

N65928.AR.001057  
NTC ORLANDO  
5090.3a

LETTER SUMMARIZING ANALYTICAL RESULTS FROM IN SITU GROUNDWATER  
TREATABILITY STUDY AT OPERABLE UNIT 4 (OU 4) NTC ORLANDO FL  
7/12/2000  
HARDING LAWSON ASSOCIATES

04.06.04.0007  
00250

**Harding Lawson Associates**



02545-033

July 12, 2000

Commanding Officer  
Southern Division, Naval Facilities Engineering Command  
2155 Eagle Drive  
North Charleston, SC 29406

**ATTN: Ms. Barbara Nwokike, Code 187300**

**SUBJECT: Operable Unit 4, Groundwater Treatability Studies  
In-Situ Chemical Oxidation Pilot Study  
Naval Training Center, Orlando, Florida  
Contract No. N62467-89D-0317/135**

Dear Barbara:

The pilot study evaluating in-situ chemical oxidation using potassium permanganate ( $\text{KMnO}_4$ ) as a groundwater source area technology was begun at Naval Training Center (NTC), Orlando Operable Unit (OU) 4 on February 14, 2000. This letter report presents the interim results through approximately the midpoint of the pilot study, May 26, 2000 (groundwater sampling round 8). This pilot study has demonstrated that injection of  $\text{KMnO}_4$  in the OU 4 source area is a viable alternative for site remediation.

This letter report includes a summary of system installation, startup, operation, and performance monitoring. It includes an interpretation of the results through May 26, and provides preliminary conclusions and recommendations designed to allow finalization of the draft Orlando OU 4 Feasibility Study (FS) with updated performance criteria for the  $\text{KMnO}_4$  alternative. Final conclusions and recommendations will be presented in the final report at the conclusion of this pilot test.

Based on the results presented herein, and weighing alternatives already evaluated in the draft OU 4 FS, we recommend that the Navy proceed with full-scale implementation of in-situ chemical oxidation using  $\text{KMnO}_4$  in the OU 4 source area.

## **INTRODUCTION**

OU 4 is located at Area C, at NTC Orlando, Florida (Figure 1). OU 4 consists of Study Areas 12, 13, and 14 at Area C (Figure 2). Building 1100, located in Study Area 13, was constructed in 1943 and was used as a laundry and dry-cleaning facility. Prior to construction of the facility in 1943, the land was undeveloped. Laundry operations at Building 1100 ended in 1994. Building 1100 was identified during the Environmental Baseline Survey (EBS) as a site where releases of hazardous materials had occurred.

Several investigations have already occurred at OU 4, either under the Base Realignment and Closure (BRAC) Act site screening program or under subsequent efforts to characterize the contamination discovered during the site screening investigation. Results from the investigations conducted at OU 4 to date are summarized in the OU 4 Remedial Investigation (RI) Workplan



Ms. Barbara Nwokike  
July 12, 2000  
Page 2

(ABB Environmental Services, Inc. [ABB-ES], 1997b) and the redline/strikeout version of the Final OU 4 RI Report (Harding Lawson Associates [HLA], 2000).

These investigations have identified a plume of chlorinated solvent-contaminated groundwater originating from the area around Building 1100, the former base laundry, and migrating into the adjacent Lake Druid. Contour lines illustrating the approximate defined boundary of the groundwater plume are shown on Figure 3. Volatile organic compounds (VOCs) detected in groundwater and surface water from Lake Druid included tetrachloroethene (PCE), trichloroethene (TCE), *cis*-1,2-dichloroethene (DCE), *trans*-1,2-DCE, 1,1-DCE, and vinyl chloride (VC). Source areas appear to be multiple and are likely located adjacent to and beneath Building 1100. The approximate extent of the suspected multiple source areas is also shown on Figure 3. No source area associated with the southern portion of the plume has been identified. Because VOC concentrations are several orders of magnitude lower than in the northern plume, the source for the southern plume was likely a small release that has either been depleted or removed.

Based on the OU 4 Focused Field Investigation (ABB-ES, 1996a), the source investigation (ABB-ES, 1997c), and the OU 4 RI (HLA, 2000), the vertical extent of the chlorinated solvent groundwater plume ranges from approximately 4 to 45 feet below land surface (bls). Total groundwater VOCs in excess of 30 milligrams per liter (mg/L) have been detected in the source area(s), and up to approximately 6 mg/L between the laundry and Lake Druid. The maximum depth of the plume in the source area shown on Figure 3 is approximately 30 to 35 feet bls, increasing to 45 feet bls in downgradient areas. The water table between Lake Druid and the laundry varies seasonally from less than 1 foot to 7 feet bls, with the greatest depths to water occurring at the laundry itself.

The soil density of the surficial aquifer typically ranges from medium dense to dense, with the exception of a hard layer (very dense) approximately 15 to 20 feet bls, with varying thickness of 2 to 5 feet. However, this hard layer does not appear to act as either a hydraulic or chemical barrier.

In 1997, the US Geological Survey (USGS) re-evaluated the results from a pumping test that had been conducted at OU 4 in August 1996 (USGS, 1998). The USGS analysis of the pumping test data indicated that the surficial aquifer could be separated into two zones. From the groundwater surface to approximately 20 to 25 feet bls, the horizontal hydraulic conductivity is about 10 ft/day. Below that point to approximately 55 feet bls, the horizontal hydraulic conductivity is about 40 ft/day. In both zones the vertical hydraulic conductivity was determined to be about three times lower than the horizontal hydraulic conductivity.

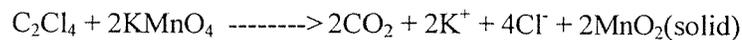
## IN SITU CHEMICAL OXIDATION PROCESS

In-situ chemical oxidation involves the injection of a chemical oxidant into the zone of contamination. The contaminant is destroyed through contact with the chemical oxidizer. Byproducts include carbon dioxide, water, and chloride (when chlorinated compounds are oxidized). The oxidation is non-specific, and all compounds present that can be oxidized by a given reagent will react. Chlorinated compounds (particularly those with double bonds, such as PCE, TCE, DCE, etc) are readily destroyed when contacted with chemical oxidants.

Ms. Barbara Nwokike  
 July 12, 2000  
 Page 3

The two most common chemical oxidants used for in-situ oxidation are the Fenton's reagent (hydrogen peroxide and ferrous sulfate) and  $\text{KMnO}_4$ . The Fenton's reaction is highly exothermic and also produces quantities of oxygen from the decomposition of excess hydrogen peroxide. The reactants are unstable and short-lived. This process has been commercialized and is offered by several firms that specialize in this technology.

$\text{KMnO}_4$  has been shown to be an effective oxidant for PCE and TCE (Schnarr et al, 1997; Hood et al, 1998; West et al, 1997). In-situ oxidation is accomplished when an aqueous solution of  $\text{KMnO}_4$  is injected or flushed through the source area. The basic stoichiometry for the oxidation of PCE is as follows:



This reaction does not generate excess heat and any excess  $\text{KMnO}_4$  is stable, allowing it to be flushed through a source area by pumping to maximize contact with the contaminant zone.  $\text{KMnO}_4$  has also been shown to be more effective at oxidizing PCE and TCE than the Fenton's process (West et al, 1997).

### IN-SITU CHEMICAL OXIDATION PILOT TEST OBJECTIVES

The objective of the chemical oxidation pilot test is to provide site-specific performance data for the  $\text{KMnO}_4$  technology at OU 4. Site-specific performance factors to be evaluated during the pilot test are as follows:

1. Ability to create and maintain groundwater circulation cell;
2. Optimum  $\text{KMnO}_4$  aqueous concentration required to oxidize the OU 4 source area VOCs;
3. Ability to treat source area VOCs both above and below the layer of dense sand; and
4. Maximum reduction of groundwater VOC concentrations achievable with this technology.

### PILOT TEST INSTALLATION AND OPERATION

#### Well Installation

Wells were installed for the pilot study to allow extraction and injection of groundwater (thereby creating a treatment cell), and to supplement existing wells for monitoring groundwater above and below the hard layer. The number and locations of the new wells were selected based on results from hydraulic modeling of the site as described in the work plan (HLA, 1999).

Three injection wells (IW-2, IW-3, and IW-4) were installed adjacent to the northeast corner of Building 1100 (Figure 3). These wells are spaced approximately 10 feet apart. Each injection

Ms. Barbara Nwokike  
July 12, 2000  
Page 4

well has a 4-inch inside diameter (ID) and a total depth of approximately 35 feet. The wells are screened from 5 to 30 feet bls and have a 5 foot sump from 30 to 35 feet bls. Three extraction wells (RW-2, RW-3, and RW-4) were also installed approximately 65 feet to the west of the injection wells (Figure 3). These wells are spaced approximately 10 feet apart. Each extraction well has a 4-inch ID and a total depth of approximately 35 feet. The extraction wells are screened from 10 to 30 feet bls and have a 5 foot sump from 30 to 35 feet bls.

Three deep wells and seven shallow wells were installed for the pilot study. The three deep wells were installed below the hard layer and are 2-inch ID, a total depth of 30 feet, and are screened from 20 to 30 feet bls. The seven shallow wells are ½-inch ID microwells installed to a total depth of approximately 20 feet, screened above the hard layer with 9-foot pre-packed screens from 11 to 20 feet bls. The location of all wells within the pilot study treatment zone is shown on Figure 4 (shallow wells have GMP-xx designation and deep wells have OLD-13-xx designation).

The shallow microwells were installed using a GeoProbe direct push rig. All other wells were installed with a Rotasonic drilling rig.

