

Xpert Design and Diagnostics' (XDD) In Situ Chemical Oxidation Process Using Potassium Permanganate (KMnO_4)

Innovative Technology Evaluation Report



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National Risk Management Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

Notice

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Foreword

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Sally C. Gutierrez, Director
National Risk Management Research Laboratory

Abstract

Xpert Design and Diagnostic's (XDD) potassium permanganate in situ chemical oxidation (ISCO) process was evaluated under the EPA Superfund Innovative Technology Evaluation (SITE) Program at the former MEC Building site located in Hudson, New Hampshire. At this site, both soil and groundwater are contaminated with chlorinated volatile organic compounds (VOCs). The VOCs are primarily perchloroethylene (PCE), trichloroethylene (TCE), and cis-1,2-dichloroethylene, (cDCE). Three saturated stratigraphic zones, occurring between 6 and 25 feet (1.8 to 7.6 m) below land surface (bls) and within an approximate 1,200 ft² (111.5 m²) area, were targeted for ISCO treatment. Little [320 lb (145 kg)] potassium permanganate was able to be injected into the shallow, gravelly sandy zone, whereas 1,500 lbs (680 kg) and 1860 lbs (845 kg) were injected into the intermediate peat and deep, silty sand layers, respectively. The average soil concentrations of PCE decreased by 96 percent and 88.5 percent, in the peat and deep layers, respectively. The average soil TCE concentrations decreased by 92 and 98 percent, in the peat and deep layers, respectively. However, cDCE exhibited a no change (+1 percent) and strong increase (+2,570 percent) in the peat and deep layers. The average final ground water concentrations were 746, 612, and 3,090 µg/L PCE, TCE and cDCE, respectively, which were below the site specific remediation performance standards of 750, 5,500, 17,500 µg/L. No chlorinated ethylenes were measurable in samples with visible potassium permanganate but potassium permanganate was not evenly injected into the target formation.

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Abbreviations and Acronyms

AQCR	Air Quality Control Regions
AQMD	Air Quality Management District
ARARs	Applicable or Relevant and Appropriate Requirements
ASTM	American Association of Testing and Materials
ALSI	Analytical Laboratory Services Inc.
Aries	Aries Engineering, Inc.
As	Arsenic
bgs	Below ground surface
BFB	Bromofluorobenzene (tune performance compound for SW 8260)
CA	Chloroethane
CAA	Clean Air Act
Cl-ethenes	Chlorinated ethenes
CERI	Center for Environmental Research Information
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CPT	Cone penetrometer technology
CWA	Clean Water Act
Cr	Chromium
DCA	1,1-dichloroethane
DCE	1,1-dichloroethylene
°C	Degrees Celsius
cDCE	cis-1,2-dichloroethene
DNAPL	Dense non-aqueous phase liquid
DPT	Direct push technology
ECD	Electron capture detector
EW	Evaluation well
EPA	U.S. Environmental Protection Agency
ft ²	Square feet / square foot
ft ³	Cubic feet / cubic foot
Gal	Gallons
GC/MS	Gas chromatography/mass spectroscopy
g/L	Grams per liter
G&A	General and administrative
GW-1	Groundwater criteria for NHDES
GMP	Groundwater Management Permit
Hg	Mercury
H ₂ O ₂	Hydrogen peroxide
HSWA	Hazardous and Solid Waste Amendments
ICAL	Initial calibration standard
In	Inch
ID	Inner diameter
IDW	Investigation derived waste
ISCO	In situ chemical oxidation
ITER	Innovative Technology Evaluation Report

Abbreviations and Acronyms (Cont'd)

IW	Injection well
KMnO ₄	Potassium permanganate
Kg	Kilogram
KVA	Kilovolt amperes
LLC	Limited liability corporation
L	Liter
LL	Lower limit (of a specified confidence interval)
LCS	Laboratory control sample
LRL	Laboratory reporting limit
LDR	Land disposal restriction
LRPCD	Land Remediation and Pollution Control Division
MEC	formerly Nashua Electric Motors
MeOH	Methanol
MSDS	Material Safety Data Sheet
MS/MSD	Matrix spike/matrix spike duplicate
MCLs	Maximum contaminant levels
MCLGs	Maximum contaminant level goals
MIP	Membrane interface probe
m	Meter
m ²	Square meters
MDL	Method detection limit
MnO ₂	Magnesium oxide
MnO ₄	Permanganate
NH	New Hampshire
mg/L	Milligrams per liter
ml	Milliliters
MV	Millivolt
MW	Monitoring well
NAAQS	National ambient air quality standards
NCP	National Oil and Hazardous Substances Pollution Contingency Plan
NPDES	National Pollutant Discharge Elimination System
NPDWS	National primary drinking water standards
NRML-CI	National Risk Management Research Laboratory (EPA-Cincinnati)
NSCEP	National Service Center for Environmental Publications
NPDWS	National primary drinking water standards
NHDES	New Hampshire Department of Environmental Services
OSHA	Occupational Safety and Health Administration
ORD	Office of Research and Development (EPA)
OSWER	Office of Solid Waste and Emergency Response
OSC	On-scene coordinator
O&M	Operation and maintenance
OD	Outside diameter
ORP	Oxygen reduction potential
PCE	Perchloroethene or tetrachloroethene
PID	Photoionization detector
PPE	Personal protective equipment
PQL	Practical quantitation limit

Abbreviations and Acronyms (Cont'd)

PE	Professional engineer
PG	Professional geologist
PVC	Polyvinyl chloride
POD	Portable oxidant delivery system
POTW	Publicly owned treatment works
QAPP	Quality assurance project plan
QA	Quality assurance
QC	Quality control
Rfs	Response factors
RDL	Reporting detection limit
RPD	Relative percent difference
RSD	Relative standard deviation
RPM	Remedial project manager
RPS	Remediation Performance Standard
RCRA	Resource Conservation and Recovery Act
R&D	Research and development
SDWA	Safe Drinking Water Act
SAIC	Science Applications International Corporation
SARA	Superfund Amendments and Reauthorization Act
Se	Selenium
SOD	Soil oxidant demand
SOP	Standard operating procedure
SW-846	Test methods for evaluating solid waste, physical/chemical methods
SWDA	Solid Waste Disposal Act
SITE	Superfund Innovative Technology Evaluation
1,1,1-TCA	1,1,1-Trichloroethane
TCE	Trichloroethene
TER	Technology Evaluation Report
TSA	Technical Systems Audit
TSR	Technical Systems Review
TOC	Top of casing
TSCA	Toxic Substances Control Act
TSD	Treatment, storage, and disposal
UL	Upper limit (of specified confidence interval)
µg/Kg	Micrograms per kilogram
µg/L	Micrograms per liter
µV	Microvolts
USEPA	United States Environmental Protection Agency
VP	Vertical profile
VC	Vinyl chloride
VOCs	Volatile organic compounds
XDD	Xpert Design and Diagnostics, LCC
yd ³	Cubic yards
Zn	Zinc

Acknowledgments

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Cover Photographs: Clockwise from top left are **1)** Installation of Multi-Chamber Monitoring Well; **2)** Jugs of granular KMnO_4 (20 L); **3)** KMnO_4 in deep silt zone core sample (post-treatment sampling event) **4)** Tanker (left) of pre-mixed KMnO_4 oxidant solution (used for first injection) and water tanker (right) used for batching operation **5)** dark purple KMnO_4 in well purge water; **6)** Adding granular KMnO_4 during batch operation, and **7)** Back end of XDD Portable Oxidant Delivery (POD) trailer-mounted unit, showing distribution manifold and flow meters.

Executive Summary

Introduction

This report summarizes the findings of an evaluation of the Xpert Design and Diagnostic's (XDD) in situ chemical oxidation (ISCO) process at the former MEC Building site located in Hudson, New Hampshire. At this site, both soil and groundwater are contaminated with chlorinated volatile organic compounds (VOCs) due to releases from a former underground concrete storage tank. The tank was removed in May 1997.

Site contamination occurs as a dense non-aqueous phase liquid (DNAPL) at about 23-25 ft (7 to 7.6 m) below land surface (bls) and as dissolved phase VOCs in soil and groundwater, primarily from 6-25 ft (1.8 to 7.6 m) bls. The VOCs consist primarily of chlorinated ethenes, including perchloroethylene (PCE), trichloroethylene (TCE), cis-1, 2-dichloroethylene, (cDCE), vinyl chloride (VC), and toluene. Ethane compounds, such as 1,1,1-trichloroethane (1,1,1-TCA) and 1,1-dichloroethane (1,1-DCA), are also present. The soil contamination is concentrated in three stratigraphic zones occurring between 6 and 25 feet (1.8 to 7.6 m) below land surface (bls); including an upper gravelly silty-sand zone (6-13 ft bls), a thin peat zone (12-14 ft), and a fine sandy-silt zone (14-26 ft). The DNAPL occurs at the interface of the sand-silt zone and a basal till. The three stratigraphic zones were targeted for ISCO treatment.

Project Objectives

There were two primary objectives for the demonstration; one for soil and one for groundwater. The soil objective was to determine if the XDD's process could reduce concentrations of the chlorinated ethenes PCE, TCE, cDCE, and VC by 90% over the course of the demonstration comparing pre-treatment to post-treatment. The 90% reduction objective was to be determined on a "paired sample evaluation" (i.e., pre-treatment versus post-treatment samples collected in close proximity to one

another). The comparison was to be conducted for each soil zone and for all three zones combined.

The primary objective for groundwater was to determine if the XDD's process could reduce concentrations of specific VOCs to below their respective 0.5% solubility limit based on post-treatment results. VOCs having such a Remediation Performance Goal (RPG) included PCE (750 µg/l), TCE (5,500 µg/l), and cDCE (17,500 µg/l). The groundwater objective also specified that 90% of the samples evaluated from post-treatment sampling were required to meet this goal (i.e., If 10 pre-treatments samples were above the limit to start, at least 9 post-treatment results would have to be below the limit).

Treatment Design

XDD's treatment design included installation of three well clusters within an approximate 1,200 ft² area to serve as injection points for potassium permanganate (KMnO₄), the oxidant chosen by XDD for treating the site VOCs. The three well clusters were installed to form a triangle, each cluster being about 18 feet apart and each consisting of a well screened in each of the three stratigraphic zones targeted for treatment. Each well cluster injection had an estimated diameter of influence was 20 feet. Thus, injections were to overlap laterally.

Oxidant Injection & Monitoring

Injection of KMnO₄ into all three well clusters began in early June 2005. Just prior to this first injection the EPA SITE Program sampled soils and groundwater to establish baseline VOC concentrations. Soon after the start of oxidant injection, there was noted short-circuiting of KMnO₄ to the surface in two of the well clusters. This was evidenced by KMnO₄ oozing from surface cracks shortly after injecting the oxidant into deep wells screened at 20-25 ft (6.1-7.6 m) bls. Due to suspected failed well seals,

the two well clusters in question were replaced and a second injection was conducted in October of 2005 into replacement wells. When combining the two injections, just over 15,000 gallons (5,640 L) and approximately 3,700 lbs (1,680 kg) of KMnO_4 was injected into the three well clusters combined, at concentrations ranging from 25 to 40 g/l. Of the total mass of KMnO_4 injected, approximately 1,860 lbs (840 kg) was injected into the deep zone, approximately 1,500 lbs (680 kg) was injected into the middle peat zone, and approximately 320 lbs (145 kg) was injected into the shallow zone.

Following the injection phase of the project, groundwater was monitored to gain insight into the ongoing effectiveness of the process. The monitoring included noting the visual presence of KMnO_4 , tracking of a bromide tracer used for the first injection, and analyzing samples for target VOCs and metals. For each event a total of 15 wells were sampled (five for each of the three zones). Following the initial baseline event and immediately preceding the second injection, a second groundwater baseline was needed to establish baseline VOC concentrations for the two replacement injection well clusters. Two additional intermediate events were conducted after both injections but well before the final post-treatment soil and groundwater sampling event.

The final post-treatment sampling event for both soils and groundwater was conducted in March 2006 about nine months after the first injection and just over five months after the second injection. At this time KMnO_4 was still visible in the deep zone groundwater and was observed in deep zone soil cores. However, KMnO_4 was not observed in soil or groundwater collected from the shallow or middle peat zones. In fact KMnO_4 was visually observed in just one peat zone well (IW-3i) following oxidant injection and was never visually observed in shallow zone groundwater samples collected after the injections.

Results - Introduction

The two primary objectives were evaluated using the VOC analytical results from the pre-treatment (baseline) and post-treatment (final) sampling events. **Table ES-1** provides a general overall summary of these results. For determining if the soil contaminant removal efficiency was 90% or greater on a paired soil sample basis (i.e., the primary objective), eligible sample pairs were selected for statistical evaluation. (Note: due to high laboratory reporting limits resulting from field methanol extractions of soils, some sample pairs lacked quantified data results and so some of these pairs were not deemed eligible for evaluation).

The primary objective for groundwater was to evaluate the effectiveness of XDD's process in reducing concentrations of PCE, TCE, and cDCE in groundwater to below their corresponding RPS of 750 $\mu\text{g/l}$, 5,500 $\mu\text{g/l}$, and 17,500 $\mu\text{g/l}$. The QAPP specified that to meet this objective more than 90% of eligible samples had to meet those regulatory criteria, as to reject the null hypothesis (i.e., have pre-treatment concentrations reduced to below the RPS based on post-treatment sampling results). However, there were fewer than expected instances where criteria were exceeded prior to treatment. As a result, only those instances where such criteria were exceeded could be evaluated statistically to determine if the objective was met.

Soil VOC Results

The soil VOC data was highly variable. High sample concentration variability at DNAPL sites is commonly observed, particularly at sites with heterogeneous lithologies. Of the four critical VOCs evaluated (PCE, TCE, cDCE, and VC), TCE had the best overall percentage of sample pairs showing reductions > 90% (40.9% for all zones combined). However, VC fared the best for percentage of eligible pairs showing contaminant decreases of any magnitude. For all zones combined, 82.1% of eligible sample pairs for VC showed contaminant reductions from baseline to final sampling; including 88.9% in the shallow zone and 70% in the peat zone.

Soils were also statistically evaluated on an average pre-treatment versus post-treatment basis, using the hypothesis test suggested in the Quality Assurance Project Plan (QAPP) that the process will remove 90% of contamination. For this evaluation, all pre-treatment and post-treatment soil data was used so that pre- and post-treatment sample population was equal. This meant including non-detect values, which were assigned a value of one half ($\frac{1}{2}$) the laboratory reporting limit. The null hypothesis tested is that the contamination removed does not exceed 90%. This null hypothesis was tested for 16 sets of analyte-zone combinations (i.e., the four combinations for PCE would be PCE-shallow zone, PCE-peat zone, PCE-deep zone, and PCE-all three zones combined). Accepting the null hypothesis results in a finding that the process does not meet demonstration objectives; rejecting the null hypothesis results in a finding that the process meets the demonstration objective. In using a two-sided 95% confidence interval to test a one-sided hypothesis, the null hypothesis could not be rejected for any of the 16 combinations. Thus, the objective was not met for any combination.

Table ES-1. Summary of Results.

Soil VOC Treatment					
Paired Analysis	PCE				
	Shallow Zone	5 of 17 eligible pairs show a decrease; 4 of 17 eligible pairs show a decrease > 90%			
	Middle (Peat) Zone	7 of 9 eligible pairs show a decrease; 4 of 9 eligible pairs show a decrease > 90%			
	Deep Zone	11 of 15 eligible pairs show a decrease; 6 of 15 eligible pairs show a decrease > 90%			
	All Zones Combined	23 of 41 eligible pairs show a decrease; 14 of 41 eligible pairs show a decrease > 90%			
	TCE				
	Shallow Zone	6 of 14 eligible pairs show a decrease; 4 of 14 eligible pairs show a decrease > 90%			
	Middle (Peat) Zone	6 of 7 eligible pairs show a decrease; 4 of 7 eligible pairs show a decrease > 90%			
	Deep Zone	1 of 1 eligible pair shows a decrease; and 1of 1 eligible pair shows a decrease > 90%			
	All Zones Combined	13 of 22 eligible pairs show a decrease; 9 of 22 eligible pairs show a decrease > 90%			
	cDCE				
	Shallow Zone	14 of 26 eligible pairs show a decrease; 4 of 26 eligible pairs show a decrease > 90%			
	Middle (Peat) Zone	14 of 19 eligible pairs show a decrease; 6 of 19 eligible pairs show a decrease > 90%			
	Deep Zone	1 of 2 eligible pairs show a decrease; 0 of 2 eligible pairs show a decrease > 90%			
	All Zones Combined	29 of 47 eligible pairs show a decrease; 10 of 47 eligible pairs show a decrease > 90%			
	VC				
Shallow Zone	16 of 18 eligible pairs show a decrease; 8 of 18 eligible pairs show a decrease > 90%				
Middle (Peat) Zone	7 of 10 eligible pairs show a decrease; 2 of 10 eligible pairs show a decrease > 90%				
Deep Zone	There were no eligible pairs in the deep zone.				
All Zones Combined	23 of 28 eligible pairs show a decrease; 10 of 28 eligible pairs show a decrease > 90%				
Averaged Results		Number of Samples	Average Pre-Treatment Concentration (µg/Kg)	Average Post-Treatment Concentration (µg/Kg)	% Change
	PCE				
	Shallow Zone	30	4,721	54,395	+ 1,050
	Middle (Peat) Zone	27	21,120	1,105	- 94.8
	Deep Zone	30	194,523	12,586	-93.5
	All Zones Combined	87	75,259	23,440	-68.9
	TCE				
	Shallow Zone	30	962	7,099	+ 638
	Middle (Peat) Zone	27	2,825	291	- 89.7
	Deep Zone	30	306	102	-66.7
	All Zones Combined	87	1,314	2,573	+ 95.8
	cDCE				
	Shallow Zone	30	4,400	3,983	- 9.48
	Middle (Peat) Zone	27	17,217	15,601	- 9.39
	Deep Zone	30	126	741	+ 488
	All Zones Combined	87	6,904	6,471	- 6.27
	VC				
	Shallow Zone	30	524	118	- 77.5
	Middle (Peat) Zone	27	4,700	6,693	+ 42.4
	Deep Zone	30	109	103	- 5.5
All Zones Combined	87	1,677	2,154	+ 28.4	

Table ES-1. Summary of Results (Continued).

Groundwater VOC Treatment					
	VOC exceeding criteria & Well which exceeded	Pre-Treatment Concentration (µg/l)	Post-Treatment Concentration (µg/l)	Remediation Performance Standard (µg/l)	Goal Attained
Analysis of Individual Wells Having VOCs above Criteria	PCE in IW-1s (Shallow Zone)	5,200	1,090 / 1,360 Avg. = 1,225	750	No
	PCE in EW-2s (Shallow Zone)	6,830	4,190 / 5,560 Avg. = 4,875	750	No
	PCE in EW-4d (Deep Zone)	2,310	< 0.5 / < 0.5 Avg. = < 0.5	750	Yes
	TCE in IW-1s (Shallow Zone)	11,200	572 / 766 Avg. = 669	5,500	Yes
	TCE in EW-2s (Shallow Zone)	7,090	4,810 / 7,430 Avg. = 6,120	5,500	No
	cDCE in IW-1s (Shallow Zone)	31,000	3,630 / 3,620 Avg. = 3,625	17,500	Yes
	cDCE in IW-1i (Middle Peat Zone)	50,100	20,100 / 16,700 Avg. = 18,400	17,500	No
Analysis of Zone having concentrations of PCE above Criteria	PCE in the five Shallow Zone Wells	2,450 (avg. of 5 values)	1,390 (avg. of 10 values)	750	No
Other Observations					
KMnO ₄ in Groundwater	<p>KMnO₄ visually observed in deep zone samples for all deep wells after the first injection up through final event sampling; indicating good presence and persistence in deep zone.</p> <p>KMnO₄ not observed in any shallow zone samples after either injections; but detection of bromide tracer in the same wells indicates possible exhausting of oxidant by high SOD.</p> <p>KMnO₄ observed in just one intermediate (peat) zone sample on one occasion (i.e., about 4 months after first injection event at the point of injection). But bromide tracer present. This also indicates possible exhausting of oxidant by high SOD.</p>				
Metals in Groundwater	There is no evidence indicating that metals were mobilized by XDD's process. On an average basis, concentrations of most of the metals analyzed showed little change throughout the five groundwater sampling events.				
Estimated Cost (XDD ISCO Process)	Using a hypothetical site having characteristics similar to the demonstration site, a size of about 100,000 ft ³ and 3,700 yd ³ (i.e., 3.7 times the volume treated for the demonstration), the cost for implementing a 10-injection well ISCO treatment system and monitoring effectiveness over a 1-month period is estimated at \$139,000				

However, it should be noted when using a two-sided 95% confidence interval to test a one-sided hypothesis, the hypothesis is actually being tested at the 97.5% level. Testing the hypothesis at the 90% hypothesis testing level results in rejecting the null hypothesis (i.e., meeting the objective) in one instance; namely PCE in the peat zone. PCE had a measured 94.8% decrease in the peat zone; from a 21,120 µg/kg baseline average to a 1,105 µg/kg post-treatment average.

Soil was also qualitatively evaluated via cone penetrometer technology (CPT) and membrane interface probe (MIP) surveys. A total of 18 CPT /MIP survey points were completed prior to baseline sampling. During this survey, CPT/MIP logs were used to identify specific subsurface zones and the highest concentration areas to target for soil sampling. Although the final survey was scaled down, results were fairly consistent with the quantitative laboratory data. In the deep zone, there was a slight decrease of the PID signal in the vicinity of the two CPT/MIP points located within the more contaminated portion of the DNAPL plume. However, in the shallow zone there was a marked increase of the PID signal at those same locations.

Groundwater - VOC Results

On an individual well basis, there were only seven instances where any of the three critical VOCs exceeded their respective RPS prior to treatment. Of these seven instances VOCs were reduced to below the criteria in three cases and were reduced to very close to the criteria in two other instances. However, statistically, the null hypothesis was not rejected for any of the three compounds.

On a per zone basis, there were apparent reductions from baseline to final in the shallow zone for PCE (43%), TCE (60%), and cDCE (61%), however the null hypothesis was accepted because out of five instances where the pre-treatment value exceeded the criteria, reductions to below the criteria occurred in just three cases. The shallow zone, in fact, was the only zone of the three that had an average pre-treatment concentration for a particular contaminant above the criteria. When averaging results for all shallow zone wells, PCE averaged 2,450 µg/l in the shallow zone prior to treatment, which exceeded its RPS of 750 µg/l. PCE averaged 1,390 µg/l following treatment.

Averaged results in the intermediate peat zone showed sharp increases in PCE and TCE, and a sharp decrease in cDCE. The majority of this variation, however, was attributable to one well which was closest to the source area. The only VOC measured pre-treatment above its criteria in an intermediate well was cDCE, which did show a significant reduction from pre- to post-treatment (from

50,100 µg/l to an average of two sample results of 18,400 µg/l). However, this final result was still above its criteria of 17,500 µg/l). For the intermediate zone the null hypothesis was not rejected for each of the three contaminants.

Averaged results of all deep zones wells showed no appreciable change in pre- vs. post-treatment concentration for the three VOCs. For the deep zone the null hypothesis was not rejected for each of the three contaminants. However PCE, the only VOC measured pre-treatment above its criteria in a deep well, did show a significant reduction to below the criteria (from 2,310 µg/l to < 0.5 µg/l).

When all zones are combined as a single sample set (i.e., representing all site groundwater) PCE was the only VOC of the three that had a baseline average above its criteria of 750 µg/l. The average PCE baseline concentration was 1,020 µg/l and the average final PCE concentration was 746 µg/l. For the combined zone scenario, the null hypothesis was accepted for each of the three contaminants, including PCE.

Groundwater - KMnO₄

Potassium permanganate, KMnO₄, is visually observable in groundwater at relatively low concentrations (i.e., 1 ppm). Therefore, following the initial injection of the oxidant, KMnO₄ was visually monitored in the groundwater during sample collection. There were two observations of note regarding the presence of KMnO₄.

1. KMnO₄ was visually seen in all deep zone wells following the first injection, but was seen in only one well on one occasion in the intermediate zone (a well receiving injected KMnO₄ about four months earlier). KMnO₄ was not observed in any shallow zone well at any time.
2. In most instances, target VOCs were reduced to below detectable levels when KMnO₄ was visually present.

Due to its higher capacity to receive fluids, more KMnO₄ was injected into the deep zone relative to the peat zone and, especially, the shallow zone. Taking this into account, and knowing that the peat zone contained substantial humic material, the two observations above imply that the mass of KMnO₄ injected into the shallow and peat zones may not have been sufficient to overcome high SOD suspected in these two zones. The detection of a bromide tracer ion at some measurable concentration in all shallow and peat zone wells following the first injection imply that the initial injected oxidant solution (containing KMnO₄) was indeed injected to those areas.

On the other hand, the mass of KMnO_4 injected into the deep zone appears to have been more than sufficient to treat deep zone groundwater, especially since the KMnO_4 persisted long after target VOCs were apparently oxidized.

This observation is more fully supported by the soil oxidant demand (SOD) test for the soils at the MEC site, performed by XDD (2005). They found that the shallow, gravelly sands required 4.6 to 21.0 g KMnO_4 per Kg sand; 104.7 to 146.9 g KMnO_4 per Kg peat; and 1.8 to 5.6 g KMnO_4 per Kg deep silty sand.

Groundwater - Metals Results

There were no data suggesting that metals were mobilized due the XDD process. On an average basis, most of the metals analyzed did not change significantly in concentration throughout the five groundwater sampling events. Some metals (e.g., As, Be, Cr, Mg, and Zn) actually showed decreased concentrations in the shallow zone from baseline to final sampling events. Substantial increases in average manganese (Mn) concentrations in the peat and deep groundwater zones for the second baseline sampling event is attributed to the influx of Mn from the initial injection of KMnO_4 into a nearby injection

well cluster. Increases of Cr and Mg in the deep zone groundwater following both the first and second injections, and an increase in Se in the deep zone groundwater following the second injection were not sustained as the average concentrations of these three metals reverted back to an average value very close to baseline levels.

Costs of applying the XDD ISCO process were estimated for a larger scale hypothetical site that was approximately 3.7 times the treatment area of the demonstration site. The cost to install a 10-injection well ISCO treatment system, utilizing XDD's POD to deliver oxidant to approximately 100,000 ft^3 (3,700 yd^3) of DNAPL-contaminated soil and groundwater, and monitor effectiveness over a 1-month period is estimated at \$139,000. If further treatment were required (i.e., re-injection), thus extending the treatment period, the cost would increase by a considerable amount. The largest cost categories for the application of the XDD ISCO technology at a site having characteristics similar to those described for the hypothetical site are 1) consumables and supplies (41%) and 2) labor (21%), together accounting for 62% of the total cost. The other major costs, as estimated, include startup and fixed (18%), and analytical services (9.7%).

Section 1.0 Introduction

This Section provides background information about this Superfund Innovative Technology Evaluation (SITE) demonstration, the SITE Program, discusses the purpose of this Innovative Technology Evaluation Report (ITER), and describes the Xpert Design and Diagnostic's (XDD) in situ chemical oxidation (ISCO) process using potassium permanganate (KMnO_4) to treat chlorinated ethenes in soil and groundwater. Key contacts are listed at section's end for inquiries regarding additional information about the SITE Program, XDD's technology, and the Demonstration.

1.1 Background

XDD's ISCO process using KMnO_4 was demonstrated under the SITE Program from May 2005 to May 2006 at the former MEC Building site in Hudson, New Hampshire. The specific area treated at the former MEC site was a relatively small 1,200 ft^2 (114 m^2) area that was characterized as being contaminated with a dense non-aqueous phase liquid (DNAPL) and dissolved-phase volatile organic compounds (VOCs), primarily chlorinated ethenes.

The source of the contamination was a concrete holding tank located adjacent to what is referred to as the "former MEC Building". MEC (formerly Nashua Electric Motors) repaired and rebuilt electric motors at the property from the mid-1970s up until approximately 1990. The subsurface concrete holding tank, which had reportedly overflowed during their tenure, caused the contamination of underlying soil and groundwater. The tank was removed in May 1997.

The general contaminant source area is defined in **Figure 1-1**, which is from a Remedial Action Plan prepared in January 2001 (Aries Engineering, 2001). The approximate 80 ft long x 50 ft wide x 26 ft deep plume (24 m x 15 m x 7 m) depicted in Figure 1-1 was generated from 1) initially

conducting vertical profiles (VPs) of soil and groundwater VOC headspace data via a Photovac Gas Chromatograph (GC); 2) comparing those data to a subset of samples that were analyzed in a laboratory; and 3) calculating a ratio between the laboratory-analyzed data and headspace data to generate estimated VOC concentrations. Aries conducted this characterization in May 1998. Soil and groundwater at the site are contaminated, primarily with perchloroethylene (PCE), trichloroethylene (TCE), cis-1,2-dichloroethylene, (cDCE), and vinyl chloride (VC).

The USEPA SITE program conducted a preliminary site assessment at the former MEC during 2003. Sampling and analysis of monitoring wells in the vicinity of the former MEC building revealed VOCs in excess of GW-1 standards. The highest concentrations detected were near the former tank spillage. GW-1 standards are essentially equivalent to federal drinking water standard maximum contaminant levels (MCLs). Specifically the New Hampshire Department of Environmental Services (NHDES) regulates VOCs at the site that had exceeded their respective GW-1 numeric cleanup standards at least once in 2003. These include the following VOCs:

- Perchloroethene (PCE)
- Trichloroethene (TCE)
- cis-1,2 Dichloroethane (cDCE)
- Vinyl Chloride (VC)
- Toluene
- 1,1,1-Trichloroethane (1,1,1-TCA)
- 1,2-Dichloroethane (1,1-DCA)

The areal extent of the pilot-scale treatment system's injection and monitoring wells was approximately 1,200 ft^2 (~35 ft x 35 ft) or 114 m^2 . The locations of the oxidant injection wells and the monitoring wells are provided in Section 4.0 as Figure 4-1.

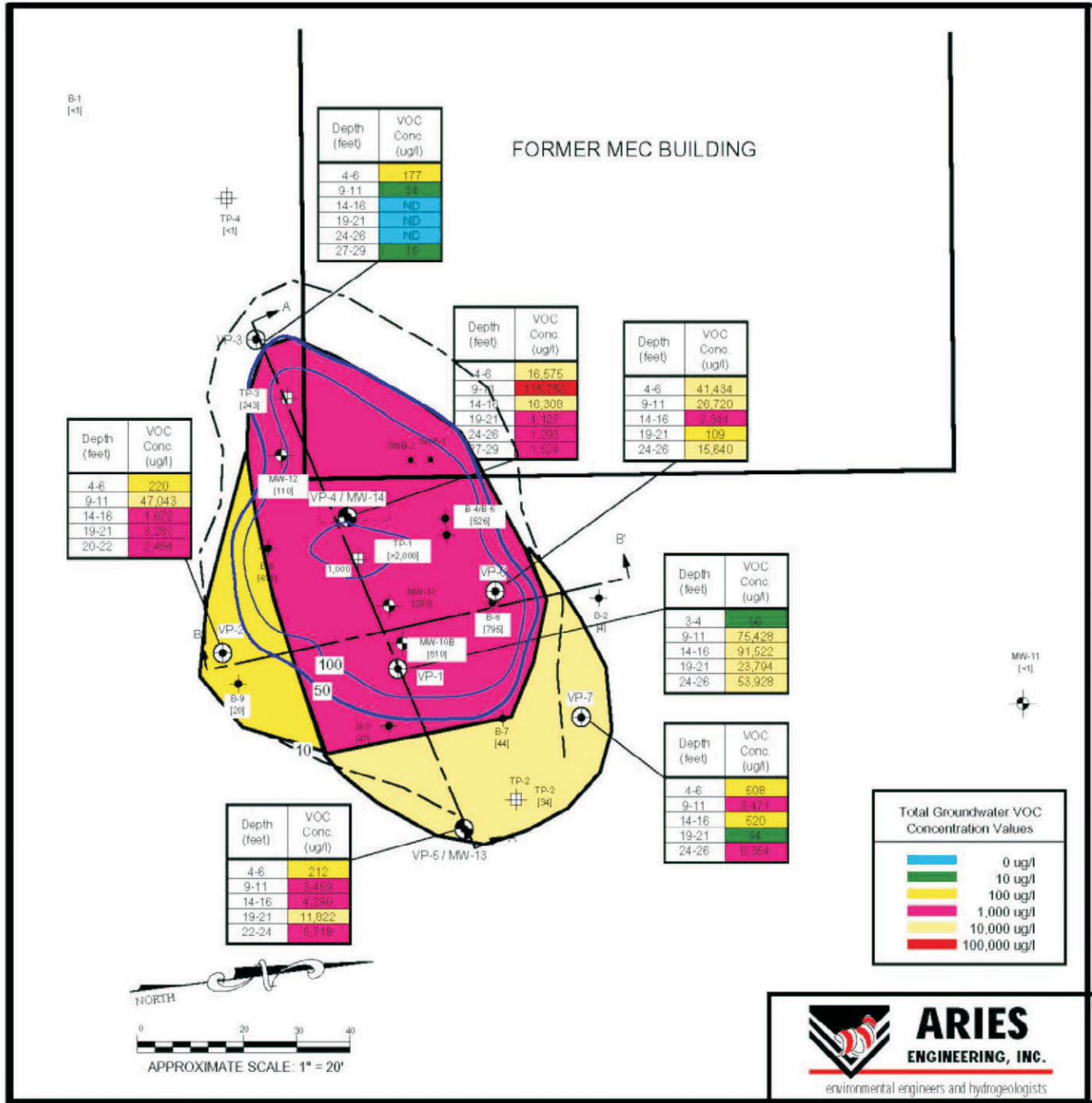


Figure 1-1. Former MEC Building Source Area (Source: Aries Engineering Inc., January 2001).

The demonstration of XDD's ISCO process was initiated in May of 2005 with pre-treatment cone penetrometer technology and membrane interface probe (CPT/MIP) characterization, followed by baseline soil sampling and the installation of three clusters of injection wells and three multi-chambered monitoring wells aligned parallel with the general northeasterly groundwater flow direction. The well installation was followed by baseline groundwater sampling. The demonstration concluded in March of 2006 with final post-treatment soil and groundwater sampling. **Figure 1-2** is a time line of major events that occurred during the demonstration.

Both injection well clusters and multi-chamber well clusters were screened at three separate depth intervals; 4-9 ft (1.2-2.7 m) bls, 13-14 ft (4-4.3 m) bls, and 20-25 ft (6.1-7.6 m) bls to target an upper gravelly sand zone, a thin zone of peat, and a lower sandy-silt zone, respectively. The injection wells also served as monitoring wells. Thus, there was a total of 15 monitoring points; five for each of the three soil horizons.

The injection wells were spaced approximately 15-20 ft (4.6-6.1 m) apart from each another to provide adequate coverage of the demonstration area and provide overlap of a calculated 10-foot (3 m) radius of influence.

There were two primary objectives of the demonstration: 1) to determine if the XDD ISCO process could remove 90% of target VOCs from paired soil samples in all three horizons, and 2) to determine if the process could reduce concentrations of critical VOCs in groundwater to below the following Remediation Performance Standards (RPS):

▶	PCE	750 µg/l
▶	TCE	5,500 µg/l
▶	cDCE	17,500 µg/l
▶	VC	no Standard

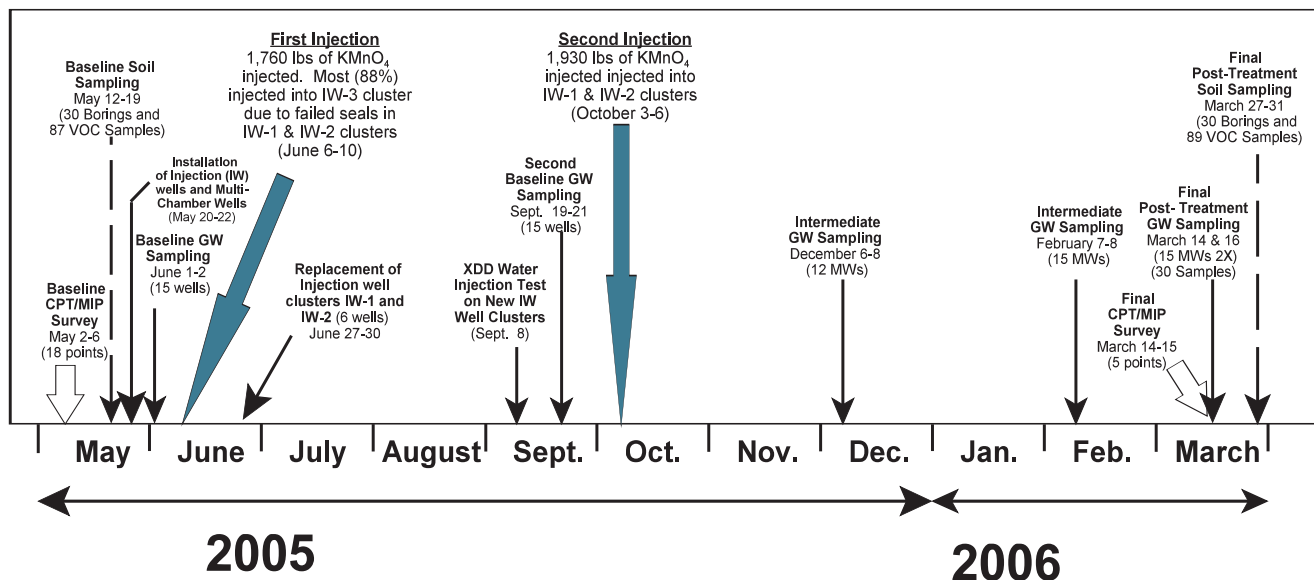


Figure 1-2. Time Line of Demonstration Events.

