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A Full-Scale Demonstration of In Situ Chemical Oxidation Through Recirculation at the X-701B Site

O. R. West
S. R. Cline
W. L. Holden
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B. M. Schlosser
J. E. Thate
D. A. Pickering
T. C. Houk

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Field Operations and TCE Degradation

O. R. West, S. R. Cline, W. L. Holden, F. G. Gardner,
B. M. Schlosser, J. E. Thate, D. A. Pickering
Oak Ridge National Laboratory, Oak Ridge, TN

T. C. Houk
Lockheed Martin Energy Systems
Technology Applications, Piketon, Ohio

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Executive Summary

In situ chemical oxidation is an emerging remediation technique in which chemical oxidants are delivered to the subsurface to rapidly degrade organic contaminants. Laboratory-scale experiments have demonstrated that potassium permanganate ($KMnO_4$) and hydrogen peroxide (H_2O_2), if applied at sufficient loadings to contaminated soils, can effectively oxidize trichloroethylene (TCE) and perchloroethylene (PCE). Between the two oxidants, $KMnO_4$ is more stable and may result in a higher rate of TCE degradation.

In 1996, researchers at Oak Ridge National Laboratory (ORNL) proposed an oxidant delivery technique involving injection and recirculation of the oxidant solution into a contaminated aquifer through multiple horizontal and vertical wells. This technique would be applicable to saturated, hydraulically conductive formations. In the spring of 1997, the Department of Energy (DOE) at the Portsmouth Gaseous Diffusion Plant (PORTS) agreed to collaborate with the DOE's Subsurface Contaminants Focus Area to conduct a field-scale treatability study using in situ chemical oxidation through recirculation (ISCOR). PORTS agreed to support the demonstration at the X-701B site where the technology can potentially be used to remediate TCE-contaminated groundwater and sediments. The ISCOR field demonstration took advantage of existing infrastructure and extensive site characterization data generated from previous field demonstrations at X-701B. The field test was implemented using a pair of previously installed horizontal wells that transect an area of DNAPL contamination. Groundwater was extracted from one horizontal well, pumped to an existing pump and treat facility, dosed with $KMnO_4$, and re-injected into a parallel horizontal well approximately 90 ft away. The field demonstration lasted approximately one month. Treatment effectiveness was determined by comparing contaminant levels in pre-treatment, during, and post-treatment groundwater samples and pre- and post-treatment soil samples

Analytical results from the field demonstration indicate that ISCOR is effective at oxidizing TCE in the saturated zone. Lateral and vertical heterogeneities within the Gallia impacted the ability to deliver oxidant solution uniformly throughout the area between the horizontal wells. Furthermore, TCE in the neighboring low-permeability formations (the Sunbury and Minford layers) was not affected by oxidant recirculation through the Gallia. The oxidant may not have had time to diffuse from the Gallia into the Sunbury or Minford formations given the short duration of this test. However, in general, TCE was not detected where oxidant was present in samples collected from Gallia monitoring wells within the test region. Reduction of the TCE mass within the more conductive Gallia formation will lead to an overall reduction of TCE mobility within the X-701B area. Long-term groundwater monitoring will be required to fully assess the impact of this demonstration on the ISCOR test region.

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ACRONYMS AND CHEMICAL SYMBOLS

bgs	below ground surface
C_2HCl_3	TCE
Cl^-	chloride ion
CO_2	carbon dioxide
DNAPL	dense non-aqueous phase liquids
DOE	Department of Energy
GC/ECD	gas chromatograph with an electron capture detector
H^+	hydrogen ion
H_2O	water
H_2O_2	hydrogen peroxide
ISCOR	in situ chemical oxidation through recirculation
ISTR	in situ treatment recirculation
$KMnO_4$	potassium permanganate
Mn	manganese
MnO_2	manganese dioxide
MnO_4^-	permanganate ion
ORNL/ESD	Oak Ridge National Laboratory, Environmental Sciences Division
ORNL/GJ	Oak Ridge National Laboratory, Grand Junction
P & T	pump and treat
PCE	tetrachloroethylene or perchloroethylene
PORTS	Portsmouth Gaseous Diffusion Plant
RCRA	Resource Conservation and Recovery Act
RFI	RCRA facility investigation
TCE	trichloroethylene
VOC	volatile organic contaminants

