

June 2010

Fast-Track Remedial Design of Full-Scale ISCO Application Using Pilot Scale Testing and Field Screening Parameters

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Recommended Citation

Dombrowski, Paul M. P.E.; Weir, Barbara A. Ph.D., P.E., L.S.P.; Kelly, Kara M. P.E.; and Brown, James P.E. (2010) "Fast-Track Remedial Design of Full-Scale ISCO Application Using Pilot Scale Testing and Field Screening Parameters," *Proceedings of the Annual International Conference on Soils, Sediments, Water and Energy*: Vol. 15 , Article 16.
Available at: <http://scholarworks.umass.edu/soilsproceedings/vol15/iss1/16>

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Cover Page Footnote

The authors would like to extend thanks to William Abrahams-Dematte, Stan Hatfield, and Richard Purdy for their support in completing sampling and field analysis.

Chapter 15

FAST-TRACK REMEDIAL DESIGN OF FULL-SCALE ISCO APPLICATION USING PILOT SCALE TESTING AND FIELD SCREENING PARAMETERS

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ABSTRACT

As a result of drum re-finishing operations, soil and groundwater at the Ottati and Goss Superfund Site in Kingston, NH, are contaminated with chlorinated volatile organic compounds (VOCs); benzene, toluene, ethylbenzene, and xylene (BTEX); and 1,4-dioxane. After re-evaluation of the selected remedy for groundwater, pump and treat, EPA changed the remediation approach to in-situ chemical oxidation (ISCO) through an Amended Record of Decision in September 2007. At that time, EPA established a goal for the site to attain construction complete status within one year, by September 30, 2008.

Activated persulfate was selected as the chemical oxidant for its capability to oxidize 1,4-dioxane, in addition to the other VOC contaminants of concern. Bench-scale and field pilot scale test were completed for three areas of the site to collect site-specific information to evaluate persulfate's ability to destroy the contaminants of concern and to optimize full-scale remediation design in three discrete source areas at the site. Base-activated persulfate was injected in Areas A and B in December 2007, and pilot test injection was completed in Area C in early February 2008, after vertical profiling was completed throughout Area C. Groundwater sampling for laboratory analysis was planned for 6 and 12 weeks after injection in each area; however, it was known during pilot test planning that the full-scale design would need to be completed by the end of March 2008, before all laboratory results would be available. In order to complete the design, an intensive evaluation of field geochemistry parameters and field screening chemical analysis was performed to assess radius of influence, oxidant

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persistence, and aquifer behavior. Field screening analyses included residual persulfate via a permanganate titration, sulfate via colorimetry, and sodium via an ion-selective electrode. The field screening and field geochemistry results were used heavily in completing the full-scale ISCO design. The laboratory analytical results noted significant decreases in concentrations of chemicals of concern in wells where geochemistry and field parameters were observed to change. This article discusses pilot test planning, performance monitoring, and full-scale design using data collected from the pilot test for this fast-track remediation. The full-scale application was completed between July and September 2008, and was the largest persulfate ISCO injection performed to date.

Keywords: in-situ chemical oxidation, sodium persulfate, pilot test, field screening analysis

1. INTRODUCTION

In-situ chemical oxidation (ISCO) has been demonstrated to be a robust remediation technology for treatment of numerous organic contaminants (Huling and Pivetz, 2006). Primary advantages of this technology are that degradation is rapid and that contaminants are treated in place in the subsurface, eliminating or minimizing extraction and ex-situ treatment (pump and treat).

In January 1987, EPA issued a Record of Decision (ROD) for the Ottati and Goss/Kingston Steel Drum Superfund Site in Kingston, New Hampshire that selected remedial actions for all areas of the site, including pump and treat for groundwater (USEPA, 1987). In 2006, EPA determined that the ROD-selected remedy for groundwater should be re-evaluated, to take into account the effects of remedial actions previously performed at the site that have changed the Site groundwater plumes, the revised conceptual site model since the 1986 Feasibility Study was prepared, and advances in remedial technologies. A Feasibility Study Addendum (FSA) Report for groundwater was completed in the spring of 2007 that evaluated the originally-selected remedy (pump and treat) in comparison to ISCO (M&E, 2007). Using investigation data collected between 2004 and 2007 to better delineate groundwater contamination, the FSA Report suggested that an ISCO remedy would be more cost-effective and timely than pump and treat. As a result, EPA issued an Amended ROD in September 2007 to change the selected remedy for groundwater to ISCO (USEPA, 2007). At that time, EPA established a goal for the site to attain construction complete status within one year, by September 30, 2008 (end of fiscal year 2008).

AECOM (formerly Metcalf & Eddy|AECOM) was tasked to perform bench-scale and field pilot scale testing to collect site-specific information to support the

remedial design for full-scale ISCO. Activated persulfate was the selected oxidant for pilot studies due to this oxidant's demonstrated ability to oxidize all site contaminants, including 1,4-dioxane, as well as its stability and longer anticipated residence time in the subsurface compared to ozone or Fenton's Reagent (which are also capable of breaking down VOCs and 1,4-dioxane) (Huling and Pivetz, 2006; ITRC, 2005). Bench-scale testing included estimating total oxidant demand (TOD) of site soils, as well as, conducting base demand tests to quantify base addition required to create alkaline conditions for base-activation of sodium persulfate. The pilot-scale treatability test consisted of injection of base-activated sodium persulfate into the saturated overburden in three pilot test areas (Area A, Area B, and Area C). The three pilot test areas lie within three distinct residual source areas that were targeted in the FSA Report (M&E, 2007) for full-scale groundwater remediation based on historical groundwater and soil sampling (Figure 1).

1.1 Site Setting and History

The Ottati & Goss/Kingston Steel Drum Superfund Site is located along Route 125 in Kingston, Rockingham County, New Hampshire. The 58-acre site is divided by Route 125 and is comprised of three distinct sections. The first section is a 5.89-acre parcel, historically referred to as the Great Lakes Container Corporation and Kingston Steel Drum (GLCC/KSD) area. This portion of the site is fenced and is now owned by the State of New Hampshire. The second section is 29 acres and is referred to as the Ottati and Goss (O&G) portion of the site. The third section is a 23-acre marsh located east of Route 125. From the late 1950's through 1980 drum reconditioning activities were performed at the site. The reconditioning operations included caustic rinsing of drums and disposal of the rinse water in a dry well near South Brook. Two leaching pits (lagoons) were also used at the site and were known as the "Kingston Swamp" and the "caustic lagoon." The Kingston Swamp and the caustic lagoon were reported to have been backfilled in 1973 and 1974, respectively.

Investigations of the site revealed that the soil throughout the site was contaminated with VOCs, polychlorinated biphenyls (PCBs), acid/base/neutral compounds (ABNs), metals, and cyanide at high concentrations at numerous locations and that groundwater was contaminated with VOCs, 1,4-dioxane, arsenic and other metals in several distinct plumes. VOCs and PCBs were measured in sediments in North Brook, South Brook.

Several remediation and removal actions were completed for contaminated soil and sediment at the site, including an EPA emergency removal action that processed and removed more than 4,000 drums and excavation and removal actions performed by potentially responsible parties (PRPs). In 1993, EPA, the

New Hampshire Department of Environmental Services (NHDES), and the PRPs entered into a Consent Decree. This agreement resulted in most parties contributing to a cash settlement, rendering the remainder of the costs at the site to be paid for by the Federal Superfund. In 2000, EPA contracted the U.S. Army Corps of Engineers – New England District to perform soil and sediment remediation at the site via excavation and treatment by low temperature thermal desorption (LTTD). Between August 2001 and June 2002, approximately 72,350 tons of VOC- and PCB-contaminated soil was excavated and treated in an on-site LTTD plant (ECC, 2003). In addition, remediation and restoration of six acres of wetland in Country Pond Marsh resulted in approximately 9,500 tons of sediment being excavated, transported, and disposed of off-site.

