I_c - 1.64)0.3 + 0.5$
Iterate until the change in n, $\Delta n < 0.01$

6 Estimated permeability, k_{SBT} based on Normalized SBT_n (Lunne et al., 1997 and table below)

7 Equivalent SPT N_{60}, blows/ft Lunne et al. (1997)

$$\frac{(q_t/p_a)}{N_{60}} = 8.5\left(1 - \frac{I_c}{4.6}\right)$$

8 Equivalent SPT $(N_1)_{60}$ blows/ft $(N_1)_{60} = N_{60}\,C_{N,}$
where $C_N = (pa/\sigma'_{vo})^{0.5}$

9 Relative Density, D_r, (%) $D_r^2 = Q_{tn} / C_{Dr}$
Only SBT_n 5, 6, 7 & 8 *Show 'N/A' in zones 1, 2, 3, 4 & 9*

10 Friction Angle, ϕ', (degrees) $\tan\phi' = \frac{1}{2.68}\left[\log\left(\frac{q_c}{\sigma'_{vo}}\right) + 0.29\right]$

Only SBT_n 5, 6, 7 & 8 *Show'N/A' in zones 1, 2, 3, 4 & 9*

11 Young's modulus, E_s $E_s = \alpha\, q_t$
Only SBT_n 5, 6, 7 & 8 *Show 'N/A' in zones 1, 2, 3, 4 & 9*

12 Small strain shear modulus, Go
a. $G_o = S_G\,(q_t\;\;\sigma'_{vo}\;pa)^{1/3}$ *For SBT_n 5, 6, 7*
b. $G_o = C_G\,q_t$ *For SBT_n 1, 2, 3& 4*
Show 'N/A' in zones 8 & 9

13 Undrained shear strength, s_u $s_u = (q_t - \sigma_{vo}) / N_{kt}$
Only SBT_n 1, 2, 3, 4 & 9 *Show 'N/A' in zones 5, 6, 7 & 8*

14 Over Consolidation ratio, OCR $OCR = k_{ocr}\,Q_{t1}$
Only SBT_n 1, 2, 3, 4 & 9 *Show 'N/A' in zones 5, 6, 7 & 8*

The following updated and simplified SBT descriptions have been used in the software:

SBT Zones		**SBT_n Zones**	
1	sensitive fine grained	1	sensitive fine grained
2	organic soil	2	organic soil
3	clay	3	clay
4	clay & silty clay	4	clay & silty clay
5	clay & silty clay		
6	sandy silt & clayey silt		

7	silty sand & sandy silt	5	silty sand & sandy silt
8	sand & silty sand	6	sand & silty sand
9	sand		
10	sand	7	sand
11	very dense/stiff soil*	8	very dense/stiff soil*
12	very dense/stiff soil*	9	very dense/stiff soil*

*heavily overconsolidated and/or cemented

Track when soils fall with zones of same description and print that description (i.e. if soils fall only within SBT zones 4 & 5, print ‘clays & silty clays’)

Estimated Permeability (see Lunne et al., 1997)

SBT_n	Permeability (ft/sec)	(m/sec)
1	$3x\ 10^{-8}$	$1x\ 10^{-8}$
2	$3x\ 10^{-7}$	$1x\ 10^{-7}$
3	$1x\ 10^{-9}$	$3x\ 10^{-10}$
4	$3x\ 10^{-8}$	$1x\ 10^{-8}$
5	$3x\ 10^{-6}$	$1x\ 10^{-6}$
6	$3x\ 10^{-4}$	$1x\ 10^{-4}$
7	$3x\ 10^{-2}$	$1x\ 10^{-2}$
8	$3x\ 10^{-6}$	$1x\ 10^{-6}$
9	$1x\ 10^{-8}$	$3x\ 10^{-9}$

Estimated Unit Weight (see Lunne et al., 1997)

SBT	Approximate Unit Weight (lb/ft^3)	(kN/m^3)
1	111.4	17.5
2	79.6	12.5
3	111.4	17.5
4	114.6	18.0
5	114.6	18.0
6	114.6	18.0
7	117.8	18.5
8	120.9	19.0
9	124.1	19.5
10	127.3	20.0
11	130.5	20.5
12	120.9	19.0

Pore Pressure Dissipation Tests (PPDT)

Pore Pressure Dissipation Tests (PPDT's) conducted at various intervals can be used to measure equilibrium water pressure (at the time of the CPT). If conditions are hydrostatic, the equilibrium water pressure can be used to determine the approximate depth of the ground water table. A PPDT is conducted when penetration is halted at specific intervals determined by the field representative. The variation of the penetration pore pressure (*u)* with time is measured behind the tip of the cone and recorded.

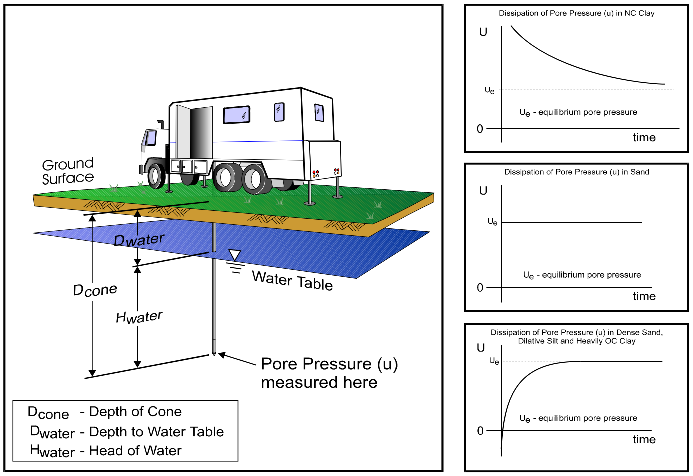
Pore pressure dissipation data can be interpreted to provide estimates of:

- Equilibrium piezometric pressure
- Phreatic Surface
- In situ horizontal coefficient of consolidation (c_h)
- In situ horizontal coefficient of permeability (k_h)

In order to correctly interpret the equilibrium piezometric pressure and/or the phreatic surface, the pore pressure must be monitored until it reaches equilibrium, *Figure PPDT*. This time is commonly referred to as t_{100}, the point at which 100% of the excess pore pressure has dissipated.

A complete reference on pore pressure dissipation tests is presented by Robertson et al. 1992 and Lunne et al. 1997.

A summary of the pore pressure dissipation tests are summarized in Table 1.



Water Table Calculation

$$D_{water} = D_{cone} - H_{water}$$

where $H_{water} = U_e$ (depth units)

Useful Conversion Factors:
1psi = 0.704m = 2.31 feet (water)
1tsf = 0.958 bar = 13.9 psi
1m = 3.28 feet

Figure PPDT

Seismic Cone Penetration Testing (SCPT)

Seismic Cone Penetration Testing (SCPT) can be conducted at various intervals during the Cone Penetration Test. Shear wave velocity (Vs) can then be calculated over a specified interval with depth. A small interval for seismic testing, such as 1-1.5m (3-5ft) allows for a detailed look at the shear wave profile with depth. Conversely, a larger interval such as 3-6m (10-20ft) allows for a more average shear wave velocity to be calculated. Gregg's cones have a horizontally active geophone located 0.2m (0.66ft) behind the tip.

To conduct the seismic shear wave test, the penetration of the cone is stopped and the rods are decoupled from the rig. An automatic hammer is triggered to send a shear wave into the soil. The distance from the source to the cone is calculated knowing the total depth of the cone and the horizontal offset distance between the source and the cone. To calculate an interval velocity, a minimum of two tests must be performed at two different depths. The arrival times between the two wave traces are compared to obtain the difference in time (Δt). The difference in depth is calculated (Δd) and velocity can be determined using the simple equation: v = Δd/Δt

Multiple wave traces can be recorded at the same depth to improve quality of the data.

A complete reference on seismic cone penetration tests is presented by Robertson et al. 1986 and Lunne et al. 1997.

A summary the shear wave velocities, arrival times and wave traces are provided with the report.

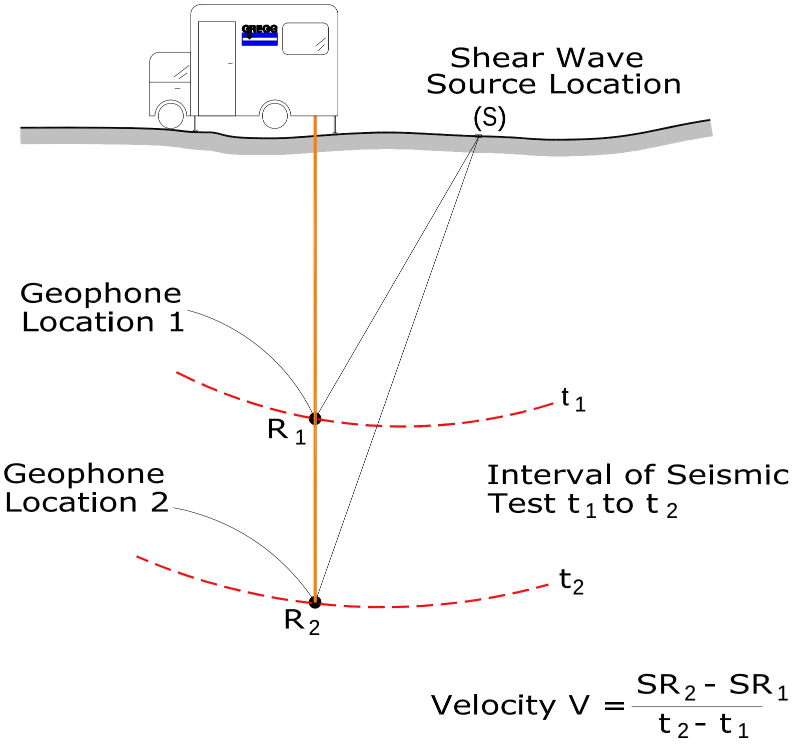


Figure SCPT

Groundwater Sampling

Gregg Drilling & Testing, Inc. conducts groundwater sampling using a sampler as shown in *Figure GWS*. The groundwater sampler has a retrievable stainless steel or disposable PVC screen with steel drop off tip. This allows for samples to be taken at multiple depth intervals within the same sounding location. In areas of slower water recharge, provisions may be made to set temporary PVC well screens during sampling to allow the pushing equipment to advance to the next sample location while the groundwater is allowed to infiltrate.

The groundwater sampler operates by advancing 44.5mm (1¾ inch) hollow push rods with the filter tip in a closed configuration to the base of the desired sampling interval. Once at the desired sample depth, the push rods are retracted; exposing the encased filter screen and allowing groundwater to infiltrate hydrostatically from the formation into the inlet screen. A small diameter bailer (approximately ½ or ¾ inch) is lowered through the push rods into the screen section for sample collection. The number of downhole trips with the bailer and time necessary to complete the sample collection at each depth interval is a function of sampling protocols, volume requirements, and the yield characteristics and storage capacity of the formation. Upon completion of sample collection, the push rods and sampler, with the exception of the PVC screen and steel drop off tip are retrieved to the ground surface, decontaminated and prepared for the next sampling event.

For a detailed reference on direct push groundwater sampling, refer to Zemo et. al., 1992.