1. INTRODUCTION

1.1 TECHNOLOGY DESCRIPTION

In situ chemical oxidation is an emerging remediation technique in which chemical oxidants are delivered to the subsurface to rapidly degrade organic contaminants. For the past 5 years, engineers and scientists at the Environmental Sciences Division of Oak Ridge National Laboratory (ORNL/ESD) have been developing this technology for in situ degradation of dense non-aqueous phase liquids (DNAPL) such as trichloroethylene (TCE) and tetrachloroethylene (PCE). Laboratory-scale experiments performed to date at ORNL have demonstrated that potassium permanganate ($KMnO_4$) and hydrogen peroxide (H_2O_2), if applied at sufficient loadings to contaminated soils, can effectively oxidize TCE and PCE. The following describes the overall chemical reaction for $MnO4^-$ oxidation of TCE:

$$2MnO_4^- + C_2HCl_3 \rightarrow 2CO_2 + 2MnO_2 + 3Cl^- + H^+. \quad (1)$$

Oxidation by H_2O_2 occurs through a Fenton's reagent reaction catalyzed by iron:

$$C_2HCl_3 + 3H_2O_2 \rightarrow 2CO_2 + 2H_2O + H^+.+ Cl^- \quad (2)$$

Between the two oxidants, $KMnO_4$ was generally found to result in higher degradation of TCE and PCE under a wider range of subsurface conditions when compared to H_2O_2. Furthermore, $KMnO_4$ is inherently more stable than H_2O_2, the latter tending to decompose rapidly to H_2O and O_2 when brought in contact with soil material. The relative stability of $KMnO_4$ makes it more attractive and effective for applications where oxidizing power must be maintained over longer time periods, such as when the oxidant needs to be flowed over long distances to treat large volumes of subsurface media.

To continue moving in situ chemical oxidation towards widespread use and commercial viability, techniques for delivering chemical oxidants in adequate amounts to the subsurface are being developed. In FY96, a field demonstration conducted at the Kansas City Plant tested the efficacy of soil mixing to deliver $KMnO_4$ solutions to TCE-contaminated dense clays. Deep soil mixing is an aggressive subsurface manipulation technique for source areas and it is suitable for delivering reagents to low-permeability soils. However, an alternative approach must be found for sites where the physical disruption of contaminated deposits brought about by soil mixing is not always desirable, feasible or necessary. For example, subsurface media may have high enough permeabilities that physical disruption of the soil is not required, or the depth of contamination or overlying structures preclude soil mixing. Furthermore, soil mixing may not be the best approach for saturated subsurface media. If pores are already filled with groundwater, only a limited amount of fluid oxidant can be introduced into the subsurface even if the soil were disrupted by mixing.

In 1996, ORNL researchers proposed an oxidant delivery technique that can potentially work in saturated permeable subsurface media (e.g., hydraulic conductivity $>10^{-4}$ cm/s). The approach, which ORNL has referred to as in situ chemical oxidation through recirculation (ISCOR), involves injection and recirculation of the oxidant solution into a contaminated aquifer through

multiple horizontal and vertical wells. The advantages of this approach include: (1) better control of oxidant and contaminant migration within the treatment zone when compared to well injections alone, (2) the introduction of higher volumes of oxidant solutions because existing soil pore water is extracted prior to oxidant injection, and (3) potentially lower overall cost for treating larger volumes of soil and for multiple oxidant dosings when compared to deep soil mixing.