1.2 Conceptual Site Model

Soil and groundwater at the site were contaminated with chlorinated VOCs, BTEX VOCs, and 1,4-dioxane from both surface releases and a leachfield from former drum re-finishing operations that were conducted at the site. As noted in Section 1.1, contaminated unsaturated soil was excavated, treated on-site, and backfilled. However, contamination in saturated soil and groundwater remains. Additionally, some soil contamination located very close to Route 125 was not excavated due to concerns of undermining the road. Contamination is confined to the subsurface and therefore there is no current exposure pathway. Investigations of the site indicate that residual groundwater contamination at the site exists in three distinct residual source areas as shown on Figure 1.

Area A is located at the approximate center of the State-owned portion of the site. The residual plume from this area travels easterly toward Route 125, and groundwater contaminants include BTEX and chlorinated solvent compounds. The highest concentrations and potential source of VOC contamination have been noted in the western portion of Area A, in the vicinity of a former caustic lagoon. 1,4-Dioxane concentrations are generally low in Area A. Groundwater vertical profiling conducted prior to the ISCO pilot testing measured groundwater pH between 9.0 and 10.0 throughout most of Area A. Depth to bedrock ranges from approximately 20 to 36 feet below ground surface moving from west to east across this area, and no layer of weathered bedrock above competent bedrock has been observed in Area A. However a layer of smaller boulders/large cobbles was laid down in the western portion of Area A at a depth of approximately eight to ten feet below grade, at the bottom of the soil excavation pit during the remediation of the unsaturated zone soils by LTTD.

Area B is located in the southeast corner of the State-owned portion of the site, bordering Route 125. Soil borings advanced in Area B indicate that aquifer soils (~5 feet below ground surface to bedrock) are finer in texture and less

permeable than those observed in Area A. Contaminants were likely retained in the finer soils in this area and have been slowly migrating to the east beneath Route 125 or discharging to South Brook just before it flows under Route 125. Based on historical data prior to the ISCO pilot test, the highest site-wide concentrations of 1,4-dioxane (>200 ug/L) and total VOC concentrations greater than 20,000 ug/L have been measured in groundwater samples collected from Area B. Depth to bedrock ranges from approximately 18 to 33 feet bgs south to north across this area. Based on soil boring logs, a layer of weathered bedrock is present in the southern portion of Area B, with thickness between one and three feet.

Area C is located north of the State-owned portion of the site where a plume of lower total VOC concentrations lies roughly parallel to North Brook. Area C includes portions of palustrine forested, palustrine scrub/shrub and palustrine emergent wetlands, in addition to portions of forested wetland. There is standing water within some portions of Area C. The primary contaminant in Area C is 1,4-dioxane, which has been found at low concentrations (3 to 40 ug/L) in groundwater beneath a large area (greater than 2.5 acres). In addition, elevated concentrations of PCE (60 to 213 ug/L) and TCE (44 ug/L) were detected in groundwater at several vertical profiling locations sampled in January 2008.

Following the source soil removal action in 2002, soil texture is fairly consistent in the top five to eight feet (vadose zone) where soil was removed, remediated via thermal desorption and replaced. The replacement of the treated soils included compaction of the material before placing a final loam and topsoil cover over the site, and the permeability of the treated soils is poor such that after heavy rains most of the infiltrating water remains in the upper two feet consisting of loam and topsoil. Below five to eight feet, the textures range from fine-medium sand to coarse sand and gravel. Finer texture deposits appear to be located in the southeast corner of the site (Area B). Groundwater at the site generally flows from west to east, and eventually discharges to the marsh and Country Pond, located east of Route 125. Hydraulic conductivity values, estimated using the Waterloo profiler technique, ranged in Area A from 1.5×10^{-5} to 3.9×10^{-4} centimeters per second (cm/s). Hydraulic conductivity values estimated in Area B ranged between 9.3×10^{-6} and 1.6×10^{-4} cm/s.

To the north and south of the site are two easterly flowing brooks that drain the upland areas surrounding the site. North Brook and South Brook both travel through culverts beneath New Hampshire Route 125 and discharge to County Pond Marsh. Both North and South Brook are hydraulically connected with the shallow groundwater, and therefore, flow is subject to seasonal groundwater fluctuations.

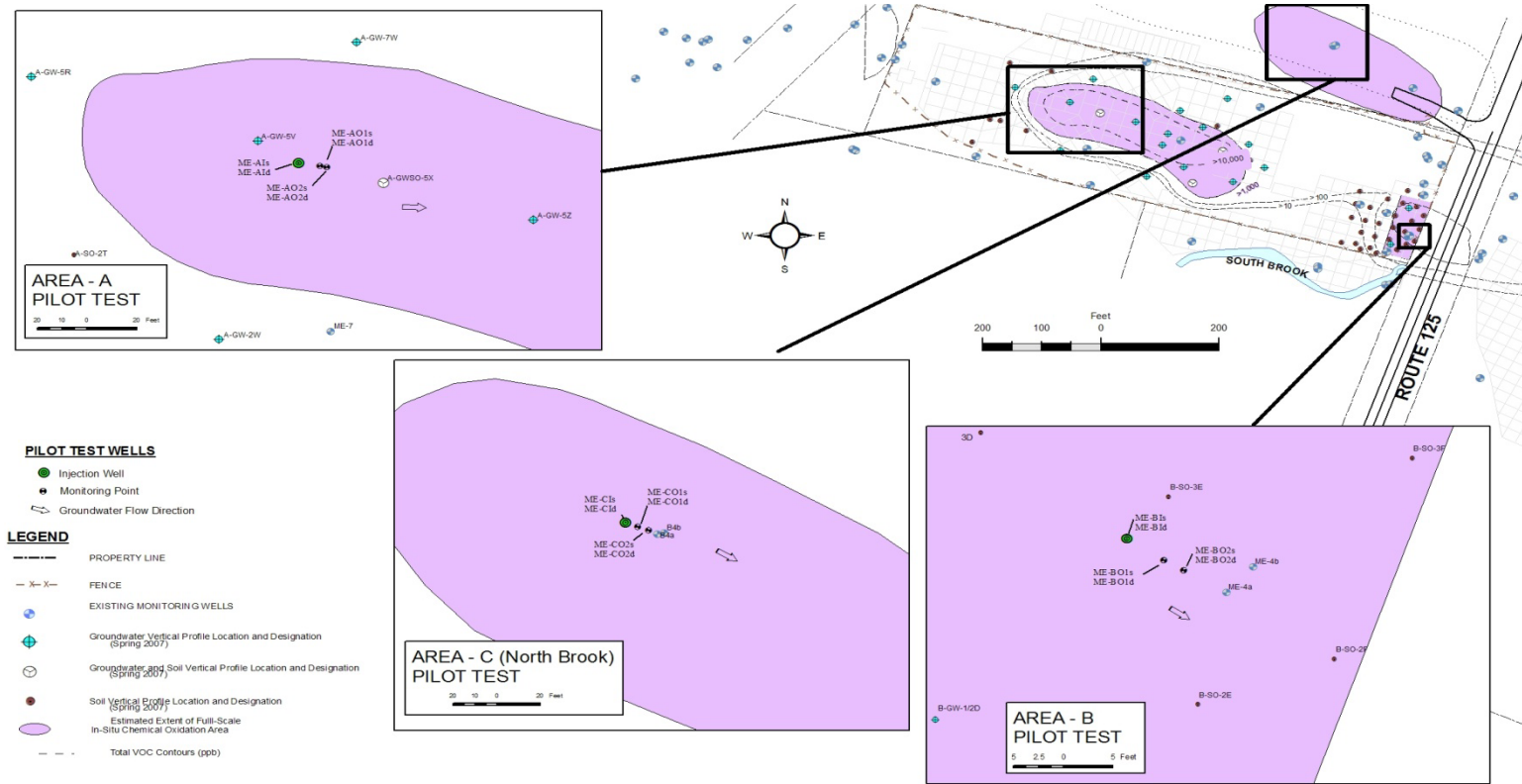


Figure 1. Site Map Showing Three Chemical Oxidation Pilot Test Areas

1.3 Treatability Pilot Test Objectives

The pilot-scale treatability test consisted of injection of chemical oxidant (activated persulfate) into the three discrete pilot test areas, one per residual source areas (Area A, Area B, and Area C). The bench-scale testing included quantifying the natural oxidant demand of site soils to assist in selecting oxidant dosages and estimating the quantity of base required to be added for alkaline activation for persulfate. The specific objectives for the field pilot treatability tests included:

