



University of  
Massachusetts  
Amherst

## **Evaluation Of In Situ Chemical Oxidation Of Soils At A Mixed Waste Site And Assessment Of Effects On Ground Water Quality.**

Item Type	conference;article
Authors	Bost, Richard C.;Perry, Robert G.
Download date	2025-03-20 13:44:03
Link to Item	<a href="https://hdl.handle.net/20.500.14394/43566">https://hdl.handle.net/20.500.14394/43566</a>

## PART IV: Chemical Oxidation

### Chapter 10

# EVALUATION OF IN SITU CHEMICAL OXIDATION OF SOILS AT A MIXED WASTE SITE AND ASSESSMENT OF EFFECTS ON GROUND WATER QUALITY

Richard C. Bost<sup>§</sup> and Robert G. Perry  
*Environmental Resources Management (ERM), Houston, Texas, USA*

### ABSTRACT

In Situ Chemical Oxidation (ISCO) entails the introduction of chemical oxidant into the subsurface for the oxidation and treatment of organic constituents of concern (COCs). This paper presents a case study that involved bench-scale testing and field demonstration of ISCO via Mechanical Auger Mixing (MAM) that resulted in over 95% removal of chlorinated and non-chlorinated chemicals identified as recalcitrant. Also presented are ISCO's effects on dissolved oxygen levels in the underlying aquifer. Mechanical mixing of soils with an oxidant solution is an improved remedial strategy that facilitates more effective mixing of reagents with affected soils and hence in more effective treatment than from injection of oxidant. Based on the apparent effectiveness of persulfate in bench-scale tests, ISCO utilizing persulfate and a source of alkalinity was then applied to the demonstration site. The site is a 1970s era waste disposal area where a multitude of different types of wastes were disposed. Six chemical constituents comprised the most abundant COCs at the subject site. These compounds are: 1,1-dichloroethane, vinyl chloride, acetone, 1,2-dichloroethane, benzene, and tertiary butyl alcohol. Solutions of 20% sodium persulfate and 2% of different alkaline sources were found to be most effective in bench scale tests. After the successful field demonstration, it was noted that dissolved oxygen levels increased in the underlying aquifer within about one month and persisted for about nine months. Ground water data as well as field test and bench-scale test data are presented in the paper.

**Keywords:** in-situ chemical oxidation, organic constituents of concern, aquifer, persulfate

<sup>§</sup> Corresponding Author: Richard C. Bost, 15810 Park Ten Place, Ste. 300, Houston, Texas, Tel: 281-600-1218, Email: rick.bost@erm.com

## 1. INTRODUCTION

In Situ Chemical Oxidation (ISCO) is a method for the introduction of chemical oxidants into the subsurface for the oxidation and destruction/mineralization of organic constituents as a remedial technology. However, for ISCO to be effective, the oxidant has to come into contact with the chemicals of concern (COCs). Typically this means injecting an oxidant into the affected soils and/or aquifer. While ISCO has been demonstrated to be effective at remediation of COCs within a subsurface zone of higher permeability, in areas where COCs have migrated into more clayey zones with low hydraulic conductivity, diffusion of the COCs out of the clayey zones following ISCO aquifer treatment has resulted in the rebounding of ground water concentrations following treatment.

This paper presents the results of a case study involving bench scale tests and a field-scale pilot test of the ISCO technology at a site to treat a mixture of compounds, many of which have been identified as recalcitrant. In addition, to address the issue of also treating clayey areas with low hydraulic conductivity, this paper presents the results of a field-scale pilot study that demonstrated the effectiveness of Mechanical Auger Mixing (MAM) using large six-foot diameter light augers as a means to incorporate ISCO into a predominately clayey subsurface to a depth of 25 feet below ground level.