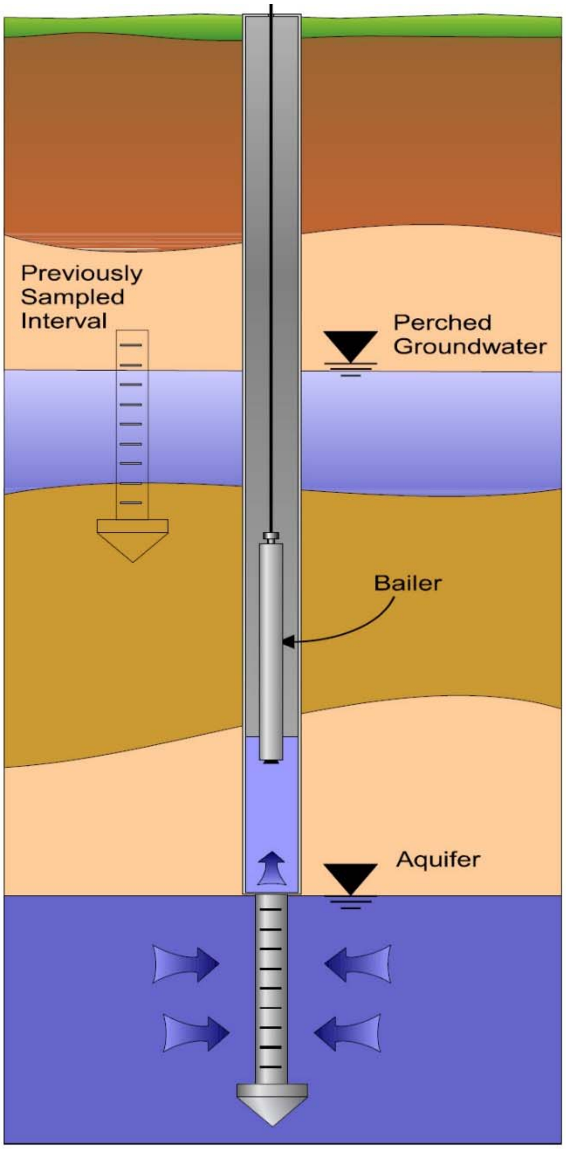


Figure GWS

Soil Sampling

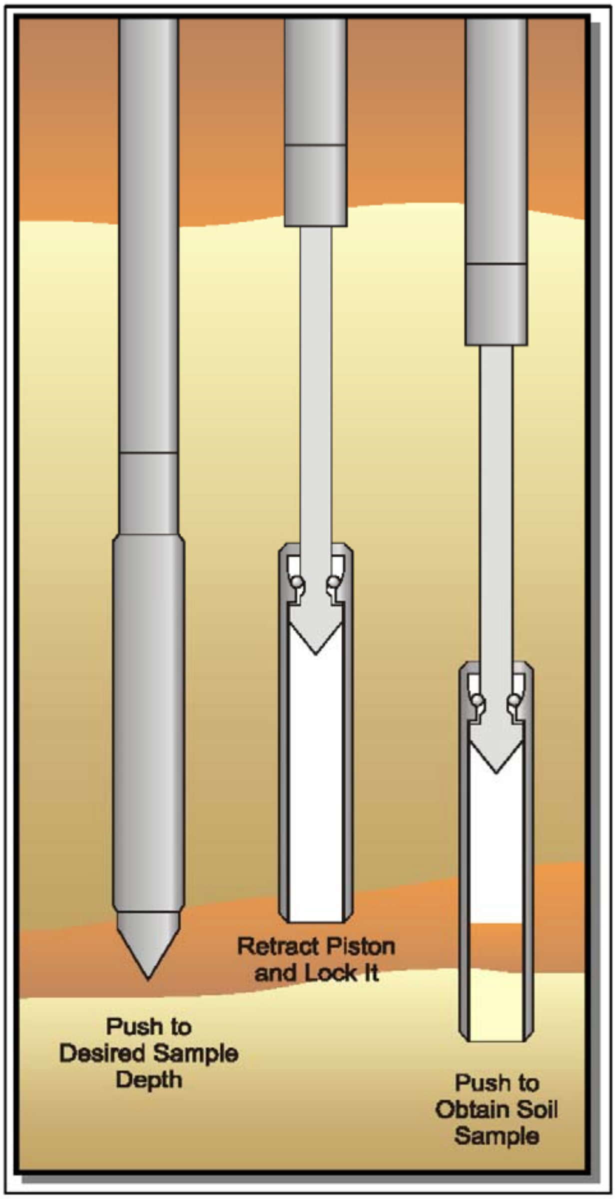


Figure SS

Gregg Drilling & Testing, Inc. uses a piston-type push-in sampler to obtain small soil samples without generating any soil cuttings, *Figure SS*. Two different types of samplers (12 and 18 inch) are used depending on the soil type and density. The soil sampler is initially pushed in a "closed" position to the desired sampling interval using the CPT pushing equipment. Keeping the sampler closed minimizes the potential of cross contamination. The inner tip of the sampler is then retracted leaving a hollow soil sampler with inner 1¼” diameter sample tubes. The hollow sampler is then pushed in a locked "open" position to collect a soil sample. The filled sampler and push rods are then retrieved to the ground surface. Because the soil enters the sampler at a constant rate, the opportunity for 100% recovery is increased. For environmental analysis, the soil sample tube ends are sealed with Teflon and plastic caps. Often, a longer "split tube" can be used for geotechnical sampling.

For a detailed reference on direct push soil sampling, refer to Robertson et al, 1998.

Ultra-Violet Induced Fluorescence (UVOST)

Gregg Drilling conducts Laser Induced Fluorescence (LIF) Cone Penetration Tests using a UVOST module that is located behind the standard piezocone, *Figure UVOST*. The laser induced fluorescence cone works on the principle that polycyclic aromatic hydrocarbons (PAH's), mixed with soil and/or groundwater, fluoresce when irradiated by ultra violet light. Therefore, by measuring the intensity of fluorescence, the lateral and vertical extent of hydrocarbon contamination in the ground can be estimated.

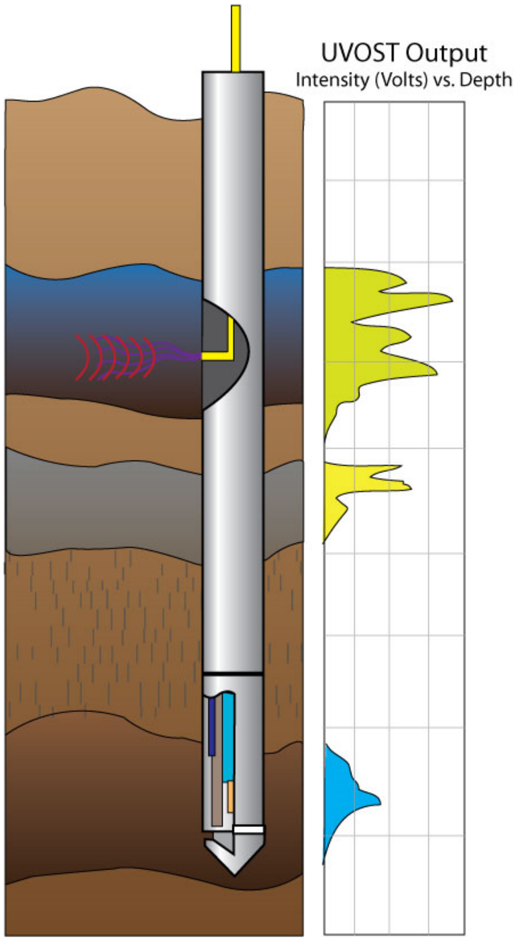
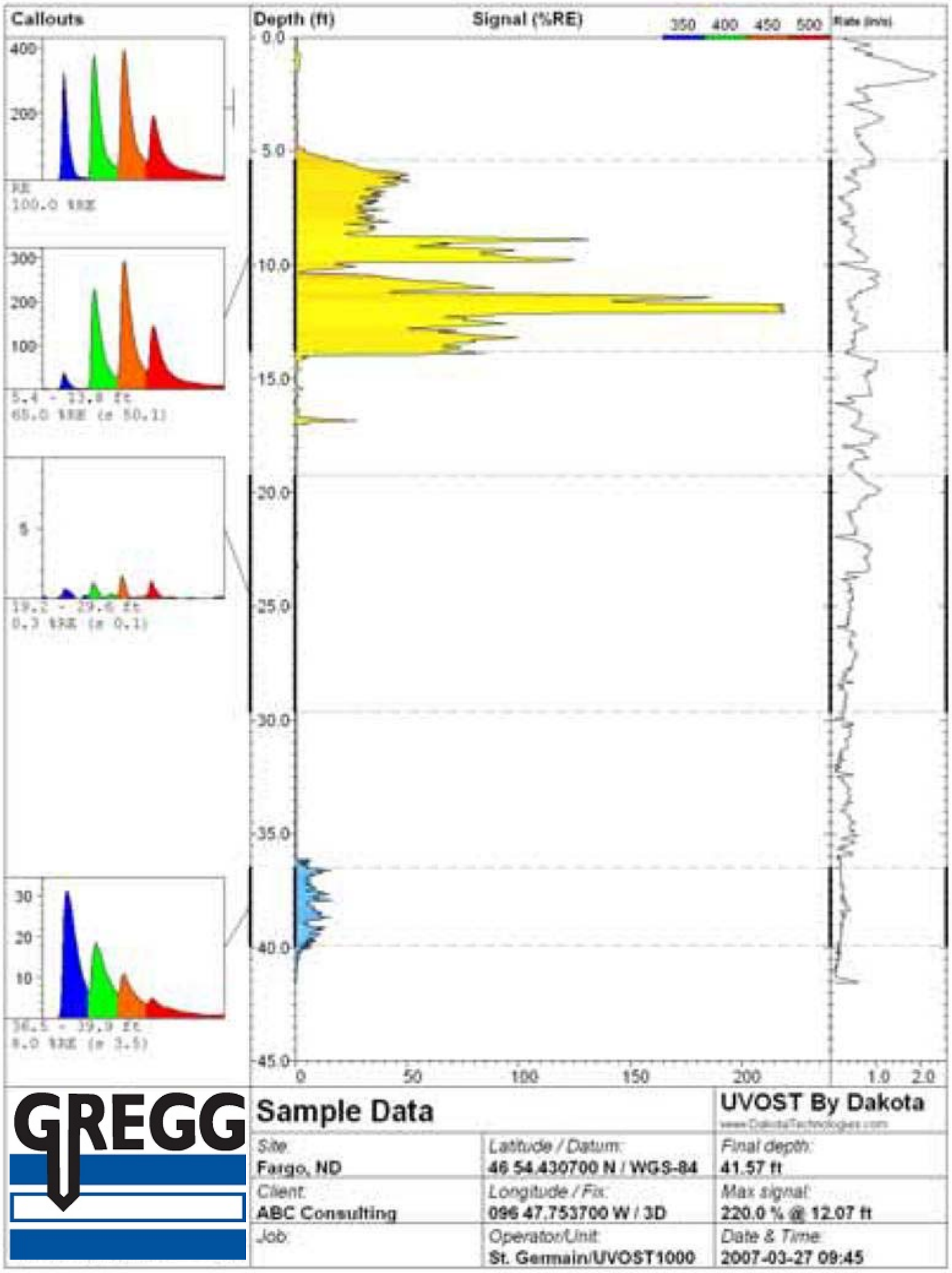


Figure UVOST

The UVOST module uses principles of fluorescence spectrometry by irradiating the soil with ultra violet light produced by a laser and transmitted to the cone through fiber optic cables. The UV light passes through a small window in the side of the cone into the soil. Any hydrocarbon molecules present in the soil absorb the light energy during radiation and immediately re-emit the light at a longer wavelength. This re-emission is termed fluorescence. The UVOST system also measures the emission decay with time at four different wavelengths (350nm, 400nm, 450nm, and 500nm). This allows the software to determine a product "signature" at each data point. This process provides a method to evaluate the type of contaminant. A sample output from the UVOST system is shown in *Figure Output*. In general, the typical detection limit for the UVOST system is <100 ppm and it will operate effectively above and below the saturated zone.

With the capability to push up to 200m (600ft) per day, laser induced fluorescence offers a fast and efficient means for delineating PAH contaminant plumes. Color coded logs offer qualitative information in a quick glance and can be produced in the field for real-time decision making. Coupled with the data provided by the CPT, a complete site assessment can be completed with no samples or cuttings, saving laboratory costs as well as site and environmental impact.



Sample Data

Site:
Fargo, ND

Client:
ABC Consulting

Job:

Latitude / Datum:
46 54.430700 N / WGS-84

Longitude / Fix:
096 47.753700 W / 3D

Operator/Unit:
St. Germain/UVOST1000

Final depth:
41.57 ft

Max signal:
220.0 % @ 12.07 ft

Date & Time:
2007-03-27 09:45

Figure Output

Hydrocarbons detected with UVOST

- Gasoline
- Diesel
- Jet (Kerasene)
- Motor Oil
- Cutting fluids
- Hydraulic fluids
- Crude Oil

Hydrocarbons rarely detected using UVOST

- Extremely weathered gasoline
- Coal tar
- Creosote
- Bunker Oil
- Polychlorinated bi-phenols (PCB's)
- Chlorinated solvent DNAPL
- Dissolved phase (aqueous) PAH's

Potential False Positives (fluorescence observed)

- Sea-shells (weak-medium)
- Paper (medium-strong depending on color)
- Peat/meadow mat (weak)
- Calcite/calcareous sands (weak)
- Tree roots (weak-medium)
- Sewer lines (medium-strong)

Potential False Negatives (do not fluoresce)

- Extremely weathered fuels (especially gasoline)
- Aviation gasoline (weak)
- "Dry" PAHs such as aqueous phase, lamp black, purifier chips
- Creosotes (most)
- Coal tars (most) gasoline (weak)
- Most chlorinated solvents
- Benzene, toluene, zylenes (relatively pure)

DAKOTA TECHNOLOGIES
UVOST LOG REFERENCE

2008-12-12

Main Plot :
Signal (total fluorescence) versus depth where signal is relative to the Reference Emitter (RE). The total area of the waveform is divided by the total area of the Reference Emitter yielding the %RE. This %RE scales with the NAPL fluorescence. The fill color is based on relative contribution of each channel's area to the total waveform area (see callout waveform). The channel-to-color relationship and corresponding wavelengths are given in the upper right corner of the main plot.

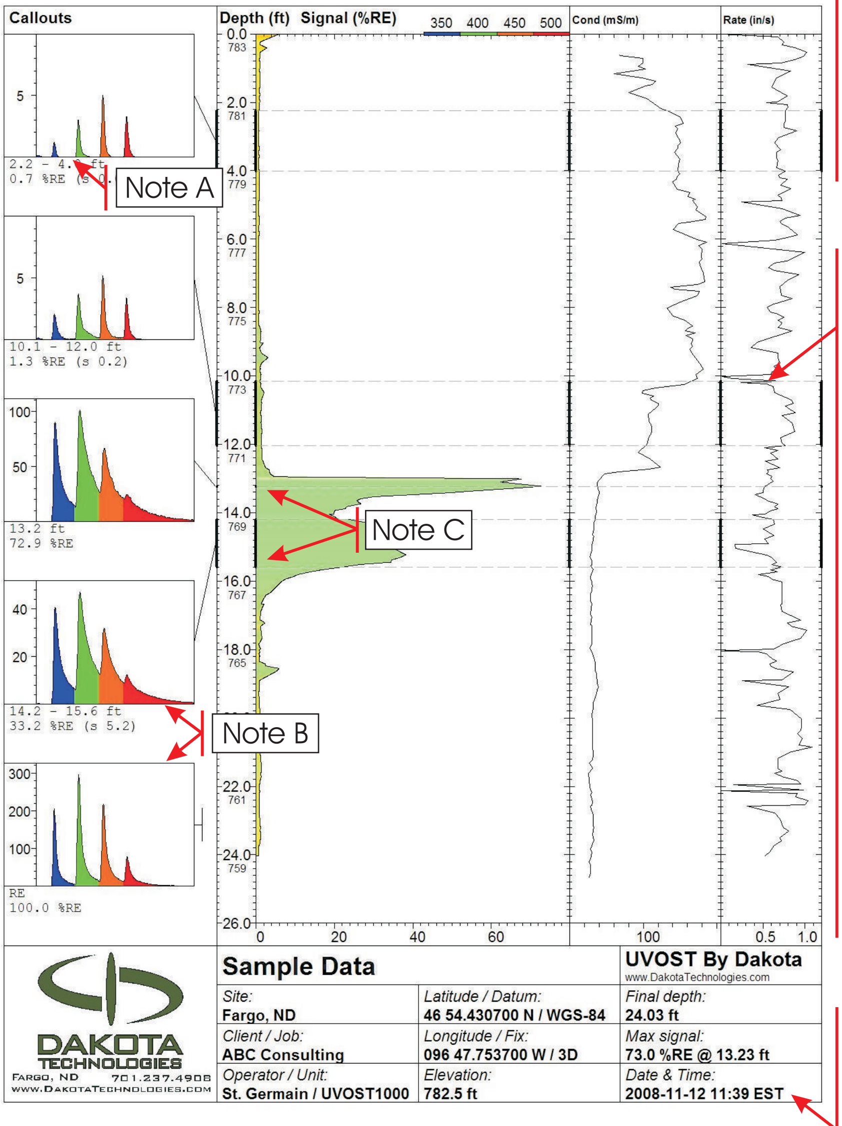
Conductivity Plot :
The Electrical Conductivity (EC) of the soil can be logged simultaneously with the UVOST data. EC often provides insight into the stratigraphy.
Note the drop in EC from 10 - 13 ft, indicating a shift from consolidated to unconsolidated stratigraphy. This correlates with the observed NAPL distribution.

