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**ISCO OF VOLATILE ORGANIC CONTAMINANTS
USING PEROXONE ACTIVATED PERSULFATE & CYCLODEXTRIN**

BY

DYLAN E.H. EBERLE

**A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY**

IN

BIOLOGICAL AND ENVIRONMENTAL SCIENCES

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2015

DOCTOR OF PHILOSOPHY DISSERTATION

OF

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**UNIVERSITY OF RHODE ISLAND
2015**

ABSTRACT

Despite recent advances, subsurface remediation of volatile organic compounds (VOCs), such as chlorinated solvents and petroleum hydrocarbons, remains a challenging environmental problem. As a result, the development of innovative methods for remediating subsurface VOC remains a major environmental priority. In addition to these priority pollutants, perfluoroalkyl acids (PFAAs) and 1,4-dioxane are contaminants of emerging concern due to their potential toxicity and prevalence in the environment. These emerging contaminants have increasingly been identified as co-contaminants at VOC release sites, and remediation strategies capable of treating VOC as well as 1,4-dioxane and PFAAs would be of great value. In this dissertation, field and laboratory studies were conducted to evaluate an innovative remediation strategy for VOC priority pollutants and determine its effects on PFAAs and 1,4-dioxane. Chapter 1 details the outcome of a solubility-enhanced *in situ* chemical oxidation (ISCO) pilot-scale field test for the remediation of VOC. Chapter 2 investigates the fate of PFAA co-contaminants during the ISCO field test detailed in Chapter 1. Finally, Chapter 3 examines the degradation of 1,4-dioxane, a recalcitrant emerging contaminant frequently detected at solvent release sites, as well as its common VOC co-contaminants 1,1,1-trichloroethane and trichloroethene, using the same novel advanced oxidation process (AOP) as in Chapters 1 and 2. The results show that the solubility-enhancing agent hydroxypropyl- β -cyclodextrin can be successfully combined with ISCO to treat VOCs under field conditions. The results also suggest that ISCO can be used safely to treat

VOCs at sites where the emerging contaminants 1,4-dioxane and PFAAs have been identified or are suspected to occur.

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me every day. Finally, I would like to dedicate this dissertation to my Grandmother and Grandfather, Rosemary and Willard Hartup, whose positive impact on my life has been and continues to be immeasurable.

PREFACE

This dissertation is written in manuscript format in accordance with the requirements of the Graduate School of the University of Rhode Island. The dissertation is divided into six sections which consist of a brief introduction, three manuscripts, a conclusion, and a series of appendices. Chapter 1 is a manuscript entitled, “Solubility-Enhanced ISCO of VOC Contaminated Soil and Groundwater: A Pilot-Scale Field Test” with the authors D. Eberle, T. Boving, and R. Ball and has been prepared for submission to the journal *Groundwater Monitoring & Remediation*. This chapter describes the results of a pilot-scale field test of a solubility-enhanced *in situ* chemical oxidation (ISCO) remediation technology performed at a former fire training area (FTA) at Joint Base Langley-Eustis (JBLE), VA. Chapter 2 is a manuscript entitled, “Impact of ISCO Treatment of VOCs on PFAA Co-contaminants at a Former Fire Training Area,” with the authors D. Eberle, T. Boving, and R. Ball and has been prepared for submission to the Journal *Groundwater Monitoring & Remediation*. This chapter details the fate and distribution of perfluoroalkyl acids (PFAAs) during the targeted remediation of VOCs. Specifically this chapter examines the effects of the ISCO field test, detailed in Chapter 1, on the PFAA co-contaminants present at the site. Chapter 3 is a manuscript entitled, “Peroxone Activated Persulfate Treatment of 1,4-Dioxane in the Presence of Chlorinated Solvent Co-Contaminants” which has been published in the Journal *Chemosphere* with the authors D. Eberle, T. Boving, and R. Ball. Chapter 3 details a laboratory based study

examining the applicability of the same novel advanced oxidation process (AOP), OxyZone[®], used in Chapters 1 and 2 for the *in situ* treatment of 1,4-dioxane.

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INTRODUCTION AND REVIEW OF THE PROBLEM

Overview:

Remediation of subsurface contamination is a challenging environmental problem in the industrialized and developing world. Of particular concern are halogenated volatile organic contaminants (VOCs) such as chloroethenes, chloroethanes, and chlorobenzenes. Contamination of soil and groundwater is often associated with industrial and military facilities and other sites where VOCs are commonly used, such as gas stations and dry cleaners. Contamination problems often result from spills, leaking storage tanks, and improper disposal of wastes (Masten et al. 1997; US EPA 1999). Due to their low water solubility, VOC remediation by conventional technologies, such as pump and treat, is often costly and inefficient. As a result, the development of innovative methods for remediating VOCs in the subsurface has become a major environmental priority (US EPA 1999; US EPA 2010a). These compounds are considered emerging contaminants and their presence at many VOC sites generates questions about how to effectively treat them (Leeson 2010; Anderson 2011; SERDP 2012).

This study attempts to determine the effectiveness of an integrated desorption-oxidation process for the remediation of groundwater and sediments contaminated with VOCs. Particularly, this study examines the potential of a peroxone ($O_3 + H_2O_2$) activated sodium persulfate (Ball 2010) *in situ* chemical oxidation (ISCO) system, available commercially as OxyZone[®], for the remediation of halogenated aliphatic and

aromatic VOCs. This study also investigates the potential of using the solubility-enhancing agent cyclodextrin (CD) to increase the efficiency of *in situ* VOC remediation efforts. In addition, the fate of common VOC co-contaminants 1,4-dioxane and PFAAs are investigated. This study consists of a pilot-scale field test as well as laboratory-scale experiments. The field test portion of this study was conducted at a VOC contaminated former fire training area (FTA) at Joint Base Langley-Eustis (JBLE), VA. The laboratory portion was conducted at the University of Rhode Island (URI) Geosciences Department. The study was carried out in collaboration with EnChem Engineering, Inc. Newton, MA, which developed the OxyZone® formulation.

Previous Work:

Solubility-Enhanced ISCO

ISCO is a VOC remediation technique considered to be effective at overcoming some of the limitations of conventional treatment processes (US EPA 1999; Huling & Pivetz 2006). ISCO is based on the delivery of a chemical oxidizing agent to contaminated soil and groundwater in order to oxidize and destroy contaminants (US EPA 1999; Huling & Pivetz 2006; Tsitonaki et al. 2010; SERDP 2011). Commonly used ISCO oxidants include permanganate (MnO_4^-), hydrogen peroxide (H_2O_2), ozone (O_3) and persulfate ($\text{S}_2\text{O}_8^{2-}$) (US EPA 1999; Rivas 2006; Ferrarese et al. 2008). The ability of an oxidant to initiate chemical reactions is measured in terms of its oxidation potential. The most powerful oxidants currently available for ISCO are the hydroxyl ($\cdot\text{OH}$) and sulfate radicals ($\cdot\text{SO}_4^-$) (Huling & Pivetz 2006). ISCO processes that produce these highly reactive free radicals are termed "Advanced Oxidation Processes" (AOPs) (Glaze et al. 1987).

AOPs utilize primary oxidation reactions to produce hydroxyl and/or sulfate radicals as byproducts leading to further oxidation via secondary reactions. Common AOP technologies include classic and modified Fenton's reagent ($\text{Fe(II)} + \text{H}_2\text{O}_2$), peroxone, and activated persulfate (Huling & Pivetz 2006).

OxyZone® is an AOP developed by EnChem Engineering (Newton, MA), which utilizes a proprietary blend of dissolved ozone, buffered sodium persulfate, food grade phosphate-based buffers and dilute hydrogen peroxide. In this patented blend, ozone and hydrogen peroxide (peroxone) are used as an activation agent to facilitate production of hydroxyl and sulfate radicals; two of the strongest oxidants available (Table i). As a result OxyZone® is able to break down organic contaminants through primary oxidation reactions via ozone and persulfate molecules, as well as through more vigorous secondary oxidation reactions via hydroxyl and sulfate radicals (Table ii). Enchem Engineering has shown OxyZone® to be an efficient and cost-effective ISCO treatment at the field-scale, and currently market it as their flagship remediation technology (Ball 2010). Relative to other ISCO technologies, activated persulfate is still a new and developing remediation strategy. As such the evaluation of this innovative activation technology is important because OxyZone® may have advantages over other competing methods.

It has been suggested that an integrated desorption-oxidation process, in which contaminants are first made more readily available for chemical oxidation via a desorption agent, could be used to dramatically increase the efficiency of chemical

oxidation remediation of organic contaminants at the field-scale (Rivas 2006). One objective of this study is to test the potential of an integrated desorption-oxidation process using CD as the desorbing agent and OxyZone® oxidant to remediate chlorinated VOC contaminated water and sediments.

ISCO reactions occur predominantly in the aqueous phase and as a result, contaminant availability is a major limiting factor. That is, contaminants with higher aqueous solubilities are more accessible for oxidation relative to less soluble compounds (Ogram et al. 1985; Sedlak & Andren 1994; Quan et al. 2003; Rivas 2006; Ferrarese et al. 2008; SERDP 2011). ISCO may also be limited by contaminant sorption to reactive solid phase sites, including organic matter. Strong sorption typically lowers the aqueous phase concentration of these compounds which makes them less accessible to oxidative destruction processes (Rivas 2006; Sun & Yan 2008; Ferrarese et al. 2008; SERDP 2011). Another important factor that limits the oxidation of VOCs is oxidant wastage on non-target compounds, such as organic matter and reduced metals (Susan J. Masten et al. 1997; Choi et al. 2002; Pierpoint et al. 2003; O'Mahony et al. 2006; Rivas 2006; Ferrarese et al. 2008; SERDP 2011). These materials readily react with oxidants, resulting in competing reactions that can dramatically decrease contaminant removal efficiency and increase treatment cost. Consequently, there is considerable interest in finding economical ways to overcome these limitations and increase the efficiency of ISCO treatments.

CDs are non-toxic cyclic sugars produced at commercial scales from cornstarch. CD molecules are ring structures composed of 6-8 linked glucose units; the number of glucose units comprising a CD ring is denoted by a Greek letter: α - for 6, β - for 7, and γ - for 8. As shown in Figure i, CD's doughnut-like structure includes a hydrophilic exterior shell and a hydrophobic interior cavity (Bender & Komiyama 1978). This structure allows CD to form inclusion complexes, or clathrates, via a host:guest relationship in which a non-polar “guest” compound is included in the hydrophobic cavity of the “host” CD molecule; this results in a complex that is overall very water soluble (Wang & Brusseau 1993; Brusseau et al. 1994). For most non-polar contaminants, including most VOCs, the hydrophobic interior of the CD molecule is thermodynamically more attractive than dissolution in water (Wang & Brusseau 1993; Brusseau et al. 1994). Therefore, through the formation of contaminant complexes, CD can be used to significantly increase the apparent solubility of non-polar contaminants, including VOCs, and greatly promote their desorption from soil matrix (Wang & Brusseau 1993; Brusseau et al. 1994; Brusseau et al. 1997; Boving et al. 1999; Boving et al. 2003). All three unsubstituted CDs (α , β , and γ) are available commercially, with β -CD being the least expensive variety (Wang & Brusseau 1993; Badr et al. 2004). However β -CD has a significantly lower aqueous solubility than both α -CD and γ -CD (Coleman et al. 1992). As a result β -CD is often chemically modified (substituted) to enhance its solubility. The most widely used derivate in environmental remediation research is hydroxypropyl- β -cyclodextrin (HPCD) (Figure ii). In addition to HPCD other substituted β -CD varieties, such as methyl- β -

cyclodextrin (MCD) and carboxyl-methyl- β -cyclodextrin (CMCD) have also been investigated (Wang & Brusseau 1995; Lindsey et al. 2003; Skold et al. 2009).

Previous studies have shown that CD can be used in combination with other remediation technologies. Laboratory and field experiments by Boving et al. 1999 and Tick et al. 2003 respectively, indicate that air stripping technology can be used to separate VOCs, such as chlorinated solvents, from CD solutions. CD greatly increased contaminant solubility, and recycling of CD solution after air-stripping was found to significantly increase remediation efficiency (Boving et al. 1999; Tick et al. 2003). Other studies have shown that solubility-enhancing agents, including CD, increase the effectiveness of bioremediation by enhancing the bioavailability of organic contaminants (Gruiz et al. 1996; Thibault et al. 1996; Boonchan et al. 1998; Wang et al. 1998; Wang et al. 2005). In addition, work by Lindsey et al. (2003) showed that CMCD could be used to successfully enhance Fenton degradation of hydrophobic pollutants. These studies show that there is great potential for using solubility-enhancing agents to increase remediation efficiency of VOCs. This supports the detailed examination of the integrated CD-OxyZone[®] remediation approach conducted in this study.

Perfluoroalkyl Acids:

PFAAs are fully-fluorinated carbon chain anthropogenic pollutants (US EPA 2009a). The US EPA and global health organizations have identified PFAAs as toxic, persistent, and bioaccumulative (OECD 2002; US EPA 2007; US EPA 2009a; Lindstrom et al. 2011). Within this class of compounds perfluoroalkyl carboxylates (PFCAs) and perfluoroalkyl sulfonates (PFSAs) have gained particular attention due to their potential

toxicity, widespread occurrence in the environment, and detection in wildlife and humans. PFAAs were produced in mass quantities prior to a voluntary phase out by their primary manufacturer 3M in 2002 (Prevedouros et al. 2006; Paul et al. 2009; US EPA 2009a). Historical global production of PFAAs is estimated to be between 69,400-104,000 tonnes (Prevedouros et al. 2006; Paul et al. 2009).

Due to their strong fluorine-carbon bonds, PFAAs are among the most stable organic compounds. They are largely resistant to hydrolysis and photolysis, as well as aerobic and anaerobic biodegradation. Long-chain PFAAs, such as perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS), were valued for their oleophobic and hydrophobic properties (Table iii; Table iv). PFOA and PFOS were commonly used in industrial and commercial processes and incorporated into non-stick, waterproof, and fire-resistant materials, such as lubricants, paints, polish, food packaging, and aqueous fire-fighting foams (Prevedouros et al. 2006; Paul et al. 2009). Both PFOA and PFOS are able to migrate through terrestrial and marine environments intact, while additional PFOS and PFOA may be produced in the environment via the degradation or biotransformation of volatile PFAA-precursors (Tomy et al. 2004; Dreyer et al. 2009; US EPA 2009a). PFOA and PFOS, as well as their salts and precursor compounds, are currently the most studied PFAAs.

The use of aqueous firefighting foams (AFFFs), sometimes referred to as aqueous film forming foams, represents a widespread PFAA point source emission to the environment (Moody & Field 2000; Prevedouros et al. 2006; Paul et al. 2009). From

1965-1975, PFSA and PFCA compounds were incorporated into AFFFs (Prevedouros et al. 2006), (3M 1992; 3M 1995; 3M 1996; Moody & Field 2000; Prevedouros et al. 2006; Place & Field 2012). Perfluorooctanesulfonyl fluoride (POSF) based products replaced PFCAs as AFFF-surfactants beginning in the early 1970s (Prevedouros et al. 2006). AFFF-related PFOS emissions to the environment are estimated to be between 61-130 tonnes PFCA and 91-460 tonnes PFSA (Prevedouros et al. 2006; Waldemer & Tratnyek 2006). Although production of PFAA-containing AFFFs has ended, stockpiles still remain and are in use. This represents a continued source of PFAAs to the environment through intentional and accidental release. The largest AFFF stockpile in the United States is owned by the U.S. Military and accounts for approximately 29% of all domestic AFFF (Place & Field 2012).

PFOA and PFOS as well as other perfluoroalkyl and polyfluoroalkyl substances (PFASs), such as fluorotelomersulfonates (FtS), have been identified in groundwater (Levine et al. 1997; Moody & Field 1999; Moody et al. 2003; Schultz et al. 2004; Cheng et al. 2008; Vecitis et al. 2010; Murakami et al. 2009; Chatwell 2012; Weiss et al. 2012) and surface water (Moody et al. 2002; Murakami et al. 2008; Oakes et al. 2010; de Solla et al. 2012). Studies of PFAA-contaminated sites suggest these compounds can persist in groundwater years after use and may be mobile in the subsurface (Levine et al. 1997; Moody & Field 1999; Moody et al. 2003; Houtz et al. 2013).

FTA represent a widespread point source of PFAAs to groundwater where they co-occur with other priority pollutants, particularly VOCs (Chapelle et al. 1996; Bermejo

et al. 1997; Levine et al. 1997; Moody & Field 1999; Moody et al. 2003; Paterson et al. 2008; Houtz et al. 2013; Mcguire et al. 2014). These FTA usually consisted of unlined pits with few if any containment structures in place. During training exercises, these pits were flooded with waste fuels, oils, hydrocarbons and halogenated solvents, ignited, and then extinguished using AFFFs. These poor management practices allowed the mix of PFAAs, fuels, solvents and other contaminants to enter local soil and groundwater systems largely untreated. The routine use of AFFFs at FTA makes these sites highly susceptible to PFAA contamination. The United States Department of Defense (DoD) alone has identified approximately 600 fire/crash/training sites that potentially have PFAA contamination (SERDP 2012). PFAA contaminated DoD FTA identified in the literature include Wurtsmith Air Force Base, MI, Tyndall Air Force Base, FL, Naval Air Station Fallon, NV, and Ellsworth Air Force Base, SD (Chapelle et al. 1996; Bermejo et al. 1997; Moody & Field 1999; Moody et al. 2003; Levine et al. 1997; Houtz et al. 2013).

Non-DoD sites where PFAAs have been found include FTA at refineries, airports, and municipal facilities. For instance, a recent survey commissioned by the Minnesota Pollution Control Agency on Fire Foam Training and Discharge Sites found PFAA contamination above Minnesota's Health Risk Limit of 300 ng/L for PFOS and/or PFOA in groundwater at 8 out of 19 sites sampled (Delta Consultants 2010). In Cologne, Germany, PFAA contamination of two drinking water wells near an FTA was linked to elevated PFAA concentrations in the blood of persons who consumed water from them (Weiss et al. 2012). The full scope of AFFF-based PFAA groundwater contamination continues to emerge as more and more sites are characterized. Thus, the need for the

cost-effective remediation of PFAA-contaminated water will likely increase in the coming years. Understanding how the presence of PFAAs affects remediation of target primary pollutants, and vice versa, has been identified as an area of critical importance and is an emerging focus of research (Moody & Field 2000; SERDP 2012; Place & Field 2012; Houtz et al. 2013).

Many remediation strategies used for VOCs, such as soil vapor extraction, sparging, and bioremediation, are ineffective on PFAAs due to their chemical properties. Sorption based remediation processes, such as granular activated carbon (GAC) and anionic resin filtration, have shown promise for PFAA removal (Hawley et al. 2012; Ochoa-Herrera & Sierra-Alvarez 2008; Yu et al. 2009). However, these *ex-situ* methods may require many years of operation until PFAA remediation targets (ng/L) will be met. Furthermore, VOC co-contaminants will compete with PFAAs for GAC sorption sites, thus limiting the applicability of these technologies in the field (Hawley et al. 2012).

ISCO is a proven technology for the remediation of hydrocarbons and chlorinated solvents. New research shows that ISCO is potentially a remediation option for PFAAs (Vecitis et al. 2010). However, not all oxidants are well suited for the degradation of PFAAs. For instance, oxidative destruction of contaminants via hydroxyl radical based AOP typically involve hydrogenation and/or hydrogen abstraction reactions (Lutze et al. 2012). The preferred reactive sites for hydrogenation reactions are C=C bonds, which PFAAs lack. Furthermore, C-F bonds are thermodynamically unfavorable for hydrogen abstraction (Lutze et al. 2012). Thus, ozone, hydrogen

peroxide, peroxone, and Fenton based systems, are poorly suited for PFAA remediation.

The use of UV irradiation has been shown to improve PFOA degradation in Fenton systems (Tang et al. 2012). Also, a laboratory study by Liu et al. (2012) found PFAA oxidation by permanganate was possible despite its relatively low oxidation potential (Table i). It is believed that permanganate can oxidize contaminants through several different pathways, including hydrogenation, hydrogen abstraction, and electron transfer (Waldemer and Tratnyek, 2006).

Sulfate radical based AOP (i.e. activated persulfate) have been shown to degrade long and short chain PFAAs via electron transfer (Kutsuna & Hori 2007). Efficient PFAA degradation has been achieved using microwave, thermal, iron, electrochemical, photochemical, and hydrogen peroxide activated persulfate technologies (Hori et al. 2005; Hori et al. 2008; Kingshott 2008; Y. Lee et al. 2012; Y.-C. Lee et al. 2012; Liu, Higgins, et al. 2012). These findings suggest that ISCO, particularly activated persulfate, has the potential to be used as an effective treatment for subsurface PFAA contamination. However, further testing at the pilot-scale is necessary to assess its performance (Hawley et al. 2012). Of particular concern are effects on co-contaminant transport and biodegradation processes, oxidative transformation of PFAA-precursors into PFAAs, as well as the oxidation of PFAAs into “dead-end products” that cannot be further treated (Moody & Field 2000; Place & Field 2012; SERDP 2012; Houtz et al. 2013). This supports the detailed examination of PFAA fate and distribution during the targeted ISCO of VOCs conducted in this study.

1,4-Dioxane

1,4-dioxane is an emerging groundwater contaminant and a likely human carcinogen (IARC 1999; Stickney et al. 2003; Mohr et al. 2010; US EPA 2010b; US EPA 2013c). While, 1,4-dioxane is regulated as a hazardous waste, there is currently no federal drinking water standards for this compound (U S EPA 2012). Due to this lack of regulation, 1,4-dioxane was not routinely analyzed until recently. For instance, prior to 1997, reliable low-level (<100 µg/L) 1,4-dioxane analysis was not available (Draper et al. 2000; Mohr et al. 2010). The lack of analyses and the limitations of the analyses that were performed (i.e. high reporting limits) means that the scale of 1,4-dioxane contamination of the subsurface is still emerging.

1,4-dioxane was primarily used as a stabilizer in chlorinated solvents. In 1985, nearly 90% of the 1,4-dioxane produced annually was used as a chlorinated solvent stabilizer, the majority of which was used to stabilize 1,1,1-trichloroethane (TCA) (US EPA 1995). 1,4-dioxane was added to TCA at concentrations between 2% to 5% by volume, in order to prevent solvent degradation caused by reactions with metal surfaces (Mohr 2001; Mohr et al. 2010). As a results, 1,4-dioxane is often found as a co-contaminant at solvent releases sites such as landfills, solvent recycling operations, vapor decreasing operations, and FTA (Mohr et al. 2010). A recent survey of groundwater data from 49 U.S. Air Force installations found 93.7% of all 1,4-dioxane detections were observed in wells with records of TCA and/or trichloroethene (TCE) contamination (Anderson et al. 2012).

Although 1,4-dioxane is commonly found at VOC sites, its properties differ significantly from its co-contaminants. 1,4-dioxane is a cyclic organic compound with two oxygen linkages (Table v). These ether functional groups make 1,4-dioxane completely miscible in water. Although volatile in its pure form, volatilization from water to air is negligible. This is reflected by 1,4-dioxane's low water-air partition coefficient (Henry's law constant) (DiGuseppi & Whitesides 2007; Mohr et al. 2010). Furthermore, 1,4-dioxane's hydrophilicity and low affinity for soil organic matter, reflected by its low octanol/water (K_{ow}) and soil organic carbon/water (K_{oc}) partitioning coefficients, results in only weak retardation by sorption processes (Table v); (DiGuseppi & Whitesides 2007; Mohr et al. 2010). This means that unlike its common chlorinated VOC co-contaminants, 1,4-dioxane is often found dissolved at the leading edge of contaminant plumes. Consequently, at many solvent release sites, 1,4-dioxane contamination is more widespread than the corresponding parent VOC plume.

Due to its low K_{ow} and K_{oc} , air stripping and adsorption are generally considered poor treatment options for 1,4-dioxane contaminated groundwater (Zenker et al. 2003; Otto & Nagaraja 2007; Mohr et al. 2010). Furthermore, 1,4-dioxane's recalcitrance and mobility limits monitored natural attenuation (MNA) treatment (ATSDR 2012). Enhanced bioremediation of 1,4-dioxane has been demonstrated in laboratory and field studies. However, the application of these technologies is limited by the fact that 1,4-dioxane metabolizing bacteria are predominantly aerobic, making it a poor fit for the anaerobic conditions found at many VOC contaminated sites (Zenker et al. 2003; Otto & Nagaraja 2007; Mohr et al. 2010; ATSDR 2012). Phytoremediation (primarily using

hybrid poplars) has been demonstrated as an effective treatment for shallow contamination, but its application may be limited by climactic and hydrogeological (i.e., depth to groundwater) conditions (Zenker et al. 2003; Mohr et al. 2010).

Chemical oxidation is a technology that shows promise for the remediation of 1,4-dioxane contaminated sites. While *ex situ* chemical oxidation processes, such as photocatalytic oxidation, take advantage of 1,4-dioxane's infinite solubility, the production of large volumes of waste water can be logistically and monetarily impractical for many sites (Mohr et al. 2010). As a result, ISCO technologies, already popular for remediation of VOC contaminated sites, are being explored for their applicability to 1,4-dioxane remediation (US EPA 1999; Huling & Pivetz 2006; Mohr et al. 2010).

Chemical species with a standard oxidation potential less than 2 V are generally considered to be ineffective for treatment of 1,4-dioxane. While oxidation via permanganate is possible, the reactions rates are very slow (half-life ($t_{1/2}$) = days) (Waldemer & Tratnyek 2006). As a result, AOP systems, particularly those capable of producing hydroxyl and/or sulfate radicals, are considered to be the most promising for ISCO treatment of 1,4-dioxane. Hydroxyl-radical based AOP capable of degrading 1,4-dioxane include peroxone, Fenton's, and combinations of H_2O_2 , O_3 , and UV light (Maurino et al. 1997; Coleman et al. 2007; Kwon et al. 2012; Zenker et al. 2003; DiGuseppi & Whitesides 2007; Mohr et al. 2010). 1,4-dioxane oxidation via sulfate radical based AOP has been demonstrated using thermal, alkaline, UV, and H_2O_2

activation techniques (Clifton & Huie 1989; Huie et al. 1991; Maurino et al. 1997; Block et al. 2004; FMC 2007; Cronk 2008; Tsitonaki et al. 2010; Mohr et al. 2010). The sulfate radical is more stable ($t_{1/2}$ = hours to weeks) than the hydroxyl radical ($t_{1/2}$ = minutes to hours). This allows the sulfate radical to travel further when injected in the subsurface (Huling & Pivetz 2006). Because 1,4-dioxane plumes often consist of low level contamination dispersed over a large area (Mohr et al. 2010), the potentially large radius influenced by activated persulfate injections make this radical species particularly attractive for the remediation of 1,4-dioxane relative to other ISCO strategies (Huling & Pivetz 2006).

With the number of known 1,4-dioxane sites increasing, the need for cost-effective remediation technologies capable of treating 1,4-dioxane as well as its common VOC co-contaminants is increasing as well. This supports the laboratory-scale experiments examining the applicability of peroxone activated persulfate for the *in situ* degradation of 1,4-dioxane conducted in this study.

Figure I: Structure of Cyclodextrin (from Jindrich 2003).

Figure II: Structure of HPCD (from Wang & Brusseau 1993).

Oxidant	Standard oxidation potential (volts)
Hydroxyl radical ($\cdot\text{OH}$)	2.8
Sulfate radical ($\cdot\text{SO}_4^-$)	2.5
Ozone (O_3)	2.1
Persulfate (S_2O_8^-)	2.0
Hydrogen peroxide (H_2O_2)	1.8
Perhydroxyl Radical ($\cdot\text{HO}_2$)	1.7
Permanganate (MnO_4^-)	1.7
Chlorine ($\text{Cl}^\cdot$)	1.4
Oxygen (O_2)	1.2
Hydroperoxide anion (HO_2^-)	-0.9
Superoxide radical ($\cdot\text{O}_2^-$)	-2.4

Table I: Oxidation potential of common ISCO oxidants (Huling & Pivetz 2006; SERDP 2011).

<i>Primary Oxidation via Ozone:</i>
$O_3 + 2H^+ + 2e^- \rightarrow O_2 + H_2O$
<i>Hydroxyl Radical Formation:</i>
$O_3 + H_2O \rightarrow O_2 + 2\cdot OH$
$2O_3 + 3H_2O_2 \rightarrow 4O_2 + 2\cdot OH + 2H_2O$
<i>Oxidation by Hydroxyl Radical:</i>
$2\cdot OH + 2H^+ + 2e^- \rightarrow 2H_2O$
<i>Primary Oxidation via Persulfate:</i>
$S_2O_8^{2-} + 2H^+ + 2e^- \rightarrow 2HSO_4^{-1}$
<i>Hydroxyl and Sulfate Radical Formation:</i>
$S_2O_8^{2-} + H_2O_2 \rightarrow 2\cdot SO_4^- + 2\cdot OH$
<i>Oxidation by Hydroxyl Radical:</i>
$2\cdot OH + 2H^+ + 2e^- \rightarrow 2H_2O$
<i>Oxidation by Sulfate Radical:</i>
$\cdot SO_4^- + e^- \rightarrow SO_4^{2-}$

Table II: OxyZone® reaction pathways (Block et al. 2004; Huling & Pivetz 2006; Ball 2010; Ball 2011)

Perfluorooctanoic Acid (PFOA)
Molecular Formula	C ₈ HF ₁₅ O ₂
	Molar Mass (g/mol)	414
	Water Solubility (g/L @ 20°C)	3.4
	Boiling Point (°C @ 760 mm Hg)	189-192
	Melting Point (°C @ 760 mm Hg)	45-56
	Vapor Pressure (mm Hg @ 20°C)	0.017
	Henry's Constant (atm·m ³ /mol)	Not Measurable
	Log K _{ow}	Not Measurable
	Log K _{oc}	2.06

Table III: Physicochemical properties of PFOA (US EPA 2013a)

Perfluorooctane Sulfonic Acid (PFOS)		
<p>(a)</p> <p>(b)</p>	Molecular Formula	C ₈ KF ₁₇ O ₃ S
	Molar Mass (g/mol)	538
	Water Solubility (g/L @ 20°C)	0.519
	Boiling Point (°C @ 760 mm Hg)	Not Measurable
	Melting Point (°C @ 760 mm Hg)	>400
	Vapor Pressure (mm Hg @ 20°C)	2.48x10 ⁻⁶
	Henry's Constant (atm·m ³ /mol)	3.05 × 10 ⁻⁹
	Log K _{ow}	Not Measurable
	Log K _{oc}	2.57
(a) = PFOS (as potassium salt); (b) = PFOS		

Table IV: Physicochemical properties of PFOS, as potassium salt, (US EPA 2013b).

	Molecular Mass (g/mol)	88.12
	Water Solubility (@ 25°C)	Miscible
	Boiling Point (°C @ 760 mm Hg)	101.32
	Melting Point (°C @ 760 mm Hg)	11.8
	Vapor Pressure (mm Hg @ 25°C)	38.09
	Henry's Constant (atm·m ³ /mol)	4.80x10 ⁶
	Log K _{ow}	0.43
	Log K _{oc}	0.54
	Specific Gravity (@20°C)	1.03

Table V: Physicochemical properties of 1,4-dioxane (DiGuseppi & Whitesides 2007; Mohr et al. 2010).

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Solubility-Enhanced ISCO of VOC Contaminated Soil and Groundwater: A Pilot-Scale

Field Test

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Abstract

Contaminant availability is often a major limiting factor for *in situ* chemical oxidation (ISCO) remediation of volatile organic compounds (VOCs). This study investigates the use of a solubility-enhancing agent to overcome this limitation and increase the efficiency of ISCO in the field. In this pilot-scale field test a novel, patented solubility-enhanced ISCO strategy (OxyZone-C®), combining a peroxone activated persulfate process (OxyZone®) and the solubility-enhancing agent hydroxypropyl-beta-cyclodextrin (HPCD), was used. Testing was conducted at a former fire training area (FTA). The major contaminants of concern were chlorinated solvents. Soil and groundwater concentrations indicative of residual phase non-aqueous phase liquid (NAPL) were observed. Field testing began in April 2013 and consisted of three major injection events and finished in August 2013. Post-treatment sampling continued through February 2014. During the demonstration an approximately two-fold increase in target VOC (tVOC) concentrations occurred in the deep zone of the aquifer and was significantly linked to the solubility-enhancing properties of the HPCD ($r_s = 0.48$, $p < 1E-7$). This increase was temporary with tVOC concentrations returning to pre-demonstration levels by the end of the pilot test. This decrease was predominately due to oxidative destruction of the solubilized VOCs and not dilution or migration off site. While this technology demonstration was not designed for full site remediation, post-treatment membrane interface probe, soil, and groundwater data show significant improvements at down gradient wells and the periphery of the NAPL source zone. To

the authors' knowledge this is the first field test of HPCD-enhanced ISCO. The results show that this type of integrated ISCO remediation is possible in the field.

Keywords: *In situ* Chemical Oxidation (ISCO), Persulfate, Remediation, Cyclodextrin, non-aqueous phase liquid, Volatile Organic Compounds (VOCs).

Introduction

Remediation of subsurface contamination is a challenging environmental problem. Of particular concern are halogenated volatile organic compounds (VOCs), such as chloroethenes, chloroethanes and chlorobenzenes. VOC contamination of soil and groundwater usually results from spills, leaking storage tanks, and improper disposal of wastes and is often associated with industrial and military facilities. Due to their comparatively low water solubility, VOC remediation by conventional technologies, such as groundwater extraction, is most often costly and inefficient. As a result, the development of innovative methods for remediating VOC contamination in the subsurface has become a major environmental priority.

In situ chemical oxidation (ISCO) is an accepted treatment technology for groundwater and soils contaminated with hydrophobic VOCs (US EPA 1999; Huling & Pivetz 2006; SERDP 2011). ISCO reactions occur predominantly in the aqueous phase and as a result ISCO is more effective at treating dissolved phase contaminants than sorbed compounds or non-aqueous phase liquids (NAPLs). Contaminants with higher aqueous solubilities are more accessible for oxidation relative to less soluble compounds (Ogram et al. 1985; Sedlak & Andren 1994; Quan et al. 2003; Rivas 2006; Ferrarese et al.

2008; SERDP 2011). ISCO reactions may therefore, be limited by the solubility of the target compounds and mass transfer into the aqueous phase. In addition to contaminant solubility, ISCO may also be limited by contaminant sorption to reactive solid phase sites, including organic matter. Strong sorption typically lowers the aqueous phase concentration of these compounds making them less accessible to oxidative destruction processes (Rivas 2006; Sun & Yan 2008; Ferrarese et al. 2008; SERDP 2011). Another important factor that limits the oxidation of VOCs is the oxidant demand of non-target compounds, such as organic matter and reduced metals (Masten et al. 1997; Choi et al. 2002; Pierpoint et al. 2003; O'Mahony et al. 2006; Rivas 2006). These materials readily react with oxidants, resulting in competing reactions, which can dramatically decrease contaminant removal efficiency and increase treatment costs. Consequently, there is considerable interest in finding economical ways to overcome these limitations and increase the efficiency of ISCO treatments. It has been suggested that an integrated desorption-oxidation process, in which contaminants are first made more readily available for chemical oxidation via a solubility-enhancing agent, could be used to increase the efficiency of ISCO at the field-scale (Rivas 2006; Tsitonaki et al. 2010). While laboratory-scale solubility-enhanced ISCO studies have been performed, to date only a few field-based studies coupling solubility-enhancing remediation technologies, such as surfactants and cosolvents, with ISCO exist in the literature (Dugan et al. 2010).

The objective of this field study was to demonstrate the performance of a patented VOC *in situ* treatment approach, OxyZone-C[®], which relies on combining the

solubility-enhancing capabilities of cyclodextrin with ISCO. For this, a peroxone activated persulfate (OxyZone®) advanced oxidation process (AOP) was used in combination with hydroxylpropyl- β -cyclodextrin (HPCD) to treat soil and groundwater contamination. This field study was carried out under pilot-scale test conditions at a former fire training area (FTA). This technology demonstration was a proof of concept and complete remediation of the site was not an objective. We consider the results to be of interest to contaminated-site managers who seek alternative treatment approaches.

Background

Cyclodextrins (CDs) are non-toxic cyclic sugars produced at commercial scales from cornstarch. CD molecules are ring structures composed of 6-8 linked glucose units with a hydrophilic exterior shell and a hydrophobic interior cavity (Bender & Komiyama 1978). This structure allows CD to form inclusion complexes, clathrates, via a host:guest relationship in which a non-polar “guest” compound is included in the hydrophobic cavity of the “host” CD molecule; this results in a complex that is overall very water soluble (Wang & Brusseau 1993; Brusseau et al. 1994). For most non-polar contaminants, the hydrophobic interior of the CD molecule is thermodynamically more attractive than dissolution in water. Thus, through the formation of contaminant complexes, CD can be used to significantly increase the apparent solubility of non-polar contaminants, including VOCs, and greatly promote their desorption from soil matrix (Wang & Brusseau 1993; Brusseau et al. 1994; Brusseau et al. 1997; Boving et al. 1999; Boving et al. 2003).

Surfactant-enhanced solubilization is based on the formation of micelles, and concentrations must be kept above the critical micelle concentration (CMC) in order to be effective (Harwell et al. 1999). In contrast, CD-enhanced solubilization is usually one-to-one, resulting in a much higher molar-efficiency than surfactants (Boving & Brusseau 2000). Furthermore, unlike many surfactants, CDs are both non-toxic and biodegradable (Gould & Scott 2005; Fenyvesi et al. 2005). One of the most used derivatives in environmental remediation research is HPCD (Figure 1.1). Other substituted β -CD varieties, such as methyl- β -cyclodextrin (MCD) and carboxyl-methyl- β -cyclodextrin (CMCD) have also been investigated (Wang & Brusseau 1995; Lindsey et al. 2003; Skold et al. 2009).

Previous laboratory work has investigated the combination of CD with AOPs (Landy et al. 2012). The combination of CD and Fenton based AOP was first examined by Lindsey et al. (2003), who showed that CMCD could be used to create ternary pollutant-CD-iron complexes to overcome problems treating low solubility polychlorinated biphenyls (PCBs). Building upon these findings, the addition of CMCD and HPCD has been shown to improve the oxidation of trinitrotoluene and benzo[a]pyrene in Fenton based systems (Yardin & Chiron 2006; Matta et al. 2008; Veignie et al. 2009). Recently, the combination of CD and activated persulfate based AOP has been investigated. Work by Liang and Huang (2007) showed that HPCD could be used in combination with iron activated persulfate to degrade chlorinated VOCs. As expected, HPCD increased the aqueous contaminant mass available for oxidation without major degradation of the solubilization agent by the oxidant. The contaminant degradation was most successful

when sulfate radical production was slow and continuous. Follow-up column studies by Liang and Lee (2008) showed that longer contact times between oxidant and contaminant may be necessary to efficiently degrade the increased aqueous mass of contaminant when combining HPCD with iron activated persulfate. Similar findings were observed by Eberle (2012), when treating saturated aqueous mixtures of polycyclic aromatic hydrocarbons (PAHs) with peroxone activated persulfate (OxyZone®).

The oxidant used during this study is a patented peroxone activated persulfate AOP, developed by EnChem Engineering, Inc. (Newton, MA) and marketed under the trade name OxyZone® (Ball 2010; Ball 2011). OxyZone® utilizes a proprietary blend of dissolved ozone, sodium persulfate, food grade phosphate-based buffers and dilute hydrogen peroxide. In this blend, hydrogen peroxide and dissolved ozone facilitate the production of hydroxyl ($\text{OH}^\bullet$) and sulfate ($\text{SO}_4^{\bullet-}$) radicals, two of the strongest oxidants available. OxyZone® has been shown to efficiently degrade a wide range of organic contaminants including polycyclic aromatic hydrocarbons, chlorinated solvents, and 1,4-dioxane (Eberle 2012; Eberle et al. 2016)

Site History

Training Area 15 (TA-15) is a former FTA at Joint Base Langley-Eustis (JBLE), adjacent to Newport News, Virginia. Constructed in 1968, the facility consisted of a smokehouse, above ground burn tanks, a zig-zag pattern burn pit, underground fuel and water piping, and an oil and water separator (Watson 1997; ECC & Malcolm Pirnie Inc. 2008). During fire training exercises, the pits were flooded with a mix of waste fuels, oils, hydrocarbons, and halogenated solvents, then ignited, and extinguished. Monthly

fire training activities were conducted at the site from 1968 to 1980. The facility was abandoned in 1980; all subsurface structures were removed and the site was covered with fill material. Irregular fire training activities at the site continued until approximately 1990, using an above ground bermed burn pit located approximately 15 m from the former zig-zag pit (Figure 1.2).

Methods

Field Methods

A conceptual site model was developed based on data from prior site investigations (ECC & Malcolm Pirnie Inc. 2008) in combination with new field investigation activities. Beginning in February 2012 a baseline pre-treatment subsurface investigation was performed to characterize site soil and groundwater and to develop an understanding of current contaminant architecture and hydrogeological site conditions prior to AOP treatment. The baseline pre-treatment subsurface investigation included the installation of 36 wells, the collection of 40 soil borings and the completion of 23 temporary membrane-interface probe (MIP) borings (Figure 1.3).

Deep and shallow screened injectors were utilized to distribute oxidant throughout the aquifer. For deep injection, wells I-1, I-4, I-8, and I-10, were installed with 1.5 m screens between 3.4 and 6.1 m below ground surface (bgs). For shallow injection, wells I-5, I-6, I-7, and I-9 were installed with 1.5 m screens between 1.5 and 3.7 m bgs. Wells U-16, U-17, U-18, U-19, and U-20 were dual screened wells equipped with multi-port samplers allowing for collection of groundwater samples from two aquifer depths. These wells were used to monitor conditions between 1.5 m to 3 m bgs

and 3.7 m to 5.2 m bgs. When discussing samples from dual screened wells, “D” will be added when referring to a sample from the deep screened portion of the well and “S” will be added when referring to a sample from the shallow screened portion, e.g. U-16D or U-16S.

Groundwater and soil samples were collected following Department of Defense guidelines (DoD EDQW 2013). A YSI multimeter (YSI Inc., Yellow Springs, Ohio, USA) equipped with a flow-through cell was used to continuously measure pH, temperature, oxidation-reduction potential (ORP), dissolved oxygen (DO), and specific conductance (SpC) during well purging under low-flow conditions. Parameter values were recorded once they stabilized. Persulfate concentrations were measured using a CHEMetrics (Midland, VA, USA) persulfate kit, which uses a visual ferric thiocyanate method. Soil samples were collected from split-spoon soil borings in accordance with ASTM D1586-99 (ASTM 2008). Soil borings were screened for VOC with a handheld headspace photoionization detector before the collection of subsamples. All soil and groundwater samples were stored on ice (4 °C) and immediately shipped to the University of Rhode Island (URI, Kingston, RI) or TestAmerica, Inc. (TA) laboratories for analysis. In addition to VOCs, TA analyzed a subset of soil and groundwater samples for semi-volatile organic compounds (SVOCs), metals and anions.

MIP is a semi-quantitative screening tool for detection of VOCs. Pre and post-remediation MIP surveys were conducted by Columbia Technologies, LLC (Baltimore, Maryland) using a Geoprobe® direct push technology (DPT) rig. The probe was outfitted

with a photoionization detector (PID) a flame ionization detector (FID), and an electron capture detector (ECD). In general, the PID is used to detect aromatic hydrocarbons, such as benzene; the FID is used to detect straight-chained hydrocarbons, such as methane and butane, and the ECD is used to detect chlorinated VOCs , such as trichloroethene (TCE).

The pre-remediation MIP survey was performed March 21-23, 2012 and consisted of 23 locations examined continuously to depths ranging from approximately 6 m to 8.5 m bgs. The post-remediation survey was performed December 9-11, 2013 and consisted of 24 locations. The post-remediation boring locations were selected to match the 23 borings advanced during the March 2012 pre-remediation survey with an additional boring (EMP24).

Subsurface microbial activity was monitored using BioTrap[®] samplers. This was done to determine the total viable microbial biomass and tentatively identify changes in microbial populations before, during, and after ISCO and HPCD treatment. Samplers were deployed four different times throughout the study, at wells MW-3, MW-2904, I-1, and I-4. Sample incubation periods ranged from 50 to 72 days. Afterwards, samplers were shipped to Microbial Insights, Inc. (Knoxville, TN) for phospholipid fatty acid (PLFA) analysis.

Analytical Methods

The majority of VOC soil and groundwater samples were analyzed by URI with split samples sent to TA for quality assurance. At URI, VOCs were analyzed following

modified U.S. EPA methods 8260C, 5035A, and 5030C (US EPA 2006; US EPA 2003; US EPA 2002). An OI analytics Eclipse 4660 purge and trap was used for sample concentration and injection. Samples were analyzed on a Shimadzu GCMS-QP5000 gas chromatography–mass spectrometer (GCMS). 49 VOC contaminants were analyzed by GCMS in SCAN mode and internal standards were used to track purge efficiency.

The analysis of soil and/or groundwater samples for SVOCs and anions was performed by TA. Note that the properties of the three dichlorobenzene (DCB) isomers were analyzed by both VOC and SVOC techniques. Typically, higher DCB concentrations were reported by the VOC method than the SVOC method although relative differences between samples were consistent. In the following discussions, only the VOC method results for DCB are reported. Groundwater samples were analyzed for total metals (unfiltered) by TA as well as URI during site characterization. During the primary demonstration groundwater samples were analyzed for dissolved metals (filtered at 0.45 μm and acidified) by TA. Microbial data was analyzed by Microbial Insights laboratories (Knoxville, TN, USA).

Analysis of HPCD concentrations was conducted using a HPCD/2-(p-toluidinyl)-naphthalene-6-sulfonate (TNS) complexation method (Kondo et al. 1976). HPCD/TNS complexes were measured via fluorescence spectrophotometer (excitation: 387 nm, emission: 478 nm). The practical quantification limit (PQL) for field samples was 100 mg/L HPCD.

Undiluted OxyZone® has a SpC of approximately 40 mS/cm and as a result, SpC, along with ORP and DO, was used to track oxidant distribution. This measure does not, however, distinguish between sodium persulfate and breakdown products, such as sodium or sulfate. Therefore, direct conversion of SpC readings to sodium persulfate concentrations is not possible.

Groundwater concentration isocontour maps were created in Surfer 11 (Golden Software, Golden, Colorado, USA) using inverse distance weighting (IDW). Statistical analyses were conducted following Interstate Technology and Regulatory Council (ITRC) recommendations and guidelines (ITRC 2013).

Site Characterization

Site geology consists of an approximately 6 m surficial aquifer underlain by a stiff blue clay confining unit. This surficial aquifer consists of a shallow zone ~0.6 m - 3 m bgs made up of low permeability silty sand and organic silt ($K = 0.5$ m/d), and a deep zone ~3.0 m - 6 m bgs, consisting of high permeability poorly sorted sand ($K = 4.9$ m/d) (Figure 1.4). The water table was 0.3 m - 0.6 m bgs, but shallower levels have been observed during heavy rain events. The site is tidally influenced by the James River to the west and wetlands to the north/northeast. Typical tidal variation in the water table is approximately 8 cm. The predominant direction of groundwater flow is to the northwest towards the James River, although the hydraulic gradient is very shallow, approximately 2×10^{-3} . Site groundwater is brackish, with average chloride concentrations of 1,100 mg/L and 300 mg/L, and SpC of 5.2 mS/cm and 0.65 mS/cm, observed in deep

screened and shallow screened wells respectively. Site groundwater is slightly acidic, with median pH of 5.0 and 6.3 observed in the deep and shallow zones, respectively.

The pre-treatment MIP survey was conducted in the northeastern corner of the FTA where a hotspot had previously been identified, near historic monitoring well MW-2904 (ECC & Malcolm Pirnie Inc. 2008). The largest responses were for the ECD detector, which was in good agreement with previous investigations showing chlorinated VOCs as the predominant site contaminants. The greatest contamination was identified at EMP06, the closest MIP point to MW-2904, where contamination exceeded the ECD maximum detection limit, $\geq 12.8 \times 10^6$ microvolts (μV) from 1 m to 8 m depth (Figure 1.5).

Following the initial MIP screening soil and groundwater samples were collected and analyzed to further characterize contamination at the site. The highest VOC contamination was found in the approximate location of the zig-zag pit (Figure 1.2). This source zone was subdivided into three 6.1 m x 9.1 m Test Cells (1-3) with the highest levels of VOC contamination found centrally within Test Cell 1. The highest groundwater contamination was observed in shallow screened well I-5 where 1,1,1-trichloroethane (1,1,1-TCA), tetrachloroethene (PCE), and dichlorobenzenes (all isomers, DCBs) concentrations of 110 mg/L, 23 mg/L, and 31 mg/L were observed, accounting for over 85% of the total detected aqueous VOC mass. In the deep zone the highest contamination was observed at MW-2904 where 1,1,1-TCA, PCE and DCBs concentrations of 6.3 mg/L, 15 mg/L, and 18 mg/L were observed, and accounted for

greater than 94% of all detected VOCs. These very high aqueous VOC concentrations, often in exceedance of 1% of their effective solubility, are indicative of the presence of NAPL (US EPA 1992). Similarly, soil VOC concentrations confirmed the presence of NAPL with pre-demonstration soil VOC concentrations greater than 1 g/kg observed in samples from I-5, I-6, U-16, SB-2, and SB-3, at depths ranging from 1.5 m bgs to 5.5 m bgs. In these highly contaminated soil samples, 1,1,1-TCA, PCE, and DCBs were the major fraction of VOCs detected, making up 93% to 98% of the total detected VOC mass. These soil concentrations are in good agreement with the observed groundwater VOC data.

Besides 1,1,1-TCA, PCE, and DCBs, other chlorinated solvents, such as dichloroethenes and dichloroethanes, as well as petroleum derivatives, such as benzene, toluene, ethylbenzene, and xylenes (BTEX), were detected in site groundwater and soil. Based off of these findings, 20 VOCs were recognized as the primary contaminants of concern at the site (Table 1.1). Although samples analyzed by URI and TA were screened for a total of 73 and 49 VOC compounds respectively, it was determined that these 20 VOC contaminants would be used to primarily assess the performance of the technology during the pilot test and are henceforth referred to as, “target VOCs” (tVOC).

Because of the site’s history as a FTA, and the likely use of perfluoroalkyl acids (PFAAs) containing aqueous firefighting foams (AFFFs), a small number of soil and groundwater samples were analyzed for PFAAs by TA and the Colorado School of Mines.

The results of this preliminary screening confirmed the presence of PFAA contamination in both site groundwater and soil. PFAA concentrations were particularly elevated in Test Cell 1 where perfluorooctanesulfonic acid (PFOS) groundwater concentrations as high as 300 µg/L were measured. Based on these preliminary findings the decision was made to monitor the distribution of PFAAs during the demonstration. The results of this PFAA investigation are presented in Eberle et al. (2015).

Target VOC
1,1,1-Trichloroethane
1,1,2-Trichloroethane
1,1-Dichloroethane
1,1-Dichloroethene
1,2,4-Trichlorobenzene
1,2-Dichlorobenzene
1,2-Dichloroethane
1,3-Dichlorobenzene
1,4-Dichlorobenzene
Benzene
Chlorobenzene
cis-1,2-Dichloroethene
Ethylbenzene
m-Xylene & p-Xylene
o-Xylene
Tetrachloroethene
Toluene
trans-1,2-Dichloroethene
Trichloroethene
Vinyl chloride

Table 1.1: Target VOCs (tVOC).

Testing of Injection Schemes:

One of the concerns when injecting reactive agents into the subsurface was ensuring proper contact time between the oxidant, the contaminant, and the solubility-enhancing agent. To address this, preliminary testing in Test Cells 2 and 3 was performed to evaluate two different oxidant and HPCD delivery methods. In both Test Cells 2 and 3, the total volume of OxyZone® and HPCD administered was the same (Table 1.S1). In Test Cell 2 a “sequential” injection technique was utilized. In this scheme two large pulses of OxyZone® (3030 L) were injected before and after a single large pulse of 3% HPCD (1510 L). In Test Cell 3 a “pulsed” injection technique was utilized. In this scheme, alternating smaller injections of OxyZone® (760 L each) and 3% HPCD (190 L to 380 L) were used. This preliminary testing was performed December 11-14, 2012. The performance of these two injection methods was evaluated using only aqueous data because soil samples were not available.

Results and Discussion:

Testing of Injection Scheme:

The sequential injection scheme used in Test Cell 2 resulted in solubility enhancement followed by destruction of most VOCs (Figure 1.S1). In groundwater, tVOC decreased by approximately 60% to 75% at U-13, U-14, and U-15 following the first OxyZone® injection. After the subsequent HPCD injection, tVOC concentrations increased by approximately 106% to 173% above initial baseline levels at wells U-13, U-15, and U-16D. Following the second, and final, OxyZone® injection, tVOC concentrations then dropped by 46% to 87% relative to the HPCD-enhanced levels.

Intermediary breakdown products, such as ketones and halo-methanes, were observed in monitoring wells within Test Cell 2 (Fowler et al. 2011).

The pulsed injection scheme used in Test Cell 3 did not result in distinct solubility enhancement and reductions in tVOC were not observed. At the end of the test tVOC groundwater concentrations increased at three of the four wells nearest to the injection well (I-3). Overall the results suggest that pulsing slugs of HPCD and oxidant was counterproductive for lowering groundwater VOC concentrations and proved to be more labor intensive without producing a clear benefit.

Based on this preliminary testing, a sequential injection scheme was adopted for use during the primary technological demonstration in Test Cell 1 (Table 1.2). During the primary demonstration in Test Cell 1, surfacing of injected liquids occurred. Surfacing was most prevalent with using shallow zone wells I-5, I-6, and I-9 making I-7 the only reliable shallow injector well. This limited injection into the shallow zone and resulted in the deep zone receiving approximately twice the volume of oxidant, 33,360 L versus 17,380 L, over the course of the study. In subsequent tests, smaller volumes of more concentrated oxidant were used to allow for the injection of greater mass into the shallow zone without surfacing. Treatments in July and August consisted of only OxyZone® injections, using a more concentrated (100 g/L sodium persulfate) formulation to minimize the potential migration of oxidant and HPCD outside of Test Cell 1.

ISCO Treatment Results:

The primary ISCO demonstration was conducted during the spring and summer 2013 in Test Cell 1. A total of approximately 50,740 L OxyZone® and 3,020 L HPCD solution were injected in three separate injection events (Table 1.2). Before and after the injection of HPCD solution, tap water (2,550 L & 1,660 L) was injected to provide a temporary buffer between the solubility-enhancing agent and the oxidant. This enveloped HPCD injection scheme was designed to minimize possible oxidant wastage. Isocontour maps of SpC readings and HPCD concentrations are presented in Figures 1.6 and 1.7 to show the distribution of oxidant and solubility-enhancing agent during the demonstration. Table 1.3 summarizes the most important observations and resulting interpretations.

During the demonstration elevated ORP and SpC readings, above 400 mV and 10 mS/cm respectively, indicative of oxidative conditions, were commonly observed within Test Cell 1. Following injection, OxyZone-C® appears to have remained predominantly within the immediate vicinity of Test Cell 1. Monitoring wells EC-1, EC-2, and EC-3 remained at or below 6 mS/cm SpC and 0.1 mg/L HPCD throughout the test, showing minimal down gradient migration of OxyZone-C®. Advective transport of OxyZone-C® solutions away from the treatment zone appears to have been slow, due in part to the shallow gradient and tidal action present at the site. At the end of the demonstration, elevated ORP readings, between 400 mV and 700 mV, were still detected at 28 out of 37 deep screened wells sampled, showing that highly oxidative conditions remained in the deep zone nearly 6 months after the final oxidant injection. Furthermore, low levels of HPCD were still detected in wells I-1, I-2, I-5, I-8, and I-10 more than 8 months after

injection. This was advantageous as the persistence of OxyZone-C® reagents combined with the shallow hydraulic gradient led to prolonged contact time between injected solutions and the target treatment area without the implementation of hydraulic controls.

Injection Event	Date	Solution	DEEP				SHALLOW			
			I-1	I-4	I-8	I-10	I-5	I-6	I-7	I-9
1st	4/25/2013	OxyZone	110	2080	-	-	450	-	-	-
	4/26/2013	OxyZone	50	1090	-	-	-	380	-	-
	4/27/2013	OxyZone	-	1440	-	-	-	80	-	-
	5/2/2013	OxyZone	-	-	300	230	-	-	180	50
	5/3/2013	OxyZone	-	-	-	640	-	-	1250	-
	5/4/2013	OxyZone	-	-	1890	480	-	20	760	640
	5/5/2013	OxyZone	-	780	-	1310	40	-	910	-
	5/13/2013	Water	-	-	-	-	280	-	280	10
	5/14/2013	Water	380	470	380	380	-	-	-	280
	5/15/2013	Water	-	-	90	-	-	-	-	-
		HPCD	190	660	470	570	470	-	470	-
		HPCD	40	-	150	-	-	-	-	-
	5/16/2013	Water	60	380	280	380	280	-	280	-
		OxyZone	-	1140	-	380	-	-	760	-
	5/17/2013	OxyZone	40	930	1230	510	260	-	930	640
2nd	5/18/2013	OxyZone	20	1210	830	-	320	-	760	1020
	5/19/2013	OxyZone	-	980	1210	1970	-	-	-	-
	7/11/2013	OxyZone*	-	-	950	-	190	-	1140	380
	7/12/2013	OxyZone*	-	980	-	980	-	-	780	660
3rd	7/13/2013	OxyZone*	-	1290	380	490	380	-	-	300
	7/14/2013	OxyZone*	20	660	-	280	80	-	-	280
	8/12/2013	OxyZone*	-	550	440	-	300	-	230	-
	8/13/2013	OxyZone*	80	860	640	730	220	-	850	290
	8/14/2013	OxyZone*	80	860	790	550	120	-	530	210
	8/15/2013	OxyZone*	110	220	-	570	190	-	420	380
Total Vol. (Well):			1180	16580	10030	10450	3580	480	10530	5140
Total Vol.:			38240				19730			
Total Vol. OxyZone:			33360				17380			
Total Vol. HPCD:			2080				940			
Total Vol. Water:			2800				1410			

Table 1.2: Injection history for Test Cell 1 “Sequential” injection scheme. All volumes are in liters (L) . *OxyZone® used in these injections was a 100 g/L persulfate solution.

Event	Observation	Interpretation
Apr 23, 2013: Baseline sampling of groundwater conditions prior to the 1st injections in Test Cell 1	SpC: 0.5 mS/cm to 9.6 mS/cm HPCD: 0.1 g/L to 0.8 g/L in the deep zone only	SpC readings reflect the brackish nature of site groundwater; the detected HPCD is remnant from preliminary injection scheme testing in Test Cells 2 and 3
May 13, 2013: Groundwater conditions following the injection of oxidant but prior to the injection of HPCD	SpC: >10 mS/cm at I-1, I-4, I-8, I-10, U-16D, U-17D, U-19D and U-20D HPCD: Not detected in shallow or deep zone	High SpC, up to 42 mS/cm at I-10, indicate good distribution of oxidant solution within the Test Cell
May 30, 2013: Groundwater conditions 11 days after the 1st injection event	SpC: >20 mS/cm observed in the deep zone at I-10, I-8, U-17D, U-19D, and U-20D; >10 mS/cm were seen in the shallow zone at I-5, I-7, and I-9 HPCD: > 5 g/L in the deep zone at I-1, U-16D and U-17D; > 1 g/L in the shallow zone at I-5 and I-7	Good radial oxidant and HPCD distribution within the deep zone; lesser amounts of reactive agents present in the shallow zone due to daylighting problems
Jul 10, 2013: Groundwater conditions 52 days after the first injection event and immediately preceding the 2nd injection event	SpC: >17 mS/cm seen at wells I-8, U-20D, MW-2904, U-5 and I-10, and U-21D. HPCD: Reductions of ≥30% at wells I-1, U-16D, U-17D, U-18D, and U-19D; Highest conc., >3 g/L, remained within Test Cell 1 at wells I-1, U-16D and U-20D.	Oxidant and HPCD conc. continued to dissipate in the shallow zone with little apparent radial distribution; In the deep zone advective transport of oxidant and HPCD downgradient and outside test area was minimal
Jul 22, 2013: Groundwater conditions 8 days after the 2nd injection event	SpC: ≥ 40 mS/cm at I-10, I-8, I-9 and I-5. HPCD: The highest conc. (>1 g/L) remained within Test Cell 1 at wells I-1, I-8 and U-16D	Following the 2nd oxidant injections the highest SpC readings were still measured at the injectors in both the deep and shallow zones; HPCD concentrations in the shallow and deep zones continued to decline
Aug 12, 2013: Groundwater conditions 29 days after the 2nd injection event but prior to the 3rd injection event	SpC: Highest readings, >20 mS/cm, observed in deep zone at wells MW-2904, U-21D and I-10. HPCD: Highest conc., > 1 g/L, at U-20D, MW-2904 and I-5	HPCD was still detectable in the deep zone of Test Cell #1, but had moved slightly downgradient to the area of wells U-20D and MW-2904; SpC readings in the shallow zone declined at all wells
Oct 13, 2013: Groundwater conditions 50 days after the 3rd and final injection event	SpC: Highest readings, >30 mS/cm, in the deep treatment zone moved slightly down-gradient to the area of injector I-10 and well U-21D HPCD: Similar to Aug. sampling, the highest conc., > 1 g/L, were at I-5, I-1, and U-20D	Elevated SpC remained throughout Test Cell 1 in both the shallow and deep treatment zones; HPCD conc. were similar to those seen in the previous sampling; significant transport of HPCD down gradient of Test Cell #1 was not observed
Feb 13, 2014: Final groundwater conditions 133 days from the previous sampling event and 183 days from the 3rd injection event.	SpC: >10 mS/cm remained within Test Cell-1 at I-5, I-8, I-10, U-17D, U-19D, U-20D, and U-21D HPCD: Conc., between 0.1 and 0.6 g/L, remained around injectors I-1, I-2, I-5, I-8 and I-10	In general by the end of the demonstration SpC and HPCD in both the deep and shallow zones had returned to near pre-injection levels; Although elevated SpC and low level HPCD remained at some wells within Test Cell 1

Table 1.3: Injection timeline for Test Cell 1 “Sequential” injection scheme. Isocontour maps of SpC readings and HPCD concentrations are presented in Figures 1.6 and 1.7.

VOCs

Groundwater

Figure 1.8 shows isocontour maps of changes in groundwater tVOC contamination during the demonstration. In the April 23, 2013 pre-treatment sampling

event, the highest deep zone tVOC groundwater concentrations were detected in the northwestern corner of Test Cell 1; tVOC concentrations of 20 mg/L or more were observed at U-4, U-5, U-20D, and MW-2904. In the shallow zone, the highest pre-treatment tVOC groundwater concentrations were observed in the center of Test Cell 1, with concentrations of 240 mg/L and 120 mg/L at I-5 and I-6, respectively. These high tVOC groundwater concentrations are indicative of NAPL being present in this area. However, tVOC concentrations at U-18S, U-19S, and U-20S were all below 1 mg/L. This very sharp horizontal tVOC gradient within the shallow zone suggests that any migration of VOC from the hotspot at I-5 and I-6 is predominantly downward into the deep zone rather than radially outward.

After the injection of HPCD, on May 15 and 16, 2013, a sharp increase in groundwater tVOC concentrations was observed within the deep zone of Test Cell 1 (Figure 1.8). At wells U-16D and I-1, tVOC concentrations increased 5.3 and 8.8 fold by the end of May and remained elevated in the deep zone at concentrations above 100 mg/L (wells I-1 and U-20D) until mid-August 2013. Between October 2013 and February 2014, tVOC concentrations declined to near or below pre-demonstration levels at most wells (Figure 1.8). In the final February 2014 post-treatment sampling concentrations below 10 mg/L were observed at all deep screened wells except U-4, U-20D, MW-2904, I-8, and I-1.

The distribution of tVOC contamination in the shallow zone was essentially constant throughout the test (Figure 1.8). High concentrations, typically exceeding 100

mg/L and reaching as high as 260 mg/L, were observed at I-5 and I-6 throughout the study. However, monitoring wells U-17S, U-18S, U-19S, and U-21S all remained below 3 mg/L tVOC. The stagnation of concentrations in the shallow zone most likely reflects the minimal horizontal distribution of oxidant and solubility-enhancing agent because of the surfacing problems during injection.