### 1.1 Site Hydrogeology

Investigations at the site previously identified the local geology to be comprised of a surficial clayey zone found from approximately 0 to 18 feet below ground surface (bgs), a shallow transmissive zone from about 18 to 22 feet bgs, another clayey zone from about 22 to 30 feet bgs, a deeper transmissive zone from about 30 to 80 feet bgs, and a deeper clayey zone below 80 feet to approximately 180 feet bgs. The shallow transmissive zone is generally comprised of silts and clayey silts with occasional lenses of silty sand up to 2.5 feet thick. In contrast, the deeper aquifer is predominantly sand and is typically 50 to 55 feet thick. The shallow aquifer is confined by the surficial clay above and the underlying clay below while the deeper aquifer is confined by the overlying clay above and the deeper aquitard below. Aquifer tests indicate that the best conceptual model for the intermediate intervening clay unit is that of a "leaky" confining layer.

### 1.2 Site COCs and Mass Distribution

The constituents found in at the site were predominately chlorinated hydrocarbons, petroleum related hydrocarbons, and tert-butyl alcohol (TBA) and acetone. The predominated constituents found at the site, in order of mass, were 1,1-dichlorethane (1,1-DCA), vinyl chloride, benzene, TBA and acetone. While these five constituents accounted for most of the constituent mass at the site, over 20 other compounds had been reported present in soil and ground water samples. A mass balance of COC constituents in the soil indicated that in the source area about 40% of the mass was in the surficial clay, about 30% in the shallow sand, about 24% in the underlying clay and less than 1.0% in the dissolved phase in the shallow and deeper aquifer. Because of the large

percentage of overall mass in the surficial and intermediate clays, ISCO treatment in only the transmissive aquifers would only result in a small overall percentage reduction in COC mass and would leave significant mass in the clays that would over time migrate by infiltration or diffusion back into the sands. Therefore, the challenge is to effectively mix an oxidant into the clays. The method that was investigated in this case study was to use MAM to liquefy the upper clay while injecting an oxidant.

## **2. LITERATURE SEARCH**

Prior to conducting the pilot test, an extensive literature search was conducted to assess the applicability of ISCO and to determine which of the oxidants on the market today would be the most effective at treating the constituents of concern (COCs) found in the shallow soils and ground water at the subject site. Based on the literature search, several studies were found that identified sodium persulfate as the oxidant that would be most effective at treating the site COCs. Two of the primary sources utilized include:

- Philip A. Block, Ph.D., Richard J. Watts, Ph.D., Amy L. Teel, Ph.D., Richard A. Brown, Ph.D: An Examination of Persulfate Activation and Reactivity, presented at the fourth International Conference on Oxidation and Reduction Technologies for In-Situ Treatment of Soil and Groundwater Marriott Chicago O'Hare, Chicago, Illinois, USA.
- Richard Brown, George Skladany, David Robinson; Joe Fiacco, John McTigue: Comparing Permanganate and Persulfate Treatment Effectiveness for Various Organic Contaminants, presented at The First International Conference on Oxidation and Reduction Technologies for In-Situ Treatment of Soil and Groundwater (ORTs-1) Niagara Falls, Ontario, Canada, June 25-29, 2001.

Based on these studies, bench-scale testing was conducted using samples of the site soil and ground water to assess the effectiveness of the persulfate on treating the site COCs in each media. Other oxidants, including percarbonate, were used to compare the effectiveness of the treatment. In addition, the bench-scale testing evaluated the use of cement mixing to stabilize the treated soils and the effects of cement on the oxidation process. The study also evaluated the effects of the soil mixing process on volatilization.

## **3. BENCH SCALE TESTING**

Bench-scale studies were conducted to evaluate the effectiveness of ISCO and to provide additional data necessary for the design of the full scale implementation of MAM ISCO at the site.

The results of the bench-scale studies demonstrate that persulfate in an alkaline environment was more effective than persulfate alone at treating the site-specific COCs. While the reaction rate using persulfate was slower for some compounds (several days), the rates for reducing two of the more abundant COCs, benzene and vinyl chloride, to non-detectable levels were relatively rapid (a few hours). In the subsequent field studies, persulfate also proved to be more persistent

than percarbonate, lasting several days, whereas the percarbonate was used up very rapidly, making it ineffective for treating the slower reacting compounds.