1.2 OBJECTIVES

ORNL received funding for fiscal year 1997 from the Department of Energy's Subsurface Contaminants Focus Area to conduct a field test of this new oxidant delivery through ISCOR. In spring 1997, the Department of Energy (DOE) in Piketon, OH agreed to collaborate with ORNL and support a field test of ISCOR at the X-701B site of the Portsmouth Gaseous Diffusion Plant. Previous disposal of contaminated wastewaters in the X-701B sludge pond had led to chlorinated solvent contamination (primarily TCE) in the sediments underlying the X-701B area. Of most concern is the presence of dense non-aqueous phase liquids (DNAPLs) in the underlying Gallia aquifer that are serving as a persistent source for a groundwater plume that emanates from the holding-pond area of X-701B. Off-site migration of the X-701B plume is currently being controlled by pump-and-treat (P&T) facilities, which are costly to operate. Thus, there is a strong incentive within the PORTS Environmental Restoration program to look for innovative technologies that can effectively remove sources of groundwater plumes, and lead to significant reduction in the number of years that the P&T facilities need to be operated. For this reason, PORTS supported the ISCOR demonstration at X-701B because the technology can potentially be used to reduce DNAPL source contamination at this site.

The ISCOR field demonstration took advantage of existing infrastructure and extensive site characterization data generated by previous field demonstrations at X-701B (Korte et al., 1997). The ISCOR field test was implemented using a pair of previously installed horizontal wells (Fig. 1.1), with innovative filter materials (500 μm) instead of conventional well screens, that transect an area of DNAPL contamination within the underlying Gallia water-bearing unit. These wells were installed as part of the In Situ Treatment through Recirculation (ISTR) field demonstration conducted in 1996 (Korte et al., 1997). In the ISTR field demo, groundwater was extracted from the west horizontal well, run through an iron filings-based treatment system that reductively dechlorinated TCE, and re-injected into the east horizontal well. Re-injection of clean water into the aquifer was expected to increase DNAPL solubilization and subsequent removal from the zone between the recirculating horizontal wells. ISCOR is analogous to the ISTR approach except that the extracted groundwater is dosed with $KMnO_4$, which results in the oxidation of dissolved-phase TCE. The oxidant-dosed groundwater is then expected to reduce DNAPL mass in place when it is recirculated back through the aquifer.

The ISCOR field test was conducted from July through August 1997, and post-treatment characterization was completed in September 1997. The objectives of the ISCOR field test were (1) to evaluate ISCOR as a means for delivering oxidants to saturated, permeable subsurface materials, (2) to assess its performance in degrading DNAPLs within an aquifer, and (3) to obtain cost information for future applications at PORTS and other sites.

The purpose of this document is to provide DOE/PORTS with an overview of the ISCOR field test at X-701B, focusing on treatment operations and TCE degradation. This document will be expanded to include results and interpretation of chemical analyses beyond the basic parameters needed to assess ISCOR's overall TCE degradation performance. The expanded report will also include cost estimates for ISCOR implementations, results of geophysical monitoring during the ISCOR test, and modeling to determine the effects of heterogeneity on the distribution of oxidant through the Gallia. A copy of the expanded report will be provided to DOE/PORTS, the final version of which is expected to be completed by December 1997.