Following methodologies described in Ricker (2008), the tVOC isocontour data were used to calculate the average tVOC groundwater concentration in the deep and shallow zones within Test Cell 1, as well as make an estimate of the tVOC aqueous mass within Test Cell 1. For these calculations the available tVOC groundwater data for each sampling date was extrapolated and then cropped (blanked) to only include the area within Test Cell 1. Estimates of average groundwater concentrations and the total dissolved contaminant mass in each zone were then determined using the grid volume, grid planar area, and assumed field-based values for unit thickness, porosity, and bulk density (Ricker 2008). The results of these calculations are presented in Table 1.4 and Figure 1.9. Following the HPCD injection, the aqueous tVOC mass in the deep zone increased more than two-fold by March 30, 2013. The aqueous tVOC mass in the deep zone remained elevated throughout the second oxidant injection event in July. Following the final oxidant application, in August 2013, the aqueous mass of tVOC began to decline, reaching approximately pre-demonstration levels by the final sampling in February 2014. During the same period, tVOC concentrations in the shallow zone temporarily declined but eventually returned to baseline levels.

Date	Deep Zone 3.0 m to 6 m (saturated)		Shallow Zone 0.6 to 3m (saturated)	
	AVE Conc. (mg/L)	Mass (kg)	AVE Conc. (mg/L)	Mass (kg)
04/23/13	13.7	0.45	-	-
05/09/13	14.0	0.46	46.5	1.22
05/13/13	19.7	0.65	43.7	1.15
05/16/13	13.4	0.44	34.0	0.89
05/23/13	26.3	0.86	31.4	0.82
05/30/13	30.7	1.01	43.6	1.14
07/09/13	32.6	1.07	35.9	0.94
07/22/13	30.0	0.98	31.4	0.83
08/12/13	37.0	1.21	40.6	1.07
10/03/13	28.6	0.94	45.6	1.20
02/12/14	13.8	0.45	44.0	1.16

Table 1.4: Estimated dissolved mass of target VOCs during the primary demonstration in Test Cell 1. The 4/24/2013 sampling only included 5 out of 10 shallow screened wells and, as a result, a representative estimate could not be performed. A detailed injection history is presented in table 1.2. In brief the injections were: OxyZone® 4/25/13 - 5/5/2013; Water and HPCD 5/13/13 - 5/16/16; OxyZone® 5/16/13 - 5/19/13; OxyZone® 7/11/13 - 7/14/2013; OxyZone® 8/12/13 - 8/15/13.

The non-parametric spearman's rank correlation (spearman's rho) was used to test for a statistically significant relationship between the solubility-enhancing agent HPCD and the observed increase in tVOC groundwater concentrations during the demonstration. tVOC concentrations were normalized (C/C_0) relative to the initial concentration observed in the April 23, 2013 pre-treatment sampling event. HPCD non-detects were left-censored using half the PQL (50 mg/L). Very strong positive correlations between HPCD and tVOC concentrations were observed at wells U-18D, U-17D, and U-16D ($r_s \geq 0.80$, $n = 8$, $p < 0.05$). In addition, moderate to strong positive

correlations at 90% confidence were observed at U-12, U-20D, EC-4, and I-1 ($r_s = \geq 0.57$, $n = 6-8$, $0.1 > p > 0.05$). Although HPCD concentrations as high as 3.7 g/L were observed at I-5, a negative correlation resulted ($r_s = -0.639$, $n = 8$, $0.1 > p > 0.05$), showing that the presence of HPCD did not result in increased tVOC concentrations at this heavily contaminated well. This observation is consistent with Boving et al. (1999), who found that HPCD concentrations >5 g/L are required to measurably increase the aqueous phase VOC concentration when flushing a NAPL contaminated soil medium. In addition to individual well analysis, a site-wide correlation analysis was performed using only deep screened wells with 6 or more paired VOC and HPCD samples. A statistically significant, moderately strong monotonic correlation ($r_s = 0.48$, $n = 113$, $p < 1E-7$) was observed between HPCD concentrations and tVOC concentrations (Figure 1.S2). Thus, the increases in tVOC concentrations in the deep zone were significantly linked to the solubility-enhancing properties of the HPCD.

Bulk VOCs

In the pre-treatment MIP survey, contamination at 12 of the 23 MIP locations was so great that it exceeded the ECD maximum detection limit ($\geq 12.8 \times 10^6 \mu V$) showing high levels of chlorinated VOCs. At EMP01, EMP07, EMP12, and EMP22 major contamination was identified between 1 and 4 m bgs. At EMP05, EMP11, and EMP21 major contamination was identified predominantly at 4 m bgs or deeper. PID detector response was generally low at all MIP locations remaining below $10^6 \mu V$ at all borings except EMP06. Elevated FID detector response was most commonly seen in the upper 2 m with readings above $10^6 \mu V$ observed at 10 out of 23 MIP borings. The results of this

pre-treatment survey confirmed the presence VOC contamination at the site, and revealed that the contamination in the source zone was much more extensive than previously known.

A post-treatment MIP survey was performed and the results compared to the pre-treatment survey. In general, reductions in PID and ECD response were observed for both peak and depth-integrated responses after treatment (Figure 1.5). ECD responses, indicative of chlorinated VOC, decreased mostly in the area surrounding Test Cell 1, while PID responses, indicative of aromatic hydrocarbons, decreased mostly within it (Figure 1.5). Of the 24 post-treatment borings, chlorinated VOC contamination only exceeded the ECD detector limits at 3 out of 24 post-treatment locations: EMP06, EMP07, and EMP24 (Table 1.S2). Comparison of pre- and post- depth integrated MIP profiles showed net changes in ECD and PID response of -11% to -86% and 5% to -57%, respectively. Increases in FID response, especially between 0.3 and 1.5 m bgs, were observed at almost all MIP locations. Net changes in depth integrated FID response were between 83% to -7.5%. The cause of these increases in FID response is not immediately evident but could be attributable to contaminant breakdown products dissolved in pore water, such as acetone, which was found at higher concentrations after treatment.

An additional MIP boring (EMP24) was completed during the post-treatment survey to specifically investigate the central part of the treatment area in which NAPL was suspected. Elevated PID, FID readings, and ECD response at or near the maximum

detection limit were observed from approximately 1 m to 6 m bgs, indicating that substantial chlorinated VOC (possibly NAPL) contamination remained. The presence of larger than anticipated amounts of VOC, and possibly NAPL, would explain why groundwater concentrations at many wells returned to near baseline levels after OxyZone-C® treatment rather than falling below.

Soil

A total of 59 soil samples were collected for VOC analysis during the December 2013 post-treatment soil investigation. 56 of those samples were collected from key locations for direct comparison to pre-demonstration soil sampling results. When discussing post-demonstration soil samples, the pre-demonstration paired sample is noted in parenthesis, i.e. SB-116(SB-3).

Analytical results for post-demonstration soils were varied, with some areas showing VOC concentration reductions while others showed no significant change or even increases in concentration. In general, the post-demonstration soil samples within and on the periphery of Test Cell 1 confirmed the post-treatment MIP findings, which showed reductions around the outer edges of Test Cell 1, but considerable contamination remaining centrally within the Test Cell.

Post-demonstration soil samples showed that considerable NAPL remained in soils situated centrally within Test Cell 1 near EMP06, and confirmed the presence of significant NAPL near EMP24. 1,1,1-TCA, PCE, and DCBs remained the major fraction of tVOC detected. Post-demonstration soil tVOC concentrations greater than 1 g/kg were

seen at SB-110(I-7), SB-113(SB-2), SB-115(I-5), and SB-116(SB-3), at depths ranging from 1.2 m to 5.49 m bgs. In addition, tVOC concentrations above 10 g/kg were observed at SB-115 (I-5) and SB-113(SB-2) at 2.4 m depth. These extremely high VOC concentrations, in some cases greater than 1% wt/wt, clearly show that NAPL remained within the interior of Test Cell 1.

When directly comparing adjacent pre- and post-demonstration soil samples in the central, most contaminated area of Test Cell 1, it is difficult to differentiate remediation-induced changes from variations due to the irregular distribution of NAPL (Table 1.5). Decreases of 0.1 g/kg or greater were observed at SB-105 (I-6) and SB-116 (SB-3) at depths between 1.8 m to 5.5 m. However, increases in tVOC of 0.5 g/kg or greater were measured at borings SB-110(I-7), SB-113(SB-2), SB-115(I-5) and SB-116(SB-3) at depths ranging from 1.8 m to 3.1 m. Several other borings showed both measurable increases and decreases in tVOC, depending on the sampled depth. For example in paired borings SB-3 and SB-116 an increase of 0.5 g/kg of total VOC was observed at 1.8 m and 2.4 m bgs, while decreases of 1.1 g/Kg and 2.1 g/Kg were found at depths of 3.1 m and 5.5 m. In general, these findings show that a VOC source zone remained.

Similar to the groundwater results, post-treatment soil samples showed reductions in contamination around the periphery of Test Cell 1. For example, at SB-112(U-16), reductions in total VOC of 99%, 86%, and 70% were observed between pre- and post-demonstration paired samples. At SB-114(U-17) reductions of 97% and 85%

were observed at 2 m and 4.5 m depth. At SB-108(U18) reductions of 50% and 99% were observed at 2 m and 4.3 m depth. At SB-106(U-20) 88% and 79% reductions were observed at 2 m and 2.4 m depth. While significant reductions were not observed at SB-107(U-19) and SB-102(U-21D), tVOC concentrations did remain stable with a maximum variation of 1.1 mg/kg observed between all paired pre- and post-demonstration samples from these locations.

Location	Sampling Boring	Closest MIP	Depth (m)	tVOC (mg/Kg)	Depth (m)	tVOC (mg/Kg)	Depth (m)	tVOC (mg/Kg)	Depth (m)	tVOC (mg/Kg)	Depth (m)	tVOC (mg/Kg)	Depth (m)	tVOC (mg/Kg)
Edges of Test Cell 1	Pre U-16	EMP07			2.1	2.1E+01			3.4	1.5E+03	4.6	9.6E+02		
	Post SB-112				1.8	2.0E-01			3.1	2.2E+02	4.3	2.8E+02		
	Pre U-17	EMP01			2.1	3.6E+00					4.6	2.0E+00		
	Post SB-114				1.8	1.0E-01					4.3	3.0E-01		
	Pre U-18	NA			1.8	7.6E+00					4.3	2.7E+02		
	Post SB-108				1.8	3.7E+00					4.3	6.0E-01		
	Pre U-19	EMP05			2.1	6.0E-01					4.6	1.0E-01		
	Post SB-107				1.8	1.5E+00					4.3	2.0E-01		
Pre U-20	EMP21			1.8	1.3E+02	2.4	5.5E+01	3.4	4.0E-01	4.6	3.5E+00			
Post SB-106				1.8	1.5E+01	2.4	1.2E+01	3.1	1.1E+00	4.3	3.9E+00			
Pre U-21D	EMP11	0.6	3.0E-01	1.8	6.0E-01			3.1	1.2E+00			5.5	3.6E+00	
Post SB-102		0.6	3.0E-01	1.8	6.0E-01			3.1	2.3E+00			5.5	3.3E+00	
Central Test Cell 1	Pre I-5	EMP24					2.4	7.7E+03						
	Post SB-115						2.4	1.3E+04						
	Pre I-6	EMP06			2.1	3.0E+03	2.4	1.2E+02						
	Post SB-105				1.8	1.1E+02	2.4	1.9E+01						
	Pre I-7	NA	0.6	3.3E+01	1.8	5.5E+00			3.1	6.2E+02				
	Post SB-110		0.6	9.4E+01	1.8	8.1E+00			3.1	1.5E+03				
	Pre SB-2	EMP-06	0.6	5.8E+00	1.8	4.2E+01	2.3	8.8E+03	3.1	8.4E+02				
	Post SB-113		0.6	7.6E+00	1.8	4.1E+01	2.4	1.1E+04	3.1	1.2E+03				
Pre SB-3	EMP-24	0.6	2.3E+01	1.8	2.5E+03	2.4	4.2E+01	3.1	1.4E+03			5.5	3.1E+03	
Post SB-116		0.6	2.6E+01	1.8	3.0E+03	2.4	8.8E+01	3.1	2.9E+02			5.5	9.4E+02	

Table 1.5: Comparison of pre- and post-demonstration soil samples from the edges and within the interior of Test Cell 1. For samples I-7(SB-110) and U-18 (SB-108) the nearest MIP point is more than 2.6 m away.

SVOC

Phenolic compounds were the most commonly detected SVOC in site soil and groundwater. The distribution of SVOC was similar to that seen for VOC with the highest levels of soil and groundwater contamination occurring in the center of Test Cell 1 at

wells I-5 and I-6. At I-6 groundwater concentrations of 8.8 mg/L, 1.5 mg/L, and 8.8 mg/L and soil concentrations of 1.5 mg/L, and 8.8 mg/L and 14 mg/kg, 3.6 mg/kg were observed for Phenol, o-methylphenol, and m-, p-methylphenol respectively.

In general post-treatment SVOC distributions were similar to that seen for VOC, with improvements on the periphery and down gradient of Test Cell 1 and higher concentrations remaining in the center of the Cell in the approximately location of the NAPL source zone. Post-treatment SVOC groundwater concentrations at wells EC-2, I-2, I-3, and I-4 generally improved, with most analytes falling below detection limits or remaining at pre-treatment baseline levels. Larger reductions were observed at EC-1 where baseline concentrations of 60 µg/L, 270 µg/L, and 140 µg/L were reduced to below detection limits for phenol, o-methylphenol, and m-,p-methylphenol. However, approximately two-fold increases in phenol, o-methylphenol, and m-, p-methylphenol were observed at I-6 in the center of Test Cell 1.

Metals

Mobilization of metals is a concern when applying ISCO in the field. Comparison of post-treatment groundwater and soil metals concentrations to pre-treatment levels suggest that some mobilization of metals occurred as a result of the demonstration and was comparable to those seen during previous ISCO work at the site. The source of these metals appears to be natural, from the subsurface soils, and presents a negligible risk relative to the VOC contamination at the site. A more in-depth discussion is provided in the supporting information.

Microbial

Sterilizations of subsurface microbial populations is a concern when applying ISCO in the field. The results of the post-treatment investigation indicate a decrease in PLFA cells counts at all locations. Measurable decreases were observed at wells MW-3, MW-2904, and I-4, where total biomass decreased by an order of magnitude or greater (Figure 1.S5). These findings correlate positively with the amount of oxidant injected into these wells, i.e. I-4 received the most oxidant of all the deep screened injectors (15,070 L), while I-1 received the least (510 L). However, a drop in biomass was observed at MW-3, which is surprising given its distance (30 m) from the test area. In general, ISCO appears to have put stress on the local microbial environment, but full sterilization did not occur and the microbial community is expected to recover in time. A more in-depth discussion is provided in the supporting information.

Conclusions:

This pilot test's principal objective was to evaluate if the limitations of contaminant availability during ISCO can be overcome by incorporating the solubility-enhancing properties of HPCD. Importantly, this technology demonstration was not designed for a full site cleanup, for which additional injections of oxidant and HPCD would have been necessary.

During this demonstration a temporary two-fold increase in the aqueous mass of tVOC occurred in the deep zone and a statistically significant positive correlation with HPCD was observed. A similar response was not seen in the shallow zone, which was at

least partially due to the poor horizontal distribution of oxidant and solubility-enhancing agent within this region. These problems resulted from unanticipated heterogeneities, leading to extensive preferential flow and surfacing when using shallow screened injectors. In addition, vertical migration of injected solutions from the shallow screened wells into the more conductive deeper zone is suspected.

The highest dissolved tVOC concentrations in the deep zone were observed after the HPCD injection and the second oxidant injection event. By the end of the demonstration, aqueous tVOC concentrations had returned to baseline levels. As indicated by the SpC measurements and lack of measurable HPCD at down gradient wells, this decrease is believed to be predominately due to oxidative destruction of the solubilized VOC and not dilution or migration outside of Test Cell 1.

There is evidence that both HPCD and persulfate were long lived in the subsurface and continued to work for months after injection. Elevated ORP readings above 400 mV were detected at the site in both the October and February post-treatment sampling, indicating that oxidative conditions remained months following the final injection. Furthermore, low levels of HPCD were still detected in wells I-1, I-2, I-5, I-8, and I-10 more than 8 months after injection. Due to the small hydraulic gradient at this particular site, this was advantageous as there was limited risk of offsite migration. However, where migration offsite is a concern, the volume of oxidant and HPCD applied may need to be adjusted to account for this issue.

Post-treatment sampling showed that residual phase NAPL remained within the treatment area and was more prevalent than first believed. Due to the continued dissolution of the remaining NAPL, groundwater tVOC concentrations near the center of Test Cell 1 remained high even after treatment. However, reductions in aqueous tVOC concentrations of 20% to 90% were observed at multiple wells indicating reduced contamination migrating away from the source zone. This is supported by MIP and soil data which show considerable VOC removal occurred at the periphery and down gradient of Test Cell 1. Although substantial contamination remains within Test Cell 1, it is clear that site conditions have improved as a result of the technology test.

From a practical application standpoint, the use of a solubility-enhancing agent was probably not necessary at this particular site, due to the presence of NAPL and the large mass of contaminant already available in the aqueous phase. Instead, the addition of a solubility-enhancing agent would perhaps be best suited as a polishing treatment after conventional ISCO has destroyed most of the source zone NAPL. The addition of HPCD to the ISCO treatment process could be particularly useful at sites where the mass transfer of contaminants from the sorbed phase is the rate limiting step and tailing prevents the site from coming into compliance.

From a proof of concept standpoint, the treatment had its intended effect. The incorporation of HPCD into an ISCO treatment resulted in a temporary increase in the aqueous phase mass of tVOC available for oxidation and its subsequent destruction. The results clearly demonstrate that this type of solubility-enhanced ISCO remediation is

possible in the field. To the authors' knowledge this is the first pilot-scale field test of HPCD enhanced ISCO.

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Supporting Information

The following supporting information is available for this article:

Table 1.S1: Injection scheme totals during preliminary injection scheme testing

Table 1.S2: MIP detector responses

Figure 1.S1: Total tVOC during preliminary injection scheme testing in Test Cells 2 and 3

Figure 1.S2: Spearman's rho correlation for HPCD and tVOC

Figure 1.S3: Dissolved metals pre and post-demonstration

Figure 1.S4: Microbial Community Structure during demonstration

Figure 1.S5: Total Biomass during demonstration

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Figures:

Figure 1.1: Hydroxypropyl-beta-cyclodextrin (TRC 2015).

Figure 1.2: Field Site. Pilot test was conducted predominantly in approximate location of the former Zig-zag Fire Pit. The approximate location of former fire training structures are based off of information detailed in ECC & Malcolm Pirnie Inc. 2008.

Figure 1.3: Location of wells and soil borings.

Figure 1.4: Site Geology: East West Cross Section. Vertical dimensions are exaggerated by 2x. Data is compiled from borings performed in 2012 and 2013 during site characterization and historical borings. The location of the geologic cross section is shown in Figure 1. MW-2 and MW-3 are historic monitoring wells that predate this study.

Figure 1.5: Pre and post-treatment depth integrated MIP isocontour maps. Note EMP24 does not have a pre-treatment equivalent and thus was omitted from the depth-integrated response fraction change calculations.

Figure 1.6: Isocontour maps of SpC distribution during primary demonstration in Test Cell 1. Maps were created using all the available data from wells sampled on that date.

Figure 1.6 (continued): Isocontour maps of SpC distribution during primary demonstration in Test Cell 1. Maps were created using all the available data from wells sampled on that date

Figure 1.7: Isocontour maps of HPCD concentrations during primary demonstration in Test Cell 1. Maps were created using all the available data from wells sampled on that date

Figure 1.7 (Continued): Isocontour maps of HPCD concentrations during primary demonstration in Test Cell 1. Maps were created using all the available data from wells sampled on that date

Figure 1.8: Isocontour maps of tVOC distribution during primary demonstration in Test Cell 1. Maps were created using all the available data from wells sampled on that date

Figure 1.8 (Continued): Isocontour maps of tVOC distribution during primary demonstration in Test Cell 1. Maps were created using all the available data from wells sampled on that date

Figure 1.9: Estimated tVOC aqueous mass during primary demonstration in Test Cell 1.

Supporting Information: Tables

<i>Test Cell</i>	<i>Injector</i>	<i>Date</i>	<i>Injection Solution</i>	<i>Total Volume (L)</i>
2	I-2	12/11/2012	OxyZone	3030
		12/13/2012	3% HPCD	1510
		12/14/2012	OxyZone	3030
3	I-3	12/12/2012	OxyZone	760
			3% HPCD	190
			OxyZone	760
			3% HPCD	190
			OxyZone	760
			3% HPCD	190
			OxyZone	760
			3% HPCD	190
		12/13/2012	OxyZone	760
			3% HPCD	190
			OxyZone	760
			3% HPCD	190
			OxyZone	760
			3% HPCD	380
			OxyZone	760

Table 1.S1: Injection schemes used during preliminary injection scheme testing. In Test Cell 2 a “sequential” injection technique was utilized. In Test Cell 3 a “pulsed” injection technique was utilized.

MIP Point	Maximum Depth (m)	PID Response ($\mu\text{V} \times 10^6$)					
		Maximum			Integrated		
		Pre	Post	% change	Pre	Post	% change
EMP01	6.86	0.55	0.30	-44.9%	3.98	3.35	-15.9%
EMP02	6.02	0.13	0.10	-22.2%	2.27	1.90	-16.0%
EMP03	6.80	0.20	0.11	-45.3%	2.78	2.12	-23.8%
EMP04	6.78	0.22	0.12	-46.5%	2.89	2.21	-23.5%
EMP05	7.60	0.49	0.14	-70.3%	3.57	2.58	-27.9%
EMP06	8.53	2.41	0.40	-83.4%	14.39	6.16	-57.2%
EMP07	6.66	0.78	0.32	-59.2%	3.62	2.41	-33.4%
EMP08	6.86	0.17	0.10	-38.9%	2.57	2.17	-15.6%
EMP09	6.17	0.13	0.14	2.8%	2.24	2.14	-4.6%
EMP10	6.54	0.40	0.24	-40.9%	3.18	2.70	-15.1%
EMP11	6.51	0.16	0.12	-27.4%	2.63	2.19	-16.7%
EMP12	6.45	0.66	0.16	-75.8%	3.37	2.17	-35.5%
EMP13	6.52	0.15	0.12	-19.3%	2.65	2.20	-16.9%
EMP14	6.58	0.20	0.11	-43.4%	2.53	2.17	-14.5%
EMP15	6.45	0.18	0.12	-32.1%	3.18	2.11	-33.7%
EMP16	6.43	0.21	0.12	-44.5%	2.20	3.30	50.4%
EMP17	7.04	0.20	0.13	-35.2%	3.58	2.42	-32.4%
EMP18	6.77	0.20	0.11	-45.3%	2.57	2.16	-15.7%
EMP19	6.71	0.20	0.12	-40.2%	2.58	2.17	-15.7%
EMP20	6.23	0.24	0.12	-49.1%	2.48	2.12	-14.6%
EMP21	6.69	0.24	0.13	-46.9%	2.19	2.29	4.5%
EMP22	6.74	0.27	0.12	-55.7%	2.94	2.34	-20.3%
EMP23	6.23	0.29	0.13	-54.4%	2.60	2.04	-21.6%
EMP24	6.42	NA	0.96	NA	NA	6.99	NA

MIP Point	Maximum Depth (m)	FID Response ($\mu\text{V} \times 10^6$)					
		Maximum			Integrated		
		Pre	Post	% change	Pre	Post	% change
EMP01	6.86	1.90	5.44	185.6%	5.37	9.86	83.4%
EMP02	6.02	0.18	0.23	27.1%	3.13	3.16	1.0%
EMP03	6.80	0.31	0.40	31.5%	3.68	3.94	6.9%
EMP04	6.78	1.66	2.43	46.1%	4.41	5.87	33.0%
EMP05	7.60	1.07	2.05	91.2%	4.74	6.02	27.0%
EMP06	8.53	1.05	2.70	156.8%	6.23	7.90	26.9%
EMP07	6.66	0.35	0.45	28.0%	3.86	3.91	1.4%
EMP08	6.86	0.23	0.24	2.6%	3.80	3.51	-7.5%
EMP09	6.17	2.87	4.81	67.5%	7.65	9.38	22.6%
EMP10	6.54	2.15	2.30	7.0%	4.77	6.28	31.8%
EMP11	6.51	0.32	2.04	541.9%	3.62	5.24	44.8%
EMP12	6.45	0.24	0.51	107.1%	3.55	3.53	-0.8%
EMP13	6.52	0.20	0.59	203.8%	3.53	3.76	6.4%
EMP14	6.58	0.21	0.90	335.2%	3.58	4.05	13.1%
EMP15	6.45	0.78	1.65	111.0%	4.29	5.55	29.3%
EMP16	6.43	1.45	1.19	-18.3%	4.56	4.61	1.3%
EMP17	7.04	1.53	4.05	165.3%	5.44	5.84	7.3%
EMP18	6.77	1.62	3.28	101.7%	5.18	7.38	42.4%
EMP19	6.71	1.18	2.98	151.8%	4.14	7.02	69.7%
EMP20	6.23	0.31	0.35	16.2%	3.42	3.42	-0.1%
EMP21	6.69	0.26	0.41	60.4%	2.96	3.60	21.5%
EMP22	6.74	0.21	0.45	115.4%	3.65	3.78	3.8%
EMP23	6.23	0.22	0.37	69.4%	3.38	3.31	-1.9%
EMP24	6.42	NA	5.43	NA	NA	9.68	NA

MIP Point	Maximum Depth (m)	ECD Response ($\mu\text{V} \times 10^6$)					
		Maximum			Integrated		
		Pre	Post	% change	Pre	Post	% change
EMP01	6.86	12.9	3.6	-72.3%	85.6	14.5	-83.0%
EMP02	6.02	2.6	1.2	-55.2%	12.5	4.1	-67.3%
EMP03	6.80	2.6	1.1	-59.7%	12.3	4.9	-60.6%
EMP04	6.78	2.2	0.5	-77.8%	11.4	4.0	-64.9%
EMP05	7.60	12.9	2.5	-80.8%	71.9	10.1	-86.0%
EMP06	8.53	12.9	12.9	0.2%	327.6	263.5	-19.6%
EMP07	6.66	12.9	12.8	-0.5%	156.1	37.2	-76.2%
EMP08	6.86	5.8	1.2	-79.1%	23.1	7.0	-69.9%
EMP09	6.17	1.9	0.8	-55.9%	7.3	4.3	-41.1%
EMP10	6.54	12.8	8.3	-35.7%	57.0	19.8	-65.3%
EMP11	6.51	12.9	1.7	-86.6%	47.1	7.8	-83.4%
EMP12	6.45	12.9	4.6	-64.6%	126.4	21.3	-83.2%
EMP13	6.52	8.2	3.5	-56.9%	37.4	11.4	-69.5%
EMP14	6.58	12.9	1.1	-91.7%	44.5	7.4	-83.4%
EMP15	6.45	4.2	4.2	0.6%	11.6	8.7	-25.0%
EMP16	6.43	0.78	0.56	-27.7%	4.6	4.0	-11.6%
EMP17	7.04	8.3	2.4	-71.6%	15.9	7.1	-55.1%
EMP18	6.77	4.1	0.9	-77.6%	14.7	6.5	-55.6%
EMP19	6.71	7.1	1.9	-73.7%	21.1	8.5	-59.8%
EMP20	6.23	12.9	1.8	-85.7%	26.4	10.9	-58.8%
EMP21	6.69	12.9	1.7	-87.1%	50.9	9.0	-82.3%
EMP22	6.74	12.9	5.4	-58.1%	146.1	35.1	-76.0%
EMP23	6.23	12.9	2.1	-84.0%	33.2	14.2	-57.1%
EMP24	6.42	NA	13.0	NA	NA	218.2	NA

Table 1.S2: MIP detector responses.

Supporting Information: Figures

Figure 1.S1: tVOC during preliminary injection scheme testing in Cells 2 and 3. In Test Cell 2 a “sequential” injection technique was utilized. In Test Cell 3 a “pulsed” injection technique was utilized.

Figure 1.S2: Spearman's rho test showing relationship between HPCD and tVOC during the test ($r_s = 0.48$, $n = 113$, $p < 1E-7$). N is the number of paired HPCD and tVOC groundwater samples analyzed.

Figure 1.S3: Comparison of pre and post-demonstration dissolved metal concentrations. Data are for paired samples where analytes were detected above reporting limits in both pre- and post-demonstration samples. The number of paired pre and post samples is given in parentheses. Bar represent the average concentrations observed and error bars represent 1 standard deviation of the mean. JBLE background concentrations are from values reported in Watson 1997.

Metals

Groundwater

To monitor for changes in groundwater metal concentrations, dissolved metals samples were taken from 10 wells (EC-2, EC-3, I-4, I-6, MW-2904, U-16D, U-17D, U-18D, U-19D, and U-20D) pre-, during, and post-demonstration. Dissolved metals concentrations above JBLE background concentrations were observed in pre-demonstration TA-15 groundwater samples (Watson 1997). The highest concentrations were detected in well U-20D, where arsenic, chromium, lead, nickel, and zinc

concentrations of 36 µg/L, 20 µg/L, 19 µg/L, 81 µg/L, and 420 µg/L respectively were observed; all of which were above JBLE background levels.

During and after the demonstration, average aqueous phase concentrations increased for most metals (Figure 1.S3). Post-treatment arsenic, beryllium, chromium, lead, nickel, and zinc concentrations were found above JBLE background levels in multiple wells. The highest post-demonstration metals concentrations were generally associated with U-17D, where cadmium, chromium, copper, nickel and zinc concentrations of 18 µg/L, 80 µg/L, 72 µg/L, 300 µg/L, and 1,100 µg/L respectively, were observed. The highest post-demonstration levels of arsenic, beryllium, and lead were observed at wells EC-2 and U-20D, with concentrations of, 38 µg/L, 19 µg/L, and 24 µg/L respectively.

The increases in dissolved metals seen during this study were similar to those seen during a previous persulfate-based ISCO pilot test conducted at the site in 2008 and 2009 (ECC & Malcom Pirnie 2009). In this previous test, increases in dissolved metals were observed at wells MW-2904, MW-1, MW-2, and MW-3 following ISCO with concentrations of arsenic, cadmium, chromium, nickel, and zinc reaching as high as 21 µg/L, 79 µg/L, 65 µg/L, 80 µg/L, and 5700 µg/L respectively. Our findings suggest that some mobilization of metals occurred as a result of the demonstration and was comparable to those seen during previous ISCO work at the site. The source of these metals appears to be natural, from the subsurface soils, and presents a negligible risk relative to the VOC contamination at the site.

Soil

Three soil samples were analyzed for metals during the December 2013 post-treatment soil investigation. Soil concentrations of all analytes decreased by approximately 30% relative to samples collected during the baseline investigation. For instance, at SB-112(U-16) at a depth of 4.3 m bgs, the soil concentration of chromium decreased from 4.7 mg/kg to 3.6 mg/kg (23%), copper decreased from 1.4 mg/kg to 0.7 mg/kg (50%), lead decreased from 5.4 mg/kg to 3.2 mg/kg (41%), and zinc decreased from 7 mg/kg to 4.2 mg/kg (40%). These decreases in soil metal concentrations could be indicative of mobilization of metals into the aqueous phase. Although there is evidence of decreased soil and increased dissolved metal concentrations after ISCO treatment, the small number of samples collected, in addition to many non-detects and variable reporting limits for individual analytes limits the statistical significance of these results.

Figure 1.S4: Community Structure throughout the demonstration.

Figure 1.S5: Biomass throughout the demonstration.

Microbial

Groundwater

During the pre-treatment investigation, the total biomass varied between 1.43×10^5 cells/bead (MW-1) and 3.31×10^5 cells/bead (I-1) (Figure 1.S4). These baseline concentrations were consistent with moderate microbial activity. Similar community structures were determined at all wells with proteobacteria, indicated by monoenoic PLFA, making up the majority of the community (>60%).

The results of the post-treatment investigation indicate a decrease in PLFA cells counts at all locations. Measurable decreases were observed at wells MW-3, MW-2904, and I-4, where total biomass decreased by an order of magnitude or greater (Figure 1.S5). The largest decrease was recorded in well I-4, where biomass dropped from 1.4×10^5 to 9.4×10^3 cells/bead. The smallest changes were observed at well I-1 where total biomass remained above 1×10^5 cells/bead throughout the demonstration. These findings correlate positively with the amount of oxidant injected into these wells, i.e. I-4 received the most oxidant of all the deep screened injectors (15,070 L), while I-1 received the least (510 L). However, a drop in biomass was observed at MW-3, which is surprising given its distance (30 m) from the test area. This could mean that other factors, independent of the demonstration, were affecting microbial productivity at the site. In general, ISCO appears to have put stress on the local microbial environment, but full sterilization did not occur and the microbial community is expected to recover in time.

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Impact of ISCO Treatment of VOCs on PFAAs Co-contaminants at a Former Fire Training Area

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Abstract

Perfluoroalkyl acids (PFAAs) were utilized in aqueous film-forming foams (AFFF) and are now detected at many fire training areas (FTAs). The possible effects of remediation efforts aimed at volatile organic compounds (VOCs) on PFAA co-contaminants are of interest to managers of these sites. The unintentional mobilization of sorbed PFAAs and the conversion of polyfluorinated precursors to more recalcitrant PFAAs are of particular concern. In this study, soil and groundwater samples were collected before and after an extensive pilot field test of a peroxone activated persulfate (OxyZone®) *in situ* chemical oxidation (ISCO) technology at a former FTA contaminated with PFAAs and VOCs. The site geology consisted of a heterogeneous unconsolidated surficial aquifer underlain by a clay confining unit. Statistically significant decreases in PFAA groundwater concentrations were observed in post-treatment samples taken from wells screened in the deeper part of the aquifer, 48 days and 180 days after completion of the test, while concentrations in shallow screened wells remained largely unchanged. Reductions in PFAA concentrations in groundwater were supported by decreases in soil PFAA concentrations. In addition to these changes, no evidence of PFAA mobilization or conversion of precursors into PFAAs was observed. Based on these findings, the use of ISCO to treat VOCs had no discernible negative impacts on PFAA co-contaminants at the site. Rather, the data suggest PFAA site conditions may have improved from activated persulfate treatment of the VOCs, possibly due to slow oxidative PFAA decomposition.

Keywords: Perfluoroalkyl acids (PFAAs), Aqueous film-forming foams (AFFF), Perfluorooctanesulfonic acid (PFOS), *In situ* Chemical Oxidation (ISCO), Remediation

Introduction:

Perfluoroalkyl acids (PFAAs) are fully-fluorinated carbon chain, anthropogenic pollutants (US EPA 2009a; Buck et al. 2011). The US Environmental Protection Agency (EPA) and global health organizations have identified PFAAs as toxic, persistent, and bioaccumulative, (OECD 2002; US EPA 2007; US EPA 2009a; Lindstrom et al. 2011). Within this class of compounds two major families of PFAAs, perfluoroalkyl carboxylates (PFCAs) and perfluoroalkyl sulfonates (PFSA), have gained particular attention due to their widespread occurrence in the environment, including detection in wildlife and humans. PFAAs were produced in mass quantities prior to a voluntary phase out by their primary manufacturer 3M in 2002 (Prevedouros et al. 2006; Paul et al. 2009; US EPA 2009a). Although the manufacturing and use of PFAAs has been restricted or banned in most nations, significant production and use continues in China (Lim et al. 2011; Xie et al. 2013) and possibly other countries.

Due to their strong fluorine-carbon bonds, PFAAs are among the most stable organic compounds. They are largely resistant to hydrolysis, photolysis, and aerobic and anaerobic biodegradation. Long-chain PFAAs, such as perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS), were valued for their oleophobic and hydrophobic properties. PFOA and PFOS were commonly used in industrial and commercial processes and incorporated into non-stick, waterproof, and fire-resistant materials, such as lubricants, paints, polish, food packaging and aqueous film-forming foams (AFFFs) (Prevedouros et al. 2006; Paul et al. 2009). Both PFOA and PFOS can migrate through terrestrial and marine environments intact, while additional PFOS and PFOA may be

produced in the environment via the degradation or biotransformation of PFAA-precursors (Tomy et al. 2004; Dreyer et al. 2009; US EPA 2009a).

PFAAs were utilized in AFFF for their surface-tension lowering properties, which are advantageous when combating chemical fires. The use of AFFFs represents a common PFAA point source to the environment (Moody & Field 2000; Prevedouros et al. 2006; Paul et al. 2009). From 1965 to 1975, PFSA and PFCA compounds were incorporated into AFFF (3M 1992; 3M 1995; 3M 1996; Moody & Field 2000; Prevedouros et al. 2006; Place & Field 2012). Perfluorooctanesulfonyl fluoride (POSF)-based products replaced PFCAs as AFFF surfactants beginning in the early 1970s (Prevedouros et al. 2006). AFFF-related PFAA emissions to the environment from 1965 to 2004 are estimated to range from 53 tonnes to 130 tonnes PFCAs and 91 tonnes to 460 tonnes PFSAs (Prevedouros et al. 2006; Paul et al. 2009). In addition to PFAAs, AFFFs also contained other polyfluorinated compounds, such as fluorotelomersulfonates (FtS), which are potential PFAA-precursors (Place & Field 2012; Backe et al. 2013).

In the United States, production and sales of PFAA-containing AFFFs ended in 2002, but existing stockpiles may still be used (Seow 2013). The largest AFFF stockpile in the United States is owned by the U.S. Military and accounts for approximately 29% of all domestic AFFFs (Place & Field 2012). Since 3M's phase out, Chinese production of PFAAs has increased, including the production of PFAA-based AFFFs (Lim et al. 2011; Xie et al. 2013).

PFAAs, such as PFOA and PFOS, as well as potential polyfluorinated PFAA-precursors, such as FtS, have been identified in groundwater (Levine et al. 1997; Moody & Field 1999; Moody et al. 2003; Schultz et al. 2004; Cheng et al. 2010; Murakami et al. 2009; Chatwell 2012; Weiss et al. 2012; McGuire et al. 2014; Filipovic et al. 2015; Barzen-Hanson & Field 2015) and surface water (Moody et al. 2002; Oakes et al. 2010; de Solla et al. 2012; Filipovic et al. 2015). Studies of PFAA contaminated sites suggest these compounds can persist in groundwater years after use and may be mobile in the subsurface (Levine et al. 1997; Moody & Field 1999; Moody et al. 2003; Houtz et al. 2013). Fire training areas (FTAs) represent a prevalent point source of PFAAs to groundwater where they commonly co-occur with other priority pollutants, particularly volatile organic compounds (VOCs) (Chapelle et al. 1996; Bermejo et al. 1997; Levine et al. 1997; Moody & Field 1999; Moody et al. 2003; Paterson et al. 2008; Houtz et al. 2013). FTAs usually consisted of pits with few containment structures in place; during training exercises, these pits were flooded with waste fuels, oils, hydrocarbons, and/or halogenated solvents, then ignited and extinguished using AFFF. These poor management practices allowed mixtures of PFAAs, fuels, solvents, and other contaminants to enter local soil and groundwater systems untreated. The routine use of AFFFs at FTAs makes these sites highly susceptible to PFAA contamination. The United States Department of Defense (DoD) alone has identified approximately 600 fire/crash/training sites that potentially have PFAA contamination (SERDP 2012). PFAAs have also been found at civilian sites, including FTAs at refineries, airports, and municipal facilities (Delta Consultants 2010; Weiss et al. 2012). The full scope of AFFF-

based PFAA groundwater contamination continues to emerge as more sites are characterized. Thus, the need for a cost-effective remediation approach for PFAA contaminated groundwater and soil will likely increase in the coming years.

Remediation of PFAAs is challenging as many *in situ* VOC remediation strategies, such as soil vapor extraction, sparging, or bioremediation, are ineffective because of the physicochemical properties of PFAAs. *Ex situ* sorption-based remediation processes, such as granular activated carbon (GAC) and anionic resin filtration, have shown promise for PFAA removal (Hawley L. et al. 2012; Ochoa-Herrera & Sierra-Alvarez 2008; Yu et al. 2009; Lin et al. 2015). However, these above-ground methods may require many years of operation until PFAA remediation targets (ng/L) may be met. Furthermore, VOC co-contaminants will compete with PFAAs for sorption sites, potentially limiting the applicability of these technologies in the field (Hawley L. et al. 2012).

In situ chemical oxidation (ISCO) is a proven technology for the remediation of petroleum hydrocarbons and chlorinated solvents. New research shows that ISCO is potentially a remediation option for PFAAs (Vecitis et al. 2010). However, there are large differences in how different oxidants attack PFAAs. Oxidative destruction of contaminants via hydroxyl radical ($\cdot\text{OH}$)-based advanced oxidation processes (AOP) typically involve hydrogenation and/or hydrogen abstraction reactions (Lutze et al. 2012). The preferred reactive sites for hydrogenation reactions are C=C bonds, which PFAAs lack. Furthermore, C-F bonds are thermodynamically unfavorable for hydrogen abstraction (Lutze et al. 2012). Thus, hydroxyl radical based AOP such as ozone,

hydrogen peroxide, peroxone, and Fenton-based systems, are generally poorly suited for PFAA remediation (Schröder and Meesters 2005). The use of UV irradiation has been shown to improve the PFOA degradation in Fenton's reagent systems (Tang et al. 2012). A study by Mitchell et al. 2014 found that catalyzed hydrogen peroxide can degrade PFOA through superoxide and hydroperoxide radical reactions, but confirmed that the hydroxyl radical cannot effectively oxidize PFAAs. Nevertheless, substantial degradation of PFOA and PFOS has been shown using ozone and peroxone under alkaline conditions (pH 11); although degradation may have been due to other radicals produced through chain reactions rather than the hydroxyl radical itself (Lin et al. 2012).

Sulfate radical ($\text{SO}_4^{\cdot-}$) based AOPs (i.e. activated persulfate) have been shown to degrade long and short chain PFAAs via electron transfer (Kutsuna and Hori 2007). PFAA degradation has also been achieved using microwave, thermal, iron, electrochemical, photochemical, and hydrogen peroxide activated persulfate technologies (Hori et al. 2005; Hori et al. 2008; Kingshott 2008; Y. Lee et al. 2012; Liu, Higgins, et al. 2012; Petitgirard et al. 2009; Lin et al. 2012; Yang et al. 2013). Recent works have shown that activated persulfate based oxidation of PFOA can be performed at relatively low temperatures (20-40 °C), suggesting this technology could have potential as an *in situ* treatment (Y.-C. Lee et al. 2012). Together, these findings suggest that ISCO, particularly activated persulfate, has the potential to be used as an effective *in situ* treatment for subsurface PFAA contamination. Further testing at the bench and pilot-scale is necessary to assess the potential and performance of activated persulfate under field conditions (Hawley L. et al. 2012).

Understanding how the remediation of priority pollutants, such as chlorinated VOCs, affects PFAA co-contaminants has been identified as an area of critical importance and is an emerging focus of research (Moody & Field 2000; Houtz et al. 2013; Place & Field 2012; McGuire et al. 2014). General concerns include effects on co-contaminant transport and biodegradation processes. Recently studies have shown that PFAA-precursors can be degraded into PFAAs through the same AOP processes utilized by ISCO (Houtz et al. 2013). Therefore, a specific concern of ISCO is the oxidative transformation of precursors into PFAAs (Moody & Field 1999; Place & Field 2012; Houtz et al. 2013). This has important implications for the use of ISCO at VOC sites also contaminated by PFAAs; particularly at FTAs, where the co-occurrence of VOCs and AFFF-based PFAAs is likely.

In the present study, we examined the fate of PFAAs during the targeted remediation of chlorinated and non-chlorinated VOC in a non-aqueous phase liquid (NAPL) source zone. This occurred during pilot-scale field testing of an innovative ISCO method at a former FTA. The specific technology tested was a patented peroxone activated persulfate AOP (OxyZone®) used in combination with the solubility-enhancing agent hydroxypropyl-beta-cyclodextrin (HPCD). The specifics of this solubility-enhanced ISCO technology, OxyZone-C®, are described elsewhere (Ball 2010; Ball 2011; Eberle et al. 2015b; Eberle et al. 2016). The purpose of this field study was to examine the fate of PFAA co-contaminants during targeted remediation of VOCs, including PFAA degradation, conversion of precursors, and the potential formation of by-products. To the best of our knowledge this is the first study to investigate the fate of PFAA co-

contaminants during ISCO treatment of VOC soil and groundwater pollutants. These findings may be useful for site managers seeking to remediate mixed-waste contaminated sites, particularly at FTAs.

Materials and Methods

Site Description

Training Area 15 (TA-15) is a former FTA at Joint Base Langley-Eustis (JBLE), adjacent to Newport News, Virginia. Constructed in 1968, the facility consisted of a smokehouse, above ground burn tanks, a zig-zag pattern burn pit, underground fuel and water piping, and an oil and water separator. Monthly fire training activities were conducted at the site from 1968 to 1980. The facility was abandoned in 1980; all subsurface structures were removed and the site was covered with fill material. Irregular fire training activities at the site continued until approximately 1990, using an aboveground bermed burn pit located approximately 15 m from the former zig-zag pit (Figure 2.1)(ECC & Malcolm Pirnie Inc. 2008). Previous reports indicate that impacted soil was removed from the site in 1982 but the specifics of the excavation are not well known (Watson 1997). During fire training exercises, the pits were flooded with a mix of waste fuels, oils, hydrocarbons, and halogenated solvents, then ignited and extinguished. Major pollutants at the site include VOCs such as 1,1,1-trichloroethane (1,1,1-TCA), dichlorobenzene (DCB), and tetrachloroethene (PCE).

The site geology consists of an approximately 6 m surficial aquifer underlain by a clay confining unit. This surficial aquifer consists of a shallow zone ~0.6 m -3.0 m below ground surface (bgs) made up of low permeability silty sands and organic silts ($K = 0.5$

m/d), and a deep zone ~3.0 m to 6 m bgs, consisting of high permeability poorly sorted sands ($K=4.9$ m/d)(Figure 2.S1). Heavily contaminated sediments have been identified 0.3 m to 6 m bgs. The most heavily contaminated sediments are between 1.5 m to 2.1 m bgs.

The water table is 0.3 m to 0.6 m bgs, but shallower levels have been observed during heavy rain events. The site is tidally influenced by the James River to the west and wetlands to the north/northeast. Typical tidal variation in the water table is approximately 8 cm. The predominant direction of groundwater flow is to the northwest towards the James River, although the hydraulic gradient is very shallow, approximately 2×10^{-3} . Site groundwater is brackish, with average chloride concentrations of 1,100 mg/L observed in deep screened wells and 300 mg/L in shallow screened wells. Site groundwater is slightly acidic, with median pH of 5.0 and 6.3 observed in deep and shallow zones respectively over the course of the study.

Sampling

Groundwater samples were collected throughout the field test. Prior to sample collection, depth to groundwater was recorded. A YSI multimeter (YSI Inc., Yellow Springs, Ohio, USA) was used to continuously measure pH, temperature, oxidation-reduction potential (ORP), dissolved oxygen (DO), and specific conductance (SpC). Prior to testing, the wells were purged until these groundwater parameters stabilized. PFAA groundwater samples were then collected using a peristaltic pump and low-density polyethelene (LDPE) tubing under low flow conditions. Separate tubing was used for

each well and samples were collected in high-density polyethylene (HDPE) bottles with no headspace.

Two laboratories, TestAmerica Laboratories, Inc. (TA; Denver, CO) and the Colorado School of Mines Center for Environmental Risk Assessment (CSM; Denver, CO), were used to analyze PFAA samples. For TA samples, one liter of groundwater was collected in four 250 ml HDPE bottles and shipped directly from the field site for immediate analysis. For groundwater samples analyzed by CSM, 120 ml of sample was collected in two 60 ml HDPE bottles. Samples analyzed by CSM were shipped first to the University of Rhode Island (URI; Kingston, RI), where they were stored at 4°C until analysis. Samples analyzed by CSM were collected between April 2013 and February 2014 and analyzed in June 2014, resulting in holding times between approximately 110 d and 410 d. Soil samples were collected from soil borings in 250 ml HDPE bottles. A minimum of 10 g of sample was required for analysis. Throughout the study eight duplicate groundwater samples were collected to evaluate intra-laboratory consistency at CSM. In addition, ten samples, collected 2 days apart, were collected to compare inter-laboratory consistency between TA and CSM laboratories.

In addition to PFAA analysis, a subset of groundwater samples were analyzed for precursor compounds by CSM. February 2014 post-treatment samples from wells I-2, I-4, EC-3, U-16D, U-18D, and U-20D were analyzed. Additional precursor samples from I-2, taken during the November 2012 pre-treatment sampling and the October 2013 post-treatment sampling, were also analyzed.

Sample Analysis

The TA laboratory analyzed groundwater and soil samples using their proprietary method, DV-LC-0012, which follows some of the guidelines listed under US EPA Method 537 (US EPA 2009b). DV-LC-0012 is an isotope dilution method, utilizing solid phase extraction and sample concentration prior to analysis by LCMS. The CSM laboratory analyzed groundwater and soil samples following methodologies listed in Guelfo and Higgins (2013). In addition, a subset of samples were analyzed for PFAA-precursors using the total oxidative precursor (TOP) assay detailed in Houtz et al. (2013). Table 2.S1 lists the analyzed PFAAs.

Quality Control and inter laboratory Comparison

Since two different laboratories were used and samples were analyzed at different times, some variability in the results was expected. To ensure that the data from these two laboratories is comparable, a set of pretreatment samples (April 23-25, 2013) were analyzed by both TA and CSM laboratories. These samples were collected from wells I-1, I-2, 1-4, EC-2, and EC-3. The results are provided in the supporting information (Table 2.S2). In summary, there was good agreement, approximately 1:1, between the two laboratories reported concentrations for all analytes except PFOS. CSM reported approximately 40% of the PFOS concentrations observed in the TA samples (Figure 2.S2). However, the discrepancy between the reported values of the two laboratories is proportional ($R^2 = 0.989$). Generally, the inter-laboratory discrepancies in PFOS concentrations are most likely related to different calibration or analytical methods rather than sample degradation, which would have yielded non-

detects or at least greater variability in lower concentration samples. To avoid bias, where available, both TA and CSM soil and groundwater concentrations are presented together in figures and tables. Also, as a conservative measure, only the (generally lower) CSM laboratory concentrations were used in the creation of PFAA groundwater isocontour maps.

Site Characterization

A detailed account of pretreatment VOC conditions is provided in Eberle et al. (2015). In brief, major VOC contamination was found in the approximate location of the zig-zag pit (Figure 2.1, Figure 2.S3). This source zone was subdivided into three 6.1 m x 9.1 m Test Cells (1, 2 and 3) with the highest levels of VOC contamination (soil and groundwater) found in Test Cell 1 (Figure 2.2). Test Cells 2 and 3 were used for preliminary AOP injection scheme testing in December 2012, while the major pilot test was performed in Test Cell 1 in April 2013-August 2013. Post-treatment monitoring of the entire site continued till February 2014.

Deep and shallow screened injectors, with 1.5 m long screened intervals, were utilized to distribute oxidant to both zones of the aquifer. For deep injection wells I-1, I-4, I-8, and I-10 the screened interval is between 3.4 m and 6.1 m bgs. For shallow injection wells I-5, I-6 I-7, and I-9 the screened interval is between 1.5 m and 3.7 m bgs. During remediation efforts in Test Cell 1, EC-1, EC-2, EC-3, EC-4, I-2, and I-3 were used as sentry wells to monitor the possible migration of oxidants and contaminants outside of the test cell. These wells had 1.5 m long screened intervals, located between 3.0 m

and 4.9 m bgs. In addition, wells U-16, U-17, U-18, U-19, and U-20 were dual screened wells equipped with multi-port samplers allowing for collection of groundwater samples from two aquifer depths. These wells were used to monitor conditions between 1.5 m to 3 m bgs and 3.7 m to 5.2 m bgs within Test Cell 1. When discussing samples from these dual screened wells, “D” will be added when referring to a sample from the deep screened portion of the well and “S” will be added when referring to a samples from the shallow unit, e.g. U-16D or U-16S. Finally, MW-2904 was a historic monitoring well screened from 2.4 m to 5.4 m bgs.

Despite previous remediation activities, no prior PFAA analyses of site soil or groundwater had been performed. To screen the site for PFAAs, a small number of soil (n = 5) and groundwater samples (n = 11), were analyzed during site characterization (April 2012 –December 2012). The results of this preliminary screening confirmed the presence of PFAA contamination in both groundwater and soil, particularly in Test Cell 1 (Table 2.S3, Table 2.S4). Total PFAA groundwater concentrations ranged from 27.9 µg/L to 331.8 µg/L. Samples from wells screened in the deeper aquifer unit, with the exception of MW-2904, showed higher levels of PFAA contamination than those screened in the shallower unit. PFOS was the major PFAA detected in groundwater from the deep screened wells, accounting for 34%-60% of the total PFAA mass. In groundwater samples taken from shallow screened wells, PFOS was less prevalent, accounting for 19% -30% of the total PFAA mass. PFAA soil concentrations ranged from 0.4 µg/L to 276.5 µg/L. PFAA soil contamination consisted predominantly of PFOS, PFOA,

and their C₆ analogs perfluorohexane sulfonic acid (PFHxS) and perfluorohexanoic acid (PFHxA).

Remediation Time-Line

ISCO remediation activities in Test Cell 1 were conducted from April 25, 2013 through August 16, 2013 and are described in Eberle et al. (2015). In brief, 50,740 L of peroxone activated persulfate was injected in Test Cell 1 in three separate injection events in 2013: 1) April 25 – May 19; 2) July 11-July 14; 3) August 12-16). The injection of 3020 L HPCD took place on May 15-16, 2014 during the first peroxone activated persulfate injections. Deep (I-1, I-4, I-8, I-10) and shallow (I-5, I-6, I-7, I-9) screened injectors were utilized to target both zones of the aquifer. However, daylighting of injected liquids occurred predominantly when using shallow zone wells I-5, I-6, and I-9, making I-7 the only reliable shallow injector well. This limited injection into the shallow zone explains why the deep zone received approximately twice the amount of oxidant as the shallow zone, 33,360 L versus 17,380 L, over the course of the study.

Sampling Timeline

A set of PFAA groundwater baseline samples was taken prior to remediation activities in Test Cell 1 (April 23-25, 2013). Samples were collected from 14 wells screened in the deep aquifer unit (EC-1, EC-2, EC-3, EC-4, U-16D, U-17D, U-18D, U19D, U-20D, I-1, I-2, I-3, and I-4). In addition 3 samples were taken from wells screened in the shallow aquifer unit (U-20S, I-5, and I-6). These baseline pre-treatment samples were compared to two sets of post-remediation groundwater samples, taken approximately

48 days (October 2-3, 2013) and 180 days (February 11-12, 2014) following completion of oxidant injections in Test Cell 1. The post-treatment samples were collected from the same wells as the pre-treatment samples, with additional samples collected from shallow screened wells (U-16S, U-17S, U-18S, and U-19S) and deep screened well MW-2904. In addition, a set of samples was collected during remediation activities in Test Cell 1. Specifically, deep screened wells EC-2, EC-3, I-1, I-2, and I-4, were sampled on July 9-10, 2013 and deep screened well U-16D was sampled on August 8, 2013. Post-treatment PFAA soil samples were collected on December 12-14, 2013. These samples were used for comparison with pre-treatment soil samples taken during the initial site characterization (Figure 2.3).

Spatial and Statistical Analysis

PFAA groundwater concentration isocontour maps were created in Surfer 11 (Golden Software, Golden, Colorado, USA) using Kriging interpolation of concentrations between sampling locations. Changes in PFAA groundwater concentrations were assessed for statistical significance using non-parametric related sample tests performed in SPSS Statistics 20 (IBM, Armonk, New York, USA). Friedman's Two-Way Analysis of Variance Test was used to identify significant differences between the three sampling events. When a significant difference was detected by the Friedman Test it was followed by a series of post-hoc Wilcoxon Sign Rank Tests to identify where the differences lied (ITRC 2013; Wiedemeire et al. 2006; Gilbert 1987). These temporal inter-well statistical tests were performed looking at all deep screened wells

simultaneously and as two spatially separate groups consisting of wells located within Test Cell 1 (U16D, U17D, U-18, U19D, U20D, MW-2904, I-1, and I-4) and wells located outside of Test Cell 1 (EC-1, EC-2, EC-3, EC-4, I-2, and I-3). These tests were performed for each of the 9 detected individual PFAA compounds as well as the sum, total PFAAs.

Results

PFAA in Groundwater

Pre-treatment groundwater analysis showed generally lower PFAA concentrations in April 2013 than in samples collected during site characterization in 2012 (Figure 2.4). This was particularly true at wells I-2 and U-16D where total PFAA concentrations were approximately 100 µg/L lower, 90% and 40% respectively (Figure 2.4). The large reductions seen at these wells are most likely due to preliminary injection scheme testing in Test Cells 2 and 3, conducted in December 2012 (Eberle et al. 2015b).

Total PFAA and PFOS contour maps showing pre- and post-treatment concentrations are presented in Figures 2.5 and 2.6. Pre-treatment samples from the deep zone show total PFAA concentrations greater than 100 µg/L throughout Test Cell 1 and a “hotspot” around injection well I-4, where concentrations reached above 200 µg/L (Figure 2.5A). PFOS was the major PFAA constituent in most of these deep samples, accounting for between 26% and 50% of total aqueous PFAAs (Figure 2.5B). Pre-treatment PFAA concentrations in the shallow screened wells (I-5, I-6, U-20S) were low (approximately 25 µg/L) (Figure 2.4, Figure 2.6A, Figure 2.S4) and PFOS represented a

smaller fraction of the total PFAA concentration (3-18%) than in samples taken from the deeper part of the aquifer (Figure 2.6B).

The first round of post-treatment sampling showed a decrease in total PFAA in almost all deep screened wells (Figure 2.6). For instance, greater than 40% reductions in total aqueous PFAAs were observed in wells I-1, I-4, U-16D, U-17D, and U-20D (Figure 2.4, Figure 2.5A). These reductions are primarily linked to decreases in PFOS and PFHxS concentrations (Figure 2.4, Figure 2.5B and Figure 2.5C). Shallow wells U-16S, U-17S, U-18S, and U-19S were sampled only during the post-treatment sampling (Figure 2.6, Figure 2.S4). The absence of pre-treatment samples from these wells limits the interpretation of these data points. Compared to nearby wells for which pre-treatment data is available, PFAA concentrations in shallow screened wells appear to have remained largely unaffected by remediation efforts in Test Cell 1 (Figure 2.4, Figure 2.6, and Figure 2.S4). The second round of post-treatment sampling showed that PFAA concentrations either remained unchanged or continued to decrease across the site (Figure 2.4, Figure 2.5A, and Figure 2.S4).

Comparing the final post-treatment sampling to pre-treatment conditions, the greatest changes in total PFAAs were observed within the deep zone of Test Cell 1. Total PFAA reductions of 64.2 µg/L to 128.1 µg/L (-50% to -79%) were observed at wells I-1, I-4, U-16D, U-17D, and U-20D. Smaller changes were observed at wells U-18D and U-19D, near the southern border of Test Cell 1, where reductions ranged from 31.1 µg/L and 38.7 µg/L (-21% to -32%). The decrease in total PFAA was predominantly due to

reductions in PFOS and PFHxS concentrations. Specifically, wells I-4, U-16D, U-17D, and U-20D showed reductions greater than or equal to 68% and 56% for PFOS and PFHxS respectively. For the deep-screened wells outside of Test Cell 1, changes in total PFAA were generally smaller, with decreases of 1 µg/L to 43 µg/L (-1% to -25%) observed at wells EC-1, EC-3, EC-4, and I-2. A larger reduction of 63 µg/L (-63%) was observed at well EC-2, while an increase of 60 µg/L (+283%) was observed at well I-3.

In the shallow zone, wells I-5 and I-6 showed negligible changes in total PFAA, with reductions of 6 µg/L and 9 µg/L (-11% and -18%), respectively. Concentrations at well U-20S increased by 39 µg/L (+29%). For shallow screened wells where only 48-day and 180-day post-treatment samples were taken, small decreases, 0.5-20.2 µg/L, in total PFAA were observed at wells U-16S, U-18S, and U-19S, exhibiting post-treatment stability similar to that seen at I-5 and I-6. A larger decrease was observed at well U-17S, where total PFAA concentrations dropped 69.7 µg/L (-52%) between the two post-treatment sampling events. These larger reductions at U-17S may have been caused by its close proximity to I-7, which received the most oxidant of any shallow injector well.

PFAA in Soil

In general, PFAA concentrations were lower in post-treatment soil samples than in pre-treatment samples. Pre-treatment total PFAA sample concentrations ranged from 0.4 to 276.5 µg/kg, while post-treatment sample concentrations ranged from 3.3 to 57.5 µg/kg (Table 2.S4, Table 2.S5). In the available paired pre- and post-treatment soil samples, all but one result showed reductions in PFAA soil concentrations after

treatment (Table 2.1). Post-treatment soil samples collected adjacent to wells U-16 (SB-122) and I-1 (SB-109) show reductions of 34.4 and 65.3 $\mu\text{g}/\text{kg}$ (-79.0% and -91.8%) relative to pre-treatment conditions. An increase of 2.9 $\mu\text{g}/\text{kg}$ was observed after treatment at well U-20, but was considered insignificant as the limit of quantification (LOQ) for the post-treatment sample was lower than the pre-treatment sample. PFHxS:PFOS ratios in post-treatment soils ranged from 0.25 to 2.69. These ratios are similar to those seen in post-treatment groundwater.

Laboratory studies suggest that PFAAs may sorb strongly to soils (Higgins & Luthy 2006; Ferrey et al. 2012). However, leaching of PFAAs from soil into groundwater has been observed in the laboratory (Enevoldsen & Juhler 2010; Ferrey et al. 2012) and is clearly indicated by PFAA detection in groundwater at FTAs. Chain length, organic carbon, electrostatic interactions, and pH have all been identified as factors affecting PFAA distribution (Higgins & Luthy 2006; Ferrey et al. 2012). As a result the use of solid-water distribution coefficients (K_d) has been recommended over soil organic carbon-water partitioning coefficients (K_{oc}), because it makes no assumptions about the mechanism of partitioning (3M et al. 2003).

	PRE	POST	PRE	POST	PRE	POST
Date:	9/26/12	12/13/13	9/25/12	12/13/13	4/17/12	12/13/13
Well ID:	U-20	SB-106	U-16	SB-112	I-1	SB-109
Depth (m):	1.8	1.8	3.0	3.0	1.2-4.3	3.0
PFBA	ND	0.41	0.84*	0.44	ND	1.53
PFPeA	ND	0.95	1.8	2.19	ND	0.64
PFHxA	0.37*	0.70	3.4	1.97	7	0.96
PFHpA	ND	0.19	ND	0.44	3	0.21
PFOA	ND	0.12	26	0.20	2	0.23
PFNA	ND	0.07	ND	0.05	1.1	< LOQ
PFDA	ND	0.03	ND	< LOQ	ND	< LOQ
PFBS	ND	0.07	0.83*	0.22	1	0.14
PFHxS	ND	0.31	6.7	1.40	12	1.44
PFOS	ND	0.41	1.5	1.74	45*	0.70
PFDS	ND	< LOQ	ND	< LOQ	ND	< LOQ
SUM:	0.37	3.26	41.07	8.65	71.1	5.85

Table 2.1: PFAA soil comparison of parallel soil borings pre- and post-remediation. Additional soil data is in the Supporting Information. Pre-treatment samples were analyzed by TA while post-treatment samples were analyzed by CSM. The minimum limit of quantification for pre-treatment samples taken in April 2012 and Sept 2013 was between 0.68-0.72 µg/kg for each PFAA analyte. The minimum limit of quantification for PFBA, PFHpA, PFOA, PFNA, PFDoA, PFBS, PFOS, and PFDS in the post treatment samples was 0.06 µg/kg. The minimum limit of quantification for PFPeA, PFHxA, PFDA, PFUdA, and PFHxS in post-treatment samples was 0.12 µg/kg. *= Analyte was positively identified, but the quantitation is an estimate.

Currently, there is little field-based data on the partitioning of PFAAs in the subsurface (Mcguire et al. 2014). In the present study field-based PFAA log K_d were calculated for three pre-treatment and 14 post-treatment paired soil and groundwater samples. These values were calculated using the measured groundwater concentrations (µg/L) and soil concentrations (µg/kg), adjusted for moisture content. The resulting log K_d values, as well as ranges of values observed, are presented in Table 2.2. Negative log K_d values were observed for most analytes both pre- and post-treatment, indicating that PFAAs were weakly sorbed to soil at the training area throughout the demonstration.