### 3.1 Bench Scale Test Methodology and Results

The first study was conducted to demonstrate the effectiveness of In Situ Chemical Oxidation (ISCO) using alkaline persulfate to treat volatile organic compounds (VOCs) present at the site. The bench tests were conducted on the soil-ground water slurry under the following three conditions: 1) persulfate alone; 2) pH adjusted persulfate [with potassium hydroxide (KOH)]; and 3) a staged approach with an initial dose of persulfate followed by a dose of persulfate at an alkaline pH. These three conditions were measured against a control, which consisted of soil and ground water only. The tests were run in a sealed 500 mL centrifuge bottle. They were charged with 150 g of soil (sieved with a 4.75 mm screen) and 200 mL of ground water and the appropriate amounts of chemicals. Each test jar had about 200 mL of headspace. The headspace was not analyzed during the test for VOCs. The VOC data for the initial soil and ground water samples used to charge the bottles are listed in Table 1 as are the concentrations of the soil and water phases for the initial test conditions after mixing.

Table 1. Summary of T=0 Soil and Ground Water Analytical Results

ISCO Bench Scale Test		Initial Char.		T=0	
Parameter	Units	Value		Value	
Vinyl Chloride	ug/kg	<560	U	590	J
Acetone	ug/kg	3400		12000	
1,1-DCA	ug/kg	160	J	29000	J
1,2-DCA	ug/kg	<220	U	2500	
Benzene	ug/kg	<110	U	630	
Toluene	ug/kg	<560	U	<2500	U
TBA	ug/kg	1400	J	5100	J
2-Chloropropene	ug/kg	<560	U	5100	

Ground Water		Initial Char.		T=0	
Parameter	Units	Value		Value	
Vinyl Chloride	ug/L	8700		18000	
Acetone	ug/L	59000		66000	
1,1-DCA	ug/L	140000	J	220000	
1,2-DCA	ug/L	10000		14000	
Benzene	ug/L	1900		4800	
Toluene	ug/L	<5000	U	<12000	
TBA	ug/L	<100000	U	<250000	
2-Chloropropene	ug/L	48000		98000	

Notes: U = Not Detected J = Estimated Concentration

The supernatants from each of the three bench test slurries and the control were analyzed for pH, oxidation reduction potential (ORP), residual persulfate, and VOCs after 14 days and 28 days, respectively. Soils from the samples were analyzed for pH and VOCs. Table 2 presents the VOC data for the three test conditions in terms of the percent removal for each constituent relative to the control. The percent removal is given for both the aqueous phase and the total constituent mass.

Residual persulfate was also measured after 14 and 28 days by titration. The persulfate data is presented in Table 3, which also includes pH and ORP data. After 14 days, there was a 14 to 28% loss of persulfate. The persulfate/KOH test had the highest initial loss. The percent loss of persulfate after 28 days was 17 to 32%, which was not significantly greater than the initial loss. The persulfate loss was much less in the 14-28 day period than in the 0-14 day period, only 3.6 to 5.8% was lost. The results indicated that a persulfate/alkaline mix was more effective than persulfate only.

The data suggests that there was an initial consumption of persulfate. The iron present (12,000 mg/Kg) is probably reduced and reacted with the persulfate. Once the iron was oxidized, the persulfate appears to be fairly stable. On a stoichiometric basis, the iron present would have consumed about 10% of the persulfate added. This would account for the initial loss of persulfate.

The effectiveness of the persulfate/KOH requires that the pH be kept at 10 or above. This is generally accomplished by adding 0.5 moles of the alkaline, in this case KOH, per mole of persulfate. In addition, the natural soil acidity needs to be compensated for. This is generally done by titrating the soil to a pH of 10 and adding extra KOH to neutralize the soil based on this titration. It took 70 mL of 0.05 N KOH to raise the pH of 50g of soil to 10. The pH of the test jars was measured at 14 and 28 days (Table 3). The soil appears to be buffered as the pH of the persulfate only jar was 6.9 after 28 days. Typically, in the water phase only, the addition of persulfate drops the pH to < 2.0 due to the production of sulfuric acid.

The soil seems also to buffer the KOH. In the setup of the persulfate/KOH test, a 4-fold excess of KOH (based on a 0.5 mole ratio) was added. The pH of the jar was 12.5. With the staged test, after 14 days, KOH was added at a 0.5 mole ratio with a 50% excess. The pH only rose to 8.8 after 28 days, less than the expected pH of 10 – 11.