#### **Baseline Groundwater Sampling**

Groundwater samples were collected between February 1 and February 9, 2000, to provide baseline reference data prior to system startup. Groundwater samples were collected from the upper and lower zone monitoring wells, and from the extraction and injection wells, and were submitted to an off-site laboratory for analysis (see Table 1). VOC concentrations were established to provide baseline data to monitor the oxidation performance of the  $\text{KMnO}_4$ . Inorganics were also analyzed to monitor changes in concentration caused by the introduction of dissolved metals from the injected  $\text{KMnO}_4$ , and oxidation of inorganics such as iron and manganese.

Groundwater samples from 11 shallow zone wells were analyzed for halogenated VOCs during the baseline sampling event. Results are shown on Figure 4. PCE was detected in all 11 of the wells sampled at concentrations ranging from 38 micrograms per liter ( $\mu\text{g/L}$ ) to 23,000  $\mu\text{g/L}$ . TCE was detected in 9 of the monitoring wells sampled at concentrations ranging from 7  $\mu\text{g/L}$  to 8,700  $\mu\text{g/L}$ . Cis-1,2-DCE was only detected in 3 of the wells sampled at concentrations of 12  $\mu\text{g/L}$ , 31  $\mu\text{g/L}$  and 2,000  $\mu\text{g/L}$ ; however, detection limits were very high for most samples. Groundwater samples from six shallow zone wells were also analyzed for Target Analyte List (TAL) metals (see Table 1). Calcium, iron, magnesium, manganese, mercury, potassium, sodium, and vanadium were detected in the six wells sampled during the baseline sampling event. Calcium concentrations ranged from 16 to 56 mg/L. Magnesium concentrations ranged from 2 to 5.1 mg/L. Potassium concentrations ranged from 0.7 to 1.8 mg/L. Sodium concentrations ranged from 2.5 to 7.2 mg/L. Iron was detected in one sample at a concentration of 0.23 mg/L. Manganese was detected in one sample at a concentration 0.012 mg/L. Vanadium was detected in two samples at concentrations of 0.01 and 0.02 mg/L. Mercury was detected in two samples at concentrations of 0.0002 and 0.00021 mg/L, which was between the method detection level and the practical quantitation level for the analyses.

Groundwater samples from four deep zone wells were analyzed for halogenated VOCs during the baseline sampling event. Results are shown on Figure 4. PCE was detected in all 4 of the wells

Ms. Barbara Nwokike  
July 12, 2000  
Page 5

at concentrations ranging from 140  $\mu\text{g/L}$  to 3,300  $\mu\text{g/L}$ . TCE was detected in all 4 of the wells at concentrations ranging from 1,300  $\mu\text{g/L}$  to 4,700  $\mu\text{g/L}$ . Cis-1,2-DCE was detected in 3 of the wells at concentrations ranging from 700  $\mu\text{g/L}$  to 1,500  $\mu\text{g/L}$ . Deep zone groundwater samples were also analyzed for TAL metals (Table 1). Aluminum, calcium, iron, magnesium, manganese, potassium, and sodium were detected in all deep zone wells. Calcium concentrations ranged from 3.4 to 9.3 mg/L. Iron concentrations ranged from 0.072 mg/L to 3.7 mg/L. Magnesium concentrations ranged from 1.2 to 1.4 mg/L. Potassium concentrations ranged from 1.0 to 1.2 mg/L. Sodium concentrations ranged from 9.7 to 15 mg/L. Aluminum was detected in two samples at concentrations of 0.067 and 0.078 mg/L. Manganese was detected in two samples at concentrations of 0.018 and 0.028 mg/L.

Groundwater samples from the six injection and extraction wells were analyzed for halogenated VOCs during the baseline sampling event. Results are presented on Figure 4. In the 3 extraction wells, PCE was detected at concentrations ranging from 1,600  $\mu\text{g/L}$  to 8,400  $\mu\text{g/L}$ , TCE was detected at concentrations ranging from 470  $\mu\text{g/L}$  to 1,000  $\mu\text{g/L}$ , and cis 1,2 DCE was detected at concentrations ranging from 160  $\mu\text{g/L}$  to 400  $\mu\text{g/L}$ . In 2 of the 3 injection wells, TCE was detected at concentrations ranging from 110  $\mu\text{g/L}$  to 330  $\mu\text{g/L}$ , and cis 1,2 DCE was detected at concentrations of 130  $\mu\text{g/L}$  and 540  $\mu\text{g/L}$ . PCE was detected in all 3 injection wells at concentrations ranging from 68  $\mu\text{g/L}$  to 8,400  $\mu\text{g/L}$ .

Natural attenuation parameters were analyzed from six shallow zone wells and four deep zone wells and will be compared to data collected during the final sampling event at the end of the pilot study.

### **System Installation**

A system schematic is shown as Figure 5. The  $\text{KMnO}_4$  pilot study system consisted of two 1,600 gallon polyethylene tanks piped in series (Tank 1 and Tank 2), a  $\text{KMnO}_4$  feed system, extraction and injection pumps, cartridge filters used to filter the  $\text{KMnO}_4$  solution prior to injection, and a control system.

Polyethylene tubing was used to connect the three extraction wells to a polyvinyl chloride (PVC) header, which was in turn connected to the intake of an ITT Jabsco flexible impeller pump using 2-inch ID hose. Extracted groundwater was fed to Tank 1. Groundwater from Tank 1 was pumped to the  $\text{KMnO}_4$  feed system and then recycled back to the tank. Treated groundwater then flowed from Tank 1 and into the bottom of Tank 2 by gravity. The  $\text{KMnO}_4$  solution overflowed out of Tank 2 through a standpipe (to maximize residence time) to an ITT Jabsco injection pump. The solution was filtered to remove  $\text{MnO}_2$  solids and then piped to the injection wells through a header and tubing assembly identical to that used for extraction. The control system varied the injection rate to maintain the setpoint water level in Tank 2. The two-tank arrangement was used to provide adequate residence time for complete dissolution of the  $\text{KMnO}_4$  and to allow the VOCs in the extracted water to oxidize to below Maximum Contaminant Limits (MCLs) prior to injection.

### **System Startup**

Following system installation, system start up activities included  $\text{KMnO}_4$  drum sampling, system operation and adjustment, and onsite laboratory analysis.

Ms. Barbara Nwokike  
July 12, 2000  
Page 6

The  $\text{KMnO}_4$  powder was purchased from Carus Chemical in 330 pound drums.  $\text{KMnO}_4$  samples were collected from drums representing each manufacturing lot in the inventory. These samples were sent to an offsite laboratory for inorganic analysis to confirm metals concentrations were within the limits allowed by the Underground Injection Control (UIC) variance (HLA, 1999). Analytical results for 4 gram per liter (g/L)  $\text{KMnO}_4$  solutions are presented in Appendix A.

System startup began on February 11. Groundwater was extracted at a total rate of 3.5 to 4.0 gallons per minute (gpm) from all three extraction wells.  $\text{KMnO}_4$  was added at a rate that corresponded to a 4 g/L solution. Approximately 190 pounds of  $\text{KMnO}_4$  per day were required at 4 gpm. Groundwater samples were collected periodically from the extraction piping and from the  $\text{KMnO}_4$  solution in the mixing tanks. This allowed real-time evaluation of system performance, and ensured that VOC MCLs were achieved prior to injection.

As expected (based on literature and bench-scale testing), the TCE and DCE in the extracted groundwater were quickly oxidized. TCE (approximately 780  $\mu\text{g/L}$ ) and DCE (approximately 320  $\mu\text{g/L}$ ) in the extracted groundwater were not detected in the overflow from Tank 1 to Tank 2. PCE was reduced from approximately 3,000  $\mu\text{g/L}$  in the extracted groundwater to approximately 85  $\mu\text{g/L}$  in the Tank 1 overflow. PCE was oxidized to below the MCL of 3  $\mu\text{g/L}$  after 1.5 hours in Tank 2. As over 6 hours of residence time was available for the treated groundwater in Tank 2 (at 4 gpm), these results indicated that the system was capable of easily oxidizing VOCs in the extracted groundwater to below MCLs prior to injection.

### System Operation

After successfully demonstrating the ex-situ oxidation of VOCs, continuous operation of the system began on February 14. Table 2 shows the operating and sampling schedules. Various system improvements and repairs were required during the first month of operation, which reduced the number of days the system was operating. These difficulties included a leaking  $\text{KMnO}_4$  circulation pump, power failures, replacement of the extraction pump impeller, and the replacement of long lengths of polyethylene suction tubing with shorter tubing and more 2-inch hose to reduce head losses. System availability is illustrated in Table 2.

From mid-March to mid-April, the system was functioning virtually every day at 4 gpm, with the exception of some down-time due to a power failure. However, during this period the efficiency of the injection wells declined and high water levels were observed in IW-3 and IW-4. Sulfamic acid was used to treat fouling in IW-3 and IW-4 on March 31 and the water levels in these wells showed a marked decrease. IW-3 and IW-4 again required treatment with sulfamic acid on April 7 and April 10, with less effective results than previous treatments.

The extraction rate of the system was reduced to 3.0 GPM on April 11 due to high water levels in the injection wells. On April 14, the touch pad controlling the system malfunctioned, preventing adjustment to the system. Due to the inoperable touch pad and high water levels in the injection wells, the system was shut down on April 17.

The touch pad required replacement, which was performed by a Carus engineer on May 3. As addition of sulfamic acid had become less effective in addressing injection well fouling, the injection wells were redeveloped with a surge block, and a significant volume of solids was

Ms. Barbara Nwokike  
July 12, 2000  
Page 7

removed from the well sumps with a peristaltic pump. The quantity of solids in the wells was apparently due to breakthrough past the cartridge filters.