1. Evaluating injection rates in each area of the site;
2. Estimating radius of influence (horizontal spread of injected oxidant);
3. Determining time of oxidant persistence in the subsurface;
4. Assessing contaminant rebound;
5. Evaluating changes in aquifer geochemistry and metals mobility;
6. Quantifying contaminant destruction;
7. Determining the oxidant dosage for full-scale remediation.

2. MATERIALS AND PROCEDURE

The treatability pilot test injections and subsequent performance monitoring were completed in three source areas between December 2007 and May 2008. Performance monitoring consisted of well-side measurements of field geochemical parameters, field screening analyses performed on-site, and fixed laboratory analyses on samples shipped off-site.

2.1 Well Installation

In each of the three pilot test treatability areas, an injection well pair (two target vertical intervals), and two monitoring well couplets were installed between November 20 and November 30, 2007. All injection wells and monitoring wells were constructed using two-inch diameter, schedule 40 PVC with 10-slot (0.010 inch) well screen. A well construction summary is provided as Table 1. The six wells were developed using whale pumps, and development volumes pumped from each well were approximately equal to estimated water volume lost to the subsurface during drilling and installation. After well development, a minimum of one week was allowed in each well before sampling as part of the pilot test baseline monitoring event.

Table 1. Chemical Oxidation Pilot Test Well Construction Summary.

Well	Function	Screen Interval	Notes
Area A			
ME-AIS	Injection	8-13	
ME-AID	Injection	14-19	
ME-AO1S	Monitoring	7.3-10.3	~ 6 feet east of ME-AIS
ME-AO1D	Monitoring	13.7-18.7	~ 6 feet east of ME-AID
ME-AO2S	Monitoring	8-13	~ 10 feet east of ME-AIS
ME-AO2D	Monitoring	15-20	~ 10 feet east of ME-AID
Area B			
ME-BIS	Injection	8-16	
ME-BID	Injection	18.5-23.5	
ME-BO1S	Monitoring	8-16	~ 5 feet east of ME-BIS
ME-BO1D	Monitoring	18-23	~ 5 feet east of ME-BID
ME-BO2S	Monitoring	9-17	~ 7 feet east of ME-BIS
ME-BO2D	Monitoring	19-24	~ 7 feet east of ME-BID
Area C			
ME-CIS	Injection	21-29	
ME-CID	Injection	32-40	
ME-CO1S	Monitoring	19-27	~ 6 feet east of ME-CIS
ME-CO1D	Monitoring	32-40	~ 6 feet east of ME-CID
ME-CO2S	Monitoring	21-29	~ 10 feet east of ME-CIS
ME-CO2D	Monitoring	32-40	~ 10 feet east of ME-CID

2.2 Treatability Bench-Scale Studies

During well installation, soil and groundwater samples were collected from each of the three pilot test areas for treatability bench-scale studies. Saturated soil samples were collected from each of the three pilot test areas, along with representative groundwater from existing monitoring wells each of the three areas. In total, 10 discrete soil samples were collected for 10 bench-scale tests. The bench tests were performed by RedoxTech's Cary, North Carolina laboratory. Total Oxidant Demand (TOD) reactors were prepared with approximately 200 grams of soil and 300 mL of representative groundwater (approximately 1:2 soil:water ratio), with sodium persulfate at a dosage of 10g/kg. The final persulfate concentration in the vessel was determined after 12 days, and the TOD value represents the total persulfate mass consumed per unit mass of soil. For the base demand analysis, a reaction vessel was prepared with approximately 100 grams of soil and 150 mL of water, and the initial pH was measured. Sodium persulfate at a dosage of 10g/kg was added, and a volume of sodium hydroxide (NaOH 25% volumetric basis) was added to increase the pH to greater than 10.5

for one hour. Additional base addition was performed two days later to again raise the pH above 10.5. The vessels were then allowed to react for 12 days after the second NaOH titration, at which time a final pH reading was taken.

2.3 Activated Persulfate Injection

Base-activated persulfate injection into Area A and Area B was completed December 17-18, 2007. Injection into Area C was completed on February 5, 2008 after planned additional investigation activities were completed in January 2008. Sodium persulfate (FMC Kloxur) and sodium hydroxide dosages, injection pressure, and injection rates in each of the three areas are summarized on Table 2. Persulfate handling, preparation and injection for the field pilot injections were performed by Redox Tech, New England LLC, under contract to AECOM (formerly Metcalf & Eddy|AECOM). There is no source of potable water at the site, and water for mixing chemical oxidation solutions was transported to the site.

Table 2. Summary of Pilot Test Injections

Parameter	Area A		Area B		Area C	
	Shallow	Deep	Shallow	Deep	Shallow	Deep
Injection Well	ME-AIS	ME-AID	ME-BIS	ME-BID	ME-CIS	ME-CID
Vertical Interval (feet bgs)	8-13	14-19	8-16	Direct Push 22-23 / 19- 22	21-29	32-40
Persulfate Dose	1,100 lbs per 500 gallon batch (26% by weight)		1,375 lbs per 600 gallon batch (~27% by weight)		910 lbs per 500 gallon batch (22% by weight)	
NaOH Dose (25% by weight)	~20 gallons per 500 gallon batch		~25 gallons per 600 gallons batch		20 gallons per 500 gallon batch	
Injection Volume (gallons)	500	500	530	300 / 350	495	500
Volume Per Vertical Foot (gallons)	100	100	66	150 / 117	62	63
Average Injection Rate (gallons per minute)	4	8	13	4 / 9	16	5
Injection Pressure (psi)	<5	25	20	25 / 25	20	20

In each pilot test area, injection was completed into two injection wells screened at different vertical intervals as shown on Table 1, with the exception of Area B. After attempting injection into the deep interval in Area B, it was determined that construction of the injection well was not satisfactory. Bottom-up, direct-push injection (1.25" diameter rods) was performed in Area B in the following intervals: 22 to 23 feet and 19 to 22 feet. Injection rates and injection pressures were recorded during the injection testing. A summary of pilot test injection parameters and observations, including sodium persulfate dose, sodium hydroxide base activation dose, total injection volume into each location, injection flow rate, and injection pressure for each of the three areas is summarized on Table 2.

2.4 Groundwater Performance Monitoring

Groundwater monitoring wells were purged and samples collected at a low rate using a variable speed pump (peristaltic pump) following USEPA low-flow sampling methods (USEPA, 1996). The following groundwater quality parameters were measured well-side using the YSI Model 6820: pH, specific conductance ($\mu\text{S}/\text{cm}$), temperature ($^{\circ}\text{C}$), oxidation reduction potential (ORP, mV), turbidity (NTU), and dissolved oxygen (DO, mg/L). Groundwater field measurements and sampling comments were recorded on field logs. Dedicated sampling tubing was used at each well. Turbidity was measured well-side using a Lamotte 2020 Turbidimeter. Collection of groundwater samples commenced after 30 minutes of purging.