Table 2. Percent Change from Control ISCO Bench Scale Test

Aqueous Phase							
Constituent	Units	Persulfate Only		Persulfate/KOH		Staged	
		14 Day	28 Day	14 Day	28 Day	14 Day	28 Day
Vinyl Chloride	ug/L	86.7	--	96.1	97.8	65.7	9.1
Acetone	ug/L	-7.3	-54.3	98.6	99.5	-9.1	20
1,1-DCA	ug/L	34.1	61.3	99	98.7	-24.4	33.3
1,2-DCA	ug/L	7.4	28.1	99.5	99.4	-3.7	50
Benzene	ug/L	21.9	--	86.6	79	21.9	--
TBA	ug/L	-5.9	--	95.9	95	-41.2	--
2-Chloropropene	ug/L	92.3	80.2	97	97.1	96.9	91.9

Total COC Mass							
Constituent	Units	Persulfate Only		Persulfate/KOH		Staged	
		14 Day	28 Day	14 Day	28 Day	14 Day	28 Day
Vinyl Chloride	ug/L	86.7	--	96.1	97.8	65.7	--
Acetone	ug/L	-7.3	-48.4	98.6	99.4	-9.1	40.4
1,1-DCA	ug/L	34.1	61.3	99	98.7	-24.4	40.6
1,2-DCA	ug/L	7.4	31.5	99.5	99.5	-3.7	58.2
Benzene	ug/L	--	--	86.6	44.1	--	--
TBA	ug/L	-5.9	79	95.9	94	-41.2	--
2-Chloropropene	ug/L	90.6	78	97	97.3	96.9	92.7

## NOTES:

Highlight denotes that one-half the detection limit was used for calculation.

"--" denotes that detection limit was too high to use in calculations

Table 3. Summary of pH, ORP, and Residual Oxidant Measurements

<b>Day 14 Results</b>					
<b>Treatment</b>	<b>pH</b>	<b>ORP</b>	<b>Persulfate (mg/L)</b>	<b>% Loss Persulfate</b>	
<b>1</b>	Persulfate	6.7	528	42962	14.1
<b>2</b>	Persulfate + KOH	12.5	325	35801	28.4
<b>3</b>	Staged	7.1	518	41768	16.5
<b>4</b>	Control	7.8	427	0	--

## NOTES:

1. 6.0 g sodium persulfate and 1.056 g KOH added to treatment 3.

<b>Day 28 Results</b>							
<b>Treatment</b>	<b>pH</b>	<b>ORP</b>	<b>Persulfate (mg/L)</b>	<b>% Loss Persulfate</b>		<b>Soil pH</b>	
				<b>0 – 28 days</b>	<b>14 – 28 days</b>		
<b>1</b>	Persulfate	6.9	556	41172	17.7	3.6	7
<b>2</b>	Persulfate + KOH	12.5	347	34011	32	3.6	11.2
<b>3</b>	Staged	8.8	533	76224	22.2	5.8	8.8
<b>4</b>	Control	7.5	421	0	--		7.8

## NOTES:

Soil pH measured with 10 g soil and 40 mL deionized water.



Based on the results of this bench scale test, it was observed that:

- A loss of VOCs in the controls was observed over the course of the tests, with the exception of TBA. This was likely due to volatilization into the headspace.
- The second observation was that the persulfate plus KOH was effective in oxidizing each of the VOCs present. In general this system resulted in a greater than 90% reduction of the VOCs.
- Vinyl chloride was easily oxidized, responding to both persulfate alone and persulfate/KOH. 1, 1-DCA and 1, 2-DCA, were resistant to oxidation and were only completely oxidized by the persulfate/KOH.

The persulfate/KOH worked well on each of the COCs. Persulfate alone did not have better reactivity for the COCs than the persulfate/KOH. In addition, there was no apparent benefit to staging the treatment. Based on the results of the initial bench scale study, a field scale pilot study was conducted.