The well redevelopment returned injection well performance close to that experienced at original system startup; water levels increased only a few inches during injection of treated groundwater. This demonstrated that the fouling had only occurred on the inside of the well screens. The MnO<sub>2</sub> solids had not clogged the filter pack or the aquifer. Following the injection well redevelopment and filter replacement, the system was restarted at 4.0 gpm on May 4. High pressure conditions in the filter system caused shutdowns on May 6 and May 9. It was thought that solids that had accumulated in Tank 2 were now being carried out over the standpipe to the filter system. Therefore, the contents of Tank 2 were removed on May 15 with a vacuum truck and disposed of off site. Cost was minimal, as the water and solids were considered non-hazardous. The filter cartridges were replaced and the system was operated at 4.0 GPM until high-pressure conditions again caused a system shut down on May 20. The system operated intermittently until May 23. On May 23, the filters were replaced and the mixer in Tank 1 was shut off to try and reduce the amount of solids in suspension being transferred to Tank 2. The flow rate of the system was reduced to 3.0 GPM on May 26 to extend filter life. The system was operated at 3.0 GPM for the rest of the month of May.

Based on the frequent filter replacement now required, it was apparent that solids had likely been bypassing the filtration system since startup, with most of the MnO<sub>2</sub> produced during the ex-situ oxidation step (an estimated 100 to 150 grams per day) transferred into the injection wells. However, even with this quantity of solids, well clogging was not apparent until after over 40 days of operation.

### **Performance Monitoring**

Groundwater samples were collected from within the treatment cell during system operation to evaluate performance. Table 3 summarizes sampling locations and dates of sampling. Samples of influent and effluent from the system were collected when the system was running. Sodium thiosulfate was added to each water sample to consume any excess KMnO<sub>4</sub>, and prevent further VOC oxidation within the sample vials after collection. Synoptic rounds of static water level measurements were made at the beginning of each sampling event to evaluate the hydraulic performance of the treatment cell. The initial sampling schedule for performance monitoring was specified in the work plan (HLA, 1999), based on the results of groundwater modeling for the site. The actual sampling schedule was adjusted during the study to account for differences in predicted KMnO<sub>4</sub> travel times.

A round of water level measurements was collected prior to each groundwater sampling round. Water levels were measured in the wells within the treatment cell and the injection and extraction wells. Since the injection rate of the discharge pump and the amount of well clogging control the water levels in the injection wells, the water level was also measured in OLD-13-20A, which is located between IW-3 and IW-4. Water levels were also measured in OLD-13-45B, OLD-13-43C and GMP-17, which are located at the downgradient edge of the treatment cell. Background water levels were measured in the well cluster OLD-13-01A, OLD-13-40B, OLD-13-02C (located north of Building 1100) and the intermediate well OLD-13-26B, which is located

Ms. Barbara Nwokike  
July 12, 2000  
Page 8

upgradient of the treatment system inside Building 1100. Water level data are provided in Appendix B.

Evaluation of water level data for the shallow and deep zones indicates that operation of the system is altering ground water flow in the treatment cell. The groundwater gradient in the shallow zone before the system was started and when the system was not operating (during Round 7) ranged from 0.0033 to 0.0035 ft/ft (Table 4). The deep zone gradient ranged from 0.0032 to 0.0038 ft/ft before system installation and during Round 7. When the system was operating at flow rates of 3.0 and 3.5 GPM, the shallow zone gradient increased to 0.0077 ft/ft (2.26 times the equilibrium value) and the deep zone gradient increased to 0.0065 ft/ft (1.86 times the equilibrium value). At a flow rate of 4.0 GPM, the shallow zone gradient ranged from 0.0096 ft/ft to 0.0104 ft/ft (approximately 2.94 times the equilibrium value) and the deep zone gradient ranged from 0.0068 ft/ft to 0.0076 ft/ft (approximately 2.06 times the equilibrium value).

The increases in gradient measured in the shallow and deep zones appear to be consistent with the aquifer properties assumed in the site model, i.e. a shallow hydraulic conductivity of 10 ft/day, and a deep hydraulic conductivity of 40 ft/day.

Figures 6 through Figure 9 show VOC concentrations and conductivity versus time for both the shallow and deep monitoring wells. As can be seen from Figure 6, VOC concentrations in the shallow zone have decreased dramatically in several monitoring wells in the short period of operation spanning 14 weeks. At monitoring wells GMP-10, -11, -12 and -13, the concentrations of VOCs have been reduced from levels as high as 24,300  $\mu\text{g/L}$  (at GMP-11) to levels that are at or below MCLs. These four wells are all within a distance of approximately 15 feet downgradient of the injection wells. It can also be seen that at monitoring wells GMP-8, -9 and -14 (which are further downgradient in the test cell), decreases in VOC concentrations of more than an order of magnitude have occurred.

The dramatic decreases in concentration are accompanied by increases in conductivity as can be seen on Figure 8. The increase in conductivity is from an increase in dissolved solids due to the arrival of the  $\text{KMnO}_4$  at these locations.

At some locations, VOCs were initially substantially reduced from baseline, yet continued to be detected in groundwater even after the groundwater had achieved a purple color. The purple indicated that excess  $\text{KMnO}_4$  was present in groundwater at that monitoring point, which would suggest all VOCs should have been oxidized. After a brief leveling-off, VOC concentrations eventually were no longer detected at these locations. This behavior may be due to the presence of tight, low permeability zones within the aquifer that the  $\text{KMnO}_4$  was slow to penetrate, or free-phase residual PCE trapped within the sand pores. Because of the soaking effect achieved by the circulation cell, the  $\text{KMnO}_4$  eventually reached these residual VOC sources and completed the contaminant oxidation in these areas.

In the deep zone, the decreases in VOC concentrations during the first 14 weeks of this pilot test are much more modest; a decrease was not observed until after week 6 (Figure 7). And, as expected, the corresponding increases in conductivity are also small and have only begun to increase after week 6 of the test (Figure 9). It is suspected that the natural organic carbon

Ms. Barbara Nwokike  
July 12, 2000  
Page 9

concentrations are much larger in the lower zone, and therefore, the  $\text{KMnO}_4$  is being consumed by the natural organics and therefore has not yet migrated to the deep zone wells to reduce the VOC concentrations.

Changes in VOC concentrations and groundwater conductivity (Table 5) were used to evaluate actual travel times of treated groundwater within the treatment cell compared to the travel times predicted by the groundwater model. The predicted times in the work plan were based on an extraction rate of 0.92 gpm per extraction well. However, an extraction rate of 4 gpm corresponds to 1.33 gpm per well, or approximately 45 percent greater than the work plan model. Actual pilot study travel times would therefore be expected to be approximately 45 percent quicker than predicted. Actual travel times are affected by the variations in pumping rate during the pilot study (3 to 4 gpm), and variations in gradient caused by the periods when the system was not operating. The estimated travel times in the following discussion have been adjusted for the 45 percent difference in flow rates, but no attempt has been made in this letter report to account for any of the other variables that affect flow velocities.

Data from the shallow zone monitoring points indicate that treated groundwater, determined by decreases in VOC concentrations and increases in groundwater conductivity, has generally moved more rapidly in the shallow zone than predicted. Data collected during round 3 (21 run days/39 calendar days) showed decreases in VOC concentrations and increases in conductivity in GMP-14 (estimated 30 days travel time) and GMP-09 (estimated 55 days travel time). Data collected during round 7 (44/45 run days/66/67 calendar days) showed decreases in VOC concentrations and increases in conductivity in GMP-08 (estimated 85 days travel time) and GMP-09 (estimated 55 days travel time). Data collected during round 8 (53/54 run days/101/102 calendar days) showed decreases in VOC concentrations and increases in conductivity in GMP-16 (estimated 85 days travel time) and OLD-13-07A (estimated 100 days travel time).

Data from the deep zone monitoring points indicate that treated groundwater has moved more slowly in parts of the deep zone than predicted in wells located on the south side of the treatment cell (OLD-13-44B, OLD-13-42B and OLD-13-41B). Data collected from OLD-13-44B (estimated 7 days travel time) indicate that treated water did not reach that point until round 5 (33 run days/52 calendar days). Treated water did not reach OLD-13-42B (estimated 15 days travel time) until round 6 (40/41 run days/59/60 calendar days). VOC concentration has decreased in OLD-13-41B, but conductivity has not shown an increase. Decreases in VOC concentration and increases in conductivity have not been as pronounced in the deep zone monitoring points as those observed in the shallow zone. Data collected from OLD-13-45B (estimated 15 days travel time), which is located in the middle of the treatment cell, indicate that treated water reached that point by round 3 (21 run days/39 calendar days). The VOC concentrations measured during this sampling round were substantially lower than baseline values, but conductivity of the groundwater decreased.

Analysis of inorganics in the  $\text{KMnO}_4$  solution was complicated by the presence of very high dissolved solids concentrations, and also interference from the manganese introduced by the  $\text{KMnO}_4$ . Particular problems were encountered quantifying concentrations of chromium, nickel, selenium, and thallium. For example, initial chromium analysis of the  $\text{KMnO}_4$  solution reported chromium concentrations in excess of 1,000  $\mu\text{g/L}$ , compared to the MCL of 100  $\mu\text{g/L}$ . However,



Ms. Barbara Nwokike  
July 12, 2000  
Page 10

because chromium concerns had been carefully investigated during the pilot study permitting phase, it was clear these values were incorrect. Further review by the laboratory (and Carus Chemical quality control and laboratory data) confirmed actual chromium concentrations in the solution were closer to 40 µg/L. Similarly elevated concentrations of nickel, selenium, and thallium were also reported by the laboratory, occasionally even after the problems were believed to have been corrected.

Analysis of inorganics in groundwater from the monitoring points within the treatment cell identified no consistent increases in metals from the injection of the KMnO<sub>4</sub>, with the expected exception of potassium and manganese. A more thorough evaluation of inorganic data will be included in the pilot study final report.