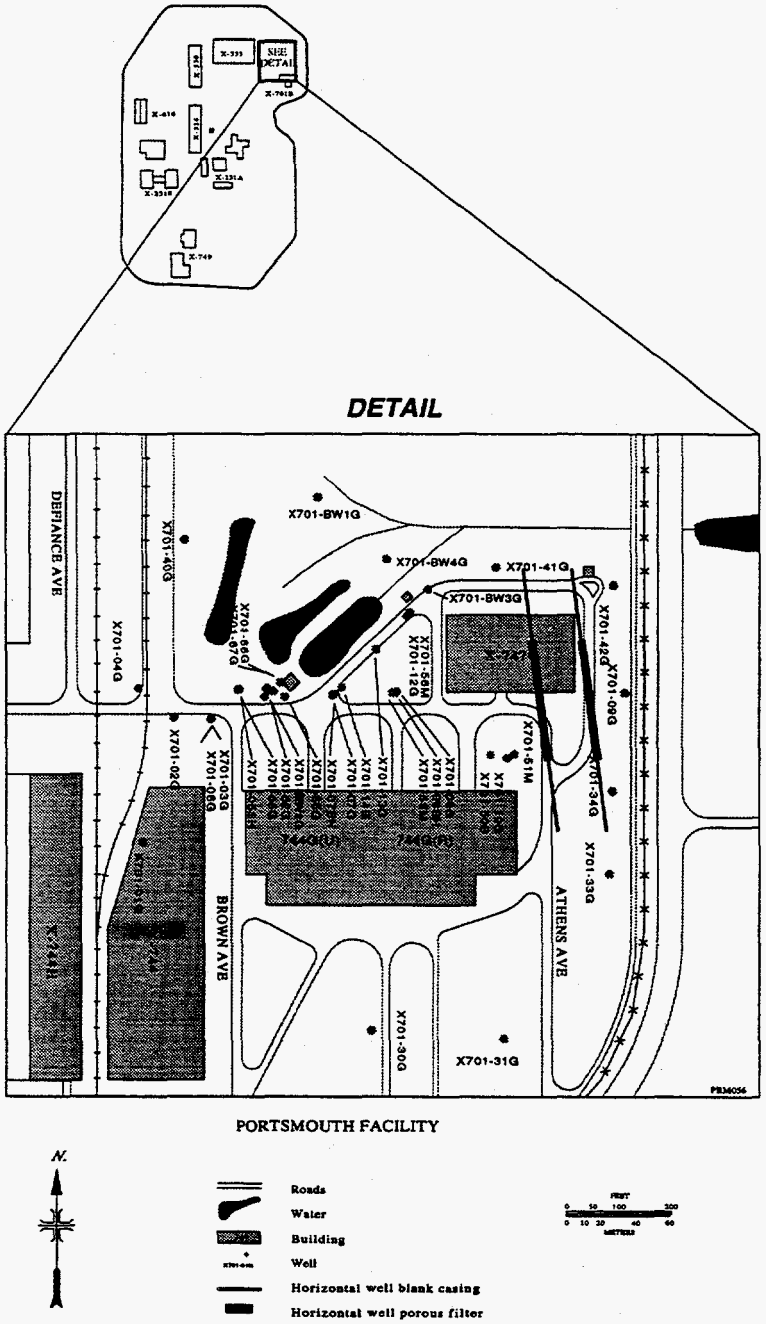


Fig. 1.1. X-701B area at PORTS showing locations of horizontal wells.

2. SITE DESCRIPTION

2.1 SITE HISTORY

The X-701B site is located in the northeastern area of PORTS (see Fig. 2.1) and contains an unlined holding pond, 200-ft by 50-ft in area (DOE 1994a). The pond was used from 1954 to 1988 for the neutralization and settling of metal-bearing acidic wastewater and solvent contaminated solutions. Most of the waste discharged to the pond originated from the X-700 Chemical Cleaning Facility and the X-705 Decontamination Building. From 1974 through 1988, slaked lime was added to the X-701B influent to neutralize its low pH and induce precipitation. This precipitation caused large amounts of sludge to accumulate in the pond and necessitated periodic dredging of the sludge. The holding pond was drained and the contaminated sludge and underlying silt and clay were removed as part of a RCRA closure action in 1990.

2.2 LITHOLOGY AND HYDROGEOLOGY

The stratigraphy underlying the X701-B site consists of the following layers: (1) Minford silt and clay with a thickness of 25 to 30 ft, (2) Gallia sand and gravel which has a thickness varying from 2 to 10 ft, (3) the Sunbury shale is the first bedrock layer which consists of a 10 to 15-ft thick, moderately hard shale that often exhibits an upper weathered zone of gray, highly plastic clay, and (4) Berea sandstone which is present at an approximate depth of 47 ft in this area (DOE 1994b). Within the region between the horizontal wells, the thickness of the Gallia layer is 5-6 ft based on characterization efforts related to the ISTR demo (Korte et. al, 1997). This was confirmed by pretreatment characterization activities conducted within the same region immediately prior to the ISCOR field test (Sect. 3).

The hydraulic conductivity of the Gallia was measured at 20 ft/day (7×10^{-3} cm/s) by a pumping test at the upgradient (west) horizontal well (Korte et al, 1997). This is comparable to values measured at other wells within PORTS that are screened within the Gallia aquifer (H. Sydnor, Lockheed Martin Energy Systems, personal communication). However, the hydraulic conductivity measured by single-well pump tests in monitoring wells located between the X-701B horizontal wells ranged from 24 to 411 ft/day (Korte et al, 1997), indicating that lateral heterogeneities exist even within the 90 ft x 200 ft region between the horizontal wells. Preferential flow was observed during a tracer test conducted as part of the ISTR demo (Korte et al, 1997). A similar pattern in permanganate transport between the horizontal wells was noted during the ISCOR demo (see Sect. 4).