Callouts :
Waveforms from selected depths or depth ranges showing the multi-wavelength waveform for that depth.

The four peaks are due to fluorescence at four wavelengths and referred to as “channels”. Each channel is assigned a color.

Various NAPLs will have a unique waveform "fingerprint" due to the relative amplitude of the four channels and/or broadening of one or more channels.

Basic waveform statistics and any operator notes are given below the callout.



Sample Data

UVOST By Dakota
www.DakotaTechnologies.com

Site: **Fargo, ND**	*Latitude / Datum:* **46 54.430700 N / WGS-84**	*Final depth:* **24.03 ft**
Client / Job: **ABC Consulting**	*Longitude / Fix:* **096 47.753700 W / 3D**	*Max signal:* **73.0 %RE @ 13.23 ft**
Operator / Unit: **St. Germain / UVOST1000**	*Elevation:* **782.5 ft**	*Date & Time:* **2008-11-12 11:39 EST**

Rate Plot :
The rate of probe advancement. ~ 0.8in (2cm) per second is preferred.

A noticeable decrease in the rate of advancement may be indicative of difficult probing conditions (gravel, angular sands, etc.) such as that seen here at ~5 ft.

Notice that this log was terminated arbitrarily, not due to "refusal", which would have been indicated by a sudden rate drop at final depth.

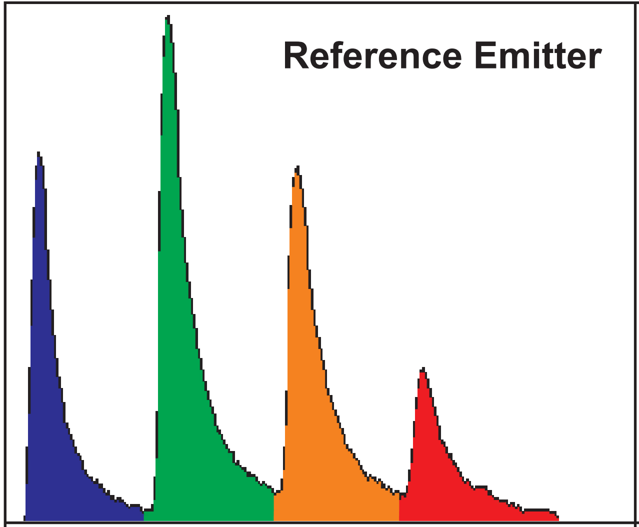
Info Box :
Contains pertinent log info including name and location.

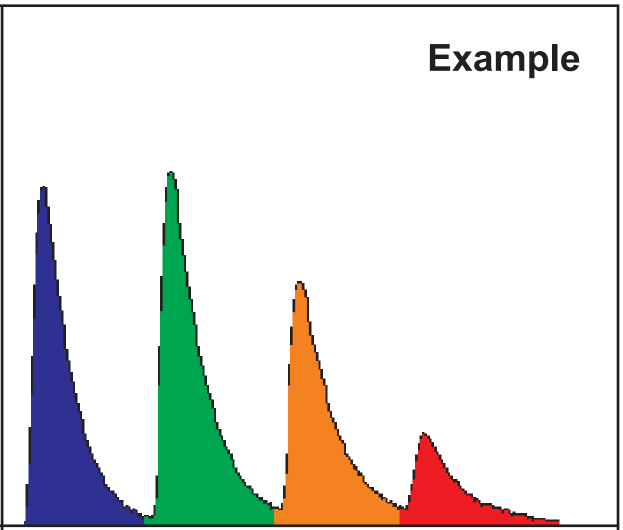
Note A :
Time is along the x axis. No scale is given, but it is a consistent 320ns wide.
The y axis is in mV and directly corresponds to the amount of light striking the photodetector.

Note B :
These two waveforms are clearly different. The first is weathered diesel from the log itself while the second is the Reference Emitter (a blend of NAPLs) always taken before each log for calibration.

Note C :
Callouts can be a single depth (see 3rd callout) or a range (see 4th callout). The range is noted on the depth axis by a bold line. When the callout is a range, the average and standard deviation in %RE is given below the callout.

Waveform Signal Calculation



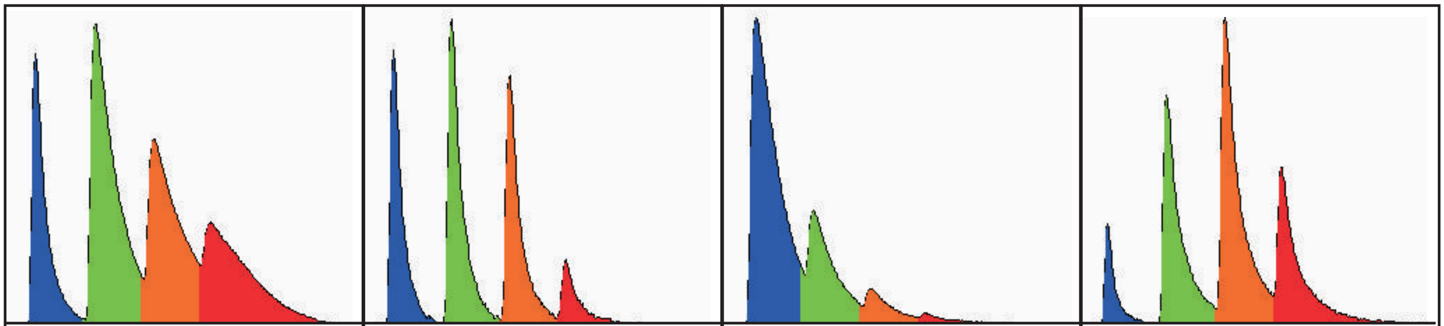


CH1		CH2		CH3		CH4		**Total**	***Channel***	CH1		CH2		CH3		CH4		**Total**
4820	+	8108	+	6249	+	2984	=	**22161**	***Area (pVs)***	4923	+	5743	+	4166	+	1735	=	**16587**
21.7		36.6		28.2		13.5		**100%**	***Percent RE***	22.3		25.9		18.8		7.8		**75%**

Data Files

***.lif.raw.bin**	Raw data file. Header is ASCII format and contains information stored when the file was initially written (e.g. date, total depth, max signal, gps, etc., and any information entered by the operator). All raw waveforms are appended to the bottom of the file in a binary format.
***.lif.plt**	Stores the plot scheme history (e.g. callout depths) for associated Raw file. Transfer along with the Raw file in order to recall previous plots.
***.lif.jpg**	A jpg image of the OST log including the main signal vs. depth plot, callouts, information, etc.
***.lif.dat.txt**	Data export of a single Raw file. ASCII tab delimited format. No string header is provided for the columns (to make importing into other programs easier). Each row is a unique depth reading. The columns are: Depth, Total Signal (%RE), Ch1%, Ch2%, Ch3%, Ch4%, Rate, Conductivity Depth, Conductivity Signal, Hammer Rate. Summing channels 1 to 4 yields the Total Signal.
***.lif.sum.txt**	A summary file for a number of Raw files. ASCII tab delimited format. The file contains a string header. The summary includes one row for each Raw file and contains information for each file including: the file name, gps coordinates, max depth, max signal, and depth at which the max signal occured.
***.lif.log.txt**	An activity log generated automatically located in the OST application directory in the 'log' subfolder. Each OST unit the computer operates will generate a separate log file per month. A log file contains much of the header information contained within each separate Raw file, including: date, total depth, max signal, etc.

Common Waveforms (highly dependent on soil, weathering, etc.)