1.2 Brief Description of the SITE Program

The U.S. Environmental Protection Agency's (EPA) SITE Program was established by EPA's Office of Solid Waste and Emergency Response and the Office of Research and Development (ORD) in response to the 1986 Superfund Amendments and Reauthorization Act, which recognized a need for an "Alternative or Innovative Treatment Technology Research and Demonstration Program." The SITE Program is administered by the ORD National Risk Management Research Laboratory (NRMRL) in the Land Remediation and Pollution Control Division (LRPCD), headquartered in Cincinnati, Ohio. The SITE Demonstration Program encourages the development and implementation of:

1. Innovative treatment technologies for hazardous waste site remediation, and
2. Monitoring and measurement.

In the SITE Demonstration Program, the technology is field-tested on hazardous waste materials. Engineering and cost data are gathered on the innovative technology so that potential users can assess the technology's applicability to a particular site. Data collected during the field demonstration are used to assess the performance of the technology, the potential need for pre- and post-processing of the waste, applicable types of wastes and waste matrices, potential operating problems, and approximate capital and operating costs.

1.3 The SITE Demonstration Program and Reports

In the past technologies have been selected for the SITE Demonstration Program through annual requests for proposal (RFP). EPA reviewed proposals to determine promising technologies for use at hazardous waste sites. Several technologies also entered the program from current Superfund projects, in which innovative techniques of broad interest were identified for evaluation under the program. More recently, EPA has selected sites that would require innovative technologies for clean-up.

Once the EPA has accepted a proposal, cooperative arrangements are established among EPA, the developer, and the stakeholders. Site owners and Developers are responsible for implementing, operating and/or maintaining their innovative systems at a selected site, and are expected to pay the costs to transport equipment to the site, operate and/or maintain any equipment on-site during the demonstration, and remove the equipment from the

site. EPA is responsible for project planning, sampling and analysis, quality assurance and quality control, preparing reports, and disseminating information.

Results of Demonstration projects are usually published in three documents: the SITE Demonstration Bulletin, the Technology Capsule, and the ITER. The Bulletin describes the technology and provides preliminary results of the field demonstration. The Technology Capsule provides more detailed information about the technology, and emphasizes key results of the field demonstration. The ITER provides detailed information on the technology investigated, a categorical cost estimate, and all pertinent results of the field demonstration. A Technology Evaluation Report (TER) is sometimes prepared, but is available by request only. The TER serves as verification documentation contains a more comprehensive presentation of the analytical data (i.e., raw data packages, etc.) collected during the demonstration. For the demonstration of the XDD ISCO process, this ITER is intended for use by remedial managers for making a detailed evaluation of the technology for a specific site and waste.

1.4 Purpose of the Innovative Technology Evaluation Report (ITER)

This ITER provides information on the XDD in situ chemical oxidation process for treating primarily chlorinated ethenes in soil and groundwater. The ITER includes a comprehensive description of this demonstration and its results and is intended for use by EPA remedial project managers, EPA on-scene coordinators, contractors, and other decision-makers carrying out specific remedial actions. The ITER is designed to aid decision-makers in evaluating specific technologies for further consideration as applicable options in a particular cleanup operation.

To encourage the general use of demonstrated technologies, the EPA provides information regarding the technology applicability to specific sites and wastes. The ITER includes technology-specific information on cost, advantages, disadvantages, and limitations; and discusses desirable site-specific characteristics. Each demonstration evaluates the performance of a technology treating a specific waste matrix. Characteristics of other wastes and other sites may differ from the characteristics of the treated waste; therefore, a successful field demonstration of a technology at one site does not necessarily ensure applicability to other sites. Only limited conclusions can be drawn from a single field demonstration.

1.5 Technology Description

In situ chemical oxidation involves the introduction of a chemical oxidant into the subsurface for the purpose of transforming ground water or soil contaminants into less harmful chemical species. The process is non-selective; therefore, any oxidizable material reacts. Consequently, the natural humic content of the soil that contacts oxidant is an important measured parameter.

XDD's ISCO process utilizes several oxidants. Specific to this demonstration, KMnO_4 was used to treat soil and groundwater contaminated with chlorinated VOCs. The KMnO_4 is the less expensive of the two common MnO_4 oxidants (the other being NaMnO_4). KMnO_4 is widely and commonly used in the wastewater treatment industry and therefore is readily available from several manufacturers.

Granular KMnO_4 is packaged and shipped in 20 Liter plastic jugs, each weighing about 55 pounds. KMnO_4 is mixed in large tanks at desired dosages with potable water, filtered to remove solids (e.g., silica) and metered for injection through a manifold and high-pressure hoses.

There are several ways to inject oxidant to the desired contaminant location. The most common method, as was the case during the demonstration, is via traditional injection wells (2 inch ID is preferred). However XDD has utilized Geoprobe push points, infiltration galleries, and even trenches and pits for shallow zone treatments. For bedrock applications, they have utilized wells equipped with packers for targeting specific fractured bedrock zones. Other manufacturers have injected in situ oxidants by hydraulic or pneumatic fracturing.

As shipped in granular form, KMnO_4 is a strong oxidizer. It is a known irritant to the respiratory system, highly corrosive to the skin, and potentially fatal if swallowed. When handling the dark purple crystalline solid during batching operations, XDD personnel wear respirators and chemical-resistant clothing (e.g., coated tyvek) to avoid breathing dusts and dermal contact. Residuals potentially generated during a full-scale ISCO treatment are

contaminated drill cuttings generated from well installation, purge water from well development and sampling of monitoring wells, and personal protective equipment.

1.6 Key Contacts

Additional information regarding XDD's technology and the SITE Program can be obtained from the following sources:

Demonstration Technology Contact

Ken Sperry, Branch Manager.
Xpert Design and Diagnostics, LLC
22 Marin Way, Unit # 3
Stratham, NH 03885
Phone: (603) 778-1100
Fax: (603) 778-2121
Web Site: www.xdd-llc.com
E-mail: sperry@xdd-llc.com

The SITE Program

Michelle Simon, Ph.D., P.E.
National Risk Management Research Laboratory
U.S. Environmental Protection Agency
26 West Martin Luther King Drive
Cincinnati, OH 45268
Phone: (513) 569-7469
Web Site: www.epa.gov/ord/SITE
E-mail: simon.michelle@epa.gov

Information on the SITE Program is available through the following on-line information clearinghouses:

- The SITE Home page (www.epa.gov/ORD/SITE) provides general program information, current project status, technology documents, and access to other remediation home pages.
- The OSWER CLU-In electronic bulletin board (<http://www.clu-in.org>) provides information on innovative treatment and site characterization technologies while acting as a forum for all waste remediation stakeholders.

Section 2.0

Technology Applications Analysis

This section addresses the general applicability of the Xpert Design and Diagnostic's (XDD) ISCO process to sites having soil and groundwater contaminated with chlorinated VOCs. The analysis is based on observations made during the SITE Program Demonstration, and from additional information received from XDD (the developer of a specialized ISCO treatment process). The results of this SITE Demonstration are presented in Section 4.0 of this report. XDD had the opportunity to discuss the applicability, other studies, and performance of the technology in **Appendix A**.

2.1 Key Features of the XDD ISCO Process

There are four key features comprising XDD's ISCO process. These include the following:

- ◆ Oxidant
- ◆ Portable Oxidant Delivery (POD) System
- ◆ Oxidant Injection Points
- ◆ Monitoring Wells

Each of these key features is discussed in the following paragraphs.

2.1.1 Oxidant

Depending on the contaminants to be treated XDD utilizes either persulfate ($S_2O_8^{2-}$) or permanganate (MnO_4^-) as the oxidizing agent. Potassium permanganate ($KMnO_4$) was the chosen oxidant at the former MEC Building site due to its ability to economically treat chlorinated ethenes. MnO_4^- is a very stable oxidant and can persist for several months in the subsurface. This stability makes it a good choice for subsurface applications (i.e., fewer injection events, fewer wells to treat the target area, and the ability to more effectively penetrate into low permeability zones). XDD utilizes two forms of MnO_4^- to treat organic contaminants,

1) sodium permanganate ($NaMnO_4$) and 2) potassium permanganate ($KMnO_4$). Each has its distinct advantages and disadvantages as discussed below.

$NaMnO_4$

Higher concentrations of MnO_4^- can be injected in the sodium form as compared to the potassium form. The most significant drawback to $NaMnO_4$ is cost ($NaMnO_4$ is five to seven times more expensive than $KMnO_4$).

$NaMnO_4$ is handled in a liquid form which is preferred over the solid (i.e., granular) $KMnO_4$ from a health and safety and materials handling perspective. The application of this liquid oxidant is simpler than injecting $KMnO_4$, which has to be pre-mixed with potable water at the desired concentration prior to injection. But because of cost, a precise knowledge of where contaminant(s) are situated is needed to implement a surgical injection strategy.

$KMnO_4$

$KMnO_4$ is preferred over $NaMnO_4$ when the subsurface lithology is complex or when soils with high humic content. This is because $NaMnO_4$ is much more expensive and thus must be precisely injected to accessible zones and not be exhausted by naturally occurring organic material. An assessment of SOD is needed to determine how much reagent may be wasted on oxidizing benign organic compounds.

$KMnO_4$ is a dark purple/bronze solid, produced in either a crystalline or free-flowing powder form. It is shipped in 20 Liter plastic jugs and has a reported shelf life of one year. It is readily manufactured due to its common use in the wastewater treatment industry and usually contains silicon dioxide as an anti-caking agent. Consequently, the created oxidant solution is filtered prior to injection to remove such unwanted solids that may clog well screens.

Table 2-1. Properties of KMnO₄.	
<i>Appearance:</i>	Dark purple/bronze odorless solid in crystalline or free-flowing powder form.
<i>Molecular Wt.</i>	158.04
<i>Spec. Gravity</i>	2.7 @ 15 °C
<i>Bulk Density:</i>	90-100 lbs/ft ³
<i>Flash Point:</i>	Not combustible
<i>Storage:</i>	Strong Oxidizer: Store in cool, dry, non-freezing area away from direct sunlight, intense heat, & combustible materials.
<i>Shelf Life:</i>	One year @ 13-32 °C
<i>Handling:</i>	Avoid dermal, gloves/goggles suggested
<i>Hazard Overview:</i>	Strong Oxidizer
<i>HMIS Ratings</i>	Health hazard - 3 (moderate) Fire hazard - 0 (minimal) Physical hazard - 0 (minimal)
<i>Water Soluble:</i>	6.38 g/100 cc @ 20 °C
<i>Sources: CHEM ONE Product Specification, rev. 2/23/04; Material Safety Data Sheet, re. 7/31/03; XDD Personal Comm., 01/26/06.</i>	

2.1.2 Portable Oxidant Delivery System

XDD's Portable Oxidant Delivery ("POD") System is an array of equipment mounted inside a utility trailer (13 by 7 ft wide, not including a trailer hitch assembly). The POD can be towed with a heavy-duty pickup truck. The following primary equipment is contained within the POD.:

- Two 300-gallon (1,140 L) chemical oxidant batching tanks which can be pumped in unison to transfer oxidant to injection wells.
- Dual oxidant metering pumps (for injecting KMnO₄ and NaMnO₄ simultaneously)
- Process Equipment (i.e., high durable/chemical-resistant totalizer flow meters) for monitoring flow rates, temperature, and pressure.
- Filtration system to remove particulate matter in the injection fluid stream.
- Manifold designed to simultaneously deliver oxidant in up to 6 injection wells.

During the demonstration, XDD performed batch operations within a bermed area in proximate vicinity to the POD. Batching was conducted in two larger chemical tanks, each having a capacity of 500 gal. (1,890 L). Jugs, each containing about 20 Liters of granular KMnO₄, were emptied into these tanks and mixed with potable water pumped from a water tanker trailer at the desired liquid KMnO₄ concentration. The KMnO₄/water solution was then mixed for ½-1 hour with a sump pump, routed through two cannister filters connected in series, and pumped onto the two 300-gallon chemical tanks within the POD unit. A piston pump within the POD pumps the oxidant through a PVC manifold assembly equipped with pressure valves and totaliser meters. The POD has the capability of routing oxidant to up to six injection wells simultaneously.

2.1.3 Oxidant Injection Points

Injection points are required to properly deliver oxidant to the desired locations by means of the most effective and economical method possible. The most common type of injection points are injection wells that are screened within an aquifer at the targeted contaminated zone. At the former MEC Building site, XDD's treatment system consisted of three injection well clusters. Each cluster consisted of three wells screened at three different depths; thus, there was a total of nine injection points. The injection wells targeting the top and bottom zones were fitted with 5-ft (1.5 m) long screens and the injection wells targeting the thin middle peat zone were fitted with 1-ft (0.3 m) long screens. All wells were flush mounted since they were located in an area immediately adjacent to a docking bay that was frequented by heavy trucks and forklifts. The locations of all demonstration wells is shown in Figure 4-1.

Injection wells require fittings for connecting a high pressure hose to the injection wellheads. XDD uses common materials and parts for these fittings, which are available at local hardware stores. As a result, existing monitoring wells can be adapted for injection as long as they are screened at the proper interval and are equipped with the appropriate slotted screens. For the demonstration XDD used ½ -inch ID high pressure hoses to injected into both 1-inch ID and 2-inch ID injection wells.

Figure 2-1 presents example schematics of injection wells comprising an injection well cluster that was used for the demonstration (IW-1 and IW-2, specifically). These wells are of traditional design and can be used for monitoring following injection of oxidant.

The number and locations of injection wells are dependent on a site's characterization. XDD has indicated that the preferred injection well construction would be comprised of a 2-inch inner diameter (ID) well having screen lengths preferably not in excess of 10 feet in length.

It should be be noted that there are direct-injection techniques that can be used to deliver oxidants which do not require an injection well. A geoprobe, equipped with drive rods of 1.25-inch O.D./0.625-inch I.D. or 2.125-inch O.D./1.5-inch I.D., can be utilized to provide a temporary casing (i.e., drive point) to allow the oxidant to be pumped subsurface without installing a well. Also, oxidant can be injected into infiltration galleries, excavated trenches, hydraulic or pneumatic fractures and pits.

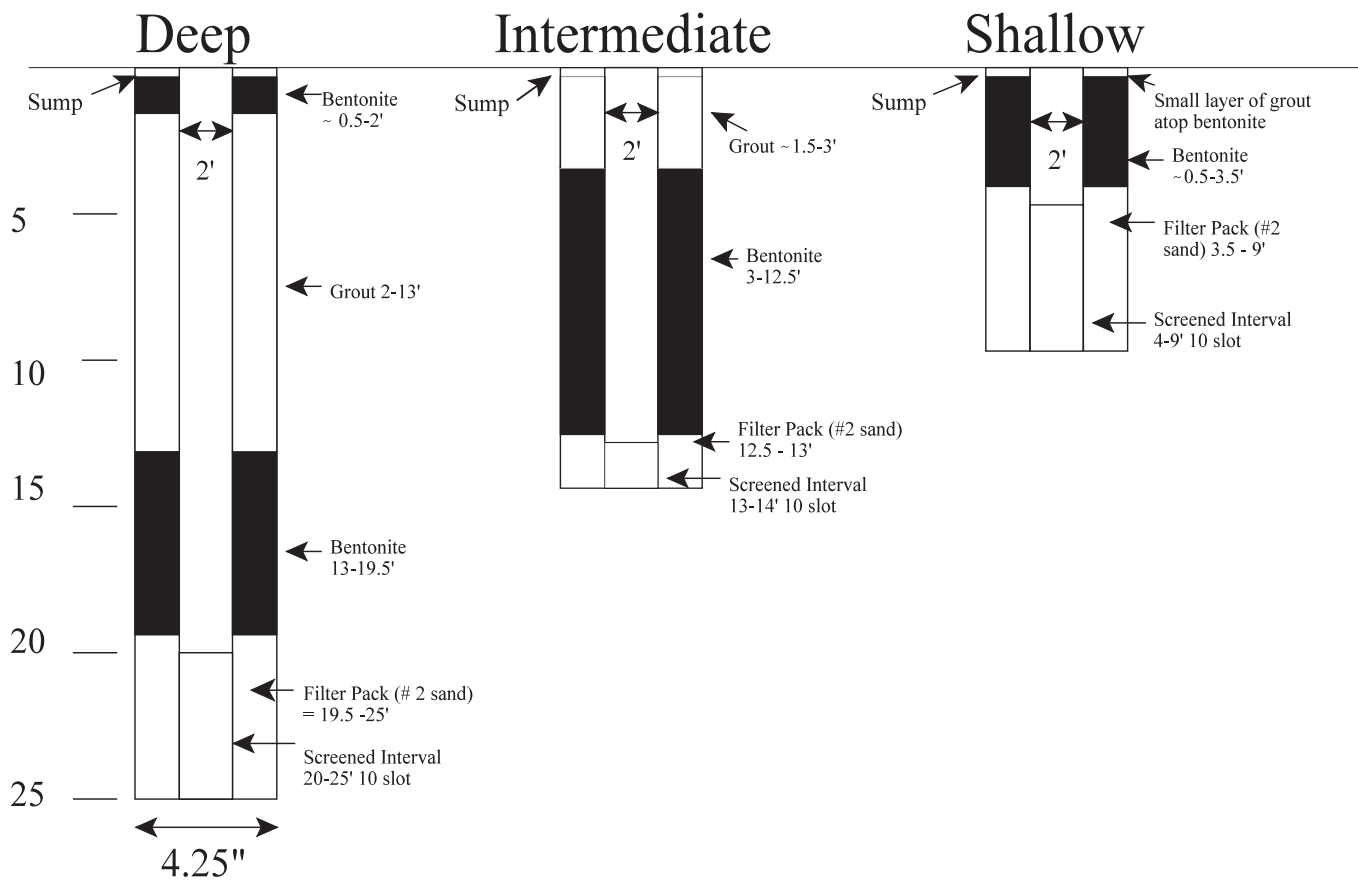


Figure 2-1. Injection Well Cluster Schematics.

2.1.4 Monitoring Wells

Monitoring wells are a necessary component for monitoring the effectiveness of an ISCO process. In many instances, existing monitoring wells can be utilized for the monitoring, dependent on their location. Also, in some instances (as was the case for the Demonstration), the injection wells can serve a dual purpose (i.e., as monitoring points). It should be noted that typically the injection wells are spaced or grouped in such a manner that they alone would not provide adequate coverage of a contaminant plume.

For the SITE Demonstration, there were two types of wells installed for monitoring; traditional wells (as shown on Figure 2-1) and “multi-chamber wells” (**Figure 2-2**). The multi-chamber wells were essentially a 3- in-1 design; each 1-inch OD casing containing three separate 7/16-inch ID wells set at different depths. All in all, there was a total of five monitoring wells for each of the three stratigraphic zones monitored (for a total of 15 wells).

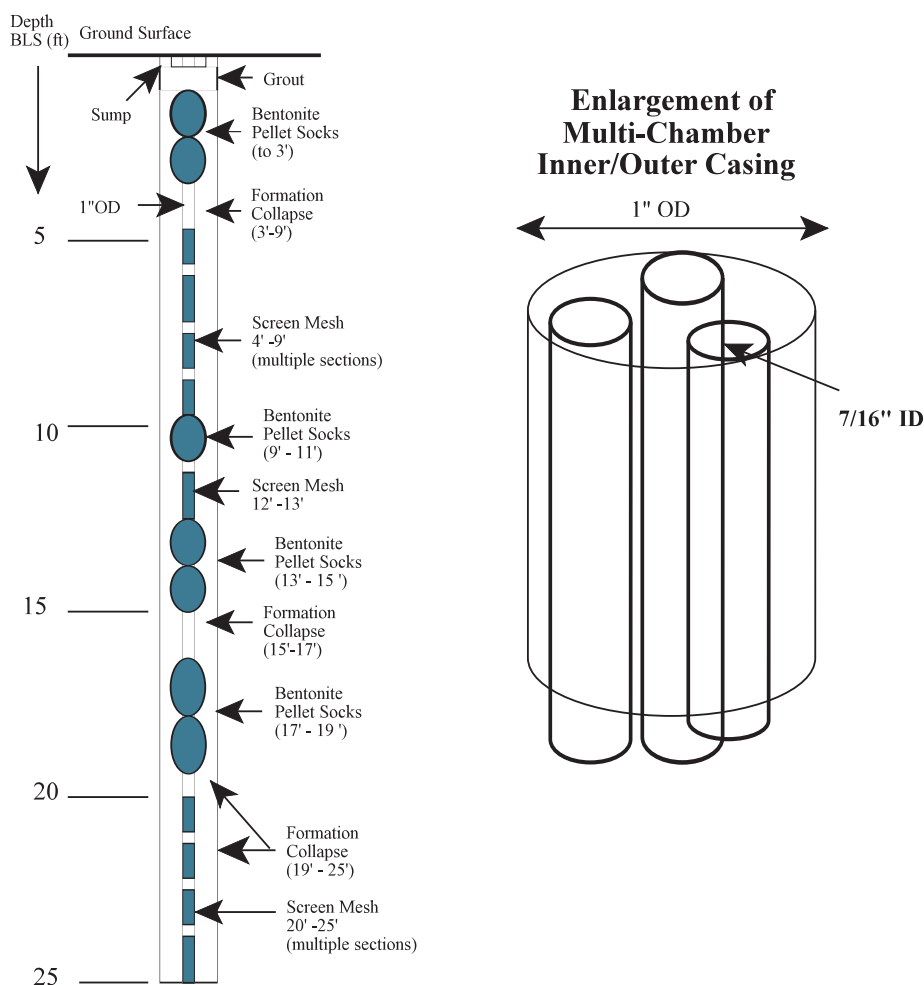


Figure 2-2. Multi-Chamber Well Schematic.

The number of monitoring wells that would be needed for a remediation project using XDD's process is highly site-specific. At a minimum, monitoring wells are typically required upgradient, downgradient, and lateral to the area to be treated. The former MEC Building site has been monitored continuously for an extended period of time to track the slow dissolution of the DNAPL and dissolved organic contaminant plume. The Site Demonstration focused on monitoring treatment effectiveness within a small area side-gradient of the main DNAPL source zone.

2.2 Operability of the Technology

The implementation of XDD's technology is broken down into an eight-step process, listed and discussed below.

1. Site Evaluation
2. Treatability Testing
3. System Design
4. Injection Well Installation
5. Pilot Testing (Water Injection Tests)
6. System Setup
7. Batching of Oxidant
8. Oxidant Injection & Monitoring
9. Equipment Decontamination
10. Monitoring Treatment Effectiveness

XDD will sometimes conduct site characterization activities themselves; but more commonly will evaluate existing characterization data for the site. But site evaluation is an important aspect, as XDD typically conducts treatability testing to determine various aspects of the contaminated soils that are to be treated. For example, prior to the demonstration XDD conducted a laboratory treatability study in order to evaluate the effectiveness of their ISCO process on contaminated soil from the site. The objectives of this treatability study were to:

- Assess the overall feasibility of using ISCO to meet the site-specific cleanup goals;
- Estimate the soil oxidant demand for the major soil units (i.e., gravelly sand, peat layer, and sandy-silty) in the treatment area;
- Develop site-specific data necessary to design an ISCO field pilot test and/or full-scale application.

Injection well installation is performed by an outside contractor. The injection wells can typically serve a dual purpose (i.e., as monitoring wells once oxidant is injected). Also, existing monitoring wells may be able to be retrofitted for injection purposes. XDD sometimes conducts water injection testing on prospective injection wells, a practice

they are utilizing more frequently. As an example, for the demonstration project at the former MEC Building site, XDD performed a small-scale water injection test at a target flow rate to monitor well seal and injection pressures of newly-installed injection wells that served as replacements for wells that had to be abandoned due to failed seals.

The following tasks comprise the basic setup of XDD's equipment (i.e., the system set-up step).

- Oxidant delivery/storage of KMnO_4
- Setup of spill guards for batch area
- Potable water delivery (tanker)
- Drop-off of rented generator
- Hookup of batch operation to POD
- Connect injection distribution system to wells

The batching process is labor intensive. For example the granular KMnO_4 used during the demonstration is containerized in 20 L jugs. The granular oxidant needs to be mixed with potable water to form an oxidant solution at the desired concentration. To do this, the jugs were manually transported to the top of a large mixing tank, where the jug contents were dumped into the tank equipped with a sump pump for mixing. Tyvek and respirators were worn during this process as a precautionary health and safety measure.

To inject oxidant, the KMnO_4 solution is pumped through one or more cannister filters (two filters, connected in series, were used during the demonstration). The filtration is needed to remove any unwanted material from the solution. Such material includes a small amount of silica (i.e., 1% or less of silica is mixed in with the granular KMnO_4 as an anti-clogging agent).

During XDD's injection process, equipment decontamination consists of periodic flushing of cannister filters, which are used to remove unwanted material (e.g., silica solids) from the oxidant solution. Following an injection event, XDD conducts a thorough flushing of the oxidant from the POD and related equipment components. To accomplish this, a neutralizing solution is used, that consists of a 5:1:1 mixture of potable water, vinegar, and hydrogen peroxide (H_2O_2), respectively. The neutralizer is pumped through the POD components, through the high pressure hoses and down into the injection wells (the small amount of injected neutralizer has a negligible effect on the subsurface).

Monitoring of treatment effectiveness is highly site-specific and very dependent on regulatory requirements as to the degree of monitoring required. This endeavor may or may

not be conducted by XDD, largely depending on whether they are serving as the site remediation contractor. Regardless, XDD would have some input into evaluating treatment results. In most cases monitoring of an ISCO process would involve at minimum a pre-treatment and post-treatment sampling event for all affected media (i.e., soils and groundwater). Typically groundwater would require continued post-treatment monitoring for an indefinite period, largely dependent on state and local regulatory requirements.

2.3 Applicable Wastes

ISCO is primarily used to treat contaminated soil and groundwater. Permanganate (MnO_4) has been widely used and has been shown to completely mineralize several common chlorinated VOCs to yield innocuous end products. MnO_4 is more effective for treating chlorinated ethenes; particularly tetrachloroethene (PCE) and trichloroethene (TCE) are most readily oxidized. However, significant degradation of chlorinated ethanes, such as 1,1,1-trichloroethane (1,1,1-TCA), has also been observed.

In addition to organics, MnO_4 also reacts with natural soil organic matter and reduced metal oxides (e.g., iron and manganese oxides).

With respect to applicable soil types, high clay soils would be expected to be less amenable to ISCO since plugging could cause the flow of groundwater to divert around areas of contamination. Deeper contamination would require more costly well installation.

2.4 Availability and Transportability of Equipment

The XDD ISCO process can theoretically be implemented anywhere injection and monitoring wells can be installed, which would include any location that can be accessed by a drill rig, or geoprobe, or other direct push technology (DPT) equipment. Since all-terrain drill rigs and DPT equipment are available, most locations would be accessible.

At the former MEC Building site, the injection system consisted of three injection well clusters, in which each cluster contained three separate wells screened in a shallow (4-9 ft), middle (13-14 ft), and deep (20-25 ft) stratigraphic zones that had been previously characterized. Nine additional small diameter wells were installed at three locations for monitoring purposes only. These wells were screened at the same depth intervals the injection wells were and were constructed with readily available

construction materials typically used for well installation.

The primary components for the KMnO_4 injection equipment used during the demonstration were contained on a single trailer (the POD). The POD can be easily mobilized with a heavy duty pickup truck. Granular KMnO_4 was shipped to the site in 20 Liter plastic jug-like containers, each weighing approximately 55 pounds. The jugs were unloaded from a truck on wooden pallets and stored in an adjacent warehouse.

During the demonstration XDD's system required periodic monitoring of basic groundwater parameters. The equipment used for these activities (e.g., water level indicators, multi-parameter water quality meters, etc.) are portable and can be easily shipped or transported to a site.

2.5 Materials Handling Requirements

Materials handling requirements for XDD's ISCO process are largely dependent on the type of oxidant used. The considerably less expensive KMnO_4 oxidant used during the demonstration requires a somewhat rigorous materials handling relative to the NaMnO_4 oxidant. Granular KMnO_4 is shipped in 20 Liter plastic jugs, each jug weighing approximately 55 pounds. During the demonstration the jugs were manually carried from a loading dock to XDD's batch set up area. To mix the oxidant with potable water the jugs had to be lifted via a ladder to the top of a mixing vessel and emptied into a tank. Due to the health and safety concerns (inhalation on KMnO_4 dust), a respirator and coated tyvek were worn during this operation. NaMnO_4 is shipped in liquid form and thus can be delivered in a large tanker, from which the oxidant can be pumped directly to the POD.

Because drilling operations are involved to install the injection wells and possibly monitoring wells, there is the potential of handling hazardous residual materials. Examples would include drumming of soil cuttings, purge water, and decontamination water.

2.6 Site Support Requirements

During the Demonstration, the equipment and supplies for the XDD ISCO process encompassed an approximate 80 ft x 30 ft area (i.e., 2,400 ft² or 220 m²). The majority of space is needed for the batching process, which requires a large water supply for diluting granular KMnO_4 (a 5,000 gallon tanker was used for the demonstration), and a bermed area adjacent to the water supply that contains two 500 gal. (1,890 L) polypropylene mixing tanks, three transfer pumps and two cartridge filters connected in series. The trailer-mounted POD and generator take up a

very small amount of space (i.e., approximately 200 ft² or 18.5 m²).

For in situ oxidation to take place effectively in groundwater, it must be technically and economically feasible for the oxidant to contact the contaminated media (i.e., both soil and groundwater). This can be a tradeoff of cost of drilling multiple wells for injecting KMnO₄ versus the cost of alternative treatments involving fewer wells (e.g., pump and treat systems). The sites where ISCO is to be used must be able to provide good access for a drill rig or DPT equipment.

XDD typically rents a gasoline or diesel powered generator (e.g., 70 KVA) to supply electric power to the POD. The peristaltic pumps needed for low flow groundwater sampling of shallow wells can operate off a car battery. Both of these items are easily rented and are usually available locally.

Electrical power may also be needed to supply lighting to an on-site trailer and a security light, and possibly for a phone and facsimile hookup. During the demonstration project, use of space within the former MEC Building was invaluable for preparing soil and groundwater samples during variable weather conditions encountered throughout the demonstration sampling events. Without the use of the building, a trailer would likely have been rented for that purpose. Other than electricity, a water source is needed for occasional decontamination activities (e.g., rinsing out the individual jugs of KMnO₄). Since XDD usually rents the water tanker during an injection event, that could also serve as a source for water used for other purposes.

2.7 Limitations of the Technology

Because permanganate reacts with natural soil organic matter and reduced metal oxides, contaminant degradation rates can be adversely affected by the presence of these competing species. Humic and fulvic acids (collectively referred to as humates) are highly susceptible to permanganate oxidation. Humic-containing soils are categorized as having a high soil oxidant demand (SOD), a term used for measuring how much oxidant the natural material in a soil could potentially use up, thus depriving the oxidant's intended use for treating organic

contaminants.

Chemical oxidation also has the potential to mobilize valence sensitive toxic metals, such as Arsenic (As), Chromium (Cr), Selenium (Se), Zinc (Zn), and Mercury (Hg), from soils into groundwater. As a result, sites that contain elevated levels of metals contaminants as well as organic contaminants should be monitored for such mobilization potential.

The porosity of the soil and groundwater flow can affect the rate and overall effectiveness of oxidation. Low porous and low conductive soils would hamper injection and retard the mobility of the oxidant. Sites having heterogeneous stratigraphy will not have consistent hydraulic properties. Small-scale high permeability zones can act as localized conduits for dissolved-phase VOCs, thus making the contaminants a hard target for injected MnO₄.

Some organic compounds are not degraded as readily by permanganate as chlorinated ethenes are. For example, toluene is known to degrade in the presence of MnO₄, but at relatively slow rates. Compounds, such as toluene and harder to degrade ethanes, are commonly found at sites having ethene contamination. Such was the case for the former MEC Building site.

2.8 ARARS for XDD's ISCO Process

This subsection discusses specific federal environmental regulations pertinent to the operation of the XDD ISCO process, referred to as Applicable or Relevant and Appropriate Requirements (ARARs). ARARs include the: (1) Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA); (2) Resource Conservation and Recovery Act (RCRA); (3) Clean Air Act (CAA); (4) Clean Water Act (CWA); (5) Safe Drinking Water Act (SDWA), and the (6) Occupational Safety and Health Administration (OSHA) regulations. These six general ARARs and state requirements for the former MEC Building site are discussed in the following subsections. Specific ARARs that may be applicable to the XDD ISCO process are identified in **Table 2-2**.

Table 2-2. Federal and State ARARs for XDD's ISCO Process.

Process Activity	ARAR	Description	Basis	Response
Waste Characterization	RCRA: 40 CFR Part 261 (or the state equivalent)	Standards apply to the identification and characterization of wastes. Chemical and physical properties of waste determine suitability for ISCO treatment.	Chemical and physical properties of waste determine its suitability for treatment by an ISCO process.	Chemical and physical analyses must be performed to determine if waste is a hazardous waste.
Waste Processing	RCRA: 40 CFR Part 264 (or the state equivalent)	Standards apply to treatment of wastes in a treatment facility.	Not likely to be applicable or appropriate for the XDD ISCO process.	When hazardous wastes are treated, there are requirements for operations, record keeping, and contingency planning.
	CAA: 40 CFR Part 50 (or the state equivalent)	Regulations govern toxic pollutants, visible emissions and particulates.	During well installation and oxidant batching/injection, any off-gas venting (i.e., from buildup of VOCs, etc.) must not exceed limits set for the air district of site. (Not likely to occur.)	Off-gases may contain volatile organic compounds or other regulated substances, although levels are likely to be very low.
Storage of auxiliary wastes	RCRA: 40 CFR Part 264 Subpart J (or the state equivalent)	Regulation governs the standards for tanks at treatment facilities.	Storage tanks for liquid wastes (e.g., decontamination waste) must be placarded appropriately, have secondary containment and be inspected daily.	If storing non-RCRA wastes, RCRA requirements may still be relevant and appropriate.
	RCRA: 40 CFR Part 264 Subpart I (or the state equivalent)	Regulation covers the storage of waste materials generated.	Potential hazardous wastes remaining after treatment (i.e., drill cuttings) must be labeled as hazardous waste and stored in containers in good condition. Containers should be stored in a designated storage area and storage should not exceed 90 days unless a storage permit is obtained.	Applicable for RCRA wastes; relevant and appropriate for non-RCRA wastes.
Determination of cleanup standards	SARA: Section 121(d)(2)(ii); SDWA: 40 CFR Part 141	Standards apply for treatment of surface water or groundwater that is to be used for drinking water supplies.	Remedial actions are required for groundwater to meet MCL goals (MCLGs) or MCLs established under the SDWA. Standards apply to surface & groundwater sources that may be used as drinking water.	Remedial actions for surface and groundwater are required to meet federal MCL goals (MCLGs) or MCLs established under SDWA; or in the case of the former MEC site the NHDES site-specific criteria.
Waste disposal	RCRA: 40 CFR Part 262	Standards that pertain to generators of hazardous waste.	Potential hazardous waste generated by ISCO process is limited to drill cuttings, well purge water, PPE, and wastes generated from decontamination.	Generators must dispose of wastes at facilities permitted to handle the waste. Generators must obtain an EPA ID number prior to disposal.
	CWA: 40 CFR Parts 403 and/or 122 and 125	Standards for discharge of wastewater to a POTW or to a navigable waterway.	Applicable and appropriate for well purge water and decontamination wastewater generated from drilling process. The ISCO process does not generate wastewater.	Discharge of wastewater to a POTW must meet pre-treatment standards; discharges to a navigable waterway must be permitted under NPDES.
	RCRA: 40 CFR Part 268	Standards regarding land disposal of hazardous wastes	Applicable for off-site disposal of auxiliary waste (e.g., drill cuttings).	Hazardous wastes must meet specific treatment standards prior to land disposal, or be treated using specific technologies.

