APPENDIX C

IN SITU CHEMICAL OXIDATION BENCH SCALE
TREATABILITY STUDY REPORT

TABLE OF CONTENTS

Page

1.0 INTRODUCTION C-1
1.1 DESCRIPTION OF ISCO C-1

2.0 TREATABILITY STUDY OBJECTIVES C-3

3.0 BENCH SCALE TREATABILITY STUDY C-4
3.1 TASK 1: INITIAL CHARACTERIZATION C-4
3.2 TASK 2: MICROCOSM TESTS C-5
3.3 TASK 3: NATURAL OXIDANT DEMAND C-7

4.0 CONCLUSIONS C-9

5.0 RECOMMENDATIONS C-10

LIST OF TABLES
(Following Appendix)

TABLE 1	INITIAL ANALYSIS OF GROUNDWATER SAMPLES
TABLE 2	INITIAL ANALYSIS OF SOIL SAMPLES
TABLE 3	CHEMICAL OXIDATION OF GROUNDWATER GW-4B WITH $KMnO_4$
TABLE 4	CHEMICAL OXIDATION OF GROUNDWATER GW-4B WITH $Na_2S_2O_8$
TABLE 5	CHEMICAL OXIDATION OF GROUNDWATER GW-4B WITH FENTON'S REAGENT
TABLE 6	CHEMICAL OXIDATION OF GROUNDWATER GW-6S WITH $KMnO_4$
TABLE 7	CHEMICAL OXIDATION OF GROUNDWATER GW-6S WITH $Na_2S_2O_8$
TABLE 8	CHEMICAL OXIDATION OF GROUNDWATER GW-6S WITH FENTON'S REAGENT
TABLE 9	CHEMICAL OXIDATION OF SOIL GP-20-1 WITH $KMnO_4$
TABLE 10	CHEMICAL OXIDATION OF SOIL GP-20-1 WITH $Na_2S_2O_8$
TABLE 11	CHEMICAL OXIDATION OF SOIL GP-20-1 WITH FENTON'S REAGENT
TABLE 12	CHEMICAL OXIDATION OF SOIL GP-25-1 WITH $KMnO_4$
TABLE 13	CHEMICAL OXIDATION OF SOIL GP-25-1 WITH $Na_2S_2O_8$
TABLE 14	CHEMICAL OXIDATION OF SOIL GP-25-1 WITH FENTON'S REAGENT
TABLE 15	ANALYSIS OF NATURAL OXIDANT DEMAND

1.0 INTRODUCTION

The GE Old Erie Canal site (Site) is located in Clyde New York. As part of an evaluation of remedial alternatives for the Feasibility Study (FS) being conducted for the Site it was proposed to perform laboratory treatability studies to determine the effectiveness of in situ chemical oxidation (ISCO) and enhanced bioremediation for treatment of the contaminants present at the Site. Conestoga-Rovers & Associates (CRA) were requested to perform an ISCO treatability study at their laboratory in Niagara Falls, New York. The following report describes the results of the ISCO laboratory treatability study and makes recommendations regarding application of the technology at the Site.

The results of the enhanced bioremediation studies are presented in Appendix B of the FS. Descriptions of the Site conditions and nature and extent of chemical presence are presented in Section 3 of the FS.

1.1 DESCRIPTION OF ISCO

ISCO is an effective technology for destroying a wide range of volatile organic compounds (VOCs), including those present at the Site (trichloroethene [TCE], cis-1,2-dichloroethene [cis-1,2-DCE], and vinyl chloride [VC]). The technology is based on the use of strong oxidizing agents to completely oxidize the VOCs within relatively short periods. In a chemical oxidation reaction, the oxidizing agent breaks the double carbon bonds in chlorinated compounds such as TCE, cis 1,2-DCE, and VC and converts them within hours into non-toxic compounds, primarily carbon dioxide and water.

The oxidizing agents most commonly used include:

i) potassium permanganate [$KMnO_4$];

ii) Fenton's Reagent (Fenton's, a solution of hydrogen peroxide and ferrous sulfate);

iii) ozone; and

iv) sodium persulfate ($Na_2S_2O_8$).

$KMnO_4$, Fenton's, and ozone are the most commonly used oxidants. $Na_2S_2O_8$ is emerging as a promising oxidizing reagent but is still in the developmental stage. $KMnO_4$ is preferred because it is demonstrated to be effective and is easier to handle than Fenton's, which is pH-dependent and requires the use of ferrous salt as a catalyst for optimum performance. The application involves simple methods and does not require the sophisticated equipment used in ozone treatment.

These oxidizing reagents react relatively quickly with chlorinated ethenes, including TCE, cis 1,2-DCE, and VC, through a series of chemical reactions, completely mineralizing them into neutral end products such as manganese dioxide (MnO_2), chloride ions, water, and carbon dioxide.

ISCO is typically a site-specific and successful treatment technology. However, its effectiveness is often a function of the effectiveness of the delivery system (being able to deliver sufficient amounts of oxidant to the impacted soil and groundwater and making sufficient "contact") and subsequent transport of the oxidant within the aquifer. The treatment performance is dependent to a great extent on the soil and groundwater chemistry.

A critical factor in the evaluation of ISCO treatment is determining the dosages of oxidant that are required to effectively oxidize the contaminants present (referred to as "stoichiometric demand") and overcome competing reactions. Competing reactions are typically caused by the presence of non-target compounds, natural organic materials such as humates and fulvates as well as reduced metal species. The consumption of oxidants by these non-target compounds is defined as natural oxidant demand (NOD). In order to determine the optimum dosage of oxidant required to effectively oxidize the contaminants present, treatability studies are required.

2.0 TREATABILITY STUDY OBJECTIVES

The primary objective of this laboratory study was to gather the data necessary to:

i) assess the effectiveness of $KMnO_4$ for treatment of the compounds of concern (VOC, primarily TCE, cis-1,2-DCE, and VC) in representative soil and groundwater samples from the Site;

ii) assess the variability of the natural oxidant demand in the treatment areas; and

iii) determine the effective concentration/dosage of oxidant required to complete treatment as expeditiously as possible.