Groundwater movement in the Gallia within X-701B area is generally from west to east, with variations from this overall trend due to surface recharge/drainage features and on-going pump-and-treat activities to control off-site contaminant migration.

2.3 SITE CONTAMINATION AND CONTROL MEASURES

Previous disposal of contaminated wastewaters in the X-701B holding pond has led to chlorinated solvent contamination (primarily TCE) in the sediments underlying the X-701B area. Of most concern is the presence of dense non-aqueous phase liquids (DNAPLs) in the Gallia that

are serving as a persistent source for a groundwater plume that emanates from the holding-pond area of X-701B and extends to the east (DOE 1994b) (Fig. 2.1). During the Quadrant II RCRA Facility Investigation (RFI), TCE was detected in a groundwater sample from well X701-09G, near the horizontal wells, at a concentration of 700,000 µg/L. The presence of TCE as a DNAPL phase can be inferred from this concentration, which is very close to the solubility limit of TCE in water. DNAPL has been observed in a number of wells within the X-701B area. ^{99}Tc was also detected at an activity of 926 pCi/L (DOE 1994a).

Migration of the X-701B plume to the southwest and discharge to the Little Beaver Creek is currently being controlled by an interceptor trench and extraction wells from which groundwater is pumped at a rate of ~50 gpm and treated using air strippers and activated carbon at the X-624 groundwater treatment facility (GTF, see Fig. 2.1). Operating time for this treatment facility is expected to be significantly reduced if a sufficient reduction of TCE contamination sources is achieved within the X-701B area.