2.8.1 CERCLA

The CERCLA of 1980 as amended by the Superfund Amendments and Reauthorization Act (SARA) of 1986 provides for federal funding to respond to releases or potential releases of any hazardous substance into the environment. As part of the requirements of CERCLA, the EPA has prepared the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) for hazardous substance response. The NCP is codified in Title 40 CFR Part 300, and delineates the methods and criteria used to determine the appropriate extent of removal and cleanup for hazardous waste contamination. SARA states a strong statutory preference for remedies that are highly reliable and provide long-term protection. It directs EPA to do the following:

- Use remedial alternatives that permanently and significantly reduce the volume, toxicity, or the mobility of hazardous substances, pollutants, or contaminants;
- Select remedial actions that protect human health and the environment, are cost-effective, and involve permanent solutions and alternative treatment or resource recovery technologies to the maximum extent possible; and
- Avoid off-site transport and disposal of untreated hazardous substances or contaminated materials when practicable treatment technologies exist [Section 121(b)].

In general, two types of responses are possible under CERCLA: removal and remedial actions. Superfund removal actions are conducted in response to an immediate threat caused by a release of a hazardous substance. Many removals involve small quantities of waste of immediate threat requiring quick action to alleviate the hazard. Remedial actions are governed by the SARA amendments to CERCLA. As previously stated, these amendments promote remedies that permanently reduce the volume, toxicity, and mobility of hazardous substances or pollutants.

The XDD ISCO process could possibly be part of a CERCLA remedial action since the toxicities of the contaminants of concern are intended to be reduced by chemical destruction or alteration. Remedial actions are governed by the SARA amendments to CERCLA. On-site remedial actions must comply with federal and more stringent state ARARs. ARARs are determined on a site-by-site basis and may be waived under six conditions: (1) the action is an interim measure, and the ARAR will be met

at completion; (2) compliance with the ARAR would pose a greater risk to health and the environment than noncompliance; (3) it is technically impracticable to meet the ARAR; (4) the standard of performance of an ARAR can be met by an equivalent method; (5) a state ARAR has not been consistently applied elsewhere; and (6) ARAR compliance would not provide a balance between the protection achieved at a particular site and demands on the Superfund remedial project manager (RPM) for other sites. These waiver options apply only to Superfund actions taken on-site, and justification for the waiver must be clearly demonstrated.

2.8.2 RCRA

RCRA, an amendment to the Solid Waste Disposal Act (SWDA), is the primary federal legislation governing hazardous waste activities. It was passed in 1976 to address the problem of how to safely dispose of the enormous volume of municipal and industrial solid waste generated annually. Subtitle C of RCRA contains requirements for generation, transport, treatment, storage, and disposal of hazardous waste, most of which are also applicable to CERCLA activities. The Hazardous and Solid Waste Amendments (HSWA) of 1984 greatly expanded the scope and requirements of RCRA.

RCRA regulations define hazardous wastes and regulate their transport, treatment, storage, and disposal. These regulations are only applicable to the ISCO process if RCRA defined hazardous wastes are present. Hazardous wastes that may be present include contaminated soil cuttings and purge water generated during well installation and development, and the residual wastes generated from any groundwater sampling activities (e.g., PPE and purge water). If wastes are determined to be hazardous according to RCRA (either because of a characteristic or a listing carried by the waste), essentially all RCRA requirements regarding the management and disposal of this hazardous waste will need to be addressed by the remedial managers.

Wastes defined as hazardous under RCRA include characteristic and listed wastes. Criteria for identifying characteristic hazardous wastes are included in 40 CFR Part 261 Subpart C. Listed wastes from specific and nonspecific industrial sources, off-specification products, spill cleanups, and other industrial sources are itemized in 40 CFR Part 261 Subpart D. RCRA regulations do not apply to sites where RCRA-defined wastes are not present.

Unless they are specifically delisted through delisting

procedures, hazardous wastes listed in 40 CFR Part 261 Subpart D currently remain listed wastes regardless of the treatment they may undergo and regardless of the final contamination levels in the resulting effluent streams and residues. This implies that even after remediation, treated wastes are still classified as hazardous wastes because the pre-treatment material was a listed waste.

For generation of any hazardous waste, the site responsible party must obtain an EPA identification number. Other applicable RCRA requirements may include a Uniform Hazardous Waste Manifest (if the waste is transported off-site), restrictions on placing the waste in land disposal units, time limits on accumulating waste, and permits for storing the waste.

Requirements for corrective action at RCRA-regulated facilities are provided in 40 CFR Part 264, Subpart F and Subpart S, which also generally apply to remediation at Superfund sites. Subparts F and S include requirements for initiating and conducting RCRA corrective action, remediating groundwater, and ensuring that corrective actions comply with other environmental regulations. Subpart S also details conditions under which particular RCRA requirements may be waived for temporary treatment units operating at corrective action sites and provides information regarding requirements for modifying permits to adequately describe the subject treatment unit.

2.8.3 CAA

The CAA establishes national primary and secondary air quality standards for sulfur oxides, particulate matter, carbon monoxide, ozone, nitrogen dioxide, and lead. It also limits the emission of 189 listed hazardous pollutants such as vinyl chloride, arsenic, asbestos and benzene. States are responsible for enforcing the CAA. To assist in this, Air Quality Control Regions (AQCR) were established. Allowable emission limits are determined by the AQCR, or its subunit, the Air Quality Management District (AQMD). These emission limits are based on whether or not the region is currently within attainment for National Ambient Air Quality Standards (NAAQS).

The CAA requires that treatment, storage, and disposal facilities comply with primary and secondary ambient air quality standards. The most likely air emissions that would be anticipated with an activity associated with ISCO would be VOC emissions generated during drilling activities. The ISCO process also uses a generator during injections. However, these potential emissions would typically be very low concentrations and are easily monitored on-site.

2.8.4 CWA

The objective of the CWA is to restore and maintain the chemical, physical and biological integrity of the nation's waters by establishing federal, state, and local discharge standards. If treated water is discharged to surface water bodies or Publicly Owned Treatment Works (POTW), CWA regulations will apply. A facility desiring to discharge water to a navigable waterway must apply for a permit under the National Pollutant Discharge Elimination System (NPDES). NPDES permits include waste discharge requirements. Discharges to POTWs also must comply with general pretreatment regulations outlined in 40 CFR Part 403, as well as other applicable state and local requirements.

Since XDD's chemical oxidation process is in situ and purge water generated during the demonstration was containerized and properly disposed of, CWA criteria did not apply for this demonstration.

2.8.5 SDWA

The SDWA of 1974, as most recently amended by the Safe Drinking Water Amendments of 1986, requires the EPA to establish regulations to protect human health from contaminants in drinking water. The legislation authorized national drinking water standards and a joint federal-state system for ensuring compliance with these standards.

The National Primary Drinking Water Standards (NPDWS) are found in 40 CFR Parts 141 through 149. Parts 144 and 145 discuss requirements associated with the underground injection of contaminated water. If underground injection of wastewater is selected as a disposal means, approval from EPA or the delegated state for constructing and operating a new underground injection well is required.

The contaminated groundwater at the former MEC Building site is not considered a source of drinking water. However, if the groundwater was to be used for drinking purposes while providing no additional treatment, the quality of the water would need to meet NPDWS. These are much more stringent than State of New Hampshire (NH) 0.5% aqueous solubility cleanup criteria specific to the former MEC Building site. **Table 2-3** provides a comparison between these site specific criteria and federal drinking water standards.

2.8.6 OSHA

CERCLA remedial actions and RCRA corrective actions must be performed in accordance with the OSHA requirements detailed in 20 CFR Parts 1900 through 1926, especially Part 1910.120, which provides for the health and safety of workers at hazardous waste sites. On-site

construction activities at Superfund or RCRA corrective action sites must be performed in accordance with Part 1926 of OSHA, which describes safety and health regulations for construction sites. State OSHA requirements, which may be significantly stricter than federal standards, must also be met.

Table 2-3. Groundwater Cleanup Criteria Comparison.		
Analyte	0.5% aqueous solubility - State Regulatory Goal for the former MEC Building site (µg/L)	National Primary Drinking Water Standards (µg/L)
PCE	750	5
TCE	5,500	5
cDCE	17,500	70
VC	NA	2
Toluene	2,750	1,000
1,1,1-TCA	6,800	200
1,1-DCA	27,500	---

If working at a hazardous waste site, all personnel involved with the installation of wells and implementation of the XDD treatment process are required to have completed an OSHA training course and must be familiar with all OSHA requirements relevant to hazardous waste sites. Workers on hazardous waste sites must also be enrolled in a medical monitoring program. The elements of any acceptable program must include: (1) a health history, (2) an initial exam before hazardous waste work starts to establish fitness for duty and as a medical baseline, (3) periodic examinations (usually annual) to determine whether changes due to exposure may have occurred and to ensure continued fitness for the job, (4) appropriate medical examinations after a suspected or known overexposure, and (5) an examination at termination.

For most sites, minimum personal protective equipment (PPE) for workers will include gloves, hard hats, steel-toe boots, and tyvek coveralls. Depending on contaminant types and concentrations, additional PPE may be required, including the use of air purifying respirators or supplied air. For an ISCO process, XDD personnel utilized coated tyvek and respirators during the batching operation to minimize inhalation and dermal exposure to the strong oxidizer used.

Noise levels would potentially be high only during drilling

activities involving the operation of a drill rig or DPT probe. During these activities, noise levels should be monitored to ensure workers are not exposed to levels above a time-weighted average of 85 decibels over an eight-hour day. Workers are required to wear hearing protection at noise levels above 85 decibels. The levels of noise anticipated are not expected to adversely effect the community, but this will depend on proximity to the treatment site.

2.8.7 State and Local Requirements

State and local regulatory agencies may require permits prior to implementing an ISCO technology and/or for specifically treating chlorinated ethenes. Specific to the State of New Hampshire, XDD was required to acquire an injection permit prior to implementing their treatment.

Most federal permits will be issued by the authorized state agency. NH requires that a Groundwater Management Permit be issued to a site owner or legally responsible person to remedy contamination associated with the past discharge of regulated contaminants, and to manage the use of the contaminated groundwater. The state may also require a Treatment, Storage, and Disposal (TSD) Permit for on-site storage of hazardous waste for greater than 90 days. An air permit issued by the state AQCR may be required if air emissions in excess of regulatory criteria, or of toxic concern, are anticipated (highly unlikely for this technology). Wastewater discharge permits may be required in the unlikely event that wastewater were to be discharged to a POTW. If remediation is conducted at a Superfund site, federal agencies, primarily the USEPA, will provide regulatory oversight. If off-site disposal of contaminated waste is required, the waste must be taken to the disposal facility by a licensed transporter.

For the Demonstration, there were cleanup standards for both the soil and groundwater. The groundwater standards were based on the solubility of DNAPL and were presented in Table 2-2 as compared to U.S. EPA's MCLs for drinking water. The State of NH soil standards, referred to as S-1 Soil Standards, are as follows:

▶	PCE	2 mg/Kg
▶	TCE	0.8 mg/Kg
▶	cDCE	2 mg/Kg
▶	VC	0.4 mg/Kg
▶	Toluene	100 mg/Kg
▶	1,1 - TCA	42 mg/Kg

Section 3.0 Economic Analysis

3.1 Introduction

The purpose of this economic analysis is to estimate costs for chlorinated ethene remediation of soil and groundwater utilizing a specialized application of in situ chemical oxidation (ISCO) developed by Xpert Design and Diagnostic's (XDD) LLC of Stratham, New Hampshire. The estimated costs for this technology are based on information provided by XDD, and observations made by SITE Program personnel during the demonstration.

The areal extent of the Demonstration treatment system's injection wells, monitoring wells, and soil borings was roughly 1,200 ft² (114 m²). Based on groundwater levels of about 3 ft bgs (as measured in June 2005, the vertical extent of contamination at the former MEC site was characterized to be roughly 22 ft (i.e., 3-25 ft bgs). Therefore the volume of groundwater and saturated soil targeted for treatment was approximately 27,000 ft³ (1,000 yd³). This size can be considered pilot-scale.

For this cost estimate a larger hypothetical site is used to better represent full-scale remediation. **Figure 3-1** illustrates a hypothetical site, having an areal extent of 100 ft x 32 ft (~32,000 ft²), or about ¾ of an acre. Basic characteristics of this hypothetical site are as follows:

- ◆ Similar to the former MEC Building site, contamination consists of chlorinated compounds (e.g., PCE, TCE, cDCE, and VC). Contaminant concentrations and cleanup goals are the same;
- ◆ Site characterization studies has identified a long, narrow DNAPL plume, approximately 100 ft long and 25 ft wide (30.5 x 7.6 m) is slowly dispersing from the source area and is following an easterly groundwater flow pattern;
- ◆ The saturated soils occur from about 18-50 ft (5.5-

15.2 m) bgs and overlay a relatively impervious bedrock. Therefore, aquifer thickness at this specific location is approximately 32 ft (9.8 m). The volume of saturated aquifer material to be treated is roughly 100,000 ft³ (100 ft x 32 ft x 32 ft).

- ◆ Site geology is similar to the demonstration site, but does not contain the thin peat layer that required an extraordinary effort to treat. Instead a loamy soil overlies the bedrock. There is a slight horizontal hydraulic gradient of ~ 0.04 ft/ft;
- ◆ Relative to the plume, there are one upgradient and two downgradient monitoring wells. However, there are no wells set within the immediate plume area. Therefore, oxidant injection wells are available for monitoring.
- ◆ The specific treatment design parameters for the hypothetical site are summarized in **Table 3-1**.

Table 3-1. Treatment Design for Hypothetical Site.			
Injection Wells		Oxidant Injection	
No. of wells	10	KMnO ₄ concentration	40 g/L
Well spacing	~18 ft	Flow Rate/per well	2 gpm
Well head ID	2 in.	Volume injected	56,000 gal (212,000 L)
Screen length	10 ft	Mass injected	14,000 lbs (635 kg)
Screened int.	30-40 ft	Area treated	100,000 ft ²
Radius of infl.	10 ft	Volume treated	37,000 yd ³
Diam. Of infl.	20 ft	Residence Time	< 1 month

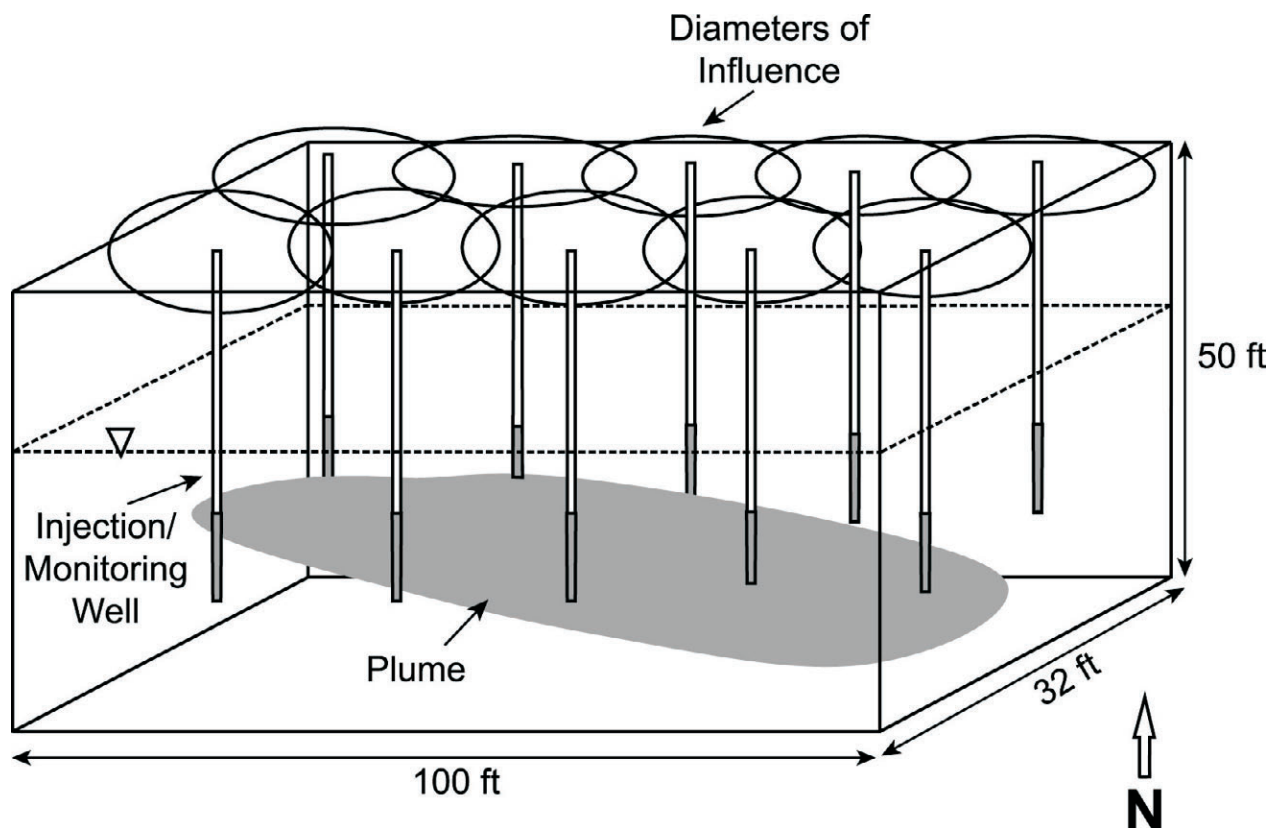


Figure 3-1 Hypothetical ISCO Site

As shown in Figure 3-1, the plume is positioned at a slight angle and is situated between 35-45 ft bgs. Groundwater is at about 18 ft bgs, thus the estimated thickness of the saturated zone is approximately 32 ft (9.8 m). XDD in some instances could use well clusters to inject oxidant at various depths (this was done during the demonstration). However for this hypothetical site setting the screens at 30-40 ft (9.1-12.2 m) bgs, should enable delivery of oxidant to the shallowest occurrences of the plume while downward flow of oxidant should enact contact with the deepest occurrences of the plume (i.e., entire plume thickness).

Although the plume is depicted as narrow (i.e., about 25 ft or 7.6 m wide), dissolved phase organic compounds occur in the groundwater surrounding the plume. Overlapping radii of influences (depicted by the circles on Figure 3-1) are a conservative way of completely enveloping the entire plume and at the same time directing oxidant to contaminated groundwater surrounding the plume.

The costs associated with implementing the XDD's ISCO process at this hypothetical site have been broken down into 12 cost categories that reflect typical cleanup activities at Superfund sites. They include the following:

- (1) Site Preparation
- (2) Permitting and Regulatory Activities
- (3) Capital Equipment
- (4) Start-up and Fixed
- (5) Labor
- (6) Consumables and Supplies
- (7) Utilities
- (8) Effluent Treatment and Disposal
- (9) Residuals Shipping, & Disposal
- (10) Analytical Services
- (11) Maintenance and Modifications
- (12) Site Restoration/Demobilization

Table 3-2 presents a categorical breakdown of the estimated costs for implementing XDD's ISCO process at the hypothetical site, assuming a single injection event and monitoring consisting of a pre-injection sampling of soil and groundwater, one intermediate groundwater sampling, and a final post-treatment sampling of soil and groundwater. As with all cost estimates, there are associated factors, issues, and assumptions that caveat specific cost values. The major factors that can affect estimated costs are discussed in subsection 3.3. Specific issues and assumptions made regarding site characteristics are incorporated into the cost estimate. They are discussed in subsection 3.4.

Table 3-2. Cost Estimate for Full-Scale Application.¹

Cost Category	Quantity	Units	Unit Cost	\$ Total	\$/Category ²	% of Total ²
1. Site Preparation					\$1,000	0.7
Site Clearing	NA	Each	\$0	\$0		
Shipment of KMnO ₄	1	Each	\$1,000	\$1,000		
2. Permitting & Regulatory Activities					\$1,000	0.7
GW Management Permit	1	Each	\$1,000	\$1,000		
Other Regulatory Requirements	NA	Each	\$0	\$0		
3. Capital Equipment					\$5,100	3.7
Storage Building (10 ft x 15 ft x 8 ft)	1	Each	\$1,000	\$1,000		
Bladder Pumps/Tubing	5	Each	\$600	\$3,000		
Pump Flow Regulator	1	Each	\$1,100	\$1,100		
4. Startup & Fixed					\$24,500	18
Treatability Study (oxidant dosing)	3	Samples	\$1,500	\$4,500		
Injection Well Installation ³	10	Each	\$2,000	\$20,000		
5. Labor					\$29,900	21
Permit Preparation Costs	4	Hours	\$80	\$320		
System Design	40	Hours	\$80	\$3,200		
Well Installation Oversight	50	Hours	\$80	\$4,000		
KMnO ₄ Injection (XDD) ⁴	120	Hours	\$60	\$7,200		
GW Evaluation Sampling (3 events)	60	Hours	\$60	\$3,600		
Soil Evaluation Sampling (2 events)	120	Hours	\$60	\$7,200		
Site Restoration/Demobilization	20	Hours	\$60	\$1,200		
Report Preparation	40	Hours	\$80	\$3,200		
6. Consumables and Supplies					\$56,300	41
Granular KMnO ₄	14,000	lbs	\$2.30	\$32,200		
Potable Water (tankers)	56,000	Gallons	\$0.10	\$5,600		
Rental - Geoprobe + mob./demob.	6	Day	\$1,400	\$8,400		
Rental - Steam Cleaner	6	Day	\$150	\$900		
Rental - XDD POD	1	Week	\$4,500	\$4,500		
Rental - Pick-Up Truck	1	Week	\$225	\$225		
Rental - Generator (70 KVA)	1	Week	\$700	\$700		
Rental - Pumps (1 sump; 2 centrifugal)	1	Week	\$135	\$135		
Rental - 500 gal. Poly Tanks w/mixer	2	Week	\$105	\$210		
Rental - H&S Equipment (PID & CGM)	3	Week	\$350	\$1,050		
Rental - GW Sampling Equipment	6	Day	\$122	\$730		
Other Miscellaneous Supplies ⁵	NA	NA	\$1,700	\$1,700		
7. Utilities	NA	NA	NA	\$0	\$0	0
8. Effluent Treatment & Disposal	NA	NA	NA	\$0	\$0	0
9. Residuals Shipping & Disposal					\$2,500	1.8
Contaminated Solids ⁶	4	Drums	\$90	\$360		
Contaminated Liquids ⁶	15	NA	\$145	\$2,175		
10. Analytical Services					\$13,500	9.7
VOCs in Soil	60	Each	\$130	\$7,800		
VOCs in Groundwater	30	Each	\$150	\$4,500		
Sample Shipments	23	Each	\$50	\$1,150		
11. Maintenance & Modifications	NA	NA	\$0	\$0	\$0	
12. Site Restoration (Borehole grouting)	2,400	Feet	\$2	\$4,800	\$4,800	3.4
				Total Estimated Cost	\$139,000	100

¹ Based on the hypothetical site characteristics described in subsection 3.1, one injection application, and a treatment period of at least 1 month.

² Cost value totals are rounded to three significant digits; % of total values are rounded to two significant digits.

³ Includes installing 2 inch ID PVC wells to 40 ft bgs using a geoprobe with DPT. Well completion materials consist of road boxes.

⁴ Includes one day to set up and five days for KMnO₄ injection.

⁵ Includes such items as PPE, well connect fittings, calibration gases, and shipping charges for rental equipment.

⁶ Solids include drill cuttings, residual sample, sample liners, visqueen, and PPE. Liquids include well development water and sample purge water.

The basis for costing each of the individual 12 categories in Table 3-2 is discussed in detail in subsection 3.5. Much of the information presented in that subsection has been derived from observations made from the SITE demonstration that was conducted over an approximate 11 month period at the former MEC Building site in Hudson, NH. Other cost information has been acquired through subsequent discussions with XDD representatives, information gathered from www.XDD-llc.com, and researching current estimates for specific cost items related to the technology.

It should be emphasized that the cost figures provided in this economic analysis are “order-of-magnitude” estimates, generally + 50% / -30%.

3.2 Conclusions

- (1) The cost to install a 10-injection well ISCO treatment system, utilizing XDD’s POD to deliver oxidant to approximately 100,000 ft³ (3,700 yd³) of DNAPL-contaminated soil and groundwater, and monitor effectiveness over a 1-month period is estimated at \$139,000. If further treatment were required (i.e., re-injection), thus extending the treatment period, the cost would increase by a considerable amount.
- (2) The largest cost categories for the application of the XDD ISCO technology at a site having characteristics similar to those described for the hypothetical site are 1) consumables and supplies (41%) and 2) labor (21%), together accounting for 62% of the total cost. The other major costs, as estimated, include startup and fixed (18%), and analytical services (9.7%).
- (3) The cost of implementing XDD’s process may be less or more expensive than the estimate given in this economic analysis, depending on several factors. Such factors may include the depth and areal extent of the contaminated media, site geology, contaminant concentration levels, the level of site preparation required, number of injection/monitoring wells needed to be installed, and the cleanup goals and process monitoring required by a regulatory agency.

3.3 Factors Affecting Estimated Cost

There are a number of factors that could affect the cost of treating soils and groundwater contaminated with chlorinated VOCs using XDD’s ISCO technology. It is apparent that the number of injection wells required to deliver the oxidant to affected areas, the quantity of oxidant needed, and the number of wells required for monitoring the treatment have very significant impacts on up-front

costs. The contaminant distribution pattern has the largest impact on the number of injection wells required to attain a sufficient area of oxidant coverage to contact and degrade the contaminants to acceptable levels. Soil humic content is a critical factor for determining the types and quantity of oxidants used, which would obviously directly affect treatment cost as well.

Site hydrogeology is an important cost consideration, since it can dictate how well the oxidant will work, the ease of which oxidant can be injected and how many injection points may be needed; regardless of whether those points are injection wells, drive points, infiltration galleries, or simple pits. The amount and spacing needed for injection and the desired screened depth intervals determine if such injection methods were feasible. In general, increased drilling locations and deeper drilling directly lead to increased drill footage costs, increased decontamination costs, and increased costs for well construction materials.

3.4 Issues and Assumptions

This section summarizes the major issues and assumptions used to estimate the cost of implementing the ISCO at full-scale. In general, the assumptions are based primarily on information provided by XDD and observations made by SAIC during the SITE demonstration.

3.4.1 Site Characteristics

Site characteristics are an important consideration for deciding whether an ISCO process is an appropriate remedy for treating chlorinated ethenes at a particular site. In general in situ processes are more appropriate when contaminated soils and groundwater are at depth; which makes excavation and disposal too costly. Site geology must be well defined to determine areas of high humic content. Specific aspects of the groundwater flow regime (i.e., flow direction and rate), as well as plume delineation, need to be known prior to installing oxidant injection wells.

The following specific assumptions have been made regarding the site characteristics of the hypothetical site.

1. The target contaminated soil hotspots have been characterized with CPT/MIP technology, as was the case with the demonstration.
2. Groundwater occurs at about 18 ft (5.5 m) bgs and has a well-defined flow pattern to the north.
3. Groundwater at the site is contaminated primarily with chlorinated ethenes (PCE and TCE) as both DNAPL and a dissolved phase mobile plume. Also present as breakdown products are cDCE and VC. Concentrations of these compounds

well exceed their respective cleanup standards. Other contaminants (e.g., metals) either are not present at the site or have inconsequential concentrations.

4. Site soils are assumed to have a low to moderate humic content, ensuring that the majority of the injected KMnO_4 will react with contaminants and not with naturally occurring humic material.
5. The site is easily accessible and secured; therefore there is no need to install special access roads, security fencing, etc. is not required. Also, there are no overhead, surface, or underground impediments that would interfere with borehole drilling and oxidant injection.

3.4.2 Design and Performance Factors

The most important design aspects of ISCO processes is the selection of oxidant, oxidant dosage, and the injection well network (i.e., the number, depth, and areal pattern of injection wells) required for optimum treatment. Injection well spacing is usually dictated by the site geology.

The following assumptions are made regarding the injection well network installed at the hypothetical site.

- (1) Ten injection wells, spaced ~ 18 ft (5.5 m) apart in two rows, will provide sufficient coverage of contaminated media above action levels.
- (2) All injection wells are constructed of 2 inch ID PVC casing and 10 ft-long, 40 slot well screens. The well screens are set at 30-40 ft bgs, above the top of bedrock at about 50 ft (15 m) bgs. Wells are flush mounted with road boxes.
- (3) As was the case with the demonstration site, push-points are not feasible. Therefore, a hollow stem auger (HSA) rig is required to drill 4½ inch ID boreholes and set the wells.
- (4) Potassium permanganate (KMnO_4) is used as the oxidizing agent of choice. A total of 15,000 gal. (56,800 L) of KMnO_4 is to be injected once into the contaminated area (1,600-1,700 gallons or 6,100-6,400 L per well), at a concentration of 40 g/L.
- (5) Treatment duration is assumed to be at minimum of one month. Additional treatment (i.e., re-injection) is not considered for costing purposes, however monitoring is mandated for one year.

3.4.3 Financial Assumptions

All costs are presented in Year 2006 U.S. dollars (unless otherwise noted) without accounting for interest rates, inflation, or the time value of money. Insurance and taxes are assumed to be fixed costs lumped into the specific

costs under the "Startup and Fixed" category. Any licensing fees and site-specific royalties passed on by the developer, for use of any proprietary injection equipment or methods, would be considered profit. Those fees are not included in the cost estimate.

3.5 Basis for Economic Analysis

In this section, each of the 12 cost categories that reflect typical clean-up activities encountered at Superfund sites, are defined and discussed. Combined, these 12 cost categories form the basis for the detailed estimated costs presented in Table 3-1. The labor costs are grouped into a single labor category (subsection 3.5.5).

3.5.1 Site Preparation

Site preparation includes all activities necessary for preparing the site for installing injection wells and injecting of the KMnO_4 oxidant. Included in this setup phase are non-labor cost for conducting any clearing and/or regrading of the site, hooking up utilities, providing for the storage of oxidant, and staging of equipment and supplies. Each of these site setup cost components is discussed in the following paragraphs.

3.5.1.1 Site Clearing

Although the XDD ISCO process does not require a large amount of setup space, such in situ processes typically involve subsurface drilling in some form. General requirements apply to all drilling operations. All impediments and surface, overhead and underground obstacles must be identified. These would include trees, utility lines and piping, sewers, drains, and landscape irrigation systems.

No site clearing of above-ground obstructions or regrading was necessary at the demonstration site, however, a survey of potential underground utility lines was required to obtain a "dig safe" clearance before drilling activities could be initiated. For this economic analysis, an assumption is made that for the hypothetical site that there is no impediments in the area of the proposed ISCO injection and monitoring operations. Thus, there is no associated cost for site clearing.

3.5.1.2 Site Setup

Site setup typically includes making arrangements to secure a trailer, hooking up utilities, etc., and shipping supplies. If the treatment is being implemented at an active facility (such as the former MEC Building site), there may be no need for a site trailer. For the hypothetical site, this also will be the case. However, due to the large quantity of oxidant to be used a small building or shed will be needed to store the many jugs of KMnO_4 oxidant away from facility workers.

Because XDD is able to power the POD, pumps, and other equipment with a large portable generator, there is no need for hooking up electricity. As a result, the non-labor costs associated with site setup phase would most only include shipment of oxidant (as explained below).

Shipment of Oxidant

After the injection wells have been installed, the KMnO_4 is shipped in bulk and properly stored at the site. (Note: granular KMnO_4 has a reported shelf life of one year and should be stored in a dry place). The KMnO_4 is packaged and shipped in 20 Liter (5.3 gal.) jugs. Each bucket contains approximately 55 pounds of KMnO_4 . For the hypothetical site, it is anticipated that a minimum of 250 buckets will be required to ship approximately 14,000 lbs (635 kg) of KMnO_4 . For large quantities such as this, the buckets are stacked and secured on wooden pallets that can be transferred to the batching area with a forklift.

XDD commonly uses a specific carrier for shipping oxidant and has estimated that shipping approximately 7,800 lbs of granular KMnO_4 to the former MEC Building site cost approximately \$900. For this cost estimate, a shipping cost of \$1,000 will be used.

3.5.2 Permitting and Regulatory Requirements

3.5.2.1 Permitting Requirements

Several types of permits may be required for implementing a full-scale ISCO remediation. Permits required may depend on the type and concentration of the contamination, the regulations covering the specific location, and the site's proximity to residential neighborhoods. For example, the New Hampshire Department of Environmental Services (NHDES) requires a site owner or legally responsible person to remedy contamination associated with the past discharge of regulated contaminants, and to manage the use of contaminated groundwater.

A Groundwater Management Permit (GMP) from the State is required for such endeavors. The application for the GMP must be prepared and stamped by a professional engineer (PE) or a professional geologist (PG) licensed in the State. There is an application fee of \$1,000.

Specific to ISCO processes there is in most cases, if not all, a requirement to obtain an injection permit. There may or may not be a fee for this. For the former MEC Building site, XDD was required to apply for and acquire an injection permit from the NHDES. However, there was no actual permit fee. Note that other states may require a fee.

3.5.2.2 Other Regulatory Requirements

The costs incurred for receiving approval from regulatory agencies to install a treatment system may include those associated with preparing site characterization reports and the feasibility study for treatment system design, and attending meetings with regulators for discussing comments and supplying related documentation for acquiring approval for implementing the treatment technology.

Depending upon the classification of the site, certain RCRA requirements may have to be satisfied as well. For active Superfund sites it is possible that the technology could be implemented under the umbrella of existing permits and plans held by the site owner or other responsible party (e.g., the GMP). Certain regions or states have more rigorous environmental policies that may result in higher costs for permits and verification of cleanup. Added costs may result from investigating all regulations and policies relating to the location of the site; and for conducting a historical background check for fully understanding the scope of the contamination. Specific to ISCO technologies, states may require that injection wells be properly abandoned/decommissioned if they are no longer to be used.

Due to the very site-specific nature of these costs, an assumption will be made that sufficient pre-existing site information exists for regulators to allow initiation of treatability and/or pilot-scale field studies. As a result, no further costs regarding regulatory requirements will be incurred.

3.5.3 Capital Equipment

In many instances ISCO processes consist of one-time applications at a particular contaminated area. As a result, the equipment for injection is required for a short period of time and is thus rented (see 3.5.6). Even if multiple injection applications are necessary, they would not occur immediately following an initial injection. Therefore, the equipment would be re-mobilized and rented again for additional injection events.

For the particular hypothetical site example used for this economic analysis, it is assumed that the only capital equipment required is an outdoor shed to store oxidant, and dedicated bladder pumps used for groundwater monitoring before and after treatment. (Note: a peristaltic pump was used for collecting demonstration groundwater samples because water was pulled from less than 25 ft bgs. Since groundwater contamination at the hypothetical site is below the maximum sample depth of peristaltic pumps (i.e., > 25 ft bgs), other alternatives must be used.

The storage shed must be large enough to contain approximately 250 jugs of KMnO_4 . If the injection were to take place in cold temperatures, the shed would need to

be heated to prevent freezing of the granular oxidant. However, for this scenario, this is not the case). The installation of the prefabricated shed for the hypothetical site is estimated to be \$1,000.

Although bladder pumps and tubing are relatively expensive, once installed these dedicated pumps 1) assure that there is no air/water contact during sampling; and 2) they eliminate the need to decontaminate sample collection equipment between wells and reduce the chance of cross-contamination or the introduction of decontamination chemicals into the groundwater. In essence, much of the capital expenditure related to the use of dedicated bladder pumps is recouped by reduced labor costs.

Teflon bladder pumps with stainless steel housings can be purchased for about \$500. Along with associated tubing, the cost of each pump is about \$600. Five of the ten injection wells are to be sampled to monitor treatment effectiveness. Therefore, the total cost for five bladder pumps is estimated to be \$3,000. A pump flow controller, estimated to cost \$1,100, is required to regulate compressed air as a cycle of pulses that corresponds to a desired groundwater flow rate out of the well. The high rental cost of this equipment justifies its purchase if used for several sampling events. The total cost for capital equipment is estimated to be approximately \$4,100.

3.5.4 Startup and Fixed Costs

Startup and fixed costs include those costs that must be incurred before treatment can commence. They are one time non-recurring costs in which labor is typically imbedded within a flat fee for a task. Based on information provided by XDD and SITE demonstration observations, these costs for full scale ISCO applications include primarily 1) initial treatability testing; 2) installation of injection wells and, if needed, 3) pilot-scale testing. Estimates for all three of these startup and fixed costs are discussed in the following subsections.

3.5.4.1 Treatability Study

Initial treatability testing is necessary for determining whether the technology is feasible at a particular site. XDD performed a two-part bench-scale treatability study prior to the demonstration; 1) A dosing study determined permanganate dosing level and exposure period for evaluating process effectiveness and assessment of feasibility of attaining site-specific cleanup goals; 2) A soil oxidant demand (SOD) study to estimate SOD for the three major soil units. The results of the treatability study helped XDD develop a site-specific strategy for applying ISCO treatment at the former MEC Building site.

Per XDD, the SOD determination is always conducted. The cost for XDD treatability studies run approximately

\$1,500 per sample. Because there are no distinct soil zones at the hypothetical site, an assumption is made that three samples of the site soils are sufficient for determining SOD, even though the site is four times larger than the demonstration site. Therefore, treatability study costs are estimated at \$4,500.