3.0 BENCH SCALE TREATABILITY STUDY

3.1 TASK 1: INITIAL CHARACTERIZATION

Samples were received from the Old Erie Canal Site on May 5, 2004. The groundwater samples were analyzed for:

i) pH; and
ii) VOCs.

Soil samples were removed from soil core liners and homogenized in glass jars. A sub-sample of soil was collected from each homogenized soil sample and analyzed for the following parameters:

i) pH;
ii) percent moisture;
iii) total organic carbon (TOC); and
iv) VOCs.

The results of the groundwater analyses are shown in Table 1 and the results of the soil analyses are shown in Table 2. Cis-1,2-DCE and VC exhibited the highest concentrations in the groundwater samples. Cis-1,2-DCE concentrations were 60.4 milligrams per liter (mg/L) and 50.2 mg/L in samples GW-6S and GW-4B respectively. VC was present at 32.7 mg/L and 21.2 mg/L in samples GW-6S and GW-4B, respectively. Toluene, ethylbenzene, and xylenes were also present in the samples at lower concentrations. Tetrachloroethene (PCE) was not detected in either groundwater sample. All soil samples contained TCE and cis-1,2-DCE at concentrations ranging from 26.4 milligrams per kilogram (mg/Kg) to 0.171 mg/Kg for TCE and 58.9 mg/Kg to 0.052 mg/Kg for cis-1,2-DCE. The concentrations of toluene, ethylbenzene, and xylenes were generally lower than the chlorinated ethene concentrations. The sample from the area in which boring GP-20 was located had the highest concentrations of VOCs, including toluene, TCE, cis-1,2-DCE, and VC at 31.6 mg/Kg, 3.8 mg/Kg, 58.9 mg/Kg, and 27.1 mg/Kg, respectively. Total organic matter (TOM) varied from 0.37 to 4.66 percent and percent moisture varied from 5.62 to 22.1. The major contributor to the TOM in sample GP-25-1 appeared to be petroleum hydrocarbons.

Based on the VOC results from the initial analyses, two soil samples (GP-20-1 and GP-25-1) were chosen for treatability testing. Both groundwater samples (GW-6S and GW-4B were selected for treatability study testing.

3.2 TASK 2: MICROCOSM TESTS

A series of microcosm tests were conducted. The groundwater microcosms were performed using the two water samples. The soil microcosm tests were performed using 100 gram (g) soil samples from the two soil samples. The tests were conducted to assess the effectiveness of the selected chemical oxidizing agents for treatment of the VOCs in the soils and to determine the optimum concentration range of the chemical oxidizing agent solution, which would be required for field treatment. Based on the specific VOC that was present at the Site, the following three chemical oxidizing agents were selected for bench-scale testing:

i) potassium permanganate ($KMnO_4$);

ii) Fenton's Reagent (Fenton's); and

iii) sodium persulfate ($Na_2S_2O_8$).

The groundwater microcosm tests consisted of placing 110 milliliters (mL) of composite groundwater in 125 mL serum bottles and injecting with 10 mL of $KMnO_4$, hydrogen peroxide (H_2O_2), or $Na_2S_2O_8$ solutions at varying concentrations. The bottles were injected with:

i) 10 mL of varying concentrations of $KMnO_4$ solution (0.05, 0.1, 0.5, and 1 percent, wet weight [w/w]);

ii) 10 mL of varying concentrations of $Na_2S_2O_8$ solution (0.5, 1, and 3 percent, w/w) catalyzed with 0.4 g of hydrogen peroxide; and

iii) 10 mL of varying concentrations of H_2O_2 (1, 5, and 10 percent, w/w) catalyzed with 200 parts per million (ppm) iron (Fe) as ferrous sulfate.

Control tests were prepared similarly but received 10 mL of water rather than oxidant solution. The bottles were sealed to prevent the loss of VOCs through volatilization and incubated at laboratory temperature, inverted, in the dark for 2 weeks. At the end of the incubation period, the water microcosms were sampled and analyzed for residual VOCs. The results of these analyses are shown in Tables 3 through 8.

The soil microcosm tests consisted of placing 100 g of soil in 4 ounce glass jars and mixing with $KMnO_4$, H_2O_2, or $Na_2S_2O_8$ solutions at varying concentrations. The samples were injected with:

i) 25 mL of varying concentrations of $KMnO_4$ solution (0.1, 0.5, 1, and 3 percent, w/w);

ii) 25 mL of varying concentrations of $Na_2S_2O_8$ solution (1, 3, and 5 percent, w/w) catalyzed with 1 g of H_2O_2; and

iii) 25 mL of varying concentrations of H_2O_2 (5, 15, and 30 percent, w/w) catalyzed with 200 ppm Fe as ferrous sulfate.

Control tests were prepared similarly but received 25 mL of water rather than oxidant solution. The jars were sealed immediately to prevent the loss of VOCs through volatilization and incubated in the dark at lab temperature for 2 weeks. After 2 days it was noticed that the purple color of the $KMnO_4$ was no longer visible even in the treatments that had received the highest $KMnO_4$ dose. Therefore, an additional dose of oxidant equal to the first dose was administered to all samples. After another 2 days the $KMnO_4$ color was no longer visible once again; therefore, a further dose of oxidant was administered to all samples. Two weeks after the first dose of oxidant, the microcosms were sacrificed and analyzed for residual VOCs. The results of these analyses are shown in Tables 9 through 14.

The results for groundwater sample GW-4B showed that all of the VOCs except toluene and xylene were removed to below the detection limit of 50 micrograms per liter (μg/L) by 1 percent $KMnO_4$ which corresponds to a loading rate of 0.8 g $KMnO_4$ per liter (/L) of groundwater. Fifty percent of the toluene was removed and 70 percent of the xylene was removed. Treatment with 3 percent $Na_2S_2O_8$ (2.4 g $Na_2S_2O_8$/L of groundwater) removed between 50 percent and 80 percent of the total VOCs. Treatment with Fenton's showed the highest removal rates in this groundwater sample. One percent H_2O_2 (0.8 g H_2O_2/L groundwater) removed between 67 percent and 99 percent of the total VOCs; 5 percent H_2O_2 (4 g H_2O_2/L groundwater) removed greater than 96 percent of the total VOCs; and 10 percent H_2O_2 (8 g H_2O_2/L groundwater) removed greater than 98 percent of the total VOCs.