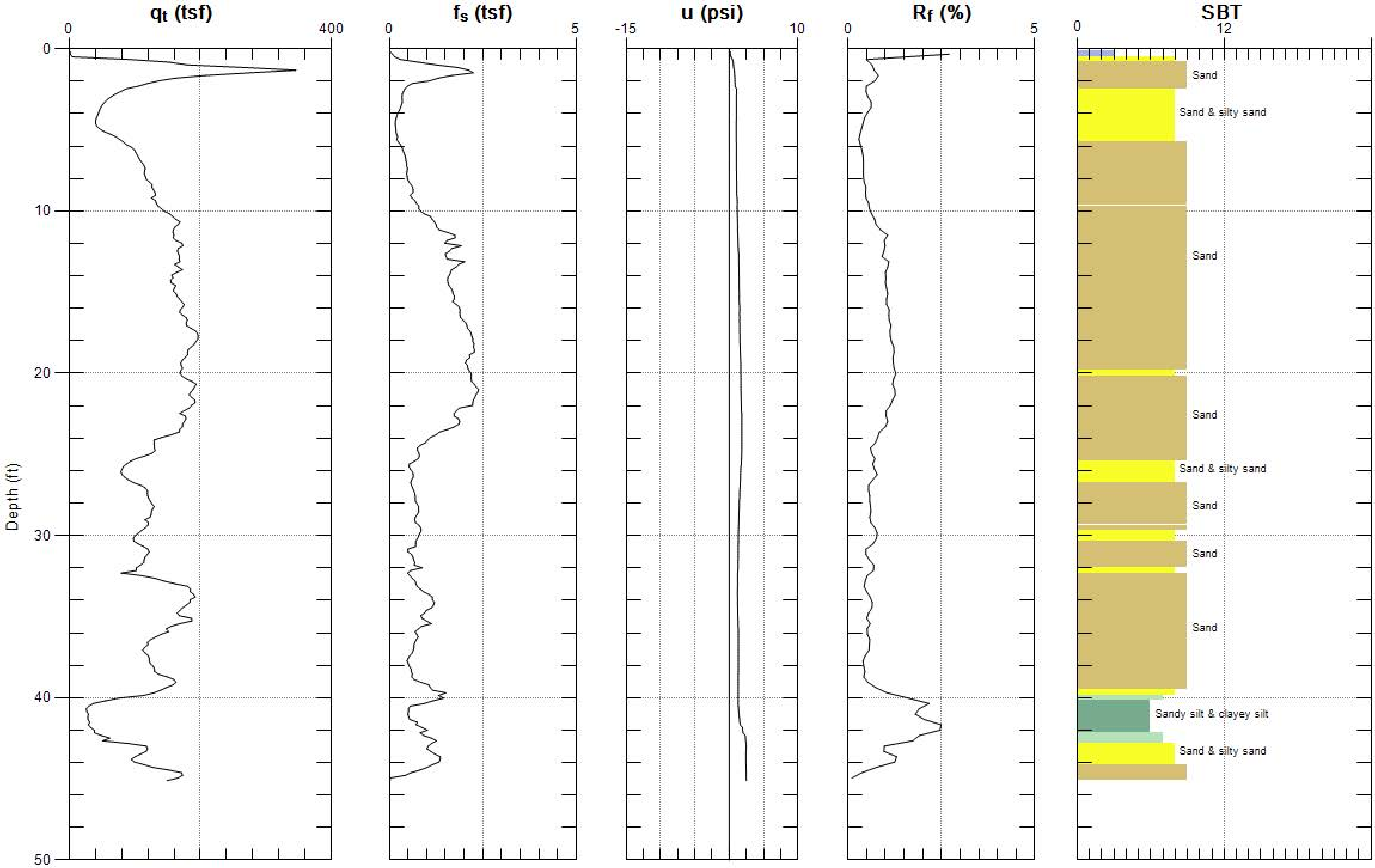


Diesel **Gas** **Kerosene** **Motor Oil**

NOREAS

Site: OU-11
Sounding: CPT-1

Engineer: RYAN
Date: 6/5/2017 09:03



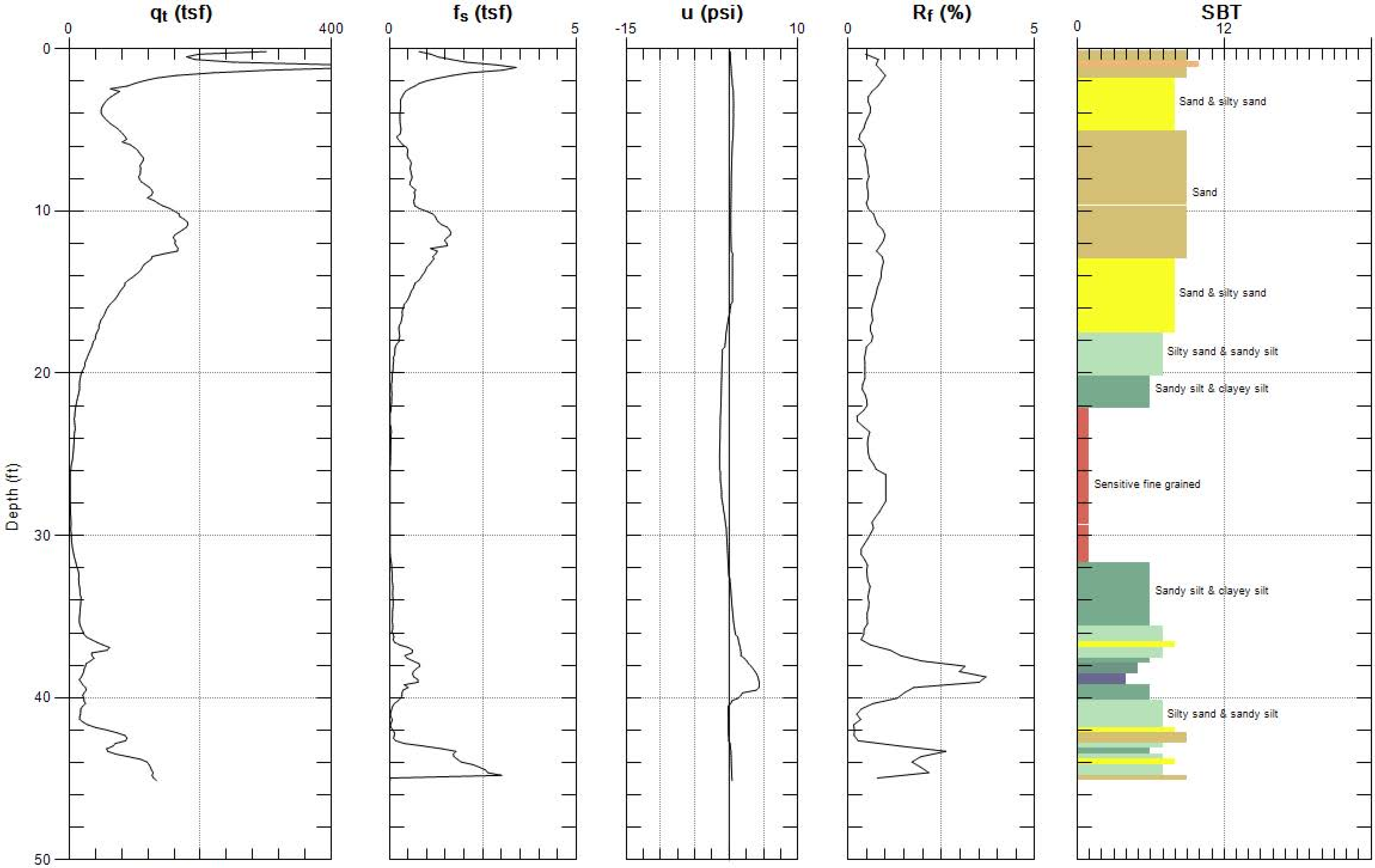
Max. Depth: 45.112 (ft)
Avg. Interval: 0.328 (ft)

SBT: Soil Behavior Type (Robertson 1990)

GREGG **NOREAS**

Site: OU-11
Sounding: CPT-2

Engineer: RYAN
Date: 6/8/2017 07:18



Max. Depth: 45.112 (ft)
Avg. Interval: 0.328 (ft)

SBT: Soil Behavior Type (Robertson 1990)

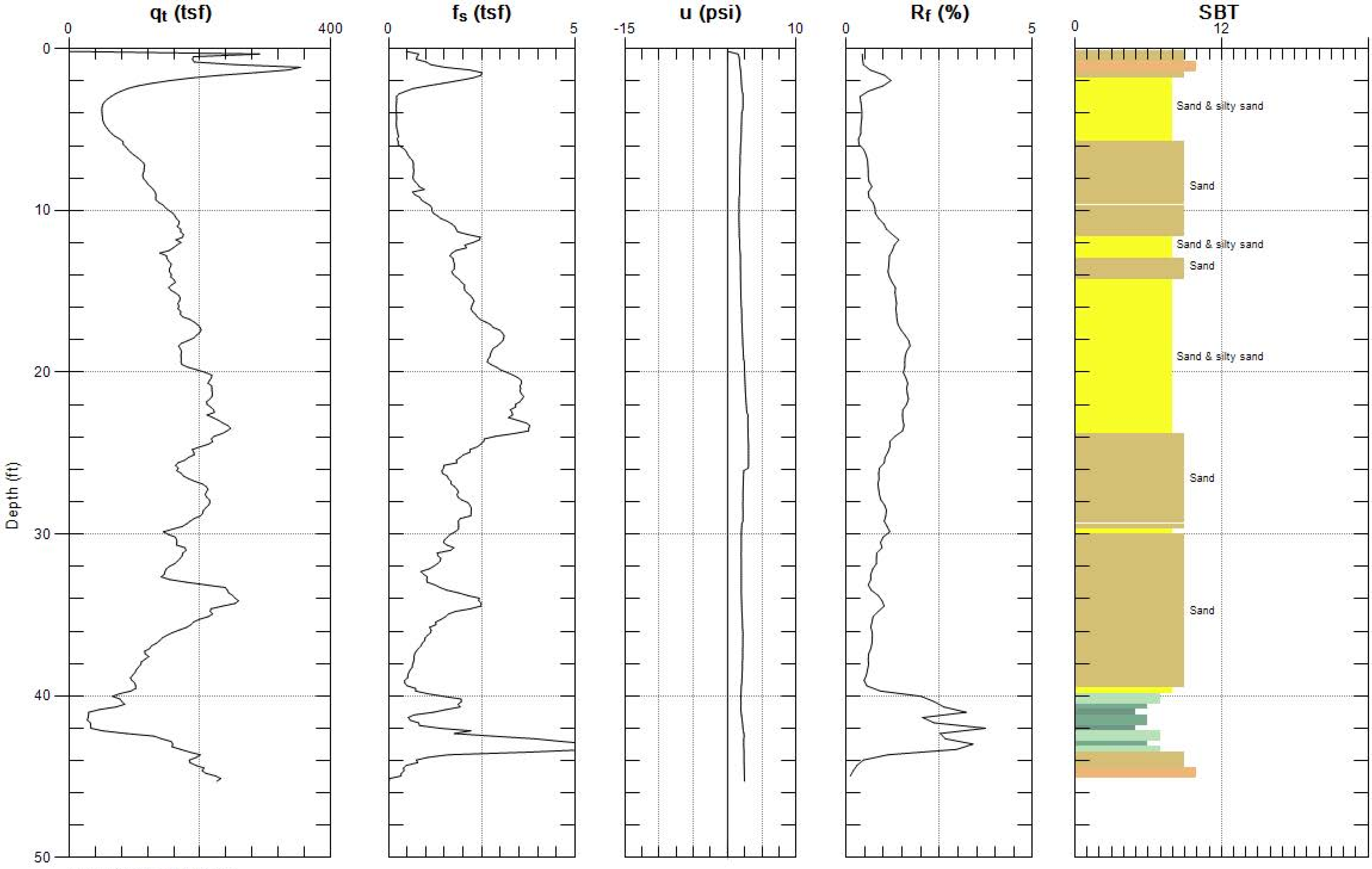
NOREAS

Site: OU-11

Sounding: CPT-3

Engineer: RYAN

Date: 6/8/2017 09:07



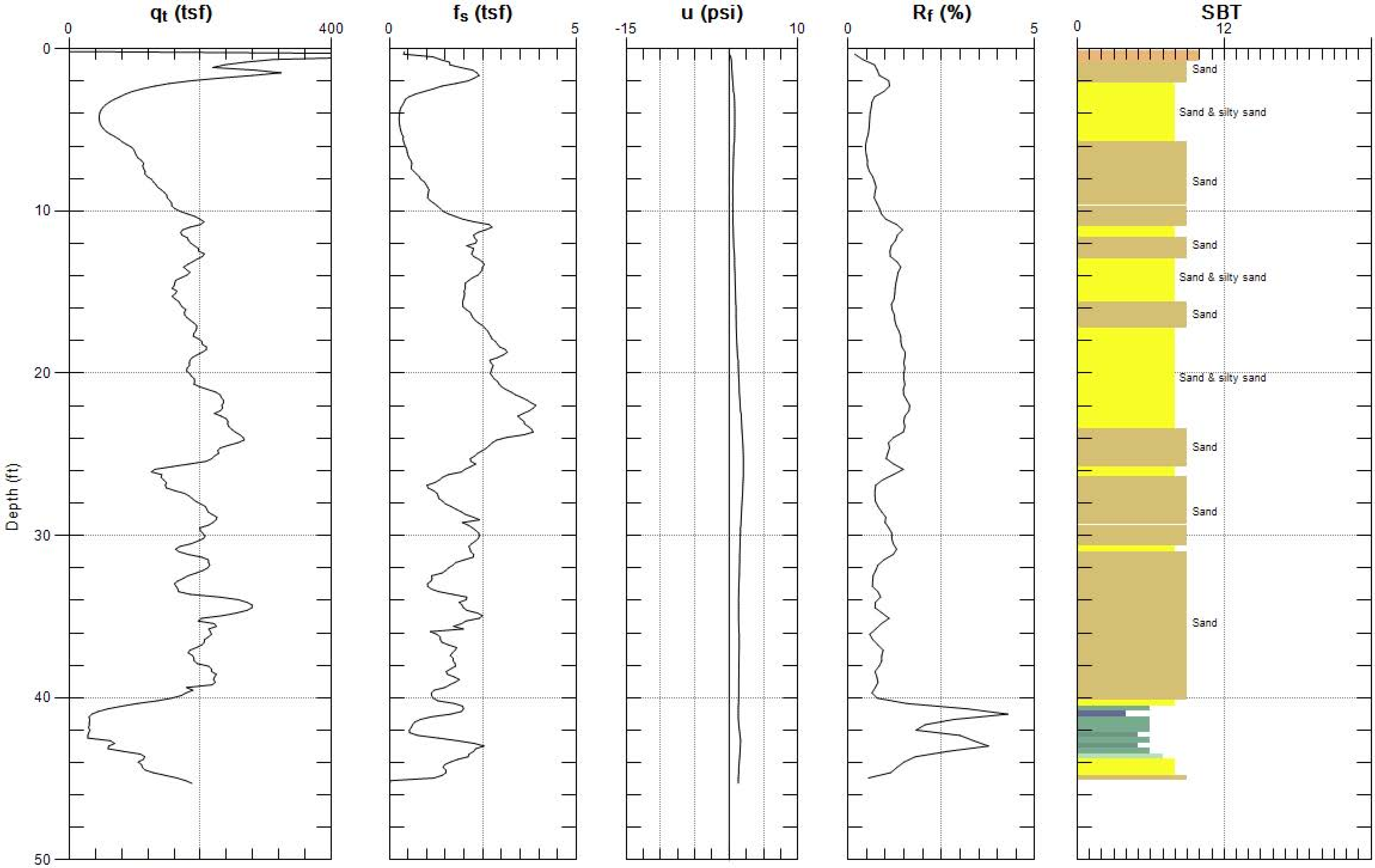
Max. Depth: 45.276 (ft)
Avg. Interval: 0.328 (ft)

SBT: Soil Behavior Type (Robertson 1990)

GREGG **NOREAS**

Site: OU-11
Sounding: CPT-4

Engineer: RYAN
Date: 6/8/2017 08:32



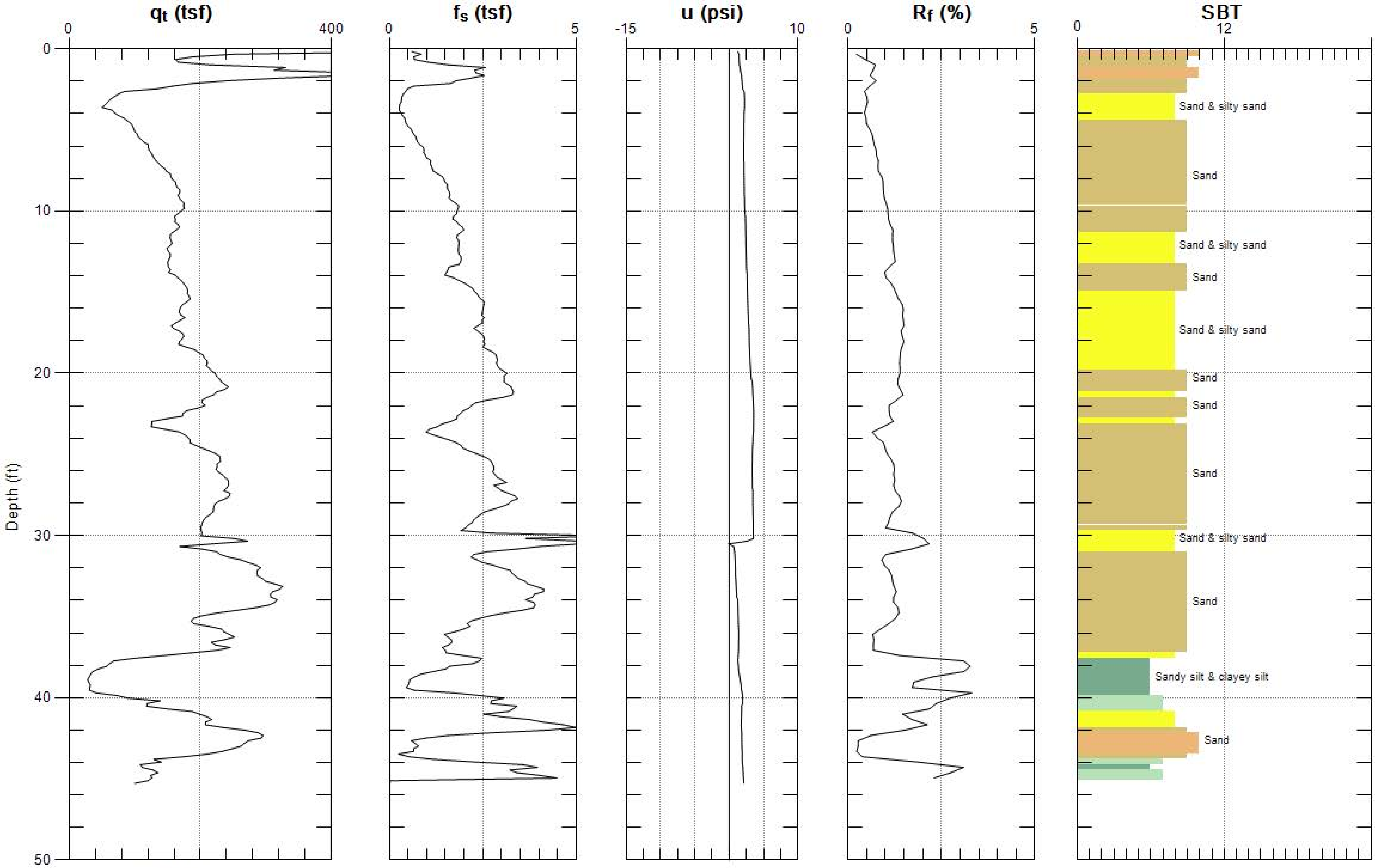
Max. Depth: 45.276 (ft)
Avg. Interval: 0.328 (ft)