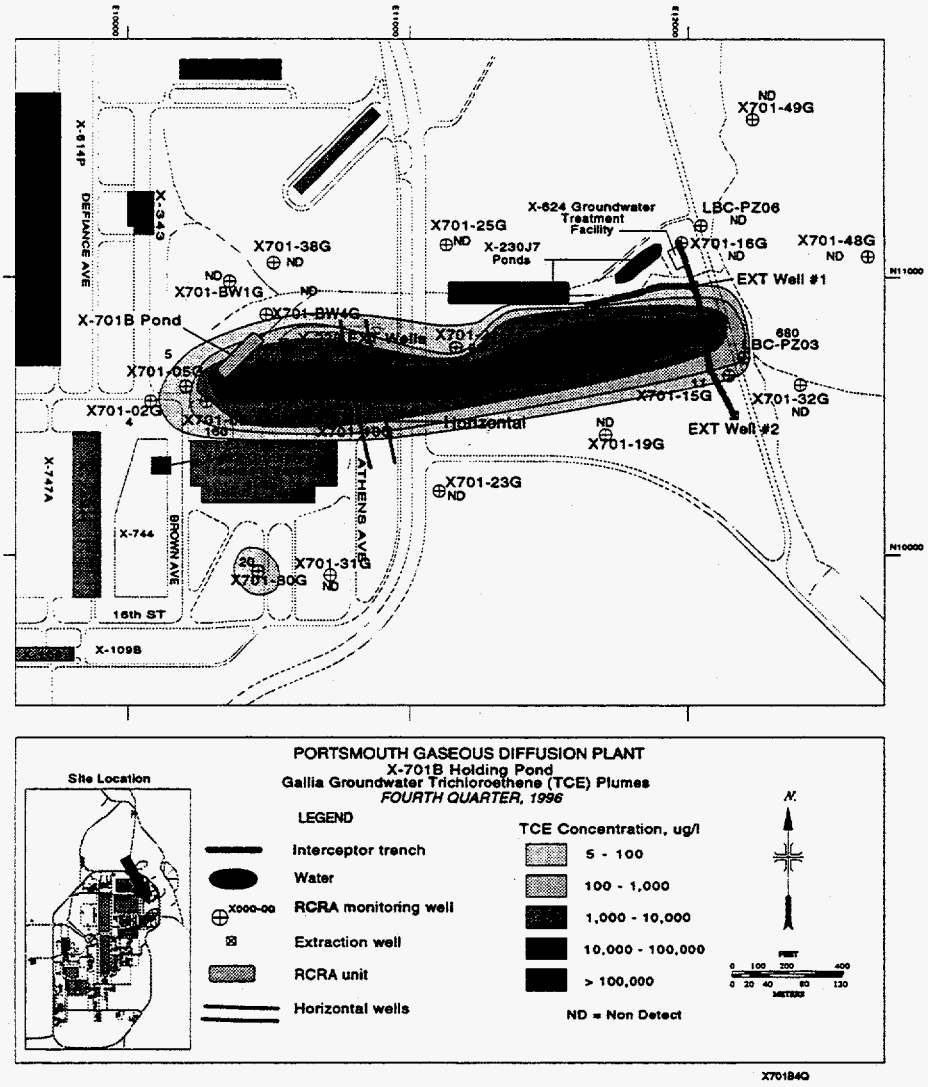


Fig. 2.1 TCE contours within the Gallia aquifer underlying the X-701B area.

3. PRETREATMENT CHARACTERIZATION

3.1 METHODS

Immediately prior to the ISCOR demonstration, 22 boreholes were drilled between the horizontal wells, as shown in Fig. 3.1. At one location, duplicate borings (< 5 ft apart) were drilled to assess the degree of heterogeneity within treatment region. Borings were drilled to the surface of the Sunbury shale layer using direct-push equipment (AMS 16000) and Geoprobe sampling tools. Drilling to bedrock was verified by visual examination of extracted soil cores. Fewer boreholes were drilled in the northern portion of the treatment region because of time constraints and the presence of a controlled-access radioactive contamination area which made sampling very time consuming. The boreholes that were drilled within the rad area showed that this region was less contaminated than the rest of the subsurface treatment zone.

Continuous core samples were obtained from the boreholes starting from a depth of 18-ft for visual examination and lithological classification. Soil samples were collected from every 1.0-ft interval from 20 to 30 ft bgs for volatile organic contaminant (VOC) analysis through hexane extraction followed by analysis of the extracts on an HP5890 gas chromatograph equipped with an electron capture detector (GC/ECD). The GC/ECD was calibrated for TCE and cis-1,2-dichloroethene (approximate detection limit at 5 ppb). Soil pH, total organic carbon, total cations (e.g., K, Mn, Fe), aerobic bacteria and particle distribution were also measured for select number of soil samples to establish background conditions.

Three-quarter in. diameter PVC wells with 5-ft screens within the Gallia layer were installed at 14 of the 22 boreholes shown in Fig. 3.1 (see Fig. 3.2 for monitoring well locations). A higher number of monitoring wells were installed around existing wells 73G through 75G since these exhibited high aqueous TCE concentrations during the ISTR demo (Korte et al., 1997). Aqueous samples were collected from each of the 3/4-in wells and for VOC content through hexane extraction followed by GC/ECD analysis. Other parameters measured include pH and conductance. Existing monitoring wells in the vicinity of the horizontal wells (09G, 34G, 41G, 42G, 71G through 81G) were also sampled for VOC analysis, pH and conductance measurements. Well 21G, which is ~250 ft east of the horizontal wells, was also sampled to establish contaminant and chemical conditions prior to recirculation. Elevated TCE concentrations in this well were observed after the ISTR and surfactant flushing demos in 1996 (S. Winters, PORTS, personal communication)