For groundwater sample GW-6S, all the VOCs except toluene and xylene were removed to below the detection limit by 1 percent $KMnO_4$, which corresponded to a loading rate of 0.8 g $KMnO_4$/L of groundwater. Sixty percent of the toluene was removed and 66 percent of the xylene was removed. Treatment with 3 percent $Na_2S_2O_8$ (2.4 g $Na_2S_2O_8$/L of groundwater) removed between 56 percent and 99 percent of the VOCs with the exception of trans-1,2-DCE, of which only 3 percent was removed. Treatment with Fenton's also showed the highest removal rates in this groundwater sample. One percent H_2O_2 (0.8 g H_2O_2/L groundwater) removed between 63 percent and 86 percent of the total VOCs; 5 percent H_2O_2 (4 g H_2O_2/L groundwater) removed greater than 96 percent of total VOCs; and 10 percent H_2O_2 (8 g H_2O_2/L groundwater) removed greater than 95 percent of the VOCs.

For soil sample GP-20-1, VOC removal with $KMnO_4$ was poor. Only VC and trans-1,2-DCE were effectively removed from the soil. Treatment with $Na_2S_2O_8$ was somewhat better. One percent $Na_2S_2O_8$ (7.5 g $Na_2S_2O_8$ per kilogram [/Kg] of soil) removed between 77 percent and 99 percent of the total VOCs. Treatment with Fenton's containing 30 percent H_2O_2 (225 g H_2O_2/Kg soil) removed between 59 percent and 99 percent of the total VOCs.

For soil sample GP-25-1, removal with $KMnO_4$ was again poor. Only cis-1,2-DCE and TCE were effectively removed from the soil. Treatment with $Na_2S_2O_8$ was again better. One percent $Na_2S_2O_8$ (7.5 g $Na_2S_2O_8$/Kg of soil) removed between 53 percent and 99 percent of the VOCs with the exception of m/p-xylene, which was not removed. Treatment with Fenton's showed good treatment of cis-1,2-DCE and TCE. However, toluene and xylene were not removed by the treatment, and appeared to increase in concentration. The increase may be because the H_2O_2 broke down the clay matrix of the soil resulting in release of additional toluene and xylene that was previously bound to the clay.

3.3 TASK 3: NATURAL OXIDANT DEMAND

The NOD of the soil samples was assessed by placing 50 g of each original homogenized soil sample in an 8 ounce jar and adding 100 mL of 1 percent $KMnO_4$. The initial $KMnO_4$ concentration was recorded by measuring the absorbance at 525 nanometers (nm) and comparing to a standard curve. Each week the jar was sampled and the $KMnO_4$ concentration was recorded.

The NOD of the groundwater sample was assessed by placing 100 mL of the composite soil in a four ounce jar and dissolving 1 g of solid $KMnO_4$ in it. The initial $KMnO_4$ concentration was recorded. Each week the jar was sampled and the $KMnO_4$ concentration was recorded.

The NOD test was run for 5 weeks. Each week the jars were analyzed for residual $KMnO_4$. For soil samples GP-16-1 and GP-25-1, all of the $KMnO_4$ added was consumed and additional quantities of $KMnO_4$ were added until the $KMnO_4$ was no longer consumed. After 5 weeks, soil sample GP-16-1 had consumed 41.6 g of $KMnO_4$/Kg soil; soil sample GP-20-1 had consumed 19.2 g of $KMnO_4$/Kg soil; soil sample GP-25-1 had consumed 45.5 g of $KMnO_4$/Kg soil; soil sample GP-32-1 had consumed 18.9 g of $KMnO_4$/Kg soil; and soil sample GP-36-1 had consumed 19.7 g of $KMnO_4$/Kg soil.

After 5 weeks, groundwater sample GW-6S had consumed 7.5 g of $KMnO_4$/L of groundwater and groundwater sample GW-4B had consumed 6.6 g of $KMnO_4$/L of groundwater. Neither groundwater sample consumed all of the $KMnO_4$, therefore the subsequent addition of $KMnO_4$ was not necessary.

The high NOD in the soil samples may be explained by the presence of petroleum hydrocarbons in the soil. The $KMnO_4$ does not appear to have completely penetrated the clay matrix; therefore the NOD data obtained using $KMnO_4$ does not reflect the true NOD of the soil. The dose rates found in the microcosms treated with Fenton's are a better reflection of the amounts needed to treat the soil.

4.0 CONCLUSIONS

Based on the results of the ISCO bench-scale treatability studies undertaken, the following conclusions are drawn:

i) the NOD of all five of the soil samples is relatively high, which is likely due to the presence of petroleum hydrocarbons. The NOD of the two water samples is considerably lower that that of the soil samples;

ii) potassium permanganate:

- potassium permanganate was effective in treating all the VOCs, except toluene and xylene in the two groundwater samples, and
- potassium permanganate was effective in treating cis and trans-1,2-DCE and TCE in the soil samples, however it did not remove any of the other VOCs present;

iii) sodium persulfate:

- sodium persulfate removed between 50 and 99 percent of the VOC in the two groundwater samples, and
- sodium persulfate removed between 53 and 99 percent of the VOC in the two soil samples; and

iv) Fenton's Reagent:

- Fenton's Reagent was effective in removing over 96 percent of the VOCs in the two groundwater samples using a dose rate of 4 g H_2O_2/L of groundwater,
- Fenton's Reagent achieved the best treatment of the VOCs in the soil samples treating between 59 and 99 percent of vinyl chloride, cis- and trans-1,2-DCE, TCE, and ethylbenzene, however toluene and xylenes were not effectively removed and in some cases increased,
- the breakdown of the clay matrix may have caused the release of previously bound VOCs from the soil, and
- the optimum dose rate for the soils was 225 g H_2O_2/Kg of soil for sample GP-25-1 and 113 g H_2O_2/Kg of soil for sample GP-20-1.