#### **4. FIELD SCALE PILOT TEST**

The purpose of the MAM ISCO pilot study was to demonstrate the feasibility of in-situ soil mixing using a chemical oxidant and to provide information for preparing full scale remediation specifications. The objectives of the MAM ISCO pilot test were to assess whether:

- MAM would be effective at liquefying the clayey soil and achieving a small clod size;
- MAM would be capable of auger mixing to a depth of 25 feet in a reasonable time frame;
- MAM would be capable of injecting a chemical oxidant solution proven to be effective based on bench-scale testing;
- The resultant soil slurry created by the soil mixing with chemical oxidant solution can be amended with lime, cement or fly ash to restore its bearing strength; and
- Vapors and air emissions from a MAM pilot hole can be controlled via available control technologies and provide an emission rate to assess whether air emission controls are necessary.

##### **4.1 Pilot Test Procedures**

A specialized auger rig was used for the pilot test; it was capable of mixing oxidant and water with the site's clayey soils as it augered through them to create a slurry of treated soil. The equipment used was similar to that typically used for full-scale implementation of the remedy using this technology. The augers were 6 feet in diameter and created a 6-foot diameter treated column to 25 feet below ground surface (bgs). An initial test boring was completed to demonstrate the feasibility of the augering technology with a candidate oxidant mix followed by the completion of four additional borings to provide design information and data for alternative oxidant formulations.

Prior to drilling, a 5-foot deep pit was excavated at each drilling location to accommodate the expansion of the soils (fluff) due to the mixing process. Some of the excavated surficial soil was used to create small berms to divert stormwater from entering the excavations. The surficial soils, although they exhibited no odors or field OVM (flame ionization detector, FID OVM) readings above background, were placed in roll-off boxes for transport and disposal.

The following test mixtures and solidification agents were used for the test borings:

- Test Hole PT-1 - Initial Feasibility Test Case - 4 percent persulfate, 2.5 percent lime, and upper 5 feet mixed slowly with dry cement by the rig or backhoe;
- Test Hole PT-2 – Alternate Solidification Agent - 4 percent persulfate, 2.5 percent lime, and upper 5 feet mixed slowly with fly ash cement by the rig or backhoe;
- Test Hole PT-3 – Base Case – 4 percent persulfate, 2.5 percent lime, and 5 percent cement slurry in full column;
- Test Hole PT-4 - Alternative Oxidant – 2 percent percarbonate, 3 percent persulfate, 2.5 percent lime, and 5 percent cement slurry in full column; and
- Test Hole PT-5 – High Persulfate Effect on Solidification – 6 percent persulfate, 4 percent lime is increased to keep same ratio to persulfate), and 5 percent cement slurry in full column.

To restore the bearing strength of the ground surface, a 5% cement mixture was injected into the slurry. After mixing, samples of the fluff were collected to estimate clod size and to assess the extent of the slurry set-up as a result of cement addition.

Prior to initiating the pilot test, each MAM location was cored and sampled to provide baseline information for geotechnical parameters and initial VOA organic concentrations.

Following the injection phase of the pilot test, soil borings were installed in each of the pilot test pits to collect samples of the treated soil. Samples were collected at three depths and at three time intervals following the injection/mixing: Initial [ $T_1$ ] (immediately following injection/mixing); Time 2 [ $T_2$ ] (one week after injection/mixing); and Time 3 [ $T_3$ ] (28 days after injection/mixing). These samples were collected to assess the effectiveness of different stabilizing agents (e.g., Portland cement and fly ash). These stabilizing agents are required to re-establish the bearing strength of the soil after mixing and treatment.

Samples of the soil mixtures were tested for VOA organics to test the effectiveness of the mixing process relative to the different mixtures injected. Samples were also collected to assess the amount of excess oxidant remaining in each test boring.

## 4.2 Pilot Test Results

The first objective of the pilot test entailed liquefying and breaking down the clayey soils to a clod size of approximately 4 to 5 inches or less in diameter. The following clod sizes were measured in the field for samples collected from the boring at the surface of the slurry, 10 ft bgs, and 20 ft bgs:

Sample Depth	Clod Size (inches)
Surface	Mostly less than 1 in. but ranges up to 2 in.
10 ft bgs	0.25 in to 1 in.
20 ft bgs	1.5 to 2 in.