## CONCLUSIONS

The objective of the chemical oxidation pilot test was to provide site-specific data supporting assessment of this alternative in the Final OU 4 FS. The following performance objectives were evaluated during the pilot test:

1. ability to create and maintain a groundwater circulation cell
2. optimum KMnO<sub>4</sub> aqueous concentration required to oxidize the OU 4 source area VOCs
3. ability to treat source area VOCs both above and below the layer of dense sand
4. maximum reduction of groundwater VOC concentrations achievable with this technology

The ability to create and maintain the treatment cell was evaluated by monitoring changes in groundwater gradient due to system operation and by monitoring groundwater quality in wells screened below the treatment cell (OLD-13-08C) or located downgradient of the treatment cell (OLD-13-43C, OLD-13-45B and GMP-17). Groundwater elevation data collected during the pilot study indicate that when the system is operating, the groundwater gradient is increased in the treatment cell above and below the layer of dense sand. Monitoring of wells screened below and downgradient of the treatment cell indicate that the effects of the treatment system are confined to the area of the treatment cell.

The ability to treat the source zone above and below the dense sand layer has been evaluated by comparing estimated travel times to the actual movement of treated water in the cell and the reduction of VOC concentrations in the treatment cell. Changes in VOC concentrations and groundwater conductivity indicate that treated water is generally moving more rapidly than predicted in the shallow zone and more slowly than predicted in the deep zone. Dramatic decreases in total VOC concentrations have occurred in the shallow zone, but have been slower to develop in the deep zone.

The reduction of contaminants achievable by this technology has been evaluated by comparing baseline VOC concentrations with data collected during the sampling rounds. The maximum

Ms. Barbara Nwokike  
July 12, 2000  
Page 11

VOC concentration detected during the baseline sampling was 24,300  $\mu\text{g/L}$  (23,000  $\mu\text{g/L}$  PCE), detected in GMP-11. By Round 6, VOC concentrations in GMP-11 were below detection limits, indicating that the technology is capable of reductions of more than 99.995% of PCE within 59 days. Furthermore, by Round 8 (101 days after startup, 53 days of system run time), VOC concentrations in four shallow monitoring wells (GMP-10, 11, 12 and 13) have been reduced to or below MCLs. Other monitoring wells at a greater distance from the injection wells showed order of magnitude reductions in VOC concentrations (GMP-08, 09, 14 and 16). Groundwater VOC concentrations will continue to be monitored until completion of the pilot study (through 16 rounds of groundwater sampling). It is expected that VOCs will no longer be detected in groundwater samples collected from the shallow zone.

In the deep zone, significant reductions in VOCs have not yet occurred. This is apparently due to much higher concentrations of natural organic material in the lower zone, which must be also be oxidized, and therefore slows the migration of the VOC oxidation front. However, every indication is that these VOCs will continue to oxidize and eventually be no longer detectable.

## RECOMMENDATIONS

It is apparent that in situ chemical oxidation using  $\text{KMnO}_4$  is very effective at destroying the VOC contamination in the source area at OU 4. We therefore recommend its full-scale application to the source zone.

The Draft Orlando OU 4 FS (HLA, 1999) evaluated in-situ oxidation using  $\text{KMnO}_4$  as a source area alternative. Various cost and performance assumptions were required for the FS evaluation. Based on the results of the pilot study to date, these assumptions can be further refined and the cost of this alternative re-evaluated for the final FS.

The recommended assumptions for full-scale implementation include:

- A maximum injected  $\text{KMnO}_4$  concentration of 4 g/L, while considering initial startup at concentrations possibly as low as 1 g/L;
- Separate injection wells for the shallow and deep zones, to allow targeting of the  $\text{KMnO}_4$  solution and preferential injection into just the deeper zone once the shallow aquifer becomes saturated with  $\text{KMnO}_4$ ;
- Replacement of the cartridge filtration system with a more efficient and less maintenance-intensive alternative, such as sand filters or rotary drum filters;
- Use of the OU 4 hydraulic model to predict  $\text{KMnO}_4$  treatment times in the shallow zone; and
- Treatment of the deep zone by multiple injection points or assuming treatment times at least double the model prediction.

The cost estimate for the  $\text{KMnO}_4$  alternative in the draft FS was competitive with the other remedial alternatives evaluated. The above refinements will further reduce the cost of this alternative. The pilot study results have also demonstrated the effectiveness and implementability

Ms. Barbara Nwokike  
July 12, 2000  
Page 12

of this technology. Based on these results, we recommend completion of a final OU 4 FS, while also preparing an OU 4 Proposed Plan that includes use of in-situ oxidation of the OU 4 source area using  $\text{KMnO}_4$ .

The  $\text{KMnO}_4$  pilot study will be completed during the week of July 24, with collection of the sixteenth and final round of groundwater data. All of the pilot study results will be included in the final  $\text{KMnO}_4$  report that will be prepared once all laboratory data has been received and evaluated.

If you have questions or comments regarding this document, please contact me at (781) 213-5652 or John Kaiser at (407) 522-7570.

Very truly yours,

**HARDING LAWSON ASSOCIATES**



Mark J. Salvetti, P.E.  
Task Order Manager

Enclosures

cc:

W. Hansel (SDIV)	S. Tsangaris (CH2M HILL)	File
C. Casey (SDIV)	S. McCoy (TetraTech)	
D. Grabka (FDEP)	R. Allen (HLA)	
N. Rodriguez (USEPA)	J. Kaiser (HLA)	

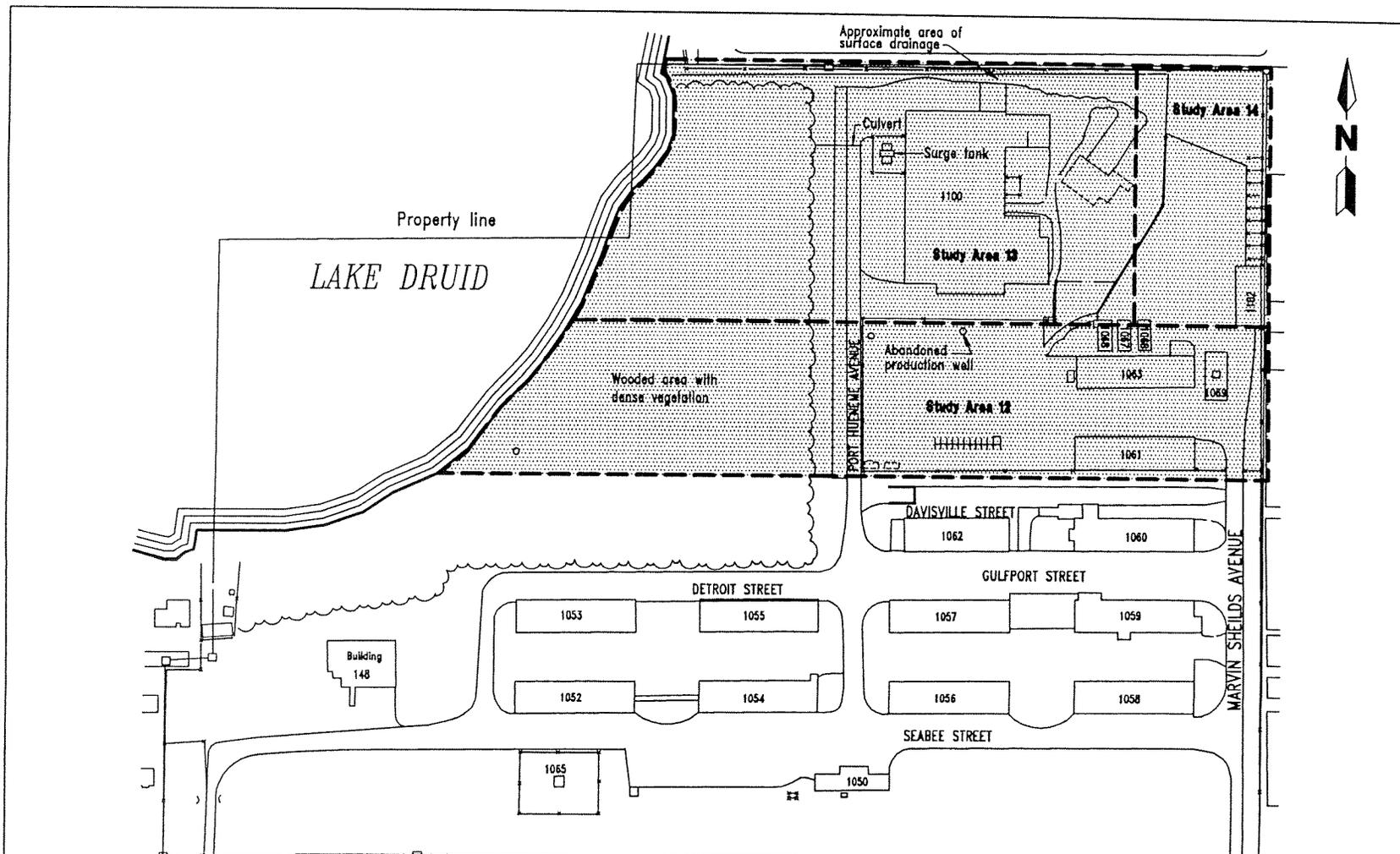
## FIGURES



**FIGURE 1  
SITE LOCATION MAP**



**INTERIM LETTER REPORT  
IN SITU CHEMICAL OXIDATION USING  
POTASSIUM PERMANGANATE  
OPERABLE UNIT 4  
NAVAL TRAINING CENTER  
ORLANDO, FLORIDA**