3.5.4.2 Injection Well Installation

The amount and location of oxidant injection points and the number of points required for monitoring effectiveness is highly site-specific. The number of injection wells required to produce an adequate ISCO is relatively high. Close injection well spacing is typically needed in heterogeneous soils to ensure adequate coverage. For the hypothetical site a total of 10 injection wells, each screened from 30-40 ft (9.1-12.2 m) is assumed sufficient to inject the volume of oxidant needed to treat 3,700 yd³ of contaminated material.

XDD prefers to inject into 2-inch ID wells installed within a 4½ or 6-inch ID borehole. It should be noted that direct push technology (DPT) can be used to install wells and has the advantage of minimizing generation of contaminated soil cuttings. However, using traditional well installation methods involve auguring of larger boreholes that result in larger diameter annular spaces between the well casing and borehole sides. This makes for easier installation of a filter pack and bentonite seal. For the hypothetical site, each of the 10 injection wells is to be installed using HSA to drill 4½-inch boreholes.

An all inclusive well installation cost of \$50 per foot will be assumed for this cost estimate (i.e., cost to include mobilization, demobilization, drilling, well materials and well development). The \$50 rate would correlate to drilling costs of \$2,000 per well (i.e., there are 10 wells total to be installed at a depth of 40 ft bgs. Therefore, the estimated total injection well drilling cost is \$20,000.

The total startup and fixed costs for this economic analysis is thus estimated to be approximately \$24,500.

3.5.4.3 Pilot-Scale Testing

In addition to the bench-scale treatability study of formation material and sample groundwater, pilot-scale testing may be appropriate in certain instances. XDD sometimes conducts water injection testing on prospective injection wells, a practice they are utilizing more frequently. As an example, for the demonstration project at the former MEC Building site, XDD performed a small-scale water injection test at a target flow rate to monitor well seal and injection pressures of newly-installed injection wells. The costs of such field tests are almost exclusively labor (see 3.5.5).

3.5.5 Labor

This subsection describes the core labor costs that are associated with the XDD ISCO technology. The hourly labor rates presented are loaded, which means they are intended to include base salary, benefits, overhead, and general and administrative (G&A) expenses. Travel, per diem, and standard vehicle rental have not been included in these figures. The labor tasks have been broken down into subcategories that represent distinct phases of technology implementation (**Table 3-3**).

Table 3-3. Estimated Labor Costs.		
Category	Hours	Cost
Permit Preparation	4	\$320
System Design	40	\$3,200
Injection Well Installation	50	\$4,000
Oxidant Injection	120	\$7,200
Treatment Monitoring	180	\$10,800
Site Restoration/Demobilization	20	\$1,200
Report Preparation	40	\$3,200
Totals	454	\$29,920

3.5.5.1 Permit Preparation

As discussed in subsection 3.5.2 there is a fee for certain permits. However, researching permit requirements and preparing applications takes time and thus incurs a labor cost. If a groundwater management permit and injection permit are to be required for the hypothetical site the applications would have to be submitted by either a professional engineer (PE) or professional geologist (PG) licensed in the particular state that the site is located in.

Assuming that both applications are prepared and submitted by a PE or PG in two hours at \$80/hr, permit preparation costs can be estimated at \$320.

3.5.5.2 System Design

In most all instances system design is conducted by the remediation contractor, in this case XDD. The information that XDD needs for system design are the 1) amount of contaminants present (i.e., mass and extent) and 2) Site hydrogeological information. For the SITE demonstration the system design was a joint effort among EPA, SAIC, XDD, the site owner and their remediation contractor. Although the demonstration project was smaller in scale than the remediation scenario used for this economic

analysis, the experimental design for evaluating treatment effectiveness was relatively complex.

Per XDD, it takes roughly 1-2 people any where from 2-5 days to complete a proposed treatment strategy, depending on complexity. For this cost estimate, the primary labor task relating to system design would involve a senior level scientist or engineer reviewing existing site characterization data for the hypothetical site, reviewing results from SOD treatability testing of site samples, calculating oxidant mass and concentration, and determining location, depth, and number of injection wells needed to adequately treat the contaminated DNAPL plume. Assuming a 40-hr week sufficient to accomplish this task, and a labor rate of \$80/hour, an estimated labor cost of \$3,200 would be incurred for system design.

3.5.5.3 Injection Well Installation Oversight

Although drilling and well installation labor activities are performed by a drilling contractor, the remediation contractor (e.g., XDD) at a site would be responsible for logging boreholes, monitoring for VOCs and explosive conditions, and ensuring that well construction and installation is conducted in accordance with design specifications. It should be noted that since the hypothetical site is adequately characterized, geologic descriptions would not be required when drilling the boreholes for injection wells.

During the demonstration, it took approximately four days for a subcontracted driller to mobilize to the site, install six injection wells to an average drilling depth of 16 ft using a hollow stem auger (HSA), conduct flush mount well completion with road boxes, develop the wells, and demobilize. Assuming that the drilling subcontractor is local and that there are only minor drilling impediments, the time required to mobilize, install 10 injection wells 40 feet through unconsolidated sediments with similar well completion, and demobilize is estimated to take approximately one week. Assuming 10-hour days are required for subcontractor oversight, a geologist's labor at an \$80/hour rate would result in \$4,000 in oversight labor.

3.5.5.4 Oxidant Injection

Assuming the site is within a ½ day or less driving distance (i.e., the demonstration site), mobilization and equipment setup can be done in one day by two people. The following tasks comprise the basic setup of equipment.

- Oxidant delivery/storage of KMnO_4
- Setup of spill guards for batch area
- Potable water delivery (tanker)
- Drop-off of rented generator
- Hookup of batch operation to POD
- Connect injection distribution system to wells

Injection of KMnO_4 or other oxidant, as observed during the demonstration, involves three basic steps; 1) a batching operation in which granular KMnO_4 is mixed with potable water to form an oxidant solution at the desired concentration; 2) pumping the KMnO_4 solution from one or more mixing vessels through a series of cannister filters and onto the POD; and 3) pumping oxidant from the POD down the wells via high pressure hoses.

During the demonstration, the injection rates for individual wells were varied on a regular basis to control seepage of oxidant. Flow rates during the second injection event ranged from 1.7 to 2.6 gpm for individual wells, the higher injection rates were typically for the deeper wells. The injection event took two people four days to inject a little over 1,900 lbs (862 kg) of KMnO_4 into a total of 10 injection wells. At this same rate, it would take the same two individuals 28 days to batch, transfer, and inject over seven times that amount of KMnO_4 (14,000 lbs or 635 kg).

However, all of the wells at the hypothetical site are set in a formation similar to the demonstration site's deep zone, which was able to take a large volume of oxidant (i.e., XDD was able to inject about 480 lbs (218 kg) of oxidant daily into the deep wells. Assuming XDD could inject via their POD the same amount into six wells at the hypothetical site simultaneously, they could inject a total of about 2,900 lbs (1,320 kg) of oxidant daily.

At this rate, XDD could inject all 14,000 lbs of oxidant in five full days. If a day of mobilization and setup is included, the injection event could be completed in six days and would take two people and a total of 120 hours to complete. Thus, at a \$60 per hour rate for the estimated 120 labor hours, the labor cost for the KMnO_4 injection phase would total \$7,200.

3.5.5.5 Treatment Monitoring

As previously discussed, the contamination in the soil and groundwater at the hypothetical site has been assumed to be fully characterized prior to installation of the XDD ISCO injection wells. For monitoring the technology effectiveness on both the soil and groundwater, at least two soil and groundwater sampling events are required. A pre-injection "baseline" event is typically desired to assess pre-treatment concentration levels for both soil and groundwater. Intermediate events, conducted after treatment, but prior to the estimated treatment completion time, are used to determine the rate of treatment progress and to assess any trends. Final post-treatment monitoring is required to determine if treatment goals have been met.

For the hypothetical site, a reasonable scenario for collecting treatment verification samples would be to collect groundwater samples from five of the 10 injection wells a week or two before the KMnO_4 injection date to establish

a true pretreatment groundwater baseline. At about the same time approximately 10 soil samples, randomly-selected within the 100 ft x 32 ft x 32 ft defined contaminated zone, would be collected to establish a baseline soil concentration. Following the first two weeks of treatment, an intermediate groundwater sampling of the same five wells would be conducted to evaluate groundwater contaminant trends. Finally, after at least one month has passed since the end of the injection date, a final post-treatment sampling of both soil and groundwater would be conducted to verify treatment effectiveness. These six sampling events are summarized as follows.

1. Pre-Injection Soil (Baseline)
2. Pre-Injection Groundwater (Baseline)
3. Post-Injection Groundwater (Intermediate)
4. Post-Treatment Soil (Final)
5. Post-Treatment groundwater (Final)

Groundwater Sampling

For this cost analysis, it will be assumed that the two-person sampling team can mobilize to the site, setup, purged and sample the five wells, ship the samples to an off-site laboratory, and demobilize in one 10-hour day. Therefore, each of the three groundwater sampling events would incur 20 hours of technician labor at \$60/hr; or \$1,200. Thus, from the time just prior to KMnO_4 injection until one year following the KMnO_4 injection, a labor cost of \$3,600 would be incurred for groundwater sampling.

Soil Sampling

Collection of soil samples to determine the technology effectiveness was difficult and time consuming during the demonstration. Two events, a pre-treatment baseline and final post-treatment, are deemed sufficient so long as enough samples are collected to provide a statistically significant sample set.

A geoprobe was used for collecting soil samples during the final sampling event at the demonstration site. A total of 30 samples was collected from each of three lithologic zones (for a total of 90 samples). However, Although the hypothetical site is larger there is only one contaminated zone. Therefore, an assumption is made that 30 soil samples from this zone prior to treatment and again one month after treatment will provide an adequate statistical sample set for evaluating treatment effectiveness.

For the demonstration, sampling at 30 locations took approximately four days, however three discrete depth zones were sampled. Since there is essentially one affected zone at the hypothetical site, it is assumed that samples from the 30 locations can be collected in three 10-hour days. Thus, combining baseline and post-treatment verification sampling (i.e., 60 samples), six 10-

hour days are assumed sufficient to complete all soil sampling. Other than the geoprobe crew, two technicians at \$60 per hour can collect, prepare, and ship the on-site methanol-extracted soil samples in this time period. This would equate to \$1,200 of labor per day or a total of \$7,200 of total labor for soil sampling.

Therefore, total treatment monitoring labor costs (groundwater plus soil) is estimated at \$10,800.

3.5.5.6 Site Restoration/Demobilization

For the XDD ISCO process, the primary activity for demobilizing from the demonstration site involved a thorough flushing of the oxidant from the POD and related equipment components. To accomplish this, XDD uses a neutralizing solution that consists of a 5:1:1 mixture of potable water, vinegar, and hydrogen peroxide (H_2O_2), respectively. The neutralizer is pumped through the POD components and all of the high pressure hoses and injected down the injection wells (the small amount of neutralizer has a negligible effect on the subsurface).

For the demonstration, the demobilization effort took approximately one day for two people to complete. Therefore, it is assumed that demobilization will take two people, working a ten-hour day (20 hours total) to demobilize. At a loaded rate of \$60/hr per technician, the total demobilization labor cost is estimated at \$1,200.

3.5.5.7 Report Preparation

Labor for report preparation can be quite variable, depending upon the complexity of the data and client expectations. For this economic analysis an assumption is made that XDD will prepare a brief final report containing the basic information and data needed for a third party to evaluate. The report would include the following information at a minimum.

- Brief description of the site (including a site map);
- Re-summarizing of the treatability study results;
- Injection Summary (volume, mass, dosages, etc.)
- Map of Injection points, wells, and borings
- Groundwater sample results for all three events;
- Soil sample results for both events;
- Results of quality assurance samples;
- Brief interpretation of results and conclusions.

It is estimated that it would take a senior level engineer or scientist a week (i.e., 40 hours) to prepare such a report. At a loaded rate of \$80/hr, report preparation is estimated at \$3,200.

3.5.6 Consumables & Supplies

Consumables and supplies for implementing a full-scale ISCO process comprise a significant amount of total costs. They are estimated at \$56,350 for this economic analysis.

Consumable and supply costs can be segregated into three separate subcategories: 1) Consumables (i.e., materials consumed or used up); 2) Equipment Rentals; and 3) Miscellaneous Supplies. Each of these subcategories is discussed separately in the following subsections.

3.5.6.1 Consumables

The two major consumable items associated with XDD's ISCO process are 1) the oxidant itself ($KMnO_4$) and 2) potable water that is needed to mix with the oxidant to form an injectable solution at a desired oxidant concentration. Note that water is considered a consumable in this instance (as opposed to a utility).

$KMnO_4$

The injected $KMnO_4$ is considered a consumable because it is consumed after injection. During the demonstration, XDD injected approximately 15,000 gal. (57,000 L) of $KMnO_4$ solution into about 1,000 yd^3 of contaminated material. The 3,700 yd^3 of contaminated material at the hypothetical site is 3.7 times greater in volume. Therefore, there would need to be about 56,000 gal. (212,000 L) of oxidant/water solution injected at a similar dosage, or 5,600 gal. of solution injected per the 10 injection wells.

The bulk purchase price of treated granular $KMnO_4$ is reported by XDD to be \$2.30 a pound. Using a $KMnO_4$ concentration of 30 g/L, approximately 14,000 lbs (7 tons) of granular $KMnO_4$ would be required to produce 56,000 gallons of oxidant solution. At the \$2.30/lb price, the cost of granular $KMnO_4$ is estimated to be \$32,200.

Potable Water

The potable water that is used to make up the oxidant solution is also a consumable item. During the demonstration XDD utilized 5,000 gal. (18,900 L) tankers to supply potable water at the site at a cost of \$0.10 per gallon. This cost included delivery and use of the tanker. The cost of 56,000 gallons of potable water is therefore estimated at \$5,600.

3.5.6.2 Equipment Rental Costs

For this economic analysis equipment rentals include costs for non-capital equipment required to perform four basic functions. These include 1) Direct Push Technology (DPT) for conducting baseline and post-treatment soil sampling; 2) Equipment for injecting oxidant; 3) Equipment for health & safety monitoring during field activities; and 4) Equipment for conducting groundwater sampling. Each of these rental categories is discussed separately as follows:

Soil Sampling

Final event soil sampling at the demonstration site was accomplished with DPT employed by a geoprobe. Although this work is almost always subcontracted out, the use of the geoprobe is costed out on a daily basis (i.e., rented equipment). The cost of the geoprobe, including a daily mobilization charge for a local drilling company, is estimated at \$1,400/day. During the demonstration, a geoprobe was able to collect 90 discrete soil samples from 30 locations in about four days. If 30 locations are sampled at a depth of about 40 feet bls to collect both baseline and post-treatment soil samples at the hypothetical site, it will be assumed that soil sampling can be completed in six days. Therefore, the total geoprobe rental cost is estimated at \$8,400.

Directly associated with geoprobe soil sampling is steam cleaning of DPT samplers and push rods to prevent cross contamination between boreholes. Steam cleaner rental is estimated at \$150 per day, or \$900 for the six-day event.

Oxidant Injection

The primary rented item for injecting oxidant is XDD's Portable Oxidant Delivery System (POD). XDD's POD is a trailer-mounted unit specifically designed for injecting and monitoring delivery of oxidant at up to six injection points simultaneously. The unit's primary components include batch tanks, mixers, a metering pump, a distribution manifold, and chemically-resistant digital flow meters that measure flow rates and total flow volumes. The POD can be rented on a daily basis for \$1,500 or \$4,500 weekly.

During the demonstration, XDD was injected up to 1,000 gal. (3,800 L) of oxidant solution into deep zone wells (i.e., 25 ft bls) in a 10-hour day. Since the POD can deliver oxidant to six wells at a times, it is assumed that XDD could inject 6,000 gal. (22,700 L) of oxidant solution per day at the hypothetical site. Therefore, rental of the POD is estimated at \$4,500.

Directly associated with the POD is a rented pickup truck, used to transport the POD and supplies, and to mobilize personnel to and from the site on a daily basis. The truck is rented out at \$225 per week. Other rented equipment needed by XDD for injection include a 70-KVA generator (\$700/week), transfer pumps (a combined \$135/week), and two 500 gallon mixing tanks (a combined \$210/week). Together, these items add up to an additional \$1,270/week.

Health and Safety Monitoring

A photoionization detector (PID) and combustible gas indicator (CGI) are standard health and safety requirements for drilling operations (i.e., well installation and soil sampling). The PID can also be used to screen drill cuttings to aid in the determination of disposal options.

Drilling operations should consist of just two events; 1) one week to install wells immediately followed by three days of soil sampling, and 2) three days of post-treatment soil sampling. A PID and CGI can be rented for \$200 a week and \$150 a week, respectively (i.e., a combined \$350 per week. A conservative time frame estimate for use is three weeks for both events. Therefore, the cost of renting these field monitoring instruments is conservatively estimated at \$1,050.

Groundwater Sampling

Groundwater sampling during the demonstration was conducted with a rented peristaltic pump. However, as previously discussed, purchased bladder pumps are to be used at the hypothetical site for sampling groundwater below 25 ft bgs (see 3.5.3). Sampling equipment is still required for low flow purging and sampling of wells. The largest rental cost is for use of a multi-parameter water quality meter. This instrument combines the measurement capabilities of several instruments and can be rented for \$100 per day (includes a flow-through cell).

In addition to the multi-parameter meter, a water level indicator is required for recording water levels during the low-flow purging/sampling. A water level indicator can be rented for \$22/day, thus the combined rental equipment needed is \$122/day. For the six days required (i.e., 3 events x 2 days), total rental costs are estimated at \$730.

3.5.6.3 Miscellaneous Supplies

Miscellaneous supplies could include a whole array of items that by themselves are relatively insignificant in cost, but combined would add up to a sizable cost needing consideration. These items may include, but are not limited to, the following items shown in **Table 3-4**.

Table 3-4. Estimated Miscellaneous Supplies Costs.			
Item	Unit Cost	No.	Total
Soil Sample Liners	\$10/Each	60	\$600
Decon. Containment	\$100/Each	1	\$100
Personal Protective Equip.	\$20/day	20	\$400
Calibration gases/solutions	50/Each	2	\$100
Well couplings	\$2/Each	10	\$20
Rental Shipping charges	\$80/Each	6	\$480
Total Estimate			\$1,700

As shown in Table 3-4, total miscellaneous supplies are estimated at \$1,700, the largest component being soil sample liners used for the geoprobe sampling.

3.5.7 Utilities

The predominant utility required for XDD's oxidant injection is the electricity required to operate the POD and associated pumps. Electricity is also required for powering an air compressor during groundwater sampling. Certainly, the proximity of the demonstration site to a readily available facility would make this a minor issue. However, at a remote site, logistics can get complicated. It may even be necessary to use a gasoline or diesel powered generator if electrical hookup is not practicable.

A small additional electrical cost may be needed to supply lighting to the trailer and a security light, and possibly for a phone and facsimile hookup. Other than electricity, a water source may be needed for occasional decontamination activities; however, those costs are considered negligible.

During the demonstration, both electricity and water was available from the former MEC Building. For this economic analysis, the same is assumed for the hypothetical site. Thus, no costs for utilities are included.

3.5.8 Effluent Treatment and Disposal

For this technology there is no effluent. Therefore, it is assumed that there will be no effluent treatment and disposal expense. Disposal of small amounts of decontamination wastewater generated from cleaning sampling equipment is considered negligible and therefore no costs are included for this category.

3.5.9 Residuals Shipping and Disposal

The ISCO technology generates essentially no waste streams per se. However, investigation derived wastes (IDW) are typically generated when installing injection and monitoring wells, and when collecting soil and groundwater samples for evaluating treatment effectiveness.

The IDW generated for an ISCO remediation can be subdivided into two broad categories; 1) Waste Solids, and 2) Waste Liquids. During the demonstration, waste solids consisted of soil cuttings from HSA drilling for well installation, residual soil sample material, and miscellaneous waste solids (i.e., visqueen and wood from the decontamination pad, PPE, used sample liners, etc.). Waste liquids consisted of well development water, sampling equipment decontamination water, and purge water generated during groundwater sampling.

For the hypothetical site it is assumed that DPT will be used for both well installation and soil sampling (i.e., not HSA). Therefore, no soil cuttings will be generated. However, there will be residual soil sample material. Since only about $\frac{3}{4}$ of one drum of residual sample material was generated for the 90 samples collected during the demonstration final event, it is assumed that just one drum

of residual material will be generated from the 60 samples collected for the hypothetical site sampling scenario. As was the case with the demonstration, three additional drums of waste solids (e.g., sample liners, visqueen, PPE, etc.) will be assumed generated for the hypothetical site scenario. Disposal of waste solids cost \$90 per drum. Therefore, the total cost of disposing the four waste solid drums is estimated at \$360.

Based on the demonstration IDW, generation of waste liquids is anticipated to substantially exceed waste solid generation in volume. During the demonstration about 2.6 drums of well development water was generated for six 2-inch ID wells representing about 90 feet of water column. The water column for each of the 2-inch ID hypothetical site wells is 22 feet, thus a total 220 feet of water column should generate about 370 gallons of development water, or about seven 55-gallon drums.

Also, during the demonstration steam cleaning of DPT equipment used to bore about 1,200 feet of soil generated four 55-gallon drums of decontamination water. For the hypothetical site a total of 60 samples will be collected from an approximate 35-ft depth, which equates to roughly 2,100 ft. of boring footage. This would equate to 1.75 times the demonstration volume of decontamination water generated and would require seven drums for containment. Purge water from both baseline and post-treatment events should add another drum. All in all there are an estimated 15 liquid drums requiring disposal.

Disposal of waste liquids cost \$145/drum. Therefore, disposal costs for the 15 drums of waste liquids are estimated at \$2,175. Total disposal costs for the hypothetical site (solids + liquids) is estimated at approximately \$2,530. It should be noted that there is a minor charge for pickup and manifesting, which will be considered negligible for this cost estimate. Table 3-5 below summarizes the estimated disposal costs.

Table 3-5. Estimated Residuals Shipping/Disposal Costs.

Item	Unit Cost	No.	Total
Waste Solids			
Residual Soil Sample	\$90/Drum	1	\$90
Miscellaneous Solids	\$90/Drum	3	\$270
Waste Liquids			
Well Development Water	\$145/Drum	7	\$1,015
Decontamination Water	\$145/Drum	7	\$1,015
Sample Purge Water	\$145/Drum	1	\$145
Total Estimate			\$2,535

3.5.10 Analytical Services

The level of testing required to substantiate successful ISCO treatment at full scale (i.e., at the hypothetical site) is assumed to be significantly scaled down from the SITE Demonstration sampling plan. For this cost analysis, a treatment period of one month is assumed and the two-event soil and three-event groundwater sampling schedule discussed previously (see 3.5.5.4) is considered adequate to monitor and evaluate treatment effectiveness.

Although the site owner or the site owner's contractor would likely collect these samples, the state or local regulatory agency may require independent analysis of the samples by an outside laboratory (especially for final post-treatment samples).

It is also being assumed that for both soil and groundwater the only required analytical parameter is for volatile organic compounds (VOCs); for soil SW-846 Method 5035/8260B (including total solids analysis for soil samples to report results on a dry weight basis) and SW-846 8260B for water. VOC analyses are essential since specific VOCs are the target contaminants. Other analyses, such as metals, are considered optional (i.e., metals' analyses may provide insight as to whether the ISCO process mobilizes metals or not, however metals are not considered a concern at the hypothetical site).

Table 3-6 provides an estimate for the cost of analytical samples for the hypothetical site sampling scenario.

Table 3-6. Estimated Analytical Costs ¹			
Item	Unit Cost	No.	Total
Soils ²			
Baseline Event	\$130/Sample	30	\$3,900
Post-treatment Event	\$130/Sample	30	\$3,900
Groundwater			
Baseline Event	\$150/Sample	10	\$1,500
Intermediate Event	\$150/Sample	10	\$1,500
Post-treatment Event	\$150/Sample	10	\$1,500
Sample Shipments			
Soil ³	\$50/Shipment	20	\$1,000
Groundwater	\$50/Shipment	3	\$150
Total Estimate			\$13,450
¹ Costs include QC sample analyses. ² Total solids analysis included for reporting dry weight soils ³ ≤MeOH 500 ml shipped in any container (3 borings max.)			

As shown in Table 3-6, the total cost of analytical costs for the hypothetical site scenario is \$13,450. Assumptions include that QA/QC samples (e.g., MS/MSDs, trip blanks, etc.) are included in the unit cost values shown.

3.5.11 Maintenance and Modifications

During the actual demonstration injections, maintenance activities and/or system modifications were performed on an as needed basis. For example, routine maintenance consisted of periodic flushing of cannister filters, which were used to remove unwanted material (e.g., silica solids) from the oxidant solution. On the infrequent occasion that a pump malfunctioned, it was either repaired or changed out. In instances where maintenance and/or modification were required, XDD was able to perform those activities without major disruption to the injection process. As a result, there were no additional labor costs or parts costs associated with those activities.

For the hypothetical site, the same will be assumed (i.e., no additional cost for maintenance and modifications during injection). Also, with respect to post-oxidant injection monitoring events, no maintenance per se was conducted during the demonstration. Thus for this cost estimate it is assumed that no maintenance cost and/or modification costs will be incurred.

It should be noted that for the demonstration, some injection wells had to be replaced due to short-circuiting problems. However, this did not relate to the XDD ISCO process.

3.5.12 Site Restoration

Site restoration is typically performed at the conclusion of the treatment project. It is assumed that the flush-mounted injection wells that were installed for oxidant injection will remain on-site for future monitoring purposes; or in the unlikely case that re-injection of additional oxidant (i.e., either additional KMnO₄ or a different oxidant) is needed at a later date. Therefore the abandonment of injection wells, a major site restoration cost if needed, will not apply in this case.

As was the case with the demonstration site, site restoration related non-labor costs for the hypothetical site will consist almost exclusively of grouting of soil sample boreholes to seal off contaminant pathways to and from the subsurface. Grouting expenses can vary significantly. For this cost estimate, an average borehole depth of 40 feet and a cost of \$2 per foot is assumed. Since there is a total of 60 boreholes to grout (i.e., 30 baseline and 30 post-treatment), total borehole grouting costs are estimated at \$4,800.

Section 4.0

Technology Effectiveness

4.1 Introduction

4.1.1 Project Background

XDD's ISCO process was evaluated under the EPA SITE Program at the former MEC Building site located in Hudson, NH. Soil and groundwater at this site are contaminated with DNAPL and dissolved-phase contaminants, such as TCE, cDCE, PCE, 1,1,1-TCA, 1,1-DCA, toluene and VC. The contamination originated from releases from an underground concrete holding tank. The tank was removed in March 1997. Concentrations within the site soils were measured prior to the demonstration as high as the percent range. The overall goal of the study was to evaluate the ability of XDD's ISCO process to reduce levels of specifically targeted organic compounds in contaminated soil by 90% and to reduce targeted groundwater contaminants to below remediation performance standards set specifically for the site.

This pilot-scale study was initiated in August 2004 (pre-demonstration activities) and concluded in May 2006. The study focused on a small contaminated area located just downgradient of the former concrete tank excavation site.

Figure 4-1 shows this demonstration study area, including locations of the demonstration injection wells (IW), evaluation wells (EW), and soil boring locations. The areal extent of this area was about 1,200 ft² (370 m²). The vertical extent of site contamination is roughly 22 ft or 6.7 m (i.e., 3-25 ft bgs). Therefore the volume of groundwater and saturated soil targeted for treatment was 27,000 ft³ (8,200 m³ or 1,000 yd³).

A total of two soil and five groundwater sampling events were conducted during the demonstration. A pre-treatment baseline and post-treatment final soil sampling event were conducted in which approximately 90 soil samples were collected from three stratigraphic zones. For groundwater, emphasis was placed on the final post-treatment sampling

in which 15 wells were sampled twice to produce 30 sample results. A day of well recovery was spaced between the two sampling rounds. Both the soil and groundwater samples were analyzed for VOCs and other parameters of interest. Results of VOC analyses were evaluated statistically to determine if primary project objectives were met.

4.1.2 Project Objectives

Specific objectives for this SITE demonstration were developed and defined prior to the initiation of field work. These objectives were subdivided into two categories; primary and secondary. Primary objectives are those goals that support the developer's specific claims for the technology demonstrated. These objectives are usually evaluated using both descriptive and inferential statistical analyses and require quantitative results to draw conclusions regarding technology performance. Secondary objectives are also in support of developer claims, however, the data analysis associated with these objectives are considered less rigorous. Secondary objectives pertain to information that is useful, and do not necessarily require the use of quantitative results to draw conclusions regarding technology performance.

Critical data support primary objectives, and non-critical data support secondary objectives. Critical measurements were formally evaluated against the demonstration target level using statistical hypothesis tests that are summarized in subsection 4.5.

Table 4-1 presents the two primary and four secondary objectives of the demonstration, and summarizes the method(s) by which each was evaluated. *Objectives 1-4* are addressed in this section. *Objective 5* was not evaluated because adequate permeability data was not acquired from the CPT/MIP survey. The cost estimate (*Objective 6*), is discussed in Section 3.

Former MEC Building

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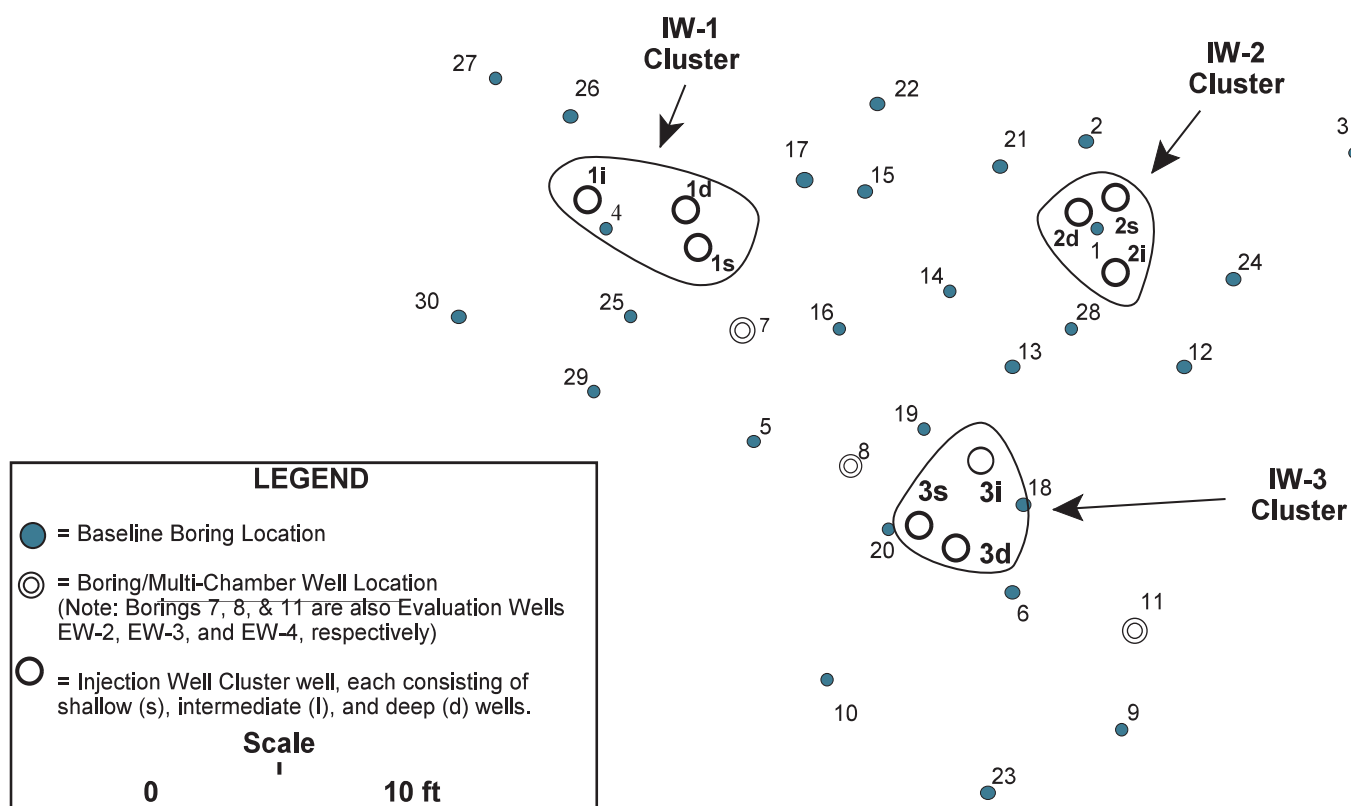


Figure 4-1. Map of Study Area Showing Demonstration Soil Boring and Well Locations.

Table 4-1. Demonstration Objectives.

Objective	Description	Method of Evaluation
Primary Objectives		
Objective 1	Determine if there is a statistically significant reduction of VOCs in soil (specifically chlorinated ethenes) over the period of the demonstration; and specifically show that the XDD oxidation process can remove 90% of the VOCs from soil for all three contaminated soil horizons.	Determine for each horizon and each individual compound (PCE, TCE, cDCE and VC) the removal efficiency by comparing the analysis of soil samples taken before and after the demonstration test period (baseline and final sampling events). Note: XDD's claim was specific to chlorinated ethenes but the SITE Program also assessed the impact of the technology on chlorinated ethanes.
Objective 2	Determine whether the XDD oxidation process can reduce concentrations of contaminants in the groundwater to below the 0.5% solubility limit of 750 µg/L, 5,500 µg/L, and 17,500 µg/L for PCE, TCE, and cDCE, respectively. These remediation performance standards are not for drinking water; they were provided by the state of New Hampshire to specifically address this site.	Determined by analysis of groundwater samples collected during the final post-treatment sampling episode; in which each sample is considered spatially and temporally separated such that a statistically significant number of samples are collected for analysis.
Secondary Objectives		
Objective 3	Assess the Impact of the Organic Matter in the Peat and its effect on Oxidant Depletion.	Collect samples of peat material at each boring location during baseline and final sampling events and determine on average if there is a depletion of humic content in samples due to the ISCO process.
Objective 4	Evaluate the potential for mobilization of valence sensitive toxic metals (i.e., As, Cr, Se, Zn) into the groundwater system.	Sample and analyze groundwater within and downgradient of the source area for metals at designated periods throughout the course of the demonstration.
Objective 5	Evaluate the effect of MnO ₄ on permeability reductions in the contaminated media due to the formation of MnO ₂ . Rapid buildup of MnO ₂ can occur when treating with MnO ₄ where high levels of DNAPL saturation occur, leading to pore plugging and an overall reduction in permeability.	Performing in situ permeability tests before and after treatment within the three stratigraphic zones, (i.e., fill material, peat, and sandy-silt).
Objective 6	Collect and compile information and data pertaining to the cost of implementing the XDD ISCO process.	Acquire cost estimates from past SITE experience, and from the developer (XDD). Cost treatment for full-scale treatment of similar contaminated material. Break down estimates into 12 cost categories that reflect typical cleanup activities at Superfund sites (See Section 3).

4.2 Site Description

4.2.1 Site Location and History

The approximate four-acre former MEC property contains a 36,000 square foot former MEC building and associated paved and unpaved parking and storage areas. MEC (formerly Nashua Electric Motors) repaired and rebuilt electric motors at the property from the mid 1970s up until approximately 1990. During this time frame, releases from an underground concrete holding tank has contaminated soil and groundwater in the vicinity of the southeast corner of the former MEC Building.

Aries Engineering, Inc. (Aries) is the remediation contractor for the former MEC Building site. Per Aries, the concrete holding tank was excavated in May of 1997. A total of 1,175 gallons (4,400 L) of liquids and five 55-gallon drums of sludge was removed from the tank (personal communication between Aries and SAIC, June 2006).

Currently, Aries is conducting monitoring activities at the site in accordance with the site New Hampshire Department of Environmental Services (NHDES) Groundwater Management Permit (GMP), which was issued December 5, 1997 and renewed on January 17, 2003. There are specific remediation goals for VOC contaminants at the former MEC Building site, both for soils and groundwater. These goals are referred to as Remediation Performance Standards (RPS) and are presented in **Table 4-2**.

Table 4-2. Remediation Performance Standards.		
VOC	Soil Standards (mg/Kg) ¹	Groundwater Standards (µg/l) ²
PCE	2	750
TCE	0.8	5,550
cDCE	2	17,500
VC	0.4	---
Toluene	100	2,570
1,1,1-TCA	42	6,800
1,1-DCA	3	27,500
¹ State of NH S-1 standards (Aries Engineering, Inc. July 2001). ² State of NH 0.5% aqueous solubility goal (SAIC, May 2005).		

Attainment of the RPS via treatment, such as the XDD ISCO process, may allow for the utilization of natural attenuation as a follow-on treatment option (personal communication between Aries and SAIC, June 2006).