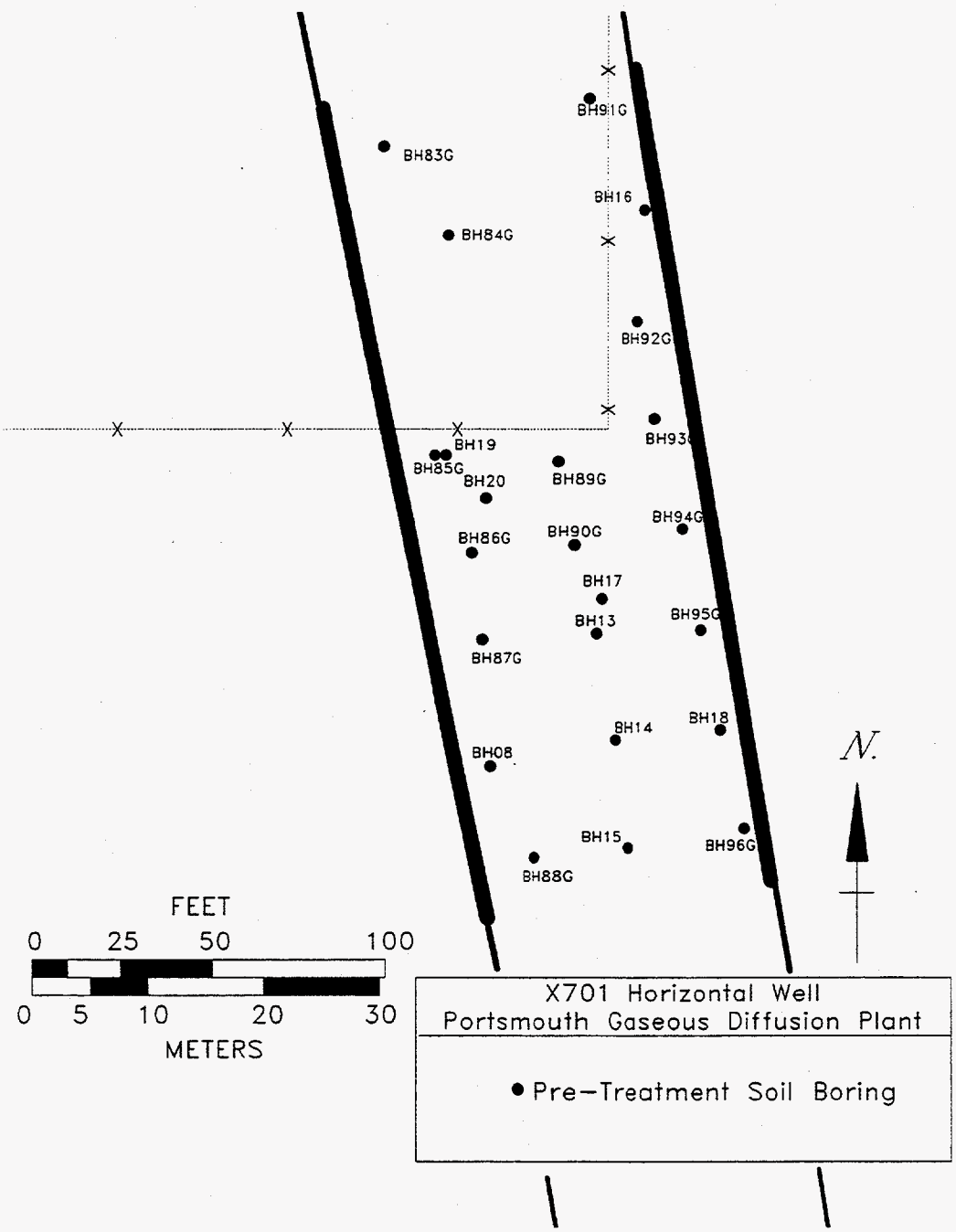


Fig. 3.1 Locations of pretreatment boreholes at the ISCOR field test site.