Monitoring to evaluate the performance of the ISCO injection consisted of two types: contaminant monitoring and geochemical monitoring. For contaminant monitoring, groundwater samples were collected from pilot observation wells and sent to a fixed laboratory for analysis of the site contaminants of concern including VOCs, 1,4-dioxane, and select metals (arsenic, chromium, iron, manganese). One round was performed approximately 6 weeks after in-situ addition of activated persulfate, and a second round of samples was collected approximately 12 weeks after injection to evaluate potential rebound of contamination. Geochemical monitoring consisted of measurement of field geochemical parameters (pH, ORP, dissolved oxygen, specific conductance, turbidity, and temperature) and collection of a grab sample for field analysis of persulfate, sulfate (the breakdown product of persulfate), and sodium. Geochemical monitoring was performed at a higher frequency than contaminant monitoring to evaluate the persistence and distribution of the injected persulfate and temporal trends in aquifer geochemistry in the four pilot test monitoring wells in each pilot test area. In Area A and Area B, geochemistry performance monitoring was performed prior to injection (baseline) and approximately 0.5 weeks, 1.5 weeks, 3.5 weeks, 6 weeks, 8 weeks, and 12 weeks after injection. In

Area C performance monitoring was performed prior to injection (December 2007) and approximately 0.5 weeks, 1 week, 2 weeks, 4 weeks, 6 weeks, 8 weeks, and 12 weeks after injection. Additional geochemical monitoring was performed in Area B and Area C using existing monitoring wells (well ME-4A in Area B and wells B-4A and B4B in Area C). Geochemistry measurements in these wells were used to provide an additional lateral monitoring location for evaluation of radius of influence of the ISCO injections. Geochemistry performance monitoring was completed in these wells less frequently than in the four pilot test performance monitoring wells.

2.4.1 Field Screening Analysis

Groundwater samples were analyzed for sodium, sulfate, and persulfate on-site in a field laboratory trailer. Sulfate is a breakdown product of persulfate, while sodium acts as a conservative tracer upon dissociation of sodium persulfate. Elevated sulfate and/or sodium concentrations in monitoring wells, compared with baseline, were assumed to be a result of the influence of sodium persulfate injection. Field screening analyses were performed on all geochemistry performance monitoring events listed in the previous section.

Residual persulfate concentrations were measured via a potassium permanganate (0.5 N KMnO_4) titration into a solution containing known volumes of groundwater sample and ferrous ammonium sulfate (0.50 N $\text{Fe}(\text{NH}_4)_2(\text{SO}_4)_2 \cdot 6\text{H}_2\text{O}$). Sodium concentrations in groundwater samples were quantified using a Fisher Scientific accumet Glass Membrane Sodium Combination ion-selective electrode. Sodium analysis was performed using the relative millivolt (mV) mode on a solution of 50 milliliters (mL) of sample and 2 mL of ionic strength adjuster (ISA). Three decadal standards (10 mg/L, 100 mg/L, and 1,000 mg/L) were used to develop a standard curve. Sulfate concentrations were measured using a Hach colorimeter (Model # DR 890).

2.4.2 Fixed Laboratory Analysis

Groundwater samples were collected and analyzed off-site as part of performance monitoring of contaminants of concern before injection (baseline), six weeks after injection, and 12 weeks after injection. VOCs analysis was performed through the EPA Contract Laboratory Program. 1,4-Dioxane analysis was performed by Columbia Analytical Services (Kelso, WA) by extraction and GC/MS SIM analysis using EPA Method 8270C. In addition, laboratory analysis was performed for arsenic, iron, manganese, chromium, and sodium by the USEPA Region 1 Office of Environmental Measurement and Evaluation (OEME)

laboratory in Chelmsford, MA per the USEPA Region 1 Standard Operating Procedure for metals analysis by Inductively Coupled Plasma Spectrometry.

3. DATA AND ANALYSIS

Bench-scale test results were conducted prior to the scheduled field pilot test injections to select appropriate dosages of persulfate and basic activator. Performance results and observations from the ISCO pilot test were used in the design of the site-wide remediation approach. Key design parameters for the full-scale design, based on pilot test data, include injection radius of influence, injection grid spacing, injection intervals, injection volumes, chemical dosages, and injection rates.

To ensure EPA Region 1 funding would be in place to meet the goal of construction complete in September 2008, the Basis of Design Report needed to be completed by March 30, 2008. Week 6 contaminant monitoring in Area C was performed on March 18, 2008, and Week 12 contaminant monitoring in Area A and Area B was performed on March 12, 2008. Therefore the design of the full-scale remediation approach needed to rely primarily on the frequent geochemistry monitoring completed in each area.

3.1 Bench-Scale Tests

Two discrete bench scale analyses were performed prior to the field pilot tests: total oxidant demand and soil base demand. TOD results were generally low and fairly consistent in all three pilot test areas of the site, generally between 1.6 and 2.8 g/kg. Slightly elevated TOD readings were measured from two samples: one collected from the eastern portion of Area A (22 feet deep; 6.2 g/kg) and one collected near the pilot test injection wells in Area B (12 to 15 feet deep; 5.4 g/kg). The TOD results are summarized on Table 3. Due to the observance of one elevated TOD result in both Area A and Area B and the higher contamination measured in these areas, slightly higher persulfate dosages were selected for the pilot test injections, as shown on Table 2.

From the base demand analysis, generally low doses of NaOH (25%), ranging between 0.8 and 2.3 milliliters (mL) per kg soil, were required to initially raise the pH to greater than 10.5. One soil-groundwater slurry from Area C required significantly more base to raise the pH (12.5 mL/kg); however, this sample location was outside of the Area C pilot test location as well as the area eventually targeted for full-scale ISCO in Area C based on the January 2008 groundwater vertical profiling investigation. After twelve days of persulfate-base-soil reaction time, the pH in five of the ten base demand vessels was circumneutral (between

6.0 and 8.0) and the pH of two samples (ME-AIP-18 and ME-BIP-22) remained above 8.0. These results suggested that the soil in the pilot test areas would likely have sufficient buffering capacity to maintain an elevated pH with persulfate addition and minimize extreme drops in pH due to sulfuric acid formation. Although, the post-reaction pH of two of the ten samples was approximately 3.0, no change was made to the base dosage for the pilot test based on the bench scale results. However, these two final acidic results did suggest that a low pH may be expected to be observed in monitoring wells in some portions of the site following a persulfate injection due to the breakdown of persulfate and the subsequent formation of sulfuric acid. The base demand results are summarized on Table 3.

3.2 Water Quality and Field Screening Parameters

Water quality parameters and field screening analyses were recorded to evaluate the persistence and the transport of the injected solution in the subsurface. Several consistent geochemical changes were noted in performance monitoring wells that were impacted by injection of base-activated sodium persulfate, including detection of residual persulfate, increase in ORP, increase in sulfate, increase in sodium, and increase in specific conductance.

Persulfate was observed to persist in the subsurface for a period of approximately four to six weeks in all three pilot test areas, which is consistent with observations from other similar injections based on discussions with FMC and literature (Huling and Pivetz, 2006). The persulfate persistence from the pilot test was not representative of the persistence observed at full-scale; however. After the full-scale injection performed from July to September 2008, residual persulfate was measured in performance monitoring wells four to seven months following injections. This longer persistence following full-scale injection may have been caused by a combination of factors: the large quantities injected, injection through a grid system compared to a single injection well location, and cold temperatures which decrease persulfate activation rates. However, low temperature is less likely related to the longer persistence observed at full scale, since the pilot test injections were performed during cold weather (December 2007 and February 2008), when groundwater temperatures were likely similar to those during the months following the full-scale injection (September 2008-March 2009).