Because pre-treatment and post-treatment paired soil and groundwater samples were taken between 8 days and 78 days apart, these values have limitations and should be viewed as estimates.

Analyte	Pre-Treatment			Post-Treatment		
	AVE log K_d	log K_d range	n	AVE log K_d $\pm$ SD	log K_d range	n
PFBA	-0.44	-0.78 – -0.10	2	-0.51 $\pm$ 0.29	-1.09 – -0.12	14
PFPeA	-0.65	-0.89 – -0.41	2	-0.72 $\pm$ 0.42	-1.65 – -0.03	14
PFHxA	-0.43	-0.81 – -0.18	3	-0.81 $\pm$ 0.45	-1.95 – -0.13	14
PFHpA	-0.20	-0.28 – -0.13	2	-0.78 $\pm$ 0.44	-1.87 – -0.24	14
PFOA	-0.28	-0.65 – 0.09	3	-0.76 $\pm$ 0.43	-1.58 – -0.17	14
PFNA	0.23	N/A	1	-0.47 $\pm$ 0.38	-1.03 – 0.15	13
PFBS	-0.43	-1.19 – 0.23	3	-0.71 $\pm$ 0.35	-1.54 – -0.28	14
PFHxS	-0.36	-0.82 – 0.16	3	-0.77 $\pm$ 0.47	-1.99 – -0.16	14
PFOS	-0.76	-2.12 – -0.03	3	-0.52 $\pm$ 0.53	-1.49 – 0.39	14
PFBA	-0.44	-0.78 – -0.10	2	-0.51 $\pm$ 0.29	-1.09 – -0.12	14

Table 2.2: Field-based partition coefficients and ranges for PFAAs for pre- and post-demonstration samples. Pre-treatment K_d are based on sediment samples collected in April 2012 and September 2012 and on groundwater samples collected in April 2012 and December 2012, respectively. Post-treatment K_d are calculated from groundwater samples collected in February 2014 and soil samples collected in January 2014.

PFAA Precursors

The conversion of PFAA-precursors to more recalcitrant PFAAs may be a concern when using ISCO. The occurrence of this conversion can be studied by inspecting the mass ratio of PFHxS:PFOS. In the original 3M AFFF, most likely used by the military at this site, that ratio was approximately 1:10, although variations likely occurred (Backe et al. 2013; Houtz et al. 2013). An increase in the ratio of PFHxS:PFOS may indicate transformation of C₆ precursor compounds to PFHxS.

In the case of the groundwater, samples taken during site characterization (April 2012 – December 2012) showed PFHxS:PFOS ratios already elevated relative to those found in the original AFFF. That is, PFHxS:PFOS in deep screened wells ranged from 0.22-0.99, while ratios in shallow screened wells ranged from 1.00-1.83. These higher PFHxS:PFOS ratios, particularly those in the shallow wells, could be indicative of *in situ* generation of PFHxS from precursors as a result of aerobic biological processes in the more oxygenated upper aquifer unit (Houtz et al. 2013; McGuire et al. 2014).

Figures 2.5D and 2.6D show the ratio of PFHxS:PFOS throughout the remediation effort. Based on pre- and post-treatment PFHxS:PFOS ratios, there is little evidence for ISCO induced transformation of precursor compounds. That is, ratios of PFHxS:PFOS remained less than 3 in all pre-treatment and post-treatment samples collected from deep screened wells. Furthermore, where increases in the ratio of PFHxS:PFOS occurred, it was usually due to decreases in PFOS concentrations rather than increases in the concentration of PFHxS (Figure 2.5, Figure 2.58). Ratios of shallow zone pre- and post-treatment samples at wells I-5, I-6, and U-20S were less than 4. PFHxS:PFOS ratios

greater than 4 were found at wells U-17S, U-18S, and U-19S (Figure 6D). However, without pre-treatment samples it is impossible to determine if these higher ratios are due to ISCO activity in Test Cell 1 or if ratios were already higher in this area prior to treatment.

Well I-2 is the only well where both pre- and post-treatment samples were analyzed for precursors by the TOP assay. For the pre-treatment sample taken in November 2012, significant production of perfluorobutyric acid (PFBA), perfluoropentanoic acid (PFPeA), and PFHxA was observed (Table 2.S6). The largest increase was observed for PFHxA, which increased by 111.7 µg/L. The production of PFHxA in the TOP assay is consistent with the 3M AFFF formulations thought to have been used at the site (Houtz et al. 2013). The C₆ precursors were likely perfluorohexane sulfonamide amine and perfluorohexane sulfonamide amino carboxylate as 3M AFFF were electrochemical-based (Houtz et al. 2013).

In I-2 post-treatment samples collected in October 2013 and February 2014, no PFBA or PFPeA precursors were observed. Although production of PFHxA was observed in both samples it was much less, 2.8 µg/L and 6.7 µg/L respectively, than in the pre-treatment I-2 sample. These findings suggest that PFBA, PFPeA, and PFHxA precursors were degraded or destroyed as a result of the ISCO pilot test. February post-treatment samples from wells EC-3, U-16D, U-18D, U-20D, and I-4 also showed small production of PFHxA (3-9 µg/L) consistent with that seen in the I-2 samples (Table 2.S6). This suggests that similar levels of PFHxA precursors remain throughout the site. Despite the

identification of their precursors prior to the demonstration, significant increases in PFBA, PFPeA, and PFHxA were not observed in post-treatment groundwater samples. Thus, based on the available data, ISCO induced conversion of precursors to PFAAs does not appear to have occurred.

Discussion

The use of ISCO to treat the VOC priority pollutants at the site resulted in decreases in PFAA co-contaminant concentrations. Friedman's Test results confirmed that statistically significant differences in total PFAA groundwater concentrations exist between the pre-treatment and two post-treatment samplings when looking at all wells simultaneously ($K = 3$, $N = 13$, $df = 2$, $\chi^2 = 12.923$, $p = 0.002$). Post-hoc Wilcoxon Sign Rank Tests showed that differences between the pre- and post- treatment total PFAA concentrations in the deeper aquifer zone were statistically significant for both post-treatment sampling events (APR 2013 vs OCT 2013, $N = 13$, $Z = -2.201$, $p = 0.028$, $r = -0.43$) (APR 2013 vs FEB 2013, $N = 13$, $Z = -2.691$, $p = 0.007$, $r = -0.53$). However, changes between the 48 day and 180 day post-treatment sampling events were not significant (OCT 2013 vs FEB 2014, $N = 14$, $Z = -0.973$, $p = 0.331$, $r = -0.18$). Similar findings were observed for the 9 individual PFAA compounds (Table 2.S7, Table 2.S8). These findings indicate that total aqueous PFAA concentrations were significantly lower after ISCO treatment and that these lower levels are stable and represent a new baseline for the site. Possible explanations for the observed decreases include dilution, displacement, sorption, and oxidative destruction.

When separated into two groups consisting of wells located within and outside of Test Cell 1, there was a statistically significant difference in total PFAA concentrations for wells within Test Cell 1 ($K = 3$, $N = 7$, $df = 2$, $\chi^2 = 10.571$, $p = 0.005$). For wells outside of the treatment area, there was no statistically significant difference in total PFAA groundwater concentrations ($K = 3$, $N = 6$, $df = 2$, $\chi^2 = 4.333$, $p = 0.115$). Similar to tests using all wells, the post-hoc Wilcoxon Ranked Sign Test showed a significant difference between the pre-treatment and two post treatment samplings, (APR 2013 vs OCT 2013, $N = 7$, $Z = -2.366$, $p = <0.05$, $r = -0.63$) (APR 2013 vs FEB 2013, $N = 7$, $Z = -2.366$, $p = <0.05$, $r = -0.63$); while the difference between the two post-treatment samplings was not statistically significant (OCT 2013 vs FEB 2014, $N = 8$, $Z = -0.140$, $p = >0.05$, $r = -0.04$). These findings suggest that displacement was not the cause of the decreases in aqueous PFAA concentrations as changes in PFAA groundwater concentrations were localized to within the treatment area. If flushing of PFAAs outside of the treatment area were the cause of these reductions then changes in PFAA concentrations at sentry wells surrounding the treatment area would be expected.

In addition to pre- and post-remediation samples, a number of samples were also taken in July and August during the actual ISCO treatment. Samples from wells within Test Cell 1 (Figure 2.4, wells I-1, I-4, and U-16D) had lower PFAA concentrations than both pre- and post-treatment samples. These finding are most likely due to temporary dilution due to the injection of treatment solutions. This interpretation is supported by the fact that similar decreases were not observed in samples taken from wells outside of Test Cell 1 (Figure 4, wells EC-2, EC-3, I-2) at the same time. While there

is evidence for short term dilutions, most likely due the injection of treatment solutions, it does not account for the long term decreases in PFAA concentrations observed in the October 2013 and February 2014 samplings, 48 days and 180 days after completion of the test.

These findings imply that the significant reductions in PFAA groundwater concentrations in the deep unit were not caused purely by displacement or dilution. Although the effects of dilution may have been observed within Test Cell 1 during the treatment, a similar trend was not observed at monitoring wells outside of Test Cell 1. Due to the shallow hydraulic gradient and tidal action present at the site, migration of injected solutions outside of the test area was minimal (Eberle et al. 2015). As a result, physical processes such as flushing and dilution are unlikely to be the sole cause of the observed long term reductions in aqueous PFAAs.

One-dimensional column test have shown that the application of ISCO is likely to result in changes in PFAA transport (McKenzie et al. 2015). Permanganate and catalyzed hydrogen peroxide have been shown to increase PFAA transport while persulfate based ISCO has been shown to decreased PFAA mobility. In the present study, reductions in PFAA concentrations were observed in both site soil and groundwater samples (Table 2.1 and Figure 2.5). Comparison of pre- and post-treatment K_d values show that the soil-groundwater distribution of PFAAs was not substantially altered by the application of ISCO (Table 2.2). This suggests that the increased sorption of PFAAs as a result of persulfate based ISCO is unlikely to be the sole cause of the observed reductions.

The formation of cyclodextrin inclusion complexes with PFAAs, such as PFOA and PFBA, has been observed in the laboratory (Karoyo et al. 2011; Karoyo et al. 2014). Based on the available data, the injection of HPCD during this ISCO pilot test had no measurable impact on aqueous PFAA concentrations. Solubility enhancement was not expected either, given the dominance of VOCs over PFAAs at the site, which would have led to preferential complexation of VOCs by HPCD.

Since dilution, displacement, and sorption alone do not appear to fully account for the decrease in aqueous PFAAs, our results suggest that oxidative destruction of PFAAs may have occurred. Strongly oxidizing conditions, ORP between 400 mV and 700 mV, were still present in the majority of deep screened wells during the final February 2014 post-treatment sampling 6 months after the final oxidant injections (Eberle et al. 2015b). This long period of sustained oxidative conditions may have provided an environment in which slow oxidative decomposition of PFAAs could occur.

Future work is needed to confirm these findings and determine if they are typical of ISCO application at PFAA contaminated sites. In particular a greater number of pre-treatment soil and precursor TOP assay samples would help further elucidate the mechanism of PFAA reductions. In addition pre and post-treatment fluoride data would provide additional evidence for or against oxidative decomposition as the mechanism of PFAA reduction. Nevertheless, based on the available data our results suggest that slow oxidative decomposition of PFAAs may be possible in the field when using activated persulfate based ISCO technologies.

Conclusions

The ISCO remediation strategy applied at this site was based on the injection of a patented peroxone activated persulfate AOP (OxyZone®). PFAA concentrations decreased significantly following treatment with little evidence of rebound. PFAA concentrations in down gradient wells, outside of the test area, did not increase during treatment. Aqueous reductions in PFAAs were also mirrored by decreases in soil PFAA concentrations. Changes to PFAA mobility were not observed as pre- and post-treatment K_d values were similar. These findings suggest that reductions in PFAA groundwater concentrations may have been due to degradation by the oxidant rather than hydraulic displacement or increased sorption.

Based on our findings the use of an AOP to treat VOC *in situ* had no discernible negative impacts on PFAA co-contaminants at the site. Our observations suggest that slow oxidative PFAA decomposition may occur in the field when utilizing sodium persulfate based ISCO. Future work is needed to determine if these findings are typical or atypical of ISCO application at sites where PFAA co-contaminants are present. This information is valuable for site managers who may consider using activated persulfate based ISCO to treat VOC contamination at sites where PFAAs are known or likely to be present.

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Supporting Information

Table 2.S1: Chemical Structure of PFAAs detected at the site

Table 2.S2: Comparison of TA and CSM laboratory samples

Table 2.S3: Groundwater concentrations observed during site characterization

Table 2.S4: Soil PFAA Concentrations in pre-treatment soil borings

Table 2.S5: Soil PFAA concentrations in post-treatment soil borings

Table 2.S6: Results of precursor TOP assay

Table 2.S7: Summary of Friedman Test Analysis Results.

Table 2.S8: Summary of Wilcoxon Ranked Sign Test Analysis Results.

Figure 2.S1: Geologic cross sections

Figure 2.S2: Comparison of TA and CSM laboratory samples

Figure 2.S3: Detailed Site Plan

Figure 2.S4: Groundwater PFAA concentrations for individual wells not included in the discussion

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Figures

Figure 2.1: Field Site. A pilot test was conducted in the approximate location of the former zig-zag Fire Pit. Image modified from ECC & Malcolm Pirnie Inc. 2008.

Figure 2.2: Pilot test area showing the three test cells. Preliminary injection scheme tests were performed in Test Cell 2 and Test Cell 3 (December 2012). The major pilot test was performed in Test Cell 1.

Figure 2.3: Location of pre- and post-remediation PFAA soil samples.

Figure 2.4: Selected individual well PFAA groundwater concentrations. TA denotes a sample analyzed by TestAmerica, CSM denotes the CSM laboratory. The symbols "*" and "#" denote that the presented data is the average of 2 or 3 duplicate samples respectively.

Figure 2.5: Isocontour maps for samples collected from deep screened wells. A = total PFAA. B = PFOS. C = PFHxS. D = PFHxS:PFOS. Only wells that were sampled are shown. All samples were analyzed by the CSM laboratory

Figure 2.6: Isocontour maps based off of samples from shallow screened wells. A = total PFAA. B = PFOS. C = PFHxS. D = PFHxS:PFOS. Only wells that were sampled are shown and all samples were analyzed by the CSM laboratory.

Supporting Information: Tables

Perfluorocarboxylates	
Perfluorobutyric acid (PFBA)
Perfluoropentanoic acid (PFPeA or PFPA)
Perfluorohexanoic acid (PFHxA)
Perfluoroheptanoic acid (PFHpA)
Perfluorooctanoic acid (PFOA)
Perfluorononanoic acid (PFNA)
Perfluorodecanoic acid (PFDA)
Perfluoroundecanoic acid (PFUdA or PFUndA or PFUnA)
Perfluorododecanoic acid (PFDoA or PFDodA)
Perfluorosulfonates	
Perfluorobutane sulfonic acid (PFBS)
Perfluorohexane sulfonic acid (PFHxS)
Perfluorooctane sulfonic acid (PFOS)
Perfluorodecane sulfonic acid (PFDS)

Table 2.S1: Chemical Structure of PFAAs detected at the site and common abbreviations. In addition to these compounds, the Test America laboratory also screened for perfluorotetradecanoic acid (PFTeA), perfluorotridecanoic acid (PFTriA), and perfluorooctanesulfonamid (FOSA). The CSM laboratory screened for perfluoroheptanesulfonate (PFHpS). However, none of these additional compounds were detected in site soil or groundwater.

Well-ID	Date	Lab	PFBA	PFPeA	PFHxA	PFHpA	PFOA	PFNA	PFBS	PFHxS	PFOS	Total PFAA	AVE TOTAL
EC-2	4/23/2013	TA	2.3	13.0	17.0	6.5	10.0	0.9	2.7	40.0	92.0	184.4	161.7
	4/25/2013	CSM	3.3	11.1	19.7	6.6	6.9	0.5	3.5	48.0	39.4	139.0	
EC-3	4/23/2013	TA	4.2	12.0	16.0	9.2	14.0	1.5	3.0	46.0	150.0	255.9	217.3
	4/24/2013	CSM	3.9	14.2	21.4	6.7	11.4	0.7	4.5	59.4	56.6	178.7	
I-1	4/23/2013	TA	2.1	21.0	28.0	7.4	4.3	0.2	1.2	25.0	9.5	98.7	97.1
	4/25/2013	CSM	2.4	21.2	27.9	6.2	3.7	0.3	1.4	24.9	7.5	95.4	
I-2	4/23/2013	TA	2.4	9.9	15.0	5.4	4.8	0.2	5.0	23.0	12.0	77.7	75.3
	4/25/2013	CSM	2.7	13.0	17.9	3.8	3.3	0.1	3.1	20.4	8.6	72.8	
I-4	4/23/2013	TA	6.2	18.0	25.0	11.0	17.0	1.7	4.3	64.0	200.0	347.2	286.4
	4/25/2013	CSM	4.3	17.3	25.2	9.1	11.6	0.8	5.0	66.4	86.0	225.6	

Table 2.S2: Comparison of TA and CSM laboratory samples collected between April 23 and April 25 2013. These samples are prior to remediation activities in Test Cell 1.

Well ID	Date	Lab	PFBA	PFPeA	PFHxA	PFHpA	PFOA	PFNA	PFBS	PFHxS	PFOS	Total PFAA
EC-1	4/24/12	TA	1	3.9	6.1	1.7	2.4	0.1	1.8	19	25	61.0
EC-2	4/24/12	TA	1.9	7	10	3.2	5.4	0.6	2.6	39	130	199.7
I-1	4/24/12	TA	2.6	10	14	5.7	8.9	0.7	2.1	32	62	138.0
I-2	4/24/12	TA	2.4	14.0	27	6.7	13	0.4	3.8	57	160	270.3
I-2*	11/19/12	CSM	3	11.3	21.9	5.6	11.2	0.4	7.4	85.1	134.5	280.4
I-4	12/4/12	TA	4	12	17	5.8	12	0.9	6.4	80	110	248.1
I-5	12/4/12	TA	0.7	5	6.5	1.2	2	0.1	2.1	13	7.1	37.7
I-6	12/4/12	TA	1.4	4.9	6.4	1.6	3	0.2	2.2	13	13	45.7
MW-2904	12/4/12	TA	0.6	2.5	2.9	0.6	1.2	0.1	1.1	9.4	9.5	27.9
U-16D	12/11/12	TA	5.1	14	22	11	21	1.7	13	44	200	331.8
U16S	12/11/12	TA	1.2	7.7	8	1.4	2.1	0.2	1.9	19	18	59.5

Table 2.S3: Groundwater concentrations observed during site characterization.

*Average of three duplicate samples.

ID	units	I-1	I-2	U-12	U-16	U-20
Depth	m	1.2-4.3	1.2-4.3	2.1	3.0	1.8
PFBA	µg/Kg	ND	1.9	0.43*	0.84	ND
PFPeA	µg/Kg	ND	5.5	0.36*	1.8	ND
PFHxA	µg/Kg	7 [#]	18	1	3.4	0.37*
PFHpA	µg/Kg	3	5	ND	ND	ND
PFOA	µg/Kg	2	6.7	ND	26	ND
PFNA	µg/Kg	1.1	ND	ND	ND	ND
PFDA	µg/Kg	ND	ND	ND	ND	ND
PFBS	µg/Kg	1	6.4	0.61*	0.83	ND
PFHxS	µg/Kg	12	83	1.2	6.7	ND
PFOS	µg/Kg	45*	150 [#]	ND	1.5	ND
PFDS	µg/Kg	ND	ND	ND	ND	ND
SUM	µg/Kg	71.10	276.50	3.60	41.07	0.4

Table 2.S4: Soil PFAA concentrations in pre-treatment soil borings. Soil sample locations are shown in Figure 3.3. All PFAA concentrations are in µg/kg. Soil samples were collected during well installation. Wells I-1 and I-2 were installed and collected in April 2012; U-12, U-16 and U-20 were collected in Sept. 2012. The minimum limit of quantification detection for pre-treatment samples was between 0.68-0.72 µg/kg for each PFAA analyte. (*) indicates that the compound was positively identified, the quantitation is an estimate. ([#]) indicates that the compound was integrated manually. These samples were analyzed by TA.

ID	SB-101	SB-105	SB-106	SB-106	SB-107	SB-107	SB-108	SB-108	SB-109	SB-111	SB-112	SB-112	SB-114	SB-114
Depth (m)	4.3	1.8	1.8	4.3	1.8	4.3	1.8	4.3	3	4.3	1.8	3	1.8	4.3
PFBA	0.59	0.24	0.41	1.31	0.28	0.45	0.35	0.46	1.53	1.2	0.65	0.44	1.68	1.05
PFPeA	1.63	0.41	0.95	7.07	1.11	1.32	1.3	1.45	0.64	4.7	2.45	2.19	10.03	4.95
PFHxA	2.5	0.41	0.7	9.43	2.24	2.44	2.13	2.18	0.96	6.12	2.81	1.97	9.75	5.52
PFHpA	0.89	0.12	0.19	2.08	0.4	0.71	0.34	0.85	0.21	2.42	0.61	0.44	2.28	1.93
PFOA	1.11	0.12	0.12	0.96	0.24	0.7	0.18	1.04	0.23	2.62	0.34	0.2	1.77	2.87
PFNA	0.07	0.02	0.07	0.14	0.03	0.2	0.03	0.15	< LOQ	0.29	0.06	0.05	0.3	0.33
PFDA	< LOQ	< LOQ	0.03	0.04	< LOQ	< LOQ	< LOQ	< LOQ	< LOQ	< LOQ	< LOQ	< LOQ	0.05	0.18
PFBS	0.66	0.08	0.07	0.6	0.23	0.25	0.2	0.29	0.14	0.83	0.45	0.22	0.58	0.67
PFHxS	8.08	0.83	0.31	5.08	2.11	3.99	1.48	4.83	1.44	11.85	2.57	1.4	3.63	16.17
PFOS	6.83	0.51	0.41	4.21	1.14	15.85	0.55	7.49	0.7	17.5	3.63	1.74	4.9	23.78
PFDS	BLOQ	BLOQ	< LOQ	< LOQ	< LOQ	< LOQ	< LOQ	< LOQ	< LOQ	< LOQ	< LOQ	< LOQ	< LOQ	< LOQ
Total PFAA	22.37	2.75	3.3	30.9	7.79	25.92	6.56	18.74	5.85	47.53	13.57	8.64	34.96	57.45

Table 2.S5: Soil PFAA concentrations in post-treatment soil borings. Soil sample locations are shown in Figure 3.3. All PFAA concentrations are in µg/kg. All soil borings were collected December 12-14 2013. The minimum limit of quantification (LOQ) for PFBA, PFHpA, PFOA, PFNA, PFDoA, PFBS, PFOS, and PFDS in the post treatment samples was 0.06 µg/kg. The LOQ for PFPeA, PFHxA, PFDA, PFUdA, and PFHxS in post-treatment samples was 0.12 µg/kg. These soil samples were analyzed by the CSM laboratory.

Sample	Date	PFBA	PFPeA	PFHxA	PFHpA	PFOA	PFNA	PFBS	PFHxS	PFOS
		Δ ug/L								
I-2	11/19/2012	8.73	12.87	111.7	NS	NS	NS	1.81 ⁺	NS	NS
I-2	10/3/2013	NS	NS	2.8	NS	NS	NS	NS	NS	NS
I-2	2/11/2014	NS	NS	6.1	NS	NS	NS	NS	NS	NS
EC-3	2/11/2014	NS	NS	9.1	NS	NS	NS	NS	NS	NS
U-16D	2/12/2014	0.81	NS	5.0	NS	NS	NS	NS	NS	NS
U-18D	2/12/2014	NS	NS	9.0	NS	NS	NS	NS	NS	NS
U-20D	2/12/2014	NS	NS	4.2	NS	NS	NS	NS	NS	NS
I-4	2/13/2014	NS	NS	5.2	NS	NS	NS	NS	NS	NS

Table 2.S6: Results of precursor TOP assay. Positive values indicate the net amount of each compound formed from precursors during the TOP assay. NS indicates no significant difference between compound concentrations before and after oxidation ($p < 0.05$: 2 tailed t test). (†) The sulfonates (PFSAs) are generally not thought to be produced in the TOP assay, so the detection of low PFBS is likely an artifact due to sampling handling or analytical error.

Well Groups	Sampling Events Being Compared	K	N	Data Points	p Value									
					sumPFAAs	PFOS	PFHxS	PFBS	PFNA	PFOA	PFHpA	PFHxA	PFPeA	PFBA
ALL	APR vs OCT vs FEB	3	13	39	0.002	0.012	0.002	0.009	0.002	0.001	0.003	0.007	0.008	0.035
Outside Test Cell	APR vs OCT vs FEB	3	6	18	0.115	0.311	0.115	0.513	0.223	0.119	0.223	0.311	1.83	0.607
Inside Test Cell	APR vs OCT vs FEB	3	7	21	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.012	1.71	0.032

Table 2.S7: Summary of Friedman Test Analysis Results. Bolded values indicate significance at $p < 0.05$.

Wells Being Compared	Sampling Events Being Compared	K	N	Data Points	z Value									
					Total PFAAs	PFOS	PFHxS	PFBS	PFNA	PFOA	PFHpA	PFHxA	PFPeA	PFBA
ALL Wells	APR vs OCT	2	13	26	-2.201	-2.201	-2.201	-1.99	-2.14	-2.27	-2.201	-2.341	-1.818	-1.363
	APR vs FEB	2	13	26	-2.691	-2.341	-2.76	-2.41	-2.41	-2.51	-2.621	-2.132	-2.621	-2.275
	OCT vs FEB	2	14	28	-0.973	-1.601	-1.224	-1.13	-0.85	-0.53	-0.282	-0.722	-0.408	-0.408
Outside Test Cell	APR vs OCT	2	6	12	-0.734	-0.314	-0.734	-0.31	-0.53	-0.94	-0.734	-0.943	-0.943	-0.734
	APR vs FEB	2	6	12	-1.153	-0.524	-1.572	-1.15	-0.94	-1.21	-1.153	-0.314	-0.943	-0.524
	OCT vs FEB	2	6	12	-1.153	-1.572	-1.363	-1.15	-1.26	-1.36	-0.943	-0.524	-0.105	-0.524
Inside Test Cell	APR vs OCT	2	7	14	-2.366	-2.366	-2.366	-2.37	-2.37	-2.37	-2.366	-2.366	-1.947	-1.183
	APR vs FEB	2	7	14	-2.366	-2.366	-2.366	-2.37	-2.37	-2.37	-2.366	-2.197	-2.366	-2.201
	OCT vs FEB	2	8	16	-0.14	-0.84	-0.28	-0.56	-0.07	-0.42	-0.42	-0.420	-0.56	-0.140
Wells Being Compared	Events Being Compared	K	N	Data Points	r Value									
					Total PFAAs	PFOS	PFHxS	PFBS	PFNA	PFOA	PFHpA	PFHxA	PFPeA	PFBA
ALL Wells	APR vs OCT	2	13	26	-0.43	-0.43	-0.43	-0.39	-0.42	-0.45	-0.43	-0.46	-0.36	-0.27
	APR vs FEB	2	13	26	-0.53	-0.46	-0.54	-0.47	-0.47	-0.49	-0.51	-0.42	-0.51	-0.45
	OCT vs FEB	2	14	28	-0.18	-0.30	-0.23	-0.21	-0.16	-0.10	-0.05	-0.14	-0.08	-0.08
Outside Test Cell	APR vs OCT	2	6	12	-0.21	-0.09	-0.21	-0.09	-0.15	-0.27	-0.21	-0.27	-0.27	-0.21
	APR vs FEB	2	6	12	-0.33	-0.15	-0.45	-0.33	-0.27	-0.35	-0.33	-0.09	-0.27	-0.15
	OCT vs FEB	2	6	12	-0.33	-0.45	-0.39	-0.33	-0.36	-0.39	-0.27	-0.15	-0.03	-0.15
Inside Test Cell	APR vs OCT	2	7	14	-0.63	-0.63	-0.63	-0.63	-0.63	-0.63	-0.63	-0.63	-0.52	-0.32
	APR vs FEB	2	7	14	-0.63	-0.63	-0.63	-0.63	-0.63	-0.63	-0.63	-0.59	-0.63	-0.59
	OCT vs FEB	2	8	16	-0.04	-0.21	-0.07	-0.14	-0.02	-0.11	-0.11	-0.11	-0.14	-0.04

Table 2.S8: Summary of Wilcoxon Ranked Sign Test Analysis Results. Z values are based on positive ranks. $|Z| > 1.960$ = significant at the 0.05 level (2-tailed). Bolded values indicate a significant difference. Effect size (r values) are also provided.

Supporting Information: Figures

Figure 2.S1: Geologic cross sections. Vertical dimensions are exaggerated by 2x. Data is compiled from borings performed in 2012 and 2013 during site characterization and historical borings.

Comparison of TestAmerica and CSM Reported PFAA Concentrations April 23-25, 2013

Figure 2.S2: Comparison of laboratory PFAA concentrations reported by TestAmerica and CSM. Except for PFOS, there is a good consistency between the labs for all other analytes.

For PFBA, PFPeA, PFHxA, PFHpA, PFNA, PFBS, and PFHxS, variations in measured PFAA concentrations were less than 14 µg/L. However, much larger variations were observed for PFOS, particularly in the more heavily PFAA contaminated samples (Figure S2). In samples from I-1 and I-2, PFOS concentrations showed less than 4 µg/L variation between the two laboratories. However, for EC-2, EC-3 and I-4, variations in reported concentrations were 53, 93 and 114 µg/L, respectively. Despite these large differences at higher concentrations, the discrepancy between the reported values of the two laboratories is proportional ($R^2 = 0.989$) with CSM reporting approximately 40% of the PFOS concentrations observed in the TA samples (Figure 2.S2). The nature of this

discrepancy is unclear. It is difficult to identify a mechanism whereby such a consistent proportion of PFOS would have been sorbed, or degraded in the CSM samples during storage; particularly given the inert nature of these compounds. If natural processes were the cause we would expect to see some evidence in the concentrations of the other analytes. However, the maximum discrepancy between the two laboratories for all other PFAA is only 14 µg/L (Table 2.S2; Figure 2.S2). Furthermore, if natural processes were responsible, it is unlikely that any PFOS would have been detected in the low concentration samples (Wells I-2 and I-2) in the CSM samples analyzed 410 d after the TA samples. Therefore we believe this discrepancy is most likely related to different calibration or analytical method issues rather than sample degradation, which would have yielded non-detects or at least greater variability in lower PFAA concentration samples.

Figure 2.S3: Site Plan showing approximate location of former fire training structures as well as preexisting monitoring wells. The location of the remediation test cells and geologic cross sections are also shown.

Figure 2.S4: Groundwater PFAA concentrations for individual wells not included in the discussion.

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**Peroxone Activated Persulfate Treatment of 1,4-Dioxane in the Presence of Chlorinated
Solvent Co-Contaminants**

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Abstract

1,4-dioxane is often found as a co-contaminant with chlorinated volatile organic compounds (VOCs) at solvent release sites such as landfills, solvent recycling facilities, or fire training areas. Historically, soil and groundwater samples were not routinely analyzed for 1,4-dioxane and therefore the number of known 1,4-dioxane sites is still increasing. Due to its co-occurrence with chlorinated compounds, remediation strategies are needed that simultaneously treat both 1,4-dioxane as well as chlorinated VOC co-contaminants. In this proof of concept laboratory study, the fate of 1,4-dioxane was examined during the targeted destruction of aqueous phase VOC, using a peroxone activated persulfate (PAP) chemical oxidation method. Bench-scale experiments were carried out to evaluate the treatability of 1,4-dioxane as both a single-contaminant and in the presence of trichloroethene (TCE), and 1,1,1-trichloroethane (1,1,1-TCA). Possible dependencies on oxidant concentration and reaction kinetics were studied. The oxidative destruction of 1,4-dioxane, TCE and 1,1,1-TCA in single-contaminant batch systems followed pseudo-first-order reaction kinetics and even at the most dilute oxidant concentration lasted for at least 13 days. The rate of oxidation for each contaminant increased linearly with increasing persulfate concentration over the range of oxidant concentrations tested. The rate of oxidative destruction, from most easily degraded to least, was: TCE > 1,4-dioxane > 1,1,1-TCA. Oxidation rates were up to 87% slower in a mixture of these three compounds. Although additional tests are necessary, our data suggest that PAP oxidation of 1,4-dioxane might aid in the cleanup of VOC contaminated sites.

Keywords: 1,4-Dioxane, Activated Persulfate, Peroxone, 1,1,1-Trichloroethane, Advanced Oxidation Process

1. Introduction

1,4-dioxane is an emerging groundwater contaminant and a likely human carcinogen (IARC 1999; Stickney et al. 2003; Mohr et al. 2010; US EPA 2013c). EPA risk assessments indicate that a drinking water concentration of 0.35 µg/L represents a 10^{-6} cancer risk and the current screening level for 1,4-dioxane in tap water is 0.67 µg/L (US EPA 2013c). However, while 1,4-dioxane is regulated as a hazardous waste, there are currently no federal drinking water standards for this compound (U S EPA 2012). Due to this lack of regulation, 1,4-dioxane was not routinely monitored at solvent release sites. Furthermore, prior to 1997, reliable low-level (<100 µg/L) 1,4-dioxane analysis was not routinely available (Draper et al. 2000; Mohr et al. 2010). The lack of analyses and their limitations means that the scale of 1,4-dioxane subsurface contamination is still emerging.

In the past, 1,4-dioxane was primarily used as a stabilizer in chlorinated solvents. Nearly 90% of the 1,4-dioxane produced in 1985 was used to stabilize 1,1,1-trichloroethane (1,1,1-TCA) (US EPA 1995). 1,4-dioxane was added to 1,1,1-TCA at concentrations between 2% and 8% by volume to prevent solvent degradation caused by reactions with metal surfaces (Mohr 2001; Mohr et al. 2010). 1,4-dioxane has a higher boiling point (~101°C) than 1,1,1-TCA (~74°C), and as a result even higher 1,4-

dioxane concentrations are often found in 1,1,1-TCA residuals associated with vapor degreasing operations (Mohr 2001; Zenker et al. 2003; Mohr et al. 2010).

The association of 1,4-dioxane with 1,1,1-TCA is well documented. However, its association with trichloroethene (TCE) is a topic of debate (Mohr 2001; Zenker et al. 2003; Mohr et al. 2010). A survey of 20 wells in Kanagaw, Japan showed that detection of 1,4-dioxane was highly correlated with detection of 1,1,1-TCA ($R = 0.872$), while correlation with TCE was much weaker ($R = 0.023$) (Abe 1999). However, a recent survey of groundwater data from 49 U.S. Air Force installations found 64.4% of all 1,4-dioxane detections were observed in wells with records of TCE contamination, but without detection of 1,1,1-TCA (Anderson et al. 2012). In addition, 93.7% of all 1,4-dioxane detections were in wells with records of 1,1,1-TCA and/or TCE contamination (Anderson et al. 2012). These studies suggest that 1,4-dioxane can co-exist with 1,1,1-TCA, TCE, or more likely both. Hence, from the perspective of a site manager the presence of chlorinated volatile organic compounds (VOCs), particular 1,1,1-TCA or TCE, is a likely indicator of 1,4-dioxane contamination (Anderson et al. 2012). With the number of known 1,4-dioxane sites increasing, there is a need for cost-effective remediation technologies, particularly for simultaneously treating 1,4-dioxane and its co-contaminants TCE and 1,1,1-TCA.

1,4-dioxane is considered a recalcitrant contaminant that is difficult to remediate with common treatment technologies. Due to its low K_H and K_{OC} , air stripping and adsorption are generally considered poor treatment options for 1,4-dioxane

contaminated groundwater (Zenker et al. 2003; Otto & Nagaraja 2007; Mohr et al. 2010). 1,4-dioxane's recalcitrance and mobility limits monitored natural attenuation (MNA) treatment (ATSDR 2012). Enhanced bioremediation of 1,4-dioxane has been demonstrated in laboratory and field studies. However, the application of these technologies is limited by the fact that 1,4-dioxane-metabolizing bacteria are predominantly aerobic, making it a poor fit for the anaerobic conditions under which most VOCs degrade (Zenker et al. 2003; Otto & Nagaraja 2007; Mohr et al. 2010; ATSDR 2012). Furthermore, the presence of 1,1,1-TCA and dichloroethenes have been shown to inhibit the biodegradation of 1,4-dioxane by both metabolizing and co-metabolizing bacteria strains (Mahendra et al. 2013). Phytoremediation using hybrid poplars has been demonstrated as an effective treatment for shallow contamination, but its application may be limited by climactic and hydrogeological (i.e., depth to groundwater) conditions (Zenker et al. 2003; Mohr et al. 2010). Conventional chemical oxidation technologies with oxidants having a standard oxidation potential of less than 2.0 V are generally considered ineffective for the treatment of 1,4-dioxane. For example, oxidation via permanganate (1.7 V) is possible, but the reactions rates are very slow (half-life ($t_{1/2}$) > days) (Huling & Pivetz 2006; Waldemer & Tratnyek 2006; SERDP (Strategic Environmental Research and Development Program) 2011).

Advanced oxidation processes (AOPs), capable of producing hydroxyl and/or sulfate radicals, have been investigated for treating 1,4-dioxane. Currently, the most developed chemical oxidation treatments for 1,4-dioxane are hydroxyl radical based AOPs. These technologies include photocatalytic degradation (Hill et al. 1997; Mehrvar

et al. 2000; Mehrvar et al. 2001; Mehrvar & Anderson 2002; Coleman et al. 2007; Lam et al. 2007; Vescovi et al. 2010), sonochemical oxidation (Beckett & Hua 2000; Beckett & Hua 2003; Son et al. 2006), peroxone (Adams et al. 1994; Suh & Mohseni 2004), combined ultraviolet light and hydrogen peroxide (Maurino et al. 1997; Coleman et al. 2007), and combined photocatalytic and sonochemical oxidation (Nakajima et al. 2004; Nakajima et al. 2007). When applied in the field, these technologies are employed as *ex situ* treatments and take advantage of 1,4-dioxane's infinite solubility. While extraction and aboveground treatment of 1,4-dioxane using AOPs is well established as a viable remediation strategy, it is not without its limitations. *Ex situ* treatments may require years of continuous operation and may produce a waste water stream that must be properly discharged, making it logistically and monetarily impractical at some sites. As a result there is interest in developing alternative *in situ* AOP treatments for 1,4-dioxane, which may represent a more cost-effective solution at some sites.

Activated persulfate is an AOP that shows promise as an *in situ* 1,4-dioxane treatment. 1,4-dioxane plumes often consist of low-level contamination dispersed over a large area. Activated persulfate AOPs are promising because persulfate is more stable in the subsurface than hydrogen peroxide and ozone, and the sulfate radical is more stable than the hydroxyl radical; permitting oxidative solutions to travel further when injected in the subsurface (ITRC 2005; Huling & Pivetz 2006; Tsitonaki et al. 2010; SERDP 2011). The potentially larger radius influenced by injected activated persulfate solutions makes these treatments attractive for *in situ* remediation of 1,4-dioxane (Huling & Pivetz 2006; Tsitonaki et al. 2010; Mohr et al. 2010). Field practitioners have reported

success treating 1,4-dioxane *in situ* with activated persulfate (Block et al. 2004; FMC 2007; Cronk 2008; Paul et al. 2010). However, there are currently only a few studies in the literature detailing activated persulfate based 1,4-dioxane treatments amenable to *in situ* application (Félix-Navarro et al. 2007; Felix-Navarro et al. 2013; Zhao et al. 2014; Zhong et al. 2015).

This study investigates the fate of 1,4-dioxane and its common VOC co-contaminants TCE and 1,1,1-TCA during treatment with a novel peroxone activated persulfate (PAP) based AOP (U S EPA 1999; Ball 2010). Bench-scale laboratory experiments were conducted to evaluate the treatability of 1,4-dioxane as both a single compound and in the presence of TCE and 1,1,1-TCA co-contaminants at ambient temperatures (25°C). Possible dependencies on oxidant concentration, ionic strength, and reaction kinetics were studied in single compound and mixed compound systems. These studies were designed to advance our knowledge of the simultaneous treatment of aqueous phase 1,4-dioxane and chlorinated VOC co-contaminants.

2. Materials and Methods

2.1 Materials

The target contaminants were 1,4-dioxane (99.5% purity, ACROS), TCE, (99.5+% purity, Fisher Scientific), and 1,1,1-TCA (99.0+% purity, Fluka). Chemicals used for preparing, measuring, and quenching the PAP oxidant solution were purchased from Fisher Scientific and included sodium persulfate, sodium phosphate dibasic anhydrous, 30% hydrogen peroxide, potassium iodide, 1% starch indicator and 1N sodium

thiosulfate pentahydrate. Calcium chloride dihydrate was used to alter ionic strength and was also purchased from Fisher Scientific. 1,1,1-TCA, TCE, and pentafluorobenzene standards were obtained from Ultra Scientific. 1,4-dioxane and 1,4-dioxane-D8 standards were obtained from SPEX CertiPrep. Working standards were diluted in purge-and-trap grade methanol (99.9+% purity, Fisher Scientific). ACS grade methanol (99.8% purity, Fisher Scientific) was used for rinsing and cleaning of equipment. An incubator (Fisher Scientific) was used for regulating the sample temperature. Deionized water was prepared using a MilliQ water filtration system. Ozone was generated using a Pacific Ozone L11 Ozone Generator and ultra-high purity oxygen (Airgas, OX300).

2.2 Analytical

1,4-dioxane, TCE, and 1,1,1-TCA were analyzed by gas chromatography-mass spectrometry (GCMS) using a Shimadzu GC-17A/GCMS-QP5000 equipped with a Restek Rxi®-624Sil MS Column (30 m, 0.25 mmID, 1.4 μ m). Aqueous samples were injected into the GCMS via an OI Analytical Eclipse 4660 purge-and-trap sample concentrator equipped with a #7 trap (Tenax) and a 25 mL sparge vessel.

Analysis of 1,4-dioxane was performed in selected ion monitoring (SIM) mode. A 1,4-dioxane-D8 internal standard was used to correct for variations in purge efficiency. The following equation was used for sample correction

$$(1) C_a = C_i \times \left(\frac{M_a}{M_i} \right)$$

where C_a is the estimated concentration of the target analyte, C_i is the known concentration of the added internal standard, M_a is the measured concentration of the target analyte and M_i is the measured concentration of the internal standard. 1,4-dioxane samples with internal standard recovery less than 60% or greater than 140% were re-run until recovery was within the desired range. The purge- and-trap and GCMS conditions used for analysis of 1,4-dioxane are listed in the supporting information (Table 3.S1, Table 3.S2).

Analysis of TCE and 1,1,1-TCA was performed in Scan mode. A pentafluorobenzene internal standard tracked the purge efficiency of 1,1,1-TCA and TCE samples, but was not used for concentration correction. 1,1,1-TCA and TCE samples were accepted if pentafluorobenzene internal standard recovery was between 80 and 120%. The detailed VOC purge-and-trap and GCMS conditions are listed in the supporting information (Table 3.S3, Table 3.S4).

2.3 Oxidant Generation

PAP is a patented technology commercially available as OxyZone® (Ball 2010) from Enchem Engineering, Inc. (Newton, MA). Both dissolved ozone and dilute hydrogen peroxide are used to activate buffered sodium persulfate at ambient temperatures. This facilitates the production of hydroxyl (2.8 V) and sulfate (2.5 V) radicals, two of the strongest oxidants available. As a result, PAP destroys organic contaminants through primary oxidation reactions by ozone (2.1 V) and persulfate (2.0 V), as well as through more vigorous secondary oxidation reactions involving hydroxyl radical and sulfate

radicals (Huling & Pivetz 2006; Ball 2010; Ball 2011; SERDP (Strategic Environmental Research and Development Program) 2011).

The PAP solution was prepared in a bench-scale reactor (Figure 3.1). No more than 3 h prior to use, 3.5 L of a 60 g/L sodium persulfate and 7.29 g/L disodium phosphate buffer solutions were prepared in an amber glass vessel and mixed with deionized water using a Teflon-coated stir bar. A 3% hydrogen peroxide solution was prepared from a 30% stock solution. Once fully dissolved, the buffered persulfate solution was pumped into the reactor through the bottom. Oxygen flow was initiated and the reactor was pressurized to 15 psig (103.4 kPa). Gaseous ozone was then supplied to the reactor at a rate of 0.38 g/h for 25 min. 220 µl of the 3% hydrogen peroxide solution was injected at 6 min, 9 min, 12 min, 15 min, and 18 min. At 25 min, gas flow to the reactor was interrupted and the PAP solution was withdrawn from the bottom valve of the reactor for immediate use.

2.4 Experimental Procedure

Contaminant solutions were prepared from stock solutions containing 40 mg/L 1,4-dioxane, 60 mg/L 1,1,1-TCA, 60 mg/L TCE, and 60 g/L PAP. Appropriate volumes of contaminant solution, ultrapure DI water, and PAP were combined in amber glass bottles with Teflon seals. For the ionic strength experiment the appropriate amount of calcium chloride dihydrate was dissolved in the combined ultrapure DI water and 1,4-dioxane stock prior to the addition of PAP. In the individual contaminant experiments, 1

L of the reactive solution was prepared, while for the multi-contaminant experiments the volume was 4 L.

The solutions were gently mixed by hand for 1 min and allowed to equilibrate for 15 min in an incubator at 25°C. The solutions were then quickly transferred to labeled 125 ml amber glass jars using a glass separatory funnel. The glass jars were capped with Teflon lids, sealed with no headspace, and returned to the incubator for storage at 25°C. At the time of sampling, the jars was opened and duplicate samples were quickly transferred (using disposable glass pipets) to 40 ml volatile organic analysis (VOA) amber glass vials containing 6 ml of a 1N sodium thiosulfate solution to quench any remaining oxidant. Each vial was stored at 4 °C until analysis. The mass of the VOA, added volume of thiosulfate and sample volume were recorded. The remaining solution was used to measure oxidation reduction potential (ORP) and pH using Cole-Parmer probes (59001-77, 059001-12).

In the multi-contaminant experiment persulfate anion concentrations were measured by thiosulfate titration. A 16 ml subsample was transferred to a 20 ml VOA and mixed with 4 ml of 22 g/L potassium iodide solution. The solution was mixed on a vortex shaker for 15 s and then allowed to react for 1 h. The solution was then titrated with 2.1 g/L thiosulfate against 1 ml of starch solution, which was added near the end of the titration (Haselow et al. 2003).

To determine the relationship between the rate of oxidative destruction of the contaminants and the amount of oxidant required, approximately 0.04 mM 1,4-dioxane,

1,1,1-TCA, and TCE solutions, either as single compounds or as mixtures, were treated with increasing amounts of PAP. Oxidant:contaminant molar ratios were calculated as moles persulfate prior to activation to moles VOC. The ratios in the single-contaminant systems ranged from 0:1 (control) to 1900:1 (Table 3.1). A 500:1 ratio was used in the ionic strength experiment (Table 3.2).

The multi-contaminant system experimental procedures were identical to the single-contaminant systems except that the solution contained a mixture of 1,4-dioxane (10.3 μM), TCA (9.4 μM), and TCE (14.8 μM) and was treated with 4.2 mM of PAP. The molar oxidant:contaminant ratios for the three compounds were 280:1, 450:1, and 410:1 for 1,4-dioxane, 1,1,1-TCA and TCE, respectively. The total VOC oxidant:contaminant ratio was approximately 120:1 (Table 3.3).

3. Results and Discussion

3.1 Oxidation of 1,4-Dioxane, 1,1,1-TCA, and TCE in single-contaminant systems

In single-contaminant aqueous phase experiments, the 1,4-dioxane concentration decreased exponentially over time (Figure 3.2). The reaction rates increased with oxidant concentration and are well described by pseudo-first-order kinetics (Table 3.1).

For the 990:1 system, the reaction was so rapid that more than 50% of the 1,4-dioxane had already been degraded after the first sampling interval (6 h). By the second sampling time (18 h), no detectable 1,4-dioxane remained. For the 490:1 system 1,4-dioxane degraded beyond the limit of detection by the 24 h sampling. Due to the rapid

reaction rates ($t_{1/2} < 6\text{ h}$) during the initial 72 h experiment, a second 24 h experiment with a denser sampling interval was used for rate calculations and confirmed the results observed in the 72 h experiment. For reference, the molar oxidant:contaminant ratio of undiluted PAP used commercially to treat VOC contaminated aquifers is about 6-10 times more concentrated than that used in the 990:1 system.

Oxidation slowed with decreasing oxidant:contaminant ratios and was the slowest ($t_{1/2} = 231\text{ h}$) for the 10:1 system with only 20% reduction in 1,4-dioxane concentration observed after 72 h. A follow-up experiment showed that oxidation was continuous for at least 312 h (Figure 3.S11) and the pseudo-first order reaction rate was $k_1 = 0.003\text{ h}^{-1}$. These data demonstrate that it is possible to degrade 1,4-dioxane even with dilute PAP solutions (10:1) and that the degradation process proceeds for at least 13 days. The apparent longevity of the PAP oxidant offers the possibility of injecting slugs of PAP solution into a 1,4-dioxane contaminated aquifer and exploiting its lasting reactivity to reach deep into the polluted area, assuming that the batch test result can be replicated under field conditions.

PAP degraded both TCE and 1,1,1-TCA at 25 °C (Table 3.1, Figures 3.S12 and 3.S13). Of these two 1,4-dioxane co-contaminants, TCE was much faster degraded than 1,1,1-TCA. The fact that 1,1,1-TCA can be readily oxidized by PAP is an advantage over thermally activated persulfate oxidation of 1,1,1-TCA, which prior studies have shown is recalcitrant to oxidation at ambient temperatures (20-30 °C) (Gates-Anderson et al. 2001; Liang et al. 2003; Huang et al. 2005; Waldemer & Tratnyek 2006; Huling & Pivetz

2006; Gu et al. 2011; Xu et al. 2014). As for 1,4-dioxane, the rate of VOC degradation increased with increasing oxidant:contaminant ratios and the reaction kinetics are pseudo-first-order over the range of oxidant:contaminant ratios investigated (Table 3.1).

1,4-dioxane was destroyed by PAP about 13 times slower than TCE, but eight times more rapidly than 1,1,1-TCA. This observation is illustrated by plotting the degradation rate (k_1) for each of the three contaminants against the corresponding molar oxidant:contaminant ratio (Figure 3.3). The coefficient of determination (R^2) for all three correlations is high (≥ 0.894), which indicates that the rate of oxidation for each contaminant is predictable from the oxidant concentration within the range tested.

Besides contaminant concentrations, ORP and pH were monitored throughout the single-contaminant experiments (Figure 3.S1-3.S8). ORP ranged from 200 to 600 mV and generally increased with increasing oxidant:contaminant ratios (Figure 3.S1, 3.S5, 3.S7 and 3.S9). The observed ORP fluctuated in some of the control solutions (deionized water). This was attributed to memory effects of the ORP probe.

The initial pH ranged from 7.3 to 8.6 and was directly related to the amount of buffered PAP added to the solution. The pH fell throughout the course of the experiment (by up to 3.3 pH) indicating the production of protons. The decrease in pH was most pronounced in the TCE system and smaller (0.2-1.2 pH) in the case of 1,4-dioxane and 1,1,1-TCA. Similar drops in pH during persulfate oxidation of organics have been documented in several other persulfate systems (Huang et al. 2002; Liang et al.

2003; Block et al. 2004; Huang et al. 2005; Waisner et al. 2008; Liang et al. 2011; Paul et al. 2010; Miraglio 2009; Chen et al. 2009). The reason for decreasing pH values over time is the production of sulfate, an extremely weak conjugate base, which can lead to production of sulfuric acid (Kolthoff & Miller 1951). The severity of pH drop in both laboratory and field systems is a function of the buffering capacity and the oxidant dosage (SERDP 2011).

3.2 Effect of Ionic Strength on 1,4-Dioxane Oxidation

Table 3.2 shows the results of the ionic strength experiment. The higher the ionic strength of the solution, the slower the 1,4-dioxane degradation. Substantial 1,4-dioxane inhibition was observed when the ionic strength exceeded 0.2 M/L. This is most likely due to the increased presence of radical scavenging chloride ions. Chloride has been shown to inhibit persulfate oxidation of other contaminants such as TCE and MTBE at similar temperatures and concentrations (Huang et al. 2002; Liang, Wang, et al. 2007; Tsitonaki et al. 2010). Further, with increasing initial calcium chloride concentration, the pH of the solution decreased. This is most likely due to increased displacement of phosphate from solution through the formation of calcium monohydrate phosphate (CaHPO_4), resulting in decreased buffering capacity. This would also account for a cloudy precipitate observed in the higher CaCl_2 concentration solutions (7 and 70 mM/L). The lower pH in these systems may have also contributed to the observed slower reaction rates. However, Félix-Navarro et al. (2007), observed oxidation of 1,4-dioxane by persulfate to be increased at lower pH. This suggests that the cause of the slower

reactions rates in the present study was indeed due to the increased ionic strength. However, future work explicitly examining the effects of pH on PAP oxidation of 1,4-dioxane is needed. The results of this experiment suggest that the ionic strength of typical groundwaters would not be a substantial limiting factor when applying PAP to treat 1,4-dioxane in the field. The effects of ionic strength might need to be considered when working in brackish waters.

3.3 Oxidation in Multi-Contaminant System

Mirroring the results of the single-contaminant experiments, the compound most rapidly destroyed was TCE, followed by 1,4-dioxane and then 1,1,1-TCA, of which 60% was degraded after 96 h of exposure to PAP. The concentration of each compound decreased exponentially over time (Figure 3.4). The corresponding reaction rates and half-lives are summarized in Table 3.3. Observed half-lives ranged from 3.0 h for TCE to 69.3 h for 1,1,1-TCA, with 1,4-dioxane at 12.2 h.

The rates observed in the multi-contaminant experiment were compared to those obtained for each compound in the single-contaminant experiments. Since the reaction rates are dependent on the initial oxidant concentration, the linear equations shown in Figure 3.3 were used to predict the rates of each compound at the molar oxidant:contaminant ratios used in the multi-contaminant experiment. For 1,4-dioxane and 1,1,1-TCA the rates were interpolated, whereas for TCE the rate was extrapolated.

The predicted oxidation rate constants and half-lives for all three contaminants are shown in Table 3.3. The data indicates that the observed rate (0.057 h^{-1}) of 1,4-dioxane oxidation in the multi-contaminant system was 38% slower (0.092 h^{-1}) than that predicted based on the single-contaminant experiments. Similarly, the oxidation of 1,1,1-TCA and TCE in a multi-contaminant system was slower than predicted from the single-contaminant system by 44% and 87%, respectively (Figure 3.3).

As observed during the single-contaminant oxidation experiments, the pH decreased by 1.2 pH, while the ORP rose from 240 mV to 380 mV (Figure 3.S12, Figure 3.S13). The persulfate concentration remained two orders of magnitude higher than the initial VOC concentrations throughout the experiment, justifying the use of a pseudo-first-order rate model (Figure 3.S14).

4. Conclusions

PAP is capable of degrading 1,4-dioxane, TCE, and 1,1,1-TCA in aqueous phase experiments at ambient temperatures (25°C). The destruction of 1,1,1-TCA at ambient temperature sets PAP apart from the thermally activated persulfate approach, which shows little effectiveness degrading this compound at ambient temperatures. TCE was the contaminant most rapidly oxidized, with 1,4-dioxane and 1,1,1-TCA following in order of decreasing destruction rates. Overall, these results indicate that 1,4-dioxane is more difficult to degrade than chlorinated ethenes, but more susceptible to oxidation compared to chlorinated ethanes. Since all three contaminants often co-occur,

monitoring the progress of the oxidative treatment with PAP must be measured against the compound with the slowest degradation rate; 1,1,1-TCA in this study.

The destruction rates and half-lives obtained from single-contaminant systems were faster than those observed in a multi-contaminant system. However, the observed decrease in degradation rates in a multi-contaminant system was less than an order of magnitude slower than that of the single-contaminant systems, which still allows for rapid treatment of mixed-waste contaminant systems.

Finally, our experiments clearly demonstrate that it is possible to degrade 1,4-dioxane with dilute solutions of PAP (10:1) and that the degradation process is continuous for at least 13 days, which was the ultimate duration of our laboratory experiments. This finding is particularly important because it supports PAP as a potential long-term *in situ* treatment alternative for 1,4-dioxane polluted groundwater plumes. However, it needs to be investigated if the longevity of the PAP oxidant solution can be replicated under field conditions, where temperatures are lower than ambient and where natural organic matter and other compound may compete for the oxidant.

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Tables:

Molar Ratio	Contaminant Concentration (mg/L)	Contaminant Concentration (mM/L)	Persulfate (g/L)	Persulfate (mM/L)	k_1 (h ⁻¹)	$t_{1/2}$ (h)	R ²
1,4-Dioxane							
1030:1*	3.6	0.041	10.1	42.4	0.357	1.9	0.960
990:1	3.8	0.043	10.1	42.4	-	<6h	-
510:1*	3.6	0.041	5.0	21.0	0.138	5.0	0.864
490:1	3.8	0.043	5.0	21.0	0.152	4.6	0.879
98:1	3.8	0.043	1.0	4.2	0.020	34.7	0.939
10:1 [#]	3.6	0.041	0.1	0.42	0.003	231	0.972
10:1	3.8	0.043	0.1	0.42	0.003	231	0.926
1,1,1-TCA							
1900:1	5.9	0.044	19.9	83.6	0.063	11.0	0.980
960:1	5.9	0.044	10.1	42.4	0.042	16.5	0.982
480:1	5.9	0.044	5.0	21.0	0.029	23.9	0.976
TCE							
110:1	5.3	0.040	1.0	4.2	0.445	1.6	0.971
53:1	5.3	0.040	0.5	2.1	0.273	2.5	0.980
25:1	5.3	0.040	0.25	1.0	0.127	5.5	0.995
10:1	5.3	0.040	0.1	0.4	0.067	10.3	0.974

Table 3.1: Oxidation of 1,4-dioxane, 1,1,1-TCA, and TCE by PAP in single-contaminant systems. TCE and 1,4-dioxane experimental duration was 72 h. 1,1,1-TCA experimental duration was 312 h. [#]A 312 h duration 1,4-dioxane experiment using a 10:1 ratio was also run and confirmed the results observed in the 72 h experiment (supporting materials). *Reaction rate was so rapid ($t_{1/2} < 6h$) during the initial 72 h experiment that a second 24 h experiment with a denser sampling interval was used for rate calculations and confirmed the results observed in the 72 h experiment.

Molar Ratio	1,4-Dioxane (mM/L)	Sodium Persulfate (mM/L)	Disodium phosphate (mM/L)	Calcium Chloride (mM/L)	Ionic Strength (M/L)	pH _{final}	k ₁ (h ⁻¹)	t ½ (h)	R ²
500:1	0.042	21	4.3	0	0.076	7.5	0.156	4.4	0.928
500:1	0.042	21	4.3	0.7	0.078	7.4	0.141	4.9	0.916
500:1	0.042	21	4.3	7	0.097	5.8	0.103	6.7	0.968
500:1	0.042	21	4.3	70	0.286	5.1	0.065	10.7	0.962

Table 3.2: Oxidation of 1,4-dioxane by PAP under various ionic strengths. The duration of this experiment was 8 hours.

VOC	Molar Ratio	Contaminant Concentration ($\mu\text{M/L}$)	Predicted		Observed	
			$k_1(\text{h}^{-1})$	$t_{1/2}(\text{h})$	$k_1(\text{h}^{-1})$	$t_{1/2}(\text{h})$
1,4-Dioxane	280:1	14.8	0.092	7.5	0.057	12.2
1,1,1-TCA	450:1	9.4	0.018	38.5	0.010	69.3
TCE	410:1	10.3	1.763	0.4	0.231	3.0
Total	120:1	34.5				

Table 3.3: Observed versus predicted PAP oxidation rates in the multi-contaminant system. Total PAP concentration: 4.2 mM (as persulfate). The predicted values are calculated from the rate/molar ratio relationships shown in Figure 3.3 derived from the single-contaminant systems.

Figures:

Figure 3.1: PAP Generator Design. 1" = 2.54 cm. SS = stainless steel.

Figure 3.2: Oxidation of 1,4-dioxane by PAP. Four oxidant:contaminant ratios were investigated. The 10:1 reaction was shown to continue for at least 312 h (supporting information). The reaction for the most concentrated oxidant formulations, 510:1 and 1030:1, was so rapid that a second 24 h experiment, with a denser sampling interval, was conducted to capture degradation in those systems. Error bars of some data points are obscured by the datum point symbol.

Figure 3.3: The degradation rates (k_1) for 1,1,1-TCA, 1,4-dioxane, and TCE are plotted against the molar oxidant:contaminant ratio. The data indicate that the rate of oxidation for each contaminant is predictable within the range tested.

Figure 3.4: Simultaneous oxidation of 1,4-dioxane, TCE, and 1,1,1-TCA by PAP. The initial concentration of each of the three compounds was approximately 1.3 mg/L. The total molar concentration of all the compounds combined was 0.035 mM. Based on this concentration, the total VOC oxidant:contaminant ratio was approximately 120:1. Error bars of some data points are obscured by the datum point symbol.

Supporting Information: Tables

The purge and trap method used for the analysis of 1,4-dioxane is based on methods developed by Draper et al. (2000), OI Analytical (2006), and Environmental Laboratory Services (2009).

Settings	Time/Temp
Trap:	
Trap Type:	#7 (Tenax)
Sample Temp:	
Spurge Mount:	40 C
Sample:	35 C
Purge Times & Temp:	
Purge Time:	11 min
Dry Purge Time:	1 min
Trap Temp:	40 C
Water Management Temps:	
Purge:	120 C
Desorb:	40 C
Bake:	240 C
Bake:	
Bake Time:	10 min
Trap Temp:	210 C
Desorb Time & Temp:	
Desorb Time:	0.5 min
Trap Temp:	190 C
Desorb Preheat:	
Trap Temp:	125 C
Heated Zones:	
Transfer Line:	120 C
Valve Oven:	120 C

Table 3.S1: Purge and trap conditions for 1,4-dioxane analysis

Injector Temp:	240°C
Interface Temp:	230°C
Oven Temp:	45°C (hold 4.5 min.) to 100°C @ 12°C/min. to 240°C (hold 1.3 min) @ 25°C/min.
Column Inlet Pressure:	31.3 kPa
Column Flow:	0.8 mL/min
Linear Velocity:	31.5 cm/sec
Split Ratio:	35
Total Flow:	28 mL/min
Detector:	SIM mode, m/z (88, 58, 96, 64, 46)

Table 3.S2: GCMS conditions for 1,4-dioxane analysis

Settings	Time/Temp
Trap:	
Trap Type:	#7 (Tenax)
Sample Temp:	
Sparge Mount:	40 C
Sample:	30 C
Purge Times & Temp:	
Purge Time:	11 min
Dry Purge Time:	N/A
Trap Temp:	20 C
Water Management Temps:	
Purge:	100 C
Desorb:	Ambient
Bake:	240 C
Bake:	
Bake Time:	5 min
Trap Temp:	200 C
Desorb Time & Temp:	
Desorb Time:	0.5 min
Trap Temp:	180 C
Desorb Preheat:	
Trap Temp:	170 C
Heated Zones:	
Transfer Line:	120 C
Valve Oven:	120 C

Table 3.S3: Purge and trap conditions for TCE and 1,1,1-TCA analysis

Injector Temp:	225°C
Interface Temp:	230°C
Oven Temp:	35°C (hold 5 min.) to 60°C @ 11°C/min. to 220°C (hold 2.0 min) @ 20°C/min.
Column Inlet Pressure:	86.9 kPa
Column Flow:	1.6 mL/min
Linear Velocity:	45.6 cm/sec
Split Ratio:	15
Total Flow:	26.7 mL/min
Detector:	Scan mode, m/z (41-300)

Table 3.S4: GCMS conditions for TCE and 1,1,1-TCA analysis

Supporting Information: Figures

ORP and pH in 72 h 1,4-dioxane Single-Contaminant Oxidation Experiment:

Figure 3.S1: ORP in 72 hour 1,4-dioxane single-contaminant oxidation experiment

Figure 3.S2: pH in 72 hour 1,4-dioxane single-contaminant oxidation experiment

ORP and pH in 312 h 1,4-Dioxane Single-Contaminant Oxidation Experiment:

Figure 3.S3: ORP in 312 h 1,4-dioxane single-contaminant oxidation experiment

Figure 3.S4: pH in 312 h 1,4-dioxane single-contaminant oxidation experiment

ORP and pH in 24 h 1,4-Dioxane Single-Contaminant Oxidation Experiment:

Figure 3.S5: ORP in 24 h 1,4-dioxane single-contaminant oxidation experiment

Figure 3.S6: pH in 24 h 1,4-dioxane single-contaminant oxidation experiment

ORP and pH in 312 h 1,1,1-TCA Single-Contaminant Oxidation Experiments:

Figure 3.S7: ORP in 312 h 1,1,1-TCA single-contaminant oxidation experiment

Figure 3.S8: pH in 312 h 1,1,1-TCA single-contaminant oxidation experiment

ORP and pH in 72 h TCE Oxidation Experiments

Figure 3.S9: ORP in 72 h TCE single-contaminant oxidation experiment

Figure 3.S10: ORP in 72 h TCE single-contaminant oxidation experiment. Note: scale of y-axis differs from previous figures.