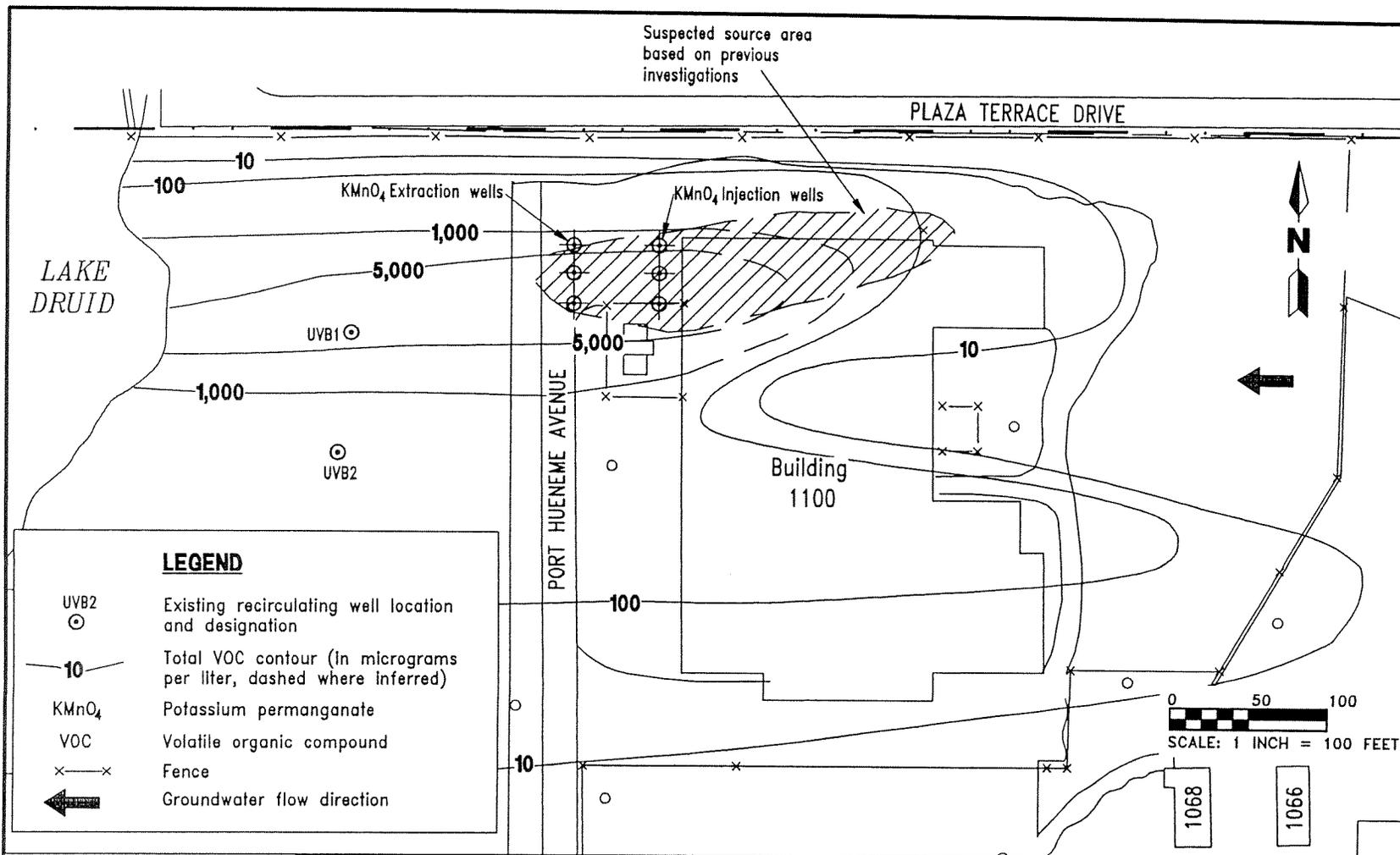


0 125 250  
 SCALE: 1 INCH = 250 FEET

**FIGURE 2**  
**MAP OF AREA C**



**INTERIM LETTER REPORT**  
**IN SITU CHEMICAL OXIDATION USING**  
**POTASSIUM PERMANGANATE**  
**OPERABLE UNIT 4**  
**NAVAL TRAINING CENTER**  
**ORLANDO, FLORIDA**



**FIGURE 3  
PILOT STUDY LOCATION**



**INTERIM LETTER REPORT  
IN SITU CHEMICAL OXIDATION USING  
POTASSIUM PERMANGANATE  
OPERABLE UNIT 4  
NAVAL TRAINING CENTER  
ORLANDO, FLORIDA**



C

Combined Rec  
at Sta

3,50  
780  
320

-13-IW2

100  
50  
50

OLD-13

8  
0  
50

133

IW4

400  
00  
40

0

Simms

Roof overhang

Wall

Building  
1100

Loading  
dock

PORT HUENEME

**LEGEND**

⊕ OLD-13-43C Monitoring well and designation

⊕ OLD-13-46B Proposed monitoring well designation

⊕ GMP-4 Microwell location and designation

● GMP-16 Proposed microwell location

● Q033 Temporary monitoring well location

⊕ OLD-13-RW4 Proposed recovery well and designation

GMP Groundwater

IW Injection well

RW Recovery well

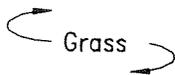
3,400 Tetrachloroethene

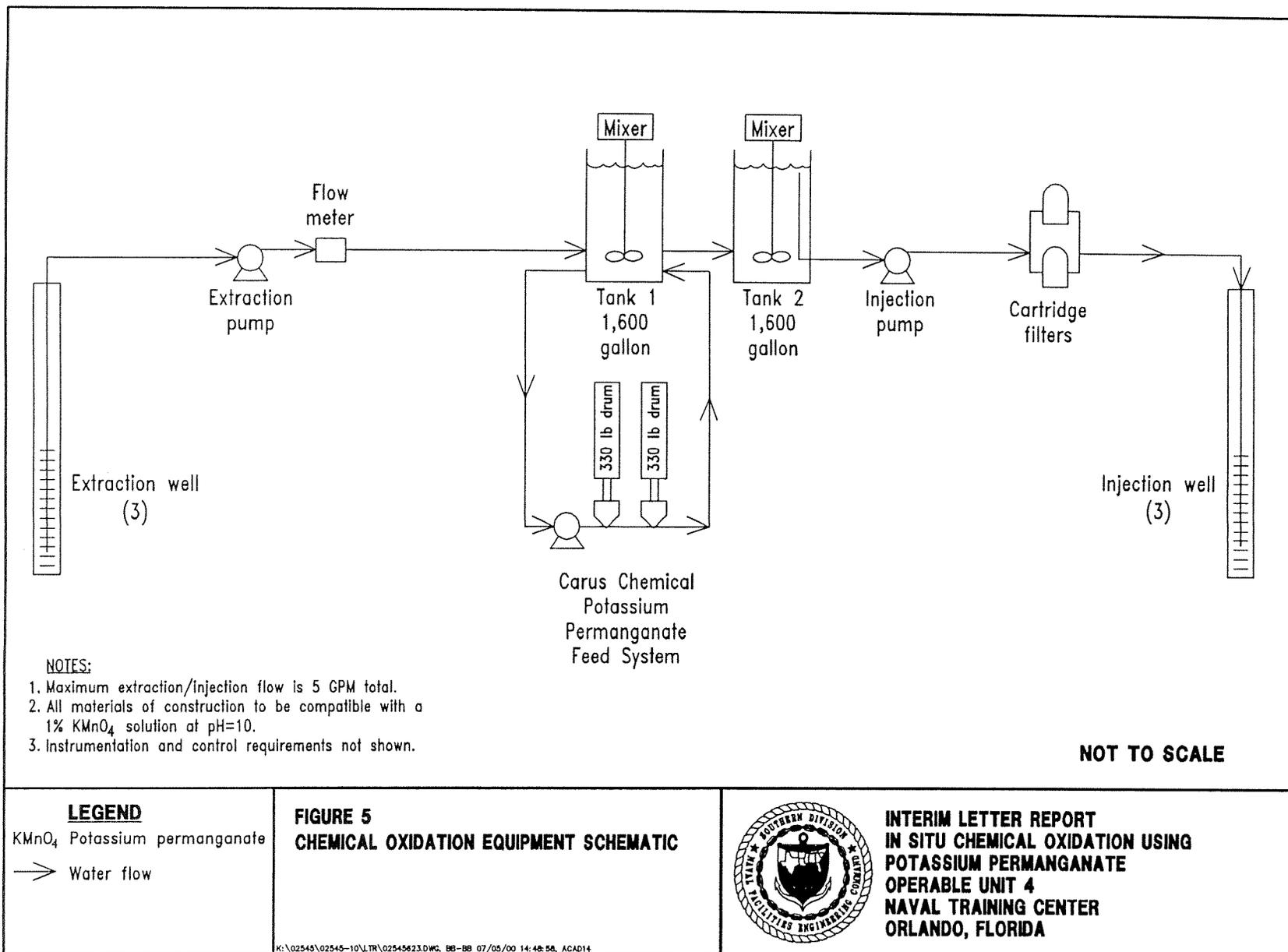
520 Trichloroethylene

240 cis-Dichloroethene

**GROUNDWATER CONCENTRATIONS**

**INTERIM LETTER REPORT  
IN SITU CHEMICAL OXIDATION USING  
POTASSIUM PERMANGANATE  
OPERABLE UNIT 4  
NAVAL TRAINING CENTER  
ORLANDO, FLORIDA**