5.0 RECOMMENDATIONS

Based on the results of the ISCO treatability studies, the NOD of the Site soil is too high for ISCO to be a cost-effective treatment. However, ISCO be could be used to effect an initial decrease VOC levels. The residual concentrations of VOCs remaining in the soil could then be treated by natural attenuation or enhanced natural attenuation. If initial treatment with ISCO is selected as a component of the Site remedy, Fenton's Reagent is recommended for use as the oxidizing agent. The recommended dose rate for ISCO using Fenton's Reagent is 113-225 g H_2O_2/Kg of soil. Whether 113 g or 225 g is used will depend on the area to be treated.

APPENDIX C

TABLES

TABLE 1

INITIAL ANALYSIS OF GROUNDWATER SAMPLES
OLD ERIE CANAL CHEMICAL OXIDATION STUDY
OLD ERIE CANAL SITE
CLYDE, NEW YORK

Sample ID	***Units***	***GW-6S***	***GW-4B***
pH	S.U.	7.6	7.7
Vinyl Chloride	µg/L	32700	21200
Cis-1,2-Dichloroethylene	µg/L	60400	50200
Trichloroethylene	µg/L	ND (2)	857
Toluene	µg/L	6770	202
Perchloroethylene	µg/L	ND (2)	ND (2)
Ethylbenzene	µg/L	20.1	24.5
m/p-Xylene	µg/L	116	43.8
o-Xylene	µg/L	25.8	16.1

Notes:
S.U. Standard Units

TABLE 2

INITIAL ANALYSIS OF SOIL SAMPLES
OLD ERIE CANAL CHEMICAL OXIDATION STUDY
OLD ERIE CANAL SITE
CLYDE, NEW YORK

Sample ID	***Units***	***S-GP-16-1***	***S-GP-20-1***	***S-GP-25-1***	***S-GP-32-1***	***S-GP-36-1***
pH	S.U.	7.8	8.1	7.9	7.7	8.0
Percent Moisture	%	22.1	15.1	27.8	5.62	18.8
Total Organic Matter (TOM)	%	4.66	0.37	2.08	1.13	0.46
Vinyl Chloride	µg/kg	ND (4)	27100	ND (4)	ND (4)	ND (4)
Cis-1,2-Dichloroethylene	µg/kg	1410	58900	11900	778	50.2
Trichloroethylene	µg/kg	8940	3780	26400	196	171
Toluene	µg/kg	ND (2)	31600	2690	91.7	ND (2)
Perchloroethylene	µg/kg	356	ND (2)	ND (2)	59.9	64.6
Ethylbenzene	µg/kg	ND (2)	215	71.7	ND (2)	ND (2)
m/p-Xylene	µg/kg	ND (2)	1130	214	150	ND (2)
o-Xylene	µg/kg	ND (2)	351	ND (2)	48.5	ND (2)

Notes:
S.U. Standard Units

TABLE 3

CHEMICAL OXIDATION OF GROUNDWATER GW-4B WITH $KMnO_4$
OLD ERIE CANAL CHEMICAL OXIDATION STUDY
OLD ERIE CANAL SITE
CLYDE, NEW YORK

Sample ID	*Units*	*Control*	*0.05% $KMnO_4$*	*0.1% $KMnO_4$*	*0.5% $KMnO_4$*	*1.0% $KMnO_4$*
Loading Rate	g/L	0	0.04	0.08	0.4	0.8
Vinyl Chloride	µg/L	30100/22600	4410/2860	781/769	ND(2)/ND (2)	ND(2)/ND (2)
1,1-Dichloroethylene	µg/L	20.7/16.6	20.1/20.5	14.6/14.9	ND(2)/ND (2)	ND(2)/ND (2)
Trans-1,2-Dichloroethylene	µg/L	50.4/43.0	12.3/11.8	ND(2)/ND (2)	ND(2)/ND (2)	ND(2)/ND (2)
Cis-1,2-Dichloroethylene	µg/L	39400/55700	24200/40200	37700/37700	15.1/18.9	ND(2)/ND (2)
Trichloroethylene	µg/L	552/495	555/500	469/468	4.95/5.80	ND(2)/ND (2)
Toluene	µg/L	86.6/83.5	104/80.3	93.6/84.1	103/96.1	47.2/39.4
Ethylbenzene	µg/L	16.9/14.8	17.0/13.9	15.9/16.6	14.2/13.7	ND(2)/ND (2)
m/p-Xylene	µg/L	7.97/15.5	30.2/11.9	27.4/29.1	27.9/27.9	3.83/3.55
o-Xylene	µg/L	9.24/8.72	12.1/6.80	11.0/11.6	11.2/11.2	ND(2)/ND (2)
% Vinyl chloride removed	%	-	86.2	97.1	>99	>99
% 1,1-DCE removed	%	-	<1	20.9	>99	>99
% Trans-1,2-DCE removed	%	-	74.2	>99	>99	>99
% Cis-1,2-DCE removed	%	-	32.3	20.7	>99	>99
% TCE removed	%	-	<1	10.5	>99	>99
% Toluene removed	%	-	<1	<1	<1	49.1
% Ethylbenzene removed	%	-	2.40	<1	12.0	>99
% m/p-Xylene removed	%	-	<1	<1	<1	68.6
% o-Xylene removed	%	-	<1	<1	<1	>99

Notes:
Duplicate samples separated by "/"

TABLE 4

CHEMICAL OXIDATION OF GROUNDWATER GW-4B WITH $Na_2S_2O_8$
OLD ERIE CANAL CHEMICAL OXIDATION STUDY
OLD ERIE CANAL SITE
CLYDE, NEW YORK