Figure 3.S11: Results of 312 h 1,4-dioxane oxidation experiment at 10:1 oxidant:contaminant ratio. The results confirmed the findings observed in the 72 h duration 10:1 experiment and show that PAP oxidation of 1,4-dioxane may continue for up to 13 days. Error bars of some data points are obscured by the datum point symbol.

Figure 3.S12: Oxidation of 1,1,1-TCA by PAP. Three oxidant:contaminant ratios were investigated. Due to the more recalcitrant nature of 1,1,1-TCA elevated oxidant:contaminant ratios and a longer experimental duration (312 h) was used. Error bars of some data points are obscured by the datum point symbol.

Figure 3.S13: Oxidation of TCE by PAP. Four oxidant:contaminant ratios were investigated. Since TCE is more easily oxidized than 1,4-dioxane, lower oxidant:contaminant ratios were used. Error bars of some data points are obscured by the datum point symbol.

ORP and pH in 96 h Multi-Contaminant Oxidation Experiment

Figure 3.S14: ORP in 96 h multi-contaminant oxidation experiment

Figure 3.S15: pH in 96 h multi-contaminant oxidation experiment. Note: scale of y-axis differs from previous figures.

Persulfate Concentration in 96 h Multi-Contaminant Oxidation Experiment

Figure 3.S16: Persulfate Concentration in 96 h multi-contaminant oxidation experiment. Data points represent the average of two measurements and error bars denote the range.

Works Referenced in Supplementary Materials

Draper, W.M. et al., 2000. Trace-level determination of 1,4-dioxane in water by isotopic dilution GC and GC-MS. *The Analyst*, 125(8), pp.1403–1408.

Environmental Laboratory Services, 2009. 1,4-Dioxane Determination Rev D, ELS-105.

OI Analytical, 2006. Low-level Detection of Ethanol, 1,4-Dioxane, and Other Oxygenates Using the Eclipse Purge-and-Trap Sample Concentrator. In *Conference on Analytical Chemistry and Applied Spectroscopy*. O.I. Analytical, p. 12.

CONCLUSIONS AND OUTLOOK

Despite recent advances, the remediation of subsurface volatile organic compounds (VOCs) remains a complex and challenging problem. Innovative *in situ* strategies, such as *in situ* chemical oxidation (ISCO), offer many advantages over conventional methods such as pump and treat. However, the basic physicochemical properties of many VOCs, particularly their low solubility, still represent a major barrier to achieving remediation goals at many sites. Tailing and rebound often lead to extended periods of operation, long after the bulk of the contaminant mass has been removed. Developing remediation strategies capable of overcoming the limitations of contaminant solubility may provide a way to speed site closure. In addition to contaminant solubility, remediation of VOC can be further complicated by the presence of co-contaminants, whose physicochemical properties differ significantly for the target VOC. Perfluoroalkyl acids (PFAAs) and 1,4-dioxane are two emerging contaminants that are increasingly being detected as co-contaminants at solvent release sites. Understanding how strategies aimed at remediating VOCs affect these emerging contaminants is of critical importance. Ultimately, the goal is to develop technologies capable of reducing remediation times for established priority pollutants while also safely degrading emerging contaminants, or at least not increasing the risks associated with them. This study was designed to try and address these issues and help advance the field of subsurface environmental remediation.

Chapter 1 focused on a pilot-scale field test in which a solubility-enhancing agent, hydroxypropyl- β -cyclodextrin (HPCD), was used to increase contaminant availability during ISCO. Chapter 2 examined the effects of this ISCO field test on the PFAA co-contaminants present at the site. Chapter 3 detailed a laboratory based study examining the applicability of the same novel advanced oxidation process (AOP), OxyZone[®], used in Chapters 1 and 2 for the *in situ* treatment of 1,4-dioxane and its common VOC co-contaminants 1,1,1-Trichloroethane (1,1,1-TCA) and trichloroethene (TCE).

The findings of Chapter 1 show that implementation of HPCD based solubility-enhanced ISCO is possible in the field. The application of HPCD during OxyZone[®] treatment of VOC, lead to a measurable rise and fall in the aqueous mass of target VOC in the deep zone of the aquifer and a statistically significant positive correlation with HPCD was observed. Although residual phase non-aqueous phase liquid (NAPL) remained, post-treatment membrane interface probe, soil, and groundwater data showed significant reductions on the edges of the source zone and improvements at down gradient wells. From a proof of concept standpoint, the treatment had its intended effect. The incorporation of HPCD into an ISCO treatment resulted in a temporary increase in the aqueous phase mass of target VOC available for oxidation and its subsequent destruction.

Due to the presence of NAPL and the large mass of contaminant already available in the aqueous phase, the use of a solubility-enhancing agent was probably not

necessary at this particular site. As such, the next step is to test this technology at sites where tailing and rebound due to sorbed contaminants but not NAPL are preventing them from coming into compliance. For the treatment of VOC the addition of a solubility-enhancing agent would perhaps be best suited as a polishing treatment after conventional ISCO has destroyed the bulk of the contaminant mass. In this treatment train approach, solubility-enhanced ISCO would be used as a preemptive measure against rebound and tailing. HPCD-enhanced ISCO might also be amenable to the remediation of polycyclic aromatic hydrocarbons (PAHs). PAHs are priority pollutants but generally have much lower aqueous solubilities than the VOC featured in this study. As a result, much less HPCD would be needed to significantly increase the aqueous mass of PAHs available for oxidation, potentially resulting in an even more efficient process. During this study, the risk of offsite migration of injected solutions was small. However, future work needs to be done to determine if this technology can be optimized for locations where migration offsite is a concern. Lastly, once optimized, a robust cost comparison with conventional ISCO technologies is needed to determine if HPCD-enhanced ISCO is a truly feasible remediation strategy at the field-scale.

The findings of Chapter 2 show that the use of an AOP to treat VOC *in situ* had no discernible negative impacts on PFAA co-contaminants at the site. Rather, the available evidence suggests that ISCO may have improved conditions at the site, most likely through oxidative degradation. Significantly lower PFAA concentrations were observed at the site following treatment. Moving forward, the degradation of PFAAs believed to have occurred during this field test needs to be confirmed through laboratory testing.

Increased PFAA sampling during future ISCO remediation at sites with these co-contaminants is also needed to determine if the observations in this study are representative and can be replicated at other sites.

The findings of Chapter 3 show that peroxone activated persulfate (PAP), OxyZone®, is capable of degrading 1,4-dioxane, TCE and 1,1,1-TCA in aqueous phase experiments at ambient temperatures. 1,4-dioxane was more difficult to degrade than chlorinated ethenes, but more susceptible to oxidation compared to chlorinated ethanes. The results demonstrate that it is possible to degrade 1,4-dioxane in the presence of its common VOC co-contaminants. Furthermore, degradation of 1,4-dioxane can be achieved with dilute solutions of PAP (10:1) and the degradation process is continuous for at least 13 days. These findings suggest that PAP could have potential as a long-term *in situ* treatment alternative for 1,4-dioxane polluted ground water plumes. However, further investigation is needed to determine whether the longevity of the PAP oxidant solution can be replicated under field conditions. The aqueous batch experiments used in this study need to be followed up with more complex column experiments that better mimic field conditions. This will help determine if and how field testing of PAP for the remediation of the large dilute plumes commonly associated with 1,4-dioxane should be conducted.

The findings of this dissertation are promising. They show that HPCD can be successfully combined with ISCO to treat VOC under field conditions. They also suggest that ISCO can be safely used to treat VOC at sites where the emerging contaminants 1,4-

dioxane and PFAAs have been identified or are suspected to occur. Although further work is needed, these findings represent a meaningful contribution to the field of subsurface environmental remediation.

APPENDIX A: LIST OF ABBREVIATIONS

Abbreviation	Full Name
(1,1,1-TCA)	1,1,1-trichloroethane
(AFCEC)	Air Force Civil Engineer Center
(AFFF)	Aqueous firefighting foam
(AOP)	Advanced oxidation process
(bgs)	Below ground surface
(BTEX)	Benzene, toluene, ethylbenzene, and xylenes
(CDs)	Cyclodextrins
(CMC)	Critical micelle concentration
(CMCD)	Carboxyl-methyl- β -cyclodextrin
(CSM)	Colorado School of Mines Center for Environmental Risk Assessment
(DCB)	Dichlorobenzene
(DO)	Dissolved oxygen
(DPT)	Direct push technology
(ECD)	Electron capture detector
(EPA)	US Environmental Protection Agency
(FID)	Flame ionization detector
(FTA)	Fire training area
(FtS)	Fluorotelomersulfonates
(GAC)	Granular activated carbon
(HDPE)	High-density polyethylene
(HPCD)	Hydroxypropyl-beta-cyclodextrin
(IDW)	Inverse distance weighting
(ISCO)	<i>In situ</i> chemical oxidation
(ITRC)	Interstate Technology and Regulatory Council
(JBLE)	Joint Base Langley-Eustis
(Kd)	Solid-water distribution coefficients
(Koc)	Soil organic carbon-water partitioning coefficients
(LDPE)	Low-density polyethelene
(MCD)	Methyl- β -cyclodextrin
(MIP)	Membrane-interface probe
(MNA)	Monitored natural attenuation
(NAPL)	Non-aqueous phase liquid
(ORP)	Oxidation-reduction potential
(PAHs)	Polycyclic aromatic hydrocarbons
(PAP)	Peroxone activated persulfate
(PCBs)	Polychlorinated biphenyls

(PCE)	Tetrachloroethene
(PFAAs)	Perfluoroalkyl acids
(PFBA)	Perfluorobutyric acid
(PFCAs)	Perfluoroalkyl carboxylates
(PFHxA)	Perfluorohexanoic acid
(PFHxS)	Perfluorohexane sulfonic acid
(PFOA)	Perfluorooctanoic acid
(PFOS)	Perfluorooctanesulfonic acid
(PFPeA)	Perfluoropentanoic acid
(PFSAs)	Perfluoroalkyl sulfonates
(PID)	Photoionization detector
(PLFA)	Phospholipid fatty acid
(POSF)	Perfluorooctanesulfonyl fluoride
(PQL)	practical quantification limit
(SERDP)	Strategic Environmental Research and Development Program
(SIM)	Selected ion monitoring
(SpC)	Specific conductance
(SVOCs)	Semi-volatile organic compounds
(TA)	TestAmerica Laboratories, Inc.
(TA-15)	Training Area 15
(TCE)	Trichloroethene
(TNS)	2-(p-toluidinyl)-naphthalene-6-sulfonate
(TOP)	Total oxidative precursor
(tVOC)	Target VOCs
(VOA)	Volatile organic analysis
(VOC)	Volatile organic compounds

Table A1: List of abbreviations used in this dissertation.

APPENDIX B: METHODS AND INSTRUMENTATION

Groundwater and sediment field and laboratory samples were collected and analyzed following standardized methods detailed in Table B1. A list of analytical instrumentation and other resources used during this study are given in Table B2. Hazardous wastes were collected, handled, and disposed of following University of Rhode Island rules and regulations. Detailed analytical methodologies used for the analysis of cyclodextrin, VOC, and 1,4-dioxane, are detailed in the following appendix.

Parameter	Matrix	Method	Laboratory	Container Type and Quantity	Sample Quantity	Preservation	Holding Time
VOCs	Solid	EPA 8260B	URI/Test America	3 x 40 ml clear glass VOA vials with TFE septa (1 unpreserved)	5 g or 10 g	DI water or methanol, ≤6°C	14 d
VOCs	liquid	EPA 8260B	URI/Test America	4 x 40 ml clear glass VOA w/ TFE septa	40 ml	HCL to pH <2, and or Thiosulfate, ≤6°C,	14 d
SVOCs	solid	EPA 8270C	Test America	1 x 8 oz amber glass jar	50 g	≤6°C	14 d
SVOCs	liquid	EPA 8270C	Test America	2 x 1 amber glass bottles, TFE caps	1000 ml	≤6°C	7 d
Metals	solid	EPA 6010B	Test America	1 x 8 oz glass jar	50 g	≤6°C	6 mo
Metals	liquid	EPA 6010B	Test America	1 x 250 ml plastic/glass bottle	250 ml	HNO 3 to pH <2	6 mo
Sulfate	liquid	EPA 9038	Test America	1 x 125 ml plastic bottle	125 ml	≤6°C	28 d
Microbes	liquid	PFLA	Microbial Insights	Bio-trap	-	≤4°C	2 d
TOC	liquid	SM 5310B/V, 9060	Test America	3x40 ml or 1x250 ml, amber glass w/cap	40 ml or 250 ml	HCL to pH <2, ≤6°C,	28 d
DOC	liquid	SM 5310B/V, 9060	Test America	1 x 250 ml amber glass with TFE cap	250 ml	HCL to pH <2, ≤6°C, following filtration	28 d
Chloride	liquid	EPA 300	Test America	1 x 125 ml plastic/glass bottle	125 ml	-	28 d
Nitrate	liquid	EPA 301	Test America	1 x 125 ml plastic/glass bottle	125 ml	≤6°C	28 d
Phosphate, -ortho	liquid	SM 4500 OP	Test America	1 x 250 ml plastic/glass bottle	250 ml	≤6°C	2 d
Ammonia	liquid	LACHAT	Test America	1 x 250 ml plastic/glass bottle	250 ml	H 2 SO 4 to pH<2, ≤6°C	28 d
BOD	liquid	SM 5210	Test America	1 x 500 ml plastic/glass bottle	500 ml	≤6°C	2 d
COD	liquid	EPA 410.4	Test America	1 x 125 ml plastic/glass bottle	125 ml	≤6°C	28 d
PFCs	solid	DV-LC-0012	Test America	1 x 250 ml HDPE	10 g	≤4°C	14 d
PFCs	liquid	DV-LC-0013	Test America	1 x 250 ml HDPE	250 ml	≤4°C	14 d

Table B1: Sample Collection and Analytical Methods Used

Resources	Location
Shimadzu GCMS-QP5000	URI-Geosciences
OI analytics Eclipse 4660 purge and trap	URI-Geosciences
Shimadzu RF-1501 Spectrofluorophotometer	URI-Geosciences
Analytic Technologies Inc., Q45 ozone probe	URI-Geosciences
IntelliCAL ORP Probe (MTC10101)	URI-Geosciences
Semi-Batch Reactor	On loan from EnChem Engineering, Inc.
Standards and Reagents	URI-Geosciences
Pacific Ozone G21 Ozone Generator	URI-Geosciences
Journals and Reference Texts	URI Geosciences, URI Library, & Personal Collection
Graphing and Statistical Software	URI Geosciences & Personal Collection
Glassware & Chemicals	URI-Geosciences
Technical and Operational Support during Field Test.	EnChem Engineering, Inc.

Table B2: analytical instrumentation and other resources used during this study

Cyclodextrin Analysis:

This method was written by Dr. Thomas Boving at the University of Rhode Island.

The method involves analysis of HPCD/TNS complex in a fluorescence spectrophotometer (RF) using a fluorescence analyzer to determine peak height. The Method Detection Level (MDL) is determined to be 1 mg/L HPCD. Water samples may be sub-sampled into 2-ml glass vials for analysis with disposable pipettes to ensure that there is no headspace. As this is a relatively novel methodology the full method details are described in the following.

Procedures

Water samples collected in the field are contained in 20 ml glass sample vials with open caps and Teflon-faced septa. The glass vials or the caps are not reused. Each sample vial is completely filled with aqueous samples, such that no headspace of air exists, and capped. The vials are not opened until the time of sub-sampling or analysis. The samples are stored at the field site in coolers containing blue ice (or similar). Dilution solutions must be created within one to three days.

Apparatus and Materials

A fluorescence spectrophotometer (RF) is required. The RF at the field site is a Shimadzu RF 1601 fluorescence spectrophotometer. The RF includes a quartz glass cuvette with a 4 ml holding capacity.

Reagents

Reagent water is defined here as the water in which an interferant is not observed at the MDL of the parameters of interest. Field reagent water is reagent grade. 6-(p-Toluidino)-2-naphthalenesulfonic acid, sodium salt, TNS (technical grade, 85%; Aldrich Chemicals, INC), is being used as a complexation additive for the HPCD analysis in the RF.

Calibration

Calibration Standards for Laboratory Studies: The 40% HPCD solution used in the demonstration (as received) is diluted to a minimum concentration of 0.1% HPCD (= 1 g/L HPCD) by injecting 2.5 ml of 40% HPCD solution into a total of 1000 ml reagent grade water. This calibration stock solution is stored in a 1000 ml amber glass bottle. During calibration, aliquots of 0.1 ml, 0.5 ml, 1.0 ml, and 2.5 ml are removed from the 0.1% HPCD solution and injected into a total of 100 ml reagent grade water. This procedure creates standards having a concentration ranging from 1 mg/L to 25 mg/L. This concentration range has been found to result in a linear correlation between RF measurement and HPCD concentration. Using this technique, systematic errors may be detected and corrective actions taken to ensure the preparation of accurate working standards. A volume of 1 ml TNS solution has to be added to 10 ml standard solution to permit analysis. The TNS solution is prepared by dissolving 30 mg TNS in 100 ml reagent grade water. The TNS solution must be stirred for 6 to 8 hours in amber glass bottle to avoid photodegradation. After stirring, the TNS solution can be used for up to 4 hours only.

Quality Control

Blanks, duplicates (10% criterion) and triplicates (2.5% criterion) will be analyzed to assure quality control.

Instrument Procedures

Recommended operating conditions for RF are as follows:

- Excitation wavelength: 387 nm
- Emission wavelength: 478 nm
- Sample volume: 4 ml
- Temperature: between 15 and 25 °C

Sample Preparation

Samples expected to have a high HPCD concentration (i.e. samples from injection wells), 5 µl aliquot of sample is transferred from the 20-ml sample vials to the 100 ml Grade A volumetric glass flask using a 25 µl syringe. For samples expected to have medium HPCD concentration (between 2% to 10%; or 20,000 to 100,000 mg/L), a 20 µl aliquot of sample is transferred from the 20-ml sample vials to the 100 ml Grade A volumetric glass flask using a 25 µl syringe. For samples having a HPCD concentration between 0.1 to 1% (1,000 to 10,000 mg/L), a 200 µl aliquot of sample is transferred from the 20-ml sample vials to the 100 ml Grade A volumetric glass flask using a 500 µl syringe. For samples having a HPCD concentration between 0.01 to .01% (100 to 1,000

mg/L), a 2 ml aliquot of sample is transferred from the 20-ml sample vials to the 100 ml Grade A volumetric glass flask using a 2 ml syringe. The least concentrated samples (< 25 mg/L; e.g. LS11-MW03) can be analyzed undiluted. To each sub-sample, 1 ml is added of a solution containing 30 mg TNS in 100 ml reagent grade water (preparation of the TNS solution is described in Section 4.3).

Sample Analysis

A 4 mL sample of diluted sub-samples is transferred into the quartz cuvette and inserted into the RF. The HPCD calibration standard curve will be used with the appropriate extraction or injection sample.

Analyte Identification

Analyte identification is based on the signal strength of the emission energy produced by the corresponding excitation wavelength. Duplicate measurements are taken to average the emission signal used to determine the HPCD concentration.

Analyte Quantitation

The HPCD calibration standard curve is stored in the RF's internal memory. The calibration curve will have emission intensity counts on Y-axis and target concentration on X-axis. A linear regression will be used to determine the slope and y-intercept (Equation D1).

Eq. B1:
$$\text{Concentration (ppm)} = \frac{\text{Emission} - y \text{ intercept}}{\text{Slope}}$$

Interferences

Whenever a sample with an unusually high concentration is encountered, it should be followed by an analysis of reagent water to check for cross-contamination.

Safety

The operation of the RF in accordance with the instruction manual does not pose any health or safety risks. The workspace should be kept well ventilated when using the RF. Refer to the Materials Safety Data Sheets (MSDS) for additional information on environmental toxicity data and for safety information, procedures, and regulations.

Purge and Trap and GCMS Setting for VOC analysis of Field and Laboratory Samples

VOC in groundwater and sediment samples were analyzed following U.S. EPA Methods 8260C, 5035A and 5030C (U.S. EPA, 2006, 2003, 2002). VOC, were analyzed by gas chromatography-mass spectrometry (GC/MS) using a Shimadzu GC-17A/GCMS-QP5000 equipped with a Restek Rxi®-624Sil MS Column (30 m, 0.25 mmID, 1.4 µm). Sample concentration and injection was performed using an OI Analytical Eclipse 4660 purge-and-trap (PT) sample concentrator equipped with a #10 trap and a 5 mL sparge vessel.

Settings	Time/Temp
Trap:	
Trap Type:	#10 (Tenax)
Sample Temp:	
Sparge Mount:	40 C
Sample:	ambient
Purge Times & Temp:	
Purge Time:	11 min
Dry Purge Time:	N/A
Trap Temp:	20 C
Water Management Temps:	
Purge:	100 C
Desorb:	Ambient
Bake:	240 C
Bake:	
Bake Time:	5 min
Trap Temp:	210 C
Desorb Time & Temp:	
Desorb Time:	0.5 min
Trap Temp:	190 C
Desorb Preheat:	
Trap Temp:	180 C
Heated Zones:	
Transfer Line:	110 C
Valve Oven:	110 C

Table B3: Purge and trap settings for VOC analysis.

Injector Temp:	250°C
Interface Temp:	280°C
Oven Temp:	35°C (hold 2 min), to 60°C @ 14°C/min, to 85°C @ 11°C/min (hold 2 min), to 220°C @ 20°C/min (hold 2.0 min).
Column Inlet Pressure:	46.9 kPa
Column Flow:	1.0 mL/min
Linear Velocity:	35.9 cm/sec
Split Ratio:	30
Total Flow:	31.0 mL/min
Detector:	Scan mode, 1.75 min – 3.25 min @ m/z (45-300), 3.26 min – 15.5 min @ m/z (36-300).

Table B4: GCMS settings for analysis of VOC field samples April 2012 – November 2013.

Injector Temp:	225°C
Interface Temp:	230°C
Oven Temp:	35°C (hold 5 min), to 60°C @ 11°C/min, to 220°C @ 20°C/min (hold 2.0 min).
Column Inlet Pressure:	46.9 kPa
Column Flow:	1.0 mL/min
Linear Velocity:	35.9 cm/sec
Split Ratio:	30
Total Flow:	31.0 mL/min
Detector:	Scan mode, 1.75 min – 3.00 min @ m/z (45-300), 3.01 min – 16.5 min @ m/z (41-300).

Table B5: GCMS settings for analysis of VOC field samples November 2013 – January 2014.

Injector Temp:	225°C
Interface Temp:	230°C
Oven Temp:	35°C (hold 5 min.) to 60°C @ 11°C/min. to 220°C (hold 2.0 min) @ 20°C/min.
Column Inlet Pressure:	86.9 kPa
Column Flow:	1.6 mL/min
Linear Velocity:	45.6 cm/sec
Split Ratio:	15
Total Flow:	26.7 mL/min
Detector:	Scan mode, 0.51 min – 2.50 min @ m/z (45-300), 2.51 min – 16.5 min @ m/z (41-300).

Table B6: GCMS settings for analysis of VOC field samples January 2014 onward.

Limit of Detection for VOC

ID	Analyte	Peak Height										95% confidence Height	Slope	MDL µg/L (95%)
		R1	R2	R3	R4	R5	R6	R7	AVE	STDV	RSD (%)			
1	Dichlorodifluoromethane*	-	-	-	-	-	-	-	-	-	-	-	-	-
2	Chloromethane	22331	16897	23894	25605	24518	22026	19088	22051	3097	14.0	6017	4378	1.4
3	Vinyl Chloride	13529	13232	12587	17206	16548	14958	12419	14356	1919	13.4	3729	2725	1.4
4	Bromomethane	8567	7444	7704	7985	8393	8339	6955	7912	581	7.3	1129	1417	0.8
5	Chloroethane	7856	8382	8446	10813	10554	8362	7589	8857	1288	14.5	2503	1696	1.5
6	Trichloromethane*	-	-	-	-	-	-	-	-	-	-	-	-	-
7	1,1-dichloroethene	10046	10507	9871	12659	12145	11819	9182	10890	1315	12.1	2556	2239	1.1
8	1,1,2-trichloro-1,2,2-trifluoroethane	11890	11634	8640	13554	12844	11935	8649	11307	1933	17.1	3757	2065	1.8
9	Acetone	25795	23448	25077	25638	25672	25648	21191	24638	1728	7.0	3358	2424	1.4
10	Carbon disulfide	41951	41024	41432	52661	48615	45713	34269	43666	5956	13.6	11572	10035	1.2
11	Methyl Acetate	59124	52575	60194	61471	57976	60620	49786	57392	4459	7.8	8664	8003	1.1
12	Methylene Chloride	11095	11510	12907	13811	14694	12233	10623	12410	1483	11.9	2881	2051	1.4
13	MTBE	48750	43238	48751	51537	53393	49897	41427	48142	4322	9.0	8397	8345	1.0
14	Trans-1,2-Dichloroethene	17028	13604	15414	16935	17357	16445	13663	15764	1578	10.0	3067	2466	1.2
15	1,1-dichloroethane	39682	36702	40326	43137	42439	42196	35748	40033	2880	7.2	5596	6358	0.9
16	2-Butanone	48631	44035	53997	51515	60604	56214	47999	51856	5578	10.8	10837	5819	1.9
17	Cis-1,2-Dichloroethene	22315	20492	23079	24323	23746	22264	19557	22254	1711	7.7	3325	3943	0.8
18	Chloroform	32933	32073	36143	36058	35989	33856	29286	33814	2549	7.5	4954	6804	0.7
19	pentafluorobenzene (IS)	33484	33208	26543	32535	33494	35227	30590	32154	2834	8.8	5507	8165	0.7
20	1,1,1-trichloroethane	16390	16340	16185	18121	18343	16868	13817	16581	1497	9.0	2909	3422	0.9
21	cyclohexane	36896	33844	24719	39279	37255	35158	25408	33223	5830	17.5	11328	6885	1.6
22	carbon tetrachloride	14684	14248	12404	17034	16534	16304	12211	14774	1959	13.3	3806	3261	1.2
23	benzene	84257	79260	86955	88628	85474	85265	70544	82912	6181	7.5	12010	19412	0.6
24	1,2-dichloroethane	30369	26635	31342	31803	31873	32126	28458	30372	2080	6.8	4041	6076	0.7
25	1,4-difluorobenzene (IS)	59508	57565	49184	54697	55172	58886	51105	55160	3893	7.1	7564	13095	0.6
26	Trichloroethene	19341	18092	18894	20255	21219	21378	16605	19398	1719	8.9	3340	4704	0.7
27	methylcyclohexane	21537	19700	13896	23193	20486	20782	14691	19184	3518	18.3	6836	4178	1.6
28	1,2-dichloropropane	24065	22217	25080	24765	27338	26489	22172	24589	1966	8.0	3819	5395	0.7
29	bromodichloromethane	19554	16195	17742	18251	19338	19245	16067	18056	1464	8.1	2844	4544	0.6
30	cis-1,3-dichloro-1-propene	28874	24969	28904	29210	29959	28993	25465	28053	1977	7.0	3842	6816	0.6
31	Methyl Isobutyl Ketone	60151	57728	63226	67832	73363	65408	61545	64179	5242	8.2	10186	9922	1.0
32	Toluene	67051	64411	70750	73000	71363	71682	59868	68304	4773	7.0	9274	16480	0.6
33	Trans-1,3-Dichloropropene	28109	25088	29756	29569	30486	29735	25204	28278	2255	8.0	4381	6724	0.7
34	1,1,2-trichloroethane	19637	19745	20482	21065	22063	20578	18379	20278	1172	5.8	2277	3828	0.6
35	Tetrachloroethene	14297	13708	13906	16994	15952	14044	11667	14367	1706	11.0	3314	3577	0.9
36	2-Hexanone	59106	52982	68733	65003	74201	67995	60599	64088	7074	11.0	13746	9045	1.5
37	dlbromochloromethane	18271	18170	20152	19294	21676	19578	17934	19296	1332	6.9	2589	4678	0.6
38	1,2-dibromoethane	23691	22403	27324	24920	28130	27116	24826	25487	2102	8.2	4084	5047	0.8
39	Chlorobenzene-d5 (IS)	58034	56937	48672	51953	52858	55478	51009	53563	3381	6.3	6569	11392	0.6
40	chlorobenzene	56294	55907	58096	58583	63442	60694	52077	57870	3640	6.3	7072	12190	0.6
41	ethylbenzene	94956	87710	97722	101448	102233	102252	80647	95281	8292	8.7	16110	22684	0.7
42	m & p - xylene	56420	51403	54921	61368	61727	60340	47639	56260	5360	9.5	10414	13403	0.8
43	o-xylene	35063	33321	39093	35690	37146	38431	32887	35947	2402	6.7	4667	7559	0.6
44	styrene	62844	57012	62630	66477	68674	68281	55646	63081	5200	8.2	10103	14215	0.7
45	bromoforn	15119	14128	15849	16130	17140	15636	14771	15636	1025	6.6	1991	3566	0.6
46	Isopropylbenzene	93349	84607	94460	100296	93410	101632	82075	92833	7300	7.9	14184	22791	0.6
47	1,1,2,2-tetrachloroethane	43808	40598	48701	46159	48846	48844	42610	45367	3130	6.9	6082	7504	0.8
48	1,3-dichlorobenzene	38405	38181	43651	44744	47775	47852	37482	42037	3991	9.5	7755	8889	0.9
49	1,4-dichlorobenzene-D4 (IS)	29734	28531	25125	27096	26478	31761	27981	27981	2220	7.9	4313	5694	0.8
50	1,4-dichlorobenzene	45375	42271	50091	49283	50442	51215	45252	47704	3390	7.1	6588	10014	0.7
51	1,2-dichlorobenzene	41388	36301	43518	43193	43511	43325	39747	41569	2720	6.5	5285	8102	0.7
52	1,2-dibromo-3-chloropropane	6459	6091	7236	7586	7236	7548	6589	7105	754	10.6	1465	1138	1.3
53	1,2,4-trichlorobenzene	26173	22473	24151	26388	26689	24440	22051	24624	1883	7.6	3659	5037	0.7

Table B7: limit of detection study for VOC analyzed by purge and trap and GCMS using a 5 ml sparge vessel. This study used 5 ml of DI water samples spiked with 5 µg/L of all analytes. (*) indicated analyte was programmed into the original method but not screened for in subsequent analysis. (IS) indicated that this analyte was used as an internal standard in subsequent analyses.

Purge and Trap and GCMS Setting for 1,4-dioxane analysis of laboratory samples

The purge and trap method used for the analysis of 1,4-dioxane is based on methods developed by Draper et al. (2000), OI Analytical (2006), and Environmental Laboratory Services (2009). Samples were analyzed by gas chromatography-mass spectrometry (GC/MS) using a Shimadzu GC-17A/GCMS-QP5000 equipped with a Restek Rxi®-624Sil MS Column (30 m, 0.25 mm ID, 1.4 µm). Sample concentration and injection was performed using an OI Analytical Eclipse 4660 purge-and-trap (PT) sample concentrator equipped with a #7 trap and a 25 mL sparge vessel.

Settings	Time/Temp
Trap:	
Trap Type:	#7 (Tenax)
Sample Temp:	
Sparge Mount:	40 C
Sample:	35 C
Purge Times & Temp:	
Purge Time:	11 min
Dry Purge Time:	1 min
Trap Temp:	40 C
Water Management Temps:	
Purge:	120 C
Desorb:	40 C
Bake:	240 C
Bake:	
Bake Time:	10 min
Trap Temp:	210 C
Desorb Time & Temp:	
Desorb Time:	0.5 min
Trap Temp:	190 C
Desorb Preheat:	
Trap Temp:	125 C
Heated Zones:	
Transfer Line:	120 C
Valve Oven:	120 C

Table B8: Purge and Trap Conditions for 1,4-dioxane analysis

Injector Temp:	240°C
Interface Temp:	230°C
Oven Temp:	45°C (hold 4.5 min.) to 100°C @ 12°C/min. to 240°C (hold 1.3 min) @ 25°C/min.
Column Inlet Pressure:	31.3 kPa
Column Flow:	0.8 mL/min
Linear Velocity:	31.5 cm/sec
Split Ratio:	35
Total Flow:	28 mL/min
Detector:	SIM mode, m/z (88, 58, 96, 64, 46)

Table B9: GCMS Conditions for 1,4-dioxane analysis

Sparge Vessel (mL)	Analyte	Sample (Peak Area)							Average (Peak Area)	STDEV (Peak Area)	RSD (%)	99.95% Confidence (Peak Area)	Slope	MDL (99.95%)
-	-	R1	R2	R3	R4	R5	R6	R7	-	-	-	-	-	-
25	1,4-Dioxane	960	1061	939	1113	1026	1090	857	1007	92	9.1	548	177.9	3.1
25	1,4-Dioxane-d8	505	508	501	506	540	546	506	516	19	3.6	111	111.1	1.0

Table B10: minimum detection limit for 1,4-dioxane analysis using purge and trap sample and GCMS. LOD was determined using by analyzing 4 µg/L samples and a purge volume of 25 ml. Samples were created by spiking with 1 µl of a 100 mg/L standard solution.

Purge and Trap and GCMS Setting for TCE and 1,1,1-TCA analysis of laboratory samples

The analysis of TCE and 1,1,1-TCA using an OI Analytical Eclipse 4660 purge-and-trap (PT) sample concentrator, equipped with a #7 trap and a 25 mL sparge vessel, was developed so that TCE, 1,1,1-TCA and 1,4-dioxane could all be analyzed on the same instrument. This was done so that 1,4-dioxane, TCE and 1,1,1-TCA samples could all be analyzed without the need of significant maintenance , i.e., changing the trap, sparge vessel or capillary column. Samples were analyzed by gas chromatography-mass spectrometry (GC/MS) using a Shimadzu GC-17A/GCMS-QP5000 equipped with a Restek Rxi®-624Sil MS Column (30 m, 0.25 mmID, 1.4 um).

Settings	Time/Temp
Trap:	
Trap Type:	#7 (Tenax)
Sample Temp:	
Sparge Mount:	40 C
Sample:	30 C
Purge Times & Temp:	
Purge Time:	11 min
Dry Purge Time:	N/A
Trap Temp:	20 C
Water Management Temps:	
Purge:	100 C
Desorb:	Ambient
Bake:	240 C
Bake:	
Bake Time:	5 min
Trap Temp:	200 C
Desorb Time & Temp:	
Desorb Time:	0.5 min
Trap Temp:	180 C
Desorb Preheat:	
Trap Temp:	170 C
Heated Zones:	
Transfer Line:	120 C
Valve Oven:	120 C

Table B11: Purge and Trap Conditions for 1,1,1-TCA and TCE Analysis

Injector Temp:	225°C
Interface Temp:	230°C
Oven Temp:	35°C (hold 5 min.) to 60°C @ 11°C/min. to 220°C (hold 2.0 min) @ 20°C/min.
Column Inlet Pressure:	86.9 kPa
Column Flow:	1.6 mL/min
Linear Velocity:	45.6 cm/sec
Split Ratio:	15
Total Flow:	26.7 mL/min
Detector:	Scan mode, m/z (41-300)

Table B12: GCMS Conditions for 1,1,1-TCA and TCE.

Works Cited in Appendix B:

Draper, W.M. et al., 2000. Trace-level determination of 1,4-dioxane in water by isotopic dilution GC and GC-MS. *The Analyst*, 125(8), pp.1403–1408.

Environmental Laboratory Services, 2009. 1,4-Dioxane Determination Rev D, ELS-105.

OI Analytical, 2006. Low-level Detection of Ethanol, 1,4-Dioxane, and Other Oxygenates Using the Eclipse Purge-and-Trap Sample Concentrator. In *Conference on Analytical Chemistry and Applied Spectroscopy*. O.I. Analytical, p. 12.

APPENDIX C: HPCD-ENHANCED ISCO LABORATORY EXPERIMENTS

This appendix describes laboratory experiments treating volatile organic compounds (VOCs) with OxyZone® and hydroxypropyl- β -cyclodextrin (HPCD), conducted in preparation for the ISCO field demonstration described in Chapter 1. The objectives of the bench-scale studies with VOCs are given below:

- Evaluate whether the presence of (HPCD) when complexed with VOCs interfere with the analysis of either HPCD or VOCs;
- Evaluate the VOC solubility-enhancing potential of technical grade HPCD;
- Evaluate the approximate composition of the NAPL present at the field site;
- Evaluate the solubility-enhancement factor of target contaminants (as individual compounds and in a mixture) in presence of HPCD;
- Evaluate the effect of the presence of HPCD on target contaminant destruction by OxyZone® in aqueous solution;
- Evaluate the rates of VOC destruction by OxyZone®;
- Assess the natural oxidant demand (NOD) of the soil;
- Evaluate various OxyZone® injection schemes using column flushing studies of contaminated field site soil with increasing number of oxidant solution pore volumes.

1. Laboratory Study Methods

Materials

The following chemicals were used during the bench-scale studies: 1,1-dichloroethene, 99% (Pfaltz & Bauer, D15160); 1,2-dichlorobenzene, 99% purity (Acros, 11318-0010); tetrachloroethene, > 99% (Fischer, 04586-4); o-xylene, 99% (Acros, 14099-0010); 1,1,1-Trichloroethane, >99.0% purity (Fluka, 91099). 1N sodium thiosulfate pentahydrate solution (SS364-1), sodium phosphate dibasic anhydrous (S374-500), sodium persulfate (BP2637-1), 30% hydrogen peroxide (S25360) were all purchased from Fisher Scientific. Hydroxypropyl- β -cyclodextrin (CD or cyclodextrin) was purchased as Cavasol from Wacker Chemical Corp. GCMS standards were purchased from Ultra Scientific and consisted of calibration standard solutions CLP-159, CLP-156 and internal standard solution STM-341N. Working standards were made using Fisher purge-and-trap grade methanol (A453-500). ACS grade methanol was used for rinsing and cleaning of equipment. Deionized (DI) water was prepared using a MilliQ water filtration system. Dissolved ozone was created using a Pacific Ozone L11 Ozone Generator. The ORP and pH were measured using Cole-Parmer probes (EW-59001-77, EW-59001-70) and a Thermo Scientific Orion Dual Star multi-parameter meter (2115000).

Oxidant Generation

Peroxone activated buffered persulfate is a patented technology (Ball 2010) and commercially available as OxyZone[®] from EnChem Engineering (Newton, Massachusetts). The oxidant solution is generated by combining gaseous or dissolved ozone and dilute hydrogen peroxide to activate buffered sodium persulfate at ambient temperatures. This facilitates the production of hydroxyl and sulfate radicals, two of the strongest oxidizers available. As a result OxyZone[®] is able to break down organic

contaminants through primary oxidation reactions, via ozone (2.1 V) and persulfate (2.0 V) molecules, as well as through more vigorous secondary oxidation reactions, via hydroxyl radical (2.8 V) and sulfate radicals (2.5 V) (Huling & Pivetz 2006; SERDP 2011). In its commercial form, OxyZone® has proved an effective ISCO treatment for BTEX, VOCs and SVOCs contamination.

For the bench-scale experiments performed in this study the OxyZone® was prepared using a bench-scale reactor, as follows: 3.5 Liter (L) of a 60 grams (g)/L sodium persulfate and 7.29 g/L disodium phosphate solution was prepared in deionized water, no more than 3 hours prior to use, in an amber glass vessel and mixed with a stir bar. A 3% hydrogen peroxide solution was prepared using a 30% stock. Once fully dissolved the buffered persulfate solution was then pumped into the reactor through the bottom fitting. Oxygen flow was initiated and the reactor was pressurized to 15 pounds per square inch gauge (psig). Gaseous ozone was then supplied to the reactor at a rate of ~0.38 g/h ozone for 25 minutes. Then 220 microliters (µl) of the 3% hydrogen peroxide solution was injected periodical throughout the reaction time, using the circulation loop at 6 min, 9 min, 12 min, 15 min, and 18 min. At 25 minutes, gas flow was stopped to the reactor column and the OxyZone® solution was withdrawn from the bottom valve of the reactor column for use.

1.1 Evaluation of Possible Impacts of CD on VOC Quantification

Throughout the field demonstration and bench-scale laboratory testing, aqueous HPCD concentrations was measured using the “University of Rhode Island’s Standard Operating Procedure for the Field Analysis of Hydroxypropyl-β-cyclodextrin.”

This method involves the analysis of a HPCD/6-p-toluidino-2-naphthalenesulfonic acid (TNS) complex using a fluorescence spectrophotometer. An experiment was designed and performed to determine whether the presence of other VOC/HPCD complexes in solution would interfere with this analytical procedure. The experiment was also designed to determine if the presence of HPCD in solution would interfere with the analysis of aqueous VOC concentrations via purge-and-trap methodology. Since tetrachloroethene (PCE) and 1,2-dichlorobenzene (1,2-DCB) are prevalent at the demonstration site, these test contaminants were chosen to be used for this experiment. Samples with varying HPCD concentrations (0 g/L, 5 g/L, 8.5 g/L, 16 g/L, & 20 g/L) were contaminated with a consistent mass of either PCE or 1,2-DCB and allowed to equilibrate for 72 hours at ambient temperatures. Following equilibration the solutions were analyzed for HPCD and VOC concentration to determine if the presence of HPCD interfered with analysis of VOC and vice-versa.

1.2 Solubility enhancement of VOC compounds in the Presence of CD

In this experiment, 25 ml of a 50 g/L CD (or DI water for the control) solution was equilibrated with pure phase 1,1,1-TCA, PCE, 1,2-DCB, and o-xylene as an equal molar non-aqueous phase liquid (NAPL) mixture for 72 hours at ambient temperatures. Aqueous VOC concentrations were then measured. The equal molar NAPL consisting of 1,1,1-TCA (4.9 ml), PCE (4.9 ml), 1,2-DCB (5.4 ml) and o-xylene (5.8 ml) was created by combining each contaminant in a 40 ml VOA (total DNAPL volume = 21 ml) which was then kept at -10 °C until use.

1.3 Creation of a NAPL Mixture to Reflect Site Groundwater Quality

The purpose of this laboratory study was to try and determine the composition of the residual NAPL present at the site. This would allow for the creation of a representative NAPL for experiments examining the effects of HPCD and OxyZone® on the primary site contaminants.

The composition of the residual phase NAPL at the site was calculated using groundwater samples taken from well I-1 in April 2012. A modified version of Raoult's law was then used to estimate the composition (by weight) of the site NAPL. Using the calculated site NAPL composition, a representative laboratory NAPL was then prepared. Using the calculated site NAPL composition, 10 ml of a representative laboratory NAPL was prepared by combining each of the major components in a 40 ml VOA, measured by mass, which was then stored in a refrigerator at 4 °C. The accuracy of the laboratory NAPL was tested by equilibrating it with DI water and measuring the aqueous phase VOC concentrations. 2 ml of the NAPL was equilibrated with 100 ml of DI water at room temperature for 72 hours and VOC concentrations were then measured.

1.4 Solubility Enhancement of CD on a Target NAPL Contaminant Mixture

In this experiment 0.5 ml of the laboratory NAPL that reflects the groundwater concentrations measured at the test site was equilibrated with 25 ml of 0 g/L, 5 g/L, 10 g/L, 20 g/L, and 50 g/L HPCD. Solutions were equilibrated for 72 h in headspace-free VOA vials at ambient temperatures and then measured. Relative solubility increased

linearly with increasing CD concentrations for the total mass of aqueous VOC as well all individual contaminants.

1.5 Treatability studies of VOC compounds in the presence of CD

1.5.1 Treatability of Single VOC Contaminants: 24 Hour Study

Single VOC (1,1,1-TCA, PCE, or 1,2-DCB) spiked deionized waters and HPCD solutions were treated with increasing amounts of OxyZone® (0 g/L, 0.1 g/L, 0.7 g/L, 3.6 g/L, 7.2 g/L and 14.5 g/L). Experimental solutions were prepared in 20 ml using concentrated VOC and HPCD stock solutions. Solutions were allowed to react for 24 h at room temperature and then quenched with sodium thiosulfate at the end of the reaction period. Solutions were then refrigerated until analysis.

1.5.2 Treatability of Single VOC Contaminants: 72 Hour Study

Single VOCs as 1,1,1-TCA, PCE, or 1,2-DCB spiked deionized waters and HPCD solutions were treated with increasing amounts of OxyZone® (0 g/L, 0.1 g/L, 0.7 g/L, 3.6 g/L, 7.2 g/L, and 14.5 g/L). Experimental solutions were prepared in 20 ml using concentrated VOC and HPCD stock solutions. Solutions were allowed to react for 72 hours at room temperature and then quenched with sodium thiosulfate at the end of the reaction period. Solutions were then refrigerated at 4°C until analysis.

1.5.3 Treatability of VOC Mixtures with and without Excess CD: 24 Hour Study

Multiple component (1,1,1-TCA, PCE, 1,2-DCB, o-Xylene, and 1,1,-DCE) spiked deionized waters and HPCD solutions were treated with increasing amounts of

OxyZone[®] (0, 0.1, 0.7, 3.6, 7.2 and 14.5 g/l). Experimental solutions were prepared in 40 ml using concentrated VOC and HPCD stock solutions. Solutions were allowed to react for 24 hours at room temperature and then quenched with sodium thiosulfate at the end of the reaction period. Solutions were then refrigerated until analysis. The multiple-component VOC stock solution was prepared using DI water equilibrated with the 5-component target NAPL described in section 1.3. The HPCD concentration used was 10 g/L.

1.5.4 Treatability of Multiple VOC in 1:1 Molar Complexes with ~50 mg/L HPCD

A multiple-component VOC stock solution was prepared by equilibrating the 5-component target NAPL previously described in section 1.3 with 50 g/L HPCD. This stock solution was then diluted by a factor of 500 with DI water to create a 100 mg/L HPCD working stock solution in which, hypothetically, each HPCD molecule had complexed one VOC molecule (i.e., equal molar ratio of VOCs and CD). This stock solution was then used to create experimental solutions treated with increasing amounts of OxyZone[®] (0 g/L, 0.1 g/L, 0.7 g/L, 3.6 g/L, 7.2 g/L and 14.5 g/L). The initial total VOC and HPCD concentration in these experiments were 1380 µg/L and 50 mg/L respectively. Solutions were allowed to react for 24 h at room temperature and then quenched with sodium thiosulfate at the end of the reaction period. Solutions were then refrigerated until analysis.

1.6 Oxidative Rate Studies

1.6.1 Rate of Single VOC Compound Oxidation

Experimental solutions were prepared in a manner similar to that described in section 1.5.1. Multiple replicates of a VOC spiked solution, treated with 7.2 g/L OxyZone®, were prepared so that samples with the same initial conditions could be collected at various times for analysis. Samples were periodically quenched with sodium thiosulfate at designated time intervals and refrigerated until analysis.

1.6.2 Rate of Multiple Contaminant Mixture Oxidation with and without Excess CD (10 g/L)

Experimental solutions were prepared in a manner similar to that described in section 1.5.2. Multiple replicates of a VOC spiked solution, treated with 7.2 g/L OxyZone®, were prepared. Samples were periodically quenched with sodium thiosulfate at designated time intervals and refrigerated until analysis.

1.6.3 Rate of Multiple Contaminant Oxidation with CD (50 mg/L) in 1:1 Complexes

Experimental solutions were prepared in a manner similar to that described in section 1.5.3. However, the four-component equal molar NAPL described in section 1.2 was used to generate the VOC-saturated stock solutions used in this experiment. Multiple replicates of a VOC spiked solution, treated with 7.2 g/L OxyZone®, were prepared. Samples were periodically quenched with sodium thiosulfate at designated time intervals and refrigerated until analysis.

1.6.4 Rate of 1,1,1-TCA Oxidation

Experimental solutions were prepared in 40 ml VOA using a concentrated 1,1,1-TCA stock solution and treated with one of three 7.2 g/L of sodium persulfate

treatments: alkaline persulfate, OxyZone®, or an alkaline OxyZone® variant. Phosphate buffers were used to adjust the pH. The experimental duration was 13 days. Samples were periodically quenched with sodium thiosulfate at designated time intervals and refrigerated until analysis. Initial 1,1,1-TCA concentration was 1,200 µg/L.

1.7 Natural Oxidant Demand

The natural oxidant demand (NOD) was determined for the site soils from three representative depths within the treatment area. The NOD tests were conducted using the standard permanganate method as described in (Haselow et al. 2003). The same author also describes a method for persulfate NOD, which we adopted for testing the OxyZone® NOD.

1.8 Column Studies

Four column tests were performed with contaminated soil from the field site to simulate *in situ* conditions and evaluate injections schemes. Soil samples were collected during prior site investigations and artificially contaminated in the laboratory. Three of the soil columns were flushed with varying pore volumes of OxyZone®; the fourth column was flushed with deionized water. After homogenization, contaminated soil was packed into four 2 cm by 4 cm glass columns. Each column was pre-saturated with deionized water and allowed to rest for 48 hours before testing. All flushing was performed with a syringe pump at a flow rate of 1 ml/min. Column A was flushed with 20 pore-volumes of OxyZone®, allowed to rest for 24 h, and then flushed with 2 pore volumes of deionized water. Column B was flushed with 9 pore-volumes of OxyZone®,

allowed to rest for 24 h and then flushed with 2 pore-volumes of deionized water.

Column C was flushed with 6 pore-volumes of OxyZone®, allowed to rest for 24 h, and then flushed with 2 pore-volumes of deionized water. Column D was flushed with 20 pore-volumes of deionized water, allowed to rest for 24 h, and then flushed with 1 pore-volume of deionized water.

2. Laboratory Studies Results

2.1 Evaluation of Possible Impacts of CD on VOC Quantification

This experiment was performed due to concerns that the high concentrations of HPCD in solution could impact the analysis of VOCs or vice versa. The results from this experiment, summarized in Table C1, indicate that the presence of HPCD in solution did not interfere with the analysis of the two target contaminants PCE and 1,2-DCB. Variations in measured PCE and 1,2-DCB concentrations were within the normal variation of the purge and trap analytical method. Additionally, the presence of these target contaminants did not interfere with the measurement of aqueous HPCD concentrations, as variations in measured HPCD concentrations were minimal. These results are plotted in Figure C1.

Sample ID	HPCD Concentration (g/L)	VOC Concentration (mg/L)
Control 1	BDL	-
Control 2	4.8	-
Control 3	8.5	-
Control 4	16.1	-
Control 5	20.7	-
1,2 DCB 1	BDL	27.9*
1,2 DCB 2	4.5	29.0
1,2 DCB 3	8.5	27.9
1,2 DCB 4	16.0	26.0
1,2 DCB 5	20.3	25.3
PCE 1	BDL	21.1
PCE 2	4.6	20.9
PCE 3	8.6	24.5
PCE 4	16.4	21.7
PCE 5	21.5	18.3*
HPCD analyzed by the TNS complexation method. VOCs measured by Purge-and-Trap 1,2-DCB: GCMS Method RSD: 6.5% RSD of Samples: 5.5% PCE: GCMS Method RSD: 11.8% RSD of Samples: 10.3% *Average of Two Measurements		

Table C1: measured VOC concentrations in solutions with varying concentration of HPCD

Figure C1: Measured HPCD concentration versus nominal HPCD concentration

2.2. Solubility enhancement of VOC compounds in the presence of CD

In this experiment, the VOC solubility enhancement using technical grade HPCD at a concentration of 5% (wt/wt) was evaluated with site contaminants as single VOC components and as part of a four-component equal molar mixture. The results were then compared to literature solubility values of the VOCs.

In evaluating the solubility enhancement by HPCD on an organic compound the following equation can be used:

$$\text{Eq. C1)} \quad S_{E_i}^O = S_A^O(1 + K_{CW}C_{CD}) = S_A^OE_i^O$$

Where S_A^O is the pure-compound aqueous solubility; C_{CD} is the HPCD concentration (%), K_{CW} is the HPCD partitioning coefficient, E_i^O is the pure compound solubility-enhancement factor at HPCD concentration i , and $S_{E_i}^O$ is the HPCD-enhanced (apparent) solubility in equilibrium with a single-component organic-liquid at CD concentration i , (McCray et al. 2000).

In the present study, the solubility-enhancement factor in a single component system using 5% HPCD was 16.2, 8.1, 7.9, and 4.3, for 1,2-DCB, PCE, o-xylene and 1,1,1-TCA, respectively, as presented in Table C2 (in column 4). Using equation (C1), it is possible to compare the solubility enhancement observed in our study for a 5% HPCD solution to predicted values using K_{CW} values presented in McCray et al. (2000) and McCray & Brusseau (1998) as shown in Table C2. The enhancement factors observed in our study for single-component systems are similar to those predicted using data from McCray et

al., 2000 with the exception of PCE. However, the solubility enhancement observed for PCE in the present study is in good agreement with that observed in batch experiment by Boving & Brusseau (2000).

In the four-component equal molar NAPL experiment, the solubility of each contaminant in DI water was depressed as expected, and approximately equal to the concentrations predicted by Raoult's Law from equation (2); also shown in Table C2:

Eq. C2)
$$S_A = S_A^0 X_N$$

where S_A is the measured apparent solubility of a compound in equilibrium with an organic-liquid mixture and X_N is the mole fraction of the compound in the organic-liquid mixture.

If the multi-component organic-liquid mixture behaves ideally, a HPCD-enhanced Raoult's law can be used to predict the solubility enhancement:

Eq. C3)
$$S_E = S_A^0 X_N E_i^0$$

where S_E is apparent solubility of the compound in equilibrium with an organic-liquid mixture.

Solubility enhancement, E_i^0 , of PCE and o-xylene, using 5% HPCD in the four-component equal molar system, was similar to that observed in the single-component experiments. However, the relative observed solubility enhancement of 1,2-DCB and 1,1,1-TCA were

approximately 30% and 100% higher, respectively, than in the single-component system.

Previous work by Carroll & Brusseau (2009) found that the distribution of compounds between HPCD and water was independent of the organic-liquid mixture composition when examining single, dual, and three-component systems; suggesting that HPCD induced solubility enhancement was ideal for each compound. All of the contaminants investigated in that study were monocyclic aromatic compounds (toluene, ethyl benzene and butyl benzene), while those used in the present study represented a wider range of contaminant types; chloroethanes, chloroethenes, chlorobenzenes, and mono-aromatic hydrocarbons. Thus, the non-ideal solubility enhancement observed in the present experiment may be explained by the more complex nature of the mixture tested. In addition a wide range of aqueous solubilities have been reported in the literature for 1,1,1-TCA for ambient temperatures (20-25 °C) ranging from 480-4500 mg/L which may further complicate the dissolution behavior in the four-component system (US EPA 1993; Montgomery & Welkom 1989). This suggests that it may be necessary to assess the solubility enhancement potential of HPCD on a representative site specific NAPL as these experiments suggest the solubility enhancement will be non-ideal and difficult to predict.

	Measured (mg/l)		Calculated		Literature Values		
As Single Contaminants	S_A^O	$S_{E_i}^O$ in 5% CD	E_i^O in 5% CD	Log K_{cw}	E_i^O in 5% CD	Log K_{cw}	Log K_{ow}
o-DCB	130	2100	16.2	2.48	16.25 ^B	2.48 ^B	3.4 ^A
PCE	160	1300	8.1	2.15	4.97 ^B / 8.1 ^C	1.9 ^B / 2.15 ^C	2.6 ^A
o-XYL	140	1100	7.9	2.14	8.57 ^B	2.18 ^B	2.95 ^A
TCA	1500	6500	4.3	1.82	3.4 ^D	1.68 ^D	2.47 ^A
	Measured (mg/l)		Calculated		Predicted		
As Equal Molar NAPL Mixture	S_A^O	$S_{E_i}^O$ in 5% CD	E_i^O 5% HPCD	Log K_{cw} DNAPL	S_A^O (mg/L)	$S_{E_i}^O$ (mg/l) in 5% CD	E_i^O 5% in CD
o-DCB	40	850	21.3	2.61	30	520	17.3
PCE	55	450	8.2	2.16	40	320	8.0
o-XYL	55	400	7.3	2.10	35	280	8.0
TCA	290	2500	8.6	2.18	380	1600	4.2
Total VOC	440	4200	9.5	2.23	485	2720	5.6
A = From Montgomery and Welkom 1989 B = Predicted from values in McCray et al. 2000 GWMR C = From Boving and Brusseau, 1999 D = From McCray and Brusseau, 1999							

Table C2: Solubility enhancement of target compounds (as individual compounds and in mixture) in the presence of HPCD (Montgomery & Welkom 1989; McCray et al. 2000; Boving et al. 1999; McCray & Brusseau 1998).

2.3 Creation of a NAPL Mixture to Reflect Site Groundwater Quality

A synthetic laboratory NAPL contaminant mixture was created that would reflect the groundwater concentrations measured at the test site. Of the detected VOCs at injection well I-1, greater than 90% of the total aqueous phase contaminant mass was accounted for by 1,1,1-TCA, PCE, and dichlorobenzene (ortho, meta, and para) shown in Table C3. The estimated site NAPL composition shows that the majority of the residual phase NAPL at the site consists of PCE and DCB as shown in Table C4. Despite high aqueous phase concentrations, 1,1,1-TCA was shown to account for only a small fraction of the NAPL present, due in part to its relatively higher aqueous solubility.

Table C5 shows the composition of the simplified, synthetic laboratory NAPL that was created. For the purposes of simplification, 1,2-dichlorobenzene (1,2-DCB) and o-xylene were used to represent the total dichlorobenzene and BTEX fraction of the site NAPL in the laboratory NAPL respectively. The measured aqueous phase VOC of the NAPL-equilibrated DI water shown in Table C5 (column 5) was in good agreement with the predicted values shown in Table C3. When compared with VOC concentrations at injection well I-1 shown in Table C5, the relative proportion of each contaminant in the laboratory NAPL-equilibrated water was in reasonable agreement. However, measured VOC concentrations show that groundwater at injection well I-1 is likely diluted approximately 8 times compared to water in direct equilibrium with NAPL. This suggests that injection well I-1 is near, but not directly within, the center of VOC mass. Wells I-5 and I-6 were installed following the completion of this experiment in October, 2012 and

found to be even more contaminated than I-1. Specifically, VOC concentrations in injection wells I-5 and I-6 are apparently diluted only approximately 2 times relative to the expected concentrations for NAPL-equilibrated water. This suggests that injection wells I-5 and I-6 are closer to or within the contaminant source zone. Injection wells I-5 and I-6 are shallow screened wells suggesting that residual phase NAPL contamination may be trapped in the upper aquifer units consisting of low permeability organic silts and silty-sands.

VOC	I-1	
	mg/L	% of Total (Molar basis)
1,1-dichloroethane	0.43	2.65
1,1-dichloroethene	0.68	4.21
1,1,1-trichloroethane	4.90	22.0
Trichloroethene	0.01	0.01
Tetrachloroethene	9.30	33.2
Benzene	0.002	0.02
Toluene	0.02	0.11
ethylbenzene	0.06	0.33
m & p - xylene	0.12	0.66
o-xylene	0.03	0.16
1,2-dichlorobenzene	6.10	24.8
1,3-dichlorobenzene	0.93	3.77
1,4-dichlorobenzene	2.00	7.96
1,2,4-trichlorobenzene	0.06	0.18
Total	24.64	

Table C3: Aqueous VOC detected in well I-1 during April 2012 sampling

Estimated Site NAPL Composition	% WT
1,1-dichloroethene	0.10
1,1-dichloroethane	0.04
1,1,1-trichloroethane	6.58
Tetrachloroethene	39.42
Toluene	0.02
Ethylbenzene	0.22
m & p - xylene	0.43
o-xylene	0.10
1,3-dichlorobenzene	4.2
1,4-dichlorobenzene	19.3
1,2-dichlorobenzene	28.5

Table C4: Estimated site NAPL composition based on groundwater concentrations from well I-1 in April 2012.

Dominant contaminants Detected Fort Eustis groundwater from Well I- 1, April 2012	Estimated DNAPL Composition	Theoretical Aq. Conc. at Equilibrium with DNAPL		Measured Aq. Conc. At Equilibrium with DNAPL		I-1 Groundwater April 2012		I-5 Groundwater October 2012		I-6 Groundwater October 2012	
	Wt %	mg/L	Wt % of total	mg/L	Wt % of Total	mg/L	Wt % of Total	mg/L	Wt % of Total	mg/L	Wt % of Total
1,1-Dichloroethene	0.1%	7.8	4.4%	2.5	1.3%	0.7	2.9%	9	11.5%	7.7	7.2%
1,1,1-Trichloroethane	7.4%	41	22.9%	55	29.6%	4.9	20.3%	11	14.1%	32.0	30.0%
Tetrachloroethene	44.3%	61	34.1%	54	29.0%	9.3	38.6%	23	29.5%	24.0	22.5%
Total BTEX*	0.8%	2.1	1.2%	1.5	0.8%	0.2	0.8%	2	2.6%	1.5	1.4%
Total Dichlorobenzene	47.3%	67	37.5%	73	39.2%	9	37.3%	31	39.7%	41.5	38.9%
Total:		179		186		24.1		78		107	

Table C5: Comparison of the artificial DNAPL contaminated water versus predicted concentrations at wells I-1, I-5, and I-6.

2.4 Solubility Enhancement of CD on a Target NAPL Contaminant Mixture

This experiment measured the solubility-enhancing potential of technical grade HPCD on a target NAPL contaminant mixture that reflects the groundwater concentrations measured at the test site. The results showed that relative solubility increased linearly with increasing CD concentrations for the total mass of aqueous VOC as well as all individual contaminants shown in Figure C2 and Figure C3. 1,1-DCE showed the smallest solubility-enhancement factor of less than five (in the 50 g/L CD solution). The greatest solubility-enhancement factor was observed for 1,1,1-TCA and PCE at greater than 12 (in the 50 g/L CD solution). Interestingly, 1,1,1-TCA represented only 7.4% of the total NAPL, while PCE represents 44.3%, yet both yielded similar solubility enhancements. The HPCD partitioning coefficient, K_{CW} , values were calculated for each contaminant in the mixture at the four HPCD concentrations tested, as well as for the total VOC, and are presented in Table C6. The average K_{CW} for the site NAPL differed from those in previous single-component and four-component experiments. These findings confirmed that the partitioning of NAPL compounds in a mixture is complicated; depending on a combination of contaminant solubility, affinity for HPCD and relative proportion (mole fraction) in the mixture. Therefore, when assessing the potential of HPCD-based remediation, it seems prudent to test HPCD solubilizing effect on a representative site NAPL, as the solubility enhancement may not follow ideal behavior. Thus, using a site specific NAPL-based K_{CW} may prove a better predictive tool than those obtained from individual contaminant tests.

VOC	logK _{cw} (5 g/L)	logK _{cw} (10 g/L)	logK _{cw} (20 g/L)	logK _{cw} (50 g/L)	logK _{cw} (AVG)	logK _{cw} (50 g/L)	logK _{cw} (50 g/L)
	Site NAPL	Site NAPL	Site NAPL	Site NAPL	Site NAPL	Single Compound	Equal Molar NAPL
1,2-DCB	2.04	2.21	2.31	2.16	2.18	2.48	2.61
PCE	2.61	2.46	2.52	2.37	2.49	2.15	2.16
o-xylene	2.18	2.05	2.22	2.07	2.13	2.14	2.10
1,1,1-TCA	2.66	2.62	2.53	2.36	2.54	1.82	2.18
1,1-DCE	2.41	2.31	2.00	1.81	2.13	N/A	N/A
Total	2.41	2.40	2.42	2.26	2.37	N/A	2.23

Table C6: LOG(K_{cw}) calculated for HPCD solutions ranging from 5-50 g/l.

FIGURE C2: Apparent solubility enhancement of individual VOCs by HPCD.

FIGURE C3: Apparent solubility enhancement of Total VOC by HPCD.