In all three pilot test areas baseline ORP values were generally between -200 and -100 millivolts (mV). In wells where residual persulfate was measured to be greater than 1,000 ug/L, ORP values were observed to increase to between +200 and +500 mV.

Table 3. Summary of Bench Scale Studies.

Sample ID	Soil Sampling Location/Depth	Oxidant Demand (g S ₂ O ₈ / kg soil)	Initial pH	Total NaOH Added (mL NaOH/kg soil)	Final pH (12 days)
AREA A					
ME-AIP-12	Area A pilot test area (depth 12-13 feet)	2.5	8.6	1.3	6.4
ME-AIP-12-Dup	Field Duplicate	2.3	9.0	0.8	6.0
ME-AIP-18	Area A pilot test area (depth 18 feet)	1.6	9.1	1.1	8.5
ME-AP1-16	Area A - eastern portion (depth 13.5-17 feet)	2.6	8.3	1.6	6.4
ME-AP1-24	Area A - eastern portion (depth 22 feet)	6.2	7.1	2.3	3.4
AREA B					
ME-BIP-14	Area B pilot test area (depth 12-15 feet)	5.4	7.9	2.3	3.0
ME-BIP-22	Area B pilot test area (depth 18-20 feet)	2.0	8.1	1.9	9.8
ME-BP1-16	Area B northwestern portion (depth 14-15 feet)	2.5	8.1	1.6	7.3
Area C					
ME-CIP-25	Area C pilot test area (depth 25 feet)	1.8	7.2	1.4	7.6
ME-CIP-36	Area C pilot test area (depth 36 feet)	2.0	7.0	1.2	6.0
ME-C08-30	East of Area C pilot test (depth 30 feet)	2.8	4.9	12.5	5.2

Groundwater pH increased to alkaline conditions shortly after injection due to the base activation in only three pilot test monitoring wells (ME-AO1S, ME-

AO1D, and ME-BO2D). However, alkaline pH in groundwater was only observed to persist for a period of 0.5 to 1.5 weeks. Therefore, the injection solution was likely transported as a result of pressurized injection into these three wells where alkaline pH values were measured. Generation of sulfuric acid in site groundwater as a result of the breakdown of added sodium persulfate caused the pH to drop in several monitoring wells to values between pH 3.0 and 4.0. During pilot test monitoring, the lowest pH readings in all three areas occurred between 1.5 and 3.5 weeks after injection, following which groundwater pH increased.

Significant increases from baseline of specific conductance, sulfate, and sodium in monitoring wells corresponds to those wells where residual persulfate was observed and ORP was measured to increase to oxidizing conditions (>200 mV). Geochemistry monitoring results in select pilot test monitoring wells are tabulated on Table 4. Temporal trends in these geochemical parameters are summarized graphically for Area A wells ME-AO1S and ME-AO2D on Figure 2 and for Area B wells ME-BO1S and ME-BO2D on Figure 3.

In the absence of fixed laboratory data, changes in water quality and field screening parameters were critical in assessing radii of influence and designing the injection grid spacing for full-scale ISCO injection in each area. For water quality parameters and field screening analyses, less importance was placed on specific values compared to relative changes from baseline conditions. In evaluating changes to the field screening and water quality parameters after pilot test injections, compared to baseline readings, were classified into three categories (Yes, Partially, and No) as shown on Table 5, with Parameter Assessment Criteria defined in Table 6. In addition, laboratory analysis results from the six week performance monitoring event were available for Area A and Area B when the full-scale design was finalized, and these analytical results were also operationally defined on Table 5 and were considered in estimating oxidant distribution and radius of influence. Radius of influence distance estimate in each area was inclusive of the monitoring wells where most parameters were classified as "Yes" or "Partially." Accordingly, radius of influence was estimated to be between six and ten feet in Area A, between five and eight feet in Area B, and greater than six but less than ten feet in the deeper portion of the Area C pilot test area.

Table 4. Summary of Groundwater Geochemical Parameters After Injection in Select Wells.
 Water quality parameters and field screening parameters were measured frequently following injection to evaluate oxidant persistence and distribution.

Location	ME-AO1D (13.7-18.7' bgs - 6 feet from Injection Well)						ME-AO2D (15-20' bgs - 10 feet from Injection Point)					
	baseline	1/2 week	1.5 weeks	3.5 weeks	6 weeks	12 weeks	baseline	1/2 week	1.5 weeks	3.5 weeks	6 weeks	12 weeks
Sampling Event	baseline	1/2 week	1.5 weeks	3.5 weeks	6 weeks	12 weeks	baseline	1/2 week	1.5 weeks	3.5 weeks	6 weeks	12 weeks
pH (standard units)	7.47	8.94	3.63	4.33	6.58	4.15	9.79	9.38	4.79	5.09	6.51	4.97
ORP (mV)	-174	18	369	410	-69	358	-273	-354	419	225	-158	235
Specific Conductance (µS)	360	568	7,738	4,246	835	3,872	643	1,795	5,423	4,656	1,954	3,207
Sodium (mg/L)	58	139	1809	1232	73	579	159	405	1,182	1,226	221	573
Persulfate (mg/L)	0	89	0	803	0	no sample	0	0	1,607	119	0	no sample
Sulfate (mg/L)	22	18	6,665	2,440	262	2,700	7	NR	2,758	3,050	801	2,700

Location	ME-BO1S (8-16' bgs - 5 feet from Injection Well)						ME-BO2D (Screen 19-24' bgs - 8 feet from Injection Point)					
	baseline	1/2 week	1.5 weeks	3.5 weeks	6 weeks	12 weeks	baseline	1/2 week	1.5 weeks	3.5 weeks	6 weeks	12 Weeks
Sampling Event	baseline	1/2 week	1.5 weeks	3.5 weeks	6 weeks	12 weeks	baseline	1/2 week	1.5 weeks	3.5 weeks	6 weeks	12 Weeks
pH (standard units)	8.20	4.64	4.41	3.32	3.86	5.11	9.24	12.57	8.95	4.11	3.15	4.66
ORP (mV)	-203	372	479	554	72	132	-151	278	255	502	456	210
Specific Conductance (µS)	1,071	20,170	19,290	18,290	13,745	7,180	779	6,243	2,036	18,380	13,960	17,170
Sodium (mg/L)	269	5,539	5,317	5,900	1,294	1,443	187	19,110	6,983	6,339	988	4,424
Persulfate (mg/L)	0	13,864	8,033	833	0	no sample	0	81,813	19,159	7,140	60	no sample
Sulfate (mg/L)	0	7,278	10,968	8,120	9,296	4,900	8	8,068	6,698	11,120	8,638	12,800

Table 5. Summary of Pilot Test Radius of Influence Assessment Parameters. Parameter Assessment Criteria were operationally defined for this site-specific pilot test.

Injection Interval	Shallow Injection (8-13')		Deep Injection (14-19')	
Well	ME-AO1S	ME-AO2S	ME-AO1D	ME-AO2D
Distance from Injection Point	6 feet	10 feet	6 feet	10 feet
↑ Residual Persulfate	□	□	□	■
↑ ORP	□	□	■	■
↑ Sulfate	□	□	■	■
↑ Sodium	□	□	■	■
↓ Concentration of chlorinated VOCs	■	■	□	□
↓ Concentration of BTEX VOCs	■	■	■	□

Injection Interval	Shallow Injection (8-16')		Deep Injection (18.5-23.5')	
Well	ME-BO1S	ME-BO2S	ME-BO1D	ME-BO2D
Distance from Injection Point	5 feet	7 feet	6 feet	8 feet
↑ Residual Persulfate	■	□	■	■
↑ ORP	■	□	■	■
↑ Sulfate	■	■	■	■
↑ Sodium	■	□	■	■
↓ Concentration of chlorinated VOCs	■	■	■	□
↓ Concentration of BTEX VOCs	■	□	■	□
↓ Concentration of 1,4-dioxane	▣	□	▣	□

Injection Interval	Shallow Injection (20-28')		Deep Injection (32-40')	
Well	ME-CO1S	ME-CO2S	ME-CO1D	ME-CO2D
Distance from Injection Point	6 feet	10 feet	6 feet	10 feet
↑ Residual Persulfate	□	□	■	□
↑ ORP	□	□	■	□
↑ Sulfate	□	□	■	□
↑ Sodium	□	□	■	□

Table 6. Site-Specific Definitions for Assessment Parameters.