Sample ID	*Units*	*Control*	*0.5% $Na_2S_2O_8$*	*1.0% $Na_2S_2O_8$*	*3.0% $Na_2S_2O_8$*
Loading Rate	g/L	0	0.4	0.8	2.4
Vinyl Chloride	µg/L	30100/22600	6510/6990	6250/6030	6050/6140
1,1-Dichloroethylene	µg/L	20.7/16.6	10.2/8.48	7.66/8.13	3.94/3.51
Trans-1,2-Dichloroethylene	µg/L	50.4/43.0	32.5/30.8	31.0/31.0	26.1/26.5
Cis-1,2-Dichloroethylene	µg/L	39400/55700	19200/29200	29600/31000	15600/22300
Trichloroethylene	µg/L	552/495	355/318	289/293	222/190
Toluene	µg/L	86.6/83.5	44.5/35.4	31.0/33.4	15.9/13.7
Ethylbenzene	µg/L	16.9/14.8	7.43/7.10	6.17/6.35	2.92/3.12
m/p-Xylene	µg/L	7.97/15.5	13.7/12.4	11.1/11.8	5.56/5.54
o-Xylene	µg/L	9.24/8.72	6.37/5.80	5.17/5.20	2.35/2.95
% Vinyl chloride removed	%	-	74.4	76.7	76.9
% 1,1-DCE removed	%	-	49.9	57.7	80.0
% Trans-1,2-DCE removed	%	-	32.2	33.6	43.7
% Cis-1,2-DCE removed	%	-	49.1	36.3	60.1
% TCE removed	%	-	35.7	44.4	60.6
% Toluene removed	%	-	53.0	62.1	82.6
% Ethylbenzene removed	%	-	54.2	60.5	80.9
% m/p-Xylene removed	%	-	<1	2.43	52.7
% o-Xylene removed	%	-	32.2	42.3	70.5

Notes:
Duplicate samples separated by "/"

TABLE 5

CHEMICAL OXIDATION OF GROUNDWATER GW-4B WITH FENTON'S REAGENT
OLD ERIE CANAL CHEMICAL OXIDATION STUDY
OLD ERIE CANAL SITE
CLYDE, NEW YORK

Sample ID	*Units*	*Control*	*1.0% H2O2*	*5.0% H2O2*	*10.0% H2O2*
Loading Rate	g/L	0	0.8	4.0	8.0
Vinyl Chloride	µg/L	30100/22600	1350/108	29.5/79.2	ND(2)/ND (2)
1,1-Dichloroethylene	µg/L	20.7/16.6	6.24/5.92	ND(2)/ND (2)	ND(2)/ND (2)
Trans-1,2-Dichloroethylene	µg/L	50.4/43.0	7.90/5.75	1.73/2.86	ND(2)/ND (2)
Cis-1,2-Dichloroethylene	µg/L	39400/55700	6270/3440	484/773	151/408
Trichloroethylene	µg/L	552/495	126/86.2	16.8/23.3	7.18/11.6
Toluene	µg/L	86.6/83.5	7.03/4.06	ND(2)/ND (2)	ND(2)/ND (2)
Ethylbenzene	µg/L	16.9/14.8	ND(2)/ND (2)	ND(2)/ND (2)	ND(2)/ND (2)
m/p-Xylene	µg/L	7.97/15.5	ND(2)/ND (2)	ND(2)/ND (2)	ND(2)/ND (2)
o-Xylene	µg/L	9.24/8.72	ND(2)/ND (2)	ND(2)/ND (2)	ND(2)/ND (2)
% Vinyl chloride removed	%	-	97.2	99.8	>99
% 1,1-DCE removed	%	-	67.4	>99	>99
% Trans-1,2-DCE removed	%	-	85.4	95.1	>99
% Cis-1,2-DCE removed	%	-	89.8	98.7	99.4
% TCE removed	%	-	79.7	96.2	98.2
% Toluene removed	%	-	93.5	>99	>99
% Ethylbenzene removed	%	-	>99	>99	>99
% m/p-Xylene removed	%	-	>99	>99	>99
% o-Xylene removed	%	-	>99	>99	>99

Notes:
Duplicate samples separated by "/"

TABLE 6

CHEMICAL OXIDATION OF GROUNDWATER GW-6S WITH $KMnO_4$
OLD ERIE CANAL CHEMICAL OXIDATION STUDY
OLD ERIE CANAL SITE
CLYDE, NEW YORK

Sample ID	*Units*	*Control*	*0.05% $KMnO_4$*	*0.1% $KMnO_4$*	*0.5% $KMnO_4$*	*1.0% $KMnO_4$*
Loading Rate	g/L	0	0.04	0.08	0.4	0.8
Vinyl Chloride	µg/L	14300/36900	24000/13700	16900/15900	ND(2)/ND (2)	ND(2)/ND (2)
1,1-Dichloroethylene	µg/L	11.4/11.0	11.2/8.15	10.8/11.1	4.38/ND (2)	ND(2)/ND (2)
Trans-1,2-Dichloroethylene	µg/L	32.1/43.4	23.2/18.5	15.6/16.2	ND(2)/ND (2)	ND(2)/ND (2)
Cis-1,2-Dichloroethylene	µg/L	39400/64300	39900/42800	41900/41600	3990/4100	ND(2)/ND (2)
Trichloroethylene	µg/L	8.44/10.8	14.6/8.94	9.23/7.57	4.64/4.18	ND(2)/ND (2)
Toluene	µg/L	4320/5880	4210/2780	4260/4100	4030/3580	1560/2600
Ethylbenzene	µg/L	9.96/10.7	9.51/8.74	8.92/8.67	12.5/11.4	ND(2)/ND (2)
m/p-Xylene	µg/L	56.0/60.0	74.1/71.5	68.7/71.9	72.6/71.8	24.9/24.7
o-Xylene	µg/L	13.6/14.7	17.1/16.9	15.7/16.5	16.3/16.0	4.81/4.82
% Vinyl chloride removed	%	-	26.4	35.9	>99	>99
% 1,1-DCE removed	%	-	13.6	2.23	>99	>99
% Trans-1,2-DCE removed	%	-	44.8	57.9	>99	>99
% Cis-1,2-DCE removed	%	-	20.3	19.5	92.2	>99
% TCE removed	%	-	<1	12.5	54.1	>99
% Toluene removed	%	-	31.5	18.0	25.4	59.2
% Ethylbenzene removed	%	-	11.7	14.9	<1	>99
% m/p-Xylene removed	%	-	<1	<1	<1	57.2
% o-Xylene removed	%	-	<1	<1	<1	65.9