2.5 Treatability studies of VOC compounds in the presence of CD

2.5.1 Treatability of Single VOC Contaminants: 24 Hour Study

A 24 hour experiment was conducted to examine the impact of OxyZone® on VOCs in aqueous solutions with and without HPCD. A comparison of the results in Figure C4 demonstrated that the presence of HPCD clearly hinders OxyZone® destruction of all three VOCs and at all concentrations of OxyZone® (quantified as the persulfate concentration). In addition, it appears that there may be some HPCD destruction at high OxyZone® concentrations over the 24 hours of experiments shown in Figure C5.

2.5.2 Treatability of Single VOC Contaminants: 72 Hour Study

A 72 hour experiment was conducted to examine the treatability of VOCs in HPCD containing and non-HPCD containing aqueous solutions over a longer period of time. The presence of 11.6 g/L of HPCD decreased VOC destruction by OxyZone® to varying degrees as shown in Figure C6, possibly because some of the VOCs are “protected” from oxidation by being encapsulated by HPCD. The presence of HPCD in solution had greatest effect on the destruction of 1,1,1-TCA and the smallest effect on PCE, the most abundant test site contaminant.

In addition, some HPCD destruction (oxidation) was observed during these experiments as approximately 40% HPCD destruction was observed at the highest OxyZone® concentration over the test period of 72 h as shown in Figure C7. Experiments were later conducted to investigate the kinetics of this interaction.

Figure C4: Aqueous VOC concentration following 24 hour treatment with increasing amounts of Oxyzone® with and without HPCD. Initial VOC concentrations in samples without HPCD: 1,1,1-TCA = 3,160 µg/l; PCE = 3,840 µg/l; 1,2-DCB = 4,630 µg/l. Initial VOC concentrations in samples with HPCD: 1,1,1-TCA = 2,580 µg/l; PCE = 3,630 µg/l; 1,2-DCB = 3,780 µg/l.

Figure C5: Changes in HPCD concentration following 24 hour treatment with increasing amounts of Oxyzone®; starting HPCD concentrations was 10 g/l.

Figure C6: Aqueous VOC concentrations ($\mu\text{g/l}$) following 72 hour treatment with increasing amounts of Oxyzone[®] with and without HPCD notes: Initial HPCD concentration = ~ 11.6 g/l. Initial VOC concentration in samples without HPCD: 1,1,1-TCA = $4,670$ $\mu\text{g/l}$; PCE = $13,300$ $\mu\text{g/l}$; 1,2-DCB = $5,900$ $\mu\text{g/l}$. Initial VOC concentration in samples with HPCD: 1,1,1-TCA = $5,450$ $\mu\text{g/l}$; PCE = $13,300$ $\mu\text{g/l}$; 1,2-DCB = $5,670$ $\mu\text{g/l}$.

Figure C7: Aqueous HPCD concentrations following 72 hour treatment with increasing amounts of Oxyzone®. Initial HPCD Concentration = ~11.6 g/l. Initial VOC concentration in samples: 1,1,1-TCA = 5,450 µg/l; PCE = 13,300 µg/l; 1,2-DCB = 5,670 µg/l.

2.5.3 Treatability of VOC Mixtures with and without Excess CD: 24 Hour Study

OxyZone® is capable of degrading all major contaminants present at the site. However, different oxidant concentrations are necessary to treat the various contaminants. For instance, o-xylene and 1,2-DCB are destroyed even in dilute OxyZone® solutions (i.e., 3.6 g/L persulfate), whereas 1,1,1-TCA is more recalcitrant at all OxyZone® concentrations (see Figure C8).

The VOC treatment results, summarized in Figure C9, show that when excess HPCD is present at 10 g/l, (i.e. more CD than needed to form 1:1 complexes) VOC destruction by OxyZone® is much less efficient than in the absence of HPCD seen in Figure C8. This is presumably because the excess HPCD is consuming a significant portion of the OxyZone®, that could otherwise be oxidizing the VOCs. Figure C10 shows that almost 18% of the HPCD was oxidized by the highest level of OxyZone®.

These results demonstrate that HPCD concentrations must be carefully adjusted to obtain optimal complexation ratios. Failure to do so could result in the creation of additional oxidant demand if the HPCD dosing is too high or decreased VOC solubility enhancement if the dosing is too low. The ideal HPCD concentration should be determined based on expected or known contaminant concentrations within the treatment zone.

FIGURE C8: 24 hour batch experiment; treating site contaminants with increasing Oxyzone® concentrations, HPCD not present. Initial total VOC concentration was 3,630 µg/l.

Figure C9: Aqueous VOC concentrations after 24 h batch experiment; treating site contaminants with increasing Oxyzone®. In the presence of 10 g/l HPCD. Initial total VOC concentration was 3,240 µg/l.

Figure C10: Aqueous HPCD concentrations after 24 h batch experiment of treating site contaminants with increasing Oxyzone®. Initial HPCD concentration: 10 g/l. Initial total VOC concentration was 3,240 µg/l.

2.5.4 Treatability of Multiple VOCs in 1:1 Molar Complexes with ~ 50 mg/L HPCD

The HPCD concentration selected for this batch experiment was close to the ideal concentration to form a 1:1 molar VOC: HPCD complex with no un-complexed excess HPCD present. Under these conditions, OxyZone® was shown to destroy VOCs even when CD is present in solution (see Figure C11), similarly to no HPCD at all (Figure C8). As usual, while only small amounts of 1,1,1-TCA were destroyed, most all the other VOCs were totally destroyed.

As expected, HPCD measurement data shown in Figure C12 did show decreasing HPCD concentrations (initial concentration of 50 mg/l) during the 24 hours of treatment of VOC (total initial concentration 1,380 µg/l) with increasing OxyZone® strength. In the 14.5 g/L OxyZone® treatment solution, approximately 87% of HPCD was degraded over the 24 hour treatment period.

This data suggests that co-injection of OxyZone® and HPCD, would be relatively inefficient since a significant portion of the injected HPCD would likely be degraded during mixing with OxyZone® and entering the subsurface, before having the opportunity to form complexes with organic contaminants. The injection of alternating slugs of OxyZone® and HPCD during the field application would likely limit this problem.

FIGURE C11: Aqueous VOC concentrations after 24 h batch experiment; treating site contaminants with increasing Oxyzone®. Initial total VOC concentration was 1,380 µg/l. 50 mg/l HPCD concentration = no excess HPCD (i.e., all CD had complexed a VOC molecule).

Figure C12: Aqueous HPCD concentrations after 24 h batch experiment. Initial total VOC concentration was 1,380 $\mu\text{g/l}$. HPCD concentration was such that, theoretically, there was no excess HPCD (i.e. all HPCD had complexed a VOC molecule).

2.6 Oxidative Rate Studies

2.6.1 Rate of Single VOC Compound Oxidation

All three major site contaminants are oxidized by OxyZone® as single contaminants. However, oxidation of 1,1,1-TCA is an order of magnitude slower than that of PCE and 1,2-DCB. This difference can be seen in Table 3-7, and Figure C13, Figure C14, and Figure C15.

VOC	Co (µg/L)	K ₁ (h ⁻¹)	T½ (h)	R ²
TCA	3140	0.019	36.5	0.944
PCE	3800	0.699	1.0	0.997
1,2-DCB	4750	0.246	2.8	0.992

Table C7: Pseudo-first-order oxidation rate constants for single VOC, experiments in DI water with 7.2 g/l OxyZone® as persulfate.

Figure C13: oxidation of 1,1,1-TCA in DI water by Oxyzone®. Initial 1,1,1-TCA concentration = 3,140 µg/l. Oxyzone® 7.2 g/l as persulfate.

Figure C14: Oxidation of PCE in DI water by Oxyzone®; initial PCE concentration = 3,800 µg/l. Oxyzone® 7.2 g/l as persulfate.

FIGURE C15: Oxidation of 1,2-DCB in DI water by Oxyzone®.

2.6.2 Rate of Multiple Contaminant Mixture Oxidation with and without Excess CD (10 g/L)

Additional OxyZone® oxidation experiments were performed in a multiple VOC mixture. Figure C16 shows the results over the 24 hour test for five VOCs with no HPCD present. Significant destruction was observed for all VOCs except 1,1,1-TCA. Pseudo-first order rate constants and half-lives were calculated and listed in Table C8. Figure C17 shows the results of the same experiment but in the presence of 10 g/l of HPCD. A comparison of HPCD-containing and non-HPCD-containing results demonstrate how the presence of HPCD slows VOC destruction by OxyZone®. There is also evidence as shown in Figure C18 that OxyZone® was degrading the HPCD in the experiment.

VOC	Co (µg/L)	K ₁ (h ⁻¹)	T _{1/2} (h)	R ²
1,1,1-TCA	1400	0.0108	64.2	0.787
PCE	950	0.3737	1.9	0.997
1,2-DCB	1100	0.5355	1.3	0.977
1,1,-DCE	250	0.7476	0.9	0.957
O-Xylene	25	1.6645	0.4	0.974
Total	3725	-	-	-

Table C8: Pseudo-first-order rate constant for oxidation of individual VOCs in a multi-component mixture 7.2 g/l Oxyzone® as persulfate. No HPCD Present.

FIGURE C16: Oxidation of individual VOC in a multi-component VOC mixture by Oxyzone®. Total initial VOC was 3725 µg/l. No HPCD was present in this experiment. 7.2 g/l OxyZone®

FIGURE C17: VOC concentrations during oxidation of individual VOCs in a multi-component VOC mixture by Oxyzone®. Total initial VOC was 3,725 µg/l. Excess 10 g/l HPCD present in this experiment. 7.2 g/l OxyZone®

FIGURE C18: HPCD concentration during oxidation of individual VOC in a multi-component VOC mixture by Oxyzone®. Total initial VOC was 3,725 µg/l. Initial 10 g/l HPCD. 7.2 g/l OxyZone®.

2.6.3 Rate of Multiple VOC Oxidation with and without CD in ~1:1 Complexes

Destruction of the target VOCs by a 7.2 g/L OxyZone® solution in the absence of HPCD is shown over an 8 hour reaction period in Figure C19. Complete destruction of o-xylene, 1,2-DCB, and PCE was observed within the eight-hour period but significant destruction of 1,1,1-TCA was not observed during this reaction period. The destruction of 1,2-DCB, o-xylene, and PCE closely follow first-order kinetics. The observed pseudo-first-order rate constants are tabulated in Table C9. The highest observed reaction rate constant was for the destruction of o-xylene, which was twice that of 1,2-DCB and three times that of PCE.

The same experiment was then performed in the presence of 37.4 mg/L (initial concentration) of HPCD, an approximately 1:1 molar ratio to the VOC concentration. Under these conditions, VOC contaminant destruction was visibly slower in the presence of HPCD when compared to the results in Figure C19 and complete destruction was only observed for o-xylene. As with the no HPCD experiment, significant destruction of 1,1,1-TCA was not observed during the reaction period.

A linearized plot of this data, shown in Figure C20, of the same data shows that the destruction of 1,2-DCB, o-xylene, and PCE also follows first-order kinetics when HPCD is present and the observed rate constants are tabulated in Table C9.

The highest observed reaction rate was again for the destruction of o-xylene, which, in this case, was three times that of 1,2-DCB and four times that of PCE. The presence of the CD has the effect of significantly reducing contaminant destruction

rates. The destruction rate constants for o-xylene, PCE, and 1,2-DCB were reduced by 60%, 67%, and 70%, respectively. These results offer further evidence that the application of CD to groundwater with already high aqueous contaminant concentrations may be detrimental to treatment efficiency and should be reserved for the least soluble contamination or for those contaminants that are more soluble, but not yet solubilized.

HPCD destruction by 7.2 g/L OxyZone® was monitored in samples containing the same simulated VOC mixture of field VOCs as well as samples containing only HPCD without VOCs. HPCD destruction over the eight-hour reaction period is shown in Figure C21. A significant loss of HPCD at approximately 50%, was observed in the first 30 minutes of the test, followed by much slower degradation thereafter. As would be expected, greater destruction of HPCD was observed when no VOCs were present in solution. The destruction of the HPCD does not follow first-order rate kinetics due to significant drop in the first 30 minutes. The kinetics may be variable due to the presence of ozone early in the test. When the first 30 minutes are ignored, the destruction closely follows first-order with rate constants of 0.055 h^{-1} and 0.271 h^{-1} for HPCD in the presence of VOCs and HPCD alone, respectively (See Table C10). The ORP and pH changes observed during these experiments are shown in Figures C22 and C23 and Figures C24 and C25, respectively for experimental solutions with and without CD.

Contaminant(s)	VOC (ug/L)	HPCD (mg/L)	K ₁ (h ⁻¹)	t ½ (h)	R ²
Without CD					
1,1,1-TCA	1700	0	NA	NA	NA
PCE	240	0	0.4399	1.58	0.9785
1,2-DCB	220	0	0.6248	1.11	0.981
O-xylene	270	0	1.4833	0.47	0.9838
Total	2430	0			
With CD					
1,1,1-TCA	1300	37.4	NA	NA	NA
PCE	240	37.4	0.1467	4.72	0.913
1,2-DCB	600	37.4	0.1854	3.74	0.973
O-xylene	270	37.4	0.5963	1.16	0.989
Total	2410	37.4			

Table C9: Pseudo-first-order rate data for oxidation of individual VOC in a multi-component VOC mixture 7.2 g/l OxyZone® as persulfate. With the CD condition, the concentration was such that, theoretically, there was no excess HPCD, (i.e., all CD had complexed a VOC molecule).

VOC ($\mu\text{g/L}$)	HPCD (mg/L)	k_1 (h^{-1})	$t_{1/2}$ (h)	R^2
0	37.4	0.2712	2.5	0.994
2410	37.4	0.0548	12.6	0.985

Table C10: Pseudo-first-order rate data for oxidation of HPCD

FIGURE C19: Oxidation of individual VOC in a multi-component VOC mixture in the absence of HPCD. 7.2 g/l OxyZone®. Total initial VOC was 2,430 µg/l. No HPCD was present in this experiment.

Figure C20: Oxidation of individual VOC in a multi-component VOC mixture complexed with 1:1 molar HPCD. 7.2 g/l Oxyzone®. Initial VOCs: 2,410 µg/l. 37.4 mg/l HPCD (total HPCD concentration such that, theoretically, there was no excess HPCD (i.e., all HPCD had complexed a VOC molecule).

Figure C21: HPCD concentration over time during treatment with Oxyzone® with and without the presence of VOC. 7.2 G/L OxyZone®. Initial VOCs: 2,410 µg/l. 37.4 mg/l HPCD (total HPCD concentration such that, theoretically, there was no excess HPCD (i.e., all HPCD had complexed a VOC molecule)).

FIGURE C22: Oxidation / reduction potential (ORP) during Oxyzone® treatment of DI solutions with and without VOCs.

Figure C23: Oxidation / reduction potential (ORP) during Oxyzone® treatment of 37.4 mg/l VOC solutions with and without HPCD

FIGURE C24: pH during Oxyzone[®] treatment of DI solutions with and without VOC. 7.2 g/l OxyZone[®].

FIGURE C25: pH during Oxyzone[®] treatment of 37.4 mg/l VOC solutions with and without HPCD. 7.2 g/l OxyZone[®].

2.6.4 Rate of 1,1,1-TCA Oxidation

After observing the poor destruction of 1,1,1-TCA by normal concentration OxyZone®, additional experiments were performed with alkaline OxyZone® and alkaline persulfate. The results in Figure C26 show that the destruction rate of 1,1,1-TCA by normal OxyZone® and alkaline-activated persulfate were both significantly faster than by alkaline OxyZone®; and alkaline-activated persulfate was slightly faster than OxyZone®. Concentrations of 1,1,1-TCA were reduced to below detection limits after 7 days in samples treated with OxyZone® and alkaline-activated persulfate. The destruction of 1,1,1-TCA closely followed pseudo-first-order kinetics with all oxidant mixtures and is shown in Table C11. The destruction rate of 1,1,1-TCA, by OxyZone®, was determined to be approximately 10 times slower than that of PCE. The changes in pH and ORP during the experiments are shown in Figures C27 and C28.

VOC	Co (µg/L)	K ₁ (h ⁻¹)	T½ (h)	R ²
Alkaline OxyZone	1,200	0.004	173	0.520
OxyZone	1,200	0.033	21	0.971
Alkaline Persulfate	1,200	0.074	9.4	0.994

Table C11: Pseudo-first-order rate data for 1,1,1-TCA oxidation by different oxidants

Figure C26: Destruction rate data for 1,1,1-TCA oxidation experiment.

FIGURE C27: pH data for 1,1,1-TCA oxidation experiment.

FIGURE C28: ORP data for 1,1,1,-TCA oxidation experiment.

2.7 Natural Oxidant Demand

The natural oxidant demand (NOD) of site soil was quantified with potassium permanganate and OxyZone[®]. The results in Table C12 demonstrate that relative to conventional permanganate treatment, less OxyZone[®] is needed to overcome natural/background concentration of oxidizable compounds. The upper most 4 feet of the soil horizon have a noticeably higher NOD than the deeper horizons. The top layer at the site consists of anthropogenic fill whereas the deeper horizons are natural sediments. The fill material apparently contains more oxidizable compounds. Because the OxyZone[®] treatment will focus on the deeper, less NOD demanding parts of the aquifer, these results indicate that the loss of oxidant due to natural organic matter will be small.

Location	Depth (ft)	Oxidant	NOD (g/Kg)
U4	0-4	KMnO4	>16.4
U5	10-14	KMnO4	3.7
U7	12-16	KMnO4	3.9
U4	0-4	OxyZone®	5.5
U5	10-14	OxyZone®	1.5
U7	12-16	OxyZone®	1.9

Table C12: Results of natural oxidant demand test with field site material from three representative horizons within the treatment zone

2.8 Column Studies

Column tests were performed with soil from the field site to evaluate different oxidant delivery schemes. Of the number of co-contaminants present at the site, we selected 1,1,1-TCA, PCE, and dichlorobenzenes to study the effectiveness of oxidant treatment, and the columns were artificially contaminated with an equal molar mixture under the following conditions:

- Column A was flushed with 20 pore-volumes of OxyZone®, allowed to rest for 24 h, and then flushed with 2 pore volumes of deionized water.
- Column B was flushed with 9 pore-volumes of OxyZone®, allowed to rest for 24 h, and then flushed with 2 pore-volumes of deionized water.
- Column C was flushed with 6 pore-volumes of OxyZone®, allowed to rest for 24 h, and then flushed with 2 pore-volumes of deionized water.
- Column D was flushed with 20 pore-volumes of deionized water, allowed to rest for 24 h, and then flushed with 1 pore-volume of deionized water.

The results of these tests are summarized in Figures C29 through C32. The total reductions in aqueous contaminant concentrations are presented in Table C13 and Figure C33. The greatest aqueous mass reductions were observed in soil Columns A and B with total reductions of 4,604 µg/L and 5,984 µg/L, respectively. There was significant variability in starting aqueous contaminant concentrations between the columns. For example, the starting aqueous concentration in Column B was more than five times greater than that of Column D. Therefore, the results are not directly comparable.

Column	VOC in PV ₀ (µg/l)	VOC in PV Final (µg/l)	Aqueous Reduction in VOC effluent (µg/l)	PV OxyZone®	PV Total
A	4,976	372	4,604	20	22
B	6,906	922	5,984	9	11
C	2,233	762	1,470	6	8
D	1,302	527	775	0	21

Table C13: Aqueous phase VOC concentration reductions in soil column effluent pv = pore volumes

Figure C29: Soil column A - effluent contaminant concentrations

FIGURE C30: Soil column B – effluent contaminant concentrations

FIGURE C31: Soil column C – effluent contaminant concentrations

FIGURE C32: Soil column D – effluent contaminant concentrations

Figure C-33: Aqueous phase VOC concentration reductions in soil column effluent

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APPENDIX D: MANUSCRIPT 1 DATA

Well Information

Well ID	Date Installed	Well Diameter (cm)	Total Depth (m bgs)	Screen Interval (m bgs)	Elevation (TOC-m)
WELLS INSTALLED BY ENCHEM ENGINEERING					
I-1	4/17/2012	3.81	4.9	3.4-4.9	0.89
I-2	4/17/2012	3.81	4.9	3.4-4.9	0.90
I-3	5/8/2012	3.81	4.9	3.0-4.6	0.84
I-4	5/8/2012	3.81	4.9	3.0-4.6	0.82
I-5	9/26/2012	1.91	3.0	1.5-3.0	0.91
I-6	9/26/2012	1.91	3.0	1.5-3.0	0.89
I-7	4/30/2013	1.91	3.7	2.1-3.7	NA
I-8	4/30/2013	1.91	6.1	4.6-6.1	NA
I-9	4/30/2013	1.91	3.7	2.1-3.7	NA
I-10	4/30/2013	1.91	6.1	4.6-6.1	NA
EC-1	4/18/2012	3.81	4.9	3.4-4.9	0.81
EC-2	4/18/2012	3.81	4.9	3.4-4.9	0.93
EC-3	5/8/2012	3.81	4.9	3.0-4.6	0.88
EC-4	5/8/2012	3.81	4.9	3.0-4.6	0.74
U1	5/8/2012	1.91	5.2	2.1-5.2	0.77
U2	5/8/2012	1.91	5.2	2.1-5.2	0.77
U3	5/8/2012	1.91	5.2	2.1-5.2	0.83
U4	5/9/2012	1.91	5.2	2.1-5.2	0.91
U5	5/9/2012	1.91	5.2	2.1-5.2	0.87
U6	5/9/2012	1.91	5.2	2.1-5.2	0.94
U7	5/9/2012	1.91	5.2	2.1-5.2	0.92
U8	5/10/2012	1.91	5.2	2.1-5.2	0.98
U9	5/10/2012	1.91	5.2	2.1-5.2	0.90
U10	9/25/2012	1.91	4.6	3.0-4.6	0.95
U11	9/25/2012	1.91	4.6	3.0-4.6	0.89
U12	9/26/2012	1.91	4.6	3.0-4.6	0.76
U13	9/25/2012	1.91	4.6	3.0-4.6	0.82
U14	9/25/2012	1.91	4.6	3.0-4.6	0.78
U15	9/25/2012	1.91	4.6	3.0-4.6	0.82
U16	9/25/2012	1.91	5.2	1.5-3.0 & 3.7-5.2	0.85
U17	9/25/2012	1.91	5.2	1.5-3.0 & 3.7-5.2	0.84
U18	9/26/2012	1.91	5.2	1.5-3.0 & 3.7-5.2	0.85
U19	9/26/2012	1.91	5.2	1.5-3.0 & 3.7-5.2	0.84
U20	9/26/2012	1.91	5.2	1.5-3.0 & 3.7-5.2	0.86
U21S	4/24/2013	1.91	5.2	1.5-3.0	NA
U21D	9/28/2012	1.91	3.0	3.7-5.2	NA
WELLS INSTALLED BY MALCOM PIRNIE					
MW-1	6/9/2005	5.08	5.8	4.3-5.8	0.90
MW-2	6/9/2005	5.08	5.6	4.1-5.6	1.04
MW-3	6/9/2005	5.08	5.9	4.3-5.9	1.00
DMW-2904	NA	5.08	24.3	21.2-24.3	NA
WELLS INSTALLED BY MONTGOMERY WATSON					
MW-2904	5/20/1993	5.08	5.4	2.4-5.4	0.88
MW-2905	5/20/1993	5.08	6.0	3.0-6.0	NA
MW-2906	5/22/1993	5.08	6.1	3.0-6.1	NA

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[illegible]

name	comment
<i>Q</i> = <i>Q</i> ₁ + <i>Q</i> ₂ + <i>Q</i> ₃ + <i>Q</i> ₄ + <i>Q</i> ₅ + <i>Q</i> ₆ + <i>Q</i> ₇ + <i>Q</i> ₈ + <i>Q</i> ₉ + <i>Q</i> ₁₀ + <i>Q</i> ₁₁ + <i>Q</i> ₁₂ + <i>Q</i> ₁₃ + <i>Q</i> ₁₄ + <i>Q</i> ₁₅ + <i>Q</i> ₁₆ + <i>Q</i> ₁₇ + <i>Q</i> ₁₈ + <i>Q</i> ₁₉ + <i>Q</i> ₂₀ + <i>Q</i> ₂₁ + <i>Q</i> ₂₂ + <i>Q</i> ₂₃ + <i>Q</i> ₂₄ + <i>Q</i> ₂₅ + <i>Q</i> ₂₆ + <i>Q</i> ₂₇ + <i>Q</i> ₂₈ + <i>Q</i> ₂₉ + <i>Q</i> ₃₀ + <i>Q</i> ₃₁ + <i>Q</i> ₃₂ + <i>Q</i> ₃₃ + <i>Q</i> ₃₄ + <i>Q</i> ₃₅ + <i>Q</i> ₃₆ + <i>Q</i> ₃₇ + <i>Q</i> ₃₈ + <i>Q</i> ₃₉ + <i>Q</i> ₄₀ + <i>Q</i> ₄₁ + <i>Q</i> ₄₂ + <i>Q</i> ₄₃ + <i>Q</i> ₄₄ + <i>Q</i> ₄₅ + <i>Q</i> ₄₆ + <i>Q</i> ₄₇ + <i>Q</i> ₄₈ + <i>Q</i> ₄₉ + <i>Q</i> ₅₀ + <i>Q</i> ₅₁ + <i>Q</i> ₅₂ + <i>Q</i> ₅₃ + <i>Q</i> ₅₄ + <i>Q</i> ₅₅ + <i>Q</i> ₅₆ + <i>Q</i> ₅₇ + <i>Q</i> ₅₈ + <i>Q</i> ₅₉ + <i>Q</i> ₆₀ + <i>Q</i> ₆₁ + <i>Q</i> ₆₂ + <i>Q</i> ₆₃ + <i>Q</i> ₆₄ + <i>Q</i> ₆₅ + <i>Q</i> ₆₆ + <i>Q</i> ₆₇ + <i>Q</i> ₆₈ + <i>Q</i> ₆₉ + <i>Q</i> ₇₀ + <i>Q</i> ₇₁ + <i>Q</i> ₇₂ + <i>Q</i> ₇₃ + <i>Q</i> ₇₄ + <i>Q</i> ₇₅ + <i>Q</i> ₇₆ + <i>Q</i> ₇₇ + <i>Q</i> ₇₈ + <i>Q</i> ₇₉ + <i>Q</i> ₈₀ + <i>Q</i> ₈₁ + <i>Q</i> ₈₂ + <i>Q</i> ₈₃ + <i>Q</i> ₈₄ + <i>Q</i> ₈₅ + <i>Q</i> ₈₆ + <i>Q</i> ₈₇ + <i>Q</i> ₈₈ + <i>Q</i> ₈₉ + <i>Q</i> ₉₀ + <i>Q</i> ₉₁ + <i>Q</i> ₉₂ + <i>Q</i> ₉₃ + <i>Q</i> ₉₄ + <i>Q</i> ₉₅ + <i>Q</i> ₉₆ + <i>Q</i> ₉₇ + <i>Q</i> ₉₈ + <i>Q</i> ₉₉ + <i>Q</i> ₁₀₀ + <i>Q</i> ₁₀₁ + <i>Q</i> ₁₀₂ + <i>Q</i> ₁₀₃ + <i>Q</i> ₁₀₄ + <i>Q</i> ₁₀₅ + <i>Q</i> ₁₀₆ + <i>Q</i> ₁₀₇ + <i>Q</i> ₁₀₈ + <i>Q</i> ₁₀₉ + <i>Q</i> ₁₁₀ + <i>Q</i> ₁₁₁ + <i>Q</i> ₁₁₂ + <i>Q</i> ₁₁₃ + <i>Q</i> ₁₁₄ + <i>Q</i> ₁₁₅ + <i>Q</i> ₁₁₆ + <i>Q</i> ₁₁₇ + <i>Q</i> ₁₁₈ + <i>Q</i> ₁₁₉ + <i>Q</i> ₁₂₀ + <i>Q</i> ₁₂₁ + <i>Q</i> ₁₂₂ + <i>Q</i> ₁₂₃ + <i>Q</i> ₁₂₄ + <i>Q</i> ₁₂₅ + <i>Q</i> ₁₂₆ + <i>Q</i> ₁₂₇ + <i>Q</i> ₁₂₈ + <i>Q</i> ₁₂₉ + <i>Q</i> ₁₃₀ + <i>Q</i> ₁₃₁ + <i>Q</i> ₁₃₂ + <i>Q</i> ₁₃₃ + <i>Q</i> ₁₃₄ + <i>Q</i> ₁₃₅ + <i>Q</i> ₁₃₆ + <i>Q</i> ₁₃₇ + <i>Q</i> ₁₃₈ + <i>Q</i> ₁₃₉ + <i>Q</i> ₁₄₀ + <i>Q</i> ₁₄₁ + <i>Q</i> ₁₄₂ + <i>Q</i> ₁₄₃ + <i>Q</i> ₁₄₄ + <i>Q</i> ₁₄₅ + <i>Q</i> ₁₄₆ + <i>Q</i> ₁₄₇ + <i>Q</i> ₁₄₈ + <i>Q</i> ₁₄₉ + <i>Q</i> ₁₅₀ + <i>Q</i> ₁₅₁ + <i>Q</i> ₁₅₂ + <i>Q</i> ₁₅₃ + <i>Q</i> ₁₅₄ + <i>Q</i> ₁₅₅ + <i>Q</i> ₁₅₆ + <i>Q</i> ₁₅₇ + <i>Q</i> ₁₅₈ + <i>Q</i> ₁₅₉ + <i>Q</i> ₁₆₀ + <i>Q</i> ₁₆₁ + <i>Q</i> ₁₆₂ + <i>Q</i> ₁₆₃ + <i>Q</i> ₁₆₄ + <i>Q</i> ₁₆₅ + <i>Q</i> ₁₆₆ + <i>Q</i> ₁₆₇ + <i>Q</i> ₁₆₈ + <i>Q</i> ₁₆₉ + <i>Q</i> ₁₇₀ + <i>Q</i> ₁₇₁ + <i>Q</i> ₁₇₂ + <i>Q</i> ₁₇₃ + <i>Q</i> ₁₇₄ + <i>Q</i> ₁₇₅ + <i>Q</i> ₁₇₆ + <i>Q</i> ₁₇₇ + <i>Q</i> ₁₇₈ + <i>Q</i> ₁₇₉ + <i>Q</i> ₁₈₀ + <i>Q</i> ₁₈₁ + <i>Q</i> ₁₈₂ + <i>Q</i> ₁₈₃ + <i>Q</i> ₁₈₄ + <i>Q</i> ₁₈₅ + <i>Q</i> ₁₈₆ + <i>Q</i> ₁₈₇ + <i>Q</i> ₁₈₈ + <i>Q</i> ₁₈₉ + <i>Q</i> ₁₉₀ + <i>Q</i> ₁₉₁ + <i>Q</i> ₁₉₂ + <i>Q</i> ₁₉₃ + <i>Q</i> ₁₉₄ + <i>Q</i> ₁₉₅ + <i>Q</i> ₁₉₆ + <i>Q</i> ₁₉₇ + <i>Q</i> ₁₉₈ + <i>Q</i> ₁₉₉ + <i>Q</i> ₂₀₀ + <i>Q</i> ₂₀₁ + <i>Q</i> ₂₀₂ + <i>Q</i> ₂₀₃ + <i>Q</i> ₂₀₄ + <i>Q</i> ₂₀₅ + <i>Q</i> ₂₀₆ + <i>Q</i> ₂₀₇ + <i>Q</i> ₂₀₈ + <i>Q</i> ₂₀₉ + <i>Q</i> ₂₁₀ + <i>Q</i> ₂₁₁ + <i>Q</i> ₂₁₂ + <i>Q</i> ₂₁₃ + <i>Q</i> ₂₁₄ + <i>Q</i> ₂₁₅ + <i>Q</i> ₂₁₆ + <i>Q</i> ₂₁₇ + <i>Q</i> ₂₁₈ + <i>Q</i> ₂₁₉ + <i>Q</i> ₂₂₀ + <i>Q</i> ₂₂₁ + <i>Q</i> ₂₂₂ + <i>Q</i> ₂₂₃ + <i>Q</i> ₂₂₄ + <i>Q</i> ₂₂₅ + <i>Q</i> ₂₂₆ + <i>Q</i> ₂₂₇ + <i>Q</i> ₂₂₈ + <i>Q</i> ₂₂₉ + <i>Q</i> ₂₃₀ + <i>Q</i> ₂₃₁ + <i>Q</i> ₂₃₂ + <i>Q</i> ₂₃₃ + <i>Q</i> ₂₃₄ + <i>Q</i> ₂₃₅ + <i>Q</i> ₂₃₆ + <i>Q</i> ₂₃₇ + <i>Q</i> ₂₃₈ + <i>Q</i> ₂₃₉ + <i>Q</i> ₂₄₀ + <i>Q</i> ₂₄₁ + <i>Q</i> ₂₄₂ + <i>Q</i> ₂₄₃ + <i>Q</i> ₂₄₄ + <i>Q</i> ₂₄₅ + <i>Q</i> ₂₄₆ + <i>Q</i> ₂₄₇ + <i>Q</i> ₂₄₈ + <i>Q</i> ₂₄₉ + <i>Q</i> ₂₅₀ + <i>Q</i> ₂₅₁ + <i>Q</i> ₂₅₂ + <i>Q</i> ₂₅₃ + <i>Q</i> ₂₅₄ + <i>Q</i> ₂₅₅ + <i>Q</i> ₂₅₆ + <i>Q</i> ₂₅₇ + <i>Q</i> ₂₅₈ + <i>Q</i> ₂₅₉ + <i>Q</i> ₂₆	

Analysis		MW-1		MW-2		MW-3	
Altitude (m)	Sample	Qual	Result	Qual	Result	Qual	Result
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0
1,164.0	Carbon (graphite)	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0	1,164.0

[illegible]

Variable	Unit	Abbreviation	Full description of the item or definition
"G"	Gram	"G"	Weight of the sample
"M"	Milligram	"M"	Weight of the sample
"K"	Kilogram	"K"	Weight of the sample
"L"	Liter	"L"	Volume of the sample
"P"	Pascal	"P"	Pressure of the sample
"Q"	Quadrant	"Q"	Angle of the sample
"R"	Radian	"R"	Angle of the sample
"S"	Second	"S"	Time of the sample
"T"	Temperature	"T"	Temperature of the sample
"V"	Volt	"V"	Voltage of the sample
"W"	Watt	"W"	Power of the sample
"X"	X-ray	"X"	Intensity of the sample
"Y"	Yield	"Y"	Percentage of the sample
"Z"	Zinc	"Z"	Concentration of the sample
"A"	Ampere	"A"	Current of the sample
"B"	Becquerel	"B"	Radioactivity of the sample
"C"	Celsius	"C"	Temperature of the sample
"D"	Degree	"D"	Angle of the sample
"E"	Euro	"E"	Value of the sample
"F"	Fahrenheit	"F"	Temperature of the sample
"H"	Hertz	"H"	Frequency of the sample
"I"	Imperial	"I"	Measurement of the sample
"J"	Joule	"J"	Energy of the sample
"K"	Kelvin	"K"	Temperature of the sample
"L"	Liter	"L"	Volume of the sample
"M"	Milligram	"M"	Weight of the sample
"N"	Newton	"N"	Force of the sample
"O"	Ounce	"O"	Weight of the sample
"P"	Pascal	"P"	Pressure of the sample
"Q"	Quadrant	"Q"	Angle of the sample
"R"	Radian	"R"	Angle of the sample
"S"	Second	"S"	Time of the sample
"T"	Temperature	"T"	Temperature of the sample
"U"	Unit	"U"	Measurement of the sample
"V"	Volt	"V"	Voltage of the sample
"W"	Watt	"W"	Power of the sample
"X"	X-ray	"X"	Intensity of the sample
"Y"	Yield	"Y"	Percentage of the sample
"Z"	Zinc	"Z"	Concentration of the sample

[illegible]

Notes

1. Qualifiers: "U" = Analyte is undetected at limit of detection.
2. "M" = Manual integrated compound.
3. "F" = If conf. Standard record ever outside ±10%.
4. "T" = Analyte was positively detected; the quantitation is an estimate.
5. "Q" = One or more sample(s) control at or less failed.
6. "Q" = One or more sample(s) control at or less failed.
7. "Q" = Analyte did not elute as usual at T_{ret} mark.
8. An asterisk (*) after the sample code indicates that the sample was analyzed UTR after the sample date indicates that the sample was analyzed UTR. All other samples analyzed by T_{ret} America.
9. "N/A" = Analyte was not analyzed for.
10. Bold values are a bit.
11. * = A low specific conductivity during the sampling suggests that the well was impacted by rain water.

VOC Soil Samples

Boring Well ID	1-1										1-2									
	3.5'		6.5'		11'		15'		16'		10'		6'		10'		10'-6"		12.5'	
	Result	Qual.	Result	Qual.	Result	Qual.	Result	Qual.	Result	Qual.	Result	Qual.	Result	Qual.	Result	Qual.	Result	Qual.	Result	Qual.
Acetone	<162	U	7,164.02	U	<100	U	<45	U	9,671.01	U	<51	U	<51	U	2,118.01	U	<51	U	<57	U
Benzene	<557	U	<139	U	<142	U	<52	U	<28	U	<51	U	<28	U	1,416.01	U	<48	U	<28	U
Bromobenzene	<464	U	<309	U	<119	U	<27	U	<25	U	<23	U	<21	U	<45	U	<48	U	<23	U
Bromomethane	<752	U	<174	U	<190	U	<43	U	<61	U	<57	U	<34	U	<45	U	<57	U	<37	U
2-Bromonitrobenzene (MBR)	<28	U	<261	U	<285	U	<64	U	<61	U	<55	U	<51	U	5,116.00	U	<55	U	<55	U
n-Butyl Benzene																				
sec-Butyl Benzene																				
tert-Butyl Benzene																				
Carbon disulfide	<1020	U	<230	U	<261	U	<59	U	<56	U	<51	U	<47	U	1,316.00	U	<51	U	<51	U
Chlorobenzene	<1020	U	<230	U	<261	U	<59	U	<56	U	<51	U	<47	U	1,316.00	U	<51	U	<51	U
Chlorobromomethane	<464	U	<109	U	<119	U	<27	U	<25	U	<23	U	<21	U	<45	U	<48	U	<23	U
Chlorodibromomethane	<464	U	<109	U	<119	U	<27	U	<25	U	<23	U	<21	U	<45	U	<48	U	<23	U
Chloroethane	<464	U	<109	U	<119	U	<27	U	<25	U	<23	U	<21	U	<45	U	<48	U	<23	U
Chloroform	<464	U	<109	U	<119	U	<27	U	<25	U	<23	U	<21	U	<45	U	<48	U	<23	U
Chloromethane	<464	U	<109	U	<119	U	<27	U	<25	U	<23	U	<21	U	<45	U	<48	U	<23	U
2-Chlorotoluene	<464	U	<109	U	<119	U	<27	U	<25	U	<23	U	<21	U	<45	U	<48	U	<23	U
4-Chlorotoluene	<464	U	<109	U	<119	U	<27	U	<25	U	<23	U	<21	U	<45	U	<48	U	<23	U
Cyclohexane	<1484	U	<547	U	<580	U	9,671.01	U	<51	U	1,616.02	U	<68	U	1,216.02	U	<65	U	<73	U
1,2-Dichloro-3-Chloropropane	<1113	U	<261	U	<285	U	<64	U	<61	U	<55	U	<51	U	<45	U	<45	U	<55	U
1,2-Dichloroethane	1,716.05	U	6,016.04	U	1,716.05	U	4,016.02	U	2,316.03	U	2,016.02	U	6,416.02	U	1,116.03	U	8,916.02	U	6,016.02	U
1,3-Dichloropropane	2,116.04	U	8,716.03	U	2,416.04	U	7,116.02	U	2,516.02	U	4,216.01	U	9,216.01	U	1,316.02	U	8,916.02	U	7,516.01	U
1,4-Dichlorobenzene	5,316.04	U	1,216.04	U	5,316.04	U	1,716.02	U	8,316.02	U	8,816.02	U	2,016.02	U	3,516.02	U	3,016.02	U	1,916.02	U
Dichloromethane	<557	U	<139	U	<143	U	<52	U	<30	U	<28	U	<26	U	<31	U	<26	U	<28	U
Dichlorodifluoromethane	NA		NA		NA		NA		NA		NA		NA		NA		<45	U	NA	
1,1-Dichloroethane	<22	U	2,316.03	U	7,316.02	U	<68	U	2,416.02	U	1,316.02	U	1,116.02	U	<40	U	2,016.01	U	<41	U
1,1,1-Trichloroethane	<464	U	<109	U	<119	U	<27	U	<25	U	<23	U	<21	U	<45	U	<48	U	<23	U
1,1-Dichloroethene	2,116.04	U	5,316.03	U	1,216.04	U	<59	U	8,616.01	U	2,416.02	U	6,416.02	U	5,616.02	U	4,016.02	U	2,816.02	U
1,2-Dichloroethene, Total	2,116.04	U	<174	U	<190	U	<43	U	<41	U	<37	U	<34	U	<41	U	6,316.00	U	<37	U
cis-1,2-Dichloroethene	2,116.04	U	<174	U	<190	U	<43	U	<41	U	<37	U	<34	U	<41	U	6,316.00	U	<37	U
trans-1,2-Dichloroethene	<1113	U	<261	U	<285	U	<64	U	<61	U	<55	U	<51	U	<45	U	<45	U	<55	U
1,2,3-Trichloropropane	<660	U	<152	U	<166	U	<58	U	<56	U	<52	U	<50	U	<45	U	<45	U	<52	U
1,2,3-Trichloropropane, Isomer																				
1,1-Dichloropropene																				
cis-1,3-Dichloropropene	<557	U	<139	U	<143	U	<52	U	<30	U	<28	U	<26	U	<31	U	<26	U	<28	U
trans-1,3-Dichloropropene	<557	U	<139	U	<143	U	<52	U	<30	U	<28	U	<26	U	<31	U	<26	U	<28	U
1,4-Dioxane	2,616.03	U	7,716.02	U	2,616.03	U	<38	U	<36	U	<32	U	<30	U	<26	U	1,416.01	U	<32	U
Bis-Benzene	<132	U	<174	U	<190	U	<43	U	<41	U	<37	U	<34	U	<41	U	<37	U	<37	U
Benzobenzene	<139	U	<139	U	<143	U	<52	U	<30	U	<28	U	<26	U	<31	U	<26	U	<28	U
2-Methoxybenzene	<139	U	<139	U	<143	U	<52	U	<30	U	<28	U	<26	U	<31	U	<26	U	<28	U
Isopropyl Benzene	<557	U	<139	U	<143	U	<52	U	<30	U	<28	U	<26	U	<31	U	<26	U	<28	U
4-Propyl Benzene	<557	U	<139	U	<143	U	<52	U	<30	U	<28	U	<26	U	<31	U	<26	U	<28	U
Methyl Acetate	<557	U	<139	U	<143	U	<52	U	<30	U	<28	U	<26	U	<31	U	<26	U	<28	U
Methyl Ethyl Ether	<557	U	<139	U	<143	U	<52	U	<30	U	<28	U	<26	U	<31	U	<26	U	<28	U
Methyl Propyl Ether	<557	U	<139	U	<143	U	<52	U	<30	U	<28	U	<26	U	<31	U	<26	U	<28	U
Methyl Tertiary Butyl Ether	<557	U	<139	U	<143	U	<52	U	<30	U	<28	U	<26	U	<31	U	<26	U	<28	U
Methyl Acetate	2,316.03	U	<547	U	4,716.02	U	<58	U	<56	U	<54	U	<52	U	<47	U	NA		<51	U
4-Methyl-2-pentanone (MIBK)	<928	U	<217	U	<236	U	<51	U	<49	U	<46	U	<43	U	<41	U	6,616.00	U	<46	U
Naphthalene																				
N-Propylbenzene	<660	U	<152	U	<166	U	<58	U	<56	U	<52	U	<50	U	<45	U	<45	U	<52	U
Styrene																				
1,1,1,3,3,3-Hexachlorocyclohexane	<732	U	<174	U	<190	U	<43	U	<41	U	<37	U	<34	U	<41	U	<37	U	<37	U
1,1,2,2,3,3-Hexachlorocyclohexane	1,916.05	U	6,416.04	U	2,316.05	U	4,116.02	U	3,316.03	U	3,816.02	U	1,316.03	U	2,216.03	U	3,016.03	U	1,016.03	U
Heptachlorocyclohexane	2,916.05	U	2,416.02	U	3,316.02	U	<32	U	<30	U	<28	U	<26	U	<31	U	3,916.00	U	<28	U
Toluene																				
1,2,3-Trichlorobenzene	2,516.03	U	9,516.02	U	2,616.03	U	<38	U	<36	U	<32	U	<30	U	<26	U	<24	U	<32	U
1,2,4-Trichlorobenzene	9,216.04	U	3,316.04	U	1,116.05	U	2,416.02	U	1,416.03	U	<37	U	2,216.02	U	7,416.02	U	2,916.02	U	2,216.02	U
1,1,1-Trichloroethene	2,516.03	U	9,516.02	U	2,616.03	U	<38	U	<36	U	<32	U	<30	U	<26	U	<24	U	<32	U
1,1,2-Trichloroethene	2,516.03	U	9,516.02	U	2,616.03	U	<38	U	<36	U	<32	U	<30	U	<26	U	<24	U	<32	U
1,1,2,2-Tetrachloroethane	<660	U	<152	U	<166	U	<58	U	<56	U	<54	U	<52	U	<47	U	3,816.01	U	6,716.01	U
Trichloroethylene	NA		NA		NA		NA		NA		NA		NA		NA		<19	U	NA	
1,2,3-Trichloropropane																				
1,2,4-Trichloropropane																				
1,2,4,4-Tetrachlorobutene	2,516.03	U	<261	U	<285	U	<64	U	<61	U	<55	U	<51	U	<45	U	3,316.00	U	<45	U
1,1,2,2,3,3-Hexachlorocyclopentadiene	5,316.03	U	<261	U	<285	U	<64	U	<61	U	<55	U	<51	U	<45	U	3,316.00	U	<45	U
n-Xylene, p-Xylene	2,416.03	U	4,416.02	U	8,416.02	U	<32	U	<30	U	<28	U	<26	U	<31	U	6,016.00	U	<28	U
o-Xylene	5,516.05	U	2,416.02	U	8,416.02	U	<32	U	<30	U	<28	U	<26	U	<31	U	6,016.00	U	<28	U
Total VOCs																				

Boring Well ID		Sample Depth		140		141		142		143		144		145		146		147		148		149		150		151		152		153		154		155		156		157		158		159		160		161		162		163		164		165		166		167		168		169		170		171		172		173		174		175		176		177		178		179		180		181		182		183		184		185		186		187		188		189		190		191		192		193		194		195		196		197		198		199		200		201		202		203		204		205		206		207		208		209		210		211		212		213		214		215		216		217		218		219		220		221		222		223		224		225		226		227		228		229		230		231		232		233		234		235		236		237		238		239		240		241		242		243		244		245		246		247		248		249		250		251		252		253		254		255		256		257		258		259		260		261		262		263		264		265		266		267		268		269		270		271		272		273		274		275		276		277		278		279		280		281		282		283		284		285		286		287		288		289		290		291		292		293		294		295		296		297		298		299		300		301		302		303		304		305		306		307		308		309		310		311		312		313		314		315		316		317		318		319		320		321		322		323		324		325		326		327		328		329		330		331		332		333		334		335		336		337		338		339		340		341		342		343		344		345		346		347		348		349		350		351		352		353		354		355		356		357		358		359		360		361		362		363		364		365		366		367		368		369		370		371		372		373		374		375		376		377		378		379		380		381		382		383		384		385		386		387		388		389		390		391		392		393		394		395		396		397		398		399		400		401		402		403		404		405		406		407		408		409		410		411		412		413		414		415		416		417		418		419		420		421		422		423		424		425		426		427		428		429		430		431		432		433		434		435		436		437		438		439		440		441		442		443		444		445		446		447		448		449		450		451		452		453		454		455		456		457		458		459		460		461		462		463		464		465		466		467		468		469		470		471		472		473		474		475		476		477		478		479		480		481		482		483		484		485		486		487		488		489		490		491		492		493		494		495		496		497		498		499		500		501		502		503		504		505		506		507		508		509		510		511		512		513		514		515		516		517		518		519		520		521		522		523		524		525		526		527		528		529		530		531		532		533		534		535		536		537		538		539		540		541		542		543		544		545		546		547		548		549		550		551		552		553		554		555		556		557		558		559		560		561		562		563		564		565		566		567		568		569		570		571		572		573		574		575		576		577		578		579		580		581		582		583		584		585		586		587		588		589		590		591		592		593		594		595		596		597		598		599		600		601		602		603		604		605		606		607		608		609		610		611		612		613		614		615		616		617		618		619		620		621		622		623		624		625		626		627		628		629		630		631		632		633		634		635		636		637		638		639		640		641		642		643		644		645		646		647		648		649		650		651		652		653		654		655		656		657		658		659		660		661		662		663		664		665		666		667		668		669		670		671		672		673		674		675		676		677		678		679		680		681		682		683		684		685		686		687		688		689		690		691		692		693		694		695		696		697		698		699		700		701		702		703		704		705		706		707		708		709		710		711		712		713		714		715		716		717		718		719		720		721		722		723		724		725		726		727		728		729		730		731		732		733		734		735		736		737		738		739		740		741		742		743		744		745		746		747		748		749		750		751		752		753		754		755		756		757		758		759		760		761		762		763		764		765		766		767		768		769		770		771		772		773		774		775		776		777		778		779		780		781		782		783		784		785		786		787		788		789		790		791		792		793		794		795		796		797		798		799		800		801		802		803		804		805		806		807		808		809		810		811		812		813		814		815		816		817		818		819		820		821		822		823		824		825		826		827		828		829		830		831		832		833		834		835		836		837		838		839		840		841		842		843		844		845		846		847		848		849		850		851		852		853		854		855		856		857		858		859		860		861		862		863		864		865		866		867		868		869		870		871		872		873		874		875		876		877		878		879		880		881		882		883		884		885		886		887		888		889		890		891		892		893		894		895		896		897		898		899		900		901		902		903		904		905		906		907		908		909		910		911		912		913		914		915		916		917		918		919		920		921		922		923		924		925		926		927		928		929		930		931		932		933		934		935		936		937		938		939		940		941		942		943		944		945		946		947		948		949		950		951		952		953		954		955		956		957		958		959		960		961		962		963		964		965		966		967		968		969		970		971		972		973		974		975		976		977		978		979		980		981		982		983		984		985		986		987		988		989		990		991		992		993		994		995		996		997		998		999		1000		1001		1002		1003		1004		1005		1006		1007		1008		1009		1010		1011		1012		1013		1014		1015		1016		1017		1018		1019		1020		1021		1022		1023		1024		1025		1026		1027		1028		1029		1030		1031		1032		1033		1034		1035		1036		1037		1038		1039		1040		1041		1042		1043		1044		1045		1046		1047		1048		1049		1050		1051		1052		1053		1054		1055		1056		1057		1058		1059		1060		1061		1062		1063		1064		1065		1066		1067		1068		1069		1070		1071		1072		1073		1074		1075		1076		1077		1078		1079		1080		1081		1082		1083		1084		1085		1086		1087		1088		1089		1090		1091		1092		1093		1094		1095		1096		1097		1098		1099		1100		1101		1102		1103		1104		1105		1106		1107		1108		1109		1110		1111		1112		1113		1114		111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Boring/Vial ID	Sample Depth(s)	SB-5				SB-101 (BC-1)				SB-102 (21D)			
		6.04		21.3		3.05		18.3		6.01		18.3	
		Result	Qual.	Result	Qual.	Result	Qual.	Result	Qual.	Result	Qual.	Result	Qual.
Sample Date	24-Apr-13	10'		14'		14'		14'		14'		10'	
Analyzer (All units in µg/kg)		Result	Qual.	Result	Qual.	Result	Qual.	Result	Qual.	Result	Qual.	Result	Qual.
Acetone		<97	U	<580.9	U	1.1E+02	U	<21	U	<29	U	<43	U
Benzene		<272	U	<285.7	U	1.2E+01	J	1.3E+01	C	<23	U	<35	U
Bromobenzene		<60.6	U	<238	U	<43.5	U	<13	U	<18	U	<27	U
Bromochloroethane		<97	U	<389.9	U	<20	U	<36	U	<29	U	<43	U
2-Bromodichloroethane		1.7E+02	U	<571.3	U	<30	U	<31	U	1.5E+02	C	<45	U
n-Butyl Benzene													
n-Butyl Benzene													
Carbon tetrachloride		<113.3	U	<523.7	U	<27.5	U	<28	U	<40	U	<42	U
Chlorobenzene		1.5E+02	U	5.3E+01	U	1.7E+02	U	<15	U	<22	U	<23	U
Chlorobromobenzene		<60.6	U	<238	U	<43.5	U	<13	U	<18	U	<27	U
Chlorodibromobenzene		<101.8	U	<214.1	U	<57.4	U	<39	U	<55	U	<58	U
Chloroethane		<101.8	U	<214.1	U	<57.4	U	<39	U	<55	U	<58	U
Chloroethene		<101.8	U	<214.1	U	<57.4	U	<39	U	<55	U	<58	U
2-Chloroethane													
4-Chloroethane													
Cyclohexane		<1053.4	U	<561.7	U	<35.5	U	<44	U	<59	U	<60	U
1,2-Dichloro-4-Chloropentane		<145.4	U	<571.3	U	<30	U	<31	U	<44	U	<45	U
Dibromobenzene													
1,2-Dibromobenzene		3.0E+04	U	2.2E+03	U	3.0E+04	U	3.0E+04	C	3.0E+04	C	3.0E+04	C
1,3-Dibromobenzene		8.9E+03	U	7.0E+04	U	6.0E+02	U	4.0E+01	C	4.0E+01	C	4.0E+01	C
1,4-Dibromobenzene		<72.7	U	<285.7	U	<15	U	<15	U	<22	U	<23	U
Dichlorobromobenzene		<0	U	<0	U	<0	U	<0	U	<0	U	<0	U
Dichlorodibromobenzene		6.1E+03	U	4.0E+03	U	1.0E+03	U	<23	U	<33	U	<34	U
1,1-Dichloroethane		<113.3	U	<523.7	U	<27.5	U	<28	U	<40	U	<42	U
1,2-Dichloroethane		1.0E+04	U	2.0E+04	U	2.2E+03	U	2.0E+02	U	2.2E+02	C	2.0E+02	C
trans-1,2-Dichloroethene		1.0E+04	U	<389.9	U	1.3E+02	U	<21	U	<29	U	<43	U
trans-1,2-Dichloroethene		<145.4	U	<571.3	U	<30	U	<31	U	<44	U	<45	U
1,2-Dichloropropane		<84.8	U	<333.3	U	<47.5	U	<18	U	<26	U	<28	U
1,2-Dichloropropane													
1,2-Dichloropropane													
1,2-Dichloropropane													
trans-1,2-Dichloropropene		<72.7	U	<285.7	U	<15	U	<15	U	<22	U	<23	U
trans-1,2-Dichloropropene		<72.7	U	<285.7	U	<15	U	<15	U	<22	U	<23	U
1,4-Dioxane		2.0E+02	U	2.2E+03	U	2.0E+02	U	<18	U	2.2E+01	C	<26	U
Bis-Benzene		<97	U	<580.9	U	<20	U	<21	U	<29	U	<30	U
Bis-Benzene													
Bis-Benzene													
2-Benzene		1.0E+02	U	1.3E+03	U	<74	U	<39	U	2.0E+01	C	<27	U
Isopropylbenzene		<72.7	U	<285.7	U	<15	U	<15	U	<22	U	<23	U
Methyl Acetate		1.0E+03	U	1.0E+03	U	8.3E+01	U	<26	U	<45	U	<58	U
Methyl Acetate		<121.2	U	<456.1	U	<25	U	<26	U	<45	U	<58	U
Methyl Acetate		<105.9	U	<267.7	U	<34.5	U	<40	U	2.0E+01	C	<20	U
4-Methyl-2-pentanol (MIBK)		<121.2	U	<456.1	U	<25	U	<26	U	<45	U	<58	U
Naphthalene													
N-Propylbenzene		<84.8	U	<333.3	U	<47.5	U	<18	U	<26	U	<28	U
1,1,1,2-Tetrachloroethane		<97	U	<389.9	U	<20	U	<21	U	2.0E+01	C	<20	U
1,1,2,2-Tetrachloroethane		1.0E+02	U	2.0E+02	U	2.0E+01	U	<15	U	2.0E+01	C	<23	U
Toluene		7.0E+02	U	3.1E+03	U	5.0E+02	U	<18	U	5.0E+01	C	<26	U
1,2,3-Trichlorobenzene		4.2E+02	U	2.5E+04	U	1.0E+04	U	<21	U	2.0E+02	U	<29	U
1,1,1-Trichloroethane		2.5E+02	U	<33.3	U	<15	U	<16	U	2.0E+01	C	<20	U
1,1,2-Trichloroethane		<0	U	<0	U	<0	U	<0	U	<0	U	<0	U
1,2,3-Trichloropropene													
1,2,4-Trichlorobenzene		<218.2	U	<857	U	<44.9	U	<46	U	<66	U	<68	U
1,2,4-Trichlorobenzene		6.0E+02	U	4.0E+03	U	8.0E+01	U	<23	U	3.0E+01	C	<30	U
m-Xylene & p-Xylene		2.1E+02	U	9.7E+02	U	1.5E+01	U	<15	U	1.0E+01	C	<23	U
o-Xylene		8.4E+04	U	6.0E+05	U	1.0E+04	U	6.2E+02	U	4.7E+02	C	5.7E+02	C
Total VOCs													

Notes:
1. Qualifier: "U" = Analyte undetectable at limit of detection; "M" = Manual integrated compound; "DQ" = Analyte detected but not quantified
2. "P" = Analyte was positively identified; the quantitation was estimated; "Q" = One or more quality control criteria failed
3. "N/A" = Analyte was not analyzed
4. Bold values indicate a hit.

Boiling/Wet ID Sample Depth (m)	SR-114 (SR-2)										SR-114 (U7)										SR-114 (U4)									
	0.61		1.83		2.44		3.05		3.67		4.27		4.87		5.47		6.07		6.67		7.27		7.87		8.47		9.07			
	Result	Qual	Result	Qual	Result	Qual	Result	Qual	Result	Qual	Result	Qual	Result	Qual	Result	Qual	Result	Qual	Result	Qual	Result	Qual	Result	Qual	Result	Qual	Result	Qual		
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13			
Sample Depth	13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13									

Sample Depth	Sample Date	0.61		1.83		2.44		3.68		4.27		5.49	
		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13		13-Dec-13	
		Result	Qual	Result	Qual	Result	Qual	Result	Qual	Result	Qual	Result	Qual
Acetone		<33	U	<1374	U	1.8E+03	U	<37	U	<774	U	<81	U
Benzene		6.5E+01	C	4.0E+02	C	4.0E+01	C	4.0E+01	C	1.5E+02	C	1.5E+02	C
Bromobenzene		<20	U	<809	U	<219	U	<25	U	<198	U	<84	U
Bromomethane		<33	U	<1374	U	<531	U	<59	U	<37	U	<774	U
2-Bromonitrobenzene		1.3E+02	C	<2060	U	<536	U	1.3E+02	C	<162	U	<1162	U
n-Butyl Benzene													
sec-Butyl Benzene													
tert-Butyl Benzene													
Carbon disulfide		<45	U	<1889	U	<483	U	<54	U	<140	U	<1005	U
Carbon tetrachloride		<45	U	<1889	U	<483	U	<54	U	<140	U	<1005	U
Chlorobenzene		4.0E+01	C	4.4E+03	C	3.9E+02	C	7.2E+02	C	<28	U	2.4E+03	C
Chlorobromomethane		<20	U	<809	U	<219	U	<25	U	<198	U	<84	U
Chlorodibromomethane		1.1E+02	C	<536	U	<59	U	<37	U	<774	U	<81	U
Chloroethane		<33	U	<1374	U	<531	U	<59	U	<37	U	<774	U
Chloroethene		<33	U	<1374	U	<531	U	<59	U	<37	U	<774	U
Chloromethane		<33	U	<1374	U	<531	U	<59	U	<37	U	<774	U
2-Chlorotoluene				<54360	C	<8774	C	<584	C	<7953	C	<19580	C
4-Chlorotoluene													
Cyclohexane		<45	U	<2747	U	<702	U	<79	U	<655	U	<1549	U
1,2-Dichloro-2-Chloropropane		<49	U	<2060	U	<536	U	<59	U	<162	U	<1162	U
1,2-Dichloroethane		2.0E+01	C	6.0E+05	D	2.3E+04	D	8.0E+04	D	3.0E+04	D	3.0E+04	D
1,3-Dichlorobenzene		3.0E+02	C	1.1E+05	C	2.0E+03	C	1.3E+03	C	5.0E+03	C	5.0E+03	C
1,4-Dichlorobenzene		8.3E+02	C	2.4E+05	C	7.4E+03	C	2.6E+04	D	1.2E+04	D	1.2E+04	D
Dichlorobromomethane		<24	U	<1030	U	<263	U	<30	U	<238	U	<581	U
Dichlorodifluoromethane		<40	U	<1610	U	<401	U	<46	U	<357	U	<891	U
1,1,2-Dichloroethane		2.7E+04	D	1.8E+04	C	1.2E+03	C	2.7E+03	C	<557	U	3.1E+03	C
1,1,2,2-Tetrachloroethane		4.0E+02	C	7.0E+03	C	3.0E+03	C	2.0E+03	C	4.0E+02	C	5.7E+03	C
1,2-Dichloroethene, Total		1.2E+02	C	<1374	U	<531	U	<59	U	<37	U	<774	U
cis-1,2-Dichloroethene		<49	U	<2060	U	<536	U	<59	U	<162	U	<1162	U
trans-1,2-Dichloroethene		<49	U	<2060	U	<536	U	<59	U	<162	U	<1162	U
1,2-Dichloropropane													
1,2-Dichloropropane, Isomer													
1,1-Dichloropropane													
cis-1,3-Dichloropropene		<24	U	<1030	U	<263	U	<30	U	<238	U	<581	U
trans-1,3-Dichloropropene		<24	U	<1030	U	<263	U	<30	U	<238	U	<581	U
1,4-Dioxane		1.2E+02	C	9.0E+03	C	9.7E+01	C	6.5E+02	C	1.7E+02	C	1.7E+02	C
Diethylbenzene		<33	U	<1374	U	<531	U	<59	U	<37	U	<774	U
Dibenzodioxane		6.7E+01	C	6.2E+03	C	<658	U	3.0E+02	C	<363	U	1.4E+03	C
2-Hexanone		<24	U	<1030	U	<263	U	1.0E+01	C	<238	U	<581	U
Isopropyl Benzene		4.9E+02	C	<1777	U	2.0E+03	C	<49	U	<397	U	<989	U
Methyl Acetate		<41	U	<1610	U	<401	U	<46	U	<357	U	<891	U
Methyl tert-Butyl Ether		<41	U	<1610	U	<401	U	<46	U	<357	U	<891	U
Methyl Chloride		1.0E+02	C	2.3E+03	C	<702	U	1.5E+02	C	<655	U	<1549	U
Methyl Isobutyl Ether		<41	U	<1610	U	<401	U	<46	U	<357	U	<891	U
4-Methyl-2-pentanone (MIBK)		<41	U	<1777	U	<439	U	<49	U	<397	U	<989	U
Naphthalene													
N-Propylbenzene		<28	U	<1332	U	<337	U	<34	U	<278	U	<678	U
Styrene		<33	U	<1374	U	<531	U	1.0E+01	C	<317	U	<774	U
1,1,1,2-Tetrachloroethane		1.1E+01	C	1.2E+06	D	1.2E+04	D	8.0E+04	D	2.1E+04	D	2.1E+04	D
1,1,2,2-Tetrachloroethane		9.7E+02	C	1.8E+03	C	5.3E+01	C	2.0E+02	C	<238	U	4.0E+02	C
Toluene		<28	U	1.2E+04	C	<307	U	9.9E+02	C	6.0E+02	C	5.4E+03	C
1,2,3-Trichlorobenzene		<33	U	7.0E+05	D	3.0E+04	D	7.0E+04	D	2.3E+04	D	1.2E+05	D
1,1,1-Trichloroethane		3.0E+02	C	<1332	U	<337	U	6.2E+01	C	<278	U	<678	U
1,1,2-Trichloroethane		<40	U	<1610	U	<401	U	<46	U	<357	U	<891	U
Trichlorobenzene													
Trichlorofluoromethane													
1,2,3-Trichloropropane													
1,2,4-Trimethyl Benzene		<28	U	<2691	U	<691	U	<69	U	<541	U	<1382	U
1,2,4-Trichlorobenzene		1.0E+02	C	<2060	U	<536	U	<59	U	<162	U	<1162	U
n-Nonane & n-Decane		1.0E+02	C	1.9E+04	C	1.0E+02	C	1.3E+03	C	3.0E+02	C	3.0E+03	C
n-Xylene		1.3E+02	C	3.9E+03	C	<263	U	3.0E+02	C	<238	U	6.0E+02	C
Total VOCs		2.7E+04	C	3.0E+06	C	9.2E+04	C	2.0E+05	C	9.0E+04	C	9.4E+05	C

1. Qualifiers: "U" - Analyte undetected at limit of detection; "M" - Manual in-quant compound; "E" - Analyte detected but not quantified

"P" - Analyte was positively identified, the quantitation is in milligrams. "Q" - One or more quality control criteria failed

"F" - Analyte was not detected in the sample, but was detected in the control sample. The concentration of the analyte in the control sample was used to estimate the concentration of the analyte in the sample.