	Persulfate	ORP	Sulfate	Sodium	↓ COC Concentration
■ – Yes	>1,000 mg/L	>200 mV	>500 mg/L	>1000 mg/L	>60%
▣ - Partially	>BL + 200 mg/L	≥ 0 mV	>100 mg/L	> 10 x BL	>30%
□ – No	≤BL + 200 mg/L	< 0 mV	≤100 mg/L	≤ 10 x BL	≤30%

3.3 Fixed Laboratory Results

The primary objective of the pilot test treatability study was to evaluate the extent that ISCO can reduce concentrations and mass of contaminants of concern in the ground at the Ottati and Goss Site. Contaminant concentrations were measured before the pilot test injections and destruction was quantified six and twelve weeks after the injection in each area. The ISCO pilot test demonstrated that BTEX and chlorinated VOC concentrations in groundwater could be effectively decreased in-situ. Overall, the concentrations of BTEX and chlorinated VOCs were reduced 50 to 95 percent from baseline concentrations following pilot-scale ISCO injection in pilot test monitoring wells in Areas A and B. Concentrations of PCE decreased in nearly all monitoring wells. In several wells, VOC concentrations were noted to increase, and these increases are potentially due to desorption of contamination from soil particles and/or to contaminated water being pushed vertically to different depths or laterally to different areas. Concentrations of chloromethane and acetone, likely oxidation byproducts, were also noted to increase in some pilot test monitoring wells. Performance monitoring results from Week 12 indicated further reductions in concentrations of both BTEX and chlorinated VOCs in all four monitoring wells in Area A and in wells ME-BO1S and ME-BO1D between Week 6 and Week 12. Groundwater contaminant concentrations in wells ME-BO2S and ME-BO2D were observed to increase (compared to both baseline and Week 6 concentrations), and this is likely the result of desorption of VOCs from heavily contaminated soil. Concentrations of primary contaminants of concern prior to and after injection of persulfate in pilot test Area A are presented in Table 7. The effectiveness of persulfate in destroying 1,4-dioxane in-situ at the Ottati and Goss site was not clearly demonstrated from the activated persulfate pilot test injections. Baseline concentrations in performance monitoring wells in Areas A and C were nearly all less than the Interim Cleanup Level of 3 ug/L specified in the Amended ROD. In Area B, baseline concentrations of 1,4-dioxane ranged between 16 and 64 ug/L, and concentrations were reduced by 25 to 40 percent after the pilot test injections. In Area B, it is possible that the persulfate being consumed through oxidation of

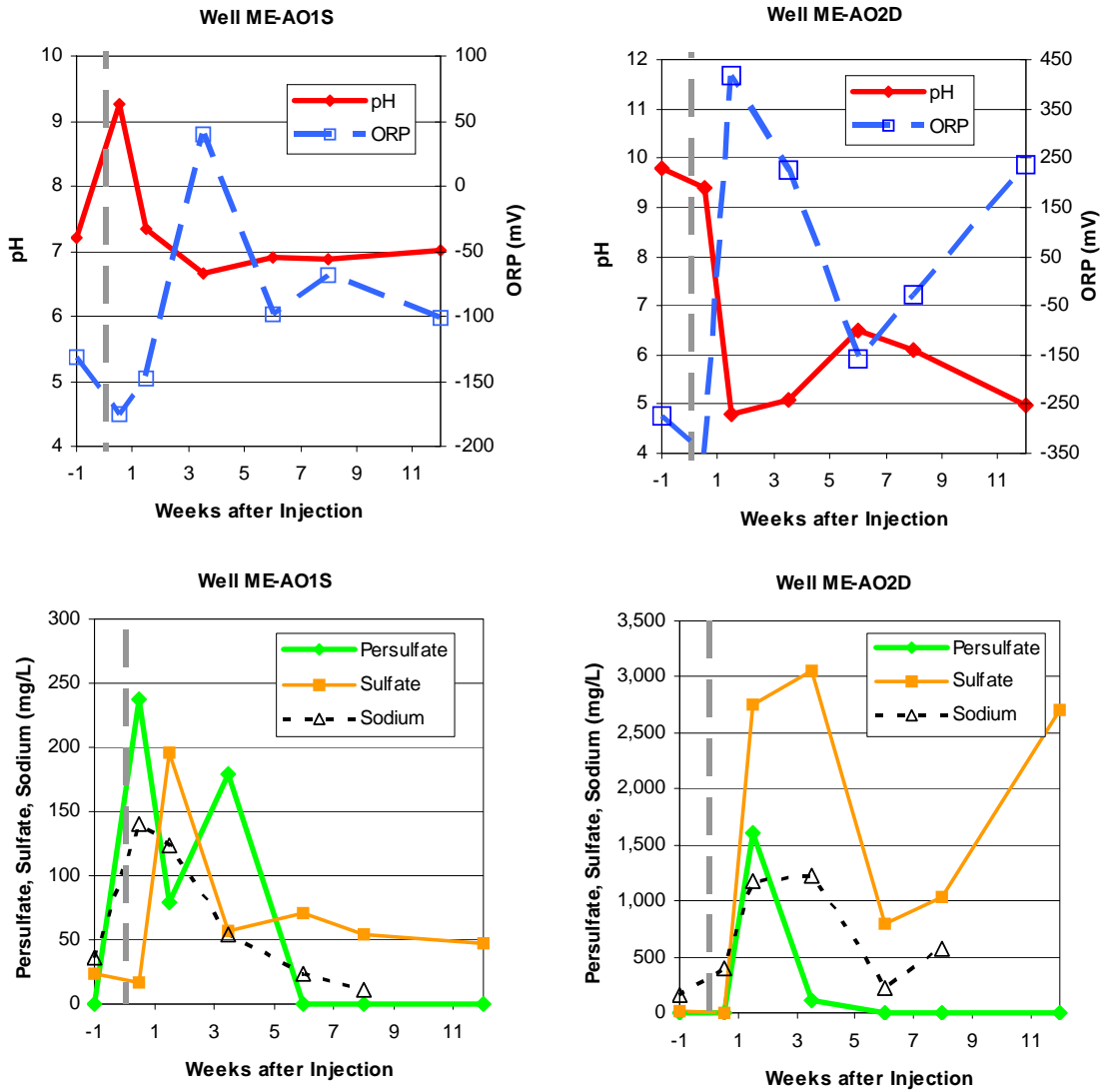


Figure 2. Temporal Summary of Water Quality and Field Screening Parameters Monitoring in Area A Monitoring Wells: ME-AO1S and ME-AO2D.