4.2.2 Site Lithology and Hydrogeology

4.2.2.1 Lithology

Characterization of the demonstration study area lithology has resulted from several field investigation efforts; most notably the drilling of numerous soil borings and installation of several injection and monitoring wells. Site-specific lithology and geology were acquired via descriptions of 87 soil samples collected from the 30 soil borings shown in Figure 4-1. An approximate equal number of samples were collected from each of the three stratigraphic zones targeted for the ISCO treatment. The shallowest sample collection intervals were 6-7 feet below land surface (bls). (The upper 0-6 ft bls consists of asphalt underlain with rubble and debris; this material was not sampled).

Figure 4-2 is a generalized cross section showing distinct stratigraphic zones comprising the demonstration study area. These include an: 1) upper debris zone, 2) the three zones that were sampled for characterization and chemical analysis, 4) a basal till, and 5) underlying bedrock. Brief descriptions of these zones are as follows:

Upper Fill/Debris Layer 0-6 ft bls (Not Sampled)

The upper 6 feet of the demonstration site consists of fill material, including large chunks of concrete, rocks, plywood, shredded wood, etc. This zone was not sampled.

Top Gravelly Sand Zone 6-13 ft bls (Sampled)

Just below the upper fill material, there is a zone of loose gravelly-sand, with silt; which has an olive to grey color. This zone extended to about 6-13 feet bls. Samples from this zone were saturated since groundwater was typically just 3½-4 feet bls. Wood fragments were frequently encountered in this zone and hydrocarbon odors were noted for several boring samples. A total of 30 baseline and 30 final soil samples were collected from this zone.

Middle Peat Zone 12-14 ft bls (Sampled)

At this approximate depth interval there exists a relatively thin peat zone, black in color, that varies in thickness from 0.2 ft. to 3.2 ft (0.6-0.98 m). At several locations the peat was partly composed of shredded wood fibers or wood chunks; and contained twigs, leaves, and bark. The peat occurred as shallow as 9 ft bls and as deep as 15.8 ft bls. Based on baseline and final borehole drilling, the peat was absent in boring location No. 30. Boring 30 is located on the south edge of the study area (Figure 4-1), not far from the former tank location. The peat may have been removed during excavation of the holding tank and surrounding soil material. A total of 27 baseline peat samples and 29 final peat samples were collected from this zone.

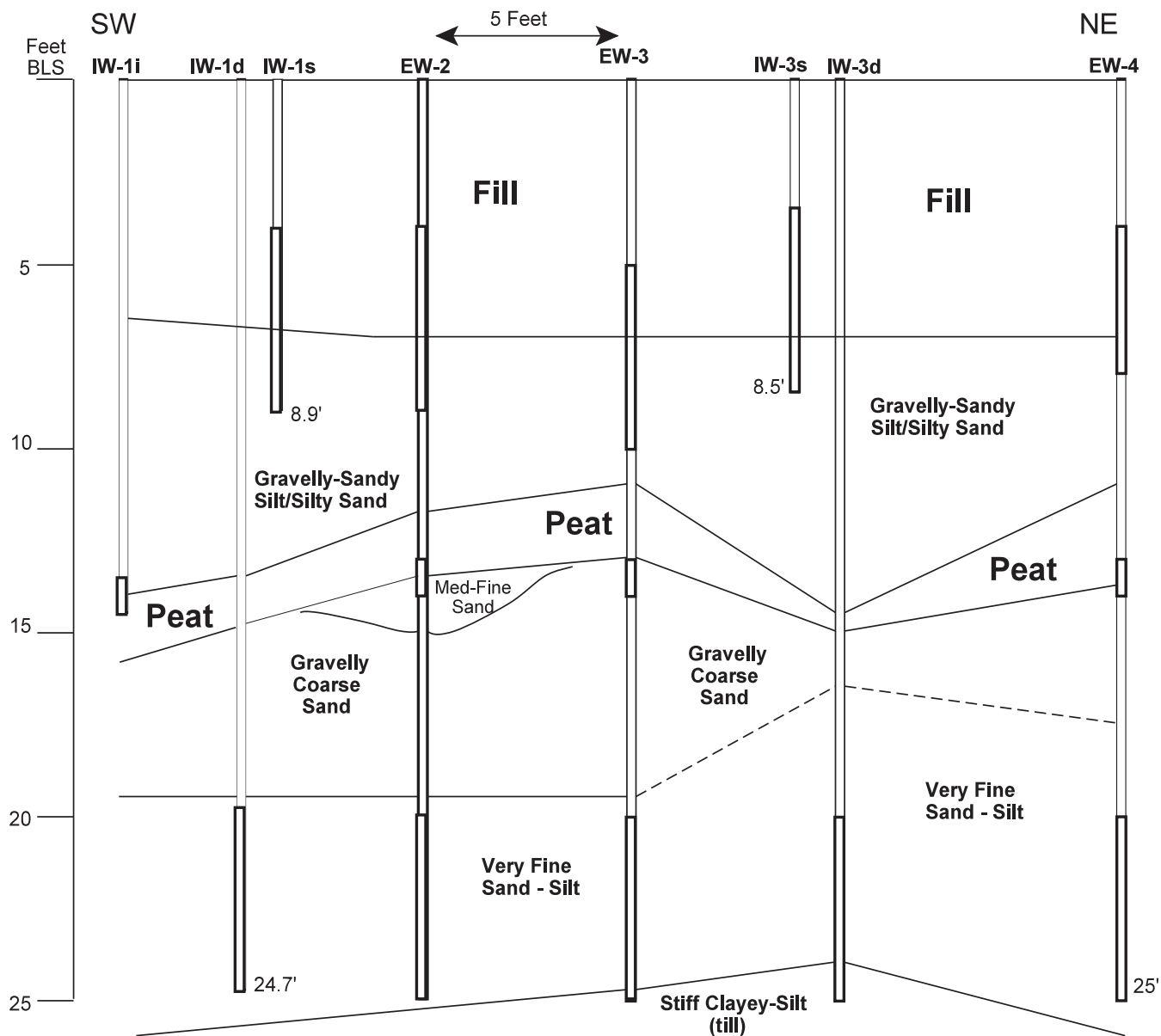


Figure 4-2. Cross Section Showing Stratigraphic Zones of Study Area.

Lower Sandy-Silt Zone 14-26 ft bls (Sampled)

A sandy-silt zone, olive-yellow to grey in color, extends from the bottom of the peat down to a basal till layer (anywhere from about 10-28 ft or 0.3-8.5 m bls). Typically this zone grades from a very coarse or gravelly-sand to a finer sandy-silt to pure silt. Product (i.e., DNAPL) was commonly observed in this zone. A total of 30 baseline and 30 final soil samples were collected from this zone.

Basal Till Layer 26-30 ft (Not Sampled)

This layer was not sampled but provided a reference point for collecting lower zone samples (i.e., the most contaminated portion of the overlying sandy silt was sampled). PID readings typically were the highest just above this till layer.

Bedrock 30 ft (Not Sampled)

Bedrock occurs roughly at 30 ft (9.1 m) bls and reportedly consists of a highly weathered quartz-biotite schist. Bedrock was encountered when drilling IW-3d at around 30 ft (9.1 m) bls and at boring location No. 9 at about 31 ft bls.

4.2.2.1 Hydrogeology

Site overburden groundwater generally flows in a northeasterly direction across the entire former MEC Building area. Horizontal hydraulic gradient, based on Aries's 2003 and earlier site groundwater data, is approximately 0.04 feet/foot (ft/ft) or 0.12 m/m between two monitoring wells located in the immediate vicinity of the study area. In addition, site vertical gradients have been measured by Aries (e.g., Aries observed vertically upward hydraulic gradients ranging between 0.04 ft/ft to 0.1 ft/ft in a monitoring well couplet upgradient of the study area).

4.3 Pre-Demonstration Activities

For this demonstration, a significant amount of time and effort was devoted to pre-demonstration activities (Phase 1). These activities included preliminary sampling for site characterization (e.g., monitoring well installation; and soil and groundwater sampling), laboratory methanol (MeOH) extraction studies on soil samples, a treatability study conducted by the ISCO developer (XDD), and cone penetrometer technology and membrane interface probe (CPT/MIP) survey. Each of these pre-demonstration activities is discussed in the following subsections.

4.3.1 Preliminary Sampling

SAIC conducted pre-demonstration sampling during the latter part of August, 2004. The purpose of the preliminary sampling was twofold:

1. Gain a better understanding of the distribution of

the target VOCs within the context of the lithologic and hydraulic regimes of the site media and;

2. Acquire samples for an XDD treatability study.

Three contaminated soil zones (gravelly sand, peat, and silty sand) were sampled at each of three locations and three sets of nested monitoring wells (nine total) were installed at the same locations. Eight soil samples (3 gravel/sand, 2 peat, and 3 silty sand) were collected from separate boreholes near an existing well located in the immediate vicinity of the demonstration site. Also, one groundwater sample was collected from that same well.

Results of the pre-demonstration sampling indicated that contaminant levels at the site were sufficient for purposes of the demonstration. Samples collected from an existing monitoring well indicated that concentrations of cDCE were well above the RPS. However, TCE and PCE were below these standards. Although based on just sampling of one well, the data suggest that oxidation may have been in-process in the sampled groundwater, as the more chlorinated compounds were detected at lower concentrations (below the RPS) and one of the known breakdown products (e.g., cDCE) was at a much higher concentration.

4.3.2 MeOH Extraction Studies

Based upon previous experience with peat and several published laboratory studies, it had been anticipated that VOCs would be difficult to extract from the site peat material using the standard 1:1 MeOH to soil ratio. As a result, a series of MeOH extraction studies was conducted on peat and other material collected from the site, with native concentrations of contaminants. A detailed description of the extraction study procedures and results are presented in the QAPP (SAIC, May 2005).

The difficulty with a 1:1 MeOH to soil extraction occurs because the contaminants reach an equilibrium with peat and MeOH. Thus, significant contamination remains on the peat even after two or three subsequent extractions. In order to find an optimum extraction procedure for the peat material, a set of experiments was performed by extracting the peat in MeOH following standard SW-846 protocol (i.e., soxhlet extractions). Additional studies varied the procedure by using sonication and heating. Resulting data suggested that much more contamination was present in the peat than that suggested by the initial test results.

Further studies reinforced the notion that sonication and heating of the MeOH extract removed some additional VOC contamination from the peat, other than what was found in the original extraction using standard SW-846 procedures. However, in every case it appeared that some contamination remained in the peat material. Even after

the final extraction, the procedure continued to recover and remove some portion of the contamination. Overall the results of the extraction study suggested that standard SW-846 procedures would not be robust enough to remove the VOCs present in the peat at the site.

An additional extract sample, extracted in a 10 to 1 ratio of MeOH to peat instead of the usual 1 to 1 ratio, resulted in removal of almost all the contaminants of interest in the very first extraction. This suggested that the equilibrium between the MeOH and peat was affected by increasing the MeOH volume in contact with peat material. Subsequent studies were then undertaken to determine the ideal MeOH to peat ratios for the demonstration.

Results of these subsequent studies suggested that a higher concentration of MeOH to peat was needed for the peat instead of the standard 1:1 ratio. The drawback of this increased ratio is increased detection limits.

Results of these pre-demonstration analytical studies were implemented for the demonstration. For the demonstration a 5:1 milliliters (ml) of MeOH to grams of soil, was used for the middle peat and lower sandy-silt zones. A 1:1 ml of MeOH to grams of soil was used for the top gravelly-sand zone.

4.3.3 Treatability Study

A laboratory treatability study was conducted by XDD prior to the demonstration in order to evaluate the effectiveness of their ISCO process on contaminated soil from the site. The objectives of this treatability study were to:

- Assess the overall feasibility of using ISCO to meet the site-specific cleanup goals;
- Estimate the soil oxidant demand (SOD) for the major soil units (i.e., gravelly sand, peat layer, and silty sand) in the treatment area;
- Develop site-specific data necessary to design an ISCO field pilot test and/or full-scale application.

The treatability study is detailed in a separate report prepared by XDD (XDD, January 2005). Permanganate (MnO_4) was the chosen oxidant for the study. MnO_4 is an oxidizer used extensively in wastewater treatment and drinking water purification processes. MnO_4 is a very stable oxidant and can persist for several months in the subsurface. This stability makes it a good choice for subsurface applications (i.e., fewer injection events, fewer wells to treat the target area, and the ability to more effectively penetrate into low permeability soil zones).

MnO_4 also reacts with natural soil organic matter and reduced metal oxides (e.g., iron and manganese oxides, etc.). Contaminant degradation rates are influenced by the

presence of these competing species. SOD is one measure of these additional demands that consume oxidant. Because the SOD exerts a competitive demand on the oxidant, it must typically be satisfied to ensure complete oxidation of the VOC compounds.

The individual soil samples that were used in the SOD testing were combined into three composite soil samples representative of the three major soil units at the site: 1) gravelly sand, 2) peat, and 3) sandy silt.

Laboratory testing consisted of two separate evaluations:

1. SOD testing for evaluating utilization rates of variable MnO_4 concentrations in a soil/groundwater system, and
2. Testing the destruction efficiency of the VOCs.

SOD Testing

Eight representative soil samples were evaluated for the SOD procedure, which involved preparing eight separate 40 mL VOA vials (batch reactors) with approximately 10 grams (g) of each soil sample. This produced eight vials for each of the eight soil samples (64 total).

The reactor vials were then dosed with KMnO_4 oxidant solution at four different concentrations; approximately 2, 5, 10, and 20 grams per liter (g/L) KMnO_4 prepared using distilled water. Two reactor vials were prepared at each oxidant concentration for duplicating analyses on each soil sample. Controls, consisting of four MnO_4 solution concentrations (plus four duplicate control samples with no soil added), were created at the start of the test and analyzed to evaluate if there were losses of MnO_4 over the duration of the test.

All the reactor vials and controls were allowed to equilibrate over a fourteen-day test period. On Days 3, 7, 10, and 14, aqueous samples from each vial were measured by a colorimeter for oxidant solution concentration change. A second dose of oxidant was applied to peat samples on Day 17 and samples from those peat reactors were analyzed for oxidant concentration changes on Days 24, 28, and 34. XDD (January 2005) reported SOD test results as follows:

XDD Averaged SOD Results (g/Kg)

<u>Zone</u>	<u>Sample 1</u>	<u>Sample 2</u>	<u>Sample 3</u>
Shallow Gr. Sand	21.0	4.6	8.8
Middle Peat	104.7	---	146.9
Deep Silty Sand	5.6	1.8	2.3

VOC Destruction Efficiency Testing

VOC destruction efficiency testing involved placing a specific volume of groundwater/soil in a concentrated MnO_4 solution; and then placing the solution into a batch reactor (40-ml glass VOA vial) for a specified exposure period.

Approximately 38 mL of 20 g/L oxidant (as KMnO_4) solution was prepared for site groundwater (from MW-10) and 10 grams of each soil sample were added into each batch reactor. Six identical batch reactors for each soil composite were prepared (18 reactor vials total) as follows:

- Four reactor vials to be sacrificed at four different time intervals for the analysis of VOCs;
- One duplicate reactor for VOCs analysis; and
- One reactor vial used to monitor changes in oxidant concentration throughout the test duration.

In addition to the above reactors, three “no oxidant” control reactors (one per soil composite) were prepared identically to the other reactors. The controls were used to assess losses in VOC concentrations due to mechanisms other than chemical oxidation (e.g., volatilization, biodegradation, etc.). To minimize volatilization losses, all batch reactors were completely filled with either oxidant solution or groundwater to zero headspace.

In the peat composite, MnO_4 appeared to be very effective in destroying high levels of cDCE and VC. Also, it appeared that most of the cDCE was destroyed after the first dose of oxidant. PCE and TCE were not evaluated due to very low/non-detect results in the control samples. Toluene exhibited reasonable reduction rates in the peat composite even though this compound typically reacts slowly with MnO_4 . Interestingly, the chlorinated ethanes (1,1,1-TCA and 1,1-DCA) also appeared to exhibit significant reductions. Available literature suggests that these compounds do not react directly with MnO_4 . However, there may be other reactions occurring in the presence of the oxidant that may cause degradation (i.e., other reactive species may be forming, other abiotic processes, etc.).

Nearly complete destruction of cDCE, VC, and toluene was observed in the shallow composite. TCE, present at relatively low concentrations in the aqueous control, was nonetheless reduced to non-detectable levels. PCE was not detected in control samples, thus it was not evaluated.

Partial destruction of 1,1,1-TCA, and 1,1-DCA was also observed in the aqueous phase of the shallow composite. However, soil concentrations of 1,1-DCA were higher in all of the treated reactor vials as compared to the soil control sample (approximately 2 to 7 times higher). This trend for 1,1-DCA was also observed in the deep composite soil samples (discussed in the next section).

Nearly complete destruction of cDCE, VC, and toluene was observed in the soil and aqueous phases of the deep composite. Significant reduction of TCE was also observed in the Deep Composite tests. The Deep Composite control was the only sample in the study to exhibit significant aqueous TCE concentrations. The aqueous TCE concentration in the control sample was 1,780 $\mu\text{g/L}$. This was significantly higher than the aqueous baseline TCE level (40.4 $\mu\text{g/L}$). Based on this, it appeared that the aqueous phase TCE in the control resulted from soil desorption. Although not certain, it seemed further supported by the fact that the deep composite soil control was the only control that exhibited detectable TCE on the soils, although relatively low (152 $\mu\text{g/Kg}$).

Consistent with other tests, significant destruction of 1,1,1-TCA, and 1,1-DCA was also observed in the aqueous phase samples. However, soil concentrations of 1,1-DCA in the Deep Composite test appeared to increase (approximately 3 to 8 times higher) as compared to the control sample (similar to the Shallow Composite test).

Summary of Treatability Testing

Soils were mixed together to create three separate soil composites representative of each of the three major stratum at the site (i.e., shallow gravelly sand composite, peat composite, and deep silty sand composite samples). The soil composites were dosed with approximately 20 g/L KMnO_4 solution. The peat composite was dosed twice due to the high oxidant utilization rates.

PCE was not present in any of the soil composite reactors, and as such could not be evaluated. The remaining VOCs (including TCE, cDCE, VC, 1,1,1-TCA, 1,1-DCA, and toluene) were present in one or more of the samples and were therefore evaluated for destruction efficiency. Only cDCE and toluene were detected in the studies at levels above the anticipated clean-up goals for the site. These two compounds were reduced to below the clean-up levels during the treatability study.

Aqueous TCE, cDCE, and VC were effectively destroyed in all tests as anticipated. Even in the peat composite where SOD was very high, the cDCE and VC were destroyed rapidly and during the initial dose of oxidant. This is a positive result since there was some concern that VOCs would be difficult to treat in the presence of such a high oxidant demand.

Chlorinated ethanes (1,1,1-TCA and 1,1-DCA) are typically not thought to be directly oxidizable by MnO_4 . However, test results indicated that there was up to 75% reduction of 1,1,1-TCA and 64% reduction of 1,1-DCA in the aqueous phase deep composite sample. As anticipated, reduction of these two ethanes in the peat composite samples were

slightly less efficient (49% reduction of 1,1,1-TCA and 41% reduction of 1,1-DCA in the aqueous phase). The actual mechanisms for destruction of these compounds in the presence of MnO_4 are not fully known, but this behavior has been observed at other sites.

Toluene also was significantly reduced (aqueous phase reduction of >99% in the Deep and Shallow Composites, and up to 62% in the Peat Composite). Toluene is known to degrade at relatively slow rates in the presence of MnO_4 .

Based on the results published by XDD's chemical oxidation laboratory testing report (XDD, January 2005) and the summarized results noted above, ISCO was determined to be an effective treatment for the majority of the targeted VOCs at the site. Although the SOD is very high in the peat zone, significant reduction was observed for many of the target VOCs.

4.3.4 CPT/MIP Characterization

Cone Penetrometer Technology (CPT) and Membrane Interface Probe (MIP) was utilized for pre- and post-treatment characterization of the demonstration study area. CPT is basically a soil conductivity logging tool used to interpret lithology. The MIP is used to determine position and approximate concentration of VOCs (i.e., the MIP is not quantitative, but its detector response can be used at a particular site to estimate soil concentrations). These two logging tools, developed by Geoprobe Systems, can be combined into the same probe to collect subsurface information (Christy, no date).

A total of 18 CPT/MIP survey points was completed prior to baseline sampling. During this survey, CPT/MIP logs were used to identify specific subsurface zones and the highest concentration areas to target for soil sampling. Following both XDD injections, a post-treatment CPT/MIP survey was conducted that was significantly scaled down from the baseline survey. A total of 5 CPT/MIP survey points were completed to adequate depths. The reduced number of post-treatment survey locations makes comparison to the baseline data difficult. Kriging contour lines are dramatically different due to the absence of data.

Figure 4-3 shows the maximum response of the MIP's photo-ionization detector (PID) in micro volts (μV) for a below-surface depth range of 0-18 ft (5.5 m), both for baseline and final post-treatment. **Figure 4-4** shows the maximum response of the MIP's PID in μV for a below-surface depth range of 18-36 ft (5.5-11 m), both for baseline and final post-treatment. The baseline event plots are collectively based on 14 MIP baseline points and the final event plots are based on 5 final MIP points. Each MIP survey point identified as a blue cross on the plots.

The more detailed baseline map shows that about 20% of the study area plume extends beneath the former MEC Building. This generally favors the use of an in situ treatment (especially for soil), since excavation near and beneath such a permanent structure is undesirable. The baseline map also reveals a concentrated circular-shaped plume, approximately 60 ft in diameter, whose center is in the immediate vicinity of the former concrete holding tank location. The highest μV response of $2.00\text{E} +06 \mu\text{V}$ comprises an approximate 30 ft-diameter area. The response rapidly dissipates beyond this area. Comparison of baseline to final PID shallow zone plots (**Figure 4-3**) show a potential increase of the maximum PID signal (vs. baseline) at locations 2-3 and 2-5. In the deep zone (**Figure 4-4**), there is a slight decrease of the maximum PID signal (vs. baseline) in the vicinity of locations 2-4 and 2-5.

In addition to the PID detector, the MIP is also equipped with an electron capture detector (ECD), which is responsive to chlorinated compounds. **Figures 4-5 and 4-6** show the maximum response of the ECD in μV for below-surface depth ranges of 0-18 ft (5.5 m) and 18-36 ft (5.5-11 m), respectively. These baseline and final event plots are also collectively based on the 14 MIP points (baseline) and 5 MIP points (final) identified as blue crosses.

Evaluation of the shallow zone baseline ECD plot (**Figure 4-5**) reveals a concentrated circular-shaped plume, similar in size and area shown by the PID shallow zone map. The only difference is increased intensity (i.e., an upper μV response of $1.00\text{E} +07 \mu\text{V}$ for the ECD versus a response of $2.00\text{E} +06 \mu\text{V}$ for the PID). It should be noted that the baseline plot in **Figure 4-5** may be misleading in showing what appears to be a second plume, detached from the main plume that surrounds the former MEC building. The contours that comprise the shape of this apparent plume are interpolations from the single MIP point 4-2, which may only be an isolated contaminated spot. Comparison of the baseline and final plots show no appreciable difference in the maximum ECD response before and after injection.

The deep zone baseline ECD plot (**Figure 4-6**) also shows a concentrated plume emanating from the contaminant source area. However, the shape of the plume is more elliptical than circular and it is oriented in a southwest to northeast pattern. This is consistent with groundwater flow direction and is similar to the Aries plume characterization (refer back to **Figure 1-1**). Possibly, the deeper zone map is showing DNAPL that has settled along the top of the basal till layer and bedrock and is very slowly dispersing to the northeast. When comparing the baseline and final plots, there is no appreciable difference between the maximum ECD response before and after injection.

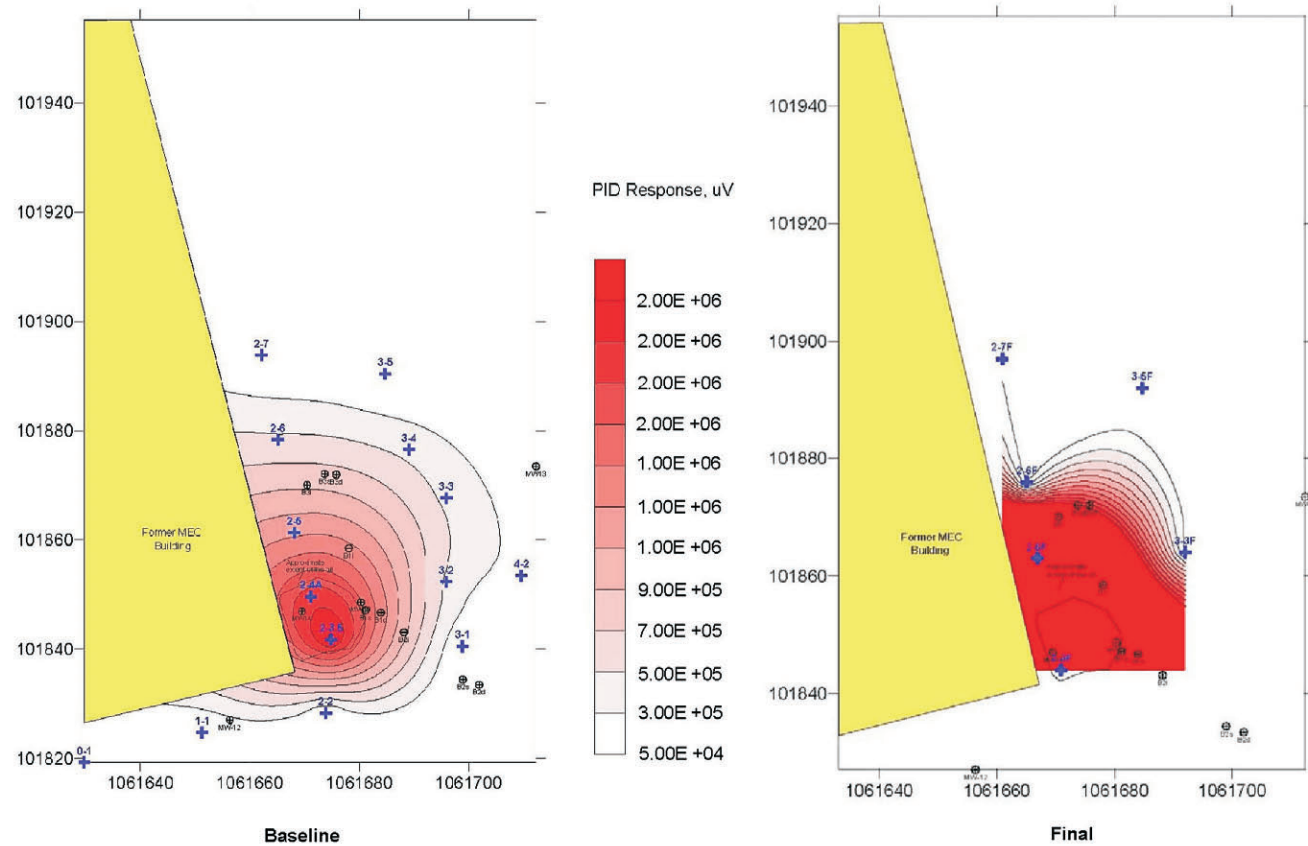


Figure 4-3. Maximum MIP PID Response for Shallow Zone Soil (0-18 ft) - Baseline Vs. Final.

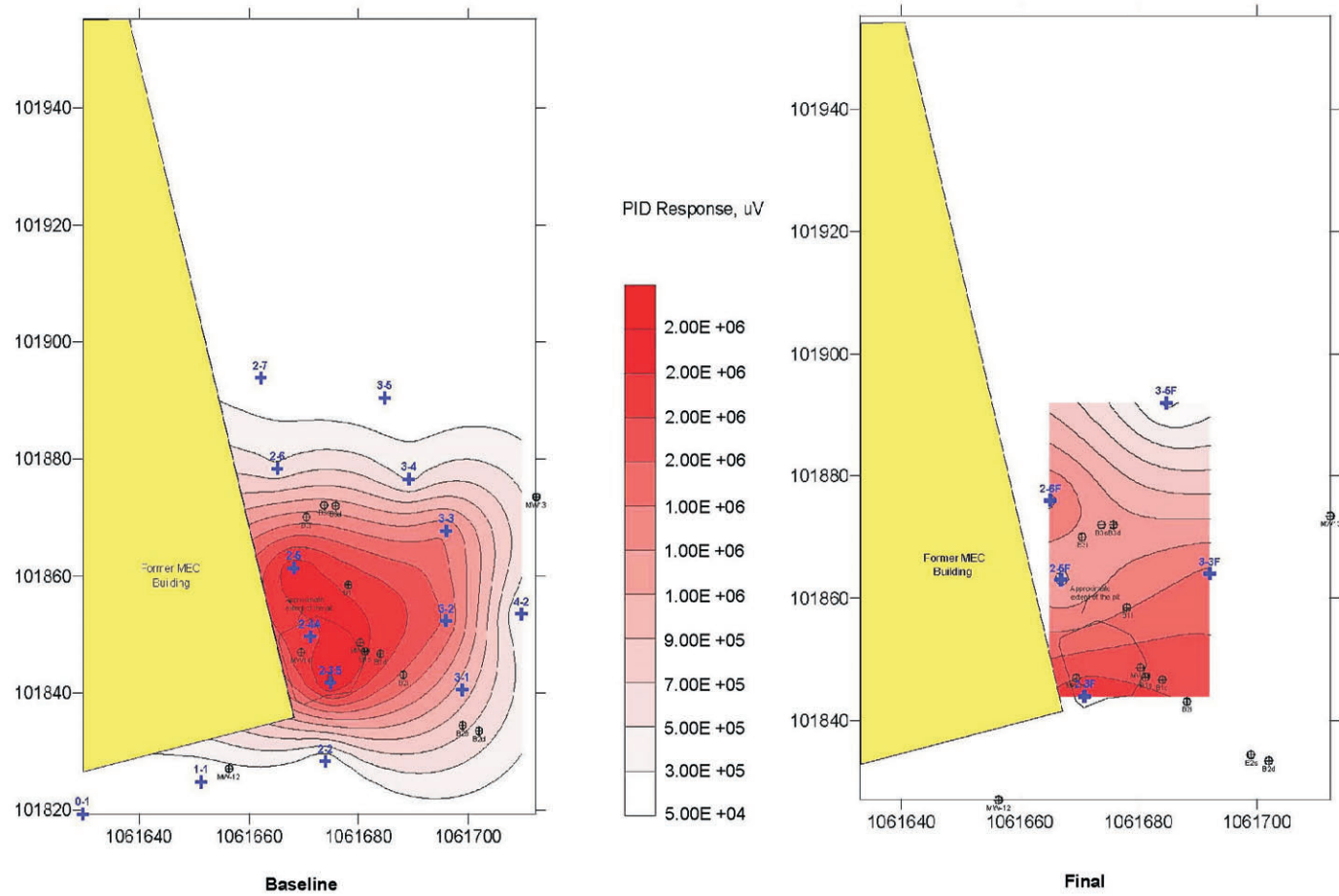


Figure 4-4. Maximum MIP PID Response for Deep Zone Soil (18-36 ft) - Baseline Vs. Final.

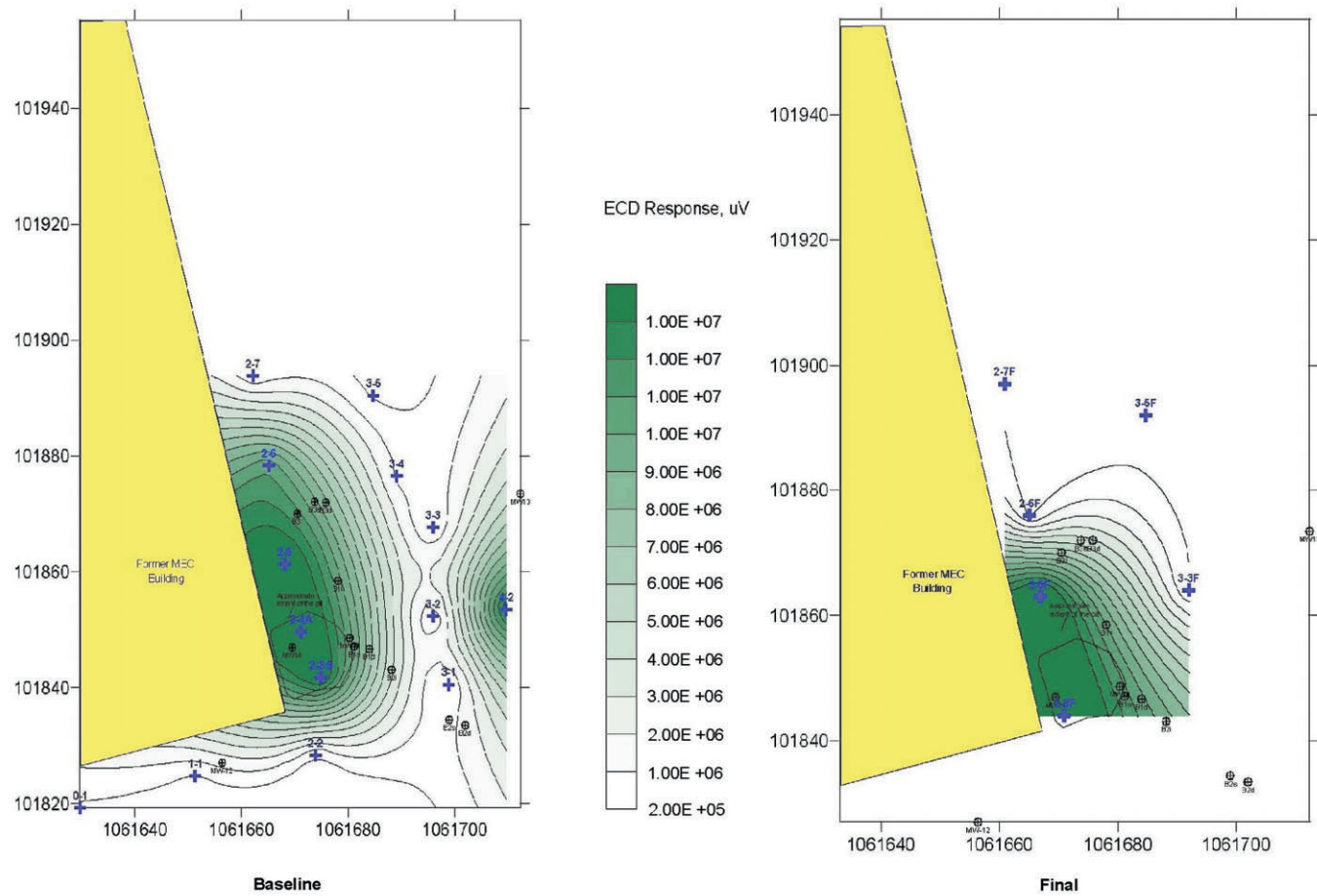


Figure 4-5. Maximum MIP ECD Response for Shallow Zone Soil (0-18 ft) - Baseline Vs. Final.

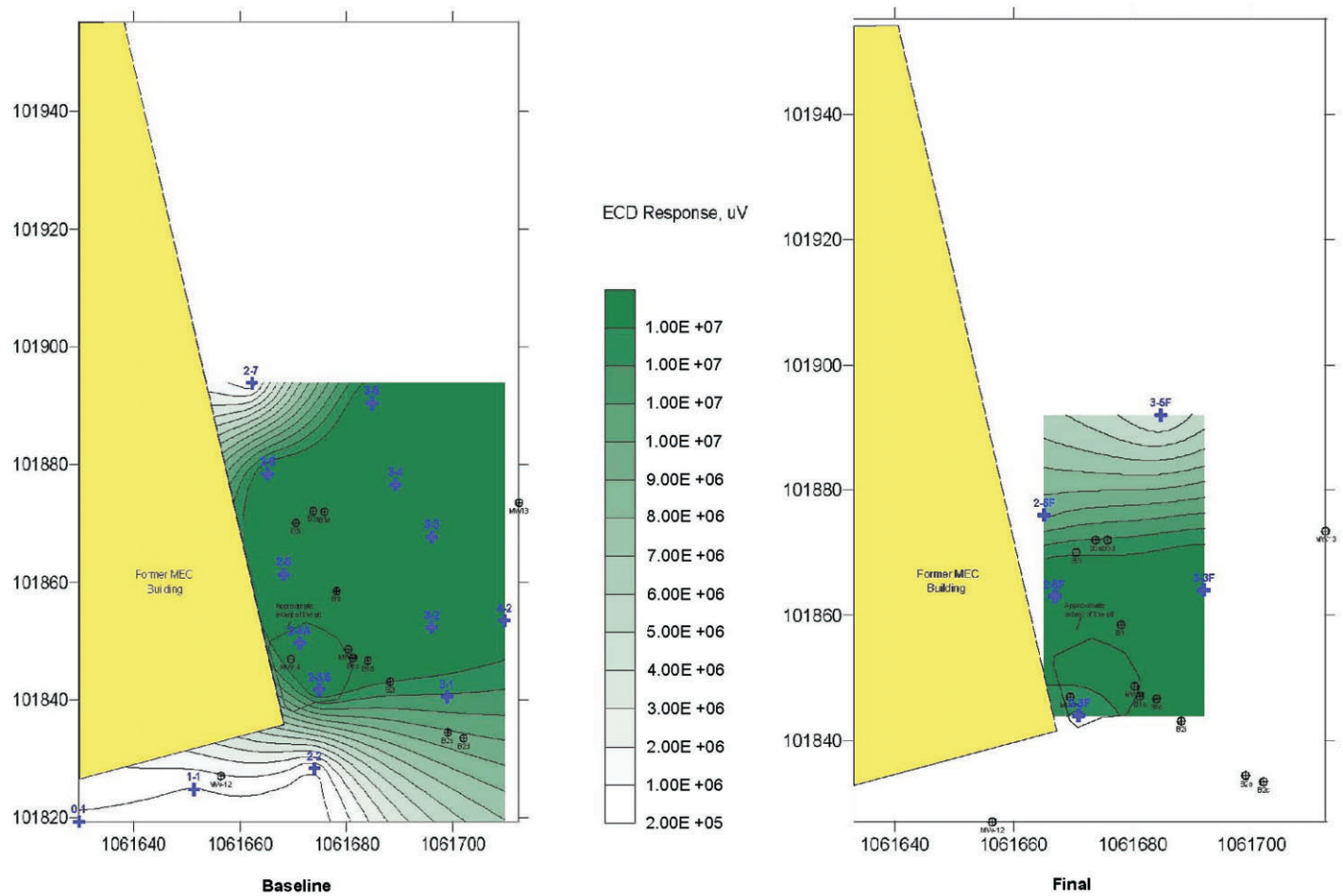


Figure 4-6. Maximum MIP ECD Response for Deep Zone Soil (18-36 ft) - Baseline Vs. Final.