SBT: Soil Behavior Type (Robertson 1990)

GREGG **NOREAS**

Site: OU-11
Sounding: CPT-5

Engineer: RYAN
Date: 6/8/2017 07:59



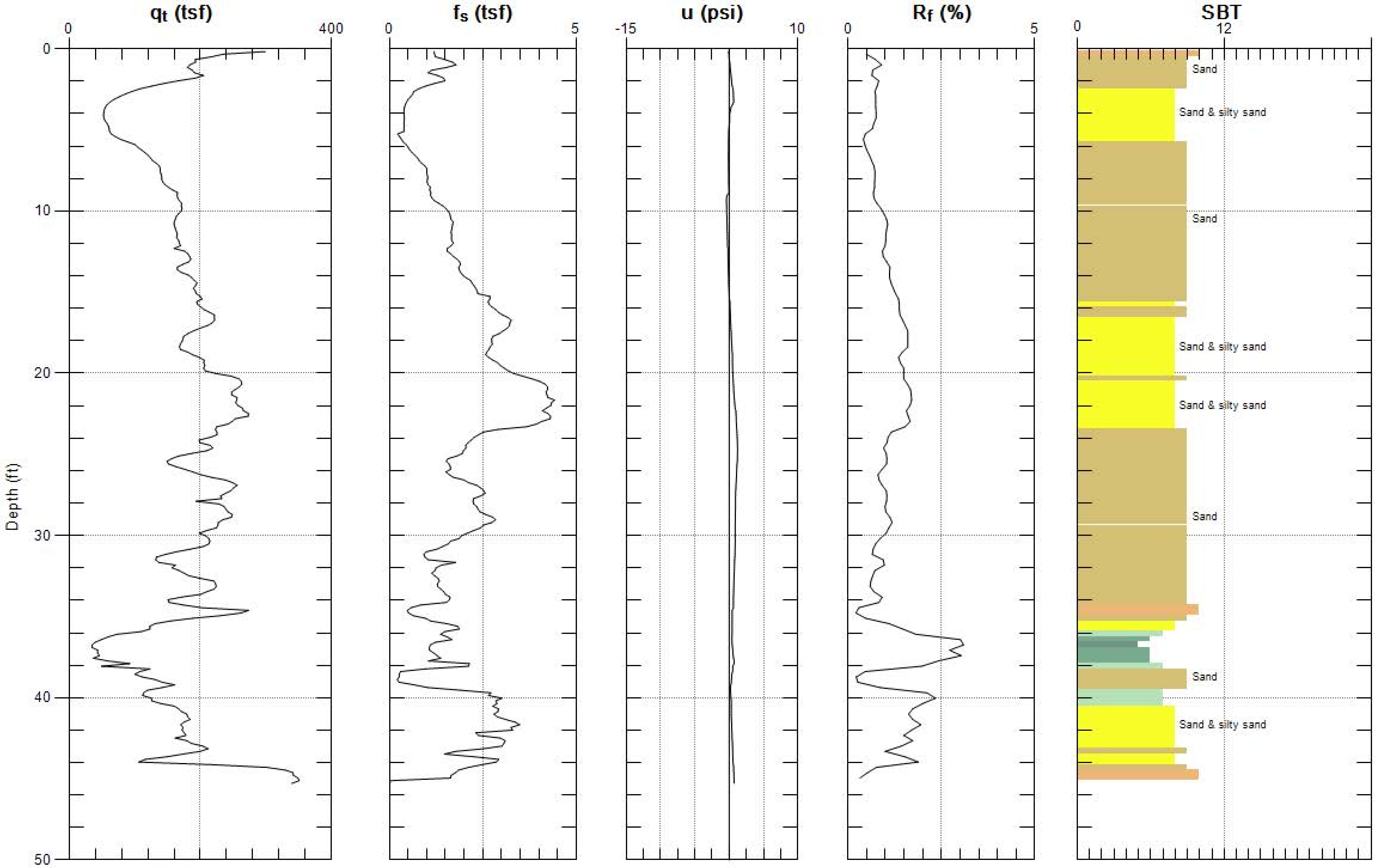
Max. Depth: 45.276 (ft)
Avg. Interval: 0.328 (ft)

SBT: Soil Behavior Type (Robertson 1990)

NOREAS

Site: OU-11
Sounding: CPT-6

Engineer: RYAN
Date: 6/8/2017 06:49



Max. Depth: 45.276 (ft)
Avg. Interval: 0.328 (ft)

SBT: Soil Behavior Type (Robertson 1990)

APPENDIX H
SODIUM PERSULFATE FLUX AND MASS BALANCE CALCULATIONS

Persulfate Cylinder Release Rate Calculation

1.0 Purpose/Objective

Calculate sodium persulfate flux from cylinders using sodium persulfate vs. time data and seepage velocity estimates.

2.0 Procedure

Use emprical relationship between sodium persulfate concentration in deep samples from wells and time in combination with derived formula relating flux to seepage velocity and sodium persulfate concentration.

3.0 References/Data Sources

Maximum sodium persulfate flux from cylinders was 18 mg persulfate/day/cm^2 in treatability test which is equal to 22 mg sodium persulfate/day/cm^2.

4.0 Assumptions

Assume porosity in borehole for calculation of flow rates from seepage velocity

$\varepsilon := 0.3$

Assume that negligible persulfate mass is outside of the deep sampling horizon used in the analysis. Assumption is verified by mass balance at end of calculation.

5.0 Calculations

Define borehole cross-sectional area for flow

$\text{Diameter}_{\text{borehole}} := 18\text{in}$

$\text{Length}_{\text{borehole}} := 15\text{ft}$ This is the water table thickness

$\text{Area}_{\text{borehole}} := \text{Diameter}_{\text{borehole}} \cdot \text{Length}_{\text{borehole}} = 22.5\,\text{ft}^2$

Define cylinder circumferential area for persulfate release

$\text{Diameter}_{\text{cylinder}} := 2.5\text{in}$

$\text{Length}_{\text{cylinder}} := 18\text{in}$

$\text{Number}_{\text{cylinders}} := 20$ 24 cylinders were installed (both wells) but because of lower water level only 10 were submerged. This is validated by the Carus autopsy report

$$\mathrm{Area}_{cylinder} := \pi \cdot \mathrm{Diameter}_{cylinder} \cdot \mathrm{Length}_{cylinder} \cdot \mathrm{Number}_{cylinders} = 18241.4692 \cdot cm^2$$

Seepage velocity is uncertain and we have 2 estimates. The first is the design value and the last is based on data from the conductivity sensor in DMW-07

$$\mathrm{Velocity}_{seepage} := \begin{pmatrix} 7.8 \\ 12.2 \end{pmatrix} \frac{cm}{day}$$

see excel spreadsheet for calcs: '012816 Conductivity Profile Test for seepage velocity estimation.xlsx'

State empirically derived exponential relationship between persulfate concentration in borehole wells and time.

$$k_1 := 4137.1 \frac{mg}{L}$$

See excel spreadsheet 'ESTCP Dioxane_masterspreadsheet.xlsx' longevity tab

$$k_2 := \frac{-0.00648}{day}$$

Set time to value of 0 days to determine maximum flux

$$t := 0day$$

$$C_{borehole} := k_1 \cdot \exp(k_2 t) = 4137.1 \cdot \frac{mg}{L}$$

$$\mathrm{Flux}_{max} := \frac{C_{borehole} \cdot \mathrm{Area}_{borehole} \cdot \varepsilon \cdot \mathrm{Velocity}_{seepage}}{\mathrm{Area}_{cylinder}} = \begin{pmatrix} 11.1 \\ 17.4 \end{pmatrix} \cdot \frac{mg}{day \cdot cm^2}$$

Set time to value of 134 days to determine flux at final sampling event.

$$t := 134day$$

$$C_{borehole} := k_1 \cdot \exp(k_2 t) = 1736.1588 \cdot \frac{mg}{L}$$

$$\mathrm{Flux}_{min} := \frac{C_{borehole} \cdot \mathrm{Area}_{borehole} \cdot \varepsilon \cdot \mathrm{Velocity}_{seepage}}{\mathrm{Area}_{cylinder}} = \begin{pmatrix} 4.7 \\ 7.3 \end{pmatrix} \cdot \frac{mg}{day \cdot cm^2}$$

Now integrate the flux over the measurement time period

$t_f := 134\text{day}$

$$\text{Flux}_{\text{average}} := \int_{0\text{day}}^{t_f} k_1 \cdot \exp(k_2\, t)\, dt \frac{\text{Area}_{\text{borehole}} \cdot \varepsilon \cdot \text{Velocity}_{\text{seepage}}}{\text{Area}_{\text{cylinder}} \cdot t_f} = \begin{pmatrix} 7.4 \\ 11.6 \end{pmatrix} \cdot \frac{\text{mg}}{\text{day} \cdot \text{cm}^2}$$

These values are reasonable compared to the maximum value measured in the lab (22)

Now calculate the mass of persulfate released and compare that to the amount of persulfate in the cylinders upon installation.

Cylinders were removed after 399 days and were found to contain negligible persulfate based on Carus autopsy. Calculate total mass released per cylinder for this period based on extrapolation.

$t_f := 399\text{day}$

$$\text{Mass}_{\text{released}} := \int_{0\text{day}}^{t_f} k_1 \cdot \exp(k_2\, t)\, dt \left(\text{Area}_{\text{borehole}} \cdot \varepsilon \cdot \text{Velocity}_{\text{seepage}}\right) = \begin{pmatrix} 28.9 \\ 45.2 \end{pmatrix} \cdot \text{kg}$$

Cylinder weight is 2.879 kg based on Carus data sheet. Sodium persulfate percentage is 79% based on 24FEB2017 Carus report. Calculate original mass in cylinder

$$\text{Mass}_{\text{sodium.persulfate.in.cylinders}} := 2.879\text{kg} \cdot 79\% \cdot \text{Number}_{\text{cylinders}} = 45.4882 \cdot \text{kg}$$

This value is close to the maximum value of 45.2 kg. The assumption that the deep sampling horizon captured most of the persulfate is reasonable if the upper bound of estimated mass released is used. This value is based on the higher seepage velocity estimate. If the lower seepage velocity estimate is used, then about half of the persulfate is missing.

APPENDIX I
DETAILED COST ESTIMATES

S1		Parameter	Unit	Unit price	Unit				Total price				Notes
					1-ft spacing	2.5-ft spacing	5-ft spacing	10-ft spacing	1-ft spacing	2.5-ft spacing	5-ft spacing	10-ft spacing	
General	**Plume dimension**	Plume length	ft		400	400	400	400					
		Plume width	ft		100	100	100	100					
		Thickness of treatment zone	ft		20	20	20	20					
		Bottom depth of treatment zone	ft		40	40	40	40					
	System configuration	Spacing	ft		1	2.5	5	10					
		Borehole diameter	inches		8	8	8	8					
		# of barriers	barrier		1	1	1	1					
		# of rows per barrier	rows		1	1	1	1					
		# of boreholes with 4-inch ID cylinder wells required	boreholes		100	40	20	10					
		# of 2-inch ID MWs	MWs		10	10	10	10					assume upgradient and downgradient wells every 100 horizontal feet
	Persulfate mass	Cylinder length	ft		1.5	1.5	1.5	1.5					
		Weight of 1 cylinder length	kg		2.879	2.879	2.879	2.879					
		% sodium persulfate	by weight		79%	79%	79%	79%					
		Total weight of sodium persulfate per cylinder well	kg		30	30	30	30					
		Total weight of sodium persulfate	lbs		67	67	67	67					
		# of changeout per year	changeouts		2	2	2	2					
		Total weight of sodium persulfate per year	lbs		13343	5337	2669	1334					
	IDW	Amount of drill cutting generated per borehole	ft3		14.0	14.0	14.0	14.0					
		Total drill cutting generated	ft3		1689	768	461	307					with 10% contingency
		Total drill cutting generated	tons		102	47	28	19					assume 120 lbs/ft3 of soil
		Amount of aqueous IDW generated per borehole	gallons		250.0	250.0	250.0	250.0					assume to include development & decon water
		Total drill cutting generated	gallons		30250	13750	8250	5500					with 10% contingency
Capital		**Bench-scale treatability/pilot testing**	Lump Sum	1	200000	200000	200000	200000	**$ 200,000**	**$ 200,000**	**$ 200,000**	**$ 200,000**	
	Drilling	Mobilization/Demobilization	Lump Sum	$ 3,500	4	2	1	1	$ 14,000	$ 7,000	$ 3,500	$ 3,500	assume 4 rigs out onsite @ all time
		Per Diem (4 crews with 2 people each)	Per day	$ 1,200	27.5	12.5	7.5	5	$ 33,000	$ 15,000	$ 9,000	$ 6,000	assume 4 rigs out onsite @ all time
		Hollow-Stem Auger Drilling for cylinder wells and MWs	per foot	$ 35	4400	2000	1200	800	$ 154,000	$ 70,000	$ 42,000	$ 28,000	
		4" cylinder well installation	per foot	$ 20	4000	1600	800	400	$ 80,000	$ 32,000	$ 16,000	$ 8,000	
		2" MW installation	per foot	$ 20	400	400	400	400	$ 8,000	$ 8,000	$ 8,000	$ 8,000	
		Surface Completion	each	$ 350	110	50	30	20	$ 38,500	$ 17,500	$ 10,500	$ 7,000	assume traffic-rated surface completion
		Decontamination & IDW management	per hour	$ 400	55	25	15	10	$ 22,000	$ 10,000	$ 6,000	$ 4,000	assume 1/2 hr per well
		Well development	per hour	$ 200	110	50	30	20	$ 22,000	$ 10,000	$ 6,000	$ 4,000	assume 1 per well
		Borehole Abandonment	per foot	$ 10	4400	2000	1200	800	$ 44,000	$ 20,000	$ 12,000	$ 8,000	assume all wells will be abandoned
		Total drilling cost							**$ 416,000**	**$ 190,000**	**$ 113,000**	**$ 77,000**	
	IDW disposal	IDW roll-off dropoff/pickup	Lump Sum	$ 595	1	1	1	1	$ 595	$ 595	$ 595	$ 595	
		IDW roll-off rental	per month	$ 450	3	3	3	3	$ 1,350	$ 1,350	$ 1,350	$ 1,350	
		Handling/transport/disposal of non-hazardous soil cuttings in roll offs	per ton	$ 200	102	47	28	19	$ 20,400	$ 9,400	$ 5,600	$ 3,800	assume 4 roll-off onsite @ all time
		21,000-gal tank drop off/removal	Lump Sum	$ 3,000	1	1	1	1	$ 3,000	$ 3,000	$ 3,000	$ 3,000	assume 4 tanks onsite
		21,000-gal tank rental	per month	$ 4,800	3	3	3	3	$ 14,400	$ 14,400	$ 14,400	$ 14,400	
		Handling/transport/disposal of hazardous purge/decon/well development water	per gallon	$ 1	30250	13750	8250	5500	$ 28,738	$ 13,063	$ 7,838	$ 5,225	assume 4 roll-off onsite @ all time
		21,000 tank clean out	per tank	$ 3,500	4	4	4	4	$ 14,000	$ 14,000	$ 14,000	$ 14,000	
		Total IDW cost							**$ 82,000**	**$ 56,000**	**$ 47,000**	**$ 42,000**	
	fate der	Persulfate cylinder	per foot	$ 80	2000	800	400	200	$ 160,000	$ 64,000	$ 32,000	$ 16,000	