"N" - Analyte was not analyzed for.

4. Bold values indicate in the

SVOC Groundwater Samples

Analyte (All units in µg/L)	EC-1				EC-2				I-1			
	4/24/2012		2/11/2014		4/24/2012		2/11/2014		4/24/2012		2/13/2014	
	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier
4-Nitroaniline	<3.9	U	<3.9	U	<3.9	U	<3.9	U	<3.9	U	<4.0	U
4-Nitrophenol	<9.7	U	<9.6	U	<9.8	U	<9.7	U	<9.7	U	<9.9	U
Benzyl alcohol	0.48	J	0.31	J	2.1	J	<0.97	U	2.9	J	12	J D
4-Bromophenyl phenyl ether	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U	<9.9	U
2,4-Dimethylphenol	280	D	<3.9	U	2.1	J	<3.9	U	420	D	22	J D
1,4-Dichlorobenzene	630	D	150		540	D	120		1600	D	1500	D
4-Chloroaniline	<4.8	U	<4.8	U	<4.9	U	<4.9	U	<4.9	U	<5.0	U
2,2'-oxybis[1-chloropropane]	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U	<9.9	U
Phenol	60		<4.8	U	4.1	J	<4.9	U	500	D	1700	D
Bis(2-chloroethyl)ether	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U	<9.9	U
Bis(2-chloroethoxy)methane	<3.9	U	<3.9	U	<3.9	U	<3.9	U	<3.9	U	<4.0	U
Bis(2-ethylhexyl)phthalate	1.5	J	<0.96	U M	2.2	J	<0.97	U	1.3	J	<9.9	U
Di-n-octyl phthalate	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U	<9.9	U
Hexachlorobenzene	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U	<9.9	U
Anthracene	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U Q	<9.9	U
1,2,4-Trichlorobenzene	5.1	J	1.8	J	6.3	J	2	J	27		27	J D
2,4-Dichlorophenol	36		1.5	J	4.5	J	<1.9	U	13		80	J D
2,4-Dinitrotoluene	<3.9	U	<3.9	U	<3.9	U	<3.9	U	<3.9	U	<4.0	U
1,2-Diphenylhydrazine	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U	<9.9	U
Pyrene	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U Q	<9.9	U
Dimethyl phthalate	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U	<9.9	U
Dibenzofuran	<0.97	U	<0.96	U	<0.98	U	<0.97	U	1	J	<9.9	U
3 & 4 Methylphenol	140		<0.96	U	2.3	J	<0.97	U	750	D	810	D
Benz[a]biperylene	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U Q	<9.9	U
Indeno[1,2,3-cd]pyrene	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U Q	<9.9	U
Benzo[b]fluoranthene	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U Q	<9.9	U
Fluoranthene	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U Q	<9.9	U
Benzo[k]fluoranthene	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U Q	<9.9	U
Acenaphthylene	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U Q	<9.9	U
Chrysene	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U Q	<9.9	U
Benzo[a]pyrene	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U Q	<9.9	U
2,4-Dinitrophenol	<1.9	U	<1.9	U	<2.0	U	<1.9	U	<1.9	U	<2.0	U
4,6-Dinitro-2-methylphenol	<9.7	U	<9.6	U	<9.8	U	<9.7	U	<9.7	U	<9.9	U
Dibenz[a,h]anthracene	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U	<9.9	U
1,3-Dichlorobenzene	240	D	54		180		46		690	D	570	D
Benzo[a]anthracene	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U Q	<9.9	U
4-Chloro-3-methylphenol	<4.8	U	<4.8	U	<4.9	U	<4.9	U	<4.9	U	<5.0	U
2,6-Dinitrotoluene	<3.9	U	<3.9	U	<3.9	U	<3.9	U	<3.9	U	<4.0	U
N-Nitrosodi-n-propylamine	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U	<9.9	U
N-Nitrosodimethylamine	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U	<9.9	U
Benzoic acid	<48	U Q	<48	U	<48	U Q	13	J	<49	U Q	680	J D
Hexachloroethane	<3.9	U	<3.9	U	<3.9	U	<3.9	U	<3.9	U	<4.0	U
4-Chlorophenyl phenyl ether	<3.9	U	<3.9	U	<3.9	U	<3.9	U	<3.9	U	<4.0	U
Isophorone	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U	<9.9	U
Acenaphthene	<0.97	U	<0.96	U	<0.98	U	<0.97	U	0.55	J Q	<9.9	U
Diethyl phthalate	3.7	J	<0.96	U	<0.98	U	<0.97	U	0.42	J	<9.9	U
Di-n-butyl phthalate	1.6	J	<3.9	U	<3.9	U	<3.9	U	<3.9	U	<4.0	U
Phenanthrene	0.72	J	<0.96	U	0.73	J	<0.97	U	2.4	J Q	<9.9	U
Buryl benzyl phthalate	<3.9	U	<3.9	U	1	J	<3.9	U	<3.9	U	<4.0	U
N-Nitrosodiphenylamine	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U	<9.9	U
Fluorene	0.72	J	<0.96	U	0.39	J	<0.97	U	1.5	J Q	<9.9	U
Carbazole	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U	<9.9	U
2,6-Dichlorophenol	4.7	J	<3.9	U	<3.9	U	<3.9	U	1.7	J	<4.0	U
Hexachlorobutadiene	<9.7	U	<9.6	U	<9.8	U	<9.7	U	<9.7	U	<9.9	U
Pentachlorophenol	<3.9	U	<3.9	U	<3.9	U	<3.9	U	<3.9	U	<4.0	U
2,4,6-Trichlorophenol	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U	<9.9	U
2-Nitroaniline	<3.9	U	<3.9	U	<3.9	U	<3.9	U	<3.9	U	<4.0	U
2-Nitrophenol	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U	9.5	J D
Naphthalene	3.2	J	<0.96	U	0.63	J	<0.97	U	12	Q	8.7	J D
2-Methylnaphthalene	3.7	J	<0.96	U	1.4	J	<0.97	U	17		9.1	J D
2-Chloronaphthalene	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U	<9.9	U
3,3'-Dichlorobenzidine	<9.7	U	<9.6	U	<9.8	U	<9.7	U	<9.7	U	<9.9	U
Benzidine	<9.7	U	<9.6	U	<9.8	U	<9.7	U	<9.7	U Q	<9.9	U
N-Nitrosopyrrolidine	<3.9	U	<3.9	U	<3.9	U	<3.9	U	<3.9	U	<4.0	U
2-Methylphenol	270	D	<3.9	U	<3.9	U	<3.9	U	91		39	J D
1,2-Dichlorobenzene	1600	D	340		1300	D	260		4300	D	4400	D
2-Chlorophenol	24		<3.9	U	<3.9	U	<3.9	U	4.5	J	<4.0	U
2,4,5-Trichlorophenol	<0.97	U	<0.96	U	<0.98	U	<0.97	U	<0.97	U	<9.9	U
Nitrobenzene	<1.9	U	<1.9	U	<2	U	<1.9	U	<1.9	U	<2.0	U
3-Nitroaniline	<1.9	U	<1.9	U	<2	U	<1.9	U	<1.9	U	<2.0	U

Notes:

1. Qualifiers: "U" = Analyte undetected at limit of detection; "M" = Manual integrated compound;

"J" = Analyte was positively identified, the quantitation is an estimate; "Q" = One or more quality control criteria failed.

2. An asterisk (*) after the sample date indicates that the sample was analyzed at URI.

All other samples analyzed by Test America.

3. "NA" = Analyte was not analyzed for.

4. **Bold** values indicate a hit.

Analyte (All units in µg/L)	I-2				I-3				I-4			
	4/24/2012		1/16/2013		5/21/2012		1/15/2013		12/4/2012		2/13/2014	
	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier
4-Nitroaniline	<4	U	<3.8	U	<3.8	U	<3.8	U	<3.9	U	<3.8	U
4-Nitrophenol	<9.9	U	<9.6	U Q	<9.5	U	<9.6	U	<9.7	U	<9.5	U
Benzyl alcohol	0.98	J	<0.96	U	0.5	J	0.37	J	<0.97	U	0.58	J
4-Bromophenyl phenyl ether	<0.99	U	<0.96	U	<0.95	U	<0.96	U	<0.97	U	<0.95	U
2,4-Dimethylphenol	120		0.65	J	<3.8	U	<3.8	U	2.3	J	<3.8	U Q
1,4-Dichlorobenzene	52		230		26		2.9	J	160		370	D
4-Chloroaniline	<5	U	<4.8	U	<4.7	U	<4.8	U	<4.9	U	<4.7	U
2,2'-oxybis[1-chloropropane]	<0.99	U	<0.96	U	<0.95	U	<0.96	U	<0.97	U	<0.95	U
Phenol	5.3	J	<4.8	U	<4.7	U	<4.8	U	<4.9	U	<4.7	U
Bis(2-chloroethyl) ether	<0.99	U	<0.96	U	<0.95	U	<0.96	U	<0.97	U	<0.95	U
Bis(2-chloroethoxy) methane	<4	U	<3.8	U	<3.8	U	<3.8	U	<3.9	U	<3.8	U
Bis(2-ethylhexyl) phthalate	2.1	J	2.4	J	<0.95	U	2.4	J	4.5	J	0.71	J
Di-n-octyl phthalate	<0.99	U	<0.96	U	<0.95	U	<0.96	U	<0.97	U	<0.95	U
Hexachlorobenzene	<0.99	U	<0.96	U	<0.95	U	<0.96	U	<0.97	U	<0.95	U
Anthracene	<0.99	U Q	<0.96	U	<0.95	U	<0.96	U	<0.97	U	<0.95	U Q
1,2,4-Trichlorobenzene	0.77	J	3.4	J	0.34	J	<0.96	U	9.5	J	4.5	J
2,4-Dichlorophenol	2.5	J	2.3	J	<1.9	U	<1.9	U	1.8	J	2.5	J Q
2,4-Dinitrotoluene	<4	U	<3.8	U	<3.8	U	<3.8	U	<3.9	U	<3.8	U
1,2-Diphenylhydrazine	<0.99	U	<0.96	U Q	<0.95	U	<0.96	U	<0.97	U	<0.95	U
Pyrene	<0.99	U Q	<0.96	U	<0.95	U	<0.96	U	<0.97	U	<0.95	U Q
Dimethyl phthalate	<0.99	U	<0.96	U	<0.95	U	<0.96	U	0.57	J	<0.95	U
Dibenzofuran	<0.99	U	<0.96	U	<0.95	U	<0.96	U	0.36	J	<0.95	U
3 & 4 Methylphenol	26		2.3		<0.95	U	<0.96	U	2.8	J	<0.95	U Q
Benzo[a,b]perylene	<0.99	U Q	<0.96	U	<0.95	U	<0.96	U	<0.97	U	<0.95	U Q
Indeno[1,2,3-cd]pyrene	<0.99	U Q	<0.96	U	<0.95	U	<0.96	U	<0.97	U	<0.95	U Q
Benzo[b]fluoranthene	<0.99	U Q	<0.96	U	<0.95	U	<0.96	U	<0.97	U	<0.95	U Q
Fluoranthene	<0.99	U Q	<0.96	U	<0.95	U	<0.96	U	<0.97	U	<0.95	U Q
Benzo[k]fluoranthene	<0.99	U Q	<0.96	U	<0.95	U	<0.96	U	<0.97	U	<0.95	U Q
Acenaphthylene	<0.99	U Q	<0.96	U	<0.95	U	<0.96	U	<0.97	U	<0.95	U Q
Chrysene	<0.99	U Q	<0.96	U	<0.95	U	<0.96	U	<0.97	U	<0.95	U Q
Benzo[a]pyrene	<0.99	U Q	<0.96	U	<0.95	U	<0.96	U	<0.97	U	<0.95	U Q
2,4-Dinitrophenol	<20	U	<19	U Q	<19	U	<19	U	<19	U	<19	U
4,6-Dinitro-2-methylphenol	<9.9	U	<9.6	U Q	<9.5	U	<9.6	U	<9.7	U	<9.5	U
Dibenz[a,h]anthracene	<0.99	U	<0.96	U	<0.95	U	<0.96	U	<0.97	U	<0.95	U
1,3-Dichlorobenzene	21		100		7.9	J	1.1	J	79		130	
Benzo[a]anthracene	<0.99	U Q	<0.96	U	<0.95	U	<0.96	U	<0.97	U	<0.95	U Q
4-Chloro-3-methylphenol	<5	U	<4.8	U Q	<4.7	U	<4.8	U	<4.9	U	<4.7	U
2,6-Dinitrotoluene	<4	U	<3.8	U	<3.8	U	<3.8	U	<3.9	U	<3.8	U
N-Nitrosodi-n-propylamine	<0.99	U	<0.96	U	<0.95	U	<0.96	U	<0.97	U	<0.95	U
N-Nitrosodimethylamine	<0.99	U	<0.96	U	<0.95	U	<0.96	U	<0.97	U	<0.95	U Q
Benzoic acid	10	J Q	13	J	16	J	<48	U	<49	U	18	J Q
Hexachloroethane	<4	U	<3.8	U	<3.8	U	<3.8	U	<3.9	U	<3.8	U
4-Chlorophenyl phenyl ether	<4	U	<3.8	U	<3.8	U	<3.8	U	<3.9	U	<3.8	U
Isophorone	<0.99	U	<0.96	U	<0.95	U	<0.96	U	<0.97	U	<0.95	U
Acenaphthene	<0.99	U Q	<0.96	U	<0.95	U	<0.96	U	<0.97	U	<0.95	U Q
Diethyl phthalate	0.65	J	<0.96	U	<0.95	U	<0.96	U	<0.97	U	<0.95	U
Di-n-butyl phthalate	<4	U	<3.8	U	<3.8	U	<3.8	U	<3.9	U	<3.8	U
Phenanthrene	0.34	J Q	<0.96	U	<0.95	U	<0.96	U	1.2	J	<0.95	U Q
Butyl benzyl phthalate	<4	U	<3.8	U	<3.8	U	<3.8	U	<3.9	U	<3.8	U
N-Nitrosodiphenylamine	<0.99	U	<0.96	U	<0.95	U	<0.96	U	<0.97	U	<0.95	U
Fluorene	<0.99	U Q	<0.96	U	<0.95	U	<0.96	U	0.31	J	<0.95	U Q
Carbazole	<0.99	U	<0.96	U	<0.95	U	<0.96	U	<0.97	U	<0.95	U
2,6-Dichlorophenol	<4	U	<3.8	U	<3.8	U	<3.8	U	<3.9	U	<3.8	U
Hexachlorobutadiene	<9.9	U	<9.6	U	<9.5	U	<9.6	U	<9.7	U	<9.5	U
Pentachlorophenol	<40	U	<38	U Q	<38	U	<38	U	<39	U	<38	U
2,4,6-Trichlorophenol	<0.99	U	<0.96	U Q	<0.95	U	<0.96	U	<0.97	U	<0.95	U
2-Nitroaniline	<4	U	<3.8	U	<3.8	U	<3.8	U	<3.9	U	<3.8	U
2-Nitrophenol	<0.99	U	<0.96	U	<0.95	U	<0.96	U	<0.97	U	<0.95	U Q
Naphthalene	0.93	J Q	1.1	J	<0.95	U	<0.96	U	1.6	J	0.66	J Q
2-Methylnaphthalene	0.92	J	1	J	<0.95	U	<0.96	U	4.2	J	1.3	J
2-Chloronaphthalene	<0.99	U	<0.96	U	<0.95	U	<0.96	U	<0.97	U	<0.95	U
3,3'-Dichlorobenzidine	<9.9	U	<9.6	U	<9.5	U	<9.6	U	<9.7	U	<9.5	U
Benzidine	<99	U Q	<96	U	<95	U	<96	U	<97	U	<95	U Q
N-Nitrosopyrrolidine	<4	U	<3.8	U	<3.8	U	<3.8	U	<3.9	U	<3.8	U Q
2-Methylphenol	90		0.94	J	<3.8	U	<3.8	U	<3.9	U	<3.8	U Q
1,2-Dichlorobenzene	150		600		70		2.6	J	500	D	990	D
2-Chlorophenol	<4	U	<3.8	U	<3.8	U	<3.8	U	<3.9	U	<3.8	U Q
2,4,5-Trichlorophenol	<0.99	U	<0.96	U Q	<0.95	U	<0.96	U	<0.97	U	<0.95	U
Nitrobenzene	<2	U	<1.9	U	<1.9	U	<1.9	U	<1.9	U	<1.9	U
3-Nitroaniline	<2	U	<1.9	U	<1.9	U	<1.9	U	<1.9	U	<1.9	U

Notes:

1. Qualifiers: "U"= Analyte undetected at limit of detection; "M"= Manual integrated compound;

"J"= Analyte was positively identified, the quantitation is an estimate; "Q"= One or more quality control criteria failed.

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4. **Bold** values indicate a hit.

	I-5				I-6							
	4/23/2013		2/12/2014		12/4/2012		4/23/2013		7/10/2013		2/13/2014	
Analyte (All units in µg/L)	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier
4-Nitroaniline	<77	U	<38	U	<3.9	U	<81	U	<19	U	<38	U
4-Nitrophenol	<190	U	<95	U	<9.7	U	<200	U	<48	U	<96	U
Benzyl alcohol	<19	U	24	JD	<0.97	U	<20	U	<4.8	U	14	JD
4-Bromophenyl phenyl ether	<19	U	<9.5	U	<0.97	U	<20	U	<4.8	U	<9.6	U
2,4-Dimethylphenol	12000	D	230	D	4500	D	4900	D	2600	D	7900	D
1,4-Dichlorobenzene	6200	D	4400	D	6800	D	6500	D	3300	D	4900	D
4-Chloroaniline	<96	U	<48	U	<4.8	U	<100	U	<24	U	<48	U
2,2'-oxybis[1-chloropropane]	<19	U	<9.5	U	<0.97	U	<20	U	<4.8	U	<9.6	U
Phenol	11000	D	12000	D	8000	D	8800	D	27000	D	19000	D
Bis(2-chloroethyl) ether	<19	U	<9.5	U	<0.97	U	<20	U	<4.8	U	<9.6	U
Bis(2-chloroethoxy) methane	<77	U	<38	U	<3.9	U	<81	U	<19	U	<38	U
Bis(2-ethylhexyl) phthalate	<19	U	<9.5	U	5.5	J	<20	U	<4.8	U	<9.6	U
Di-n-octyl phthalate	<19	U	<9.5	U	<0.97	U	<20	U	<4.8	U	<9.6	U
Hexachlorobenzene	<19	U	<9.5	U	<0.97	U	<20	U	<4.8	U	<9.6	U
Anthracene	<19	U	<9.5	U	0.81	J	<20	U	<4.8	U	<9.6	U
1,2,4-Trichlorobenzene	65	JD	56	JD	100	J	87	JD	33	JD	35	JD
2,4-Dichlorophenol	<38	U	340	D	94	J	<41	U	120	D	100	D
2,4-Dinitrotoluene	<77	U	<38	U	<3.9	U	<81	U	<19	U	<38	U
1,2-Diphenylhydrazine	<19	U	<9.5	U	<0.97	U	<20	U	<4.8	U	<9.6	U
Pyrene	<19	U	<9.5	U	0.65	J	<20	U	<4.8	U	<9.6	U
Dimethyl phthalate	<19	U	<9.5	U	<0.97	U	<20	U	<4.8	U	<9.6	U
Dibenzofuran	<19	U	<9.5	U	1	J	<20	U	<4.8	U	<9.6	U
3 & 4 Methylphenol	15000	D	6900	D	7600	D	8800	D	18000	D	17000	D
Benzo[a,h,i]perylene	<19	U	<9.5	U	<0.97	U	<20	U	<4.8	U	<9.6	U
Indeno[1,2,3-cd]pyrene	<19	U	<9.5	U	<0.97	U	<20	U	<4.8	U	<9.6	U
Benzo[b]fluoranthene	<19	U	<9.5	U	<0.97	U	<20	U	<4.8	U	<9.6	U
Fluoranthene	<19	U	<9.5	U	0.24	J	<20	U	<4.8	U	<9.6	U
Benzo[k]fluoranthene	<19	U	<9.5	U	<0.97	U	<20	U	<4.8	U	<9.6	U
Acenaphthylene	<19	U	<9.5	U	<0.97	U	<20	U	<4.8	U	<9.6	U
Chrysene	<19	U	<9.5	U	<0.97	U	<20	U	<4.8	U	<9.6	U
Benzo[a]pyrene	<19	U	<9.5	U	<0.97	U	<20	U	<4.8	U	<9.6	U
2,4-Dinitrophenol	<380	U	<190	U	<19	U	<410	U	<96	U	<190	U
4,6-Dinitro-2-methylphenol	<190	U	<95	U	7.4	J	<200	U	<48	U	<96	U
Dibenz[a,h]anthracene	<19	U	<9.5	U	<0.97	U	<20	U	<4.8	U	<9.6	U
1,3-Dichlorobenzene	2600	D	1600	D	2900	D	2900	D	1300	D	1600	D
Benzo[a]anthracene	<19	U	<9.5	U	<0.97	U	<20	U	<4.8	U	<9.6	U
4-Chloro-3-methylphenol	<96	U	<48	U	<4.8	U	<100	U	160	D	<48	U
2,6-Dinitrotoluene	<77	U	<38	U	<3.9	U	<81	U	<19	U	<38	U
N-Nitrosodi-n-propylamine	<19	U	<9.5	U	<0.97	U	<20	U	<4.8	U	<9.6	U
N-Nitrosodimethylamine	<19	U	<9.5	U	<0.97	U	<20	U	<4.8	U	<9.6	U
Benzoic acid	1500	D	2300	D	1200	JD	500	JD	2400	JD	<480	U
Hexachloroethane	<77	U	<38	U	<3.9	U	<81	U	<19	U	<38	U
4-Chlorophenyl phenyl ether	<77	U	<38	U	<3.9	U	<81	U	<19	U	<38	U
Isophorone	<19	U	<9.5	U	<0.97	U	<20	U	<4.8	U	<9.6	U
Acenaphthene	<19	U	<9.5	U	1.8	J	<20	U	<4.8	U	<9.6	U
Diethyl phthalate	<19	U	<9.5	U	1.1	J	<20	U	4.6	JD	<9.6	U
Di-n-butyl phthalate	<77	U	<38	U	3.4	J	<81	U	<19	U	<38	U
Phenanthrene	<19	U	<9.5	U	3.4	J	<20	U	3.7	JD	<9.6	U
Butyl benzyl phthalate	<77	U	<38	U	<3.9	U	<81	U	<19	U	<38	U
N-Nitrosodiphenylamine	<19	U	<9.5	U	<0.97	U	<20	U	<4.8	U	<9.6	U
Fluorene	<19	U	<9.5	U	2.7	J	<20	U	<4.8	U	<9.6	U
Carbazole	<19	U	<9.5	U	0.68	J	<20	U	<4.8	U	<9.6	U
2,6-Dichlorophenol	<77	U	<38	U	5.8	J	<81	U	<19	U	<38	U
Hexachlorobutadiene	<190	U	<95	U	<9.7	U	<200	U	<48	U	<96	U
Pentachlorophenol	<770	U	<380	U	<39	U	<810	U	<190	U	<380	U
2,4,6-Trichlorophenol	<19	U	<9.5	U	<0.97	U	<20	U	<4.8	U	<9.6	U
2-Nitroaniline	<77	U	<38	U	<3.9	U	<81	U	<19	U	<38	U
2-Nitrophenol	<19	U	5.4	JD	<0.97	U	<20	U	<4.8	U	<9.6	U
Naphthalene	27	JD	17	JD	35	J	28	JD	24	JD	22	JD
2-Methylnaphthalene	<19	U	18	JD	32	J	22	JD	22	JD	<9.6	U
2-Chloronaphthalene	<19	U	<9.5	U	<0.97	U	<20	U	<4.8	U	<9.6	U
3,3'-Dichlorobenzidine	<190	U	<95	U	<9.7	U	<200	U	<48	U	<96	U
Benidine	<1900	U	<950	U	<97	U	<2000	U	<480	U	<960	U
N-Nitrosopyrrolidine	<77	U	<38	U	<3.9	U	<81	U	<19	U	<38	U
2-Methylphenol	2500	D	670	D	1300	D	1500	D	2200	D	2900	D
1,2-Dichlorobenzene	20000	D	12000	D	19000	D	21000	D	10000	D	14000	D
2-Chlorophenol	<77	U	170	D	28	J	<81	U	97	D	98	D
2,4,5-Trichlorophenol	<19	U	<9.5	U	<0.97	U	<20	U	<4.8	U	<9.6	U
Nitrobenzene	<38	U	<19	U	<1.9	U	<41	U	<9.6	U	<19	U
3-Nitroaniline	<38	U	<19	U	<1.9	U	<41	U	<9.6	U	<19	U

Notes:

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"J"= Analyte was positively identified, the quantitation is an estimate; "Q"= One or more quality control criteria failed.

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3. "NA"= Analyte was not analyzed for.

4. **Bold** values indicate a hit.

SVOC Soil Samples

Boring Location		EC-1		I-3		I-4 / SB-111				I-6 / SB-105			
Actual Boring/Well ID						I-4		SB-111		I-6		SB-105	
Sample Depth (m)		0.6 - 9		4.3		3		3		2.1		1.8	
Sample Date		4/17/2012		5/8/2012		5/8/2012		12/13/2013		9/26/2012		12/12/2013	
Analyte	Units	Result	Qual.	Result	Qual.	Result	Qual.	Result	Qual.	Result	Qual.	Result	Qual.
Benzo[g,h,i]perylene	ug/Kg	20	J	<48	U	<44	U	<43	U	<37	U	<41	U
Benzoic acid	ug/Kg	<730	U	<960	U	<890	U	<870	U	1800	J	<820	U
Benzyl alcohol	ug/Kg	21	J	<48	U	17	J	<43	U	26	J	<41	U
1,2-Dichlorobenzene	ug/Kg	<37	U	<48	U	180	J	11000		220000	D	330	J
1,3-Dichlorobenzene	ug/Kg	<37	U	<48	U	24	J	1500		30000	D	22	J
1,4-Dichlorobenzene	ug/Kg	<37	U	<48	U	55	J	3400		69000	D	74	J
2,4-Dichlorophenol	ug/Kg	<73	U	<96	U	<89	U	30	J	<75	U	29	J
Dimethyl phthalate	ug/Kg	<37	U	<48	U	<44	U	110	J	<37	U	69	J
Bis(2-ethylhexyl) phthalate	ug/Kg	<73	U	250	J	160	J	<87	U	<75	U	<82	U
Fluoranthene	ug/Kg	<73	U	<96	U	<89	U	<87	U	81	J	<82	U
Fluorene	ug/Kg	<37	U	<48	U	<44	U	<43	U	480	-	<41	U
2-Methylnaphthalene	ug/Kg	<37	U	<48	U	<44	U	43	J	3600	J	<41	U
2-Methylphenol	ug/Kg	<37	U	<48	U	37	J	<43	U	2700	-	<41	U
3 & 4 Methylphenol	ug/Kg	<73	U	<96	U	270	J	730		16000	D	3000	
Naphthalene	ug/Kg	<73	U	<96	U	<89	U	<87	U	1200	-	<82	U
Phenanthrene	ug/Kg	<37	U	<48	U	<44	U	<43	U	1400	-	<41	U
Phenol	ug/Kg	<37	U	<48	U	190	J	660		14000	D	4200	
Pyrene	ug/Kg	<37	U	<48	U	<44	U	<43	U	140	J	<41	U
1,2,4-Trichlorobenzene	ug/Kg	<37	U	<48	U	<44	U	180	J	5500	J	<41	U

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- Bold** values indicate a hit.

Boring Location		U-16 / SB-112				U-20 / SB-106			
Actual Boring/Well ID		U-16		SB-112		U-20		SB-106	
Sample Depth (m)		4.6		4.9		4.6		4.9	
Sample Date		9/25/2012		12/13/2013		9/26/2012		12/12/2013	
Analyte	Units	Result	Qual.	Result	Qual.	Result	Qual.	Result	Qual.
Benzo[g,h,i]perylene	ug/Kg	<40	U	<37	U	<39	U	<38	U
Benzoic acid	ug/Kg	700	J	<740	U	<780	U	<770	U
Benzyl alcohol	ug/Kg	<40	U	<37	U	12	J	<38	U
1,2-Dichlorobenzene	ug/Kg	50000	D	3300		190	J	3000	
1,3-Dichlorobenzene	ug/Kg	6100	-	510		31	J	390	
1,4-Dichlorobenzene	ug/Kg	14000	D	1100		73	J	1100	
2,4-Dichlorophenol	ug/Kg	63	J	<74	U	<78	U	<77	U
Dimethyl phthalate	ug/Kg	<40	U	170	J	<39	U	190	J
Bis(2-ethylhexyl) phthalate	ug/Kg	830	-	<74	U	170	J	<77	U
Fluoranthene	ug/Kg	<80	U	<74	U	<78	U	<77	U
Fluorene	ug/Kg	110	J	<37	U	<39	U	<38	U
2-Methylnaphthalene	ug/Kg	920	-	120	J	24	J	<38	U
2-Methylphenol	ug/Kg	190	J	<37	U	46	J	<38	U
3 & 4 Methylphenol	ug/Kg	1100	-	<74	U	190	J	<77	U
Naphthalene	ug/Kg	250	J	<74	U	<78	U	<77	U
Phenanthrene	ug/Kg	310	J	67	J	28	J	<38	U
Phenol	ug/Kg	880	-	<37	U	97	J	<38	U
Pyrene	ug/Kg	33	J	<37	U	21	J	<38	U
1,2,4-Trichlorobenzene	ug/Kg	1900	-	280	J	<39	U	57	J

Notes:

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Field Handheld PID Readings

Pre-Demonstration Screening			Post-Demonstration Screening		
Boring	Depth (m)	PID Headspace (ppmv)	Boring	Depth (m)	PID Headspace (ppmv)
EC-1			SB-101	0.6	0.2
	1.1	6.3			
	1.8	2.3		1.8	0.5
				2.4	2.1
	3.7	75		3.7	1.9
				4.3	15.6
	4.9	1.9		4.9	1.3
				5.8	0.3
U21D			SB-102	6.1	0
	0.6	2.2		0.6	0.3
	1.8	4.2		1.8	1.3
	3.0	1.4		3.0	1.1
				4.6	6.4
				4.9	5.2
	5.5	18.3		5.5	11.4
				5.8	5.3
I-10			SB-103	6.1	0.1
	0.6	1.7		0.6	2
	1.8	2.5		1.2	0.4
	4.3	1.6		3.0	0.2
				4.3	6.8
				4.9	7.5
	5.5	3.4		5.2	28.6
I-9			SB-104	5.5	3.6
	0.6	8.6		5.8	3.3
	1.8	5.6			
	3.0	6.8		0.9	12.4
I-6			SB-105	1.8	7.8
	0.9	104		3.0	5.9
	1.8	65.6			
	2.4	26.2		1.8	656
				2.4	
				4.3	397
				4.6	88
				4.7	677
U20			SB-106	5.5	89.2
	0.6	14		6.1	6.7
	1.8	67.4		0.6	44.1
				1.8	39.4
	3.7	0.9		2.4	2.4
	4.4	2		3.0	2.3
				4.3	7.1
				4.7	14.3
U19			SB-107	5.5	20.1
	0.9	33.8		5.9	7
	1.8	4.8			
	2.7	2.4		1.8	0.7
	4.3	1.9			
	4.9	0.4		3.0	0.8
U18			SB-108	4.3	0.4
	0.6	22.6			
	1.8	24.3		5.5	5.1
	3.0	2.6		0.6	39
I-1	4.3	30.7	SB-109	1.8	14.6
				3.0	462
	1.1	446		4.3	12.8
				5.5	7.5
	2.0	645			
	3.4	920		1.2	302.4
	3.7	284		1.8	153.6
	4.1	7.8			
				2.4	290.1
	4.9	25.4		3.0	703.6
				4.3	68.9
				4.9	7.8
				5.6	7.1

Pre-Demonstration Screening			Post-Demonstration Screening		
Boring	Depth (m)	PID Headspace (ppmv)	Boring	Depth (m)	PID Headspace (ppmv)
SB-4 (I-7)	0.6	119	SB-110	0.6	2.4
	1.8	69		1.8	50.7
	3.0	475		3.0	835
				4.3	61.6
				4.7	946
I-4			SB-111	5.2	606
	1.1	24.9			
				1.2	67.5
	1.8	55.9		1.8	341
	3.0	27.6		3.0	16.7
	4.3	17.5		4.3	24.1
U16			SB-112	5.2	27
	0.6	5.1		5.5	7.1
	1.5	9.5			
				0.6	1.6
	2.1	65.6			
	3.0	334		1.8	0.3
SB-2	4.3	101	SB-113		
				3.0	120.6
	0.6	59		4.3	514.2
	1.8	162		4.7	509.6
				5.5	426.8
	2.3	1003		0.6	6.4
U17	3.0	498	SB-114	1.8	80.4
				2.1	1291
	0.6	4.9		2.4	1395
	1.2	9.9		3.0	646
				4.3	615
	2.1	2.6		5.5	36.7
	3.0	1.1			
	4.6	0.9			
I-5			SB-115	1.8	2.6
	1.2	37.7		3.0	0.4
				4.3	1.3
	1.8	212			
	2.4	306		4.9	160
				5.5	4.5
SB-3			SB-116		
				0.6	21.8
	0.6	46		1.5	662.5
				1.8	420.3
	1.5	393		2.4	616
	1.8	1180		3.4	405.3
	2.4	266		4.3	75.5
	3.0	210		4.9	1610
SB-5			SB-117	5.5	960
				5.8	44.1
				5.9	17.8
	0.6	376		0.6	8.2
				1.2	460.7
	2.1	884			
	3.0	157		1.8	513.3
	4.3	48		2.4	56.8
SB-1			SB-118	3.0	53.6
	0.6	23		4.3	186.7
				4.7	992.7
	2.0	8.4		5.5	316.2
	3.0	1		6.1	202.6
	4.3	15.3		0.6	59.1
				1.5	
				1.8	123.8
				3.0	7.6
				4.1	433.6
				4.3	279.6
				5.5	159.2
				5.9	1
				0.6	0.5
				1.8	0.6
				3.0	2
				4.3	9.2
				5.5	8

MIP Profiles

Hydroxypropyl-β-cyclodextrin Groundwater Samples

Prelim. Injection Event (Test Cells 2 & 3)					Primary Injection Event-Test Cell 1											
WellID	12/10/12	12/13/12	12/14/12 AM	12/14/12 PM	1/16/13	4/23/2013	5/9/30/13	5/13/2013	5/16/2013	5/23/2013	5/30/2013	7/10/13	7/22/13	8/12/13	10/2/13	2/12/14
EC-1					<25	<100		<100		<100	<100	<100			<100	8.6E+01
EC-2					<25	<100		<100		<100	<100	<100			1.0E+02	5.6E+01
EC-3					<25	<100		<100		<100	<100	<100			<100	3.0E+01
EC-4					<25	3.3E+02		<100		8.3E+02	2.0E+02	<100	7.0E+02	5.2E+02	9.9E+01	3.2E+01
U-1					<25	<100	<100	<100		1.1E+04	4.5E+03	3.1E+03	3.1E+03	2.1E+03	1.1E+03	3.6E+02
U-2					5.7E+02	8.0E+02		<100			8.0E+02				7.9E+02	4.5E+02
U-3	<25				<25	<100	<100	<100		<100	<100	<100	<100	<100	9.1E+01	2.6E+01
U-4						<100	<100	<100		<100	3.8E+03	1.0E+03	1.0E+03	2.1E+03	1.8E+03	6.5E+02
U-5						<100	<100	<100	1.1E+03	7.4E+02	3.3E+02	1.2E+02	<100	<100	<100	7.8E+01
U-6						<100	<100	<100	<100	<100	1.6E+03	2.7E+02	<20	<20	<20	<20
U-7						<100	<100	<100	<100	<100	1.0E+03	1.0E+03		7.0E+02	2.4E+02	<20
U-8						<100	<100	<100			<100	<100		<100	<100	<20
U-9	<25	<25	3.1E+02	1.6E+03	<25	1.3E+02	<100	<100	1.7E+02	1.1E+02	<100	2.1E+02	6.8E+02	7.7E+02	1.2E+02	1.1E+02
U-10	<25	3.8E+01	1.8E+03			<100	1.2E+02	<100	1.7E+02	3.9E+02	7.8E+02	1.1E+03	<100	<100	<100	2.5E+01
U-11						1.0E+02		<100	<100						<100	<20
U-12								<100	<100	1.5E+03	1.3E+03	4.7E+02	2.2E+02		<100	1.8E+01
U-13	<25	<25	8.5E+02												<100	6.3E+01
U-14	<25	<25	5.1E+02													<20
U-15		<25	2.4E+03	1.8E+04	1.2E+02	2.4E+02	<100	<100	2.2E+02						2.2E+02	9.0E+01
U-16D		<25	<25	<25	5.6E+02	1.7E+02	<100	<100	1.2E+02						3.6E+02	4.1E+01
U-16S						2.4E+02	9.9E+01	<100	<100	<100	8.4E+03	3.9E+03	2.4E+03	1.2E+03	<100	<100
U-17S							<100	<100	<100	<100	8.5E+03	1.4E+03	9.1E+02	5.2E+02	<100	<100
U-18D						1.1E+02	<100	<100	2.1E+02	3.2E+02	1.4E+03	8.1E+02	7.8E+02	3.9E+02	6.7E+01	<20
U-18S						<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<20
U-19D						3.1E+02	1.2E+02	1.4E+02	2.9E+02	7.9E+02	3.8E+03	2.7E+03	8.6E+02	1.0E+03	4.1E+02	4.2E+01
U-19S	<25				<25	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<20
U-20D		9.7E+02	4.9E+03	3.1E+03	4.3E+03	4.0E+02	<100	1.7E+02	9.2E+01	1.4E+03	8.5E+02	4.9E+03	7.1E+02	2.3E+03	4.4E+02	7.3E+01
U-20S						<100	<100	<100	9.2E+01	1.6E+03	1.1E+02	<100	<100	<100	<100	<20
U-21D						<100	<100	<100	1.0E+04	1.7E+03	1.7E+03	1.7E+03	6.5E+02	4.2E+02	2.6E+02	9.6E+01
U-21S							<100	<100		<100	<100	<100	<100	<100	<100	<100
Notes:																
1. All samples analyzed by TNS inclusion and fluorescence spectrophotometry.																
2. All analyses performed by the University of Rhode Island.																
3. Bold values indicate a detection.																
All Concentrations are in mg/L																

Notes:
1. All samples analyzed by TSS inclusion and fluorescence spectrophotometry.
2. All analyses performed by the University of Rhode Island.
3. Bold values indicate a detection.
4. All Concentrations are in mg/L

Groundwater Metals Samples

		EC-1				EC-2							
		4/24/2012 (UF)		2/11/2014		4/24/2012 (UF)		4/23/2013		4/23/2013 (UF)		2/11/2014	
Analyte	Units	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier
Lead	µg/L	62		22	J D	250		5.1	J	18		24	J D
Nickel	µg/L	63		86	J D	160		49		52		75	J D
Silver	µg/L	<2	U	<10	U	<2	U	<2	U	<2	U	<10	U
Thallium	µg/L	<12	U	<60	U	<12	U	<12	U	<12	U	<60	U
Antimony	µg/L	<8	U	<40	U	4.6	J	<8	U Q	<8	U Q	<40	U
Arsenic	µg/L	33		32	J D	270		6.4	J	17	J	26	J D
Beryllium	µg/L	9.5		22	D	40	D	7.1	J D	9.5	D	19	D
Cadmium	µg/L	0.68	J Q	3.1	J Q D	<0.8	U Q	1.4	J	1.2	J	<4	U Q
Chromium	µg/L	100	Q	9.4	J Q D	480	Q	0.98	J Q	27	Q	9.6	J Q D
Copper	µg/L	39	Q	15	J D	180	Q	6.6	J Q	13	J Q	10	J D
Zinc	µg/L	340		710	J D	900		190		230		180	J D
Selenium	µg/L	11	J	<60	U	52		<12	U	<12	U	<60	U
Mercury	µg/L	0.19	J	0.033	J	0.61		<0.08	U	<0.08	U	0.24	

Notes:

- Qualifiers: "U" = Analyte undetected at limit of detection; "M" = Manual integrated compound; "BQL" = Analyte detected but not quantified; "J" = Analyte was positively identified, the quantitation is an estimate; "Q" = One or more quality control criteria failed.
- An asterisk (*) after the sample date indicates that the sample was analyzed at URI.
All other samples analyzed by Test America.
- "NA" = Analyte was not analyzed for.
- Bold** values indicate a hit.
- All samples field filtered with a 0.45 µm filter, unless (UF) is noted after the sample date.

		EC-3						EC-4		I-1			
		5/21/2012* (UF)		4/23/2013		2/11/2014		5/21/2012* (UF)		4/24/2012 (UF)		4/23/2013	
Analyte	Units	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier
Lead	µg/L	2.7		4.9	J	<25	U	BQL	BQL	80		<5	U
Nickel	µg/L	55.7		49.0		52.0	J D	28.2		43		7	J
Silver	µg/L	NA		<2	U	<10	U	NA		<2	U	<2	U
Thallium	µg/L	NA		<12	U	<60	U	NA		<12	U	<12	U
Antimony	µg/L	NA		<8	U Q	<40	U	NA		<8	U	<8	U Q
Arsenic	µg/L	BQL	BQL	6.7	J	38	J D	BQL	BQL	7.8	J	<12	U
Beryllium	µg/L	NA		2.3		15	D	NA		2.3		<0.5	U
Cadmium	µg/L	BQL	BQL	2.8	J	3.3	J Q D	BQL		0.99	J Q	<0.8	U
Chromium	µg/L	8.6		<1.5	U Q	<7.5	U Q	BQL	BQL	44	Q	<1.5	U Q
Copper	µg/L	17.7		6.2	J Q	<18	U	65.1		20	Q	3.3	J Q
Zinc	µg/L	129.7		230.0		170.0	J D	294.7		400		380	
Selenium	µg/L	NA		<12	U	<60	U	NA		7.4	J	<12	U
Mercury	µg/L	NA		<0.08	U	<0.08	U	NA		0.096	J	<0.08	U

Notes:

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		I-2		I-3				I-4				I-5	
		4/24/2012 (UF)		5/21/2012 (UF)		5/21/2012* (UF)		4/23/2013		2/13/2014		4/23/2013	
Analyte	Units	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier
Lead	µg/L	570	J	7.1	J J	BQL	BQL	4.8	J	<25	U	19.0	
Nickel	µg/L	140	J	39	J J	42.8		40.0		52.0	J D	8.1	J
Silver	µg/L	<2	U	2	U J	NA		<2	U	<10	U	<2	U
Thallium	µg/L	<12	U J	12	U J	NA		<12	U	<60	U	<12	U
Antimony	µg/L	<8	U J	8	U	NA		<8	U Q	<40	U	<8	U Q
Arsenic	µg/L	150	J	12	U	BQL	BQL	<12	U	<60	U	5.7	J
Beryllium	µg/L	37	D	6.4		NA		4.1		<2.5	U	1.5	
Cadmium	µg/L	<0.8	U Q J	1	J	BQL	BQL	0.98	J	<4	U Q	1.4	J
Chromium	µg/L	430	Q	6.2	J Q J	3.9		7.2	J Q	4.6	J Q D	<1.5	U Q
Copper	µg/L	260	Q	6.4	J Q	6.6		12.0	J Q	11.0	J D	4.1	J Q
Zinc	µg/L	1500		120	J	122.5		160.0		180.0	J D	540.0	
Selenium	µg/L	42	J	12	U J	NA		<12	U	<60	U	<12	U
Mercury	µg/L	0.68		0.04	J	NA		<0.08	U	0.038	J	<0.08	U

Notes:

- Qualifiers: "U" = Analyte undetected at limit of detection; "M" = Manual integrated compound; "BQL" = Analyte detected but not quantified; "J" = Analyte was positively identified, the quantitation is an estimate; "Q" = One or more quality control criteria failed.
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		I-6							
		12/4/2012 (UF)		4/23/2013		7/10/2013		2/13/2014	
Analyte	Units	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier
Lead	µg/L	110.0		5.6	J	<5	U	<25	U
Nickel	µg/L	27.0	J Q	12.0	J	20.0	J	29.0	J D
Silver	µg/L	<2	U	<2	U	<2	U	<10	U
Thallium	µg/L	<12	U	<12	U	<12	U	<60	U
Antimony	µg/L	<8	U	<8	U Q	<8	U	<40	U
Arsenic	µg/L	12	J	<12	U	27		<60	U
Beryllium	µg/L	2.4		1.1	J	1.7		<2.5	U
Cadmium	µg/L	0.86	J	0.97	J	2.9	J Q	3.5	J Q D
Chromium	µg/L	60.0		1.2	J Q	3.3	J	3.6	J Q D
Copper	µg/L	23.0	Q	5.1	J Q	56.0	Q	22.0	J D
Zinc	µg/L	260.0		140.0	J	1000.0		1000.0	D
Selenium	µg/L	<12	U	<12	U	<12	U	<60	U
Mercury	µg/L	<0.11	U	<0.08	U	<0.08	U	<0.08	U

Notes:

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- An asterisk (*) after the sample date indicates that the sample was analyzed at URI.
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		MW-2904						U-1		U-2		U-3	
		4/23/2013		7/10/2013		2/13/2014		5/22/2012* (UF)		5/22/2012* (UF)		5/22/2012* (UF)	
Analyte	Units	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier
Lead	µg/L	15.0	J D	<25	U	<25	U	9.2		22.2		10.3	
Nickel	µg/L	46.0	J D	69.0	J D	31.0	J D	78.8		45.1		93.8	
Silver	µg/L	<10	U	<10	U	<10	U	NA		NA		NA	
Thallium	µg/L	<60	U	<60	U	<60	U	NA		NA		NA	
Antimony	µg/L	<40	U	<40	U	<40	U	NA		NA		NA	
Arsenic	µg/L	24	J D	36	J D	<60	U	BQL	BQL	BQL	BQL	BQL	BQL
Beryllium	µg/L	23	D	13	D	12	D	NA		NA		NA	
Cadmium	µg/L	2.7	J D	2.8	J Q D	<4	U Q	BQL	BQL	BQL	BQL	BQL	BQL
Chromium	µg/L	9.0	J Q D	9.0	J Q D	8.5	J Q D	18.2		6.7		15.1	
Copper	µg/L	22.0	J Q D	51.0	J Q D	49.0	J D	166.8		77.5		90.6	
Zinc	µg/L	480.0	J D	340.0	J D	200.0	J D	422.1		189.4		340.1	
Selenium	µg/L	<60	U	<60	U	<60	U	NA		NA		NA	
Mercury	µg/L	<0.08	U	<0.08	U	<0.08	U	NA		NA		NA	

Notes:

- Qualifiers: "U" = Analyte undetected at limit of detection; "M" = Manual integrated compound; "BQL" = Analyte detected but not quantified; "J" = Analyte was positively identified, the quantitation is an estimate; "Q" = One or more quality control criteria failed.
- An asterisk (*) after the sample date indicates that the sample was analyzed at URI.
- All other samples analyzed by Test America.
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Analyte	Units	U-4				U-5		U-6				U-7	
		5/22/2012* (UF)		4/23/2013		4/23/2013		5/22/2012* (UF)		4/23/2013		5/22/2012* (UF)	
		Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier
Lead	µg/L	3.9		8.9	J	14.0	J D	BQL	BQL	<5	U	BQL	BQL
Nickel	µg/L	65.1		35.0	J	170.0	J D	50.5		13.0	J	50.5	
Silver	µg/L	NA		<2	U	<10	U	NA		<2	U	NA	
Thallium	µg/L	NA		<12	U	<60	U	NA		<12	U	NA	
Antimony	µg/L	NA		<8	U Q	<40	U	NA		<8	U Q	NA	
Arsenic	µg/L	BQL	BQL	8.1	J	31.0	J D	BQL	BQL	<12	U	BQL	BQL
Beryllium	µg/L	NA		19	D	22	D	NA		2.1		NA	
Cadmium	µg/L	BQL	BQL	1.1	J	2.9	J D	BQL	BQL	0.69	J	BQL	BQL
Chromium	µg/L	7.0		9.4	J Q	78.0	Q D	13.4		4.7	J Q	13.4	
Copper	µg/L	21.6		9.3	J Q	20.0	J Q D	12.4		3.9	J Q	12.4	
Zinc	µg/L	144.4		150.0		340.0	J D	132.2		39.0	J	132.2	
Selenium	µg/L	NA		<12	U	<60	U	NA		<12	U	NA	
Mercury	µg/L	NA		0.034	J	0.34		NA		0.041	J	NA	

Notes:

1. Qualifiers: "U"= Analyte undetected at limit of detection; "M"= Manual integrated compound; "BQL" = Analyte detected but not quantified;

"J"= Analyte was positively identified, the quantitation is an estimate; "Q"= One or more quality control criteria failed.

2. An asterisk (*) after the sample date indicates that the sample was analyzed at URI.

All other samples analyzed by Test America.

3. "NA"= Analyte was not analyzed for.

4. **Bold** values indicate a hit.

5. All samples field filtered with a 0.45 µm filter, unless (UF) is noted after the sample date.

Analyte	Units	U-8		U-9		U-16D						U-16S	
		5/22/2012* (UF)		5/22/2012* (UF)		4/23/2013		7/9/2013		2/12/2014		7/9/2013	
		Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier
Lead	µg/L	BQL	BQL	BQL	BQL	17.0	J D	<25	U	16.0	J D	<5	U
Nickel	µg/L	16.7		48.0		65.0	J D	49.0	J D	76.0	J D	8.5	J
Silver	µg/L	NA		NA		<10	U	<10	U	<10	U	<2	U
Thallium	µg/L	NA		NA		<60	U	<60	U	<60	U	<12	U
Antimony	µg/L	NA		NA		<40	U	<40	U	<40	U	<8	U
Arsenic	µg/L	BQL	BQL	BQL	BQL	<60	U	59	J D	41	J D	6.2	J
Beryllium	µg/L	NA		NA		21	D	15	D	16	D	<0.5	U
Cadmium	µg/L	1.4		BQL	BQL	<4	U	<4	U Q	2.6	J Q D	<0.8	U Q
Chromium	µg/L	3.3		9.9		15.0	J Q D	10.0	J Q D	27.0	J Q D	<1.5	U
Copper	µg/L	11.6		6.7		49.0	J Q D	68.0	J Q D	44.0	J D	3.6	J Q
Zinc	µg/L	87.3		135.5		300.0	J D	250.0	J D	260.0	J D	7.0	J
Selenium	µg/L	NA		NA		<60	U	<10	U	<60	U	<12	U
Mercury	µg/L	NA		NA		0.13	J	0.15	J	0.81		<0.08	U

Notes:

1. Qualifiers: "U"= Analyte undetected at limit of detection; "M"= Manual integrated compound; "BQL" = Analyte detected but not quantified;

"J"= Analyte was positively identified, the quantitation is an estimate; "Q"= One or more quality control criteria failed.

2. An asterisk (*) after the sample date indicates that the sample was analyzed at URI.

All other samples analyzed by Test America.

3. "NA"= Analyte was not analyzed for.

4. **Bold** values indicate a hit.

5. All samples field filtered with a 0.45 µm filter, unless (UF) is noted after the sample date.

Analyte	Units	U-17D						U-17S	
		4/23/2013		7/9/2013		2/11/2014		7/9/2013	
		Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier
Lead	µg/L	17.0	J D	<5	U	<25	U	<5	U
Nickel	µg/L	85.0	J D	29.0	J	300.0	D	4.1	J
Silver	µg/L	<10	U	<2	U	<10	U	<2	U
Thallium	µg/L	<60	U	<12	U	<60	U	<12	U
Antimony	µg/L	<40	U	<8	U	<40	U	<8	U
Arsenic	µg/L	<60	U	12	J	<60	U	13	J
Beryllium	µg/L	19	D	5.1		10	D	<0.5	U
Cadmium	µg/L	3	J D	1.2	J Q	18	J Q D	<0.8	U Q
Chromium	µg/L	20.0	J Q D	35.0		80.0	Q D	<1.5	U
Copper	µg/L	62.0	J Q D	27.0	Q	72.0	J D	1.8	J Q
Zinc	µg/L	390.0	J D	140.0	J	1100.0	D	13.0	J
Selenium	µg/L	<60	U	7.9	J	<60	U	<12	U
Mercury	µg/L	0.092	J	0.048	J	0.24		<0.08	U

Notes:

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3. "NA"= Analyte was not analyzed for.

4. **Bold** values indicate a hit.

5. All samples field filtered with a 0.45 µm filter, unless (UF) is noted after the sample date.

Analyte	Units	U-18D						U-18S			
		4/23/2013		7/10/2013		2/12/2014		4/23/2013		7/10/2013	
		Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier
Lead	µg/L	6.0	J	9.5	J	13.0	J D	<5	U	<5	U
Nickel	µg/L	52.0		36.0	J	48.0	J D	2.4	J	<3	U
Silver	µg/L	<2	U	<2	U	<10	U	<2	U	<2	U
Thallium	µg/L	<12	U	<12	U	<60	U	<12	U	<12	U
Antimony	µg/L	<8	U Q	<8	U	<40	U	<8	U Q	<8	U
Arsenic	µg/L	4.9	J	12	J	<60	U	<12	U	10	J
Beryllium	µg/L	15	D	25	D	7.1	J D	<0.5	U	<0.5	U
Cadmium	µg/L	1.2	J	1.2	J Q	2.5	J Q D	<0.8	U	<0.8	U Q
Chromium	µg/L	23.0	Q	38.0		60.0	J Q D	<1.5	U Q	<1.5	U
Copper	µg/L	10.0	J Q	14.0	J Q	35.0	J D	2.1	J Q	2.9	J Q
Zinc	µg/L	130.0	J	110.0	J	190.0	J D	4.9	J	<13	U
Selenium	µg/L	<12	U	<12	U	<60	U	<12	U	<12	U
Mercury	µg/L	0.045	J	0.15	J	0.23		<0.08	U	<0.08	U

Notes:

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- An asterisk (*) after the sample date indicates that the sample was analyzed at URI.
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Analyte	Units	U-19D						U-19S			
		4/23/2013		7/10/2013		2/12/2014		4/23/2013		7/10/2013	
		Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier
Lead	µg/L	<5.0	U	<25	U	<25	U	<5	U	<5	U
Nickel	µg/L	24.0	J	96.0	J D	100.0	J D	5.2	J	3.3	J
Silver	µg/L	<2	U	<10	U	<10	U	<2	U	<2	U
Thallium	µg/L	<12	U	<60	U	<60	U	<12	U	<12	U
Antimony	µg/L	<8	U Q	<40	U	<40	U	<8	U Q	<8	U
Arsenic	µg/L	<12	U	44	J D	31	J D	<12	U	<12	U
Beryllium	µg/L	<0.5	U	3.9	J D	18	D	<0.5	U	<0.5	U
Cadmium	µg/L	0.98	J	2.8	J Q D	3	J Q D	<0.8	U	<0.8	U Q
Chromium	µg/L	6.3	J Q	8.9	J Q D	54.0	J Q D	<1.5	U Q	<1.5	U
Copper	µg/L	5.8	J Q	12.0	J Q D	29.0	J D	2.7	J Q	3.5	J Q
Zinc	µg/L	40.0	J	420.0	J D	370.0	J D	12.0	J	36.0	J
Selenium	µg/L	<12	U	<60	U	<60	U	<12	U	<12	U
Mercury	µg/L	0.059	J	0.19	J	0.71		<0.08	U	<0.08	U

Notes:

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Analyte	Units	U-20D						U-20S			
		4/23/2013		7/10/2013		2/12/2014		4/23/2013		7/10/2013	
		Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier
Lead	µg/L	19.0	J D	<25	U	15.0	J D	<5	U	<5	U
Nickel	µg/L	81.0	J D	50.0	J D	90.0	J D	3.5	J	27.0	J
Silver	µg/L	<10	U	<10	U	<10	U	<2	U	<2	U
Thallium	µg/L	<60	U	<60	U	<60	U	<12	U	<12	U
Antimony	µg/L	<40	U	<40	U	<40	U	<8	U Q	<8	U
Arsenic	µg/L	36	J D	62	J D	32	J D	<12	U	6.2	J
Beryllium	µg/L	34	D	38	D	19	D	<0.5	U	<0.5	U
Cadmium	µg/L	<4	U	<4	U Q	4.3	J Q D	<0.8	U	0.67	J Q
Chromium	µg/L	16.0	J Q D	20.0	J Q D	32.0	J Q D	2.1	J Q	<1.5	U
Copper	µg/L	26.0	J Q D	56.0	J Q D	38.0	J D	3.6	J Q	2.7	J Q
Zinc	µg/L	420.0	J D	310.0	J D	510.0	J D	15.0	J	99.0	J
Selenium	µg/L	<60	U	<60	U	<60	U	<12	U	<12	U
Mercury	µg/L	0.16	J	0.13	J	0.53		<0.08	U	<0.08	U

Notes:

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Soil

Reference Location						I-4		I-6	
Boring/Well ID		EC-1		I-3		I-4		SB-111-10	
Sample Depth (m)		0.6-0.9		4.3		3		3	
Sample Date		4/17/2012		5/8/2012		5/8/2012		12/13/2013	
Analyte	Units	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier
Antimony	ug/Kg	<640	U J Q	<910	U	<750	U J	<710	U
Arsenic	ug/Kg	1600	J	1600	J	960	J	<1200	U
Beryllium	ug/Kg	430	J	320	J	80	J	40	J
Cadmium	ug/Kg	<110	U	<150	U Q	<120	U Q	65	J
Chromium	ug/Kg	14000	J	8100	Q	6600	Q	5000	Q
Copper	ug/Kg	4800	J Q	2900	J Q	1800	J Q	1200	J
Lead	ug/Kg	9700		5000		6500		3900	
Mercury	ug/Kg	28		<26	U	<20	U	<15	U
Nickel	ug/Kg	4700		2500	J	1500	J	1300	J
Selenium	ug/Kg	<1300	U	<1800	U	<1500	U	<1400	U
Silver	ug/Kg	<210	U	<300	U	<250	U	<240	U
Thallium	ug/Kg	<1300	U	<1800	U	<1500	U	<1400	U
Zinc	ug/Kg	16000		14000		7000	J	5700	J

Notes:

1. Qualifiers: "U"= Analyte undetected at limit of detection; "M"= Manual integrated compound;

"J"= Analyte was positively identified, the quantitation is an estimate; "Q"= One or more quality control criteria failed.

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All other samples analyzed by Test America.

3. "NA"= Analyte was not analyzed for.

4. **Bold** values indicate a hit.

Reference Location		U16	
Boring/Well ID		U16	SB-112-14
Sample Depth (m)		4.6	4.3
Sample Date		9/25/2012	
Analyte	Units	Result	Qualifier
Antimony	ug/Kg	<730	U
Arsenic	ug/Kg	1000	J
Beryllium	ug/Kg	47	J
Cadmium	ug/Kg	<120	U
Chromium	ug/Kg	4700	J Q
Copper	ug/Kg	1400	J Q
Lead	ug/Kg	5400	
Mercury	ug/Kg	<21	U
Nickel	ug/Kg	1100	J Q
Selenium	ug/Kg	<1500	U
Silver	ug/Kg	<240	U
Thallium	ug/Kg	<1500	U
Zinc	ug/Kg	7000	J

Notes:

1. Qualifiers: "U"= Analyte undetected at limit of detection; "M"= Manual integrated compound;

"J"= Analyte was positively identified, the quantitation is an estimate; "Q"= One or more quality control criteria failed.

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JBLE Metals Background Concentrations:

Metals (µg/L)	JBLE Background Concentrations				EPA MCLs	VDEQ VRP SSLs	
	Dissolved Metals		Total metals			Tier II	Tier III
	AVG	STDEV	AVG	STDEV			
Antimony	30	0	60	92	6	6	83
Arsenic	4	1	10	5	10	10	210
Beryllium	3	0	3	1	4	4	58
Cadmium	4	3	3	1	5	5	5
Chromium	5	0	10	13	100	100	290
Copper	10	4	20	18	1300	1300	28000
Lead	3	2	20	21	15	15	15
Mercury	0.1	0	0.117	0.0408	2	2	2
Nickel	20	0	30	13		39	5200
Selenium	4	1	6	3	50	50	3400
Zinc	114	200	90	72		600	250000

Table 1: JBLE background concentrations for metals in groundwater as well as Environmental Protection Agency maximum contaminant levels (MCLs) and Virginia Department of Environmental Quality (VDEQ) Voluntary Remediation Program (VRP) Site Screening levels (SSLs). Sources: (Watson 1997; VDEQ 2014). The VDEQ Tier II screening levels are based on unfiltered (total metals) concentrations.

Metals (mg/Kg)	JBLE Background Soil Metals Conc.				VDEQ VRP SSLs	
	Surface Soil		Subsurface Soils		Tier II	Tier III
	AVG	STDEV	AVG	STDEV		
Arsenic	6.82	6.00	10.04	9.32	3	30
Beryllium	0.28	0.00	0.34	0.17	16	230
Cadmium	NA	NA	NA	NA	7	98
Chromium	12.28	5.80	17.39	12.79	3	63
Copper	3.87	2.50	4.71	4.49	310	4700
Lead	17.04	6.40	9.27	5.76	270	800
Mercury	0.04	0.01	0.03	0.02	1	4
Nickel	4.85	2.80	5.45	2.99	51	2200
Selenium	NA	NA	NA	NA	5	580
Zinc	24.34	15.50	22.86	12.37	745	35000

Table 2: Above are JBLE background concentrations for surface and subsurface soils and Virginia Department of Environmental Quality (VDEQ) Voluntary Remediation Program (VRP) Site Screening levels (SSLs). Sources: (Watson 1997; VDEQ 2014).