4.4 Demonstration Activities

4.4.1 Injection of Oxidant

XDD developed a 3-well cluster injection strategy for treating the chlorinated ethenes in all three soil zones at the demonstration site. Originally, a single injection event was planned. However, the originally-installed pre-packed one inch ID injection wells for two of the clusters had failed seals. They were replaced by traditional 2-inch ID wells. Thus, a second injection event was required.

Figure 4-7 is an illustration showing the locations of the three injection well clusters (IW-1, IW-2, and IW-3), the

estimated radii of influence (10 feet for each), and summarizes injected volumes of KMnO_4 for each of the wells and for each injection. **Table 4-3** provides a more detailed injection summary, including mass of KMnO_4 injected per XDD's injection logs.

All injection wells were constructed of like materials and had similar well diameters (IW-3 cluster wells are 1½-inch ID and IW-1 and IW-2 cluster wells are 2-inch ID). Well screen lengths for the shallow (s) and deep (d) zones were five feet and the screen length for the intermediate (i) a peat zone was one foot. Well cluster spacing was roughly 18 feet.

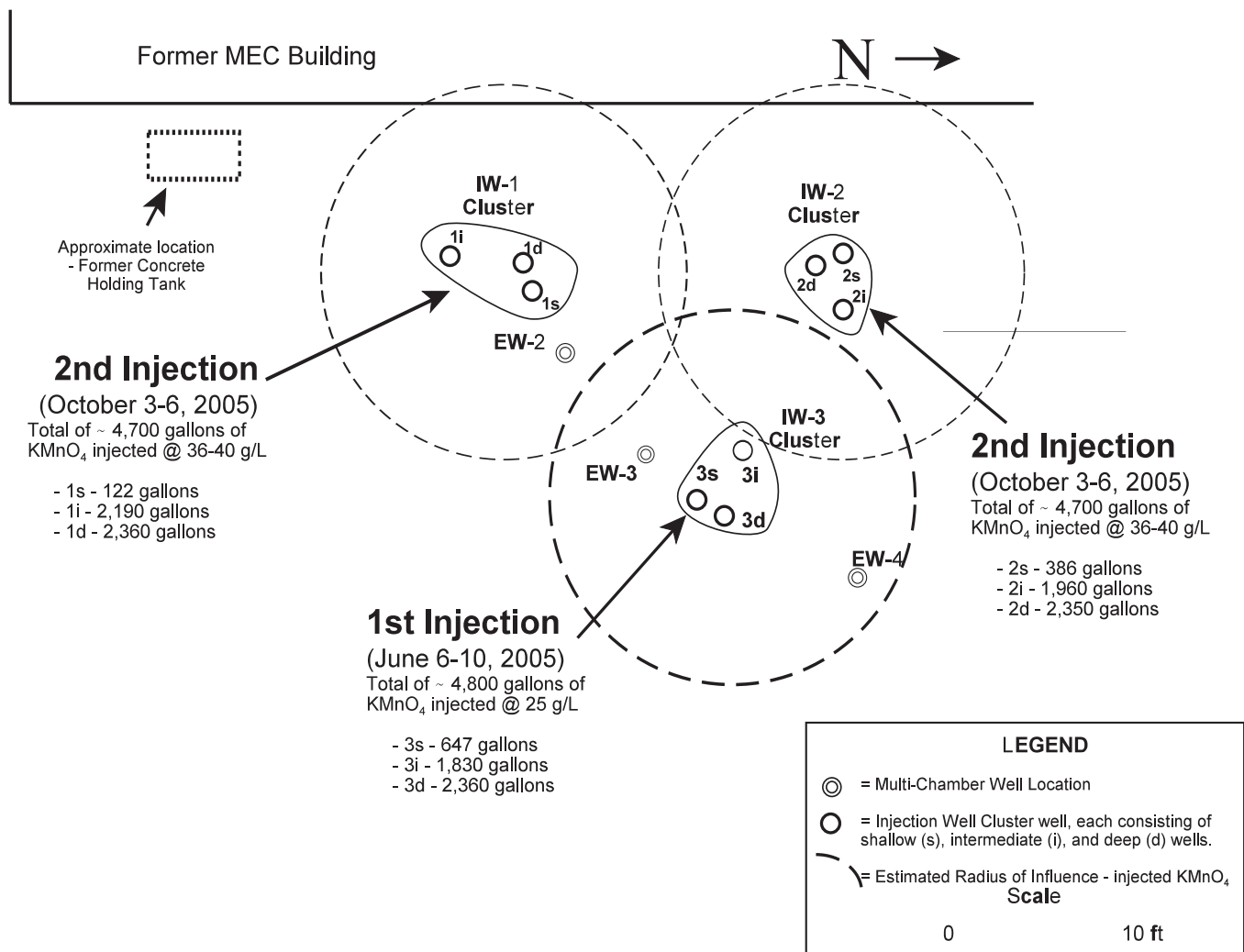


Figure 4-7. Map of KMnO_4 Injection Points.

Table 4-3. Injection Summary

<u>Zone</u>	<u>Injection Well</u>	First Injection June 6-10, 2005- second			Second Injection October 3-6, 2005			Both Injections Combined	
		Volume (gallons)	Mass (Pounds)		Volume (gallons)	Mass (Pounds)		Volume (gallons)	Mass (Pounds)
Shallow	IW-1s	3	1		122	25		125	26
	IW-2s	27	8		386	78		413	86
	IW-3s	647	208		---	---		647	208
	Total	677	217		508	103		1,185	320
Intermediate (Peat)	IW-1i	33	10		2,186	451		2,219	461
	IW-2i	152	46		1,957	403		2,109	449
	IW-3i	1,827	597		---	---		1,827	597
	Total	2,012	653		4,143	854		6,155	1,507
Deep	IW-1d	222	60		2,359	486		2,581	546
	IW-2d	251	76		2,355	486		2,606	562
	IW-3d	2,362	752		---	---		2,362	752
	Total	2,835	888		4,714	972		7,549	1,860
All Zones Combined Totals		5,524	1,758		9,365	1,929		14,889	3,687

4.4.2 Soil and Groundwater Sample Collection

Demonstration sampling and analysis began in May of 2005 with baseline soil sampling and was followed by an initial baseline groundwater sampling event, a second baseline groundwater sampling event, two intermediate groundwater sampling events, and a final event for both soil and groundwater (events and dates are listed below).

- ◆ Baseline Soil (May, 2005);
- ◆ First Baseline for Groundwater (June, 2005);
- ◆ Second Baseline for Groundwater (Sept. 2005);
- ◆ Intermediate Groundwater (December, 2005);
- ◆ Intermediate Groundwater (February, 2006);
- ◆ Final Groundwater and Soil (March, 2006)

4.4.2.1 Soil Sampling

The two soil sampling events included a baseline event to establish pre-treatment soil concentrations for VOCs and soil humic content, and a final event to determine post-treatment soil concentrations for those same parameters. Each is discussed in detail below.

Baseline Soil Sampling

The baseline soil sampling event was initiated on May 12, 2005 completed May 19, 2005, thus preceding the first injection event of early June 2005 by approximately three weeks. Soil collection was accomplished with a mini-sonic rig equipped with a direct push sampler. Boreholes were drilled at a total of 30 closely-spaced locations within the small area where a DNAPL plume had been identified (see Figure 4-1). Logs from a CPT/MIP survey were used to target hotspots at depth from which to collect soil samples. A total of 87 of the planned 90 soil samples were collected (i.e., 30 from each of three depth zones were planned; however, peat samples were not able to be collected at three borehole locations).

During baseline sampling, samples collected from the shallow zone gravelly silty-sand material were field extracted in a 1:1 MeOH to soil ratio by volume. Samples collected from the intermediate peat layer were field extracted in a 5:1 MeOH to soil ratio by volume. However, there had still been uncertainty related to the deeper zone silt as to which extraction ratio would be the most suitable.

As a result of this uncertainty, a field study (similar to the pre-demonstration MeOH extraction study described in 4.3.2) was conducted during the baseline event to ensure that field extractions of the deep zone sandy silt material would be complete.

Three samples from three boreholes were extracted in the normal fashion (1:1 MeOH to soil ratio) and three duplicates were extracted and analyzed as was done in the pre-demonstration extraction study (5:1 MeOH to soil ratio), following previously described protocols. Data was

compared to determine if the extraction efficiency was significantly increased using a 5:1 ratio of MeOH to soil compared to a 1:1 ratio. In order to avoid losing data from either increased detection limits in the 5:1 extraction or not obtaining the actual concentration of organics as may be lost from a 1:1 extraction, all lower horizon samples collected during baseline sampling were extracted in the field using both protocols (5:1 and 1:1 ratio). This required all lower horizon samples to be collected in duplicate. Three selected samples had both extracts analyzed. Results of these analyses were used to determine if additional duplicate analyses were required and to determine the better extraction ratio for the final event.

Final Soil Sampling

The final soil sampling event was conducted in late March of 2006, approximately ten months following the first injection event and about eight months following the second injection event. A total of 90 soils samples were collected with a geoprobe equipped with a macrocore sampler. The final event boreholes were drilled as close as possible to the baseline borehole locations (i.e., from 0.3 to 2 feet away) and soil samples were collected from the approximate same depth interval as were the baseline soil samples. A 1:1 MeOH to soil ratio was used for extracting the top zone samples and a 5:1 MeOH to soil ratio was used for extracting peat and bottom zone samples.

4.4.2.2 Groundwater Sampling

An initial baseline groundwater sampling event was conducted soon after the soil baseline event (i.e., the first week in June 2005). Due to failed seals in injection well clusters IW-1 and IW-2, all three wells for those clusters had to be replaced, and a second baseline groundwater event was conducted in September 2005. This event also served as an intermediate event to evaluate groundwater treated from the initial oxidant injection. Two more intermediate groundwater sample events were conducted following the second oxidant injection to evaluate target contaminant trends in groundwater.

Groundwater was sampled at a low-flow rate using a peristaltic pump. Where possible the purged groundwater was routed through a flow-through cell so parameters could be monitored with a multi-parameter direct read probe and deemed stabilized prior to sampling. In some instances this procedure could not be conducted due to an insufficient volume of well water available for purging. This was the case with the small diameter multi-chamber wells, especially those set in the low recovery shallow and peat formations. In instances where the flow-through cell and probe could not be used, groundwater samples were collected directly into the sample container following a purge of anywhere between 250 mls to 550 mls of water.

4.4.2.4 Laboratory Analyses

Table 4-4 summarizes the laboratory analyses conducted on soil and groundwater samples collected during each sampling event. Critical and non-critical measurements were conducted per the following discussion.

Critical Measurements

Critical measurements for the study included VOCs and moisture for soils, and VOCs for groundwater. Based on a pre-demonstration methanol extraction study (see 4.2.2), different MeOH to soil extraction ratios were used on different soil types that characterized each of the three zones. A 1:1 MeOH to soil extraction ratio was used for the shallow zone (dominated with gravelly silty-sand material). For the middle peat zone and the underlying deeper sandy-silt zone (where silt was prevalent), a 5:1 MeOH to soil extraction ratio was used.

To perform the field extraction procedure, the analytical laboratory had prepared pre-weighed sample containers containing the proper amount of MeOH for solvating approximately 5 grams of soil from each of the three soil horizons. The pre-weighed containers were shipped to the field site. Wide-mouth 4-ounce jars were used for 5:1

MeOH to soil ratio extracts and 40-ml vials were used for 1:1 MeOH to soil ratio extracts. This prevented extracting a particular soil type in the wrong volume of MeOH solvent.

Because soil samples for VOC analyses were placed directly into jars containing MeOH, additional sample material from each core was also placed in a separate container for moisture analysis. This measurement was considered critical since the results were used to present the VOC data on a dry-weight basis.

Groundwater samples were also analyzed for VOCs. Due to the target compounds being chlorinated VOCs, the samples were not preserved with acid. As a result, sample holding times were reduced from 28 to 7 days.

Non-Critical Measurements

Non-critical measurements for soils included humate analysis of the peat material that was located about 12-14 bls. A total of 27 samples was analyzed for each the baseline and the final sampling events. In addition groundwater was also measured for total metals and specifically for bromide since that compound was a tracer within the KMnO_4 oxidant solution used for the first injection.

Table 4-4. Summary of Laboratory Analyses.

Table 4-4. Summary of Laboratory Analyses.							
Parameter	Test Method	Method Type	NO. SAMPLES ANALYZED PER EVENT ¹				
			Baseline	Second Baseline	First Intermediate	Second Intermediate	Final
Soil							
VOCs	SW 5035/8260	Purge & Trap, GC/MS	87	---	---	---	89
% Moisture	SW 3540	Dessication	87	---	---	---	89
Humates	CA Humic Residue	Separation/TOC analyzer	27	---	---	---	27
Groundwater							
VOCs	SW 5035/8260	Purge & Trap, GC/MS	15	15	12	15	30
Bromide	EPA 300	Ion Chromatography	15	15	12	15	30
Total Metals	SW 3010/6010	Acid Digestion, ICP	15	15	12	15	30
KMnO ₄	NA	Visual Observation	---	15	12	15	30
¹ Does not include QC samples.							

¹ Does not include QC samples.

4.4.3 Process Monitoring

XDD was ultimately responsible for monitoring its system parameters during the injection phase of the demonstration. XDD's monitoring during injection consisted primarily of adjusting the flow rate of oxidant based on injection pressure readings. As a qualitative way of estimating oxidant dispersal throughout each of the three soil zones, the SITE Program visually monitored KMnO_4 during groundwater sampling rounds coupled with laboratory analysis of bromide. Bromide was used as a tracer for the first injection and was not detected in any baseline groundwater samples collected prior to oxidant injection (the bromide data for all events, including the baseline sampling, is presented in Subsection 4.5).

Figure 4-8 is an illustration showing the estimated dispersion of the KMnO_4 (shown in purple) and the bromide concentration for each well (shown adjacent to the well screen), approximately 104 days following the initial injection into the IW-3 well cluster. As illustrated in Figure 4-8, although KMnO_4 was injected into all three zones, there was no visual evidence of the oxidant in any shallow-zone wells 104 days following injection. Also, the only visual evidence of KMnO_4 in the intermediate (peat) zone was at IW-3i (the point of injection). However, there are relatively high concentrations of bromide in IW-3 and EW-3 cluster wells in the absence of visual KMnO_4 . This infers that the oxidant solution may have dispersed radially as expected (i.e., to and beyond the designed 10-foot radius of influence) but that consumption of KMnO_4 by VOCs

and/or naturally occurring humic material (especially in the peat zone) may have occurred during this time period.

Figures 4-9 and 4-10 are similar illustrations showing the estimated dispersion of the KMnO_4 and bromide concentrations at time intervals after the second injection. Both illustrations show that visual KMnO_4 has, due to the second injection, dispersed throughout the entire area of the deep zone. However, visual KMnO_4 is absent in both the shallow and intermediate (peat) zones. Although bromide diminishes in time from its injection during the first injection event, its persistence in all wells at some concentration indicates that the oxidant solution had dispersed throughout the desired treatment area. The visual absence of KMnO_4 may indicate its consumption by the contaminant and/or natural humic material as previously discussed.

It should be noted that it had been planned to inject KMnO_4 into all three injection well clusters during the initial June 2005 injection event; however an apparent failure of well seals for the IW-1 and IW-2 well clusters resulted in short-circuiting and necessitated the shutdown of injection into those wells. Only a very small volume of KMnO_4 oxidant was actually injected into those wells during the first injection event (hence the low concentrations of bromide depicted in Figure 4-8 for the IW-1 wells). Consequently, those prepacked cluster wells were removed and replaced with traditional wells, and a second injection for the IW-1 and IW-2 clusters was conducted in October of 2005.

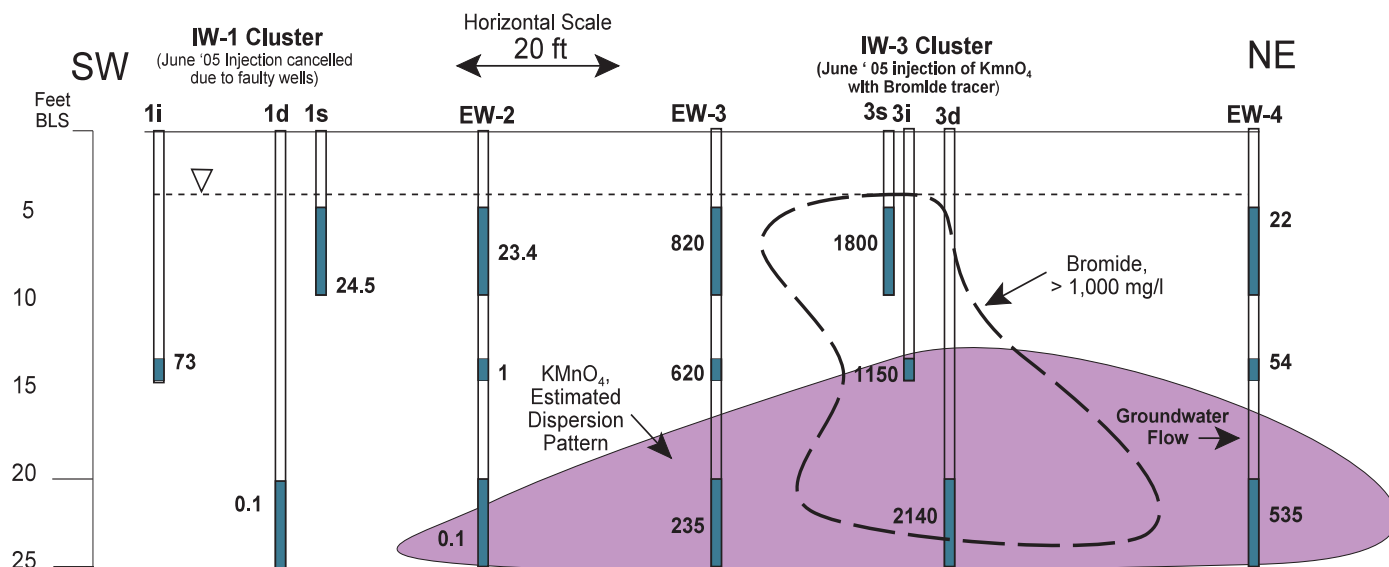


Figure 4-8. Estimated Dispersion of KMnO_4 104 Days After First Injection.

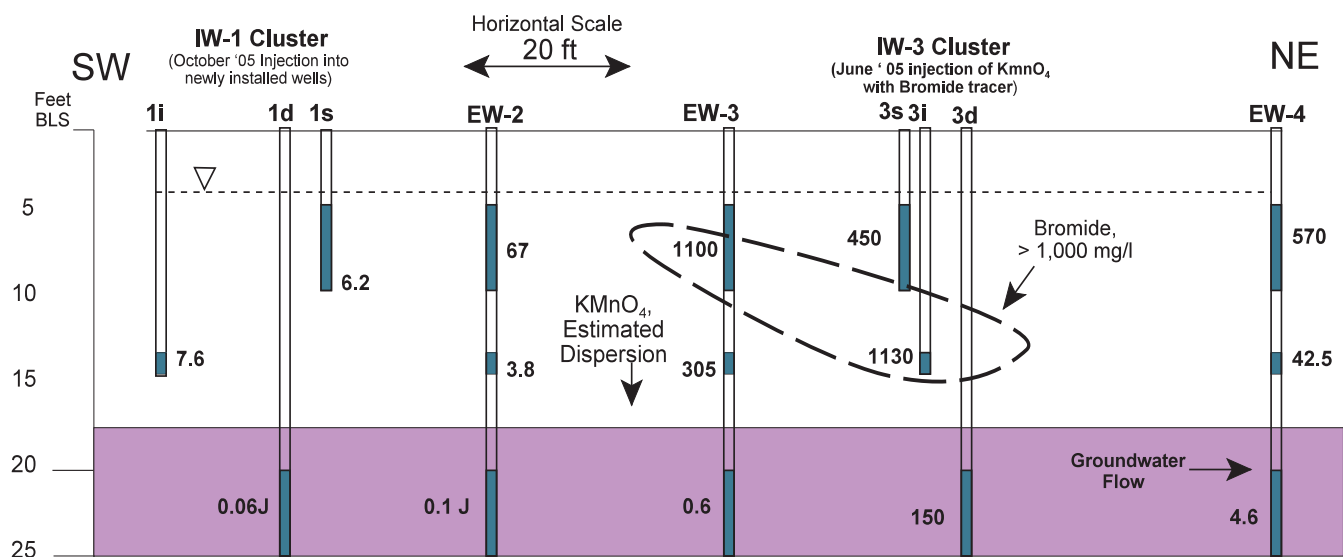


Figure 4-9. Estimated Dispersion of KMnO_4 245 Days After First Injection and 125 Days after Second Injection.

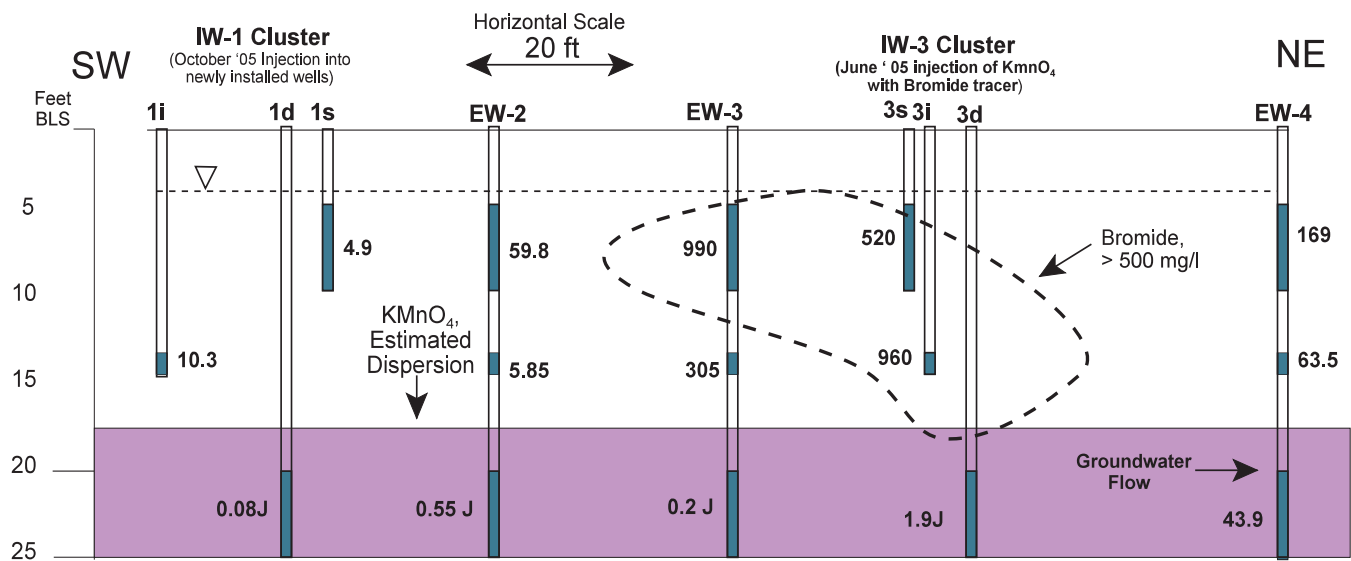


Figure 4-10. Estimated Dispersion of KMnO_4 280 Days After First Injection and 160 Days after Second Injection.

4.5 Performance and Data Evaluation

This subsection presents the performance data obtained during the XDD ISCO SITE Demonstration conducted from August 2004 to May 2006. Subsection 4.5.1 summarizes the soil analyses results soil (target VOCs in all three soil zones and humic fraction for the peat zone). Subsection 4.5.2 summarizes groundwater analyses results for target VOCs and metals. A detailed statistical evaluation of the soil and groundwater VOC data is also included. Subsection 4.5.3 summarizes data quality assurance.

4.5.1 Soil Results

Soils were evaluated as pre- and post-treatment sample pairs to determine if reductions of VOCs had occurred due to the ISCO treatment. Baseline (pre-treatment) and final (post-treatment) soil samples were collected on a "paired sample" basis; final samples were collected in the approximate same location as baseline samples (i.e., within 0.3 feet to 2 feet laterally and within about one foot vertically). Both baseline and final soil samples were analyzed for VOCs and humate content. The soil VOC data was highly variable. High sample concentration variability at DNAPL sites is commonly observed, particularly at sites with heterogeneous lithologies.

4.5.1.1 VOC Results for Soil

The primary objective for soil was to determine if XDD's ISCO process could reduce concentrations of PCE, TCE, cDCE, and VC by 90% from baseline to final sampling events (*Objective 1*). **Tables 4-5 through 4-7** present results of the baseline (pre-treatment) soil sampling versus the final (post-treatment) soil sampling for each of the four critical VOCs (PCE, TCE, cDCE, and VC) for the shallow, peat (middle or intermediate) and deep zones, respectively. Based on pre-demonstration extraction studies, shallow-zone soils were field-extracted using a 1:1 MeOH to soil ratio by volume; the middle peat and bottom zone soils were extracted using a 5:1 MeOH to soil ratio by volume.

It should be noted that due to the large number of non-detect results, due to high laboratory reporting limits resulting from the MeOH field extractions, the soil data was analyzed (i.e., evaluated) three separate ways by:

1. Analysis of soil sample pairs;
2. Analysis of averaged soil results using only detected values; and
3. Analysis of averaged soil results using all values.

Each analysis is discussed separately as follows.

Analysis of Soil Sample Pairs

Although there were 30 sample pairs planned for each of the three stratigraphic zones (i.e., a planned total of 90

pairs), not all pairs could be evaluated for treatment performance at their sampling location. This was primarily due to many of the pairs consisting of two non-detect values (i.e., values below the laboratory reporting limit or LRL). In other instances a quantified value was paired with a non-detect result having a reporting limit exceeding the quantified value. In other instances (i.e., for the peat zone), there was no baseline peat sample to pair with the post-treatment peat sample.

As a result of not being able to evaluate a significant number of soil sample pairs, a subset of "eligible pairs" was selected for descriptive evaluation and included the following:

- Sample pairs that met the original criteria set forth in the QAPP (i.e., where the baseline value was at least ten times the LRL);
- Sample pairs not meeting the QAPP criteria, but either consist of two quantified values or have one quantified value and one estimated J value;
- Sample pairs that contain one non-detect value (i.e., < the LRL); and the other value is a quantified or estimated J value that is significantly higher or lower than that reporting limit value.

Table 4-8 presents a statistical summary of the soil data based on the eligible sample pairs, as just described. For each of the four critical VOCs and for each of the three zones, table 4-8 summarizes the results of the eligible pair analysis from two perspectives:

1. Eligible pairs that show decreases in critical VOC concentration of any magnitude, and;
2. Eligible pairs that show decreases in critical VOC concentration > 90% (i.e., the primary soil objective).

As inferred in Table 4-8, it is apparent that few of the eligible paired sample sets for any of the four critical VOCs showed concentration decreases > 90% from baseline to final sampling events. Aside from the single TCE deep zone sample pair (which did show a > 90% reduction), TCE in the middle peat zone was the only instance where a 90% reduction was measured for more than ½ (i.e., 50%) of the eligible sample pairs evaluated. Of the four VOCs, TCE had the best overall percentage of sample pairs showing reductions > 90% (i.e., 40.9% for all zones combined).

With respect to the percentage of eligible pairs that showed contaminant decreases of any magnitude, VC fared the best. For all zones combined, 82.1% of eligible sample pairs for VC showed contaminant reductions from baseline to final sampling; including 88.9% in the shallow zone and 70% in the peat zone.

Table 4-5. Shallow Zone Soil Results for PCE, TCE, cDCE, and VC - Baseline Vs Final ¹

Parameter→ Boring No.	PCE (µg/kg)		TCE (µg/kg)		cDCE (µg/kg)		VC (µg/kg)	
	Baseline	Final	Baseline	Final	Baseline	Final	Baseline	Final
1	< 52.4	110	< 26.2	< 30.3	3,080	891	158	< 30.3
2	7,710	< 56.1	757	< 28	2,350	278	261	111
3	< 61.5	< 54.9	< 30.7	< 27.4	< 30.7	67.3	< 30.7	< 27.4
4	234	275,000	< 53.5	19,600	16,500	9,630	35 J	< 28.3
5	88	11,100	< 26.8	1,500	10,400	38,300	1,410	638
6	90.5	103	22.3 J	22.0 J	1,030	287	138	< 29.9
7	41,000	20.3 J	1,860	< 29.3	6,850	5,860	280	< 29.3
8	34.9 J	183	< 26.1	65	1,740	179	2,060	< 31.2
9	< 53.1	< 57.5	< 26.5	< 28.8	< 26.5	17.4 J	< 26.5	< 28.8
10	20,000	1,160	4,110	243	5,700	11,600	476	208
11	< 52.8	< 54.3	< 26.4	< 27.2	< 26.4	< 27.2	< 26.4	< 27.2
12	< 114	< 58.1	< 57.2	< 29.0	< 57.2	< 29.0	< 57.2	< 29.0
13	< 60.8	< 57.7	< 30.4	< 28.9	7,530	< 28.9	331	< 28.9
14	4,660	29,100	158	2,050	1,090	15,400	770	137
15	31.8 J	201	< 28	21.6 J	1,710	18.6 J	166	< 29.4
16	26,400	393,000	3,160	58,700	1,950	4,610	504	< 142
17	604	25.3 J	165	< 29.3	10,100	1,270	< 54.1	< 29.3
18	21.7 J	< 54.8	< 59.1	< 27.4	19.0 J	75.4	37.5	< 27.4
19	< 59.4	24.9 J	< 59.4	< 30.6	26.0 J	1,190	254	528
20	287	1,650	< 52.2	549	67.2	1,240	76.8	427
21	< 64.9	116	< 64.9	34.7	476	1,090	417	289
22	24.2 J	26.3 J	< 65.8	< 29.6	8,900	335	3,020	< 29.6
23	< 63.7	< 60.5	< 63.7	< 30.3	19.4 J	30.6	< 31.9	< 30.3
24	< 65.3	< 53.7	< 65.3	< 26.8	61.5	21.4 J	79	< 26.8
25	41.3 J	1,850	< 55.2	375	367	904	1,900	654
26	138	799,000	25.1 J	112,000	4,290	4,320	19.3 J	< 287
27	8,920	684	963	137	9,010	6,100	19.4 J	< 29.9
28	< 59.9	< 58.1	< 59.9	< 29.1	3,460	19.9 J	2,270	< 29.1
29	21,000	107,000	1,700	10,900	12,800	13,100	98.5	< 131
30	9,940	11,200	15,500	6,570	22,400	2,620	833	< 28.8

¹ Samples field extracted with a 1:1 MeOH to soil ratio by volume. J = Estimated value (i.e., value is above the detection limit but below the laboratory reporting limit).

Table 4-6. Middle Peat Zone Soil Results for PCE, TCE, cDCE, and VC - Baseline Vs Final ¹

Parameter→ Boring No.	PCE (µg/kg)		TCE (µg/kg)		cDCE (µg/kg)		VC (µg/kg)	
	Baseline	Final	Baseline	Final	Baseline	Final	Baseline	Final
1	< 385	< 421	< 192	< 210	977	413	< 192	< 210
2	< 298	< 396	< 149	< 198	97.8 J	< 198	< 149	< 198
3	< 332	< 404	< 166	< 202	< 166	< 202	< 166	< 202
4	26,600	3,380	674	2,350	21,900	24,400	1,690	2,490
5	157 J	644 J	< 189	< 454	35,800	1,090	8,270	1,920
6	936	< 549	< 175	< 549	453	2,410	< 175	< 549
7	< 863	141 J	< 431	< 234	41,300	19,700	55,100	21,300
8	< 374	509 J	< 187	< 348	< 187	< 348	< 187	< 348
9	---	< 408	---	< 204	---	< 204	---	< 204
10	< 560	338 J	< 280	< 226	< 280	413	< 280	< 226
11	< 378	< 581	< 189	< 290	< 189	< 290	< 189	< 290
12	< 291	< 494	< 145	< 247	< 145	208 J	< 145	< 247
13	< 667	< 515	< 667	< 258	1,730	< 258	212 J	< 258
14	132,000	1,660	5,130	< 466	8,020	2,230	< 750	< 466
15	< 865	< 606	< 865	< 303	280 J	662	< 432	< 303
16	77,400	< 635	6,770	< 317	17,100	467	7,850	< 317
17	243,000	< 788	40,900	< 394	51,600	7,650	< 5,980	7,310
18	< 702	< 925	< 702	< 462	1,650	1,410	< 351	< 462
19	< 693	< 728	< 693	< 364	1,710	207 J	328 J	< 364
20	< 419	< 558	< 419	< 279	< 210	272 J	< 210	< 279
21	307 J	< 599	< 535	< 299	4,430	379	1,050	< 299
22	< 888	< 821	< 888	< 410	10,800	461	3,160	< 410
23	< 364	< 594	< 364	< 297	270	1,990	< 182	< 297
24	< 307	< 542	< 307	< 271	< 153	< 271	< 153	140 J
25	---	521	---	120 J	---	62,000	---	60,900
26	2,550	4,800	1,850	433	38,300	35,000	21,800	16,200
27	34,900	999	13,600	254	181,000	159,000	10,400	36,000
28	< 405	< 378	< 405	< 189	3,180	< 189	782	< 189
29	48,000	12,100	3,380	1,190	43,600	162,000	11,500	92,400
30*	---	47,400	---	4,590	---	28,300	---	< 171

¹ Samples field extracted with a 5:1 MeOH to soil ratio by volume. * At boring 30, peat material absent, but a sand sampled due to high PID reading.
 --- no sample collected. J = Estimated value (i.e., value is above the detection limit but below the laboratory reporting limit).

Table 4-7. Bottom Zone Soil Results for PCE, TCE, cDCE, and VC - Baseline Vs Final ¹

Parameter→ Boring No.	PCE (µg/kg)		TCE (µg/kg)		cDCE (µg/kg)		VC (µg/kg)	
	Baseline	Final	Baseline	Final	Baseline	Final	Baseline	Final
1	348	< 362	< 151	< 181	< 151	< 181	< 151	< 181
2	< 150	111 J	< 150	< 177	< 150	< 177	< 150	< 177
3	< 200	< 369	< 200	< 184	< 200	< 184	< 200	< 184
4	4,740,000	31,400	6,000	< 181	< 149	< 181	< 149	< 181
5	330 J	< 333	< 169	< 166	< 169	< 166	< 169	92.3 J
6	553	166 J	< 158	< 169	< 158	< 169	< 158	< 169
7	< 174	< 357	< 174	< 178	< 174	< 178	< 174	< 178
8	243	29,600	< 163	139 J	234	< 223	< 163	< 223
9	188 J	< 395	< 201	< 197	< 201	< 197	< 201	102 J
10	2,950	< 310	< 122	< 155	< 122	< 155	< 122	< 155
11	< 169	< 385	< 169	< 192	< 169	< 192	< 169	< 192
12	< 128	< 326	< 128	< 163	< 128	< 163	< 128	< 163
13	1,590	< 310	< 133	< 155	< 133	19,500	< 133	< 155
14	249,000	< 364	< 178	< 182	< 178	< 182	< 178	< 182
15	1,260	< 536	< 167	< 268	< 167	< 268	< 167	< 268
16	< 162	< 382	< 162	< 191	< 162	< 191	< 162	< 191
17	< 153	< 1,180	< 153	< 588	< 153	< 29.3	< 153	< 588
18	301	5,240	< 131	< 193	< 131	< 193	< 131	< 193
19	4,980	< 349	< 146	< 175	< 146	< 175	< 146	< 175
20	< 185	2,930	< 185	< 163	< 185	< 163	< 185	< 163
21	2,580	< 313	< 166	< 156	< 166	< 156	< 166	< 156
22	< 167	< 409	< 167	< 204	< 167	< 204	< 167	< 204
23	998	< 296	< 156	< 148	< 156	< 148	< 156	< 148
24	< 148	< 330	< 148	< 165	< 148	< 165	< 148	< 165
25	< 182	159 J	< 182	< 185	< 182	< 185	< 182	< 185
26	< 144	< 319	< 144	< 160	< 144	< 160	< 144	< 160
27	1,910	205 J	< 173	< 211	< 173	< 211	< 173	< 211
28	384 J	< 286	< 389	< 143	503	< 143	< 389	< 143
29	13,100	15,800	< 229	< 170	< 229	< 170	< 229	< 170
30	814,000	288,000	< 1,570	< 447	< 1,570	237 J	< 1,570	< 447

¹ Samples field extracted with a 5:1 MeOH to soil ratio by volume. J = Estimated value (i.e., value is above the detection limit but below the laboratory reporting limit).