S1		Parameter	Unit	Unit price	Unit				Total price				Notes
					1-ft spacing	2.5-ft spacing	5-ft spacing	10-ft spacing	1-ft spacing	2.5-ft spacing	5-ft spacing	10-ft spacing	
	Persul cylin	Cylinder assembly	each	$ 100	100	40	20	10	$ 10,000	$ 4,000	$ 2,000	$ 1,000	estimated cost for deployment assembly
		Total persulfate cylinder cost							**$ 170,000**	**$ 68,000**	**$ 34,000**	**$ 17,000**	
	Field oversight	Labor for field oversight	per day	$ 4,400	27.5	12.5	7.5	5	$ 121,000	$ 55,000	$ 33,000	$ 22,000	assume $110/hr labor rate & 1 field geologist/engineer per rig & 10 working hours/day
		Per diem	Per day	$ 1,200	27.5	12.5	7.5	5	$ 33,000	$ 15,000	$ 9,000	$ 6,000	
		Car rental	Per day	$ 400	27.5	12.5	7.5	5	$ 11,000	$ 5,000	$ 3,000	$ 2,000	
		Field monitoring equipment	Lump Sum	$ 5,000	1	1	1	1	$ 5,000	$ 5,000	$ 5,000	$ 5,000	
		Total field oversight							**$ 170,000**	**$ 80,000**	**$ 50,000**	**$ 35,000**	
	Summary	Capital Costs							$ 1,038,000	$ 594,000	$ 444,000	$ 371,000	
		Project Management	10%						$ 104,000.00	$ 59,000.00	$ 44,000.00	$ 37,000.00	
		Project Procurement, Health and Safety, Coordination, QA/QC, Auditing, and Other Misc. Activities	15%						$ 156,000.00	$ 89,000.00	$ 67,000.00	$ 56,000.00	
		Contingency	20%						$ 208,000	$ 119,000	$ 89,000	$ 74,000	
		Total Capital Costs							**$ 1,506,000**	**$ 861,000**	**$ 644,000**	**$ 538,000**	
O&M	**Annual monitoring**	# of monitoring events per year	per year	-	2	2	2	2	-	-	-	-	assumed
		Duration of each monitoring event	days	-	3	3	3	3	-	-	-	-	
		Analytical & other ODC cost	lump sum	$ 5,000	1	1	1	1	$ 5,000	$ 5,000	$ 5,000	$ 5,000	
		Equipment & material cost	lump sum	$ 1,500	1	1	1	1	$ 1,500	$ 1,500	$ 1,500	$ 1,500	Equipment rental and misc. equipment/parts
		Monitoring Coordination	hours	$ 125	8	8	8	8	$ 1,000	$ 1,000	$ 1,000	$ 1,000	Assume 8 hrs per monitoring event
		Monitoring Labor	hours	$ 110	92	92	92	92	$ 10,120	$ 10,120	$ 10,120	$ 10,120	Assume 2 people working 10 hours/day each per monitoring event
		Reporting cost per year	hours	$ 125	100	100	100	100	$ 12,500	$ 12,500	$ 12,500	$ 12,500	Assume annual report
		Total annual monitoring cost							**$ 60,000**	**$ 60,000**	**$ 60,240**	**$ 60,240**	
	Cylinder changeout	# of changeout per year	changeouts		2	2	2	2					assumed
		Equipment & material cost	lump sum	$ 20,000	1	1	1	1	$ 20,000	$ 20,000	$ 20,000	$ 20,000	Equipment rental and misc. equipment/parts
		Persulfate cylinder	per foot	$ 80	2000	800	400	200	$ 160,000	$ 64,000	$ 32,000	$ 16,000	
		Changeout coordination	hours	$ 125	40	40	40	40	$ 5,000	$ 5,000	$ 5,000	$ 5,000	Assume 8 hrs per changeout event
		Changeout labor	hours	$ 110	250	100	50	25	$ 27,500	$ 11,000	$ 5,500	$ 2,750	Assume 2 people working 10 hours/day for each per changeout event
		Total annual changeout cost							**$ 425,000**	**$ 200,000**	**$ 125,000**	**$ 87,500**	
	Summary	Annual O&M Costs							$ 485,000	$ 260,000	$ 185,240	$ 147,740	
		Project Management	10%						$ 48,500	$ 26,000	$ 18,524	$ 14,774	
		Contingency	20%						$ 97,000	$ 52,000	$ 37,048	$ 29,548	
		Total annual O&M cost - Year 1							$ 630,500	$ 338,000	$ 240,812	$ 192,062	
		Duration (years)			1	1	1	1					
		Discount Factor			0.9346	0.9346	0.9346	0.9346					
		Net present value - O&M							**$ 589,265**	**$ 315,895**	**$ 225,063**	**$ 179,501**	
		Total annual O&M cost - Year 2-30											
		Duration (years)			29	29	29	29					
		Discount Factor			11.4741	11.4741	11.4741	11.4741					
		Net present value - O&M							**$ 7,234,420**	**$ 3,878,246**	**$ 2,763,101**	**$ 2,203,739**	
		Total capital + O&M cost							**$ 9,329,685**	**$ 5,055,141**	**$ 3,632,164**	**$ 2,921,240**	

S2		Parameter	Unit	Unit price	Unit				Total price				Notes
					3-month changeout	6-month changeout	12-month changeout	18-month changeout	3-month changeout	6-month changeout	12-month changeout	18-month changeout	
General	Plume dimension	Plume length	ft		400	400	400	400					
		Plume width	ft		100	100	100	100					
		Thickness of treatment zone	ft		20	20	20	20					
		Bottom depth of treatment zone	ft		40	40	40	40					
	System configuration	Spacing	ft		5	5	5	5					
		Borehole diameter	inches		8	8	8	8					
		# of barriers	barrier		1	1	1	1					
		# of rows per barrier	rows		1	1	1	1					
		# of boreholes with 4-inch ID cylinder wells required	boreholes		20	20	20	20					
		# of 2-inch ID MWs	MWs		10	10	10	10					assume upgradient and downgradient wells every 20 horizontal feet
	Persulfate mass	Cylinder length	ft		1.5	1.5	1.5	1.5					
		Weight of 1 cylinder length	kg		2.879	2.879	2.879	2.879					
		% sodium persulfate	by weight		79%	79%	79%	79%					
		Total weight of sodium persulfate per cylinder well	kg		30	30	30	30					
		Total weight of sodium persulfate	lbs		67	67	67	67					
		# of changeout per year	changeouts		4	2	1	0.67					
		Total weight of sodium persulfate per year	lbs		5337	2669	1334	890					
	IDW	Amount of drill cutting generated per borehole	ft3		14.0	14.0	14.0	14.0					
		Total drill cutting generated	ft3		461	461	461	461					with 10% contingency
		Total drill cutting generated	tons		28	28	28	28					assume 120 lbs/ft3 of soil
		Amount of aqueous IDW generated per borehole	gallons		250.0	250.0	250.0	250.0					assume to include development & decon water
		Total drill cutting generated	gallons		8250	8250	8250	8250					with 10% contingency
Capital	**Bench-scale treatability/pilot testing**		Lump Sum	1	200000	200000	200000	200000	**$ 200,000**	**$ 200,000**	**$ 200,000**	**$ 200,000**	
	Drilling	Mobilization/Demobilization	Lump Sum	$ 3,500	1	1	1	1	$ 3,500	$ 3,500	$ 3,500	$ 3,500	assume 4 rigs out onsite @ all time
		Per Diem (4 crews with 2 people each)	Per day	$ 1,200	7.5	7.5	7.5	7.5	$ 9,000	$ 9,000	$ 9,000	$ 9,000	assume 4 rigs out onsite @ all time
		Hollow-Stem Auger Drilling for cylinder wells and MWs	per foot	$ 35	1200	1200	1200	1200	$ 42,000	$ 42,000	$ 42,000	$ 42,000	
		4" cylinder well installation	per foot	$ 20	800	800	800	800	$ 16,000	$ 16,000	$ 16,000	$ 16,000	
		2" MW installation	per foot	$ 20	400	400	400	400	$ 8,000	$ 8,000	$ 8,000	$ 8,000	
		Surface Completion	each	$ 350	30	30	30	30	$ 10,500	$ 10,500	$ 10,500	$ 10,500	assume traffic-rated surface completion
		Decontamination & IDW management	per hour	$ 400	15	15	15	15	$ 6,000	$ 6,000	$ 6,000	$ 6,000	assume 1/2 hr per well
		Well development	per hour	$ 200	30	30	30	30	$ 6,000	$ 6,000	$ 6,000	$ 6,000	assume 1 per well
		Borehole Abandonment	per foot	$ 10	1200	1200	1200	1200	$ 12,000	$ 12,000	$ 12,000	$ 12,000	assume all wells will be abandoned
		Total drilling cost							**$ 113,000**	**$ 113,000**	**$ 113,000**	**$ 113,000**	
	IDW disposal	IDW roll-off dropoff/pickup	Lump Sum	$ 595	1	1	1	1	$ 595	$ 595	$ 595	$ 595	
		IDW roll-off rental	per month	$ 450	3	3	3	3	$ 1,350	$ 1,350	$ 1,350	$ 1,350	
		Handling/transport/disposal of non-hazardous soil cuttings in roll offs	per ton	$ 200	28	28	28	28	$ 5,600	$ 5,600	$ 5,600	$ 5,600	assume 4 roll-off onsite @ all time
		21,000-gal tank drop off/removal	Lump Sum	$ 3,000	1	1	1	1	$ 3,000	$ 3,000	$ 3,000	$ 3,000	assume 4 tanks onsite
		21,000-gal tank rental	per month	$ 4,800	3	3	3	3	$ 14,400	$ 14,400	$ 14,400	$ 14,400	
		Handling/transport/disposal of hazardous purge/decon/well development water	per gallon	$ 1	8250	8250	8250	8250	$ 7,838	$ 7,838	$ 7,838	$ 7,838	assume 4 roll-off onsite @ all time
		21,000 tank clean out	per tank	$ 3,500	4	4	4	4	$ 14,000	$ 14,000	$ 14,000	$ 14,000	
		Total IDW cost							**$ 46,783**	**$ 46,783**	**$ 46,783**	**$ 46,783**	
	fate der	Persulfate cylinder	per foot	$ 80	400	400	400	400	$ 32,000	$ 32,000	$ 32,000	$ 32,000	