Notes:
Duplicate samples separated by "/"

TABLE 7

CHEMICAL OXIDATION OF GROUNDWATER GW-6S WITH $Na_2S_2O_8$
OLD ERIE CANAL CHEMICAL OXIDATION STUDY
OLD ERIE CANAL SITE
CLYDE, NEW YORK

Sample ID	*Units*	*Control*	*0.5% $Na_2S_2O_8$*	*1.0% $Na_2S_2O_8$*	*3.0% $Na_2S_2O_8$*
Loading Rate	g/L	0	0.4	0.8	2.4
Vinyl Chloride	µg/L	14300/36900	2960/3330	2170/1990	ND(2)/ND (2)
1,1-Dichloroethylene	µg/L	11.4/11.0	6.05/6.52	5.12/5.28	3.52/2.17
Trans-1,2-Dichloroethylene	µg/L	32.1/43.4	35.5/34.7	33.7/34.5	36.3/36.8
Cis-1,2-Dichloroethylene	µg/L	39400/64300	23100/23300	22100/21800	17900/16600
Trichloroethylene	µg/L	8.44/10.8	5.49/5.75	5.13/4.90	4.40/4.06
Toluene	µg/L	4320/5880	677/693	314/366	171/138
Ethylbenzene	µg/L	9.96/10.7	4.43/4.39	3.53/3.45	ND(2)/ND (2)
m/p-Xylene	µg/L	56.0/60.0	10.2/9.62	7.07/6.78	ND(2)/ND (2)
o-Xylene	µg/L	13.6/14.7	3.23/4.00	3.27/2.54	ND(2)/ND (2)
% Vinyl chloride removed	%	-	87.7	91.9	>99
% 1,1-DCE removed	%	-	43.9	53.6	74.6
% Trans-1,2-DCE removed	%	-	7.02	9.67	3.18
% Cis-1,2-DCE removed	%	-	55.3	57.7	66.7
% TCE removed	%	-	41.5	47.8	56.0
% Toluene removed	%	-	86.6	93.3	97.0
% Ethylbenzene removed	%	-	57.3	66.2	>99
% m/p-Xylene removed	%	-	82.9	88.1	>99
% o-Xylene removed	%	-	74.4	79.4	>99

Notes:
Duplicate samples separated by "/"

TABLE 8

CHEMICAL OXIDATION OF GROUNDWATER GW-6S WITH FENTON'S REAGENT
OLD ERIE CANAL CHEMICAL OXIDATION STUDY
OLD ERIE CANAL SITE
CLYDE, NEW YORK

Sample ID	***Units***	***Control***	***1.0% H2O2***	***5.0% H2O2***	***10.0% H2O2***
Loading Rate	g/L	0	0.8	4.0	8.0
Vinyl Chloride	µg/L	14300/36900	3310/3840	423/592	296/203
1,1-Dichloroethylene	µg/L	11.4/11.0	2.88/5.34	ND(2)/ND (2)	ND(2)/ND (2)
Trans-1,2-Dichloroethylene	µg/L	32.1/43.4	6.54/8.02	ND(2)/ND (2)	ND(2)/ND (2)
Cis-1,2-Dichloroethylene	µg/L	39400/64300	8110/9020	1150/2500	2990/1580
Trichloroethylene	µg/L	8.44/10.8	3.87/2.96	ND(2)/ND (2)	ND(2)/ND (2)
Toluene	µg/L	4320/5880	650/762	70.7/93.1	102/52.3
Ethylbenzene	µg/L	9.96/10.7	3.13/3.84	ND(2)/ND (2)	ND(2)/ND (2)
m/p-Xylene	µg/L	56.0/60.0	13.5/15.7	ND(2)/ND (2)	ND(2)/ND (2)
o-Xylene	µg/L	13.6/14.7	2.92/3.49	ND(2)/ND (2)	ND(2)/ND (2)
% Vinyl chloride removed	%	-	86.0	98.0	99.0
% 1,1-DCE removed	%	-	63.3	>99	>99
% Trans-1,2-DCE removed	%	-	80.7	>99	>99
% Cis-1,2-DCE removed	%	-	83.5	96.5	95.6
% TCE removed	%	-	64.4	>99	>99
% Toluene removed	%	-	86.2	98.4	98.5
% Ethylbenzene removed	%	-	66.3	>99	>99
% m/p-Xylene removed	%	-	74.8	>99	>99
% o-Xylene removed	%	-	77.3	>99	>99

Notes:
Duplicate samples separated by "/"

TABLE 9

CHEMICAL OXIDATION OF SOIL GP-20-1 WITH $KMnO_4$
OLD ERIE CANAL CHEMICAL OXIDATION STUDY
OLD ERIE CANAL SITE
CLYDE, NEW YORK

Sample ID	*Units*	*Control*	*0.1% $KMnO_4$*	*0.5% $KMnO_4$*	*1.0% $KMnO_4$*	*3.0% $KMnO_4$*
Loading Rate	g/kg	0	0.75	3.75	7.5	22.5
Vinyl Chloride	µg/kg	4410/6260	ND(50)/ND (50)	ND(50)/ND (50)	407/ND (50)	7290/4210
1,1-Dichloroethylene	µg/kg	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)
Trans-1,2-Dichloroethylene	µg/kg	23.4/57.6	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)
Cis-1,2-Dichloroethylene	µg/kg	27400/26900	670/1010	9450/10800	2310/467	19600/15800
Trichloroethylene	µg/kg	1810/1700	657/952	2530/3090	868/296	3370/1440
Toluene	µg/kg	9480/9320	2520/3230	8180/15600	10300/2600	41000/33100
Ethylbenzene	µg/kg	174/157	101/134	123/238	127/73.4	347/243
m/p-Xylene	µg/kg	1170/965	606/861	676/1260	1080/425	2870/2110
o-Xylene	µg/kg	299/273	124/135	161/289	269/96.6	1060/960
% Vinyl chloride removed	%	-	>99	>99	>99	<1
% 1,1-DCE removed	%	-	n/a	n/a	n/a	n/a
% Trans-1,2-DCE removed	%	-	>99	>99	>99	>99
% Cis-1,2-DCE removed	%	-	96.9	62.7	94.9	34.8
% TCE removed	%	-	54.2	<1	66.8	<1
% Toluene removed	%	-	69.4	<1	31.4	<1
% Ethylbenzene removed	%	-	28.7	<1	39.2	<1
% m/p-Xylene removed	%	-	31.3	9.3	29.5	<1
% o-Xylene removed	%	-	54.6	21.3	36.1	<1