Based on field observations, approximately 75% of the soil was liquefied and was present in the mixed slurry. Large clods (up to 1 foot in diameter) were observed on the auger bit when retrieved; however, the samples of the slurry collected at all three depths showed much smaller clod sizes.

Following mixing, the fluff filled four of the five pits to within one foot of the surface. The pit for boring PT-4 (fifth pit) overflowed due to the reaction of the percarbonate with the ground water creating carbon dioxide gas. This resulted in greater expansion of the soil mixture than was observed in the other test borings. The overall fluff expansion observed at each test boring indicated that the treated soil volume was approximately two (2) times the in situ soil volume.

The second and third objectives of mixing the soil with a chemical oxidant solution to a depth of 25 feet in a reasonable time frame were also achieved. The above results were obtained after augering to a depth of 25 feet and mixing during a total augering time period of approximately one hour. No impediments were encountered during the injection of oxidant solution through the auger jets.

A summary of the persulfate and COC analyses relative to the original design mixtures for each boring are provided in Tables 4 and 5. The data show that oxidant was effectively delivered to the applicable test boring depths. Higher concentrations of oxidant were found in several of the treated soil samples than anticipated from the initial design estimates. This finding is primarily attributed to the soil having a lower bulk density than was originally estimated.

Table 4. Summary of Persulfate and Percarbonate Analytical Results

Constituents		5-7 ft			15-17 ft			23-25 ft		
		T <sub>1</sub>	T <sub>2</sub>	T <sub>3</sub>	T <sub>1</sub>	T <sub>2</sub>	T <sub>3</sub>	T <sub>1</sub>	T <sub>2</sub>	T <sub>3</sub>
<b>PT-1</b>	Persulfate	0. 89	1.79	1.19	6.54	1.19	0.56	8.92	1.79	2.38
<b>PT-2</b>	Persulfate	7. 73	1.19	0.60	6.54	1.79	4.76	7.14	4.17	4.17
<b>PT-3</b>	Persulfate	6. 54	1.79	2.98	7.73	2.38	2.08	7.14	1.79	2.38
<b>PT-4</b>	Persulfate	8. 33	2.98	2.38	7.44	2.38	1.49	5.36	4.17	2.98
	Percarbonate	5. 60	2.00	1.60	5.00	1.60	1.00	3.60	2.80	2.00
<b>PT-5</b>	Persulfate	1. 79	2.98	2.38	5.06	6.55	2.68	6.54	4.76	2.98

Table 5. Comparison of Shallow Pilot Test Soil Results

Constituents	PT-1			PT-2		
	To 2/14/2006	T <sub>1</sub> 2/20/2006	T <sub>3</sub> 3/28/2006	To 2/14/2006	T <sub>1</sub> 2/21/2006	T <sub>3</sub> 3/28/2006
1,1-DCA	1.7	8.2	0.02	22	14	U
Acetone	U	0.17	U	U	3.7	U
Benzene	0.038	0.040	U	0.63	0.11	U
TBA	U	0.24	U	0.41	0.14	U
Vinyl chloride	2.7	0.91	0.003	4.9	1.3	0.0029

  

Constituents	PT-3			PT-4		
	To 2/14/2006	T <sub>1</sub> 2/22/2006	T <sub>3</sub> 3/28/2006	T <sub>0</sub> 2/14/2006	T <sub>1</sub> 2/22/2006	T <sub>3</sub> 3/28/2006
1,1-DCA	20	27	U	76	U	U
Acetone	0.016 J	9.4	U	3.5	U	U
Benzene	0.2	0.58	U	2.3	U	U
TBA	0.4	0.41	U	0.47	U	U
Vinyl chloride	4.4	4.0	U	7.3	U	U

Table 5 Continued

Constituents	PT-5		
	T <sub>0</sub>	T <sub>1</sub>	T <sub>3</sub>
	2/14/2006	2/22/2006	3/28/2006
1,1-DCA	20	5.7	U
Acetone	U	0.18	U
Benzene	0.63	0.048	U
TBA	0.36	0.12	U
Vinyl chloride	2.8	0.39	U

NOTE: The typical detection limit for the COC analyses was 0.001 mg/kg

The fourth objective was also achieved. Fly ash, an inexpensive pozzolanic alternative to cement, was mixed with the slurry at the surface to solidify the slurry and re-establish the approximate bearing strength of the ground surface. Based on field observations the fly ash augmented slurry set up as expected.