Microbial Data

Well	Biotrap Deployment	Biotrap Collection Date	Total Biomass (cells/bead)	Community Structure (% total PLFA)						Physiological Status	
				Firmicutes (TerBrSats)	Proteobacteria (Monos)	Anaerobic metal reducers (BrMonos)	SRB/Actinomy cetes (MidBrSats)	General (Nsats)	Eukaryotes (polyenoics)	Slowed Growth	Decreased Permeability
MW-3	9/25/2012	11/19/12	1.43E+05	6.30	66.77	0.64	1.80	22.29	2.19	5.06	0.63
	5/23/2013	7/11/13	6.72E+04	0.00	77.59	0.00	0.00	22.41	0.00	1.71	0.00
	10/3/2013	12/13/13	3.53E+04	0.00	40.25	0.00	0.00	59.76	0.00	1.99	0.00
	12/13/2013	2/13/14	1.56E+04	0.00	67.17	0.00	0.00	32.83	0.00	4.34	0.00
MW-2904	9/25/2012	11/19/12	3.25E+05	7.20	64.41	1.20	1.26	23.25	2.69	0.74	0.39
	5/23/2013	7/11/13	3.58E+04	5.64	39.63	4.18	15.70	32.75	2.12	9.44	0.00
	10/3/2013	12/13/13	1.68E+04	0.00	76.35	0.00	0.00	23.65	0.00	1.85	0.68
	12/13/2013	2/13/14	1.24E+04	24.83	43.93	0.00	0.00	31.23	0.00	1.47	0.00
I-1	9/25/2012	11/19/12	3.31E+05	7.59	60.18	1.54	1.95	26.17	2.58	2.16	0.24
	5/23/2013	7/11/13	2.18E+05	12.94	50.70	4.73	3.62	25.98	2.05	0.35	0.55
	10/3/2013	12/13/13	1.54E+05	28.17	29.36	3.60	0.70	35.07	3.11	3.96	0.67
	12/13/2013	2/13/14	1.65E+05	21.21	38.08	7.78	10.52	15.77	6.65	1.76	0.20
I-4	9/25/2012	11/19/12	1.46E+05	9.87	60.10	1.37	3.48	23.92	1.27	2.08	0.38
	5/23/2013	7/11/13	7.70E+04	7.54	46.51	0.00	0.00	43.02	2.93	3.26	1.21
	10/3/2013	12/13/13	3.72E+04	3.87	40.19	0.00	0.00	21.43	34.52	2.99	0.00
	12/13/2013	2/13/14	9.38E+03	0.00	48.85	0.00	0.00	38.74	12.41	0.78	0.00

Groundwater Field Parameters

<i>Well</i>	<i>Date</i>	<i>Depth to Water (ft)</i>	<i>Temp. (°C)</i>	<i>DO (mg/L)</i>	<i>Sp. Conductance (µS/cm)</i>	<i>pH</i>	<i>ORP (mV)</i>	<i>Turbidity (NTU)</i>	<i>Sodium Persulfate (mg/L)</i>
EC-1	17-Oct-12		22.7	0.45	4,652	4.88	245.3	10.2	
	16-Jan-13	0.60	15.3	2.66	613	7.17	249.1		350
	23-Apr-13	1.25	14.8	0.75	3,824	5.27	194.8		
	25-Apr-13	1.19							
	25-Apr-13	0.60	15.5	11.00	3,208	4.22	400		
	5-May-13	0.08							
	5-May-13	0.08	15.4	0.23	5,970	6.06	326		
	9-May-13		22.2	10.88	1,594	7.20	232.6		
	14-May-13	1.15	16.1	0.70	4,295	5.37	131		
	31-May-13	1.84	18.4	0.55	4,902	5.41	240.4		
	10-Jul-13	1.89	21.0	0.34	4,769	5.18	151.8		
	13-Aug-13	0.80	21.5	0.30	6,419	4.15	371.6		
	3-Oct-13	1.52	22.4	0.10	4,300	5.01	82	40.9	
EC-2	11-Feb-14	1.32	13.2	0.54	5,148	3.86	531.7	642	
	17-Oct-12		23.0	2.62	4,417	4.64	305.1		
	16-Jan-13	0.98	16.3	7.91	3,877	5.04	319.1		
	23-Apr-13	1.08	15.3	11.30	4,253	4.16	351.9		
	25-Apr-13	1.23	15.5	7.45	3,114	4.46	343.5		
	5-May-13	0.42	17.0	1.61	4,041	5.02	351.6		
	10-May-13		18.4	17.40	2,305	5.91	258		
	14-May-13	1.46	16.4	15.45	3,684	4.25	334		
	31-May-13	2.29	18.5	9.38	4,697	4.44	506.3		
	10-Jul-13	2.19	22.0	11.43	5,085	4.00	359.9		
	13-Aug-13	1.30	22.5	8.44	5,790	3.55	473.9		
	3-Oct-13	1.84	23.3	8.25	5,497	3.69	478.3	152	
EC-3	11-Feb-14	1.61	13.2	7.30	4,564	3.82	601	119	
	17-Oct-12		22.8	2.05	475	4.81	313.7		
	16-Jan-13	0.80	16.3	6.01	4,033	5.29	345.8		
	23-Apr-13	1.92	15.3	5.59	4,692	4.37	313		
	25-Apr-13	1.09	15.2	0.18	4,255	5.22	321		
	5-May-13	0.25	16.2	1.94	3,487	5.27	349	30	
	9-May-13	1.02	18.3	20.97	3,244	6.13	278.7		
	14-May-13	1.11	16.3	15.67	3,599	4.42	355	24.4	
	31-May-13		18.6	21.51	2,862	5.09	382.9		
	10-Jul-13	2.08	21.0	3.14	4,716	4.65	215.7		
	13-Aug-13	1.00	22.5	13.57	3,348	4.52	392.1		
	3-Oct-13	1.72	22.7	4.22	5,836	4.76	169.3	99.2	
	11-Feb-14	1.46	13.8	4.23	4,760	3.81	547.2	49.2	

Well	Date	Depth to Water (ft)	Temp. (°C)	DO (mg/L)	Sp. Conductance (µS/cm)	pH	ORP (mV)	Turbidity (NTU)	Sodium Persulfate (mg/L)
EC-4	17-Oct-12		20.7	0.07	6,300	5.65	-19		
	16-Jan-13	<0.4	14.8	0.61	5,473	6.03	129.5		
	23-Apr-13	1.02	13.8	0.49	6,035	5.00	198.4		
	25-Apr-13	0.97							
	25-Apr-13	0.57	13.8	0.22	4,352	5.03	283		
	26-Apr-13		14.1	4.92	5,473	5.38	337		
	27-Apr-13		14.0	0.43	6,054	5.50	203		
	27-Apr-13		14.0	0.93	5,999	5.71	276		
	28-Apr-13	1.41	15.0	1.91	3,054	6.29	212.7		
	30-Apr-13		14.9	0.33	6,233	4.63	246		
	1-May-13	-0.68	14.1	2.13	652	5.98	224		
	3-May-13	0.20							
	4-May-13		14.1	0.63	5,427	3.85	376.5		
	4-May-13	-0.14							
	6-May-13	0.25	14.3	0.49	5,781	5.08	248		
	9-May-13		14.7	0.77	7,915	3.74	295.6		
	10-May-13	0.68	15.0	1.33	7,391	5.60	261.4		
	14-May-13	1.10	15.2	0.53	6,465	5.67	136	15.8	
	17-May-13	0.95	16.2	0.68	7,829	3.63	570.5		
	18-May-13	0.77	15.4	1.22	8,664	3.45	632		
	19-May-13	0.22	15.6	1.53	6,961	3.65	640		
	20-May-13	1.15	15.8	2.44	9,892	3.77	634		
	23-May-13	0.98	16.0	1.70	11,751	3.60	598		
	30-May-13	1.59	16.8	0.60	11,133	3.90	640.8		
	9-Jul-13	1.48	19.7	0.21	8,478	3.57	536.7	816	
	22-Jul-13	1.00	21.0	1.53	12,304	2.76	440		
	12-Aug-13	0.90	19.3	1.11	11,133	3.16	614.2	41.6	
	14-Aug-13	0.85	20.1	0.49	10,147	3.01	560.0		
	3-Oct-13	1.20	20.6	0.11	9,515	2.95	587.4	47.2	
	11-Feb-14	1.22	11.5	0.32	6,957	3.40	627.2	71.2	
I-1	17-Oct-12		22.6	0.07	4,060	5.87	-37		
	18-Dec-12		14.8	1.30	3,671	7.81	103.80		
	23-Apr-13	1.11	15.5	0.17	470	7.14	147.6		
	25-Apr-13	1.57							
	25-Apr-13	1.45	14.8	0.16	897	6.30	245		
	25-Apr-13	1.42							
	25-Apr-13	1.32							
	25-Apr-13		15.1	25.25	38,765	7.45	273		
	26-Apr-13		16.0	22.59	34,162	7.42	312		
	27-Apr-13		15.9	12.71	29,294	6.48	214		
	28-Apr-13	2.19	16.5	3.81	23,707	6.29	145.4		
	5-May-13	0.92	15.2	0.84	4,483	6.92	155.3	168	
	5-May-13	0.04	15.3	0.73	5,015	6.69	194.2	14.6	
	9-May-13		16.6	4.05	17,341	6.68	43.3		
	10-May-13	1.21	16.5	3.50	16,335	6.35	50	11.4	>140
	13-May-13	1.56	16.2	1.42	13,829	5.80	489		
	17-May-13	1.90							
	30-May-13	1.93	18.5	0.37	7,156	6.10	222		
	10-Jul-13	2.02	21.7	0.28	6,864	5.73	139.2		
	22-Jul-13	1.68	23.4	1.50	19,258	3.02	318.3		
	12-Aug-13	1.40	22.3	1.84	10,876	3.20	412.9	42.4	
	13-Feb-14	1.01	12.5	0.30	6,269	3.36	518.1	772	
I-10	13-May-13	1.39	17.0	39.40	42,287	6.59	529.6		
	31-May-13	2.10	18.6	8.37	25,790	6.19	496.6		
	9-Jul-13	2.32	20.0	0.24	26,710	5.87	277.8		
	22-Jul-13		22.8	19.04	47,152	5.67	505	28.5	
	2-Oct-13	2.15	22.4	1.41	39,055	6.00	417.9	8.26	
	3-Oct-13	1.79	23.5	0.09	12,702	2.81	444.7	1500	
	3-Oct-13	1.82	23.2	0.22	7,749	6.24	115.8	197	
	13-Feb-14	1.00	13.9	0.31	32,008	5.79	521.6	24	

Well	Date	Depth to Water (ft)	Temp. (°C)	DO (mg/L)	Sp. Conductance (µS/cm)	pH	ORP (mV)	Turbidity (NTU)	Sodium Persulfate (mg/L)
I-2	17-Oct-12		22.0	0.07	4,836	5.85	-76.7		
	18-Dec-12		15.6	18.63	27,943	7.91	503.70		
	16-Jan-13	0.90	15.3	2.23	7,079	6.32	98.1		
	23-Apr-13	1.60	14.1	0.32	5,621	3.21	428		
	25-Apr-13	1.57							
	25-Apr-13		14.6	5.53	4,702	3.42	232		
	27-Apr-13		14.6	0.37	4,033	3.81	133		
	27-Apr-13		150.0	0.94	4,479	4.41	197		
	5-May-13	0.35	15.6	0.22	4,525	4.91	181.1		
	9-Jul-13	2.25	20.3	0.15	4,509	3.90	161.5		
	3-Oct-13	1.94	22.1	0.19	5,135	5.23	-105.3	3.43	
I-3	11-Feb-14	1.81	11.3	0.11	3,905	5.61	-78.3	75.3	
	17-Oct-12		22.7	0.93	4,143	4.50	287.8		
	12-Dec-12	1.59	18.6	0.92	3,441	4.80	263		
	12-Dec-12		18.4	1.35	4,456	4.15	219		
	18-Dec-12		14.7	23.45	8,123	7.81	438.00	29.5	
	15-Jan-13	0.49	13.8	31.09	3,165	7.02	274.3		
	23-Apr-13	1.42	15.0	14.52	3,257	5.85	519.1		
	25-Apr-13	1.39							
	25-Apr-13	1.39	15.0	21.68	1,743	5.96	373		
	26-Apr-13		15.2	10.59	3,338	5.80	362		
	5-May-13	0.19	16.0	3.19	2,272	6.71	305.1		
	10-Jul-13	1.99	21.4	7.07	4,394	5.95	278.3		
	2-Oct-13	1.59	23.3	4.29	5,820	5.44	413	15.2	
	11-Feb-14	1.46	12.1	4.59	4,133	4.35	614.8	10.9	
I-4	17-Oct-12		22.1	0.08	5,505	4.11	235.7		
	11-Dec-12		17.2	0.26	3,918	3.70	272.1		
	11-Dec-12	1.39							
	18-Dec-12		15.0	1.41	4,039	7.77	290.00	17.1	
	23-Apr-13	0.85	15.2	0.56	4,862	4.21	328.2		
	25-Apr-13	1.31							
	25-Apr-13	1.21	14.6	0.14	4,396	4.25	348.9	1208	
	25-Apr-13	0.78						109.8	
	25-Apr-13	0.81							
	28-Apr-13	2.11	16.3	12.84	37,147	7.48	169.8		
	2-May-13	0.80	16.4	4.80	11,370	7.02	425.6		
	4-May-13	0.35	16.2	1.57	7,425	7.16	246.0		
	9-May-13	0.88	16.5	9.71	16,773	7.77	164.3		
	10-May-13	1.07						4.73	
	13-May-13	1.25	16.4	4.59	12,273	6.81	477.6		
	17-May-13	2.13							
	17-May-13	1.89							
	30-May-13	1.92	18.6	0.43	8,640	6.81	486		
	9-Jul-13	1.91	20.8	0.17	6,469	5.96	310.5		
	22-Jul-13	1.35	25.9	1.22	33,562	5.83	400		
	12-Aug-13	1.21	22.9	1.21	11,075	4.74	409		
	3-Oct-13	1.60	22.6	1.02	7,263	5.75	225.9	27.2	
	13-Feb-14	0.80	12.1	0.34	4,590	5.65	250.4	12.4	

Well	Date	Depth to Water (ft)	Temp. (°C)	DO (mg/L)	Sp. Conductance (µS/cm)	pH	ORP (mV)	Turbidity (NTU)	Sodium Persulfate (mg/L)
I-5	17-Oct-12		22.8	0.14	2,060	4.21	90.5		
	23-Apr-13	1.24	14.6	0.32	1,508	4.34	275.6		
	25-Apr-13	1.41	14.6	0.25	1,331	4.44	222		
	26-Apr-13		16.5	16.63	32,412	6.07	300		
	27-Apr-13		16.0	13.10	32,150	1.53	198		
	28-Apr-13	2.15	16.9	2.99	20,625	4.77	140.2		
	2-May-13	0.55	21.2	0.86	1,154	7.24	319.1		
	3-May-13	0.45	15.6	0.92	4,754	6.31	215.6		
	4-May-13	0.55	15.5	1.72	5,981	6.21	161.4		
	4-May-13	0.36							
	4-May-13	0.63	16.1	1.95	6,999	5.84	182.9		
	5-May-13	1.02	14.8	4.21	6,879	5.74	250.6	5.28	
	9-May-13	1.17	16.6	22.57	18,071	6.68	199.5		3000
	10-May-13		18.3	13.13	18,047	5.85	202.8		
	13-May-13	1.76	16.7	9.60	16,582	4.97			
	15-May-13	1.77	17.2	18.22	6,283	5.28	485		
	30-May-13	2.25	19.2	12.56	11,592	6.01	123.8		
	10-Jul-13	2.31	22.3	0.22	5,481	3.77	329.1		
	22-Jul-13	1.75	26.0	1.99	39,923	4.48	410		
	12-Aug-13	1.55	24.7	1.43	16,850	2.86	485.7		
	3-Oct-13	1.79	24.0	0.10	19,968	2.85	425.9	299	
	12-Feb-14	1.72	8.5	0.24	11,560	3.20	417.6	2721	
I-6	17-Oct-12		23.0	0.16	1,986	4.42	109.1	41.4	
	23-Apr-13	NA	14.9	0.21	1,695	4.16	361.3		
	25-Apr-13	1.45	15.1	0.21	1,437	4.32	248.4		
	25-Apr-13	0.61							
	25-Apr-13	0.59							
	25-Apr-13	0.79						12.4	
	25-Apr-13	0.91							
	25-Apr-13	0.78							
	25-Apr-13		15.0	0.72	1,945	4.30	309		
	28-Apr-13	2.05	16.6	10.03	28,608	6.17	204.1		
	9-May-13		16.5	16.17	26,250	7.26	179.7		
	10-May-13		16.5	11.11	24,233	6.82	176		
	13-May-13	1.65	16.6	6.24	20,623	6.49	538.1		
	16-May-13	1.27	17.3	1.24	9,122	3.88	562.3		1.4
	17-May-13	1.90							
	23-May-13	1.56	18.7	0.72	11,605	3.97	474.6		
	30-May-13	2.13	18.8	0.74	9,998	4.17	575		>700
	10-Jul-13	2.21	22.7	0.40	6,242	3.75	353.6		
	11-Jul-13	0.85	23.8	0.63	8,515	3.03	464.6		
	13-Jul-13		23.1	1.60	20,181	4.72	417		
	22-Jul-13		24.7		12,423	2.80	236.1		
	12-Aug-13	1.43	24.4	2.08	6,545	3.76	396		
	14-Aug-13	1.50	24.7	2.45	21,216	4.77	396.0		
	3-Oct-13	1.65	24.1	0.12	4,381	3.89	260.7	189	
	13-Feb-14	0.88	10.8	0.32	4,065	3.91	296.7	122	
I-7	5-May-13		15.1	8.38	39,938	8.12	261.4		
	13-May-13	1.80	16.1	27.63	28,290	7.07			
	17-May-13	2.03							
	30-May-13	2.15	18.8	18.85	15,034	7.30	385.2	827	
	10-Jul-13	2.00	21.5	0.43	5,761	6.49	91.2		
	22-Jul-13	1.71	23.7	2.19	22,700	6.07	100		
	3-Oct-13	1.82	21.4	0.22	7,749	6.24	115.8	197	
	13-Feb-14	0.85	10.4	0.41	3,853	6.25	106.3	1084	

<i>Well</i>	<i>Date</i>	<i>Depth to Water (ft)</i>	<i>Temp. (°C)</i>	<i>DO (mg/L)</i>	<i>Sp. Conductance (µS/cm)</i>	<i>pH</i>	<i>ORP (mV)</i>	<i>Turbidity (NTU)</i>	<i>Sodium Persulfate (mg/L)</i>
I-8	13-May-13	1.88	17.0	32.52	29,472	7.01	560		
	31-May-13	2.36	18.3	26.44	24,114	7.08	441.3		
	9-Jul-13	1.96	20.0	9.78	17,850	6.04	304.5		
	22-Jul-13	2.04	23.1	15.57	42,480	6.39	609		
	2-Oct-13	2.27	23.0	2.14	25,722	5.29	368.8	4.78	
	12-Feb-14	1.98	13.0	0.84	17,435	3.21	5.22	410	
I-9	2-May-13	1.16							
	2-May-13	1.04							
	13-May-13	1.90	16.9	19.90	14,334	6.56			
	31-May-13		18.5	14.99	17,515	6.85	532.7		
	9-Jul-13	2.23	21.9	6.95	7,209	5.13	183.6		
	22-Jul-13	1.60	24.2	1.07	40,085	5.82	604.5		
	2-Oct-13	2.06	24.2	6.80	7,817	6.18	108.3	221	
	13-Feb-14	0.80	12.1	3.79	3,340	6.20	249.2	78	
MW-1	17-Oct-12		20.8	0.15	9,962	3.41	381.3		ND
	11-Feb-14	1.71	13.1	0.22	9,026	3.43	619.2	14.9	
MW-2	17-Oct-12		22.6	0.07	1,956	6.28	-16.6		<0.7
	23-Apr-13	1.92	15.5	0.18	1,139	6.03	46.2		
	25-Apr-13	1.94							
	14-May-13	1.78	16.8	0.25	307	6.93	-29	2.44	
	10-Jul-13	2.50	21.2	0.20	4,126	4.79	262		
	13-Aug-13	1.61	23.1	0.22	405	6.20	176.3		
	2-Oct-13	2.30	22.3	0.07	9,800	2.90	563.4	20.9	
	11-Feb-14	1.95	11.5	0.35	845	6.82	380.7	16.1	
MW-3	17-Oct-12		22.7	6.61	8,045	3.40	446		
	13-Aug-13	1.55	22.8	0.53	7,999	3.82	350.9		
	2-Oct-13	2.15	22.3	0.45	8,593	3.24	525.3	12.2	
	13-Feb-14	1.10	14.2	2.51	7,720	3.56	583.7	146	56

Well	Date	Depth to Water (ft)	Temp. (°C)	DO (mg/L)	Sp. Conductance (µS/cm)	pH	ORP (mV)	Turbidity (NTU)	Sodium Persulfate (mg/L)
MW-2904	17-Oct-12		22.6	0.08	5,983	4.40	166.5		<1
	23-Apr-13	1.02	15.1	0.20	7,176	3.13	628		
	25-Apr-13	1.56							
	25-Apr-13	1.44	14.7	0.18	2,518	3.76	352.5		
	25-Apr-13	0.59							
	25-Apr-13	1.00							
	25-Apr-13	0.59							
	25-Apr-13		15.2	2.15	2,164	4.83	236		
	26-Apr-13		15.2	0.39	1,978	4.70	335		
	27-Apr-13		15.3	0.87	3,523	3.56	320		
	27-Apr-13		15.2	0.58	2,322	5.26	221		
	28-Apr-13	1.88	15.8	0.31	3,753	3.44	266.3		
	30-Apr-13		15.5	0.52	4,937	4.12	262		
	1-May-13	0.80	15.2	1.28	2,615	4.62	290		
	2-May-13	0.70							
	3-May-13		16.8	0.38	2,178	4.91	502.3		
	3-May-13		15.8	8.62	24,955	3.77	508.4		
	3-May-13	0.39	15.6	5.17	15,276	4.05	440.8	9.13	
	4-May-13	0.82	16.0	0.19	2,362	4.44	329.4		
	4-May-13	0.25	16.3	0.64	2,164	4.62	385.3		
	4-May-13	0.26	16.7	0.66	2,403	4.67	374.5		
	5-May-13	0.15	15.5	0.26	2,102	5.40	351.3		
	5-May-13		16.2	2.15	13,339	6.98	271.8		
	6-May-13	0.79	15.7	0.64	5,487	5.54	249		
	9-May-13		17.5	2.79	3,048	6.13	259.3		
	10-May-13	1.03	16.3	5.61	12,881	6.33	205.4		
	13-May-13	1.15	17.0	1.71	5,800	5.52	577		
	16-May-13	1.28	17.5	7.73	12,596	6.31	451.5		<0.7
	17-May-13	1.74							
	17-May-13	1.10	17.3	2.40	3,536	5.30	405.6		
	18-May-13	1.05	16.5	0.70	3,275	4.84	433		
	19-May-13		17.4	14.90	30,099	7.39	503		
	20-May-13	1.09	17.0	5.32	13,511	6.75	472		
	23-May-13		17.1	6.73	19,872	6.20	378.9		1000
	30-May-13		18.3	0.33	11,524	2.87	400.9		
	10-Jul-13	2.12	22.4	0.13	17,954	3.59	435.3		
	22-Jul-13	1.49	22.9		7,358	3.07	211.5		
	12-Aug-13	1.35	21.3	0.30	28,747	3.14	509.1		
	14-Aug-13	1.15	21.8	0.39	32,009	3.07	425.1		
	2-Oct-13	1.84	22.5	0.10	21,630	3.12	431.4	6.91	
	13-Feb-14	0.77	13.2	0.42	8,281	3.45	400.8	8.54	
DMW-2904	18-Oct-12		20.4	0.25	317	6.68	112.7		
MW-2905	18-Oct-12		18.6	0.09	7,704	5.22	171.9		
	12-Feb-14	4.19	8.8	0.81	6,892	6.19	89.5	42.3	
MW-2906	18-Oct-12		18.7	0.10	7,816	6.37	-58.6		
	12-Feb-14	2.95	9.4	0.58	9,173	6.53	9.4	46.1	

Well	Date	Depth to Water (ft)	Temp. (°C)	DO (mg/L)	Sp. Conductance (µS/cm)	pH	ORP (mV)	Turbidity (NTU)	Sodium Persulfate (mg/L)
U1	17-Oct-12		21.0	0.10	8,506	3.93	450.9		
	11-Dec-12	1.23	17.5	0.33	8,902	3.91	175.06		
	11-Dec-12	0.80	17.8	0.37	7,834	3.77	174.5		
	11-Dec-12	0.80	17.8	0.60	7,285	3.73	141		
	12-Dec-12	0.83	18.2	0.27	7,874	3.70	224		
	13-Dec-12		17.3	0.37	8,102	3.57	270.00		
	13-Dec-12		18.0	0.22	7,700	3.46	248.00		
	14-Dec-12		17.7	1.24	10,916	3.59	225.00		
	14-Dec-12		17.4	2.16	10,279	6.98	617.40		
	14-Dec-12		16.5	23.42	26,088	7.46	535.40		2100
	15-Jan-13	0.53	15.8	12.94	2,973	6.49	317.2		
	16-Jan-13	<0.4	15.5	0.10	11,973	4.33	199		
U2	5-May-13	-0.15	14.8	0.11	2,249	5.26	257.1		
	10-Feb-14	1.13	12.9	0.24	14,843	2.96	686.6	147	
	17-Oct-12		21.4	0.11	7,273	4.45	359.5		
	11-Dec-12	1.23	17.8	0.55	7,930	4.16	166.3	10.51	
	11-Dec-12	0.81	17.7	0.35	3,760	5.06	105.1	8.74	
	11-Dec-12	0.82	17.3	0.42	3,547	4.89	57.7		
	12-Dec-12	0.93	18.2	0.31	5,484	3.41	247		
	12-Dec-12	0.91	18.3	0.34	6,901	3.95	224		
	13-Dec-12		17.2	0.33	6,036	3.67	264.00		
	13-Dec-12		17.9	0.53	4,935	4.08	216.00	26.9	
U3	14-Dec-12		17.0	0.78	4,989	3.67	234.00		
	10-Feb-14	1.08	12.6	0.42	17,052	2.83	636	114	
	17-Oct-12		22.0	0.21	7,982	4.42	366.1		<0.7
	11-Dec-12		18.9	0.47	7,174	4.66	134.5		
	11-Dec-12	1.42							
	11-Dec-12	1.00	18.6	0.45	4,277	3.76	190.1		
	11-Dec-12	1.03	18.1	0.39	4,151	3.64	174.4		
	12-Dec-12	1.14	18.8	0.30	8,020	3.32	246		
	12-Dec-12	1.03	18.6	0.45	8,363	3.24	257		
	13-Dec-12		17.8	0.35	7,778	3.68	267.00		>700
	13-Dec-12		18.7	0.35	8,348	3.29	270.00		
	14-Dec-12		18.0	0.75	8,716	3.33	243.00		
	14-Dec-12		18.2	0.19	5,462	7.68	458.10		
	18-Dec-12		15.1	1.50	2,875	2.39	619.50		
	16-Jan-13	<0.4	14.0	0.34	3,876	4.44	484.8		
	10-Feb-14	1.32	13.0	0.32	14,427	2.70	676.4	95.2	

Well	Date	Depth to Water (ft)	Temp. (°C)	DO (mg/L)	Sp. Conductance (µS/cm)	pH	ORP (mV)	Turbidity (NTU)	Sodium Persulfate (mg/L)
U4	17-Oct-12		22.2	0.10	6,823	4.24	357.8		<1
	11-Dec-12	1.68						NR	
	11-Dec-12	1.32	18.7	0.42	2,981	4.40	449.2		
	11-Dec-12	1.30	18.2	0.35	2,374	4.32	433.3		
	12-Dec-12	1.42	18.0	0.32	4,533	3.25	254	33.7	
	12-Dec-12	1.27	18.6	0.36	4,936	3.33	245		
	13-Dec-12		18.0	0.62	10,008	3.08	310.00	83.1	7000
	13-Dec-12		18.7	0.22	4,060	3.91	231.00		
	14-Dec-12		18.0	0.60	4,871	3.26	250.00		
	14-Dec-12		18.1	0.21	3,597	7.95	298.50		
	18-Dec-12		15.1	2.82	2,278	2.38	426.30		
	16-Jan-13	0.86	15.5	0.12	7,779	3.98	440.5		
	24-Apr-13	1.15	15.9	0.19	5,709	6.16	158.2		
	25-Apr-13	1.55	15.2	0.16	4,870	3.14	293		
	25-Apr-13	0.96							
	25-Apr-13	0.96							
	25-Apr-13		14.3	0.56	4,114	3.17	259		
	26-Apr-13		15.2	0.29	1,966	3.54	328		
	27-Apr-13		15.0	0.66	2,891	4.24	217		
	28-Apr-13	1.91	16.2	2.30	2,953	3.91	203.8		
	5-May-13	0.25	15.8	0.34	12,848	4.79	286.4		
	6-May-13	0.81	15.6	1.09	5,530	3.45	345		
	10-May-13		16.1	0.74	8,065	3.55	263.6		
	13-May-13	1.65	15.3	1.27	6,848	3.12	603		
	16-May-13		17.5	3.74	4,862	3.72	505.5		
	17-May-13	1.81							
	17-May-13	1.21	17.2	2.99	11,989	4.24	547.5		
	18-May-13	1.17	16.4	2.42	7,206	2.96	520		
	19-May-13		17.3	6.93	22,563	3.25	547		
	20-May-13	1.15	17.5	2.40	14,025	3.22	466		
	23-May-13	1.69							
	24-May-13	1.28	16.4	1.36	8,565	3.21	383		
	30-May-13	1.93	17.8	0.28	6,880	3.90	321.8		
	9-Jul-13	2.16	20.5	0.23	10,516	3.18	535.2		
	13-Jul-13	1.22	19.7	2.97	10,840	3.31	553		
	12-Aug-13	1.42	21.6	0.32	9,499	2.93	624.1		
	14-Aug-13	1.28	22.2	0.36	7,584	2.90	418.0		
	2-Oct-13	1.90	22.4	0.07	9,521	2.66	563.7	127	
	11-Feb-14	1.72	12.3	0.26	8,711	3.00	705	136	

<i>Well</i>	<i>Date</i>	<i>Depth to Water (ft)</i>	<i>Temp. (°C)</i>	<i>DO (mg/L)</i>	<i>Sp. Conductan ce (µS/cm)</i>	<i>pH</i>	<i>ORP (mV)</i>	<i>Turbidity (NTU)</i>	<i>Sodium Persulfate (mg/L)</i>
U5	17-Oct-12		22.5	1.13	7,271	3.62	490.5		
	18-Dec-12		15.3	11.53	1,735	7.77	308.50	5.65	
	24-Apr-13	1.01	16.7	14.07	5,874	3.64	288.1		
	25-Apr-13	1.35	16.2	17.67	5,723	3.73			
	26-Apr-13		15.3	17.71	2,078	4.70	418		
	27-Apr-13		15.4	19.75	3,697	4.45	322		
	2-May-13	0.84							
	2-May-13	0.77						10.25	
	2-May-13	0.70						12	
	3-May-13	0.42	15.6	5.17	15,276	4.05	440.8		
	4-May-13	0.75	15.5	6.75	6,980	3.89	373.6		
	4-May-13	0.20							
	4-May-13	0.28	15.9	6.66	18,736	7.25	324.1		
	5-May-13	0.20	15.9	3.96	20,468	7.52	295		
	6-May-13	0.70	15.7	3.32	3,944	5.25	309		
	9-May-13	0.80							
	10-May-13	1.07	16.6	14.86	8,612	5.12	287.7		
	13-May-13	1.50	16.3	19.84	7,600	3.89	676		
	16-May-13		17.5	22.11	7,340	6.12	492.1		
	17-May-13	1.69							
	17-May-13		17.5	23.58	5,463	6.25	511.4		
	18-May-13	1.08	16.8	17.13	6,593	5.34	535		
	19-May-13	0.53	18.3	16.55	32,302	7.64	565		
	20-May-13	1.12	17.6	13.27	17,289	6.84	492	42.1	
	23-May-13	1.58							
	24-May-13		17.4	20.94	12,039	6.11	404		
	31-May-13	1.89	18.2	17.06	10,762	5.53	477.8		
	9-Jul-13	1.90	20.6	5.35	18,314	5.42	296.7		
	13-Jul-13	0.71	20.3	17.22	24,669	5.75	414		
	22-Jul-13		22.2	12.26	30,462	5.89	586		
	13-Aug-13	1.17	22.2	3.31	24,923	5.21	435.8		
	14-Aug-13	1.12	23.2	12.67	25,511	4.88	460.0		70
	2-Oct-13	1.70	23.0	4.57	15,545	5.76	331.8	8.98	
	13-Feb-14	0.65	12.8	3.35	6,300	5.36	325.2	26.4	

Well	Date	Depth to Water (ft)	Temp. (°C)	DO (mg/L)	Sp. Conductance (µS/cm)	pH	ORP (mV)	Turbidity (NTU)	Sodium Persulfate (mg/L)
U6	17-Oct-12		22.7	6.58	4,068	4.51	205.9		
	12-Dec-12	1.01	19.1	1.20	5,048	3.85	221		
	13-Dec-12		18.7	0.93	3,329	5.42	200.00		1400
	13-Dec-12		18.3	0.93	3,123	4.84	208.00		
	14-Dec-12		18.8	2.77	5,307	5.10	200.00		
	14-Dec-12		18.5	14.11	5,938	7.24	610.50		
	18-Dec-12		15.1	17.28	1,433	7.87	320.70		
	15-Jan-13	0.78	16.6	3.96	4,867	5.05	294.7		
	24-Apr-13	1.13	16.2	10.79	3,693	5.11	207.2		
	25-Apr-13	1.51	15.2	18.77	3,248	4.98	350.6		
	26-Apr-13		15.2	16.00	1,982	4.81	407		
	2-May-13	1.13							
	4-May-13	0.95	15.4	4.86	4,181	4.53	342.6		
	4-May-13	0.47							
	4-May-13	0.52	16.6	7.51	5,662	4.71	362.1		
	5-May-13	0.47	16.0	1.48	10,132	5.08	300.5		
	6-May-13	0.92	15.7	1.81	5,280	4.30	305		
	10-May-13		16.2	9.20	4,909	4.97	274		
	13-May-13	1.78	16.4	16.30	3,633	5.07	631		
	16-May-13		17.1	19.43	3,071	4.87	540		
	17-May-13	2.00	17.4	11.47	5,698	5.31	511.9		
	18-May-13	1.27	16.7	12.62	6,470	5.14	516		
	19-May-13	1.15	17.5	11.69	15,905	6.75	555		
	20-May-13	1.20	17.2	11.20	7,323	5.84	487	29.6	
	23-May-13	1.76							
	24-May-13	FLOODED	16.9	16.40	5,789	5.05	384.3		
	31-May-13	2.13	17.7	11.47	5,084	5.47	460.4	59.6	
	10-Jul-13	2.25	20.6	4.41	12,776	5.67	295.3		
	13-Jul-13		19.7	9.11	19,105	5.49	366		
	13-Aug-13	1.40	23.1	8.73	14,415	5.56	339.4		
	14-Aug-13	1.39	22.7	12.48	15,981	5.69	461.9		
	2-Oct-13	1.86	23.4	4.87	6,052	5.19	280.5	5.31	
	11-Feb-14	1.60	13.6	4.29	5,634	4.84	522.1	22.1	
U7	18-Oct-12		22.4	12.70	2,856	4.22	196.9		
	12-Dec-12	1.75	18.9	0.84	3,224	3.98	220		
	13-Dec-12		18.6	1.91	2,602	6.47	199.00		
	13-Dec-12		18.5	1.30	2,824	4.83	213.00		
	14-Dec-12		18.7	3.71	6,663	3.61	228.00		
	14-Dec-12		18.2	11.41	5,453	7.35	653.20		
	15-Jan-13	0.79	15.9	12.54	3,436	4.91	349.1		
	11-Feb-14	1.59	13.6	1.16	8,162	3.62	550.5	148	

<i>Well</i>	<i>Date</i>	<i>Depth to Water (ft)</i>	<i>Temp. (°C)</i>	<i>DO (mg/L)</i>	<i>Sp. Conductance (µS/cm)</i>	<i>pH</i>	<i>ORP (mV)</i>	<i>Turbidity (NTU)</i>	<i>Sodium Persulfate (mg/L)</i>
U8	18-Oct-12		22.2	7.90	1,091	5.05	168		
	12-Dec-12	1.63	18.8		2,627	3.94	210		
	13-Dec-12		18.4	0.60	4,418	5.88	213.00		
	13-Dec-12		18.2	0.36	3,833	5.80	216.00		
	14-Dec-12		18.3	1.37	4,849	3.92	206.00		
	14-Dec-12		17.7	2.70	2,963	7.60	586.30		1.4
	16-Jan-13	0.78	13.8	8.51	1,182	5.27	435		
	27-Apr-13		15.2	1.82	3,630	3.43	260		
U9	11-Feb-14	1.73	12.6	6.94	2,239	4.56	654.7	161	
	18-Oct-12		21.9	2.74	3,297	4.88	165.9		
	12-Dec-12	1.78	18.8	0.52	3,625	4.71	258		
	12-Dec-12		18.7	0.50	3,643	4.95	201		
	12-Dec-12	1.66	18.7						
	12-Dec-12	1.39	18.6	0.31	3,504	4.45	187		
	12-Dec-12	1.15							
	12-Dec-12	1.13							
	13-Dec-12		18.0	0.40	3,758	5.09	206.00		
	13-Dec-12		18.2	0.52	3,292	6.85	183.00	44.6	
	14-Dec-12		17.0	1.95	3,717	6.60	167.00		
	14-Dec-12		16.9	4.36	3,843	7.97	577.90		
	18-Dec-12		15.0	11.68	1,381	7.82	402.60		
	16-Jan-13	0.48	15.6	2.12	3,705	5.86	300.1		
	5-May-13	0.25	15.7	1.00	4,829	5.91	340.7		
U10	10-May-13		18.8	20.50	1,236	5.83	275		
	10-Feb-14	1.58	12.9	2.17	4,539	4.40	617.9	49.2	
	18-Oct-12		22.2	9.55	2,037	4.87	131.9		
	12-Dec-12	1.87	18.3	0.62	2,104	4.93	175		
	12-Dec-12	1.71							
	12-Dec-12	1.44	18.5	0.66	2,777	4.46	165		
	12-Dec-12	1.25							
	12-Dec-12	1.26							
	13-Dec-12		17.0	2.22	13,555	5.22	207.00		
	13-Dec-12		17.0	1.33	11,420	6.40	198.00		
	14-Dec-12		16.8	6.37	5,992	5.83	177.00		
	14-Dec-12		16.4	14.69	6,447	7.92	556.70	801	
	18-Dec-12		15.1	16.09	1,152	7.81	264.40	5.9	
U10	16-Jan-13	0.69	15.3	11.62	2,208	6.15	236.2		
	11-Feb-14	1.67	12.1	5.21	2,239	4.96	610	134	

Well	Date	Depth to Water (ft)	Temp. (°C)	DO (mg/L)	Sp. Conductance (µS/cm)	pH	ORP (mV)	Turbidity (NTU)	Sodium Persulfate (mg/L)
U11	17-Oct-12		23.1	1.88	2,966	5.04	117		
	12-Dec-12	1.69	18.5	0.33	2,747	4.88	479		
	12-Dec-12	1.62							
	12-Dec-12	1.29	18.7	0.42	2,545	4.73	474		
	12-Dec-12	1.09							
	12-Dec-12	1.09							
	13-Dec-12		17.9	0.84	4,526	5.70	199.00		
	13-Dec-12		17.0	1.13	16,746	5.59	218.00		
	14-Dec-12		17.2	6.21	12,940	5.85	177.00		
	14-Dec-12		16.7	11.24	10,820	7.68	550.10		
	18-Dec-12		15.9	11.50	2,965	7.75	484.00		
	23-Apr-13		14.7	14.67	2,824	5.75	232		
	26-Apr-13		15.2	12.65	2,153	5.42	357		
	2-May-13	0.88							
	4-May-13	0.81	15.4	1.57	2,157	6.58	223.6		
	4-May-13	0.33							
	4-May-13	0.43	15.8	4.60	2,298	6.17	301.1		
	5-May-13	0.25	15.4	0.71	2,874	6.34	303.4		
	10-May-13		19.3	4.00	4,045	6.26	142.1		
	13-Jul-13	1.25	21.1	19.03	4,001	5.35	440		
	13-Aug-13	1.10	22.8	4.66	4,105	4.87	222.2		
	14-Aug-13	1.30	22.8	5.27	6,348	4.87	67.9		
	2-Oct-13	1.68	23.7	1.62	4,370	5.10	201.7	8.73	
U12	11-Feb-14	1.44	13.1	1.36	3,462	5.38	268.2	11.2	
	17-Oct-12		21.7	1.26	3,909	5.00	159.4		
	14-Dec-12		17.6	1.71	4,342	7.36	162.50		
	23-Apr-13		14.0	0.57	5,386	3.34	661.4		
	28-Apr-13	1.44	16.1	3.33	2,165	4.88	115.4		
	3-May-13	<0	15.4	1.57	2,157	6.58	223.6		
	4-May-13	0.16	14.5	1.28	2,833	4.72	261.8		
	4-May-13	-0.07							
	4-May-13	0.10	15.1	1.04	3,727	5.25	177.3		
	5-May-13	-0.14	15.1	0.55	3,974	5.55	196		
	6-May-13	0.37	14.8	0.77	5,281	4.07	240		
	8-May-13		16.0	2.22	6,212	4.31	134.9		
	10-May-13	0.73	17.5	5.38	4,212	6.06	286		
	14-May-13	1.25	15.0	2.81	6,930	4.66	666		
	16-May-13	0.92	15.7	4.92	9,804	4.35	408.2		
	17-May-13	0.93	16.1	6.22	2,630	4.60	599.7		
	18-May-13	0.65	16.0	4.35	4,700	7.10	498		
	23-May-13	1.05	17.1	7.28	10,728	6.00	295.7		350
	30-May-13	1.65	16.8	1.40	11,032	6.17	311.1		
	10-Jul-13	1.69	19.9	0.30	8,264	5.69	263.9		
	22-Jul-13		21.5	0.65	12,770	4.92	366		
	2-Oct-13	1.15	21.7	0.40	12,557	5.74	459.3	28.6	
	10-Feb-14	1.13	12.8	0.30	8,179	5.15	447.3	20.2	

Well	Date	Depth to Water (ft)	Temp. (°C)	DO (mg/L)	Sp. Conductance (µS/cm)	pH	ORP (mV)	Turbidity (NTU)	Sodium Persulfate (mg/L)
U13	17-Oct-12		21.8	0.26	5,002	5.71	43.4		
	11-Dec-12		17.9	0.27	4,124	5.27	198.3		
	11-Dec-12	1.38							
	11-Dec-12	0.97	18.1	1.10	3,493	5.80	12.4		
	11-Dec-12	0.94	17.6	0.46	3,363	5.12	92.6	79.2	
	11-Dec-12	0.58	17.8	0.35	4,572	3.26	225	169	
	12-Dec-12	1.25	17.7	0.27	5,292	2.86	278		
	12-Dec-12	1.00	17.8	0.28	4,931	2.91	270		
	13-Dec-12		16.8	0.52	6,017	2.71	327.10		
	13-Dec-12		18.0	0.22	4,487	3.02	280.00		
	14-Dec-12		17.2	0.96	6,199	2.77	274.00		
	14-Dec-12		17.2	0.30	5,875	8.22	826.60		
	14-Dec-12		16.3	0.38	9,135	7.25	698.10		
	18-Dec-12		16.0	1.76	6,685	8.08	574.80		
	16-Jan-13	<0.4		7.60		5.84	345		
	26-Apr-13		14.7	5.32	3,328	4.60	333		
	27-Apr-13		14.4	0.42	5,002	4.49	181		
	3-May-13		15.4	4.86	4,181	4.52	342.6		
	5-May-13	0.00	15.0	0.17	4,753	5.05	271.7		
	10-May-13	0.90	15.7	0.35	6,727	3.92	245.1		
	14-Aug-13	0.92	21.8	0.22	5,660	2.98	580.8		
	10-Feb-14	1.27	12.5	0.26	7,351	3.36	744.2	34.9	
U14	17-Oct-12		21.9	0.29	5,258	5.81	21.2		
	11-Dec-12		17.9	0.25	4,746	5.75	404	102	
	11-Dec-12		18.9	0.43	6,514	4.84	112.2		
	11-Dec-12	1.25							
	11-Dec-12	0.78	17.7	1.06	3,764	5.35	92.1		
	11-Dec-12	0.70	17.8	0.31	5,557	3.24	232		
	12-Dec-12	1.10	17.8	0.50	23,671	2.23	311		
	12-Dec-12	0.94	18.0	0.44	24,064	2.23	303		
	13-Dec-12		15.6	0.83	22,150	2.30	354.10	36.2	
	13-Dec-12		17.5	0.65	22,106	2.62	315.00	24.4	
	14-Dec-12		17.4	3.13	25,061	2.60	326.00		
	14-Dec-12		17.2	1.59	19,581	8.03	626.00		<700
	14-Dec-12		16.6	0.90	17,169	7.23	653.60		
	18-Dec-12		15.2	2.62	8,665	8.22	648.80		
	16-Jan-13	<0.4	13.9	0.31	5,187	3.48	412.3		
	10-Feb-14	1.10	12.5	0.26	6,283	3.39	534.2	89.6	

<i>Well</i>	<i>Date</i>	<i>Depth to Water (ft)</i>	<i>Temp. (°C)</i>	<i>DO (mg/L)</i>	<i>Sp. Conductan ce (µS/cm)</i>	<i>pH</i>	<i>ORP (mV)</i>	<i>Turbidity (NTU)</i>	<i>Sodium Persulfate (mg/L)</i>
U15	17-Oct-12		22.4	0.27	5,711	5.97	87.1	1695	
	11-Dec-12		16.9	0.43	3,506	5.77	68.4	56.6	
	11-Dec-12	1.39							
	11-Dec-12	1.49							
	11-Dec-12	1.05							
	11-Dec-12	1.03							
	11-Dec-12	0.85	18.4	1.86	5,287	3.24	208		
	11-Dec-12	0.90	16.7	0.38	3,810	3.17	197.7		
	11-Dec-12	0.75	17.0	0.37	3,848	3.05	245		
	12-Dec-12	1.26	18.0	1.83	30,761	2.99	314		
	12-Dec-12	1.12	18.1	1.03	31,090	4.40	244		
	13-Dec-12		17.7	1.58	28,900	3.02	319.20		
	13-Dec-12		18.1	1.60	32,300	5.47	250.00		
	14-Dec-12		17.0	3.82	20,187	3.25	385.50		
	14-Dec-12		17.1	10.53	14,780	8.07	531.80		
	14-Dec-12		16.8	15.38	4,422	7.49	535.10		
	18-Dec-12		15.0	2.58	10,307	2.25	615.70		
	16-Jan-13	<0.4	15.2	0.10	7,985	4.81	168.9		
	23-Apr-13		14.4	0.42	6,067	4.08	445		
	26-Apr-13		15.1	0.48	351	3.82	363		
	27-Apr-13		14.9	0.56	4,530	4.38	215		
	27-Apr-13		15.3	0.65	3,674	4.67	229		
	5-May-13	0.02	15.6	0.29	4,714	5.60	218.9		
	10-May-13	0.90	15.9	0.51	6,036	4.64	218.5		
	13-Jul-13	0.75	19.5	1.13	6,981	3.43	371		
	2-Oct-13	1.60	21.9	0.07	9,379	2.76	597.5	143	
	10-Feb-14	1.31	13.1	0.16	7,057	2.95	615.8	209	

Well	Date	Depth to Water (ft)	Temp. (°C)	DO (mg/L)	Sp. Conductance (µS/cm)	pH	ORP (mV)	Turbidity (NTU)	Sodium Persulfate (mg/L)
U16D	17-Oct-12		22.5	0.80	7,189	3.48	435.1		200
	11-Dec-12		18.7	0.45	6,934	3.80	294		
	11-Dec-12		18.9	0.55	5,389	4.02	430		
	11-Dec-12		18.4	0.39	5,784	3.46	497		
	11-Dec-12		18.6	0.37	5,292	4.33	469		
	12-Dec-12		18.8	0.42	6,066	3.49	257		
	12-Dec-12	1.07	18.4	0.36	5,903	3.35	244.00		
	13-Dec-12		17.7	0.33	5,855	3.38	291.00		1400
	13-Dec-12		18.7	0.23	5,281	3.92	242.00		
	14-Dec-12		18.4	1.17	6,302	3.62	242.00		
	14-Dec-12		18.2	0.47	5,940	7.94	527.50	30	
	14-Dec-12		15.6	0.86	5,671	7.26	560.70		7000
	16-Jan-13	NA	15.2	0.12	9,183	3.90	502		
	23-Apr-13		15.0	12.21	8,449	2.91	670.6		
	25-Apr-13	NA	14.8	0.31	8,160	3.08	302		
	25-Apr-13	NA	14.3	0.40	6,360	3.12	313		
	26-Apr-13	NA	15.3	4.03	15,412	2.92	445		
	27-Apr-13	NA	15.5	6.20	18,431	3.61	348		
	27-Apr-13	NA	15.3	5.57	18,470	4.70	315		
	28-Apr-13	NA	15.6	5.63	20,507	6.01	204.5		
	30-Apr-13	NA	15.9	4.20	11,652	4.16	262		
	1-May-13	NA	15.2	3.95	19,643	3.67	339		
	2-May-13	NA	16.2	3.80	18,951	5.31	591.8		
	3-May-13	NA	15.7	0.88	12,956	4.07	278.4		
	4-May-13	NA	15.7	0.75	16,658	4.42	336.2	16.2	
	5-May-13	NA	15.7	0.50	14,625	4.21	223.7		
	6-May-13	NA	15.5	0.86	14,980	3.56	333		
	10-May-13	NA	16.3	4.49	18,661	4.64	257.7		
	13-May-13	NA	16.3	2.22	15,146	3.14	623		
	16-May-13	NA	16.5	6.39	21,143	3.13	397.4		2100
	18-May-13	NA	16.4	7.22	17,702	3.03	587		
	18-May-13	NA	16.9	5.06	18,481	3.17	630		
	30-May-13	NA	17.8	0.70	16,452	5.61	245.9		
	9-Jul-13		20.6	0.18	12,454	3.64	416	10.15	
	13-Jul-13		19.4	0.68	16,815	3.39	262		
	22-Jul-13		21.7	0.85	19,100	2.89	405		
	12-Aug-13	NA	21.1	0.47	18,284	3.27	502.1		
	14-Aug-13	NA	24.0	1.19	25,241	3.02	484.3		
	3-Oct-13	NM	22.2	0.15	17,900	2.84	439.2	10.9	
	12-Feb-14	NM	12.8	0.21	16,305	3.08	584	131	

Well	Date	Depth to Water (ft)	Temp. (°C)	DO (mg/L)	Sp. Conductance (µS/cm)	pH	ORP (mV)	Turbidity (NTU)	Sodium Persulfate (mg/L)
U16S	17-Oct-12		23.1	0.17	672	6.65	130.2		210
	11-Dec-12		17.3	0.19	3,890	5.41	206.1		
	11-Dec-12	1.21	16.0	0.52	5,744	5.33	23.4		
	11-Dec-12		16.2	0.43	6,029	4.86	110.2		
	11-Dec-12	1.01	16.8	0.46	5,887	5.02	116		
	12-Dec-12	1.28	16.1	0.47	5,241	4.05	227		
	12-Dec-12		16.3	0.39	4,551	4.54	192		
	13-Dec-12		15.8	0.33	5,132	4.35	215.00		
	13-Dec-12		16.8	0.32	6,002	5.73	214.00		
	14-Dec-12		16.2	1.02	5,382	4.16	170.00		350
	14-Dec-12		15.9	2.38	4,932	7.23	127.10		
	25-Apr-13	1.45	15.1	0.41	1,220	5.73	167		
	25-Apr-13	0.72							
	25-Apr-13	0.77							
	25-Apr-13	0.77							
	25-Apr-13	0.63							
	25-Apr-13		15.3	0.43	1,273	5.77	175		
	26-Apr-13		15.2	0.65	1,407	5.76	281	91	
	27-Apr-13		15.3	0.93	1,448	2.67	250		
	27-Apr-13		15.6	1.18	1,391	6.13	219		
	28-Apr-13	1.67	15.4	0.60	1,433	6.14	140.1		
	30-Apr-13		15.8	0.83	1,393	6.19	140	22	0.7
	2-May-13	0.73	15.4	0.67	1,205	7.25	352.2		
	3-May-13		16.0	0.38	1,070	6.46	255.5		
	4-May-13	0.31	15.7	0.35	1,284	7.13	232.4	13.1	1.4
	5-May-13	0.10	16.1	0.57	1,283	7.02	249.4		
	6-May-13	0.68	15.6	1.09	1,556	6.56	291	652 (AU)	
	10-May-13		16.6	0.23	1,315	6.98	196.2		
	13-May-13	1.37	16.3	0.48	1,229	6.64	-7.2		
	16-May-13	1.98	17.1	1.10	1,324	6.60	52.7		
	17-May-13	1.62							
	18-May-13		16.9	0.59	1,284	7.07	302		
	19-May-13	0.15	18.2	1.46	1,076	7.14	456		
	23-May-13	1.49	18.5	0.30	1,462	6.70	229.5		
	30-May-13	1.84	18.7	0.24	1,090	6.60	119.1		
	9-Jul-13	1.96	21.9	0.10	981	6.84	97.3		ND
	13-Jul-13	0.69	24.7	4.97	29	6.01	435		
	22-Jul-13	1.15	25.4	1.11	2,470	5.99	423		
	12-Aug-13	1.21	23.2	3.93	1,279	6.21	145		
	14-Aug-13	1.06	24.9	0.79	1,503	5.50	97.0	5.37	
	3-Oct-13	0.80	23.5	0.16	1,380	6.30	-158	3.42	
	12-Feb-14		9.4	0.23	1,042	6.95	56.4	20.8	
	1-May-13		15.4	1.51	1,111	6.95	232		

Well	Date	Depth to Water (ft)	Temp. (°C)	DO (mg/L)	Sp. Conductance (µS/cm)	pH	ORP (mV)	Turbidity (NTU)	Sodium Persulfate (mg/L)
U17D	17-Oct-12		21.4	2.35	7,642	3.34	523.5		4.2
	11-Dec-12		18.3	0.96	6,723	4.40	433.8		
	12-Dec-12		18.4	0.27	7,044	3.19	220		
	13-Dec-12		17.9	0.25	6,809	3.41	265.00		
	14-Dec-12		18.2	0.48	6,943	3.42	231.00		
	23-Apr-13		14.8	15.97	9,625	2.93	686.9		
	25-Apr-13	NA	14.4	0.54	8,412	3.16	377.8		
	25-Apr-13	NA	14.7	0.35	2,052	5.62	213.9		
	26-Apr-13	NA	15.0	9.36	24,547	5.05	373		
	27-Apr-13	NA	15.2	8.50	22,170	6.39	253		
	27-Apr-13	NA	15.0	12.04	27,016	6.77	257		
	28-Apr-13	NA	15.7	10.16	29,460	6.92	202.4		
	30-Apr-13	NA	15.3	5.63	24,310	6.76	250	6.8	
	1-May-13	NA	15.1	7.16	24,825	6.81	262		
	2-May-13	NA	15.7	6.67	25,308	6.88	456		
	3-May-13	NA	15.8	1.79	1,441	6.96	471		
	3-May-13	NA	15.3	0.70	895	5.73	254.3		
	4-May-13	NA	14.8	3.61	19,832	5.53	302.2	4.2	
	4-May-13	NA	15.6	3.16	26,486	7.15	265.5		
	5-May-13	NA	15.5	1.21	20,457	6.61	259.3		
	6-May-13	NA	15.1	1.86	19,756	6.34	288	53.9	
	9-May-13	NA	15.8	17.48	20,425	6.50	283.9		
	10-May-13	NA	16.2	15.37	19,768	6.49	259.3		
	13-May-13	NA	15.4	14.15	18,594	6.25	573		
	16-May-13	NA	16.2	10.98	19,169	6.17	479.4		
	17-May-13	NA	17.1	12.06	23,008	6.49	488.9		
	18-May-13	NA	16.9	16.03	29,321	7.28	509		
	19-May-13	NA	17.6	15.21	32,470	7.35	500		
	20-May-13	NA	18.2	2.77	1,139	6.48	465		
	23-May-13	NA	18.6	13.89	22,160	6.87	263.7		
	30-May-13	NA	17.9	0.62	20,278	6.32	404		
	9-Jul-13		19.5	0.20	13,276	4.00	361.7		<0.7
	11-Jul-13		19.1	0.56	13,170	4.07	252.8		
	13-Jul-13		20.1	5.57	21,184	4.25	374		
	22-Jul-13		20.7	0.80	231,479	4.96	469		
	12-Aug-13	NA	23.1	0.30	18,022	4.41	402.6		
	14-Aug-13	NA	22.7	5.20	33,539	6.26	419.4	29.1	
	3-Oct-13	NM	21.4	0.12	16,519	3.70	369.4	7.23	
	11-Feb-14		12.1	0.18	13,808	3.34	592	115	

Well	Date	Depth to Water (ft)	Temp. (°C)	DO (mg/L)	Sp. Conductance (µS/cm)	pH	ORP (mV)	Turbidity (NTU)	Sodium Persulfate (mg/L)
U17S	17-Oct-12		22.3	0.39	666	7.08	181.8		
	11-Dec-12	1.48							
	11-Dec-12	1.05	16.2	1.73	7,334	7.88	-61	20.4	
	12-Dec-12	14.86	16.4	0.31	7,097	4.73	174		
	13-Dec-12		15.6	0.30	7,050	5.11	220.00		
	14-Dec-12		16.1	0.57	7,015	4.97	185.00		
	25-Apr-13	1.35	14.4	0.47	1,366	5.72	237		
	25-Apr-13	0.68							
	25-Apr-13	0.73							
	25-Apr-13	0.71						73.7	
	25-Apr-13	0.60							
	25-Apr-13		14.6	0.97	10,225	2.99	321		
	26-Apr-13		14.7	2.20	1,502	6.25	293		
	27-Apr-13		14.7	2.00	1,461	6.65	199	14	
	27-Apr-13		15.0	1.62	1,707	6.78	192	47.6	
	28-Apr-13	1.71	16.2	1.33	1,280	6.72	164.3		
	30-Apr-13		15.4	1.33	1,121	6.79	168.2		
	1-May-13		16.1	3.32	986	6.93	211		
	2-May-13	0.69	15.7	1.12	1,393	6.90	185.5		
	3-May-13		15.8	0.64	1,380	6.54	417		
	3-May-13	0.17	15.6	0.43	2,983	5.80	222.4		
	4-May-13	0.25	15.7	0.24	1,323	6.69	222.4		
	4-May-13	0.05							
	4-May-13	0.33	15.9	0.29	132	6.86	211.6		
	5-May-13	0.25	15.8	0.54	1,172	6.73	162.3		
	6-May-13	0.65	15.5	0.58	1,111	6.67	239.3	4	
	9-May-13		16.2	1.70	1,464	6.59	251		
	10-May-13		16.1	0.22	1,514	6.61	175.8		
	13-May-13	1.46	16.0	0.32	1,255	6.75	-11		
	16-May-13	0.98	16.4	0.40	1,174	6.67	-92.7		
	17-May-13	1.60							
	17-May-13	1.15	17.3	0.31	1,240	6.63	-52.2		
	18-May-13	0.95	17.0	2.89	1,793	7.20	420		
	18-May-13						420		
	19-May-13	0.18	17.3	2.86	1,837	6.87	494		
	20-May-13	0.43	17.3	3.39	22,161	2.93	668		
	23-May-13	1.32	18.2	0.16	1,510	6.71	110.6		
	30-May-13	1.91	18.3	0.28	1,229	6.60	110.9		
	9-Jul-13	1.79	21.6	0.09	1,061	6.66	-92.3		
	11-Jul-13	1.22	21.3	0.30	1,284	6.24	0.7		
	13-Jul-13								
	22-Jul-13	1.00	23.7	0.71	3,076	5.45	213		
	12-Aug-13	1.05	23.8	0.30	1,920	6.66	-13.7	21.5	
	14-Aug-13		23.2	0.15	2,400	6.49	-43.2		
	3-Oct-13	1.54	22.5	0.15	2,038	6.15	-150.4	5.31	
	11-Feb-14	1.45	9.0	0.19	868	7.03	-51	8.92	

Well	Date	Depth to Water (ft)	Temp. (°C)	DO (mg/L)	Sp. Conductance (µS/cm)	pH	ORP (mV)	Turbidity (NTU)	Sodium Persulfate (mg/L)
U18D	17-Oct-12		22.6	0.66	5,272	4.05	240		
	13-Dec-12		18.5	0.25	3,980	5.37	209.00		
	14-Dec-12		18.5	0.77	5,712	4.40	493.00		
	23-Apr-13		15.1	0.67	5,574	3.40	612.9		
	25-Apr-13	NA	14.6	0.75	3,769	3.88	376		
	25-Apr-13	NA	15.5	0.27	695	5.73	234		
	26-Apr-13	NA	15.0	5.45	3,726	8.20	388		
	27-Apr-13	NA	15.2	0.98	5,267	4.19	280		
	27-Apr-13	NA	15.0	1.04	4,313	4.48	288		
	28-Apr-13	NA	15.8	1.05	6,176	5.14	278.3		
	30-Apr-13	NA	15.4	0.85	6,883	4.64	258		
	3-May-13	NA	15.6	1.38	7,880	4.22	481		
	3-May-13	NA	15.1	0.65	9,993	3.67	279.3		
	4-May-13	NA	15.2	0.76	15,592	3.61	365.8		
	4-May-13	NA	15.9	0.43	12,011	4.34	310.3		
	6-May-13	NA	15.5	0.60	11,166	3.63	306		
	8-May-13	NA	16.4	2.08	9,500	3.51	276		
	9-May-13	NA	16.5	1.12	10,060	4.85	345.7		
	13-May-13	NA	16.0	1.63	4,311	3.41	622		
	16-May-13	NA	16.4	1.47	13,231	3.86	607.2		
	17-May-13	NA	17.0	1.06	14,354	4.00	579.5		
	23-May-13	NA	19.3	0.69	14,703	3.49	400.9		2.1
	30-May-13	NA	17.8	0.24	14,424	3.86	472.6		
	10-Jul-13		20.6	0.28	8,948	3.46	488.1		
	11-Jul-13		20.7	0.98	11,216	3.41	398.4		
	22-Jul-13		23.1	0.44	14,430	2.56	449		
	12-Aug-13	NA	21.6	0.31	11,815	3.26	478.9		
	14-Aug-13	NA	22.1	0.59	22,207	2.80	415.5		
	3-Oct-13	NM	22.8	0.12	12,420	3.03	453.2	8.91	
	12-Feb-14		12.2	0.23	7,214	3.63	538.7	10	

Well	Date	Depth to Water (ft)	Temp. (°C)	DO (mg/L)	Sp. Conductance (µS/cm)	pH	ORP (mV)	Turbidity (NTU)	Sodium Persulfate (mg/L)
U18S	17-Oct-12		22.8	0.34	658	7.06	145.1		
	13-Dec-12		16.3	0.24	3,489	5.57	182.00		
	14-Dec-12		16.4	0.45	3,302	5.55	151.40		
	23-Apr-13		14.9	0.25	562	6.78	43.1		
	25-Apr-13	1.37	15.1	0.42	541	6.01	230		
	25-Apr-13	0.50							
	25-Apr-13	0.44							
	25-Apr-13	0.72							
	25-Apr-13		14.7	0.75	3,815	8.24	305.1		
	26-Apr-13		15.5	1.22	736	6.32	288		
	27-Apr-13		15.6	0.65	1,092	6.52	289		
	27-Apr-13		15.7	2.61	530	6.50	207		
	28-Apr-13	1.74	16.1	1.67	756	6.96	160.1		
	30-Apr-13		16.4	0.74	835	6.75	163		1.4
	3-May-13		16.0	0.47	1,041	6.45	387		
	3-May-13	0.16	15.4	1.00	1,142	6.46	272.6		
	4-May-13	0.25	15.6	0.16	858	6.61	252.6		
	4-May-13	0.03						9.5	0.7
	4-May-13	0.33	16.1	0.27	790	6.85	215.8		
	6-May-13	0.68	15.8	0.96	1,085	6.63	196		
	8-May-13		18.5	3.52	965	6.75	225.5		
	9-May-13		18.0	2.62	560	7.33	231.8		
	5/10/2013		19.7	3.28	1,906	6.69	259.3		
	13-May-13	1.36	16.2	0.22	899	6.95	-57		
	16-May-13	1.07	17.0	0.19	925	6.66	16.3		
	17-May-13	1.60							
	17-May-13	1.15	17.1	0.77	1,367	6.43	212.8		
	23-May-13	1.34	19.2	0.12	1,561	6.71	135.6		
	30-May-13	1.87	18.8	0.16	1,022	6.58	124.3		
	10-Jul-13	1.75	22.8	0.26	787	6.63	-62.5		
	11-Jul-13	0.62	23.7	1.07	793	6.97	-59.6		
	22-Jul-13	<0	26.8	0.35	7,705	3.73	69.7		
	12-Aug-13	0.66	27.0	0.83	1,833	6.26	103.1		
	14-Aug-13	0.93	25.4	3.18	1,154	6.03	-19.6		
	3-Oct-13	1.50	23.8	0.10	1,544	5.97	-152.5	79.1	
	12-Feb-14	1.25	10.0	0.26	737	7.03	4.1	21.4	