**Figure 6**  
**VOCs - Shallow**

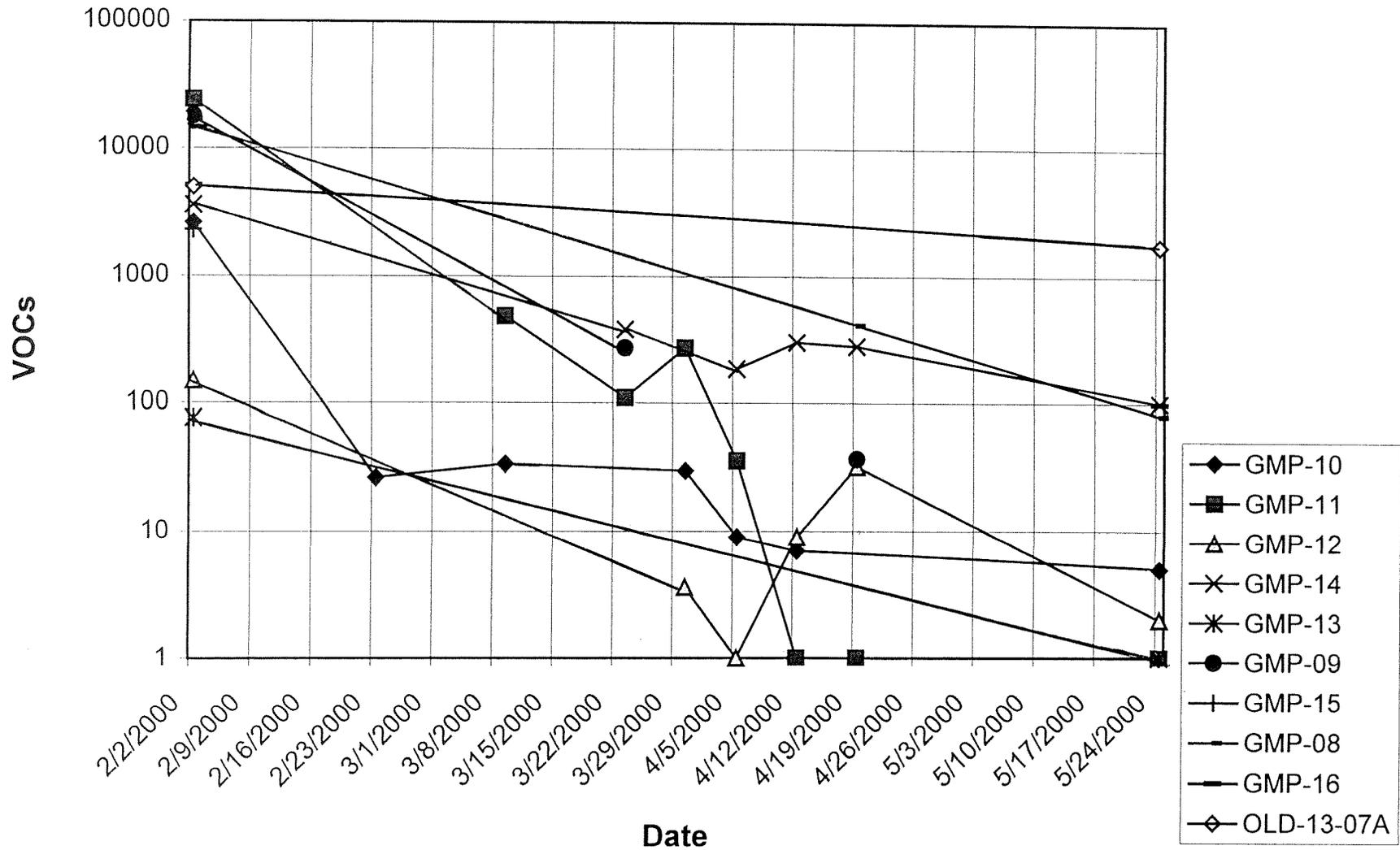


Figure 7  
VOCs-deep

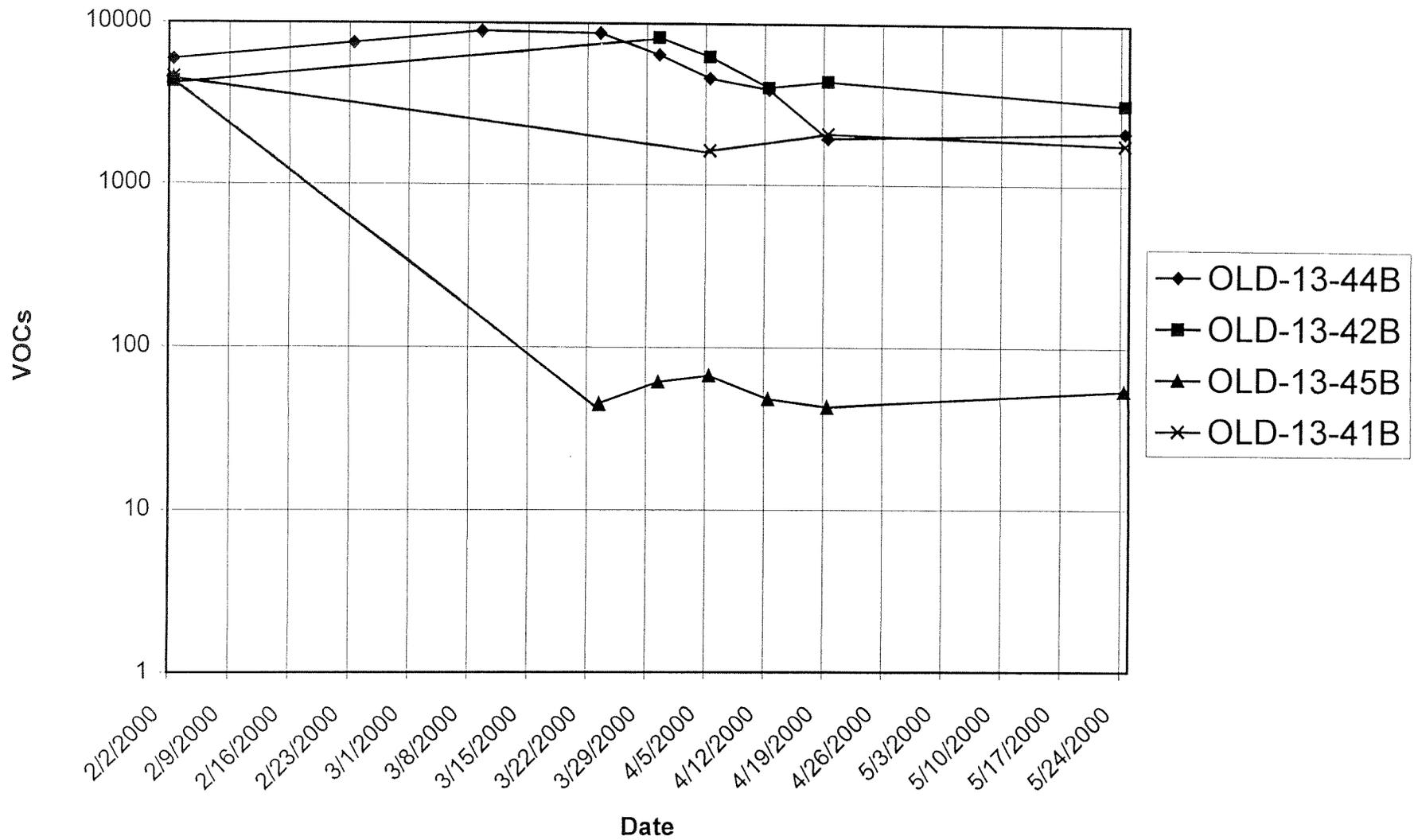


Figure 8  
Conductivity - Shallow

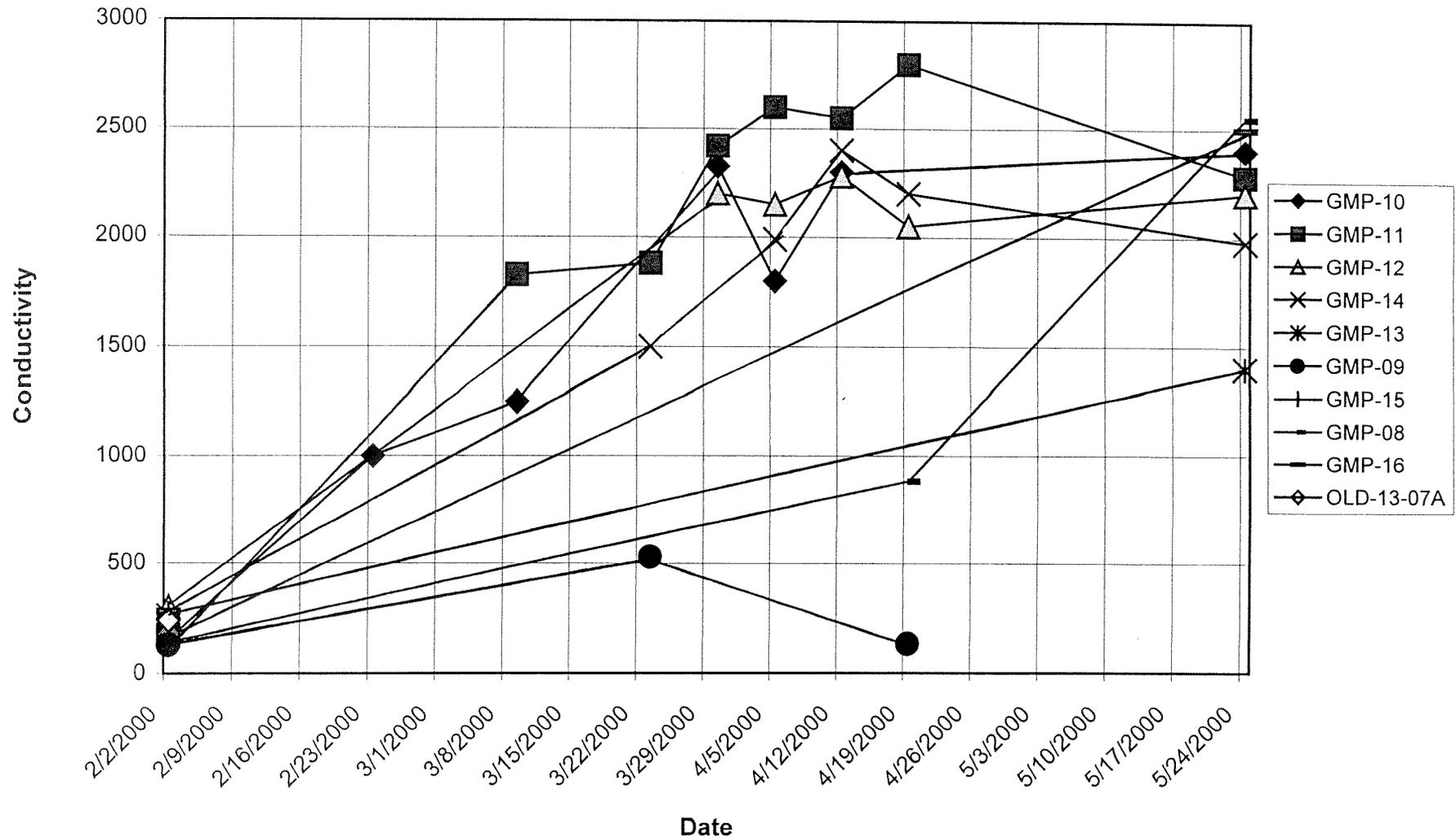
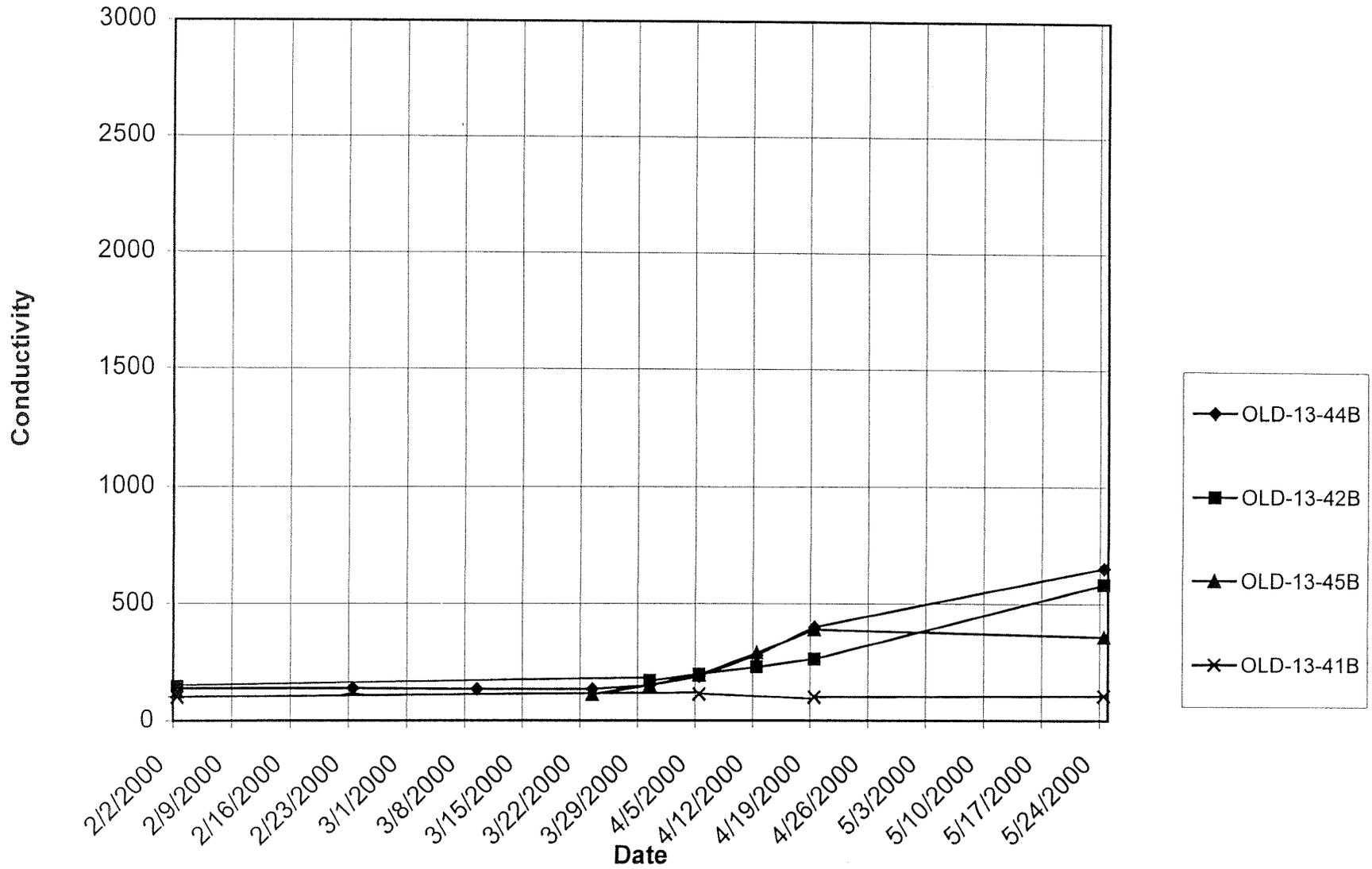


Figure 9  
Conductivity - deep wells



## **TABLES**

Table 1  
Baseline Groundwater Sampling  
OU 4 Potassium Permanganate Pilot Study

Naval Training Center Orlando  
Orlando, FL

Shallow Zone Wells							
Well ID	Total Depth (BLS)	Screen Length	Screened Interval (BLS)	Halogenated VOCs	TAL Metals	Water Quality Parameters <sup>a</sup>	Natural Attenuation Parameters <sup>b</sup>
OLD-13-07A	18.5	15	3.5-18.5 ft.	X			
GMP 07	18	3	15-18 ft.	X			
GMP 08	18	3	15-18 ft.	X			
GMP 09	18	3	15-18 ft.	X	X	X	X
GMP 10	18	3	15-18 ft.	X	X	X	X
GMP-11	18	9	9-18 ft.	X			
GMP 12	18	9	9-18 ft.	X	X	X	X
GMP 13	18	9	9-18 ft.	X	X	X	X
GMP 14	18	9	9-18 ft.	X			
GMP 15	18	9	9-18 ft.	X	X	X	X
GMP 16	18	9	9-18 ft.	X			
GMP 17	18	9	9-18 ft.		X	X	X
Deep Zone Wells							
Well ID	Total Depth (BLS)	Screen Length	Screened Interval (BLS)	Halogenated VOCs	TAL Metals	Water Quality Parameters <sup>a</sup>	Natural Attenuation Parameters <sup>b</sup>
OLD-13-41B	28 ft.	5 ft.	23-28 ft.	X	X	X	X
OLD-13-42B	28 ft.	5 ft.	23-28 ft.	X			
OLD-13-44B	30 ft.	10 ft.	20-30 ft.	X	X	X	X
OLD-13-45B	30 ft.	10 ft.	20-30 ft.	X	X	X	X
OLD-13-46B	30 ft.	10 ft.	20-30 ft.		X	X	X
System Wells							
Well ID	Total Depth (BLS)	Screen Length	Screened Interval (BLS)	Halogenated VOCs	TAL Metals	Water Quality Parameters <sup>a</sup>	Natural Attenuation Parameters <sup>b</sup>
OLD-13-IW2	35 ft.	25 ft.	5-30 ft.	X			
OLD-13-IW3	35 ft.	25 ft.	5-30 ft.	X			
OLD-13-IW4	35 ft.	25 ft.	5-30 ft.	X			
OLD-13-RW2	35 ft.	20 ft.	10-30 ft.	X			
OLD-13-RW3	35 ft.	20 ft.	10-30 ft.	X			
OLD-13-RW4	35 ft.	20 ft.	10-30 ft.	X			
Notes:							
a: Water quality parameters include Total Dissolved Solids and Color							
b: Natural attenuation parameters include off-site analysis for Total Organic Carbon and light gases (RSK 175) and on-site analysis for dissolved oxygen, ferrous iron, total iron, sulfate, hydrogen sulfide, carbon dioxide, nitrite, chloride, alkalinity and hardness							