Notes:
Duplicate samples separated by "/"
n/a Compound not present in control samples

TABLE 10

CHEMICAL OXIDATION OF SOIL GP-20-1 WITH $Na_2S_2O_8$
OLD ERIE CANAL CHEMICAL OXIDATION STUDY
OLD ERIE CANAL SITE
CLYDE, NEW YORK

Sample ID	*Units*	*Control*	*1.0% $Na_2S_2O_8$*	*3.0% $Na_2S_2O_8$*	*5.0% $Na_2S_2O_8$*
Loading Rate	g/kg	0	7.5	22.5	37.5
Vinyl Chloride	µg/kg	4410/6260	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)
1,1-Dichloroethylene	µg/kg	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)
Trans-1,2-Dichloroethylene	µg/kg	23.4/57.6	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)
Cis-1,2-Dichloroethylene	µg/kg	27400/26900	682/127	254/2520	814/205
Trichloroethylene	µg/kg	1810/1700	577/236	327/1380	644/290
Toluene	µg/kg	9480/9320	2090/319	760/4950	2470/379
Ethylbenzene	µg/kg	174/157	70.2/ND (50)	58.9/114	81.9/62.8
m/p-Xylene	µg/kg	1170/965	284/166	177.3/580	320/231
o-Xylene	µg/kg	299/273	74.3/59.2	56/148	77.1/54.2
% Vinyl chloride removed	%	-	>99	>99	>99
% 1,1-DCE removed	%	-	n/a	n/a	n/a
% Trans-1,2-DCE removed	%	-	>99	>99	>99
% Cis-1,2-DCE removed	%	-	98.5	94.9	98.1
% TCE removed	%	-	76.8	51.4	73.4
% Toluene removed	%	-	87.2	69.6	84.8
% Ethylbenzene removed	%	-	>99	47.5	56.2
% m/p-Xylene removed	%	-	78.9	64.5	74.2
% o-Xylene removed	%	-	76.7	64.3	77.1

Notes:
Duplicate samples separated by "/"
n/a Compound not present in control samples

TABLE 11

CHEMICAL OXIDATION OF SOIL GP-20-1 WITH FENTON'S REAGENT
OLD ERIE CANAL CHEMICAL OXIDATION STUDY
OLD ERIE CANAL SITE
CLYDE, NEW YORK

Sample ID	*Units*	*Control*	*5.0% H2O2*	*15.0% H2O2*	*30.0% H2O2*
Loading Rate	g/kg	0	37.5	112.5	225
Vinyl Chloride	µg/kg	4410/6260	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)
1,1-Dichloroethylene	µg/kg	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)
Trans-1,2-Dichloroethylene	µg/kg	23.4/57.6	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)
Cis-1,2-Dichloroethylene	µg/kg	27400/26900	2290/216	1090/1980	1680/1220
Trichloroethylene	µg/kg	1810/1700	941/511	838/737	780/662
Toluene	µg/kg	9480/9320	4700/791	1860/1930	1700/1010
Ethylbenzene	µg/kg	174/157	104/78.8	67.8/66.9	64.0/ND (50)
m/p-Xylene	µg/kg	1170/965	455/381	212/210	182/153
o-Xylene	µg/kg	299/273	121/73.6	58.1/64.1	56.5/47.4
% Vinyl chloride removed	%	-	>99	>99	>99
% 1,1-DCE removed	%	-	n/a	n/a	n/a
% Trans-1,2-DCE removed	%	-	>99	>99	>99
% Cis-1,2-DCE removed	%	-	95.4	94.3	94.7
% TCE removed	%	-	58.6	55.1	58.9
% Toluene removed	%	-	70.8	79.8	85.6
% Ethylbenzene removed	%	-	44.6	59.2	>99
% m/p-Xylene removed	%	-	60.9	80.2	84.3
% o-Xylene removed	%	-	66.0	78.6	81.8

Notes:
Duplicate samples separated by "/"
n/a Compound not present in control samples

TABLE 12

CHEMICAL OXIDATION OF SOIL GP-25-1 WITH $KMnO_4$
OLD ERIE CANAL CHEMICAL OXIDATION STUDY
OLD ERIE CANAL SITE
CLYDE, NEW YORK

Sample ID	*Units*	*Control*	*0.1% $KMnO_4$*	*0.5% $KMnO_4$*	*1.0% $KMnO_4$*	*3.0% $KMnO_4$*
Loading Rate	g/kg	0	0.75	3.75	7.5	22.5
Vinyl Chloride	µg/kg	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)
1,1-Dichloroethylene	µg/kg	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)
Trans-1,2-Dichloroethylene	µg/kg	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)
Cis-1,2-Dichloroethylene	µg/kg	3500/8430	429/202	467/364	218/40	608/388
Trichloroethylene	µg/kg	3180/25410	738/1880	1060/1090	659/213	1450/980
Toluene	µg/kg	267/359	285/488	218/138	257/114	290/165
Ethylbenzene	µg/kg	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)
m/p-Xylene	µg/kg	49.9/69.7	120/197	85.3/81.9	94.6/65.2	88.6/66.4
o-Xylene	µg/kg	25.0/26.5	40.8/48.8	40.2/42.8	43.2/39.8	40.2/39.6
% Vinyl chloride removed	%	-	n/a	n/a	n/a	n/a
% 1,1-DCE removed	%	-	n/a	n/a	n/a	n/a
% Trans-1,2-DCE removed	%	-	n/a	n/a	n/a	n/a
% Cis-1,2-DCE removed	%	-	94.7	93.0	97.8	91.6
% TCE removed	%	-	90.8	92.5	96.9	91.5
% Toluene removed	%	-	<1	43.1	40.7	27.3
% Ethylbenzene removed	%	-	n/a	n/a	n/a	n/a
% m/p-Xylene removed	%	-	<1	<1	<1	<1
% o-Xylene removed	%	-	<1	<1	<1	<1