The fifth objective of the pilot study was to conduct it safely and effectively while controlling air emissions. Previous site investigation test results were used to allow an initial excavation of five feet to create a bowl to contain the “fluff” (volume expansion) created by liquefying the soil column. No odors or sustained readings above background levels were noted during the excavation or augering. FID readings were also collected from the rig operator’s cabin and no readings above background were observed.

During the pilot study the boring location, excavation, and auger were enclosed within a plastic shroud and air within the shroud was routed to a series of activated carbon canisters to remove organic from the emissions prior to discharge. A week after the injection tests, no sustained FID readings above background (0 ppm) were observed in the carbon canister exhaust. The influent monitoring results showed that a maximum sustained vapor concentration in the carbon canister influent was 84 ppm. Only an ephemeral 1.2 ppm was detected in the effluent. This data documents the effectiveness of the carbon canisters at adsorbing the vapors from the soil mixing prior to air discharge from the hood.

Additional observations made during the pilot test indicated the following:

- Treated soil volume was approximately two (2) times the in situ soil volume.
- Treated soil will not have sufficient strength to support reconstruction of a road over the treated area.
- Analytical results indicate that injection of persulfate as the oxidant can destroy in practice greater than 90% of the COCs in the ground water and soil. This estimate is based on bench-scale tests that demonstrate over 90% destruction of the most predominant COCs in a laboratory setting and on analytical results for soil samples collected before and after the pilot test that demonstrated nearly 100% destruction after treatment.

### **4.3 Post Pilot Ground Water Dissolved Oxygen Data Evaluation**

Following the application of MAM ISCO to the upper 25 feet of soil, subsequent ground water monitoring indicated that the dissolved oxygen content of the shallow aquifer increased as expected, but data also indicated that the concentration of dissolved oxygen increased in the deeper aquifer within six weeks of the pilot study in a area underneath and adjacent to the location of the pilot study. Based on quarterly sampling data, the dissolved oxygen concentrations in the underlying deeper aquifer remained elevated for at least six months but had returned to pre-pilot study levels within a total of nine months. Table 6 summarizes the dissolved oxygen data for three wells in the S2 sand.

Table 6. Summary of Deep Aquifer Dissolved Oxygen Data

Date	Wells		
	A	B	C
11/22/05	0.47	0.35	0.60
02/02/06	0.42	0.40	0.35
03/29/06	5.46	1.25	0.55
09/07/06	2.54	2.20	0.17
12/07/06	0.24	0.18	0.17

Wells A and B are located just up gradient and down gradient, respectively, to the pilot study location with well A being located closer to the pilot study than well B. Well C is another deeper aquifer well, but it is located further away from and cross gradient to the pilot study location and is representative of other deeper aquifer wells further away from the location of the pilot study that did not show an increase of dissolved oxygen concentrations. The MAM ISCO field pilot study was conducted in mid-February 2006, shortly after an early February 2006 ground water sampling event. Such an increase in dissolved oxygen may have potentially acted to temporarily increase the aerobic biodegradation of some of the constituents present in the deeper aquifer.

## 5. CONCLUSIONS

The following conclusions can be drawn from the test results:

- Most remedial technologies would not be effective in treating the case study site due to the inherent difficulty of inducing oxidant, water, or air/vapor penetration and transport through soils and sediments of low conductivity in which most of the site contaminants are bound.
- Mechanical auger mixing with a chemical oxidant represents a viable alternative for addressing sites where most of the mass is located in low permeability soils and sediments.
- Persulfate with an alkaline source for controlling pH and activating persulfate is effective in treating a complex mixture of oxygen-containing hydrocarbons, and chlorinated and non-chlorinated COCs.
- Mechanical auger mixing provided an effective means of introducing the oxidant and activator into clayey soils resulting in effective removal of over 95% of the COCs using persulfate at the demonstration site.
- The addition of cement does not impact the oxidation efficiency of the persulfate. There was not a significant difference observed between the COC reduction attained with alkaline activated oxidant with/or without cement addition.