BLS - Below land surface							
VOCs - Volatile organic compounds							
TAL - Target analyte list							

Table 2  
System Calendar  
OU 4 Potassium Permanganate Pilot Study

Naval Training Center Orlando  
Orlando, FL

February	
	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29
Sampling Rounds	1
System Operations	5 Days
Flow Rates	Set up / Start up      Recirc. Pump replacement 3.5 gpm
March	
	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
Sampling Rounds	2      3      4
System Operations	7 Days      Power Out      19 Days
Flow Rates	3.5 gpm      4.0 gpm
April	
	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Sampling Rounds	5      6      6      7      7
System Operations	13 Days      Replace touch pad on control panel
Flow Rates	4.0 gpm      3.0 gpm
May	
	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
Sampling Rounds	8      8
System Operations	3 Days      1 Day      High pressure shut down      3 Days      13 Days
Flow Rates	4.0 gpm      Vacc. Truck 5/18/00      4.0 gpm      4.0 gpm      3.0 gpm

Table 3  
Performance Monitoring Groundwater Sampling  
OU 4 Potassium Permanganate Pilot Study

Naval Training Center Orlando  
Orlando, FL

Sampling Round	Date	Calendar Days since start	Run Days since start	Extraction Rate (GPM)	Locations Sampled	Comments
Round 1	Feb. 23	10	6	----	GMP-10, OLD-13-44B	System not running.
Round 2	Mar. 9	25	12	3.5	GMP-10, GMP-11, OLD-13-44B, Influent, Effluent	
Round 3	Mar. 23	39	21	4	GMP-09, GMP-11, GMP-14, OLD-13-44B, OLD-13-45B, Influent, Effluent	
Round 4	Mar. 30	46	28	4	GMP-10, GMP-11, GMP-12, OLD-13-42B, OLD-13-44B, OLD-13-45B, Influent, Effluent	
Round 5	Apr. 5	52	33	4	GMP-10, GMP-11, GMP-12, GMP-14, OLD-13-42B, OLD-13-44B, OLD-13-45B, Influent, Effluent	
Round 6	Apr. 12/13	59	40	3	GMP-10, GMP-11, GMP-12, GMP-14, OLD-13-41B, OLD-13-42B, OLD-13-44B, OLD-13-45B, OLD-13-46B, Influent, Effluent	
Round 7	Apr. 19/20	66	44	----	GMP-08, GMP-09, GMP-11, GMP-12, GMP-14, OLD-13-41B, OLD-13-42B, OLD-13-44B, OLD-13-45B	System not running.
Round 8	May 24/25	101	53	4	GMP-08, GMP-10, GMP-11, GMP-12, GMP-13, GMP-14, GMP-16, OLD-13-41B, OLD-13-42B, OLD-13-44B, OLD-13-45B, OLD-13-07A, Influent, Effluent	