S2		Parameter	Unit	Unit price	Unit				Total price				Notes
					3-month changeout	6-month changeout	12-month changeout	18-month changeout	3-month changeout	6-month changeout	12-month changeout	18-month changeout	
	Persul cylin	Cylinder assembly	each	$ 100	20	20	20	20	$ 2,000	$ 2,000	$ 2,000	$ 2,000	estimated cost for deployment assembly
		Total persulfate cylinder cost							**$ 34,000**	**$ 34,000**	**$ 34,000**	**$ 34,000**	
	Field oversight	Labor for field oversight	per day	$ 4,400	7.5	7.5	7.5	7.5	$ 33,000	$ 33,000	$ 33,000	$ 33,000	assume $110/hr labor rate & 1 field geologist/engineer per rig & 10 working hours/day
		Per diem	Per day	$ 1,200	7.5	7.5	7.5	7.5	$ 9,000	$ 9,000	$ 9,000	$ 9,000	
		Car rental	Per day	$ 400	7.5	7.5	7.5	7.5	$ 3,000	$ 3,000	$ 3,000	$ 3,000	
		Field monitoring equipment	Lump Sum	$ 5,000	1	1	1	1	$ 5,000	$ 5,000	$ 5,000	$ 5,000	
		Total field oversight							**$ 50,000**	**$ 50,000**	**$ 50,000**	**$ 50,000**	
	Summary	Capital Costs							$ 443,783	$ 443,783	$ 443,783	$ 443,783	
		Project Management	10%						$ 44,378.25	$ 44,378.25	$ 44,378.25	$ 44,378.25	
		Project Procurement, Health and Safety, Coordination, QA/QC, Auditing, and Other Misc. Activities	15%						$ 66,567.38	$ 66,567.38	$ 66,567.38	$ 66,567.38	
		Contingency	20%						$ 88,757	$ 88,757	$ 88,757	$ 88,757	
		Total Capital Costs							**$ 643,485**	**$ 643,485**	**$ 643,485**	**$ 643,485**	
O&M	**Annual monitoring**	# of monitoring events per year	per year	-	2	2	2	2	-	-	-	-	assumed
		Duration of each monitoring event	days	-	3	3	3	3	-	-	-	-	
		Analytical & other ODC cost	lump sum	$ 5,000	1	1	1	1	$ 5,000	$ 5,000	$ 5,000	$ 5,000	
		Equipment & material cost	lump sum	$ 1,500	1	1	1	1	$ 1,500	$ 1,500	$ 1,500	$ 1,500	Equipment rental and misc. equipment/parts
		Monitoring Coordination	hours	$ 125	8	8	8	8	$ 1,000	$ 1,000	$ 1,000	$ 1,000	Assume 8 hrs per monitoring event
		Monitoring Labor	hours	$ 110	92	92	92	92	$ 10,120	$ 10,120	$ 10,120	$ 10,120	Assume 2 people working 10 hours/day each per monitoring event
		Reporting cost per year	hours	$ 125	100	100	100	100	$ 12,500	$ 12,500	$ 12,500	$ 12,500	Assume annual report
		Total annual monitoring cost							**$ 60,240**	**$ 60,240**	**$ 60,240**	**$ 60,240**	
	Cylinder changeout	# of changeout per year	changeouts		4	2	1	0.66666667					assumed
		Equipment & material cost	lump sum	$ 20,000	1	1	1	1	$ 20,000	$ 20,000	$ 20,000	$ 20,000	Equipment rental and misc. equipment/parts
		Persulfate cylinder	per foot	$ 80	400	400	400	400	$ 32,000	$ 32,000	$ 32,000	$ 32,000	
		Changeout coordination	hours	$ 125	40	40	40	40	$ 5,000	$ 5,000	$ 5,000	$ 5,000	Assume 8 hrs per changeout event
		Changeout labor	hours	$ 110	50	50	50	50	$ 5,500	$ 5,500	$ 5,500	$ 5,500	Assume 2 people working 10 hours/day for each per changeout event
		Total annual changeout cost							**$ 250,000**	**$ 125,000**	**$ 62,500**	**$ 41,667**	
	Summary	Annual O&M Costs							$ 310,240	$ 185,240	$ 122,740	$ 101,907	
		Project Management	10%						$ 31,024	$ 18,524	$ 12,274	$ 10,191	
		Contingency	20%						$ 62,048	$ 37,048	$ 24,548	$ 20,381	
		Total annual O&M cost - Year 1							$ 403,312	$ 240,812	$ 159,562	$ 132,479	
		Duration (years)			1	1	1	1					
		Discount Factor			0.9346	0.9346	0.9346	0.9346					
		Net present value - O&M							**$ 376,935**	**$ 225,063**	**$ 149,127**	**$ 123,815**	
		Total annual O&M cost - Year 2-30											
		Duration (years)			29	29	29	29					
		Discount Factor			11.4741	11.4741	11.4741	11.4741					
		Net present value - O&M							**$ 4,627,642**	**$ 2,763,101**	**$ 1,830,830**	**$ 1,520,073**	
		Total capital + O&M cost							**$ 5,648,062**	**$ 3,631,648**	**$ 2,623,442**	**$ 2,287,373**	

S3		Parameter	Unit	Unit price	Unit				Total cost				Notes
					30-day reinjection	45-day reinjection	60-day reinjection	90-day reinjection	30-day reinjection	45-day reinjection	60-day reinjection	90-day reinjection	
General	Plume dimension	Plume length	ft		400	400	400	400		$ -	$ -		
		Plume width	ft		100	100	100	100		$ -	$ -		
		Effective porosity			12.5%	12.5%	12.5%	12.5%		$ -	$ -		
		Thickness of treatment zone	ft		20	20	20	20					
		Bottom depth of treatment zone	ft		40	40	40	40					
	System configuration	Injection ROI	ft		2.5	2.5	2.5	2.5					
		Borehole ID	inches		6	6	6	6					
		# of 2-inch ID Iws	wells		20	20	20	20					
		# of 2-inch ID MWs	MWs		10	10	10	10					assume MWs every 100 horizontal feet
		Treatment volume	ft3		49	49	49	49					
		Treatment volume	gallons		367	367	367	367					Conversion: 1 ft3 = 7.48052 gals
		Injection rate	gpm		5	5	5	5					assumed
		# of wells injected simultaneously	wells		10	10	10	10					
		# of injection hours	hours		2.45	2.45	2.45	2.45					
		# of injection days	days		1	1	1	1					assume 10 injection hours/day
		Mass of sodium persulfate to use to match 1c	lbs		2669	2669	2669	2669					
		# of persulfate cylinders in Scenario 1c	cylinders		20	20	20	20					
		# of feet of persulfate cylinders required in Scenario 1c	ft		400	400	400	400					
		Cylinder length	ft		1.5	1.5	1.5	1.5					
		Weight of 1 cylinder length	kg		2.879	2.879	2.879	2.879					
		% sodium persulfate	by weight		79%	79%	79%	79%					
		Total weight of sodium persulfate	kg		607	607	607	607					
		# of changeout in Scenario 1	changeouts		2	2	2	2					
		# of reinjection events	reinjection		12	8	6	4					
		Amount of sodium persulfate to be injected each event	lbs/reinjection event		222	334	445	667					
		Concentration of sodium persulfate per well	mg/L/well		3636	5454	7272	10908					
	IDW	Amount of drill cutting generated per borehole	ft3		7.9	7.9	7.9	7.9					
		Total drill cutting generated	ft3		259	259	259	259					with 10% contingency
		Total drill cutting generated	tons		16	16	16	16					assume 120 lbs/ft3 of soil
		Amount of aqueous IDW generated per borehole	gallons		250.0	250.0	250.0	250.0					assume to include development & decon water
		Total drill cutting generated	gallons		8250	8250	8250	8250					with 10% contingency
tal	**Bench-scale treatability/pilot testing**		Lump Sum	1	200000	200000	200000	200000	**$ 200,000**	**$ 200,000**	**$ 200,000**	**$ 200,000**	
	Drilling	Mobilization/Demobilization	Lump Sum	$ 3,500	1	1	1	1	$ 3,500	$ 3,500	$ 3,500	$ 3,500	assume 2 rigs out onsite @ all time
		Per Diem (4 crews with 2 people each)	Per day	$ 1,200	7.5	7.5	7.5	7.5	$ 9,000	$ 9,000	$ 9,000	$ 9,000	assume 2 rigs out onsite @ all time
		Hollow-Stem Auger Drilling for cylinder wells and MWs	per foot	$ 30	1200	1200	1200	1200	$ 36,000	$ 36,000	$ 36,000	$ 36,000	
		2" injection well installation	per foot	$ 20	800	800	800	800	$ 16,000	$ 16,000	$ 16,000	$ 16,000	
		2" ID MW installation	per foot	$ 20	400	400	400	400	$ 8,000	$ 8,000	$ 8,000	$ 8,000	
		Surface Completion	each	$ 350	30	30	30	30	$ 10,500	$ 10,500	$ 10,500	$ 10,500	assume traffic-rated surface completion
		Decontamination & IDW management	per hour	$ 400	15	15	15	15	$ 6,000	$ 6,000	$ 6,000	$ 6,000	assume 1/2 hr per well
		Well development	per hour	$ 200	30	30	30	30	$ 6,000	$ 6,000	$ 6,000	$ 6,000	assume 1 per well
		Borehole Abandonment	per foot	$ 10	1200	1200	1200	1200	$ 12,000	$ 12,000	$ 12,000	$ 12,000	assume all wells will be abandoned
		Total drilling cost							**$ 107,000**	**$ 107,000**	**$ 107,000**	**$ 107,000**	
	IDW disposal	IDW roll-off dropoff/pickup	Lump Sum	$ 595	1	1	1	1	$ 595	$ 595	$ 595	$ 595	
		IDW roll-off rental	per month	$ 450	1	1	1	1	$ 450	$ 450	$ 450	$ 450	
		Handling/transport/disposal of non-hazardous soil cuttings in roll offs	per ton	$ 200	16	16	16	16	$ 3,200	$ 3,200	$ 3,200	$ 3,200	assume 2 roll-off onsite @ all time
		21,000-gal tank drop off/removal	Lump Sum	$ 1,500	1	1	1	1	$ 1,500	$ 1,500	$ 1,500	$ 1,500	assume 2 tanks onsite
		21,000-gal tank rental	per month	$ 2,400	1	1	1	1	$ 2,400	$ 2,400	$ 2,400	$ 2,400	
		Handling/transport/disposal of hazardous purge/decon/well development water	per gallon	$ 1	8250	8250	8250	8250	$ 7,838	$ 7,838	$ 7,838	$ 7,838	assume 2 roll-off onsite @ all time
		21,000 tank clean out	per tank	$ 3,500	4	4	4	4	$ 14,000	$ 14,000	$ 14,000	$ 14,000	
		Total IDW cost							**$ 29,983**	**$ 29,983**	**$ 29,983**	**$ 29,983**	

S3		Parameter	Unit	Unit price	Unit				Total cost				Notes
					30-day reinjection	45-day reinjection	60-day reinjection	90-day reinjection	30-day reinjection	45-day reinjection	60-day reinjection	90-day reinjection	
Capi	Persulfate	Persulfate	per lbs	$ 1.48	2669	2669	2669	2669	$ 3,950	$ 3,950	$ 3,950	$ 3,950	
		Persulfate freight	Lump Sum	$ 10,000	1	1	1	1	$ 10,000	$ 10,000	$ 10,000	$ 10,000	estimated cost
		Total persulfate cost							**$ 13,950**	**$ 13,950**	**$ 13,950**	**$ 13,950**	
	Injection system	Injection system	Lump Sum	$ 5,000	1	1	1	1	$ 5,000	$ 5,000	$ 5,000	$ 5,000	estimated cost
	Field oversight	Labor for field oversight - drilling	per day	$ 2,200	7.5	7.5	7.5	7.5	$ 16,500	$ 16,500	$ 16,500	$ 16,500	assume $110/hr labor rate & injection crew of 2
		Labor for injection	per day	$ 2,200	1	1	1	1	$ 2,200	$ 2,200	$ 2,200	$ 2,200	
		Per diem	Per day	$ 600	8.5	8.5	8.5	8.5	$ 5,100	$ 5,100	$ 5,100	$ 5,100	
		Car rental	Per day	$ 200	8.5	8.5	8.5	8.5	$ 1,700	$ 1,700	$ 1,700	$ 1,700	
		Field monitoring equipment	Lump Sum	$ 5,000	1	1	1	1	$ 5,000	$ 5,000	$ 5,000	$ 5,000	
		Total field oversight							**$ 30,500**	**$ 30,500**	**$ 30,500**	**$ 30,500**	
	Summary	Capital Costs							$ 416,932	$ 416,932	$ 416,932	$ 416,932	
		Project Management	10%						$ 41,693	$ 41,693	$ 41,693	$ 41,693	
		Project Procurement, Health and Safety, Coordination, QA/QC, Auditing, and Other Misc. Activities	15%						$ 62,540	$ 62,540	$ 62,540	$ 62,540	
		Contingency	20%						$ 83,386	$ 83,386	$ 83,386	$ 83,386	
		Total Capital Costs							**$ 604,552**	**$ 604,552**	**$ 604,552**	**$ 604,552**	
O&M	Annual monitoring	# of monitoring events per year	per year	-	2	2	2	2	-	-	-	-	assumed
		Duration of each monitoring event	days	-	3	3	3	3	-	-	-	-	
		Analytical & other ODC cost	lump sum	$ 5,000	1	1	1	1	$ 5,000	$ 5,000	$ 5,000	$ 5,000	
		Equipment & material cost	lump sum	$ 1,500	1	1	1	1	$ 1,500	$ 1,500	$ 1,500	$ 1,500	Equipment rental and misc. equipment/parts
		Monitoring Coordination	hours	$ 125	8	8	8	8	$ 1,000	$ 1,000	$ 1,000	$ 1,000	Assume 8 hrs per monitoring event
		Monitoring Labor	hours	$ 110	92	92	92	92	$ 10,120	$ 10,120	$ 10,120	$ 10,120	Assume 2 people working 10 hours/day each per monitoring event
		Reporting cost per year	hours	$ 125	100	100	100	100	$ 12,500	$ 12,500	$ 12,500	$ 12,500	Assume annual report
		Total annual monitoring cost							**$ 60,240**	**$ 60,240**	**$ 60,240**	**$ 60,240**	
	Reinjection	# of reinjection per year	reinjection		12	8	6	4					assumed
		Persulfate	Lump Sum	$ 13,950	1	1	1	1	$ 13,950	$ 13,950	$ 13,950	$ 13,950	
		Reinjection coordination	hours	$ 125	40	40	40	40	$ 5,000	$ 5,000	$ 5,000	$ 5,000	
		Labor for reinjection	per day	$ 2,200	7.5	7.5	7.5	7.5	$ 16,500	$ 16,500	$ 16,500	$ 16,500	Assume 2 people working 10 hours/day for each per reinjection event
		Per diem	Per day	$ 600	7.5	7.5	7.5	7.5	$ 4,500	$ 4,500	$ 4,500	$ 4,500	
		Car rental	Per day	$ 200	7.5	7.5	7.5	7.5	$ 1,500	$ 1,500	$ 1,500	$ 1,500	
		Field monitoring equipment	Lump Sum	$ 5,000	1	1	1	1	$ 5,000	$ 5,000	$ 5,000	$ 5,000	
		Total annual reinjection cost							**$ 557,395**	**$ 371,597**	**$ 278,698**	**$ 185,798**	
	Summary	Annual O&M Costs							$ 617,635	$ 431,837	$ 338,938	$ 246,038	
		Project Management	10%						$ 61,764	$ 43,184	$ 33,894	$ 24,604	
		Contingency	20%						$ 123,527	$ 86,367	$ 67,788	$ 49,208	
		Total annual O&M cost - Year 1							$ 802,926	$ 561,388	$ 440,619	$ 319,850	
		Duration (years)			1	1	1	1					
		Discount Factor			0.9346	0.9346	0.9346	0.9346					
		Net present value - O&M							**$ 750,414**	**$ 524,673**	**$ 411,802**	**$ 298,932**	
		Total annual O&M cost - Year 2-30											
		Duration (years)			29	29	29	29					
		Discount Factor			11.4741	11.4741	11.4741	11.4741					
		Net present value - O&M							**$ 9,212,848**	**$ 6,441,419**	**$ 5,055,704**	**$ 3,669,989**	
		Total capital + O&M cost							**$ 10,567,814**	**$ 7,570,643**	**$ 6,072,058**	**$ 4,573,473**	