Well	Date	Depth to Water (ft)	Temp. (°C)	DO (mg/L)	Sp. Conductance (µS/cm)	pH	ORP (mV)	Turbidity (NTU)	Sodium Persulfate (mg/L)
U19D	17-Oct-12		22.9	0.79	6,112	3.58	453.3		
	12-Dec-12		16.4	0.78	5,753	3.45	239		
	12-Dec-12		18.8	0.28	5,482	3.62	235		
	13-Dec-12		17.5	1.94	29,822	5.80	219.80		
	13-Dec-12		17.3	1.92	26,034	8.84	211.00		
	13-Dec-12		17.2	1.50	27,135	6.25	223.00		
	14-Dec-12		16.5	11.08	31,200	6.51	202.00		
	15-Jan-13		15.8	4.33	10,760	6.82	227.1		
	24-Apr-13		15.4	1.85	8,071	5.70	187.3		
	25-Apr-13	NA	14.8	1.60	7,979	5.74	264		
	25-Apr-13	NA	15.3	3.10	2,847	6.10	275		
	26-Apr-13	NA	15.3	7.18	8,347	5.30	353		
	27-Apr-13	NA	15.3	2.24	7,781	5.60	225		
	27-Apr-13	NA	15.2	2.46	7,761	5.68	243		
	28-Apr-13	NA	16.2	1.00	8,840	6.30	212.4		
	30-Apr-13	NA	15.4	1.06	7,431	5.88	191		<0.7
	1-May-13	NA	15.2	0.86	7,723	5.58	201		
	3-May-13	NA	15.7	0.68	10,550	4.22	425		
	4-May-13	NA	15.3	0.70	8,947	5.73	254.3		<0.7
	4-May-13	NA	15.9	0.70	12,545	6.27	273.9		
	5-May-13	NA	16.2	0.41	12,797	6.39	236.3		
	6-May-13	NA	15.7	1.69	16,055	5.54	254		
	8-May-13	NA	15.9	14.31	16,248	5.55	254		
	9-May-13	NA	16.4	10.15	15,993	6.85	256.7		
	13-May-13	NA	16.2	8.30	14,485	5.51			
	16-May-13	NA	17.1	7.50	19,283	5.32	491.9		
	17-May-13	NA	17.6	5.34	17,827	5.70	467.9		
	18-May-13	NA	16.3	6.32	17,662	5.38	440		
	19-May-13	NA	18.4	4.58	11,859	5.96	505		
	20-May-13	NA	16.9	5.01	10,968	5.86	465		
	30-May-13	NA	19.5	4.22	20,446	6.09	343		
	10-Jul-13		20.9	0.30	13,757	3.67	381.2		
	13-Jul-13	0.40	20.0	3.02	14,930	4.41	262.1		
	22-Jul-13		22.6	1.28	22,744	2.70	450		
	12-Aug-13	NA	22.0	0.25	18,220	3.06	528.4		
	14-Aug-13	NA	24.0	6.34	27,432	2.90	418.8		
	3-Oct-13	NM	22.6	0.11	18,270	2.84	465	1.97	
	12-Feb-14		12.7	0.23	12,595	2.98	648	7.25	

Well	Date	Depth to Water (ft)	Temp. (°C)	DO (mg/L)	Sp. Conductance (µS/cm)	pH	ORP (mV)	Turbidity (NTU)	Sodium Persulfate (mg/L)
U19S	17-Oct-12		23.2	0.26	634	7.57	144.3		
	12-Dec-12	1.52	18.5	0.39	3,636	5.42	476		
	12-Dec-12	1.46							
	12-Dec-12	1.12	16.7	0.32	3,603	5.39	470		
	12-Dec-12	0.94							
	12-Dec-12	0.93							
	13-Dec-12		16.2	0.32	3,627	5.47	484.00		
	13-Dec-12		16.5	0.18	3,701	5.05	485.84		
	14-Dec-12		15.8	0.74	3,722	5.34	462.00		
	15-Jan-13	0.40	14.1	2.46	4,228	7.03	139.2		
	24-Apr-13	1.00	15.1	3.08	3,142	6.28	59.5		
	25-Apr-13	1.32	15.0	2.55	2,640	6.18	272		
	25-Apr-13	0.80							
	25-Apr-13	0.79							
	25-Apr-13	0.75							
	25-Apr-13		15.2	2.14	8,148	5.47	275		
	26-Apr-13		16.6	5.13	2,551	6.04	326		
	27-Apr-13		15.9	1.68	2,891	6.27	216		
	27-Apr-13		15.7	2.62	2,786	6.21	240		
	28-Apr-13	1.69	16.8	1.75	2,791	1.60	203.4		
	30-Apr-13		15.6	1.77	2,252	6.45	188		
	1-May-13		15.6	0.81	2,518	6.07	179		
	2-May-13	0.69							
	3-May-13		16.6	0.22	923	6.48	428		
	4-May-13	0.70	15.6	0.43	2,983	5.80	222.4		
	4-May-13	0.17							35
	4-May-13	0.20	16.0	1.29	3,067	6.69	259.5		
	5-May-13	0.16	16.5	0.43	2,895	6.54	228.6		
	6-May-13	0.62	15.8	1.52	3,501	6.18	215	11.7	70
	8-May-13		16.4	1.50	3,138	6.06	198.8		
	9-May-13		16.2	2.74	1,499	7.08	254.3		
	10-May-13		19.5	4.93	550	7.07	239.8		
	13-May-13	1.33	16.4	4.80	2,474	6.42	57.4		
	16-May-13	1.15	17.0	14.26	2,781	5.94	47.2		
	17-May-13	0.83	17.9	4.74	2,855	6.27	457.5		
	18-May-13	0.95	17.3	10.92	2,476	6.01	118		
	19-May-13	0.51	17.3	5.45	12,682	5.91	484		
	20-May-13	0.94	17.3	5.64	11,473	5.79	471		
	23-May-13	1.49							
	24-May-13		17.5	8.29	11,800	6.25	356.8		
	30-May-13	1.88	18.8	11.48	2,064	6.02	313.2		
	10-Jul-13	1.82	23.0	2.62	1,343	6.36	1.8		
	13-Jul-13		23.3	3.56	596	6.73	396.1		
	22-Jul-13	0.65	25.1	1.02	5,256	5.26	324.5		
	12-Aug-13	1.09	23.8	0.38	2,823	6.23	136.5		
	14-Aug-13	0.87	26.4	2.00	3,038	5.77	345.1		
	3-Oct-13	1.20	24.1	0.09	1,471	6.33	-100.2	10.21	
	12-Feb-14		9.9	0.19	593	7.91	6.7	6.15	

<i>Well</i>	<i>Date</i>	<i>Depth to Water (ft)</i>	<i>Temp. (°C)</i>	<i>DO (mg/L)</i>	<i>Sp. Conductance (µS/cm)</i>	<i>pH</i>	<i>ORP (mV)</i>	<i>Turbidity (NTU)</i>	<i>Sodium Persulfate (mg/L)</i>
U20D	17-Oct-12		22.8	1.14	5,818	3.74	356.7	1605	
	13-Dec-12		18.8	0.55	4,033	5.34	229.00	17	
	14-Dec-12		19.1	1.71	5,380	4.25	223.00		
	24-Apr-13		16.1	0.16	7,552	3.38	128.3		
	25-Apr-13	NA	15.2	1.66	6,408	3.57	324		
	25-Apr-13	NA	15.0	1.01	1,259	5.78	225		
	27-Apr-13	NA	16.0	4.90	7,628	3.47	242		
	28-Apr-13	NA	15.9	0.53	7,404	4.87	166.7		
	30-Apr-13	NA	15.6	0.43	7,988	4.21	184		1.4
	1-May-13	NA	15.3	0.45	9,204	3.70	259		
	3-May-13	NA	16.2	0.47	1,682	5.52	499		
	4-May-13	NA	15.1	0.65	9,993	3.67	279.3		
	4-May-13	NA	16.0	5.59	31,429	6.81	278.8		
	5-May-13	NA	15.7	20.30	21,911	4.41	307.9		
	6-May-13	NA	15.9	1.87	26,283	5.50	258		105
	9-May-13	NA	16.8	18.83	30,153	6.29	242.9		
	10-May-13	NA	16.6	17.28	28,631	5.17	244.1		
	13-May-13	NA	15.9	7.26	24,242	3.09	619		
	16-May-13	NA	17.7	21.05	24,711	6.37	445.8	13	>70
	17-May-13	NA	17.4	16.54	23,029	6.76	415.2		
	18-May-13	NA	17.5	20.16	41,004	7.58	503		
	19-May-13	NA	17.5	14.62	39,473	7.53	507		
	20-May-13	NA	17.7	10.12	34,207	6.93			
	30-May-13	NA	18.1	2.32	26,636	6.33	339.5		
	10-Jul-13		21.4	0.45	17,483	3.43	446.5		
	11-Jul-13		20.1	15.97	32,622	3.38	420		
	13-Jul-13		19.9	14.45	33,249	5.57	393	36.8	
	22-Jul-13		21.6	1.26	31,880	4.68	433		
	12-Aug-13	NA	21.8	0.60	23,199	3.14	462		
	14-Aug-13	NA	24.0	4.17	41,143	4.99	450.9		
	3-Oct-13	NM	22.7	0.09	25,376	2.89	427.9	14.2	
	12-Feb-14		13.0	0.27	14,645	3.11	567.1	76.4	

<i>Well</i>	<i>Date</i>	<i>Depth to Water (ft)</i>	<i>Temp. (°C)</i>	<i>DO (mg/L)</i>	<i>Sp. Conductance (µS/cm)</i>	<i>pH</i>	<i>ORP (mV)</i>	<i>Turbidity (NTU)</i>	<i>Sodium Persulfate (mg/L)</i>
U20S	17-Oct-12		23.2	0.82	621	7.02	-77.2		ND
	13-Dec-12		16.0	0.33	4,391	5.60	191.00	21.2	
	14-Dec-12		15.3	0.76	4,328	5.34	164.00		
	24-Apr-13		16.8	7.12	951	6.50	216.9		
	25-Apr-13	1.38	15.9	0.43	960	6.27	244		
	25-Apr-13	<0							
	25-Apr-13	0.24							
	25-Apr-13		15.2	0.72	534	3.66	317		
	25-Apr-13	0.77							
	27-Apr-13		16.0	4.90	7,628	3.47	242		
	28-Apr-13	1.76	16.6	0.55	1,265	6.64	172.4		
	30-Apr-13		16.2	1.62	608	6.58	175		
	1-May-13		16.4	0.77	832	6.25	235		
	2-May-13	0.88							
	2-May-13	0.70							
	3-May-13		16.5	1.55	1,224	6.04	497		
	4-May-13	0.73	15.4	1.00	1,142	6.46	272.6		
	4-May-13	0.00							
	4-May-13	0.10	16.7	0.78	1,404	6.45	202		
	5-May-13	0.25	16.4	0.41	1,306	6.45	108.1		
	6-May-13	0.70	16.1	0.63	1,492	6.02	180		28
	9-May-13		17.0	1.58	518	6.57	224.6		
	10-May-13		17.0	1.66	1,489	6.63	110.5		
	13-May-13	1.44	17.6	0.85	1,404	6.37	36.5		
	16-May-13	1.03	18.2	0.73	2,487	6.29	32.7		
	17-May-13		18.0	0.43	2,347	6.28	40		
	18-May-13	0.50	18.2	0.34	1,944	5.73	160		
	19-May-13	0.58	18.8	0.79	1,769	6.01	470		
	20-May-13	1.02	18.4	1.51	1,636	5.65	459		
	23-May-13	1.52							
	24-May-13	1.70	18.5	9.09	26,167	6.41	392		
	30-May-13	1.41	20.5	3.95	2,947	5.53	302.4		
	10-Jul-13	1.88	24.6	0.62	2,334	5.34	205.6		
	11-Jul-13	0.70	24.9	3.89	2,348	5.04	234.2		
	13-Jul-13		25.1	6.01	439	5.73	158	35.5	
	22-Jul-13	1.20	27.6	1.68	1,210	3.65	441.5		
	12-Aug-13	0.58	26.6	3.55	537	6.51	14.7		
	14-Aug-13		26.6	0.22	2,316	5.70	243.0	28.5	
	3-Oct-13	1.25	24.8	1.29	1,363	5.82	-52.6		
	12-Feb-14	0.97	6.6	1.63	1,618	6.22	249	58.4	

Well	Date	Depth to Water (ft)	Temp. (°C)	DO (mg/L)	Sp. Conductance (µS/cm)	pH	ORP (mV)	Turbidity (NTU)	Sodium Persulfate (mg/L)
U21D	26-Apr-13		15.2	4.31	6,343	4.02	555		
	27-Apr-13		15.4	0.83	6,079	4.32	223		
	2-May-13	0.88							
	3-May-13	0.54	15.8	8.62	24,955	3.77	508.4		
	4-May-13	0.74	15.4	4.92	20,305	3.56	344.7		
	4-May-13	0.27	15.2	6.93	38,052	7.25	317.1		
	5-May-13	0.31	15.8	3.40	13,527	6.24	275.3		
	6-May-13	1.07	15.9	3.11	21,088	6.77	277		
	9-May-13		16.5	26.10	23,357	7.40	232.6		
	10-May-13		19.5	13.70	10,390	6.39	236.4		
	13-May-13	1.45	16.7	16.27	9,022	5.58	582		
	16-May-13		17.7	26.63	17,452	7.03	471.2		
	17-May-13	1.99						49	
	17-May-13	2.05						397	
	17-May-13	1.35	17.7	20.13	21,810	7.34	478.1		
	18-May-13	1.26	17.0	17.10	24,522	7.49	426		
	19-May-13	NA	18.0	16.65	38,715	7.88	523		
	20-May-13	1.21	17.7	13.32	34,546	8.04	474		
	23-May-13	1.83							
	24-May-13	FLOODED	17.1	15.28	26,700	7.45	396	647 (AU)	56
	30-May-13	2.05	18.0	8.38	25,099	6.91	335		
	9-Jul-13	2.11	20.8	0.21	24,853	5.43	359.4		560
	13-Jul-13	1.07	19.7	28.11	44,575	6.61	376		
	22-Jul-13	1.61	21.6	9.99	37,428	5.90	540		
	12-Aug-13	1.00	21.2	0.59	32,021	5.49	514.3		300
	14-Aug-13		23.0	2.18	47,918	5.64	452.1		
	2-Oct-13	2.04	22.1	0.10	35,997	3.14	488.3	71.3	
	12-Feb-14	1.57	12.9	0.29	10,620	3.18	596.4	42.4	
U21S	26-Apr-13		15.6	14.14	1,960	5.03	345		
	27-Apr-13		16.0	10.17	1,820	5.60	180		
	2-May-13	1.01							
	4-May-13	0.70	16.1	1.64	2,109	5.71	287.4		
	5-May-13	0.55	16.3	2.59	1,987	6.42	283.7		
	6-May-13	1.01	16.4	3.24	2,410	6.17	260		56
	9-May-13	1.65	16.7	17.39	1,917	6.37	276.9		
	10-May-13		18.8	14.78	2,658	6.37	228.9		
	13-May-13	1.72	17.2	11.99	1,930	5.76	530.7		
	17-May-13	1.46	18.0	14.42	1,875	6.03	342.2		
	18-May-13	1.37	17.2	2.94	715	9.45	197		
	19-May-13	0.98	18.2	5.75	847	6.80	476		
	20-May-13	1.28	17.8	11.41	1,260	6.72	495		
	23-May-13	1.90							
	24-May-13	1.74	17.6	1.98	1,163	6.94	366		
	31-May-13	2.25	18.8	3.24	1,266	5.90	276		
	9-Jul-13	2.21	22.2	10.57	1,499	5.47	200.7		
	13-Jul-13	0.90	22.4	2.00	1,753	5.91	483		
	22-Jul-13	1.67	24.5	0.92	2,102	5.52	544.6		
	12-Aug-13	1.20	23.8	3.74	1,598	5.33	448.9		
	14-Aug-13		25.4	3.41	2,737	5.72	431.5		
	2-Oct-13	2.11	23.8	10.59	1,619	5.08	206.7	1.13	
	12-Feb-14	1.64	10.9	7.86	1,599	5.50	183.6	7.96	

Works Cited in Appendix D

VDEQ, Virginia Department of Environmental Quality. 2014. "Virginia DEQ - List of Tables (Selection of Contaminants of Concern)."

<http://www.deq.virginia.gov/Programs/LandProtectionRevitalization/RemediationProgram/VoluntaryRemediationProgram/VRPRiskAssessmentGuidance/Tables.aspx>

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Watson, Montgomery. 1997. "Fort Eustis, Virginia Final Remedial Investigation Report for Five Sites," 1–312.

APPENDIX E: MANUSCRIPT 2 DATA

Groundwater PFAA Samples

Sample Name	Date	Lab	pH	ORP	PFAS (1)			PFAS (2)			PFAS (3)			PFAS (4)			PFAS (5)			PFAS (6)			PFAS (7)			PFAS (8)			PFAS (9)			PFAS (10)			PFAS (11)			PFAS (12)																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																											
					Av	SD	RESD%	Av	SD	RESD%	Av	SD	RESD%	Av	SD	RESD%	Av	SD	RESD%	Av	SD	RESD%	Av	SD	RESD%	Av	SD	RESD%	Av	SD	RESD%	Av	SD	RESD%	Av	SD	RESD%	Av	SD	RESD%																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																									
Mn+Co	11/11/12	Ta	0.29	0.52	0.40	1.18	0.15	0.83	1.80	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83	0.02	1.83

Soil PFAA Samples

Pre-demonstration: Analyzed by TestAmerica, Inc. Laboratory

Boring/Well ID		I-1		I-2		U12		U16		U20	
Sample Depth		4' - 14'		4' - 14'		7'		10'		6'	
Sample Date		4/17/2012		4/17/2012		9/26/2012		9/25/2012		9/26/2012	
Analyte	Units	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier	Result	Qualifier
Perfluorobutane Sulfonate (PFBS)	ug/Kg	1		6.4		0.61	J	0.83	J	<0.69	U
Perfluorobutanoic acid (PFBA)	ug/Kg	<0.68	U	1.9		0.43	J	0.84	J	<0.69	U
Perfluorodecane sulfonate (PFDS)	ug/Kg	<0.68	U	<0.68	U	<0.71	U	<0.72	U	<0.69	U
Perfluorodecanoic acid (PFDA)	ug/Kg	<0.68	U	<0.68	U	<0.71	U	<0.72	U	<0.69	U
Perfluorododecanoic acid (PFDoA)	ug/Kg	<0.68	U	<0.68	U	<0.69	U	<0.72	U	<0.69	U
Perfluoroheptanoic acid (PFHpA)	ug/Kg	3		5		<0.69	U	<0.72	U	<0.69	U
Perfluorohexane Sulfonate (PFHS)	ug/Kg	12		83		1.2		6.7		<0.69	U
Perfluorohexanoic acid (PFHxA)	ug/Kg	7	M	18		1		3.4		0.37	J
Perfluorononanoic acid (PFNA)	ug/Kg	1.1		<0.68	U	<0.71	U	<0.72	U	<0.69	U
Perfluorooctane Sulfonamide (FOSA)	ug/Kg	<0.68	U M	<0.68	U M	<0.71	U	<0.72	U	<0.69	U
Perfluorooctane Sulfonate (PFOS)	ug/Kg	45	J	150	M	<0.71	U	1.5		<0.69	U
Perfluorooctanoic acid (PFOA)	ug/Kg	2		6.7		<0.71	U	26		<0.69	U
Perfluoropentanoic acid (PFPA)	ug/Kg	<0.68	U	5.5		0.36	J	1.8		<0.69	U
Perfluorotetradecanoic acid (PFTeA)	ug/Kg	<0.68	U	<0.68	U	<0.71	U	<0.72	U	<0.69	U
Perfluorotridecanoic Acid (PFTriA)	ug/Kg	<0.68	U	<0.68	U	<0.71	U	<0.72	U	<0.69	U
Perfluoroundecanoic acid (PFUnA)	ug/Kg	<0.68	U	<0.68	U	<0.71	U	<0.72	U	<0.69	U

Notes:

1. Qualifiers: "U"= Analyte undetected at limit of detection; "M"= Manual integrated compound.

"J"= Analyte was positively identified, the quantitation is an estimate; "Q"= One or more quality control criteria failed.

2. An asterisk (*) after the sample date indicates that the sample was analyzed at URI.

All other samples analyzed by Test America.

3. "NA"= Analyte was not analyzed for.

4. **Bold** values indicate a hit.

5. Samples Analyzed by TestAmerica Laboratories

Post-demonstration: Analyzed by Colorado School of Mines Laboratory

	PFBA (3)			PFPeA (4)			PFHxA (5)			PFHpA (6)			PFOA (7)			PFNA (8)			PFDA (9)		
	Av	SD	RSD%	Av	SD	RSD%	Av	SD	RSD%	Av	SD	RSD%	Av	SD	RSD%	Av	SD	RSD%	Av	SD	RSD%
LOQ (dilution adjusted)	0.04			0.06			0.12			0.03			0.03			0.03			0.05		
58-101-14	0.59	0.08	13.2	1.63	0.08	5.2	2.50	0.26	10.5	0.89	0.07	7.3	1.11	0.05	4.5	0.07	0.01	7.4	<LOQ		
58-114-06	1.68	0.18	10.6	10.03	0.17	1.7	9.75	0.12	1.2	2.28	0.04	1.6	1.77	0.04	2.3	0.30	0.03	8.6	0.05	0.01	12.5
58-115-06	QA/QC			0.59	0.11	19.0	0.46	0.07	16.4	0.06	0.01	16.2	0.03	0.01	34.7	<LOQ			<LOQ		
58-106-14	1.31	0.17	13.4	7.07	0.47	6.6	9.43	0.82	8.8	2.08	0.24	11.6	0.96	0.17	17.3	0.14	0.07	51.6	0.04	NA	
58-106-06	0.41	0.09	21.7	0.95	0.15	16.2	0.70	0.17	24.9	0.19	0.04	19.1	0.12	0.02	17.0	0.07	0.02	30.3	0.03	0.01	36.7
58-107-14	0.45	0.13	28.0	1.32	0.06	4.2	2.44	0.09	3.7	0.71	0.06	8.4	0.70	0.11	16.1	0.20	0.06	30.2	<LOQ		
58-107-06	0.28	0.04	13.5	1.11	0.10	8.9	2.24	0.24	10.5	0.40	0.05	12.5	0.24	0.05	21.8	0.03	0.00	1.2	<LOQ		
58-109-10	1.53	0.14	8.9	0.64	0.05	7.1	0.96	0.15	15.6	0.21	0.02	8.6	0.23	0.04	16.1	<LOQ			<LOQ		
58-108-14	0.46	0.08	16.3	1.45	0.03	2.4	2.18	0.15	6.9	0.85	0.01	1.0	1.04	0.07	6.9	0.15	0.01	8.4	<LOQ		
58-108-06	0.35	0.05	14.7	1.30	0.07	5.1	2.13	0.12	5.6	0.34	0.01	1.8	0.18	0.01	4.9	0.03	0.01	44.5	<LOQ		
58-111-14	1.10	0.42	35.2	4.70	0.72	15.4	6.12	0.87	14.2	2.42	0.38	15.7	2.62	0.27	10.5	0.29	0.10	33.6	<LOQ		
58-112-10	0.44	0.06	12.7	2.19	0.09	4.1	1.97	0.34	12.3	0.44	0.03	6.0	0.20	0.00	1.9	0.05	0.01	19.9	<LOQ		
58-112-06	0.65	0.34	37.8	2.45	0.31	12.6	2.81	0.40	14.2	0.61	0.04	7.1	0.34	0.04	11.1	0.06	0.01	12.3	<LOQ		
58-114-14	1.05	0.09	8.5	4.95	0.70	14.1	5.52	0.77	13.9	1.93	0.05	2.3	2.87	0.40	14.0	0.33	0.09	27.2	0.18	0.21	111.5
58-105-06	0.24	0.05	21.2	0.41	0.07	17.6	0.41	0.14	34.4	0.12	0.02	15.8	0.12	0.02	16.1	0.02	0.00	24.6	<LOQ		

	PFBA (3)			PFPeA (4)			PFHxA (5)			PFHpA (6)			PFOS (8)			PFDA (9)		
	Av	SD	RSD%	Av	SD	RSD%	Av	SD	RSD%	Av	SD	RSD%	Av	SD	RSD%	Av	SD	RSD%
LOQ (dilution adjusted)	0.08			0.08			0.08			0.08			0.08			0.08		
58-101-14	<LOQ			<LOQ			0.66	0.02	3.6	8.08	0.85	10.5	6.83	0.39	5.6	<LOQ		
58-114-06	<LOQ			<LOQ			0.58	0.02	4.3	3.63	0.13	3.5	4.90	0.70	14.2	<LOQ		
58-115-06	<LOQ			<LOQ			0.08	0.00	3.5	0.24	0.04	17.3	0.14	0.01	3.9	<LOQ		
58-106-14	<LOQ			<LOQ			0.60	0.15	24.6	5.08	0.75	14.8	4.21	0.37	13.6	<LOQ		
58-106-06	<LOQ			<LOQ			0.07	0.06	75.2	0.31	0.11	33.6	0.41	0.06	13.6	<LOQ		
58-107-14	<LOQ			<LOQ			0.25	0.02	6.7	3.99	0.22	5.5	15.85	3.75	23.6	<LOQ		
58-107-06	<LOQ			<LOQ			0.23	0.01	4.0	2.11	0.40	19.1	1.14	0.34	29.7	<LOQ		
58-109-10	<LOQ			<LOQ			0.14	0.01	8.0	1.44	0.19	13.4	0.70	0.07	9.5	<LOQ		
58-108-14	<LOQ			<LOQ			0.29	0.02	8.1	4.85	0.69	14.2	7.49	0.49	6.6	<LOQ		
58-108-06	<LOQ			<LOQ			0.20	0.04	21.0	1.48	0.15	9.9	0.55	0.02	4.2	<LOQ		
58-111-14	<LOQ			<LOQ			0.85	0.12	14.4	11.85	2.14	18.1	17.50	2.69	15.3	<LOQ		
58-112-10	<LOQ			<LOQ			0.22	0.01	3.4	1.40	0.06	3.6	1.74	0.17	9.8	<LOQ		
58-112-06	<LOQ			<LOQ			0.45	0.01	2.4	2.57	0.10	4.1	3.65	0.81	21.3	<LOQ		
58-114-14	<LOQ			<LOQ			0.67	0.05	4.5	16.17	4.60	28.4	23.78	6.61	27.8	<LOQ		
58-105-06	<LOQ			<LOQ			0.08	0.02	19.9	0.35	0.12	14.0	0.51	0.04	8.1	<LOQ		

Notes:

- Av: Arithmetic mean of quantifiable analyses.
- SD: Standard deviation
- RSD %: Relative standard deviation, expressed as a percentage

All samples were analyzed three times.

For a PFAA concentration to be quantified, the estimated concentration must be greater than the LOQ, have a <LOQ.

Two or three analyses were less than limit of quantification for a given analytical batch.

QA/QC: Data points had an estimated concentration greater than LOQ, but did not pass another.

N/A: Only one data point was quantified and therefore, a standard deviation was not calculatable.

Samples Analyzed by Colorado School of Mines Laboratory

Precursor PFAA Groundwater Samples

Sample	Date	PFBA	PFPeA	PFHxA	PFHpA	PFOA	PFNA	PFBS	PFHxS	PFOS
		Δ ug/L								
I-2	11/19/2012	8.73	12.87	111.7	NS	NS	NS	1.81	NS	NS
I-2	10/3/2013	NS	NS	2.8	NS	NS	NS	NS	NS	NS
I-2	2/11/2014	NS	NS	6.1	NS	NS	NS	NS	NS	NS
EC-3	2/11/2014	NS	NS	9.1	NS	NS	NS	NS	NS	NS
U-16D	2/12/2014	0.81	NS	5	NS	NS	NS	NS	NS	NS
U-18D	2/12/2014	NS	NS	9	NS	NS	NS	NS	NS	NS
U-20D	2/12/2014	NS	NS	4.2	NS	NS	NS	NS	NS	NS
I-4	2/13/2014	NS	NS	5.2	NS	NS	NS	NS	NS	NS

Notes: Samples Analyzed by Colorado School of Mines

Positive values indicate the net amount of each compound formed from precursors during the TOP assay

NS indicates no significant difference between compounds before and after oxidation ($p < 0.05$: 2 tailed t test).

APPENDIX F: MANUSCRIPT 3 DATA

1,4-Dioxane Single Contaminant Oxidation Experiments in DI Water

72 h Experiment						
Analyte	Sample ID	Time (h)	Subsample	1,4-Dioxane (µg/L)	C/Co	ln(C/Co)
1,4-Dioxane	Control	0	A	3800	1.00	0.00
1,4-Dioxane	Control	0	B	3800	1.00	0.00
1,4-Dioxane	Control	6	A	3700	0.97	-0.03
1,4-Dioxane	Control	6	B	3800	1.00	0.00
1,4-Dioxane	Control	18	A	3500	0.92	-0.08
1,4-Dioxane	Control	18	B	3500	0.92	-0.08
1,4-Dioxane	Control	24	A	3700	0.97	-0.03
1,4-Dioxane	Control	24	B	3700	0.97	-0.03
1,4-Dioxane	Control	48	A	3700	0.97	-0.03
1,4-Dioxane	Control	48	B	3500	0.92	-0.08
1,4-Dioxane	Control	72	A	3800	1.00	0.00
1,4-Dioxane	Control	72	B	3800	1.00	0.00
Analyte	Sample ID	Time (h)	Subsample	1,4-Dioxane (µg/L)	C/Co	ln(C/Co)
1,4-Dioxane	10:1	6	A	3700	0.97	-0.03
1,4-Dioxane	10:1	6	B	3800	1.00	0.00
1,4-Dioxane	10:1	18	A	3700	0.97	-0.03
1,4-Dioxane	10:1	18	B	3700	0.97	-0.03
1,4-Dioxane	10:1	24	A	3500	0.92	-0.08
1,4-Dioxane	10:1	24	B	3500	0.92	-0.08
1,4-Dioxane	10:1	48	A	3400	0.89	-0.11
1,4-Dioxane	10:1	48	B	3300	0.87	-0.14
1,4-Dioxane	10:1	72	A	2900	0.76	-0.27
1,4-Dioxane	10:1	72	B	3100	0.82	-0.20
Analyte	Sample ID	Time (h)	Subsample	1,4-Dioxane (µg/L)	C/Co	ln(C/Co)
1,4-Dioxane	98:1	6	A	3800	1.00	0.00
1,4-Dioxane	98:1	6	B	3800	1.00	0.00
1,4-Dioxane	98:1	18	A	3100	0.82	-0.20
1,4-Dioxane	98:1	18	B	2900	0.76	-0.27
1,4-Dioxane	98:1	24	A	2400	0.63	-0.46
1,4-Dioxane	98:1	24	B	2600	0.68	-0.38
1,4-Dioxane	98:1	48	A	1300	0.34	-1.07
1,4-Dioxane	98:1	48	B	1300	0.34	-1.07
1,4-Dioxane	98:1	72	A	450	0.12	-2.13
1,4-Dioxane	98:1	72	B	440	0.12	-2.16
1,4-Dioxane	98:1	576	A	-	-	-
1,4-Dioxane	98:1	576	B	-	-	-
Analyte	Sample ID	Time (h)	Subsample	1,4-Dioxane (µg/L)	C/Co	ln(C/Co)
1,4-Dioxane	490:1	6	A	2600	0.68	-0.38
1,4-Dioxane	490:1	6	B	2400	0.63	-0.46
1,4-Dioxane	490:1	18	A	510	0.13	-2.01
1,4-Dioxane	490:1	18	B	590	0.16	-1.86
1,4-Dioxane	490:1	24	A	45	0.01	-4.44
1,4-Dioxane	490:1	24	B	51	0.01	-4.31
1,4-Dioxane	490:1	48	A	-	-	-
1,4-Dioxane	490:1	48	B	-	-	-
1,4-Dioxane	490:1	72	A	-	-	-
1,4-Dioxane	490:1	72	B	-	-	-
Analyte	Sample ID	Time (h)	Subsample	1,4-Dioxane (µg/L)	C/Co	ln(C/Co)
1,4-Dioxane	990:1	6	A	1500	0.39	-0.95
1,4-Dioxane	990:1	6	B	1500	0.39	-0.95
1,4-Dioxane	990:1	18	A	-	-	-
1,4-Dioxane	990:1	18	B	-	-	-
1,4-Dioxane	990:1	24	A	-	-	-
1,4-Dioxane	990:1	24	B	-	-	-
1,4-Dioxane	990:1	48	A	-	-	-
1,4-Dioxane	990:1	48	B	-	-	-
1,4-Dioxane	990:1	72	A	-	-	-
1,4-Dioxane	990:1	72	B	-	-	-

Experiment: 1,4-Dioxane 72 h			
ID	Time (h)	ORP (mV)	pH
990:1	6.0	268	8.18
990:1	18.0	289	7.68
990:1	24.0	293	7.60
990:1	48.0	333	7.54
990:1	72.0	364	7.54
490:1	6.0	238	8.28
490:1	18.0	224	7.88
490:1	24.0	225	7.62
490:1	48.0	306	7.35
490:1	72.0	303	7.39
98:1	6.0	220	8.26
98:1	18.0	218	8.09
98:1	24.0	206	7.98
98:1	48.0	234	7.65
98:1	72.0	214	7.37
10:1	6.0	246	7.75
10:1	18.0	228	7.73
10:1	24.0	209	7.89
10:1	48.0	218	7.57
10:1	72.0	210	7.45
Control	6.0	291	7.30
Control	18.0	248	7.40
Control	24.0	242	7.89
Control	48.0	229	7.63
Control	72.0	211	7.1
Stock Pre Activation		442	8.42
Stock Post Activation		860	8.04

312 h Experiment						
Analyte	Sample ID	Time (h)	Subsample	1,4-Dioxane (µg/L)	C/Co	ln(C/Co)
1,4-Dioxane	Control	0	A	3400	0.95	-0.05
1,4-Dioxane	Control	0	B	3800	1.04	0.04
1,4-Dioxane	Control	24	A	3700	1.02	0.02
1,4-Dioxane	Control	24	B	3600	0.99	-0.01
1,4-Dioxane	Control	48	A	3400	0.95	-0.05
1,4-Dioxane	Control	48	B	3500	0.98	-0.02
1,4-Dioxane	Control	72	A	3500	0.98	-0.02
1,4-Dioxane	Control	72	B	3500	0.98	-0.02
1,4-Dioxane	Control	98	A	3400	0.95	-0.05
1,4-Dioxane	Control	98	B	3400	0.95	-0.05
1,4-Dioxane	Control	240	A	3400	0.95	-0.05
1,4-Dioxane	Control	240	B	3500	0.98	-0.02
1,4-Dioxane	Control	312	A	3500	0.99	-0.01
1,4-Dioxane	Control	312	B	3700	1.02	0.02
Analyte	Sample ID	Time (h)	Subsample	1,4-Dioxane (µg/L)	C/Co	ln(C/Co)
1,4-Dioxane	10:1	24	A	3700	1.03	0.03
1,4-Dioxane	10:1	24	B	3500	0.97	-0.03
1,4-Dioxane	10:1	48	A	3300	0.92	-0.09
1,4-Dioxane	10:1	48	B	3200	0.89	-0.12
1,4-Dioxane	10:1	72	A	2900	0.81	-0.22
1,4-Dioxane	10:1	72	B	2900	0.81	-0.22
1,4-Dioxane	10:1	98	A	3100	0.86	-0.15
1,4-Dioxane	10:1	98	B	2800	0.78	-0.25
1,4-Dioxane	10:1	168	A	2200	0.61	-0.49
1,4-Dioxane	10:1	168	B	2200	0.61	-0.49
1,4-Dioxane	10:1	240	A	1800	0.50	-0.69
1,4-Dioxane	10:1	240	B	2000	0.56	-0.59
1,4-Dioxane	10:1	312	A	1500	0.42	-0.88
1,4-Dioxane	10:1	312	B	1500	0.42	-0.88

Experiment: 1,4-Dioxane 312 h			
ID	Time (h)	ORP (mV)	pH
10:1	24.0	322	7.63
10:1	48.0	318	7.55
10:1	72.0	470	7.34
10:1	96.0	507	7.22
10:1	168.0	559	6.91
10:1	240.0	428	6.58
10:1	312.0	484	6.45
Control	24.0	353	6.80
Control	48.0	324	6.80
Control	72.0	455	6.78
Control	96.0	494	6.88
Control	168.0	NA	NA
Control	240.0	440	6.56
Control	312.0	443	6.60
Stock Post Activation		872	8.39

24 h Experiment						
Analyte	Sample ID	Time (h)	Subsample	1,4-Dioxane (µg/L)	C/Co	ln(C/Co)
1,4-Dioxane	Control	0	A	3700	1.04	0.04
1,4-Dioxane	Control	0	B	3400	0.96	-0.04
1,4-Dioxane	Control	2	A	3700	1.04	0.04
1,4-Dioxane	Control	2	B	3300	0.93	-0.07
1,4-Dioxane	Control	3	A	3600	1.01	0.01
1,4-Dioxane	Control	3	B	3500	0.99	-0.01
1,4-Dioxane	Control	4	A	3500	0.99	-0.01
1,4-Dioxane	Control	4	B	3600	1.01	0.01
1,4-Dioxane	Control	6	A	3300	0.93	-0.07
1,4-Dioxane	Control	6	B	3400	0.96	-0.04
1,4-Dioxane	Control	8	A	3300	0.93	-0.07
1,4-Dioxane	Control	8	B	3400	0.96	-0.04
1,4-Dioxane	Control	24	A	3600	1.01	0.01
1,4-Dioxane	Control	24	B	3300	0.93	-0.07
Analyte	Sample ID	Time (h)	Subsample	1,4-Dioxane (µg/L)	C/Co	ln(C/Co)
1,4-Dioxane	510:1	1	A	2800	0.79	-0.24
1,4-Dioxane	510:1	1	B	2700	0.76	-0.28
1,4-Dioxane	510:1	2	A	2400	0.66	-0.42
1,4-Dioxane	510:1	2	B	2300	0.63	-0.47
1,4-Dioxane	510:1	3	A	2000	0.56	-0.58
1,4-Dioxane	510:1	3	B	2100	0.59	-0.52
1,4-Dioxane	510:1	4	A	1900	0.53	-0.64
1,4-Dioxane	510:1	4	B	1900	0.53	-0.64
1,4-Dioxane	510:1	6	A	1800	0.49	-0.71
1,4-Dioxane	510:1	6	B	1700	0.46	-0.77
1,4-Dioxane	510:1	8	A	1300	0.36	-1.01
1,4-Dioxane	510:1	8	B	1300	0.36	-1.02
1,4-Dioxane	510:1	24	A	-	-	-
1,4-Dioxane	510:1	24	B	-	-	-
Analyte	Sample ID	Time (h)	Subsample	1,4-Dioxane (µg/L)	C/Co	ln(C/Co)
1,4-Dioxane	1030:1	1	A	2000	0.56	-0.57
1,4-Dioxane	1030:1	1	B	2300	0.65	-0.44
1,4-Dioxane	1030:1	2	A	1600	0.45	-0.79
1,4-Dioxane	1030:1	2	B	1800	0.50	-0.70
1,4-Dioxane	1030:1	3	A	1300	0.36	-1.02
1,4-Dioxane	1030:1	3	B	1400	0.39	-0.95
1,4-Dioxane	1030:1	4	A	1000	0.29	-1.25
1,4-Dioxane	1030:1	4	B	1100	0.30	-1.20
1,4-Dioxane	1030:1	6	A	600	0.16	-1.86
1,4-Dioxane	1030:1	6	B	600	0.15	-1.87
1,4-Dioxane	1030:1	8	A	200	0.04	-3.14
1,4-Dioxane	1030:1	8	B	100	0.04	-3.20
1,4-Dioxane	1030:1	24	A	-	-	-
1,4-Dioxane	1030:1	24	B	-	-	-

Experiment: 1,4-Dioxane 24 h			
ID	Time (h)	ORP (mV)	pH
Control	0.0	299	6.13
Control	2.0	418	6.21
Control	3.0	459	6.45
Control	4.0	431	6.22
Control	6.0	389	6.46
Control	8.0	392	6.35
Control	24.0	175	6.81
510:1	0.0	476	8.55
510:1	2.0	361	8.50
510:1	3.0	384	8.43
510:1	4.0	362	8.47
510:1	6.0	323	8.38
510:1	8.0	326	8.25
510:1	24.0	233	7.61
1030:1	0.0	483	8.61
1030:1	2.0	404	8.50
1030:1	3.0	426	8.45
1030:1	4.0	406	8.36
1030:1	6.0	385	8.25
1030:1	8.0	396	8.10
1030:1	24.0	402	7.70
Stock Pre Activation		402	8.76
Stock Post Activation		951	8.55

1,4-Dioxane Single Contaminant Oxidation Experiments with increasing Ionic Strength

8 h Experiment							
Analyte	Sample ID	CaCl ₂ •2H ₂ O (mg/L)	Time (h)	Subsample	1,4-Dioxane (µg/L)	C/Co	ln(C/Co)
1,4-Dioxane	Control	0	0	A	3700	1.00	0.00
1,4-Dioxane	Control	0	0	B	3700	1.00	0.00
1,4-Dioxane	Control	0	4	A	3700	1.00	0.00
1,4-Dioxane	Control	0	4	B	3800	1.03	0.03
1,4-Dioxane	Control	0	6	A	3500	0.95	-0.06
1,4-Dioxane	Control	0	6	B	3100	0.84	-0.18
1,4-Dioxane	Control	0	8	A	3900	1.05	0.05
1,4-Dioxane	Control	0	8	B	3700	1.00	0.00
Analyte	Sample ID	CaCl ₂ •2H ₂ O (mg/L)	Time (h)	Subsample	1,4-Dioxane (µg/L)	C/Co	ln(C/Co)
1,4-Dioxane	500:1	0	2	A	2400	0.65	-0.43
1,4-Dioxane	500:1	0	2	B	2100	0.57	-0.57
1,4-Dioxane	500:1	0	4	A	1900	0.51	-0.67
1,4-Dioxane	500:1	0	4	B	1800	0.49	-0.72
1,4-Dioxane	500:1	0	6	A	1600	0.43	-0.84
1,4-Dioxane	500:1	0	6	B	1500	0.41	-0.90
1,4-Dioxane	500:1	0	8	A	1000	0.27	-1.31
1,4-Dioxane	500:1	0	8	B	1200	0.32	-1.13
Analyte	Sample ID	CaCl ₂ •2H ₂ O (mg/L)	Time (h)	Subsample	1,4-Dioxane (µg/L)	C/Co	ln(C/Co)
1,4-Dioxane	500:1	103	2	A	2400	0.65	-0.43
1,4-Dioxane	500:1	103	2	B	2200	0.59	-0.52
1,4-Dioxane	500:1	103	4	A	1900	0.51	-0.67
1,4-Dioxane	500:1	103	4	B	2000	0.54	-0.62
1,4-Dioxane	500:1	103	6	A	1700	0.46	-0.78
1,4-Dioxane	500:1	103	6	B	1700	0.46	-0.78
1,4-Dioxane	500:1	103	8	A	1200	0.32	-1.13
1,4-Dioxane	500:1	103	8	B	1300	0.35	-1.05
Analyte	Sample ID	CaCl ₂ •2H ₂ O (mg/L)	Time (h)	Subsample	1,4-Dioxane (µg/L)	C/Co	ln(C/Co)
1,4-Dioxane	500:1	1030	2	A	3100	0.84	-0.18
1,4-Dioxane	500:1	1030	2	B	3100	0.84	-0.18
1,4-Dioxane	500:1	1030	4	A	2700	0.73	-0.32
1,4-Dioxane	500:1	1030	4	B	2600	0.70	-0.35
1,4-Dioxane	500:1	1030	6	A	1900	0.51	-0.67
1,4-Dioxane	500:1	1030	6	B	1800	0.49	-0.72
1,4-Dioxane	500:1	1030	8	A	1700	0.46	-0.78
1,4-Dioxane	500:1	1030	8	B	1600	0.43	-0.84
Analyte	Sample ID	CaCl ₂ •2H ₂ O (mg/L)	Time (h)	Subsample	1,4-Dioxane (µg/L)	C/Co	ln(C/Co)
1,4-Dioxane	500:1	10300	2	A	3200	0.86	-0.15
1,4-Dioxane	500:1	10300	2	B	3200	0.86	-0.15
1,4-Dioxane	500:1	10300	4	A	2700	0.73	-0.32
1,4-Dioxane	500:1	10300	4	B	2800	0.76	-0.28
1,4-Dioxane	500:1	10300	6	A	2700	0.73	-0.32
1,4-Dioxane	500:1	10300	6	B	2600	0.70	-0.35
1,4-Dioxane	500:1	10300	8	A	2200	0.59	-0.52
1,4-Dioxane	500:1	10300	8	B	2100	0.57	-0.57

1,1,1-TCA Single Contaminant Oxidation Experiments in DI Water

312 h Experiment						
Analyte	Sample ID	Time (h)	Subsample	TCA (µg/L)	C/Co	ln(C/Co)
TCA	Control	0	A	5900	1.00	0.00
TCA	Control	24	A	5300	0.90	-0.11
TCA	Control	24	B	5700	0.97	-0.03
TCA	Control	48	A	5500	0.93	-0.07
TCA	Control	48	B	5400	0.92	-0.09
TCA	Control	98	A	5600	0.95	-0.05
TCA	Control	98	B	5900	1.00	0.00
TCA	Control	168	A	5900	1.00	0.00
TCA	Control	168	B	5900	1.00	0.00
TCA	Control	240	A	5500	0.93	-0.07
TCA	Control	240	B	5700	0.97	-0.03
TCA	Control	312	A	5900	1.00	0.00
TCA	Control	312	B	5800	0.98	-0.02
Analyte	Sample ID	Time (h)	Subsample	TCA (µg/L)	C/Co	ln(C/Co)
TCA	500:1	24	A	3800.00	0.64	-0.44
TCA	500:1	24	B	3800.00	0.64	-0.44
TCA	500:1	48	A	2000.00	0.34	-1.08
TCA	500:1	48	B	2100.00	0.36	-1.03
TCA	500:1	72	A	1100.00	0.19	-1.68
TCA	500:1	72	B	1000.00	0.17	-1.77
TCA	500:1	98	A	410.00	0.07	-2.67
TCA	500:1	98	B	380.00	0.06	-2.74
TCA	500:1	168	A	33.00	0.01	-5.19
TCA	500:1	168	B	32.00	0.01	-5.22
TCA	500:1	240	A	BQL	-	-
TCA	500:1	240	B	BQL	-	-
TCA	500:1	312	A	BDL	-	-
TCA	500:1	312	B	BDL	-	-
Analyte	Sample ID	Time (h)	Subsample	TCA (µg/L)	C/Co	ln(C/Co)
TCA	960:1	6	A	5500.00	0.93	-0.07
TCA	960:1	6	B	5900.00	1.00	0.00
TCA	960:1	19.5	A	4100.00	0.69	-0.36
TCA	960:1	19.5	B	4200.00	0.71	-0.34
TCA	960:1	24	A	3400.00	0.58	-0.55
TCA	960:1	24	B	3300.00	0.56	-0.58
TCA	960:1	48	A	1300.00	0.22	-1.51
TCA	960:1	48	B	1200.00	0.20	-1.59
TCA	960:1	72	A	350.00	0.06	-2.82
TCA	960:1	72	B	350.00	0.06	-2.82
TCA	960:1	98	A	68.00	0.01	-4.46
TCA	960:1	98	B	67.00	0.01	-4.48
TCA	960:1	168	A	5.00	0.00	-7.07
TCA	960:1	168	B	5.00	0.00	-7.07
Analyte	Sample ID	Time (h)	Subsample	TCA (µg/L)	C/Co	ln(C/Co)
TCA	1900:1	6	A	4500	0.76	-0.27
TCA	1900:1	6	B	4700	0.80	-0.23
TCA	1900:1	19.5	A	2800	0.47	-0.75
TCA	1900:1	19.5	B	2800	0.47	-0.75
TCA	1900:1	24	A	2100	0.36	-1.03
TCA	1900:1	24	B	1900	0.32	-1.13
TCA	1900:1	48	A	400	0.07	-2.69
TCA	1900:1	48	B	410	0.07	-2.67
TCA	1900:1	72	A	62	0.01	-4.56
TCA	1900:1	72	B	60	0.01	-4.59
TCA	1900:1	98	A	8	0.00	-6.60
TCA	1900:1	98	B	8	0.00	-6.60
TCA	1900:1	168	A	BDL	-	-
TCA	1900:1	168	B	BDL	-	-

Experiment: TCA 312 h			
ID	Time (h)	ORP (mV)	pH
1900:1	6.0	450	8.42
1900:1	19.5	534	8.15
1900:1	24.0	500	8.11
1900:1	48.0	544	7.86
1900:1	72.0	553	7.73
1900:1	96.0	588	7.60
1900:1	168.0	605	7.47
960:1	6.0	495	8.47
960:1	19.5	440	8.17
960:1	24.0	511	8.09
960:1	48.0	510	7.88
960:1	72.0	562	7.73
960:1	96.0	581	7.61
960:1	168.0	605	7.47
480:1	24.0	504	8.00
480:1	48.0	431	7.77
480:1	72.0	560	7.65
480:1	96.0	578	7.53
480:1	168.0	606	7.33
480:1	240.0	506	7.20
480:1	312.0	541	7.14
Control	24.0	327	6.72
Control	48.0	299	7.14
Control	72.0	510	6.78
Control	96.0	538	6.46
Control	168.0	593	6.68
Control	240.0	540	6.43
Control	312.0	515	6.46
Post Activation		872	8.392

TCE Single Contaminant Oxidation Experiments in DI Water

72 h Experiment						
Analyte	Sample ID	Time (h)	Subsample	TCE (µg/L)	C/Co	ln(C/Co)
TCE	Control	0	A	5400	1.02	0.02
TCE	Control	0	B	5200	0.98	-0.02
TCE	Control	4	A	5500	1.04	0.04
TCE	Control	4	B	5400	1.02	0.02
TCE	Control	8	A	5200	0.98	-0.02
TCE	Control	8	B	5100	0.96	-0.04
TCE	Control	18	A	5200	0.98	-0.02
TCE	Control	18	B	5200	0.98	-0.02
TCE	Control	24	A	5400	1.02	0.02
TCE	Control	24	B	5200	0.98	-0.02
TCE	Control	48	A	4800	0.91	-0.10
TCE	Control	48	B	4800	0.91	-0.10
TCE	Control	72	A	4900	0.92	-0.08
TCE	Control	72	B	5100	0.96	-0.04
Analyte	Sample ID	Time (h)	Subsample	TCE (µg/L)	C/Co	ln(C/Co)
TCE	10:1	2	A	4000	0.75	-0.28
TCE	10:1	2	B	3900	0.74	-0.30
TCE	10:1	4	A	3600	0.68	-0.39
TCE	10:1	4	B	3700	0.70	-0.36
TCE	10:1	8	A	3300	0.62	-0.48
TCE	10:1	8	B	2900	0.55	-0.60
TCE	10:1	18	A	1600	0.31	-1.17
TCE	10:1	18	B	1600	0.31	-1.19
TCE	10:1	24	A	1200	0.22	-1.51
TCE	10:1	24	B	1000	0.19	-1.64
TCE	10:1	48	A	-	-	-
TCE	10:1	48	B	-	-	-
TCE	10:1	72	A	-	-	-
TCE	10:1	72	B	-	-	-
Analyte	Sample ID	Time (h)	Subsample	TCE (µg/L)	C/Co	ln(C/Co)
TCE	25:1	2	A	4000	0.75	-0.28
TCE	25:1	2	B	3900	0.74	-0.31
TCE	25:1	4	A	3500	0.66	-0.41
TCE	25:1	4	B	3500	0.66	-0.41
TCE	25:1	8	A	2200	0.42	-0.88
TCE	25:1	8	B	2200	0.42	-0.88
TCE	25:1	18	A	560	0.11	-2.25
TCE	25:1	18	B	580	0.11	-2.21
TCE	25:1	24	A	240	0.05	-3.09
TCE	25:1	24	B	220	0.04	-3.18
TCE	25:1	48	A	-	-	-
TCE	25:1	48	B	-	-	-
TCE	25:1	72	A	-	-	-
TCE	25:1	72	B	-	-	-
Analyte	Sample ID	Time (h)	Subsample	TCE (µg/L)	C/Co	ln(C/Co)
TCE	50:1	2	A	3200	0.60	-0.51
TCE	50:1	2	B	3200	0.60	-0.51
TCE	50:1	4	A	2300	0.44	-0.82
TCE	50:1	4	B	2400	0.45	-0.80
TCE	50:1	8	A	1100	0.22	-1.53
TCE	50:1	8	B	1000	0.21	-1.57
TCE	50:1	18	A	54	0.01	-4.59
TCE	50:1	18	B	51	0.01	-4.65
TCE	50:1	24	A	5	0.00	-7.03
TCE	50:1	24	B	5	0.00	-7.03
TCE	50:1	48	A	-	-	-
TCE	50:1	48	B	-	-	-
TCE	50:1	72	A	-	-	-
TCE	50:1	72	B	-	-	-
Analyte	Sample ID	Time (h)	Subsample	TCE (µg/L)	C/Co	ln(C/Co)
TCE	100:1	2	A	2600	0.49	-0.71
TCE	100:1	2	B	2600	0.49	-0.71
TCE	100:1	4	A	1300	0.25	-1.41
TCE	100:1	4	B	1300	0.25	-1.41
TCE	100:1	8	A	110	0.02	-3.87
TCE	100:1	8	B	130	0.02	-3.71
TCE	100:1	18	A	-	-	-
TCE	100:1	18	B	-	-	-
TCE	100:1	24	A	-	-	-
TCE	100:1	24	B	-	-	-
TCE	100:1	48	A	-	-	-
TCE	100:1	48	B	-	-	-
TCE	100:1	72	A	-	-	-
TCE	100:1	72	B	-	-	-

Experiment: TCE 72 h			
ID	Time (h)	ORP (mV)	pH
110:1	2.0	204	7.86
110:1	4.0	178	7.65
110:1	8.0	180	7.42
110:1	18.0	312	7.24
110:1	24.0	324	7.20
110:1	48.0	363	7.18
110:1	72.0	388	7.01
53:1	2.0	216	7.78
53:1	4.0	180	7.53
53:1	8.0	172	7.28
53:1	18.0	198	6.94
53:1	24.0	259	6.83
53:1	48.0	381	6.69
53:1	72.0	398	6.64
25:1	2.0	233	7.67
25:1	4.0	209	7.46
25:1	8.0	202	7.08
25:1	18.0	217	6.47
25:1	24.0	239	6.21
25:1	48.0	421	5.32
25:1	72.0	487	4.69
10:1	2.0	271	7.25
10:1	4.0	256	7.17
10:1	8.0	239	6.89
10:1	18.0	273	5.72
10:1	24.0	336	4.83
10:1	48.0	427	4.14
10:1	72.0	541	3.94
Control	0.0	308	6.45
Control	4.0	318	7.04
Control	8.0	304	7.29
Control	18.0	341	6.77
Control	24.0	398	6.21
Control	48.0	392	6.27
Control	72.0	381	6.46
Post Activation		788	8.204

1,4-Dioxane, TCE, TCA Contaminant Mixture Oxidation Experiments in DI Water

96 h Experiment						
Analyte	Sample ID	Time (h)	Subsample	TCA (µg/L)	C/Co	ln(C/Co)
TCA	Control	0	A	1200	1.04	0.04
TCA	Control	0	B	1100	0.96	-0.04
TCA	Control	4	A	1000	0.87	-0.14
TCA	Control	4	B	1000	0.87	-0.14
TCA	Control	8	A	1000	0.87	-0.14
TCA	Control	24	A	1000	0.87	-0.14
TCA	Control	24	B	1100	0.96	-0.04
TCA	Control	48	A	1000	0.87	-0.14
TCA	Control	48	B	1000	0.87	-0.14
TCA	Control	72	A	1000	0.87	-0.14
TCA	Control	72	B	1000	0.87	-0.14
TCA	Control	96	A	1000	0.87	-0.14
TCA	Control	96	B	930	0.81	-0.21
Analyte	Sample ID	Time (h)	Subsample	TCE (µg/L)	C/Co	ln(C/Co)
TCE	Control	0	A	1400	1.04	0.04
TCE	Control	0	B	1300	0.96	-0.04
TCE	Control	4	A	1100	0.81	-0.20
TCE	Control	4	B	1200	0.89	-0.12
TCE	Control	8	A	1200	0.89	-0.12
TCE	Control	24	A	1100	0.81	-0.20
TCE	Control	24	B	1200	0.89	-0.12
TCE	Control	48	A	1100	0.81	-0.20
TCE	Control	48	B	1000	0.74	-0.30
TCE	Control	72	A	1000	0.74	-0.30
TCE	Control	72	B	1000	0.74	-0.30
TCE	Control	96	A	1100	0.81	-0.20
TCE	Control	96	B	1000	0.74	-0.30
Analyte	Sample ID	Time (h)	Subsample	1,4-Dioxane (µg/L)	C/Co	ln(C/Co)
1,4-Dioxane	Control	0	A	1300	1.00	0.00
1,4-Dioxane	Control	0	B	1300	1.00	0.00
1,4-Dioxane	Control	4	A	1200	0.92	-0.08
1,4-Dioxane	Control	4	B	1300	1.00	0.00
1,4-Dioxane	Control	8	A	1300	1.00	0.00
1,4-Dioxane	Control	8	B	1300	1.00	0.00
1,4-Dioxane	Control	24	A	1100	0.85	-0.17
1,4-Dioxane	Control	24	B	1200	0.92	-0.08
1,4-Dioxane	Control	48	A	1200	0.92	-0.08
1,4-Dioxane	Control	48	B	1300	1.00	0.00
1,4-Dioxane	Control	72	A	1200	0.92	-0.08
1,4-Dioxane	Control	72	B	1200	0.92	-0.08
1,4-Dioxane	Control	96	A	1300	1.00	0.00
1,4-Dioxane	Control	96	B	1300	1.00	0.00

96 h Experiment						
Analyte	Sample ID	Time (h)	Subsample	TCA (µg/L)	C/Co	ln(C/Co)
TCA	450:1	0.5	A	1000	0.87	-0.14
TCA	450:1	0.5	B	1100	0.96	-0.04
TCA	450:1	1	A	990	0.86	-0.15
TCA	450:1	1	B	1000	0.87	-0.14
TCA	450:1	1.5	A	990	0.86	-0.15
TCA	450:1	1.5	B	990	0.86	-0.15
TCA	450:1	2	A	1000	0.87	-0.14
TCA	450:1	2	B	1000	0.87	-0.14
TCA	450:1	4	A	990	0.86	-0.15
TCA	450:1	4	B	930	0.81	-0.21
TCA	450:1	6	A	990	0.86	-0.15
TCA	450:1	6	B	990	0.86	-0.15
TCA	450:1	8	A	990	0.86	-0.15
TCA	450:1	8	B	1000	0.87	-0.14
TCA	450:1	10	A	930	0.81	-0.21
TCA	450:1	10	B	930	0.81	-0.21
TCA	450:1	24	A	930	0.81	-0.21
TCA	450:1	24	B	870	0.76	-0.28
TCA	450:1	48	A	810	0.70	-0.35
TCA	450:1	48	B	700	0.61	-0.50
TCA	450:1	72	A	550	0.48	-0.74
TCA	450:1	72	B	540	0.47	-0.76
TCA	450:1	96	A	420	0.37	-1.01
TCA	450:1	96	B	430	0.37	-0.98
Analyte	Sample ID	Time (h)	Subsample	TCE (µg/L)	C/Co	ln(C/Co)
TCE	410:1	0.5	A	990	0.73	-0.31
TCE	410:1	0.5	B	1000	0.74	-0.30
TCE	410:1	1	A	930	0.69	-0.37
TCE	410:1	1	B	870	0.64	-0.44
TCE	410:1	1.5	A	810	0.60	-0.51
TCE	410:1	1.5	B	810	0.60	-0.51
TCE	410:1	2	A	810	0.60	-0.51
TCE	410:1	2	B	810	0.60	-0.51
TCE	410:1	4	A	640	0.47	-0.75
TCE	410:1	4	B	520	0.39	-0.95
TCE	410:1	6	A	450	0.33	-1.10
TCE	410:1	6	B	410	0.30	-1.19
TCE	410:1	8	A	280	0.21	-1.57
TCE	410:1	8	B	380	0.28	-1.27
TCE	410:1	10	A	230	0.17	-1.77
TCE	410:1	10	B	230	0.17	-1.77
TCE	410:1	24	A	4	0.00	-5.82
TCE	410:1	24	B	3	0.00	-6.11
TCE	410:1	48	A	-	-	-
TCE	410:1	48	B	-	-	-
TCE	410:1	72	A	-	-	-
TCE	410:1	72	B	-	-	-
TCE	410:1	96	A	-	-	-
TCE	410:1	96	B	-	-	-
Analyte	Sample ID	Time (h)	Subsample	1,4-Dioxane (µg/L)	C/Co	ln(C/Co)
1,4-Dioxane	280:1	0.5	A	1200	0.92	-0.08
1,4-Dioxane	280:1	0.5	B	1100	0.85	-0.17
1,4-Dioxane	280:1	1	A	1100	0.85	-0.17
1,4-Dioxane	280:1	1	B	1300	1.00	0.00
1,4-Dioxane	280:1	1.5	A	1300	1.00	0.00
1,4-Dioxane	280:1	1.5	B	1200	0.92	-0.08
1,4-Dioxane	280:1	2	A	1200	0.92	-0.08
1,4-Dioxane	280:1	2	B	1100	0.85	-0.17
1,4-Dioxane	280:1	4	A	1100	0.85	-0.17
1,4-Dioxane	280:1	4	B	1000	0.77	-0.26
1,4-Dioxane	280:1	6	A	980	0.75	-0.28
1,4-Dioxane	280:1	6	B	920	0.71	-0.35
1,4-Dioxane	280:1	8	A	860	0.66	-0.41
1,4-Dioxane	280:1	8	B	910	0.70	-0.36
1,4-Dioxane	280:1	10	A	820	0.63	-0.46
1,4-Dioxane	280:1	10	B	840	0.65	-0.44
1,4-Dioxane	280:1	24	A	330	0.25	-1.37
1,4-Dioxane	280:1	24	B	290	0.22	-1.50
1,4-Dioxane	280:1	48	A	-	-	-
1,4-Dioxane	280:1	48	B	-	-	-
1,4-Dioxane	280:1	72	A	-	-	-
1,4-Dioxane	280:1	72	B	-	-	-
1,4-Dioxane	280:1	96	A	-	-	-
1,4-Dioxane	280:1	96	B	-	-	-

Experiment: VOC Mixture 72 h			
ID	Time (h)	ORP (mV)	pH
Control A	4.0	182	9.34
Control A	8.0	136	9.09
Control A	24.0	216	9.09
Control A	48.0	242	9.46
Control A	72.0	257	9.36
Control A	96.0	244	9.00
Control B	4.0	177	9.38
Control B	8.0	-	-
Control B	24.0	217	9.16
Control B	48.0	229	9.29
Control B	72.0	235	9.30
Control B	96.0	238	8.92
OxyZone + VOC A	0.5	243	8.16
OxyZone + VOC A	1.0	251	8.15
OxyZone + VOC A	1.5	250	8.14
OxyZone + VOC A	2.0	249	8.12
OxyZone + VOC A	4.0	247	8.04
OxyZone + VOC A	6.0	223	7.98
OxyZone + VOC A	8.0	287	7.96
OxyZone + VOC A	10.0	306	7.85
OxyZone + VOC A	24.0	289	7.66
OxyZone + VOC A	48.0	374	7.10
OxyZone + VOC A	72.0	383	7.03
OxyZone + VOC A	96.0	375	6.96
OxyZone + VOC B	0.5	241	8.16
OxyZone + VOC B	1.0	245	8.13
OxyZone + VOC B	1.5	248	8.11
OxyZone + VOC B	2.0	246	8.17
OxyZone + VOC B	4.0	235	8.07
OxyZone + VOC B	6.0	265	8.01
OxyZone + VOC B	8.0	281	7.84
OxyZone + VOC B	10.0	288	7.83
OxyZone + VOC B	24.0	287	7.72
OxyZone + VOC B	48.0	372	7.23
OxyZone + VOC B	72.0	385	7.05
OxyZone + VOC B	96.0	384	6.98
ORP Control	2.0	248	8.15
ORP Control	4.0	240	8.16
ORP Control	8.0	293	8.14
ORP Control	24.0	310	7.92
ORP Control	48.0	352	7.89
ORP Control	72.0	360	7.67
ORP Control	96.0	354	7.75
Stock Post Activation		848	8.38