Notes:
Duplicate samples separated by "/"
n/a Compound not present in control samples

TABLE 13

CHEMICAL OXIDATION OF SOIL GP-25-1 WITH $Na_2S_2O_8$
OLD ERIE CANAL CHEMICAL OXIDATION STUDY
OLD ERIE CANAL SITE
CLYDE, NEW YORK

Sample ID	*Units*	*Control*	*1.0% $Na_2S_2O_8$*	*3.0% $Na_2S_2O_8$*	*5.0% $Na_2S_2O_8$*
Loading Rate	g/kg	0	7.5	22.5	37.5
Vinyl Chloride	µg/kg	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)
1,1-Dichloroethylene	µg/kg	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)
Trans-1,2-Dichloroethylene	µg/kg	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)
Cis-1,2-Dichloroethylene	µg/kg	3500/8430	580/49.3	63.0/341	201/1140
Trichloroethylene	µg/kg	3180/25410	1420/389	141/1060	513/2720
Toluene	µg/kg	267/359	183/111	94.5/195	108/367
Ethylbenzene	µg/kg	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)
m/p-Xylene	µg/kg	49.9/69.7	81.3/98.6	73.5/70.6	71.6/89.8
o-Xylene	µg/kg	25.0/26.5	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)
% Vinyl chloride removed	%	-	n/a	n/a	n/a
% 1,1-DCE removed	%	-	n/a	n/a	n/a
% Trans-1,2-DCE removed	%	-	n/a	n/a	n/a
% Cis-1,2-DCE removed	%	-	94.7	96.6	88.8
% TCE removed	%	-	68.2	78.9	43.2
% Toluene removed	%	-	53.1	53.8	24.2
% Ethylbenzene removed	%	-	n/a	n/a	n/a
% m/p-Xylene removed	%	-	<1	<1	<1
% o-Xylene removed	%	-	>99	>99	>99

Notes:
Duplicate samples separated by "/"
n/a Compound not present in control samples

TABLE 14

CHEMICAL OXIDATION OF SOIL GP-25-1 WITH FENTON'S REAGENT
OLD ERIE CANAL CHEMICAL OXIDATION STUDY
OLD ERIE CANAL SITE
CLYDE, NEW YORK

Sample ID	***Units***	***Control***	***5.0% H2O2***	***15.0% H2O2***	***30.0% H2O2***
Loading Rate	g/kg	0	37.5	112.5	225
Vinyl Chloride	µg/kg	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)
1,1-Dichloroethylene	µg/kg	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)
Trans-1,2-Dichloroethylene	µg/kg	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)
Cis-1,2-Dichloroethylene	µg/kg	3500/8430	89.3/233	1190/1140	872/1000
Trichloroethylene	µg/kg	3180/25410	672/525	1230/537	704/791
Toluene	µg/kg	267/359	207/317	1390/377	1010/1090
Ethylbenzene	µg/kg	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)	ND(50)/ND (50)
m/p-Xylene	µg/kg	49.9/69.7	115/110	159/114	139/138
o-Xylene	µg/kg	25.0/26.5	40.7/39.9	50.9/46.0	49.5/47.9
% Vinyl chloride removed	%	-	n/a	n/a	n/a
% 1,1-DCE removed	%	-	n/a	n/a	n/a
% Trans-1,2-DCE removed	%	-	n/a	n/a	n/a
% Cis-1,2-DCE removed	%	-	97.3	80.5	84.3
% TCE removed	%	-	79.0	69.0	73.7
% Toluene removed	%	-	16.3	<1	<1
% Ethylbenzene removed	%	-	n/a	n/a	n/a
% m/p-Xylene removed	%	-	<1	<1	<1
% o-Xylene removed	%	-	<1	<1	<1

Notes:
Duplicate samples separated by "/"
n/a Compound not present in control samples

TABLE 15

ANALYSIS OF NATURAL OXIDANT DEMAND
OLD ERIE CANAL CHEMICAL OXIDATION STUDY
OLD ERIE CANAL SITE
CLYDE, NEW YORK

		Soil					*Groundwater*	
Parameters	***Units***	***GP-16-1***	***GP-20-1***	***GP-25-1***	***GP-32-1***	***GP-36-1***	***GW-6S***	***GW-4B***
Permanganate concentration at T=0	%	1.39	1.55	1.36	1.65	2.19	1.64	1.62
Permanganate concentration at T=1 week	%	0.0842	1.09	0.121	1.34	2.00	1.30	1.31
Permanganate concentration at T=2 weeks	%	ND (0.000255)	1.04	ND (0.000255)	1.29	1.97	1.51	1.55
Permanganate concentration at T=3 weeks	%	0.0253	0.637	0.0853	0.789	1.24	0.968	1.00
Permanganate concentration at T=4 weeks	%	ND (0.000255)	0.610	ND (0.000255)	0.757	1.21	0.959	0.993
Permanganate concentration at T=5 weeks	%	0.00190	0.59	0.000437	0.704	1.20	0.894	0.961
Amount of Permanganate Added at T=0	g	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Amount of Permanganate Added after T=2 w	g	0.25	0	0.50	0	0	0	0
Amount of Permanganate Added after T=4 w	g	0.25	0	0.25	0	0	0	0
Total Permanganate Added	g	1.5	1.0	1.75	1	1	1	1
Amount of permanganate consumed by NOD per kg of soil after 5 weeks	g/kg	41.6	19.2	47.5	18.9	19.7		
Amount of permanganate consumed by NOD per L of groundwater after 5 weeks	g/L						7.5	6.6

Notes:
g Grams.
g/kg Grams per Kilogram.
g/L Grams per Liter.