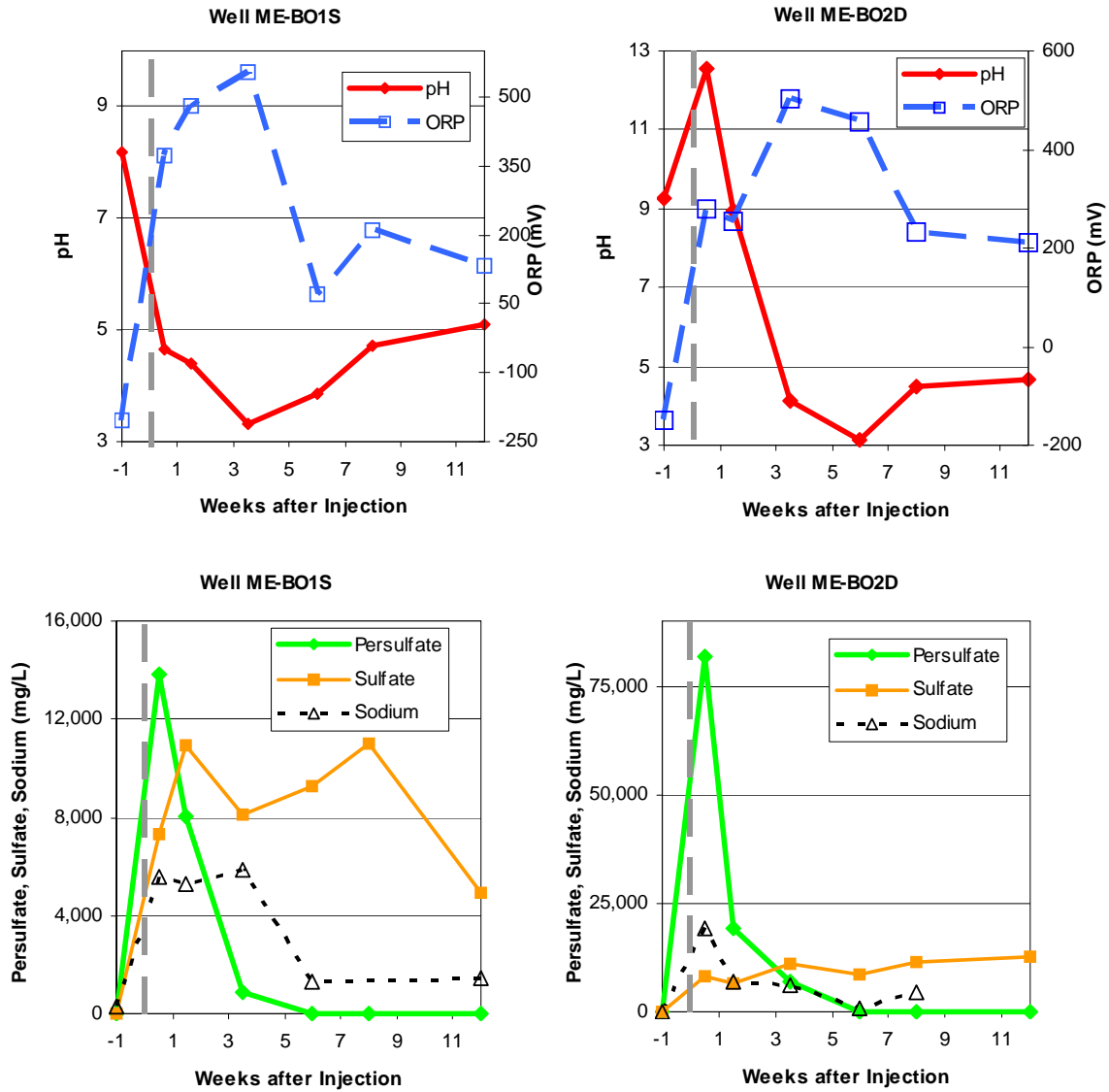


Figure 3. Temporal Summary of Water Quality and Field Screening Parameters Monitoring in Area B Monitoring Wells: ME-BO1S and ME-BO2D.

Table 7. Summary of Laboratory Analytical Results for Primary Contaminants of Concern Before and After ISCO Injection.

Concentrations shown in Area A and Area B pilot test monitoring wells. In the Area C pilot test area, concentrations of contaminants of concern were less than the Preliminary Cleanup Levels and no comparison was made between post-injection and baseline results. Total BTEX is the summation of benzene, toluene, ethylbenzene, m/p-xylene, and o-xylene.

Location	ME-AO1S			ME-AO2S		
(ug/L)	baseline	6 weeks	12 weeks	baseline	6 weeks	12 weeks
PCE	51	7.6	1.1	17	1.2	<1
TCE	10	55	<1	5.9	<1	<1
TOTAL BTEX	326	220	0	116	14.2	1.7
Location	ME-AO1D			ME-AO2D		
(ug/L)	Baseline	6 weeks	12 weeks	baseline	6 weeks	12 weeks
PCE	67	2.1	42	650	290	200
TCE	13	120	15	250	220	500
TOTAL BTEX	372	496	75	7,200	3,430	4,030
Location	ME-BO1S			ME-BO2S		
(ug/L)	baseline	6 weeks	12 weeks	baseline	6 weeks	12 weeks
PCE	130	65	15	57	<10	<20
TCE	<25	5.4	<5	<50	<10	<20
cis-1,2-DCE	230	27	7.2	270	32	<20
vinyl chloride	<25	<5	<5	<50	<10	<20
TOTAL BTEX	3,040	844	782	6,480	3,580	4,840
1,4-Dioxane	50	32	30	53	41	36
Location	ME-BO1D			ME-BO2D		
(ug/L)	Baseline	6 weeks	12 weeks	baseline	6 weeks	12 weeks
PCE	1,400	330	190	130	57	100
TCE	1,500	670	600	190	140	230
cis-1,2-DCE	3,100	970	600	350	260	600
vinyl chloride	550	210	98	87	46	92
TOTAL BTEX	11,358	3,391	4,380	1,210	298	1,461
1,4-Dioxane	64	43	48	16	17	21

other contaminants of concern more amenable to oxidation (i.e., BTEX) and natural oxidant demand in soils limited oxidation of 1,4-dioxane. The acidification of groundwater in the vicinity of the injections may also have reduced the potential for 1,4-dioxane oxidation as alkaline conditions were not

maintained to generate sulfate free radicals. However, in a study by Felix-Navarro, it was observed that oxidation rates of 1,4-dioxane by persulfate were inversely proportional to pH (Felix-Navarro et al., 2007), and therefore basic pH may not be necessarily for 1,4-dioxane oxidation by persulfate.

Contaminant rebound was noted in the deep interval of Area B, where concentrations measured six weeks after injection were lower than baseline. However, in the twelve week performance monitoring samples, contaminant concentrations were higher than the Week 6 results, and for some contaminants concentrations were greater than baseline. The deep interval in Area B was the most contaminated pilot test interval, and rebound is likely due to desorption of organic contaminants from soil particles.

Shifts in aquifer geochemistry following the ISCO pilot test (generally more oxidizing and more acidic) were noted to impact the mobility of certain metals. Large iron and manganese concentration increases (one to two orders of magnitude) were observed in the deep interval in Area A, the shallow and deep intervals in Area B, and the deep interval in Area C after ISCO injection. The measured concentrations of arsenic were lower in all pilot test monitoring wells following the ISCO injection compared to baseline in Areas A and B; however, elevated laboratory reporting limits were greater than the baseline concentrations for some wells. In a few wells the arsenic concentrations decreased between the baseline and Week 6 sampling; however, the concentration then increased between the Week 6 and Week 12 sampling events. This may suggest that as groundwater geochemistry returns to baseline conditions, arsenic concentrations may return to pre-injection concentrations. Chromium concentrations were not detected in any well in baseline or post-injection monitoring in Area A or Area C. In Area B, well ME-BO2D, the concentration of chromium was measured to be 180 ug/L in the Week 6 sample, which exceeded the federal MCL (100 ug/L); chromium was not detected (reporting limit=110 ug/L) in the Week 12 sample from this well. The only other detection of chromium in Area B was in well ME-BO1D in the baseline sample (22 ug/L).