S4		Parameter	Amount	Unit	Unit price	Total price	Notes
General	Plume dimension	Plume length	400	ft			
		Plume width	100	ft			
		Thickness of treatment zone	20	ft			
		Bottom depth of treatment zone	40	ft			
	System configuration	Length of each funnel	100	ft			
		Width of each funnel	2.5	ft			assumed
		Length of gate	15	ft			
		Total square feet of slurry wall	8000	ft2			assume slurry wall to total depth of 60 ft
		Amount of excavated materials from trenching	20000	ft3			
		Total drill cutting generated	1200	tons			assume 120 lbs/ft3 of soil
		Spacing	2.5	ft			
		Borehole diameter	8	inches			
		# of boreholes with 4-inch ID cylinder wells required	20	boreholes			to match with Scenario 1C
		# of 2-inch ID MWs	10	MWs			assume upgradient and downgradient wells every 100 horizontal feet
	Persulfate mass	Cylinder length	1.5	ft			
		Weight of 1 cylinder length	2.879	kg			
		% sodium persulfate	79%	by weight			
		Total weight of sodium persulfate per cylinder well	30.3	kg			
		Total weight of sodium persulfate	67	lbs			
		# of changeout per year	2	changeouts			
		Total weight of sodium persulfate per year	2669	lbs			
	IDW	Amount of drill cutting generated per borehole	14.0	ft3			
		Total drill cutting generated	461	ft3			with 10% contingency
		Total drill cutting generated	28	tons			assume 120 lbs/ft3 of soil
		Amount of aqueous IDW generated per borehole	250.0	gallons			assume to include development & decon water
		Total drill cutting generated	8250	gallons			with 10% contingency
		Bench-scale treatability/pilot testing	**1**	**Lump Sum**	**200000**	**$ 200,000**	
	Drilling	Mobilization/Demobilization	1	Lump Sum	$ 3,500	$ 3,500	assume 4 rigs out onsite @ all time
		Per Diem (4 crews with 2 people each)	7.5	Per day	$ 1,200	$ 9,000	assume 4 rigs out onsite @ all time
		Hollow-Stem Auger Drilling for cylinder wells and MWs	1200	per foot	$ 35	$ 42,000	
		4" cylinder well installation	800	per foot	$ 20	$ 16,000	
		2" MW installation	400	per foot	$ 20	$ 8,000	
		Surface Completion	30	each	$ 350	$ 10,500	assume traffic-rated surface completion
		Decontamination & IDW management	15	per hour	$ 400	$ 6,000	assume 1/2 hr per well
		Well development	30	per hour	$ 200	$ 6,000	assume 1 per well
		Borehole Abandonment	1200	per foot	$ 10	$ 12,000	assume all wells will be abandoned
		Total drilling cost				**$ 113,000**	
	IDW disposal	IDW roll-off dropoff/pickup	1	Lump Sum	$ 595	$ 595	
		IDW roll-off rental	3	per month	$ 450	$ 1,350	
		Handling/transport/disposal of non-hazardous soil cuttings in roll offs	28	per ton	$ 200	$ 5,600	assume 4 roll-off onsite @ all time
		21,000-gal tank drop off/removal	1	Lump Sum	$ 3,000	$ 3,000	assume 4 tanks onsite
		21,000-gal tank rental	3	per month	$ 4,800	$ 14,400	
		Handling/transport/disposal of hazardous purge/decon/well development water	8250	per gallon	$ 1	$ 7,838	assume 4 roll-off onsite @ all time
		21,000 tank clean out	4	per tank	$ 3,500	$ 14,000	
		Total IDW cost				**$ 46,783**	
pital	ion	General mobilization	5%	percent	total cost	$ 25,900	
		Excavation and disposal of trench soil	1200	tons	$ 150	$ 180,000	

S4		Parameter	Amount	Unit	Unit price	Total price	Notes
Ca	F&G installat	Slurry wall installation	8000	ft2	$ 6.50	$ 52,000	
		Disposal of extra excavated material and slurry	360	tons	$ 100	$ 36,000	
		Engineering design and permitting	1	Lump Sum	$ 250,000	$ 250,000	
		Total F&G cost				**$ 543,900**	
	Persulfate cylinder	Persulfate cylinder	400	per foot	$ 80	$ 32,000	
		Cylinder assembly	20	each	$ 100	$ 2,000	estimated cost for deployment assembly
		Total persulfate cylinder cost				**$ 34,000**	
	Field oversight	Labor for field oversight	7.5	per day	$ 4,400	$ 33,000	assume $110/hr labor rate & 1 field geologist/engineer per rig & 10 working hours/day
		Per diem	7.5	Per day	$ 1,200	$ 9,000	
		Car rental	7.5	Per day	$ 400	$ 3,000	
		Field monitoring equipment	1	Lump Sum	$ 5,000	$ 5,000	
		Total field oversight				**$ 50,000**	
	Summary	Capital Costs				$ 987,683	
		Project Management		10%		$ 98,768.25	
		Project Procurement, Health and Safety, Coordination, QA/QC, Auditing, and Other Misc. Activities		15%		$ 148,152.38	
		Contingency		20%		$ 197,537	
		Total Capital Costs				**$ 1,432,140**	
O&M	Annual monitoring	# of monitoring events per year	2	per year	-	-	assumed
		Duration of each monitoring event	3	days	-	-	
		Analytical & other ODC cost	1	lump sum	$ 5,000	$ 5,000	
		Equipment & material cost	1	lump sum	$ 1,500	$ 1,500	Equipment rental and misc. equipment/parts
		Monitoring Coordination	8	hours	$ 125	$ 1,000	Assume 8 hrs per monitoring event
		Monitoring Labor	92	hours	$ 110	$ 10,120	Assume 2 people working 10 hours/day each per monitoring event
		Reporting cost per year	100	hours	$ 125	$ 12,500	Assume annual report
		Total annual monitoring cost				**$ 60,240**	
	Cylinder changeout	# of changeout per year	2	changeouts			assumed
		Equipment & material cost	1	lump sum	$ 20,000	$ 20,000	Equipment rental and misc. equipment/parts
		Persulfate cylinder	400	per foot	$ 80	$ 32,000	
		Changeout coordination	40	hours	$ 125	$ 5,000	Assume 8 hrs per changeout event
		Changeout labor	50	hours	$ 110	$ 5,500	Assume 2 people working 10 hours/day for each per changeout event
		Total annual changeout cost				**$ 125,000**	
	Summary	Annual O&M Costs				$ 185,240	
		Project Management		10%		$ 18,524	
		Contingency		20%		$ 37,048	
		Total annual O&M cost - Year 1				$ 240,812	
		Duration (years)	1				
		Discount Factor	0.9346				
		Net present value - O&M				**$ 225,063**	
		Total annual O&M cost - Year 2-30					
		Duration (years)	29				
		Discount Factor	11.4741				
		Net present value - O&M				**$ 2,763,101**	
		Total capital + O&M cost				**$ 4,420,303**	

S5		Parameter	Unit	Unit price	Unit cost	Total cost	Notes
General	Plume dimension	Plume length	ft		400		
		Plume width	ft		100		
		Thickness of treatment zone	ft		20		
		Bottom depth of treatment zone	ft		40		
	System configuration	Spacing	ft		50		
		Borehole diameter	inches		8		
		# of rows	rows		1		
		# of 4-inch ID extraction wells	extraction wells		10		
		Groundwater velocity	ft/day		5		
		Area	ft2		2000		
		Groundwater discharge	ft3/day		10000		
		Groundwater discharge	gpm		51.9444444		
	IDW	Amount of drill cutting generated per borehole	ft3		14		
		Total drill cutting generated	ft3		154		with 10% contingency
		Total drill cutting generated	tons		10		assume 120 lbs/ft3 of soil
		Amount of aqueous IDW generated per borehole	gallons		250		assume to include development & decon water
		Total aqueous IDW generated	gallons		2750		with 10% contingency
Capital	**Bench-scale treatability/pilot testing**		**1**	**Lump Sum**	**200000**	**$ 200,000**	
	Drilling	Mobilization/Demobilization	Lump Sum	$ 3,500	1	$ 3,500	
		Per Diem (1 crew with 2 people each)	Per day	$ 300	2.5	$ 750	
		Hollow-Stem Auger Drilling for wells	per foot	$ 35	400	$ 14,000	
		4" well installation	per foot	$ 20	400	$ 8,000	
		Surface Completion	each	$ 350	10	$ 3,500	assume traffic-rated surface completion
		Decontamination & IDW management	per hour	$ 400	5	$ 2,000	assume 1/2 hr per well
		Well development	per hour	$ 200	10	$ 2,000	assume 1 per well
		Borehole Abandonment	per foot	$ 10	400	$ 4,000	assume all wells will be abandoned
		Total drilling cost				**$ 37,750**	
	IDW disposal	IDW roll-off dropoff/pickup	Lump Sum	$ 595	1	$ 595	
		IDW roll-off rental	per month	$ 450	1	$ 450	
		Handling/transport/disposal of non-hazardous soil cuttings in roll offs	per ton	$ 200	10	$ 2,000	assume 1 roll-off onsite @ all time
		21,000-gal tank drop off/removal	Lump Sum	$ 3,000	1	$ 3,000	assume 1 tanks onsite
		21,000-gal tank rental	per month	$ 4,800	1	$ 4,800	
		Handling/transport/disposal of hazardous purge/decon/well development water	per gallon	$ 1	2750	$ 2,613	assume 1 roll-off onsite @ all time
		21,000 tank clean out	per tank	$ 3,500	1	$ 3,500	
		Total IDW cost				**$ 16,958**	
	AOP stem	System	Lump sum	$ 204,000	1	$ 255,000	per quote from Calgon
		Trenching	per linear ft	$ 100	500	$ 50,000	Assume 3-ft trench in fielded area, 100 feet to AOP system

S5		Parameter	Unit	Unit price	Unit cost	Total cost	Notes
	A Sy	Extraction pumps	each	$ 1,500	10	$ 15,000	
		Total AOP system costs				**$ 320,000**	
	Field oversight	Labor for field oversight	per day	$ 1,100	22.5	$ 24,750	assume $110/hr labor rate & 1 field geologist/engineer per rig & 10 working hours/day
		Per diem	Per day	$ 300	2.5	$ 750	
		Car rental	Per day	$ 100	2.5	$ 250	
		Field monitoring equipment	Lump Sum	$ 5,000	1	$ 5,000	
		Total field oversight				**$ 30,750**	
	Summary	Capital Costs				$ 605,458	
		Project Management	10%			$ 60,546	
		Project Procurement, Health and Safety, Coordination, QA/QC, Auditing, and Other Misc. Activities	15%			$ 90,819	
		Contingency	20%			$ 121,092	
		Total capital costs				**$ 877,913**	
O&M	Annual monitoring	# of monitoring events per year	per year	-	2	-	assumed
		Duration of each monitoring event	days	-	3	-	
		Analytical & other ODC cost	lump sum	$ 5,000	1	$ 5,000	
		Equipment & material cost	lump sum	$ 1,500	1	$ 1,500	Equipment rental and misc. equipment/parts
		Monitoring Coordination	hours	$ 125	8	$ 1,000	Assume 8 hrs per monitoring event
		Monitoring Labor	hours	$ 110	92	$ 10,120	Assume 2 people working 10 hours/day each per monitoring event
		Reporting cost per year	hours	$ 125	100	$ 12,500	Assume annual report
		Total annual monitoring cost				**$ 60,240**	
	Annual Maintenance	Annual O&M Costs	Lump Sum	$ 29,178	1	$ 81,156	per quote from Calgon
		Labor for O&M	hours	$ 110	140	$ 15,400	Assume 2 people working 10 hours/day for one week
		Extraction pump changeout	each	$ 1,500	10	$ 75,000	Changeout every 5 years
		Total annual maintenance cost				**$ 171,556**	
	Summary	Annual O&M Costs				$ 231,796	
		Project Management	10%			$ 23,180	
		Contingency	20%			$ 46,359	
		Total annual O&M cost - Year 1				$ 301,335	
		Duration (years)			1		
		Discount Factor			0.9346		
		Net present value - O&M				**$ 281,628**	
		Total annual O&M cost - Year 2-30					
		Duration (years)			29		
		Discount Factor			11.4741		
		Net present value - O&M				**$ 3,457,546**	
		Total capital + O&M cost				**$ 4,617,087**	