Table 4  
Groundwater Elevations and Gradients  
OU 4 Potassium Permanganate Pilot Study

Naval Training Center Orlando  
Orlando, FL

SHALLOW ZONE										
Date		2/7/00	2/14/00	3/8/00	3/23/00	3/30/00	4/5/00	4/12/00	4/19/00	5/24/00
Sampling Round				Round 2	Round 3	Round 4	Round 5	Round 6	Round 7	Round 8
Extraction Rate		NA	NA	3.5 GPM	4 GPM	4 GPM	4 GPM	3 GPM	NA	4 GPM
Well ID	Distance									
OLD-13-26A	0			103.84	103.49	103.41	103.30	103.12	102.98	102.65
GMP-10	8	103.48	103.42	103.32	103.19	103.05	103.04	102.82	102.74	102.39
GMP-11	13	103.45	103.39	103.23	103.12	102.99	102.96	102.76	102.71	102.31
GMP-14	20	103.44	103.38	103.2	103.04	102.93	102.89	102.72	102.70	102.23
GMP-09	26	103.42	103.37	103.18	103.00	102.88	102.86	102.69	102.69	102.21
GMP-15	32	103.39	103.39	103.12	102.92	102.82	102.78	102.63	102.65	102.13
GMP-08	41	103.35	103.31	103.05	102.83	102.71	102.69	102.55	102.61	102.04
GMP-16	45	103.32	103.27	102.98	102.76	102.65	102.62	102.49	102.57	101.96
GMP-07	56	103.31	103.26	102.95	102.69	102.57	102.55	102.45	102.57	101.93
OLD-13-RW4	63	103.22	103.13	102.47	101.83	101.78	101.81	101.90	102.43	101.15
GMP-17	81	103.21	103.13	102.79	102.57	102.45	102.42	102.32	102.46	101.77
Head Difference		0.17	0.16	0.37	0.5	0.48	0.49	0.37	0.17	0.46
Gradient		0.0035	0.0033	0.0077	0.0104	0.0100	0.0102	0.0077	0.0035	0.0096
DEEP ZONE										
Date		2/7/00	2/14/00	3/8/00	3/23/00	3/30/00	4/5/00	4/12/00	4/19/00	5/24/00
Sampling Round				Round 2	Round 3	Round 4	Round 5	Round 6	Round 7	Round 8
Extraction Rate		NA	NA	3.5 GPM	4 GPM	4 GPM	4 GPM	3 GPM	NA	4 GPM
Well ID	Distance									
OLD-13-IW4	0	103.46	103.37	103.84	103.49	103.41	103.30	103.12	102.98	102.65
OLD-13-44B	21	103.37	103.28	103.06	102.89	102.77	102.73	102.60	102.60	102.06
OLD-13-42B	35	103	102.96	102.99	102.79	102.67	102.64	102.52	102.54	101.98
OLD-13-45B	36	103.33	103.26	102.98	102.79	102.67	102.63	102.51	102.56	101.98
OLD-13-41B	55	103.24	103.17	102.84	102.63	102.52	102.48	102.38	102.48	101.83
OLD-13-RW4	63	103.22	103.13	102.47	101.83	101.78	101.81	101.90	102.43	101.15
Head Difference		0.13	0.11	0.22	0.26	0.25	0.25	0.22	0.12	0.23
Gradient		0.0038	0.0032	0.0065	0.0076	0.0074	0.0074	0.0065	0.0035	0.0068
Distance - Distance of Monitoring well from injection wells										
Head Difference - Shallow Zone = GMP-10 - GMP-07 and Deep Zone = OLD-13-44B - OLD-13-41B										
Gradient - Shallow Zone = Head Difference/48 feet and Deep Zone = Head Difference/34 feet										

Table 5  
 Summary of VOC Concentrations and Groundwater Conductivity  
 OU 4 Potassium Permanganate Pilot Study

Naval Training Center Orlando  
 Orlando, FL

SHALLOW ZONE																			
Sampling Round		Baseline		Round 1		Round 2		Round 3		Round 4		Round 5		Round 6		Round 7		Round 8	
Run Days		0		5		12		21		28		33		40/41		44/45		53/54	
Calendar Days		0		10		25		39		46		52		59/60		66/67		101/102	
Well ID	Travel Time	Cond.	VOCs	Cond.	VOCs	Cond.	VOCs	Cond.	VOCs	Cond.	VOCs	Cond.	VOCs	Cond.	VOCs	Cond.	VOCs	Cond.	VOCs
GMP-10	10	152	2630	1000	26.6	1250	34			2325	30	1800	9	2300	7			2400	5
GMP-11	20	172	24300			1825	482	1880	110	2420	270	2600	36	2550	0	2800	0	2280	0
GMP-12	30	302	149							2200	3.6	2150	0	2280	9	2050	32.4	2200	2
GMP-14	45	260	3600					1500	377			1990	185	2400	300	2200	280	1980	100
GMP-13	55	238	77															1400	0
GMP-09	80	130	18000					530	271							135	37.1		
GMP-15	80	270	2300																
GMP-08	120	128	16950													880	412	2550	80
GMP-16	120	280	5120															2500	99
OLD-13-07A	140	240	5000															2000	1742
DEEP ZONE																			
Sampling Round		Baseline		Round 1		Round 2		Round 3		Round 4		Round 5		Round 6		Round 7		Round 8	
Run Days		0		5		12		21		28		33		40/41		44/45		53/54	
Calendar Days		0		10		25		39		46		52		59/60		66/67		101/102	
Well ID	Travel Time	Cond.	VOCs	Cond.	VOCs	Cond.	VOCs	Cond.	VOCs	Cond.	VOCs	Cond.	VOCs	Cond.	VOCs	Cond.	VOCs	Cond.	VOCs
OLD-13-44B	10	138	5940	138	7540	135	8930	135	8700	150	6420	190	4580	280	3900	400	1930	650	2120
OLD-13-42B	25	148	4300							171	8200	199	6260	230	4020	265	4380	580	3170
OLD-13-45B	25	121	4560					111	45	150	61	195	67	290	48	390	43	360	54
OLD-13-41B	50	100	4600									112	1620			100	2060	105	1770
Travel Time - Estimated from groundwater model																			
Cond. - Conductivity of groundwater in $\mu\text{S}/\text{cm}$																			
VOCs - Total concentration of cis1,2 DCE, TCE and PCE in $\mu\text{g}/\text{L}$																			

## REFERENCES

- ABB Environmental Services, Inc. (ABB-ES), 1996a. *Interim Remedial Action Focused Field Investigation Report, Operable Unit 4, Naval Training Center, Orlando, Florida*. Prepared for SOUTHNAVFACENGCOM, North Charleston, South Carolina (November).
- ABB-ES, 1997b. *Remedial Investigation and Feasibility Study Workplan, Operable Unit 4, Study Areas 12, 13, and 14 – Area C, Naval Training Center, Orlando, Florida*. Prepared for SOUTHNAVFACENGCOM, North Charleston, South Carolina (October).
- ABB-ES, 1997c. *Technical Memorandum, Interim Remedial Action, Focused Investigation/ Source Confirmation, Building 1100 Surge Tank, Naval Training Center, Orlando, Florida*. Prepared for SOUTHNAVFACENGCOM, North Charleston, South Carolina (May).
- Harding Lawson Associates (HLA), 1999. *Feasibility Study, Operable Unit 4, Naval Training Center, Orlando, Florida*. Prepared for SOUTHNAVFACENGCOM, North Charleston, South Carolina (January).
- HLA, 2000. *Redline/Strikeout Version of the Remedial Investigation, Operable Unit 4, Study Areas 12, 13, and 14 – Area C, Naval Training Center, Orlando, Florida*. Prepared for SOUTHNAVFACENGCOM, North Charleston, South Carolina (April).
- Hood, E.D., N.R. Thomson, and G.J. Farquhar, 1998. *In Situ Oxidation: An Innovative Treatment Strategy to Remedial Trichloroethylene and Perchloroethylene DNAPLs in Porous Media*. Presented at the 6<sup>th</sup> Symposium on Groundwater and Soil Remediation, Montreal, Quebec (March).
- Schnarr, M., C. Truax, G. Farquhar, E. Hood, T. Gonullu, and B. Stickney, 1996. *Laboratory and Controlled Field Experiments Using Potassium Permanganate to Remediate Trichloroethylene and Perchloroethylene DNAPLs in Porous Media*. *Journal of Contaminant Hydrology* (December).
- U.S. Geological Survey, 1998. *Assessment of the Potential Effects of Phytoremediation on Groundwater Flow Around Area C at Orlando Naval Training Ceter, Florida*. Water-Resources Investigations Report 98-4110.
- West, O.R., S.R. Cline, W.L. Holden, F.G. Gardner, B.M. Schlosser, J.E. Thate, D.A. Pickering. 1997. *A Full-Scale Demonstration on In Situ Chemical Oxidation Through Recirculation at the X-701B Site, Field Operations and TCE Degradation*. Prepared for the U.S. Department of Energy. Oak Ridge National Laboratory, Environmental Sciences Division, Publication No. 4727 (December).