Analyte	Zone ²	Eligible Pairs	Decreases				Decreases > 90%			
			# Dec.	% Dec.	95% LL	95% UL	# Dec.	% Dec.	95% LL	95% UL
PCE	Shallow	17	5	29.4	12.4	55.4	4	23.5	8.5	48.9
	Peat	9	7	77.8	44.2	95.9	4	44.4	16.9	74.9
	Deep	15	11	73.3	44.8	90.3	6	40	19.1	66.8
	All Combined	41	23	56.1	40.9	71.3	14	34.1	19.6	48.7
TCE	Shallow	14	6	42.9	20.6	68.8	4	28.6	10.4	61.1
	Peat	7	6	85.7	44.6	99.3	4	57.1	22.5	87.1
	Deep	1	1	100	5.0	100	1	100	5.0	100
	All Combined	22	13	59.1	38.5	79.6	9	40.9	20.4	61.5
cDCE	Shallow	26	14	53.8	32.5	71.8	4	15.4	5.4	32.5
	Peat	19	14	73.7	50	89	6	31.6	14.7	57.4
	Deep	2	1	50	2.5	97.5	0	0.0	0.0	77.6
	All Combined	47	29	61.7	47.8	75.6	10	21.3	9.6	33
VC	Shallow	18	16	88.9	67.5	98	8	44.4	23.6	67.5
	Peat	10	7	70	38.1	91.3	2	20	3.7	60.3
	Deep	0	0	---	---	---	0	---	---	---
	All Combined	28	23	82.1	64.3	92.7	10	35.7	19.2	57.6

LL = Lower limit of confidence interval. UL = Upper limit of confidence interval. Dashed line = no calculation possible.

Analysis of Averaged Soil Results Using Detected Values

In addition to analyzing soils on a paired sample basis, soil results were also evaluated on an average pre-treatment (baseline) versus post-treatment (final) basis. **Table 4-9** presents averaged results for the four critical VOC compounds (PCE, TCE, cDCE, and VC), using all quantified and estimated ("J") values. Average values are shown for the three individual lithologic zones and for all zones combined. The number of values averaged are shown in parenthesis next to each average value.

When excluding non-detected results, on an all zones combined basis, PCE is the only VOC of the four critical compounds for which there is shown a relevant decrease in average concentration (i.e., 63.5%). The averaged data suggests that there were reductions of PCE concentrations in the peat and deep zones, but an increase in PCE concentrations in the shallow zone.

On a per zone basis and accounting for a decreased sample size, the best overall reductions appear to have been achieved in the middle peat zone. On average there are relatively large decreases shown for PCE (95.6%) and TCE (91.6%). A very small average reduction is shown for

cDCE (1.03%) and VC is shown to increase on average by 161%. For the shallow zone, two VOCs showed increased average concentrations (PCE and TCE) and two VOCs showed decreased average concentrations (cDCE and VC). For the bottom zone, PCE and TCE were also shown to have decreased average concentrations and cDCE was shown to have increased average concentrations. VC could not be evaluated due to the lack of baseline data above LRLs.

Analysis of Averaged Soil Results Using All Values

To statistically determine whether the null hypothesis is rejected or not (i.e., the primary objective), all soil results comprising baseline and final pairs were evaluated (**Table 4-10**). By doing this, the sample population for baseline and final samples were the same for each of the three zones. For example, if non-detect results are included, there are 30 baseline and 30 final sample results for the shallow and deep zones; and there are 27 baseline and 27 final sample results for the middle peat zone (Note: there were three borings at which peat was encountered at 27 of the 30 borings sampled during the baseline activity).

Table 4-9. Averaged Soil Results (Excluding Non-Detects) for PCE, TCE, cDCE, and VC - Baseline Vs. Final.						
Analyte	Zone	Average Concentration, µg/Kg (sample No.)		Decrease / Increase	% Change	
		Baseline	Final			
PCE	Shallow	7,433 (19)	81,578 (20)	Increase	+ 998	
	Peat	56,585 (10)	2,509 (10)	Decrease	- 95.6	
	Deep	324,151 (18)	37,361 (10)	Decrease	- 88.5	
	All Combined	139,187 (47)	50,756 (40)	Decrease	- 63.5	
TCE	Shallow	2,584 (11)	14,184 (15)	Increase	+ 449	
	Peat	10,329 (7)	869 (5)	Decrease	- 91.6	
	Deep	6,000 (1)	139 (1)	Decrease	- 97.7	
	All Combined	5,617 (19)	10,345 (21)	Increase	+ 84.2	
cDCE	Shallow	5,074 (26)	4,424 (27)	Decrease	- 12.8	
	Peat	23,210 (20)	22,970 (21)	Decrease	- 1.03	
	Deep	369 (2)	9,869 (2)	Increase	+ 2,570	
	All Combined	12,435 (48)	12,431 (50)	No Change	- 0.03	
VC	Shallow	651 (24)	374 (8)	Decrease	- 42.5	
	Peat	10,179 (12)	26,518 (9)	Increase	+ 161	
	Deep	— (0)	97 (2)	---	---	
	All Combined	3.827 (36)	12.729 (19)	Increase	+ 233	

When including non-detected results on an all zones combined basis, PCE is still the only VOC of the four critical compounds for which there is shown a decrease of any magnitude in average concentration (i.e., 68.9%). The other compound showing a decrease, although slight, is cDCE (6.27%). Averaged data suggests that there were considerable reductions of PCE concentrations in the peat material (94.8%) and deep zone (93.5%), but an increase in PCE concentrations in the shallow zone (1,050%).

On a per zone basis and accounting for a decreased sample size, the best overall reductions appear to have been achieved in the middle peat material and in the deep zone. For the peat material, on average there are relatively large decreases shown for PCE (94.8%) and TCE (89.7%) and a small average reduction shown for cDCE (9.39%). VC is shown to increase on average by 42.4%. For the bottom zone, PCE and TCE were also shown to have considerable decreased average concentrations (93.5% and 66.7%, respectively). VC showed a slight decrease (5.5%). But cDCE, a known breakdown product, was shown to have increased by 488% on average. For the shallow zone, two VOCs showed increased average concentrations (PCE at 1,050% and TCE at 638%) and two

VOCs showed decreased average concentrations (cDCE at 9.48% and VC at 77.5%).

The hypothesis test suggested in the QAPP is that the technology will remove more than 90% of contamination. The null hypothesis tested here is that the contamination removed does not exceed 90%. That is, we test the null hypothesis:

$$H_0: \left[\frac{\text{post-treatment constituent mass}}{\text{pre-treatment constituent mass}} \right] \geq -0.9$$

against the alternative hypothesis

$$H_a: \left[\frac{\text{post-treatment constituent mass}}{\text{pre-treatment constituent mass}} \right] < -0.9$$

Accepting the null hypothesis would be a finding that the process does not meet demonstration objectives. If the null hypothesis is rejected for a given set of experimental circumstances, then the technology meets demonstration objectives for those experimental circumstances.

Table 4-10. Averaged Soil Results (Including Non-Detects) for PCE, TCE, cDCE, and VC - Baseline Vs. Final.							
Analyte	Zone (Sample No)	Average Concentration, µg/Kg		Decrease / Increase	% Change	95% ¹ LL	95% ¹ UL
		Baseline	Final				
PCE	Shallow (30)	4,721	54,395	Increase	+ 1,050	- 166	+ 2,270
	Peat (27)	21,120	1,105	Decrease	- 94.8	- 99.9	- 89.6
	Deep (30)	194,523	12,586	Decrease	- 93.5	- 103.5	- 83.5
	All Combined (87)	75,259	23,440	Decrease	- 68.9	-117	- 21.2
TCE	Shallow (30)	962	7,099	Increase	+ 638	- 310	+ 1,590
	Peat (27)	2,825	291	Decrease	- 89.7	- 100	- 79.0
	Deep (30)	306	102	Decrease	- 66.7	- 109	- 25.0
	All Combined (87)	1,314	2,573	Increase	+ 95.8	- 156	+ 348
cDCE	Shallow (30)	4,400	3,983	Decrease	- 9.48	- 73.1	+ 54.2
	Peat (27)	17,217	15,601	Decrease	- 9.39	- 68.2	+ 49.5
	Deep (30)	126	741	Increase	+ 488	- 514	+ 1,490
	All Combined (87)	6,904	6,471	Decrease	- 6.27	- 51.1	+ 38.6
VC	Shallow (30)	524	118	Decrease	- 77.5	- 92.3	+ 62.6
	Peat (27)	4,700	6,693	Increase	+ 42.4	- 91.8	+ 177
	Deep (30)	109	103	Decrease	- 5.5	- 38.8	+ 28.4
	All Combined (87)	1,677	2,154	Increase	+ 28.4	- 83.3	+ 140

¹ Values rounded to three significant digits.

Table 4-10 provides the basis for testing the null hypothesis for each of the four analytes for each of the three zones and for all zones combined. As previously discussed for each of these combinations, Table 4-10 provides an estimate in the percentage change or reduction in contamination in the third column from the right. In the last 2 columns the table also provides the lower and upper limits of the 95% confidence interval for the actual or population percentage change.

For example, consider TCE for the Peat zone. Table 4-10 shows a percentage change of -89.7% with a 95% confidence interval of (-100%, -79%).

Now for each of the 16 sets of analyte-zone combinations, the null hypothesis is accepted if the upper limit of the 95% confidence interval is greater than -90.0%. For instance, in the case of TCE in the Peat zone, the upper limit of the confidence interval is -79.0% which is greater than -90.0%. Thus, we fail to reject the null hypothesis for TCE in the Peat zone. Based on this hypothesis testing framework, we fail to reject the null hypothesis for each analyte in each zone and for each analyte in all zones combined.

We hasten to add, however, that we are using a two-sided 95% confidence interval to test a one-sided hypothesis, and therefore, the hypotheses are actually being tested at the 97.5% level. Testing these hypotheses at the 90% level, yields the same outcomes with one exception. At the 90% hypothesis testing level, the null hypothesis would be rejected for PCE in the Peat zone. The null hypothesis would be accepted for all other cases.

Statistical methods for confidence intervals provided in the tables for the soil results are provided as follows.

Statistical Methods for Confidence Intervals

In this section, confidence intervals are presented for three kinds of population quantities:

- ▶ population proportion for a binomial distribution;
- ▶ population mean values based on normal distribution theory; and
- ▶ ratios of population means based on normal distribution asymptotic theory.

Proportion

For a binomial distribution population proportion, the sample proportion is given by:

$$\bar{p} = \frac{\text{number of successes}}{n}$$

where n is the number trials or sample pairs. In case $n > 30$, a 95% confidence interval for the population, proportion p is given by Equation 1 (Eq. 1) where $t_{(0.975, n-1)}$ is the upper 97.5 percentile of the student-t distribution with $(n - 1)$ degrees of freedom. This confidence interval places 2.5 percentage points for both the upper and lower endpoints of the confidence interval.

One can multiply the confidence interval expression by 100 to translate the proportional expression into percentage points. When $n < 30$, the two-sided confidence intervals were taken from tables of exact confidence intervals for a binomial distribution. (see Table A-22 of Natrella, 1963).

Mean Value

The sample mean value is given by Eq.2. The two-sided 95% confidence interval for the population mean value is given by Eq. 3, where μ is the population mean value and

S_x^2 in Eq. 4 is the sample estimate of the variance or the square of the sample standard deviation.

Ratio of Mean Values

Define the proportion of change of in place contamination from the baseline or pretreatment measurements to the final or post-treatment measurements as:

$$p_R = \frac{\text{post-treatment constituent mass}}{\text{pre-treatment constituent mass}} - 1$$

where p_R with the pretreatment and post-measurement sample mean values by Eq. 5. From Hansen, et al. (1993),the sample variance of

$$\hat{p}_R$$

is approximated by Eq. 6. The two-sided 95% confidence interval for p_R is approximated by Eq. 7. Of course, one can multiply the confidence interval expression by 100 to translate the proportional expression into percentage points.

$\bar{p} - \frac{\sqrt{\bar{p} \cdot (1 - \bar{p})}}{\sqrt{n}} \cdot t_{(0.975, n-1)} < p < \bar{p} + \frac{\sqrt{\bar{p} \cdot (1 - \bar{p})}}{\sqrt{n}} \cdot t_{(0.975, n-1)}$	Equation (1)
$\bar{X} = \frac{1}{n} \cdot \sum_{i=1}^n X_i$ where n = sample size, and X_i are the measurements for each sample for $i = 1, \dots, n$.	Equation (2)
$\bar{X} - \frac{S_X}{\sqrt{n}} \cdot t_{(0.975, n-1)} < \mu < \bar{X} + \frac{S_X}{\sqrt{n}} \cdot t_{(0.975, n-1)}$	Equation (3)
$S_X^2 = \frac{1}{n-1} \cdot \sum_{i=1}^n (X_i - \bar{X})^2$	Equation (4)
$\hat{p}_R = \hat{R} - 1$ $= \frac{\bar{X}}{\bar{Y}} - 1$ <p>where \bar{X} denotes the sample mean of the pre-treatment measurements; where \bar{Y} denotes the sample mean of the post-treatment measurements, and $\hat{R} = \bar{X} / \bar{Y}$ with n, post-treatment measurements, and n, pre-treatment measurements</p>	Equation (5)

$S_R^2 = \frac{\hat{R}^2}{n} \cdot \left[\frac{S_X^2}{\bar{X}^2} + \frac{S_Y^2}{\bar{Y}^2} - 2 \cdot \frac{S_{XY}}{\bar{X} \cdot \bar{Y}} \right] \quad \text{where} \quad S_{X,Y} = \frac{1}{n-1} \cdot \sum_{i=1}^n (X_i - \bar{X}) \cdot (Y_i - \bar{Y})$	Equation (6)
$\hat{P}_R - \frac{S_R}{\sqrt{n}} \cdot t_{(0.975, n-1)} < P_R < \hat{P}_R + \frac{S_R}{\sqrt{n}} \cdot t_{(0.975, n-1)}$	Equation (7)

4.5.1.2 Humate Results for Soil

To assess the impact of the organic matter in the peat with respect to its effect on oxidant depletion, samples were collected from the middle peat zone during both baseline and final sampling events (*Objective 3*). **Table 4-11** presents the results of the humic acid analyses, which reflects the amount of humate material in a soil. Instead of an expected potential depletion of humic material, there is

shown a measured increase. The average of 27 baseline values was 2.6 % and the average of 26 final values was 6.0 %, an increase of 230%. Also shown in the table is that for all borings in which there are paired values, the final value is always greater with the exception of Boring No. 1. There is no obvious explanation for the measured increase in humic acid content from baseline to final.

Table 4-11. Humic Acid Results for Middle Peat Zone - Baseline Vs. Final (wt/wt %)¹

Boring No.	Baseline	Final	Boring No.	Baseline	Final
1	3.1	2.07	16	5.8	10.5
2	1.1	2.65	17	4.4	8.21
3	0.8	1.35	18	3.1	11.3
4	0.6	---	19	4.5	5.53
5	1.4	8.33	20	2.4	4.57
6	< 0.1	7.59	21	4.1	8.04
7	2.1	9.58	22	6.4	7.32
8	< 0.2	4.02	23	1.0	3.40
9	---	4.29	24	0.3	---
10	3.7	4.27	25	---	10.1
11	1.1	---	26	3.6	3.33
12	< 0.1	6.08	27	0.5	7.29
13	3.7	5.11	28	5.6	1.74
14	3.6	7.02	29	< 0.1	4.77
15	6.4	8.45	30	---	---

¹ Values rounded to maximum three significant digits. Dashed line = lack of peat material to analyze. Using ½ the reporting limit for non-detect values (i.e., < values), the average of all baseline values = 2.6% & average of all final values = 6.0%.

4.5.2 Groundwater Results

4.5.2.1 Target Ethene VOCs

The primary objective for groundwater was to evaluate the effectiveness of XDD's ISCO process in reducing concentrations of the PCE, TCE, and cDCE in the groundwater to below their corresponding Remediation Performance Standards (RPS) of 750 µg/L, 5,500 µg/L, and 17,500 µg/L, respectively. The QAPP specified that to meet the primary groundwater objective (*Objective 2*) more than 90% of eligible groundwater samples had to meet those regulatory criteria, as to reject the null hypothesis (i.e., concentrations reduced to below the RPS).

The hypothesis test proposed in the QAPP is based on the population proportion, call it p , of sample pairs that meet regulatory goals. The null hypothesis to be tested is:

$$H_0: p < \text{or } = 0.90$$

against the alternative hypothesis

$$H_A: p > 0.90.$$

Accepting the null hypothesis would be a finding that the process does not attain regulatory goals. For any experiment in which the sample proportion of pairs meeting regulatory goals do not exceed 0.90, the null hypothesis would be accepted. (Note that this does not imply that the proportion being, for example, 0.901 would be sufficient to reject the null hypothesis).

It should be noted that, beginning with the initial baseline sampling event and continuing through intermediate sampling events, there was a total of up to 15 samples collected from 5 different wells at the three distinct horizons. However, the sample number for the final post-treatment event was increased to a total of 30. This change in strategy was due to a desire to increase the sample population and thus provide better statistics.

To accomplish the increased sample number for the final event without having to install additional wells, samples were collected from the existing 15 wells on two different days ($2 \times 15 = 30$). A day (i.e., 24 hours) separated these two sampling rounds so that, based on the horizontal gradient, samples were considered independent both spatially and with respect to temporal location. In other words, the second set of samples was considered separate and independent from the first set of samples.

It also should be noted that since there were two injection events, there are two groundwater baseline events. Wells influenced by the first injection (IW-3, EW-3 and EW-4 well clusters) correlate to the April 2005 groundwater sampling event and wells influenced by the second injection (IW-1 and EW-2 well clusters) correlate to the September 2005 groundwater sampling event.

Table 4-12 presents results of the baseline (pre-treatment) groundwater sampling and the two rounds comprising the

final (post-treatment) groundwater sampling. Within Table 4-12, the cells for baseline values that were measured above the RPS are blocked (e.g., for well cluster IW-1, shallow zone, the PCE value of 5,200 µg/L is blocked because it is above the RPS of 750 µg/L).

The primary groundwater objective was evaluated three different ways; including:

1. Baseline vs. final results for each individual well; (i.e., the baseline pre-treatment value vs. the average of the 2 final post-treatment values);
2. On an overall sample set basis (i.e., the average of all 15 baseline pre-treatment values vs. the average of all 30 final post-treatment values); and
3. On a per groundwater zone basis (i.e., the average of 5 baseline pre-treatment values for each of the three zones vs. the average of 10 final post-treatment values for each of those three zones).

Individual Well Evaluation

As shown in Table 4-12, on an individual well basis, there are only seven instances where any of the three ethene compounds exceeded their respective RPS prior to oxidant injection. Therefore, there are just seven eligible baseline samples to evaluate (Note: seven pairs do not give sufficient resolution to test the null hypothesis at the 95% confidence level). However, when averaging the two final result values to attain a final post-treatment concentration, such a reduction occurred in three of seven instances (i.e., PCE in EW-4, deep; TCE in IW-1 shallow; and cDCE in IW-1 shallow). In two other instances (cDCE in IW-1 intermediate, and TCE in EW-2 shallow) reductions are measured close to the RPS. For the individual well evaluations, the null hypothesis is accepted for each of the three contaminants (i.e., the objective was not met).

Total Sample Set Evaluation

For the entire sample set, PCE was the only critical VOC that on average was above its respective RPS. On an overall contaminant average basis, PCE did show an approximate 27% reduction to very slightly below the RPS (from 1,020 µg/L to 746 µg/L). Apparent reductions are also shown for the two other critical compounds having RPSs, TCE and cDCE. TCE is shown to have an approximate 51% reduction (from an average baseline concentration of 1,260 µg/L to an average final concentration of 612 µg/L). For cDCE there is an approximate 58% reduction (from an average baseline concentration of about 7,400 µg/L to an average final concentration of approximately 3,090 µg/L). It should be noted that standard deviations are relatively high when observing the total groundwater sample set, especially for the baseline sample set. This is largely due to a high variability of contaminant concentrations among the three zone depths samples.

Table 4-12. Groundwater Results for Target Ethenes - Baseline Vs. Final.

Well Cluster ID	Zone ²	PARAMETER, Remediation Performance Standard (RPS) in µg/L ¹					
		PCE, 750		TCE, 5,500		cDCE, 17,500	
		Baseline	Final	Baseline	Final	Baseline	Final
IW-1	Shallow	5,200	1,090 1,360	11,200	572 766	31,000	3,630 3,620
	Intermediate	16.4 J	1,120 1,310	62.1	892 1,950	50,100	20,100 16,700
	Deep	208	545 5,370	1.0	< 0.5 < 0.5	1.7	< 0.5 0.34 J
IW-3	Shallow	81.7	718 637	63	677 620	4,590	2,810 1,890
	Intermediate	3.6 J	9.1 7.3	< 5.0	6.3 6.4	18.4	392 614
	Deep	369	< 0.5 < 2.5	0.75	< 0.5 < 0.5	< 0.5	< 0.5 < 2.5
EW-2	Shallow	6,830	4,190 5,560	7,090	4,810 7,430	15,500	9,510 13,600
	Intermediate	86.5	17.8 55.5	148	97.4 228	6,220	4,490 7,770
	Deep	10.6	3.0 1.5	< 1.0	< 0.5 < 0.5	< 1.0	< 0.5 < 0.5
EW-3	Shallow	141	80.1 284	290	58.7 194	3,750	341 894
	Intermediate	< 5.0	3.6 8.2	< 5.0	10.4 38.3	75.1	24.8 105
	Deep	45.9	< 0.5 < 0.5	< 0.5	< 0.5 < 0.5	< 0.5	< 0.5 < 0.5
EW-4	Shallow	2.6	0.75 1.6	2.5	3.3 7.7	345	978 5,300
	Intermediate	1.8	< 0.5 < 0.5	< 0.5	< 0.5 0.37 J	15.3	8.0 6.9
	Deep	2,310	< 0.5 < 0.5	2.1	< 0.5 < 0.5	1.6	< 0.5 < 0.5
Average ³		1,020	746	1,260	612	7,440	3,090
Standard Deviation ³		2,130	1,530	3,300	1,590	14,500	5,320
Coefficient of Variance ³		2.09	2.05	2.62	2.6	1.95	1.72
95% UL ³		2,200	1,320	3,080	1,210	15,500	5,080
95% LL ³		- 160	174	- 568	17.7	- 604	1,110

¹ Blocked values are those exceeding the RPS. Two sampling rounds were conducted for the final sampling event (March 14 & 16, 2006).

² Approximate depths for zones (i.e., screened intervals in feet bls) were as follows: Shallow (4-9), Intermediate (13-14), and Deep (20-25).

³ Values are rounded to a maximum three significant digits. For Non-detect values (i.e., < values), ½ the reporting limit was used for averaging.

J = estimated value. UL = Upper Limit of 95% confidence interval. LL = Lower limit of 95% confidence interval.

Groundwater Zone Evaluation

On a per groundwater zone basis the results are based on a small subset of the overall data set (i.e., there are just 5 baseline pre-treatment values for each of the three zones versus the average of just 10 final post-treatment values for each of those same three zones).

Shallow Zone: Standalone results for shallow zone groundwater are presented in **Table 4-13**. On average, there appears to be reductions in concentrations from baseline to final sampling for all three ethene compounds

(i.e., PCE - 43%, TCE - 60%, and cDCE - 61%). Also shown in Table 4-13, there are five instances where the baseline value for any of the three ethene compounds exceeded their respective RPS prior to oxidant injection. Of these five instances, the average of the two final event values is below the RPS in two cases (i.e., TCE in wells IW-1s and cDCE in IW-1s).

For the shallow zone evaluations, the null hypothesis is accepted for each of the three contaminants (i.e., the objective was not met).

Table 4-13. Shallow Zone Groundwater Results for Target Ethenes - Baseline Vs. Final.

Well ID	Zone ²	PARAMETER, Remediation Performance Standard (RPS) in µg/L ¹					
		PCE, 750		TCE, 5,500		cDCE, 17,500	
		Baseline	Final	Baseline	Final	Baseline	Final
IW-1s	Shallow	5,200	1,090 1360	11,200	572 766	31,000	3,630 3,620
IW-3s	Shallow	81.7	718 637	63	677 620	4,590	2,810 1,890
EW-2s	Shallow	6,830	4,190 5560	7,090	4,810 7,430	15,500	9,510 13,600
EW-3s	Shallow	141	80.1 284	290	58.7 194	3,750	341 894
EW-4s	Shallow	2.6	0.75 1.6	2.5	3.3 7.7	345	978 5,300
Average ³		2,450	1,390	3,730	1,510	11,000	4,260
Standard Deviation ³		3,300	1,920	5,150	2,520	12,500	4,240
Coefficient of Variance ³		1.35	1.38	1.38	1.67	1.13	1.00
95% UL ³		6,550	2,770	10,100	3,320	26,600	7,290
95% LL ³		- 1,652	20	- 2,670	- 290	- 4,510	1,220

¹ Blocked values are those exceeding the RPS. Two sampling rounds were conducted for the final sampling event (March 14 & 16, 2006).

² Approximate depths for zones (i.e., screened intervals in feet bls) were as follows: Shallow (4-9), Intermediate (13-14), and Deep (20-25).

³ Values are rounded to a maximum three significant digits. For Non-detect values (i.e., < values), ½ the reporting limit was used for averaging.

J = estimated value. UL = Upper Limit of 95% confidence interval. LL = Lower limit of 95% confidence interval.

Intermediate (Peat) Zone: Standalone results for intermediate zone groundwater are presented in **Table 4-14**. On average, there appears to be substantial increases for PCE and TCE; and a decrease in cDCE. The increases in PCE and TCE concentration averages are almost exclusively due to drastic increases in those compounds in well IW-1i (the IW-1 cluster is closest to the source area). In similar fashion, the decrease in average cDCE can be mostly attributed in a substantial decrease on that compound in well IW-1i.

Also shown in Table 4-14, there is one instance where the baseline value for one of the ethene compounds exceeds its respective RPS prior to oxidant injection (i.e., cDCE in IW-1i). However the average of the two final event values is 18,400 µg/L, which is above the RPS of 17,500 µg/L.

For the intermediate zone evaluations, the null hypothesis is accepted for each of the three contaminants (i.e., the objective was not met).

Table 4-14. Intermediate Zone Groundwater Results for Target Ethenes - Baseline Vs. Final.

Well ID	Zone ²	PARAMETER, Remediation Performance Standard (RPS) in µg/L ¹					
		PCE, 750		TCE, 5,500		cDCE, 17,500	
		Baseline	Final	Baseline	Final	Baseline	Final
IW-1i	Intermediate	16.4 J	1,120 1,310	62.1	892 1,950	50,100	20,100 16,700
IW-3i	Intermediate	3.6 J	9.1 7.3	< 5.0	6.3 6.4	18.4	392 614
EW-2i	Intermediate	86.5	17.8 55.5	148	97.4 228	6,220	4,490 7,770
EW-3i	Intermediate	< 5.0	3.6 8.2	< 5.0	10.4 38.3	75.1	24.8 105
EW-4i	Intermediate	1.8	< 0.5 < 0.5	< 0.5	< 0.5 0.37 J	15.3	8.0 6.9
Average ³		22.2	253	43.1	323	11,300	5,020
Standard Deviation ³		36.5	509	64.2	634	21,900	7,540
Coefficient of Variance ³		1.65	2.01	1.49	1.96	1.94	1.50
95% UCL ³		67	617	123	777	38,400	10,400
95% LCL ³		- 23	- 111	- 37	- 131	- 15,900	- 374

¹ Blocked value is that exceeding the RPS. Two sampling rounds were conducted for the final sampling event (March 14 & 16, 2006).

² Approximate depths for zones (i.e., screened intervals in feet bls) were as follows: Shallow (4-9), Intermediate (13-14), and Deep (20-25).

³ Values are rounded to a maximum three significant digits. For Non-detect values (i.e., < values), ½ the reporting limit was used for averaging.

J = estimated value. UL = Upper Limit of 95% confidence interval. LL = Lower limit of 95% confidence interval.

Deep Zone: Standalone results for deep zone groundwater are presented in **Table 4-15**. The average of all wells show no appreciable change in contaminant concentration from baseline to final sampling. However, that generalization is misleading for PCE, which shows an increase in well IW-1d but decreases in the other four wells. There are appreciable PCE concentration decreases in IW-3d and EW-4d where average baseline values of 369µg/L and 2,310 µg/L were reduced to below

detection limits in final event samples. The 2,310 µg/L average value for EW-4d was the only instance where the baseline value for PCE exceeded the RPS prior to oxidant injection.

For the deep zone evaluations, the null hypothesis is accepted for each of the three contaminants (i.e., the objective was not met).

Table 4-15. Deep Zone Groundwater Results for Target Ethenes - Baseline Vs. Final.

Well ID	Zone ²	PARAMETER, Remediation Performance Standard (RPS) in µg/L ¹					
		PCE, 750		TCE, 5,500		cDCE, 17,500	
		Baseline	Final	Baseline	Final	Baseline	Final
IW-1d	Deep	208	545 5370	1.0	< 0.5 < 0.5	1.7	< 0.5 0.34 J
IW-3d	Deep	369	< 0.5 < 2.5	0.75	< 0.5 < 0.5	< 0.5	< 0.5 < 2.5
EW-2d	Deep	10.6	3.0 1.5	< 1.0	< 0.5 < 0.5	< 1.0	< 0.5 < 0.5
EW-3d	Deep	45.9	< 0.5 < 0.5	< 0.5	< 0.5 < 0.5	< 0.5	< 0.5 < 0.5
EW-4d	Deep	2,310	< 0.5 < 0.5	2.1	< 0.5 < 0.5	1.6	< 0.5 < 0.5
Average ³		589	592	0.8	0.4	0.86	0.36
Standard Deviation ³		973	1,690	0.8	0.3	0.73	0.31
Coefficient of Variance ³		1.65	2.85	0.89	0.90	0.85	0.88
95% UL ³		1,800	1,800	1.79	0.58	1.77	0.58
95% LL ³		- 619	- 615	- 0.09	0.12	- 0.05	0.13

¹ Blocked values are those exceeding the RPS. Two sampling rounds were conducted for the final sampling event (March 14 & 16, 2006).

² Approximate depths for zones (i.e., screened intervals in feet bls) were as follows: Shallow (4-9), Intermediate (13-14), and Deep (20-25).

³ Values are rounded to a maximum three significant digits. For Non-detect values (i.e., < values), ½ the reporting limit was used for averaging.

J = estimated value. UL = Upper Limit of 95% confidence interval. LL = Lower limit of 95% confidence interval.

4.5.2.2 Non-Critical VOCs

In addition to the critical ethene compounds (PCE, TCE, and cDCE), there are three additional VOCs having an associated RPS for the former MEC building site. These included toluene and two ethane compounds 1,1,1 Trichloroethane (1,1,1-TCA), and 1,1-Dichloroethane (1,1-DCA). **Table 4-16** presents results of the baseline (pre-treatment) groundwater sampling and the two rounds comprising the final (post-treatment) groundwater sampling. Toluene was the only compound measured at baseline above the RPS in any of the wells (i.e., EW-2). Final toluene concentrations for EW-2 were measured above the RPS of 2,570 µg/L.

4.5.2.3 KMnO₄

KMnO₄ is visually observable in groundwater at relatively low concentrations (i.e., 1 ppm). Therefore, following the initial injection of oxidant solution KMnO₄ was visually monitored in all groundwater samples collected through the final post-treatment event. **Table 4-17** presents the critical VOC results of all demonstration groundwater events with respect to the presence of KMnO₄ (i.e., sample results shaded purple are those in which KMnO₄ was observed in the groundwater during sample collection). There are two

general observations that are apparent regarding the visual presence of KMnO₄.

1. KMnO₄ was seen in all deep zone wells following the first injection, but seen in only one well on one occasion in the intermediate zone (a well receiving injected KMnO₄ about four months earlier). KMnO₄ was never observed in upper zone wells.
2. In most instances, target VOCs were reduced to below LRLs when KMnO₄ was visually present.

Knowing that there was more KMnO₄ injected into the deep zone relative to the shallow and intermediate peat zones, and knowing that the peat zone contained substantial humic material, the two observations above infer that the mass of KMnO₄ injected into the shallow and peat zones may not have been sufficient or was not delivered to all desired localities. However the mass of KMnO₄ injected into the deep zone appears to have been more than sufficient to treat the deep zone groundwater, especially since the KMnO₄ persisted long after the target VOCs were apparently oxidized. It is also possible that the deep zone benefitted from downward seeping oxidant that had been targeted for the peat zone.

Table 4-16. Groundwater Results for Non-Critical VOCs - Baseline Vs. Final.

Well Cluster ID	Zone	PARAMETER, Remediation Performance Standard (RPS) in µg/L ¹					
		Toluene, 2,570		1,1,1-TCA, 6,800		DCA, 27,500	
		Baseline	Final	Baseline	Final	Baseline	Final
IW-1	Shallow	43.1	7.7 5.6	69.7	62.9 61.0	< 10	12.6 10.8
	Intermediate	1,160	1,580 1,250	< 10	166 163	709	235 192
	Deep	1.5	6.2 12.2	0.63	0.68 1.20	< 0.5	< 0.5 < 0.5
IW-3	Shallow	37.5	221 121	61.5	159 130	29.3	123 57.3
	Intermediate	645	1,630 1,780	< 5	2.1 11.2	6.0	92.6 93.4
	Deep	< 0.5	0.39 J 2.4 J	0.54	2.9 7.5	< 0.5	< 0.5 < 2.5
EW-2	Shallow	1,510	197 296	1,290	200 346	916	159 251
	Intermediate	5,770	5,660 9,250	125	4.7 J 14.7	234	79.5 199
	Deep	< 0.5	3.1 1.1	0.41 J	< 0.5 < 0.5	< 0.5	< 0.5 < 0.5
EW-3	Shallow	223	6.9 3.1	47.5	59.1 58.5	84.8	38.4 48.2
	Intermediate	234	232 467	< 5	< 0.5 1.0	21.1	7.5 18.5
	Deep	< 0.5	0.24 J < 0.5	0.39 J	< 0.5 < 0.5	< 0.5	< 0.5 < 0.5
EW-4	Shallow	154	270 166	< 0.5	< 0.5 0.24 J	14.8	34.9 67.3
	Intermediate	90	5.6 16.2	< 0.5	< 0.5 < 0.5	2.9	0.49 J 0.86
	Deep	9.4	4.2 4.3	< 0.5	3.5 3.0	< 0.5	< 0.5 < 0.5
Average ³		659	773	107	48.7	135	57.5

¹ Blocked values are those exceeding the RPS. Two sampling rounds were conducted for the final sampling event (March 14 & 16, 2006).

² Approximate depths for zones (i.e., screened intervals in feet bls) were as follows: Shallow (4-9), Intermediate (13-14), and Deep (20-25)

³ Values are rounded to a maximum three significant digits. For Non-detect values (i.e., < values), ½ the reporting limit was used for averaging.

J = estimated value.