3.4 Other Observations

In the shallow interval of Area C, no indication of oxidant injection was noted in the two monitoring wells (ME-CO1S and ME-CO2S) during the one-half and one week geochemistry sampling events. Four additional one-inch PVC wells/piezometers screened from 20 to 30 feet deep were installed approximately five feet downgradient from the shallow injection well (ME-CIS) using a direct-push drill rig to provide additional groundwater monitoring sampling to assess the distribution of the injected solution in the subsurface. Water quality measurements and analysis of field screening parameters from the four additional

shallow piezometers provided no evidence of the persulfate injection or the destination of the persulfate injected into the shallow interval. Most of the injected solution likely traveled through a preferential pathway, potentially in an upgradient direction, that the pilot test monitoring well network (two monitoring wells ME-CO1S and ME-CO2S and four piezometers) in Area C did not capture. Two deep-interval piezometers were also installed approximately six feet from the deep injection well (to the northeast and southeast of injection well ME-CID). Elevated residual conductance and increases in ORP values were observed two weeks after injection in both of the deep interval piezometers, in addition to well ME-CO1D, indicating a good oxidant distribution in the subsurface that was at least six feet across at a distance six feet from the deep injection well.

3.5 Full-Scale Basis of Design

The ISCO remediation design was completed primarily using site-specific data collected during the pilot test. At the time of remedial design and submittal of the Basis of Design Report to USEPA Region 1, fixed laboratory analytical data was only available for the samples collected six weeks after injection in Areas A and B. Therefore, changes in water quality and field screening parameters were critical in assessing radii of influence, which was used in determining injection grid spacing, and selecting injection volumes and dosages. Site-specific, full-scale design parameters are summarized on Table 8. The horizontal and vertical extent of remediation was estimated using contaminant concentrations in soil and groundwater based on site investigations, most notably the vertical profiling of soil and groundwater in all three areas.

Injection for full-scale remediation was designed to be performed using a grid approach. Spacing within the injection grid was designed to provide delivery of oxidant vertically and horizontally thoroughly throughout the portions of the site identified as needing active treatment to create contact between persulfate and the contaminants in soil and groundwater. Injection grid spacing in each area was primarily determined through the observed radius of influence from the pilot scale injection activities, where geochemistry changes and contaminant destruction were used to estimate radius of influence as summarized in Section 3.2 and on Table 5. Injection grid spacing also considered observed subsurface stratigraphy from soil boring logs, local hydrogeologic parameters (hydraulic conductivity and hydraulic gradient), and Metcalf & Eddy/AECOM in-situ injection experience at other sites in New England. To maximize potential contact between the chemical oxidant and contaminants, the injection grid spacing in each area was less than or equal to two-times the radius of influence to allow some overlapping in the subsurface of injected solutions. In Area A, where radius of influence was estimated to be between six and ten feet, a grid spacing of 16 feet was

Table 8. Full-Scale Remediation Basis of Design Parameters

Parameter	Area A	Area B	Area C
Depth to Ground Water	4.5 - 6 feet bgs	3 - 6 feet bgs	1-4 feet bgs
Depth to Bedrock	18 - 34 feet bgs	18 - 33 feet bgs	18 - 38 feet bgs
Treatment Thickness	11 - 22 feet	14 - 22 feet	4 - 19 feet
Targeted Remediation Area	30,000 sq. feet	6,000 sq. feet	15,000 sq. feet
Injection Volume	100 gallons / VLF	100 gallons / VLF	85 gallons / VLF
Sodium Persulfate Dosage	200 lbs / VLF (~24%)	205 lbs/VLF (~25%)	155 lbs/VLF (~22%)
Injection Grid Spacing	16 feet (within 10,000 ug/L TVOC isopleth) 20 feet (within 1,000 ug/L TVOC isopleth)	12 feet	16 feet (where PCE >100 ug/L) 20 feet
Injection Locations	107	55	42

incorporated into the full-scale design for the most contaminated center portion of the plume, and a grid spacing of 20 feet was chosen for the outer portions of the plume. In Area B, radius of influence was estimated to be between five and eight feet from the pilot test injections; due to the low permeability soils observed in Area B the full-scale ISCO design used a grid spacing of 12 feet throughout Area B. In the deeper portion of the Area C pilot test area, the radius of influence was estimated to be greater than six but less than ten feet; however, the pilot test area was located outside of the target area for full-scale remediation in Area C. Contamination concentrations were generally lower in Area C, so therefore 20 foot grid spacing was chosen for Area C, with the exception where PCE concentrations were noted to be greater than 100 ug/L in groundwater samples and a 16 foot grid was applied. It should be noted that the radius of influence in each area was based on injection volume and dosage used during the pilot test. Therefore for full-scale remediation design, it was assumed that using similar injection volumes for the full-scale as the pilot tests would affect the same mobile porosity in the groundwater aquifer. Volumes were designed to be approximately equivalent to the pilot test injections. Dosages were decreased slightly from the

high persulfate dosage used in the pilot test under the assumption that a grid injection approach would allow for increased contact between oxidant and contaminants.

With a successful pilot test injection in Area B using direct-push tooling, the design process evaluated performing injections through permanent injection wells and/or using temporary direct-push rods in each area of the Site To minimize time and cost associated with well installation, the design identified a large number of injection locations to be performed by direct-push injection. Similar to the single direct-push, pilot test point, the direct-push injections were designed to be "bottom-up," where injection rods are advanced to refusal (or the deepest target depth) and raised to the upper limit of the target depth interval. Semi-permanent injection wells were planned where contaminant concentrations were noted to be highest and follow-up ISCO injections were expected to be needed, including in the western portion of Area A within the 10,000 ug/L total VOC groundwater isopleth (which is near the presumed source), in Area B within the 100,000 ug/kg total VOC soil isopleth, and along the eastern boundary of Area B to reduce contaminant transport below Route 125. With this designed placement of PVC injection wells, approximately 80% of the injection points were designed to be direct-push with the remaining 20% of injection points to use injection wells.

4. CONCLUSION

The ISCO pilot test conducted at the Ottati and Goss Superfund Site successfully demonstrated that site contaminants, including chlorinated and BTEX VOCs and 1,4-dioxane, could be remediated in-situ with the injection of a strong chemical oxidant. Following the injection of base-activated persulfate through pre-constructed injection wells and through direct-push injection rods at one location, critical information was collected to design and optimize implementation of full-scale ISCO remediation. Due to the aggressive schedule required to achieve EPA's construction completion for the site, the remedial design needed to be completed without much of the fixed laboratory analysis for contaminants of concern. As a result, frequent monitoring for water quality parameters and field screening analyses was completed to evaluate the distribution and persistence of the chemical oxidant and the resulting changes in aquifer geochemistry. During remedial design for injection spacing, oxidant dosage, and volume, and it was assumed that significant destruction of site contaminants would occur in wells where persulfate, sodium, sulfate, and ORP changed significantly from baseline conditions. When all pilot test performance monitoring laboratory became available, this assumption was proved to be appropriate. The full-scale application was completed between July and September 2008, and was the largest persulfate

ISCO injection performed to date (FMC, personal communication with Phillip Block, May 26, 2010). Performance monitoring following full-scale remediation in January and April 2009 indicated significant reduction in contaminant concentrations in groundwater as well as reduction in plume area. As noted the full-scale design relied heavily on performance monitoring of water quality parameters and field analyses during the pilot test for the site's fast-track schedule. The reduction of contaminants as a result of full-scale injection suggests that the remedial design chose appropriate injection spacing and oxidant dosages based on pilot test monitoring.

5. ACKNOWLEDGEMENTS

The authors would like to extend thanks to William Abrahams-Dematte, Stan Hatfield, and Richard Purdy for their support in completing sampling and field analysis.

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