Table 4-17. KMnO₄ Vs. PCE, TCE, and cDCE Concentrations in Groundwater - All Events

Well ID	Event Zone	PARAMETER (Units), Remediation Performance Standard (RPS) in µg/L																	
		PCE (µg/L), 750						TCE (µg/L), 5,500						cDCE (µg/L), 17,500					
		IW-3 Injection (June 6-10)			IW-1 / IW-2 Injection (Oct. 3-6)			IW-3 Injection (June 6-10)			IW-1 / IW-2 Injection (Oct. 3-6)			IW-3 Injection (June 6-10)			IW-1 / IW-2 Injection (Oct. 3-6)		
		1 st BL 6/05	2 nd BL 9/05	1 st Int. 12/05	2 nd Int. 2/06	Final 3/06		1 st BL 6/05	2 nd BL 9/05	1 st Int. 12/05	2 nd Int. 2/06	Final 3/06		1 st BL 6/05	2 nd BL 9/05	1 st Int. 12/05	2 nd Int. 2/06	Final 3/06	
						R1	R2					R1	R2					R1	R2
IW-1	Shallow	220	5.200	126	343	1,090	1,360	854	11.200	638	748	572	766	6,500	31.000	3,840	1,620	3,630	3,620
	Inter.	< 10	16.4 J	13.4	102	1,120	1,310	< 10	62.1	12.3	932	892	1,950	2,180	50.100	27,800	23,800	20,100	16,700
	Deep	897	208	1.7	56.9	545	5,370	1.6	1.0	< 0.5	3.0	< 0.5	< 0.5	< 0.5	1.7	0.32 J	73.7	< 0.5	0.34 J
IW-3	Shallow	81.7	295	---	175	718	637	63	467	---	103	677	620	4,590	3,600	---	390	2,810	1,890
	Inter.	3.6 J	< 10	---	7.6	9.1	7.3	< 5.0	< 10	---	12.5	6.3	6.4	18.4	< 10	---	623	392	614
	Deep	369	< 10	< 0.5	< 0.5	< 0.5	< 2.5	0.75	< 10	< 0.5	< 0.5	< 0.5	< 2.5	< 0.5	7.5 J	< 0.5	< 0.5	< 0.5	< 2.5
EW-2	Shallow	6,820	6.830	9,760	11,600	4,190	5,560	4,410	7,090	12,800	14,600	4,810	7,430	2,540	15,500	24,700	23,400	9,510	13,600
	Inter.	68.8	86.5	10.1	52.2	17.8	55.5	144	148	28.3	136	97.4	228	9,660	6,220	11,300	8050	4,490	7,770
	Deep	12.7	10.6	< 0.5	9.9	3.0	1.5	0.37 J	< 1.0	< 0.5	31.4	< 0.5	< 0.5	0.35 J	< 1.0	< 0.5	135	< 0.5	< 0.5
EW-3	Shallow	141	201	83	256	80.1	284	290	696	113	203	58.7	194	3,750	6,510	1,950	838	341	894
	Inter.	< 5.0	< 10	5.9	15.9	3.6	8.2	< 5.0	9.4 J	18.1	62.7	10.4	38.3	75.1	137	129	203	24.8	105
	Deep	45.9	< 1.0	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 1.0	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 1.0	< 0.5	< 0.5	< 0.5	< 0.5
EW-4	Shallow	2.6	0.59	2.2	3.2	0.75	1.6	2.5	2.0	6.0	9.5	3.3	7.7	345	176	740	983	978	5,300
	Inter.	1.8	< 1.0	1.6	2.2	< 0.5	< 0.5	< 0.5	0.62 J	2.2	3.7	< 0.5	0.37 J	15.3	8.8	40.9	21.3	8.0	6.9
	Deep	2.310	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	2.1	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	1.6	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5

¹ 1st or 2nd in () denotes the injection that particular well is associated with based on its proximity to injected KMnO₄. Dashed line indicates no sample collected. J = estimated value. BL = Baseline Event. Int. = Intermediate Event; R1 = Round 1 conducted 3/14/06; R2 = Round 2 conducted 3/16/06. Blocked cells indicate value above RPS. Purple indicates KMnO₄ visually observed

4.5.2.4 Metals

Chemical oxidation has the potential to mobilize valence sensitive toxic metals, such as Arsenic (As), Chromium (Cr), Selenium (Se), Zinc (Zn), and Mercury (Hg), from soils into groundwater. As a result, sites that contain elevated levels of metals contaminants as well as organic contaminants should be monitored for such mobilization potential. In order to assess the mobilization potential of these compounds by KMnO_4 , groundwater samples were analyzed for metals for each event (*Objective 3*).

Results for the toxic metals noted above are shown in **Table 4-18**. It should be noted that significant mercury concentrations were not detected during pre-demonstration studies therefore additional mercury monitoring was not continued for demonstration sampling.

On an average basis, most of the metals analyzed did not change significantly in concentration throughout the five groundwater sampling events. Some metals (e.g., As, Be, Cr, Mg, and Zn) actually showed decreased concentrations in the shallow zone from baseline to final sampling events.

There was however a fairly substantial increase in manganese (Mn) in the intermediate (peat) and deep groundwater zones for the second baseline sampling event. This average increase can be attributed to the influx of Mn from the initial injection of KMnO_4 into the IW-3 cluster. The resulting elevated levels of Mn in those IW-3 cluster wells and nearby wells raised the overall average concentration of all wells samples for those zones.

There was also an increase of Cr and Mg in the deep zone groundwater following both the first and second injections, and an increase in Se in the deep zone groundwater following the second injection. However, for the following sampling event, the average concentrations of these three metals reverted back to an average value that was very close to their respective original levels.

4.5.2.5 Additional Observations

There is one other noted observation which may be of some importance. **Table 4-19** shows concentrations of acetone bromide, and bromoform. As previously discussed in subsection 4.4.3, bromide was used as a tracer ion in the KMnO_4 solution used for the first injection. It was noted during the intermediate groundwater sampling that bromoform formation was occurring in several of the wells. Because this was thought to be a possible concern and appeared to be a by-product of the use of the bromide tracer ion some investigation was performed as to why this

was occurring.

An interesting aspect of this investigation was that bromide showed up in several wells at significant levels (i.e., not just as residuum from the first preempted injection event), where there had been no indication of any visible KMnO_4 . Therefore it is possible that the KMnO_4 had seeped into these upper wells (based on the presence of the bromide ion) but has been exhausted leaving no excess KMnO_4 for continued oxidation.

A build-up of acetone was noted between the baseline sampling period and first injection suggesting oxidation of organic compounds was occurring. This was particularly noted in the deep wells where it appears, based upon reductions in chlorinated ethenes that the oxidation process was working the most effectively. What was also noted was the increased concentration of bromoform in upper, middle and lower wells between the baseline and first injection and the subsequent decrease between the first injection and second baseline sampling round. Bromoform is not a naturally occurring compound. In fact, the formation of bromoform is the result of a reaction between acetone and bromide (an artifact of the use of the bromide tracer ion in the KMnO_4 solution). The reduction of bromoform over time suggests that this compound was not a concern at the end of the demonstration. The formation of bromoform suggests that oxidation was occurring in all three horizons, with the greatest oxidation reactions occurring in the deep wells.

4.5.3 Quality Assurance/Quality Control

Quality Assurance (QA) may be defined as a system of activities the purpose of which is to provide assurance that defined standards of quality are met with a stated level of confidence. A QA program is a means of integrating the quality planning, quality assessment, quality control (QC), and quality improvement efforts to meet user requirements. This includes all actions taken by project personnel, and the documentation of laboratory performance and, when appropriate, field performance. The objective of a quality assurance program is to reduce measurement errors to agreed upon limits and to produce results of acceptable and known quality. The laboratory data was generated under EPA-approved method guidelines to ensure that the measurement systems employed were in control. The following sections provide information on the use of data quality indicators, limitations on data use and a detailed summary of the laboratory QC analyses associated with select project measurements.

Table 4-18. Metals Summary Results for Groundwater (mg/l). ¹

Parameter	Zone	SAMPLE EVENT				Final
		<u>1st BL 6/05</u>	<u>2nd BL 9/05</u>	<u>1st Int. 12/05</u>	<u>2nd Int. 2/06</u>	
Arsenic	Shallow	0.32 (5)	0.29 (5)	0.3 (4)	---	0.125 (10)
	Intermediate	0.07 (5)	0.11 (5)	0.18 (4)	---	0.133 (10)
	Deep	0.003 (5)	0.0 (5)	0.00 (4)	---	0.048 (10)
Beryllium	Shallow	0.003 (5)	0.001 (5)	0.002 (4)	---	0.00 (10)
	Intermediate	0.001 (5)	0.00 (5)	0.001 (4)	---	0.03 (10)
	Deep	0.001 (5)	0.00 (5)	0.00 (4)	---	0.00 (10)
Cadmium	Shallow	0.00 (5)	0.00 (5)	0.00 (4)	---	0.00 (10)
	Intermediate	0.00 (5)	0.004 (5)	0.00 (4)	---	0.00 (10)
	Deep	0.001 (5)	0.00 (5)	0.00 (4)	---	0.00 (10)
Chromium	Shallow	0.166 (5)	0.071 (5)	0.157 (4)	---	0.053 (10)
	Intermediate	0.05 (5)	0.18 (5)	0.08 (4)	---	0.164 (10)
	Deep	0.003 (5)	0.72 (5)	1.37 (4)	---	0.123 (10)
Magnesium	Shallow	27.6 (5)	13.4 (5)	31.8 (4)	16.7 (5)	17.3 (10)
	Intermediate	15.6 (5)	11.8 (5)	16.0 (4)	11.2 (5)	11.8 (10)
	Deep	8.6 (5)	12.3 (5)	29.9 (5)	9.6 (5)	14.5 (10)
Manganese	Shallow	4.5 (5)	9.5 (5)	16.8 (4)	16.5 (5)	15.5 (10)
	Intermediate	8.1 (5)	503 (5)	43.6 (4)	34.2 (5)	65.8 (10)
	Deep	0.8 (5)	825 (5)	159 (5)	102 (5)	39.4 (10)
Selenium	Shallow	0.004 (5)	0.003 (5)	0.001 (4)	---	0.003 (10)
	Intermediate	0.006 (5)	0.037 (5)	0.007 (4)	---	0.007 (10)
	Deep	0.001 (5)	0.00 (5)	68.4 (4)	---	0.002 (10)
Zinc	Shallow	0.133 (5)	0.041 (5)	1.13 (4)	---	0.037 (10)
	Intermediate	0.06 (5)	0.008 (5)	0.07 (4)	---	0.07 (10)
	Deep	0.013 (5)	0.032 (5)	0.00 (4)	---	0.04 (10)

¹ Values are averages of the # of wells sampled in () and rounded to a maximum three significant digits. Averages include estimated (J) values and 0.0 is used for non-detected values except in cases where the LRL significantly exceeded quantified values. --- No metals sample collected.

Table 4-19. Acetone, Bromide, and Bromoform Summary Results for Groundwater (µg/l) ¹

Zone	Parameter	SAMPLE EVENT				
		1 st BL 6/05	2 nd BL 9/05	1 st Int. 12/05	2 nd Int. 2/06	Final
Shallow	Acetone	15.5 (5)	13.6 (5)	12.4 (4)	< 20 (4)	9.6 (5)
	Bromide	0.0 (5)	538 (5)	574 (4)	419 (5)	462 (10)
	Bromoform	0.00 (5)	5.9 (5)	3.5 (4)	11.6 (3)	5.8 (6)
Intermediate	Acetone	45 (5)	96.8 (5)	32 (4)	192 (3)	168 (8)
	Bromide	0.0 (5)	380 (5)	78.9 (4)	298 (5)	312 (10)
	Bromoform	0.00 (5)	941 (5)	1.1 (4)	1.0 (2)	0.0 (6)
Deep	Acetone	0.0 (5)	165 (5)	84.2 (5)	41.8 (5)	68 (10)
	Bromide	0.0 (5)	582 (5)	63 (5)	31.1 (5)	9.3 (10)
	Bromoform	0.0 (5)	1,450 (5)	213 (5)	20.6 (4)	34.3 (10)

¹ Values are averages of the # of wells sampled in () and rounded to a maximum three significant digits. Averages include estimated (J) values and 0.0 is used for non-detected values except in cases where the LRL significantly exceeded quantified values. --- No sample collected.

4.5.3.1 Data Quality Indicators

To assess the quality of the data generated during this site investigation, two important data quality indicators are of primary concern: precision and accuracy. Precision can be defined as the degree of mutual agreement of independent measurements generated through repeated application of the process under specified conditions. Accuracy is the degree of agreement of a measured value with the true or expected value.

Precision was assessed by laboratory spiked duplicates and sample duplicates. In the case of spiked duplicates, precision is evaluated by expressing, as a percentage, the difference between sample and sample duplicate results. The relative percent difference (RPD) is calculated as:

$$RPD = \frac{(\text{Maximum Value} - \text{Minimum Value})}{(\text{Maximum Value} + \text{Minimum Value})} \times 100$$

To determine and evaluate accuracy, known quantities of select target analytes were spiked into selected field

Other data quality indicators influence whether a measurement is considered valid. A sample measurement must be reproducible and comparable. Comparability expresses the extent to which one data set can be compared to another. To generate comparable results, laboratory standard methods that are widely accepted were used. Data must also be representative of field conditions. Representativeness refers to the degree with which analytical results accurately and precisely reflect

samples. Equipment used to provide data for this project was tested for accuracy through the analysis of calibration check standards and laboratory control samples (LCSs). To determine matrix spike recovery, the following equation was applied:

$$\% \text{ Recovery} = \frac{C_{ss} - C_{us}}{C_{sa}} \times 100$$

where

C_{ss} = Analyte concentration in spiked sample
 C_{us} = Analyte concentration in unspiked sample
 C_{sa} = Analyte concentration added to sample

To determine the % recovery of LCS analyses or spiked blanks, the following equation was used:

$$\% \text{ Recovery} = \frac{\text{Measured Concentration}}{\text{Theoretical Concentration}} \times 100$$

actual conditions present at the locations chosen for sample collection.

4.5.3.2 Conclusions and Data Quality Limitations

A review of critical analytical sample data and associated QC analyses was performed for XDD samples. Duplicate spiked sample analyses and LCSs were used to assess precision and accuracy as discussed below. Details of the individual sample results with respect to surrogate spike

recoveries, internal standards, dilutions, etc. are presented in later subsections, along with information on calibrations, blanks, performance check standards, and other QC measurements.

The critical parameter reviewed was VOCs, specifically cDCE, TCE, PCE, as well as VC, 1,1-DCA, 1,1,1-TCA and toluene in pre- and post-treatment soils and post-treatment groundwaters. The results of the measurements designed to assess the data quality for each method are summarized below, along with a discussion of any impact on data quality.

Soil VOC Samples

Accuracy: Matrix spike duplicates were analyzed with pre- and post-treatment soil sample MeOH extracts. **Table 4-20** presents average recoveries for both events.

Table 4-20. Project Accuracy for Soil VOC Analyses.		
Compound	Pre-treatment Avg. Recovery (%)	Post-treatment Avg. Recovery (%)
cDCE	97	111
TCE	105	119
PCE	74	112
VC	127	88
1,1-DCA	112	120
1,1,1-TCA	107	121
Toluene	106	117

Average recoveries were within the QAPP specified criteria of 80-120% (VC 75-125%) with the exception of the baseline recovery of VC and PCE, and the post-treatment recovery of 1,1,1-TCA. The baseline recoveries were impacted by the spiking levels relative to the native sample concentrations; spike levels were adjusted during the post-treatment event to better accommodate the native contaminant concentrations.

Precision: Duplicate spiked samples were used to assess method precision for VOCs in soils. Where spiked levels were appropriate, average RPD values for matrix spike/matrix spike duplicate (MS/MSD) results were generally less than 20%.

Comparability: Comparability expresses the extent to which one data set can be compared to another. The methods used were clearly specified in the QAPP and reviewed before samples or data were collected.

Representativeness: Representativeness refers to the degree with which a sample exhibits average properties of the site at the particular time being evaluated. The collection of representative samples was discussed previously in the QAPP. Representative samples were collected as per QAPP approved procedures.

Detection limits: Detection limits for this project are defined as the reporting limit; the concentration determined by the lowest calibration standard as determined by the laboratory. Detection limits were adjusted as necessary based on matrix and the need for dilution. Due to the increased MeOH required for extracting peat, reporting limits were adjusted in order to meet project criteria. The typical reporting limit in soil for each of the critical compounds was 250 ug/kg, based on a 1g to 5ml methanol dilution as determined during the pre-demonstration analytical extraction study. Detection limit objectives were generally achieved for all samples; however, some samples did not meet these objectives due to high concentrations of one of the critical compounds thereby diluting the other compound concentrations or due to matrix interferences as occurred in several of the peat samples.

Groundwater VOC Samples

Accuracy: Matrix spike duplicates were analyzed to assess accuracy of the VOC analyses. Average recoveries for the groundwater MS/MSDs are summarized in **Table 4-21** for VOC spikes from the post-treatment event. Two of the 30 samples were selected for spiking and one had poor or no recovery of several critical compounds. The bottom sample of Well IW-3 had no spike recovery of cDCE, TCE, and VC and very low recovery of PCE. The results were the same for the spike and spike duplicate. The sample was noted to be thick in consistency and purple in color and although the sample and MS/MSD were analyzed at a dilution, the recovery was still non-compliant. Results from this sample (GW-F-IW3-B[2]) should be used cautiously; data for cDCE, TCE and VC should be rejected and data for PCE should be considered an estimated value potentially biased low. The other spiked sample was analyzed at two different spiking levels due to varying native sample concentrations.

Precision: Duplicate spiked samples were used to assess method precision for groundwater VOCs. Maximum RPD values ranged from 2-34%; the outlier values (RPD values >20%) were associated with the spike having inappropriately low spike levels.

Comparability: Comparability expresses the extent to which one data set can be compared to another. The methods used were clearly specified in the QAPP and reviewed before samples or data were collected.

Representativeness: Representativeness refers to the

degree with which a sample exhibits average properties of the site at the particular time being evaluated. Representative samples were collected as per QAPP approved procedures.

Table 4-21. Project Accuracy for Groundwater VOC Analysis.	
Compound	Post-treatment Avg. Spike Recovery (%)
cDCE	59
TCE	50
PCE	57
VC	47
1,1-DCA	110
1,1,1-TCA	110
Toluene	100

4.5.4 Analytical QC Results

4.5.4.1 Soil VOC Analyses

A total of 87 pre- and 89 post-treatment soil samples were collected and analyzed for VOCs. The samples were collected from 30 locations, at three depths from each location, except in instances where sample material was not available. All solid samples were extracted into methanol and the extract analyzed in accordance with SW846 Method 8260B. The discussions below provide details on the results of calibrations, surrogate recoveries, internal standard results, holding times and blank results for each event.

Soils Baseline Event

Accuracy and precision were assessed by the analysis of spiked duplicates. An LCS was also analyzed with each MS/MSD from a secondary source standard. All LCS (secondary source standard) samples were within the QAPP specified control limits of 80%-120% recovery. If the MS/MSD samples failed to meet these limits for any of the critical compounds then individual results were examined to determine cause for failure and appropriate recourse for corrective action. Because all LCS recoveries met appropriate QC limits it was determined that the cause of MS/MSD failures were matrix specific.

As noted in **Table 4-22** PCE and cDCE had low recovery values in one of the MS/MSD samples. This was due to the high native concentration of both these analytes compared to the spiking concentration used by the laboratory. When this situation occurs, natural variability of

the analytical instrumentation will overwhelm the spike recovery detection and subsequently cause low and/or high calculated spike recoveries. Because the laboratory was unable to use higher spiking concentrations and because LCSs met accuracy specifications as noted in the QAPP, rerunning and or re-spiking of the MS/MSD samples was not performed. In addition, in these same samples all other critical compounds were within acceptable spiking limits. Therefore, no further action was taken in regards to MS/MSD recoveries for both analytes noted above. In addition, one MS/MSD recovery for VC was slightly above acceptable limits (control limits: 75-125%). But because this was not too far above acceptable recovery limits and because LCS recoveries were considered acceptable, no further action was taken.

Table 4-22. Accuracy for Soil VOC - Spike Results - Baseline Event.				
Compound	# of Spikes	Spike Recovery, %		# of Outside Limits
		Avg.	Range	
cDCE	8	97	64-113	2
TCE	8	105	96-115	0
PCE	8	74	23-114	2
VC	8	127	121-135	2
1,1-DCA	8	112	106-123	1
1,1,1-TCA	8	107	95-113	0
Toluene	8	106	97-115	0

Precision for volatile organics was assessed by the analysis of duplicate MS/MSDs performed on select project samples to determine the reproducibility of the measurements. The RPD between the spiked sample concentrations was compared to the objectives given in the QAPP. RPD values for all but two critical compounds were less than the QAPP specified objective of 20%. The two critical compounds not meeting specifications were PCE and cDCE. As noted above, these were the same compounds not meeting accuracy specifications. The likely reason for these out-of-bound specifications was because of the high native concentration for both these analytes compared to the spiking concentration used by the laboratory. When this situation occurs, natural variability of the analytical instrumentation will overwhelm the spike recovery detection and subsequently cause low and/or high calculated spike recoveries along with a greater RPD variability. For the same reasons noted

above in the accuracy discussion re-running of the spiked compounds was not considered necessary. Critical compound RPDs are reported in **Table 4-23** which shows all other critical compounds met QAPP specifications.

Table 4-23. Precision for Soil VOC - Spike Results - Baseline Event.			
Compound	RPD Range, %	# of Values	# of Outside Limits
cDCE	2-42	4	1
TCE	4-8	4	0
PCE	3-67	4	1
VC	4-8	4	0
1,1-DCA	1-8	4	0
1,1,1-TCA	4-16	4	0
Toluene	4-5	4	0

Surrogate standards were added to all samples prior to analysis. Most sample surrogate recoveries met laboratory specified control limits. The few outliers noted were in samples that when re-analyzed at necessary dilutions, generally had compliant surrogates (BL-7-P[12], BL-30-SI[23], BL-27-P[13.5]). One sample (BL-28-SI[24.5]) had multiple non-compliant surrogate recoveries approximately 10-20% above control limits; this was not expected to have a significant impact on the sample data.

Soils Final Post-Treatment Event

Soil sample methanol extracts were analyzed by SW846 8260B. Several samples were analyzed past the 14 day hold time; these samples are listed in **Table 4-24**. Since most samples missed by only one day, and since the soils were preserved in methanol at the time of collection, the missed holding times are not considered to have an impact on data quality.

Table 4-24. Samples Analyzed Outside Holding Times		
Sample ID / Days Past 14	Sample ID / Days Past 14	Sample ID / Days Past 14
F29-SA-(8) / 1	F25-P-(13) / 1	F02-SI-(25) / 1
F04-SA-(8) / 4	F23-SI-(24) / 1	TB033006 / 1
F04-P-(15) / 1	F23-SA-(8) / 1	TB2033006 / 1
F04-SI-(27) / 1	F28-SI-(24) / 1	MTB033006 / 1
F25-SI-(24.5) / 1	F23-P-(11) / 1	MTB2033006 / 1
F25-SA-(8) / 4	F02-P-(13) / 1	MTB032906 / 1

Calibration requirements for SW8260B were generally met for all analyses with few minor exceptions not expected to impact data quality; for example the ICAL from April 12, 2006 had an RSD for 1,1-DCA of 15.7% and for 1,1,1-TCA the RSD was 16%. VC reporting detection limits were raised when the compound was not detected in the 0.5 ppb standard of the ICAL. Two samples were analyzed beyond the 12-hour BFB clock. The initial analysis of sample F05-SI-[24.5] missed by four minutes and the dilution was analyzed 41 minutes after expiration of the BFB period. A diluted analysis of F11-P-[11.5] was started 3 minutes after the 12-hour clock expired. The tunes and continuing calibration subsequent to these analyses met criteria so the impact on data quality is considered minimal.

Method, trip and MeOH trip blanks were analyzed with the samples. Several method blanks had low-level contamination of toluene and PCE at estimated concentrations below detection limits. A MeOH trip blank (MTB032906) also had an estimated concentration of toluene (10.6 J ug/kg) below the detection limit.

Each sample was spiked with surrogate standards; all recoveries were within control limits except for F14-SA-[8], which had a slightly elevated surrogate recovery (toluene-d8 = 148%, upper control limit = 146%). But this did not affect data quality. All internal standards met criteria.

LCSs and MS/MSDs were analyzed as required. Several LCS results had recoveries slightly above the 80-120% QAPP guideline (75-125% for VC). In particular, samples from each of the three intervals from F09, F23, F05, F18, F20 and F11 along with F02-SA were associated with LCS analyses having recoveries up to 20% above control limits for one or more VOCs. Nine spiked duplicate pairs were analyzed with post-treatment samples (**Table 4-25**).

Table 4-25. Accuracy for Soil VOC - Spike Results - Post Treatment Event.				
Compound	No. of Spikes*	Spike Recovery, %		No. Outside Limits
		Avg.	Range	
cDCE	18	111	95-130	5
TCE	18	119	105-148	4
PCE	14	112	95-136	4
VC	18	88	62-110	3
1,1-DCA	18	120	108-152	4
1,1,1-TCA	18	121	105-153	5
Toluene	14	117	95-142	4

* This column presents the # of spikes that were spiked at an appropriate level given the native sample concentration of the compound, relative to the # of spiked samples prepared; e.g., there were 18 spikes prepared but only 14 had levels of PCE suitable given the PCE concentrations in the sample.

The average recovery for 1,1,1-TCA was above the upper control limit specified in the QAPP; results for this compound may be considered slightly biased high. Most of the spiked recovery outliers were associated with two spiked duplicate pairs (F11-P and F25-SI), which had elevated recoveries for all target compounds except VC.

The MS/MSD pairs were also used to assess overall precision for the project. RPD results are summarized in **Table 4-26**. Only one spiked pair had an RPD value that exceeded the QAPP criteria of 20%.

Table 4-26. Precision for Soil VOC - Spike Results - Post-treatment Event.			
Compound	RPD Range, %	No. of Values	No. Outside Limits
cDCE	1-7	9	0
TCE	0-6	9	0
PCE	0-22	7	1
VC	0-13	9	0
1,1-DCA	0-8	9	0
1,1,1-TCA	0-8	9	0
Toluene	1-10	7	0

4.5.4.2 Groundwater VOCs - Post-treatment Results

Fifteen wells were sampled at two different times for the final groundwater event. The 30 samples were analyzed in accordance with SW 846 Method 8260B. All samples were analyzed within holding times. Calibration requirements, including GC/MS tuning with BFB and initial and continuing calibrations, were met with one exception. One initial calibration for toluene exceeded the 15% RSD criteria slightly at 16%; this had no impact on data quality. Surrogate recovery and internal standards criteria were met for all samples. All method, trip and field blanks were free from contamination.

Two samples were analyzed as spiked duplicate pairs. Sample GW-F-IW 1-M[1] was spiked at 500 ppb and then re-analyzed at a spiking level of 10,000 ppb due to elevated native concentrations of cDCE, TCE, PCE, VC and toluene. At the appropriate spiking levels, all recovery values were within control limits. Sample GW-F-IW 3-B[2] was noted to be thick and colored and was analyzed at a dilution. The MS/MSD was analyzed at the same dilution

but had non-complaint recovery values (0%) for cDCE, TCE and VC and very low recovery (2%) for PCE.

Table 4-27. Accuracy for Groundwater - Post Treatment VOCs.				
Compound	No. of Spikes ¹	Spike Recovery, %		No. Outside Limits
		Avg.	Range	
cDCE	4	59	0-119	1
TCE	4	50	0-100	1
PCE	4	57	2-113	1
VC	4	47	0-95	1
1,1-DCA	6	110	103-121	1
1,1,1-TCA	6	110	104-119	0
Toluene	4	100	93-109	0

¹ The number of spikes includes those with a spike level appropriate to the native contaminant concentration.

Precision was assessed through these same spiked duplicates, as shown in **Table 4-28**. Of the 18 RPD values assessed, all but 2 were within lab limits.

Table 4-28. Precision for Groundwater - Post-treatment VOCs.			
Compound	Maximum RPD	No. of Values	No. Outside Limits
cDCE	34	2	1
TCE	6	2	0
PCE	16	3	0
VC	22	2	1
1,1-DCA	2	3	0
1,1,1-TCA	3	3	0
Toluene	17	3	0

4.5.5 Audits

4.5.5.1 Field Audit

A Technical Systems Audit (TSA) of the field activities at the Former MEC Building Site; Hudson, NH was conducted May 13, 2005. There were no Findings requiring corrective action. However, there were two observations noted. The first observation was that the required number of baseline peat zone samples (30) was not achieved during baseline sampling. During baseline sampling using a sonic rig, peat sample material was not collected at boring locations #s 9, 25, and 30, and was thought absent at these three locations. In addition the peat material at boring # 2 was fragmented and a portion of that samples included non-peat material. As a result, there was at most 27 peat samples instead of the desired 30.

In response to this observation, results were tabulated and statistical parameters including mean, and 95% confidence intervals were calculated. Based upon actual results it was determined that the 27 samples collected during baseline would satisfy the project objective. Even prior to this calculation it was determined that a 90% completeness objective would likely meet project objectives. The goal for post-demonstration sampling was to collect at least as many samples as collected during baseline. This indeed was the case, however peat was found in borings drilled adjacent to baseline borings #s 9 and 25 using a geoprobe. The peat was again absent at boring # 30 (the closest boring to the excavated tank area). It is postulated that the peat had been excavated in the vicinity of boring 30. As for the partial peat sample at boring #2, the auditor advised the field manager to try to note the estimated composition of sample material if such an occurrence happened again. (This only happened once during baseline sampling).

The second observation noted some minor inconsistencies in record keeping, including a missing calibration check of the field balance used to measure this mass of soil sample used for the field extraction procedure and an unsigned logbook for previous days records. In response to this concern the SAIC Project Manager met with some of the same site personnel while working on another project and explained and discussed what should be included in field notebooks. This issue is often a continuing concern that needs re-training on a regular basis.

4.5.5.2 Lab Audit

A Technical Systems Review (TSR) was performed at Analytical Laboratory Services, Inc. (ALSI) in Middletown, PA on May 25, 2005. In general ALSI met all QAPP and method specifications and was expected to generate data of known quality that meet project and data quality objectives. The few issues to be addressed were either resolved on-site or corrective action was expected to be initiated promptly. These corrective actions included:

- Initiation of the tracking of surrogate standards by, at a minimum, lot # and date opened, either in the standards logbook or on the log sheets where medium level soil sample vials are prepared. ALSI was requested to provide copy of documentation to indicate that this corrective action had been complete.
- Initiation of the tracking of VOC gas standard by, at a minimum, lot # and date opened, either in the standards logbook or in the analytical logbook. ALSI was requested to provide copy of documentation to indicate that this corrective action had been complete.

Section 5.0

Other Technology Requirements

5.1 Environmental Regulation Requirements

State and local regulatory agencies may require permits prior to implementing an in situ chemical oxidation technology. Most federal permits will be issued by the authorized state agency. The specific permits required may depend on the type and concentration of the contamination, the regulations covering the specific location, and the site's proximity to residential neighborhoods. For example, the New Hampshire Department of Environmental Services (NHDES) requires a site owner or legally responsible person to acquire a Groundwater Management Permit (GMP) from the State to remedy contamination associated with the past discharge of regulated contaminants, and to manage the use of contaminated groundwater. The application for the GMP must be prepared and stamped by a PE or a PG licensed in the State. There is an application fee for this.

Since oxidant is injected underground, an injection permit may also be required. For the former MEC Building site, XDD was required to apply for and acquire an injection permit from the NHDES. However, there was no actual permit fee. Note that other states may require a fee. In some cases permitting fees may be waived for government-conducted research type projects.

An air permit issued by the state Air Quality Control Region may be required if it is anticipated that the air emissions from potential surface venting are in excess of regulatory criteria, or are of toxic concern. Wastewater discharge permits may be required if any wastewater generated from well purging and equipment decontamination activities were to be discharged to a POTW. If remediation is conducted at a Superfund site, federal agencies, primarily the U.S. EPA, will provide regulatory oversight. If off-site

disposal of contaminated waste (contaminated drill cuttings) is required, the waste must be taken to the disposal facility by a licensed transporter.

Section 2 of this report discusses the environmental regulations that may apply to XDD's ISCO process.

5.2 Personnel Issues

The number of personnel required to implement the XDD ISCO process is dependent on the size of the treatment system and the time desired for the installation. Initially, drilling and well installation labor activities are performed by a drilling contractor. These activities typically involve a minimum of two contractor personnel assigned to a drill rig or geoprobe (head driller and helper). There may be an additional contractor representative who conducts well completion and development following well installation (which can be conducted at the same time that additional wells are being installed).

During well installation activities at a remediation site, the site remediation contractor would be responsible for logging boreholes, monitoring for VOCs and explosive conditions during drilling of boreholes, and ensuring that well construction and installation are conducted in accordance with design specifications. These activities would require the services of at least one individual (preferably a geologist). XDD may or may not be present for such activities.

Based on the demonstration study requirements, XDD appears to need a minimum of two individuals to conduct the oxidant injection. The oxidant batching process is a labor intensive operation involving the shipment and handling of numerous 20 L jugs of granular oxidant. Estimated labor requirements for a full-scale treatment system are discussed in detail in Section 3 of this report.

Personnel are also required for sample collection and groundwater monitoring. During the demonstration sampling events, one to two SITE team members was required to conduct field measurements during low-flow well sampling via a multi-parameter instrument, collect groundwater samples with a peristaltic pump, and prepare the samples for shipment to an off-site laboratory.

Personnel present during sample collection activities at a hazardous waste site must have current OSHA health and safety certification. Specific to the XDD ISCO process and chemical oxidation processes in general, the primary health and safety issue is personal protection from strong oxidizers. From a health and safety and materials handling perspective, NaMnO_4 is handled in a liquid form and is preferred to solid (i.e., granular) KMnO_4 . The application of this liquid oxidant is simpler than injecting KMnO_4 , which has to be pre-mixed with potable water at the desired concentration prior to injection.

Per the MSDS for KMnO_4 , at a minimum, eye protection and protective gloves are strongly recommended to be worn during handling of oxidants. During the demonstration, the batching process involved emptying numerous 20 Liter jugs of granular KMnO_4 into large batch tanks. Due to the potential inhalation of particulate, XDD also utilized full-face air-purifying respirators and chemically-resistant tyvek in addition to the standard Level D protection. Therefore the batch operation was conducted in Level C. (Generally speaking, for most sites, PPE for workers will include steel-toed shoes or boots, safety glasses, hard hats during drilling operations, and

chemical resistant gloves).

Noise levels would be a short-term concern during drilling operations and may be of concern during injection phases, particularly near the piston pump that is contained within the XDD POD. Noise levels should be monitored for such equipment to ensure that workers are not exposed to noise levels above the time weighted average of 85 decibels over an 8-hour day. If this level is exceeded and cannot be reduced, workers would be required to wear hearing protection and a hearing conservation program would need to be implemented.

5.3 Community Acceptance

The short-term risk to the community from implementing this technology is minimal since the oxidant is injected into the ground. In fact storage of the oxidant is of more concern since granular oxidant can be combustible if not stored properly.

The level of environmental disturbance of a site would be dependent on the number of wells required and the locations of those wells. For example, if injection or monitoring wells were required to be installed in an area having vegetation, some clearing of the vegetation may be necessary to access the best injection or monitoring points. This may affect habitat areas to some extent.

Other than the intermittent noise generated during drilling and, the relatively minor level of noise generated during oxidant injection is offset by the benefits of site remediation.

Section 6.0 Technology Status

6.1 Previous Experience

Chemical oxidation's use in the wastewater treatment industry dates back many years. In the past 10 years or so, the technology has been applied to remediation at hazardous waste sites. Specific to the use of KMnO_4 for treatment of DNAPL and dissolved phase chlorinated organic contaminants at hazardous waste sites, case studies have been documented at least as far back as 1996 (EPA, 1998).

Xpert Design and Diagnostics, LLC (XDD) was founded in 1997 as a provider of innovative soil and groundwater remediation technologies. Per its web site, XDD has experience with a wide range of ISCO applications at several sites. Their Portable Oxidant Delivery (POD) unit, which was used during the demonstration, has been operating since 2003. XDD staff is reported to have worked on several hundred sites throughout the United States, Canada, Europe and Asia for private industrial and federal sector clients.

6.2 Ability to Scale Up

Based on the nature of the technology, theoretically there is no limit to the areal extent of application of an ISCO

process as long as the oxidant injection design (i.e., injection well spacing, screened interval, and oxidant dosage, etc.) is adequate. The areal extent of XDD's ISCO treatment system implemented at the former MEC Building site was roughly 1,200 ft² (113 m²). This is considered a pilot-scale application of the technology.

The pilot-scale demonstration is also not considered to be a typical remediation, not only due to its small size but also because of the atypical soil profile (i.e., the thin peat layer). XDD has reported on their web site applications of their ISCO process that are much larger than that detailed in this report. One example includes a 16-injection point system, covering an area of approximately 1,400 ft², (130 m²) and utilizing automated batching and dosing equipment capable of injecting up to 240 liters of oxidant per minute. A second example included treatment of an approximate 56,000 ft² (5,200 m²) section of an approximate 3,300 ft (100 m) long VOC plume.

XDD reports considerable research for the development of an advanced oxidation process, referred to as X-Ox. This process is intended to use persulfate alone, or used in conjunction with a proprietary transition metal to treat petroleum hydrocarbons, MTBE, chlorinated solvents, coal tar residues, PCBs, and energetic compounds.

Section 7.0

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