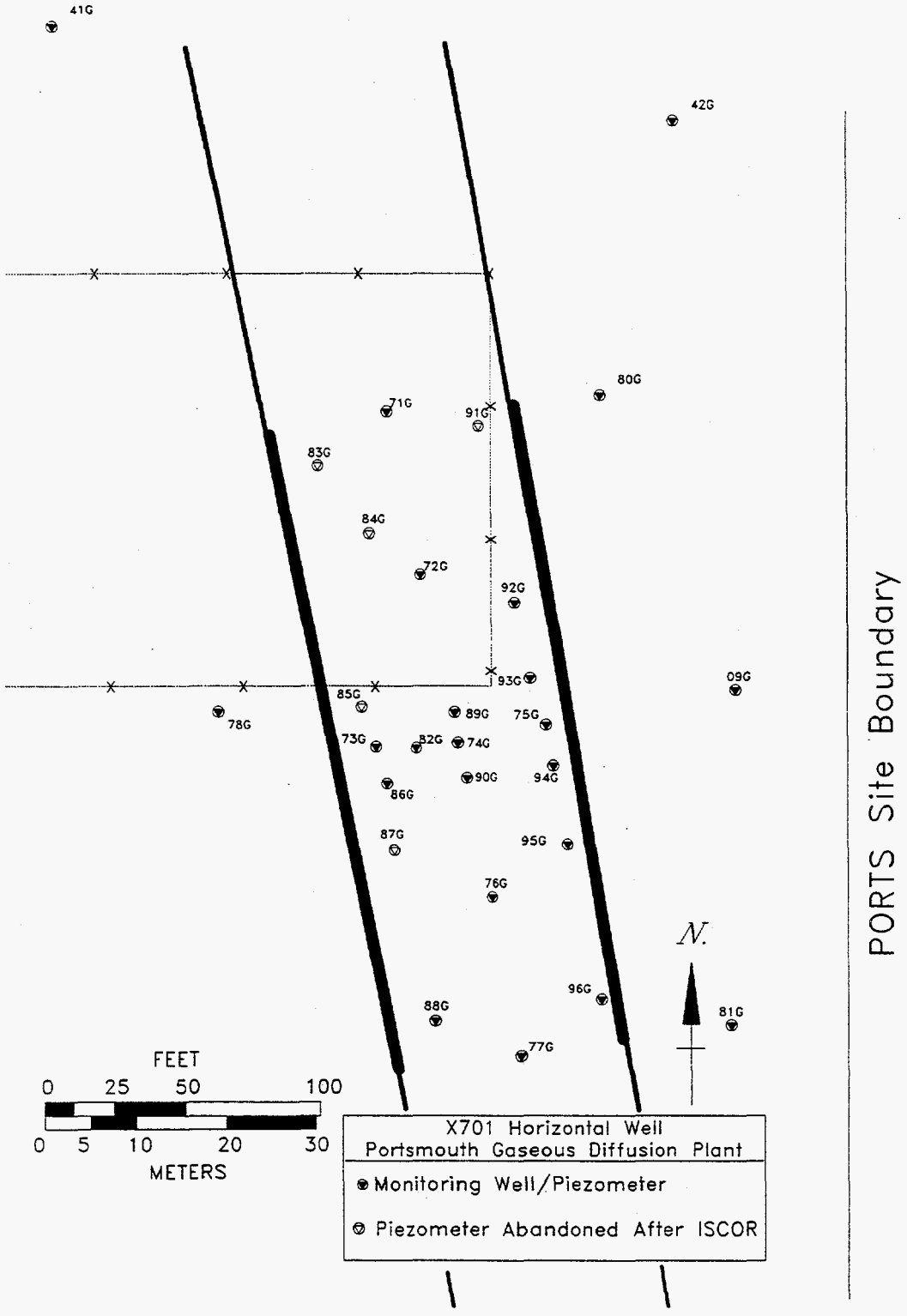


Fig. 3.2 Monitoring wells in the vicinity of the X-701B horizontal wells. Wells 83G through 96G were installed during ISCOR pretreatment characterization. Some of these wells were abandoned (i.e., removed) during the ISCOR post-treatment characterization.

3.2 RESULTS

3.2.1 LITHOLOGY

Visual observation of the continuous cores taken from the pretreatment boreholes showed that the Minford/Gallia interface and the Gallia/Sunbury interface were located at ~24 ft and ~30 bgs, respectively within the treatment region (see boring logs in Appendix A). The Minford layer consisted of a yellowish brown silt with an occasional scattering of fine to very fine sand. The Gallia layer consisted of a yellowish to reddish brown silty gravel matrix with angular 1/4 to 1"-size gravels and strong Fe staining and varying degrees of Fe-oxide cementation. Particle gradation within the Gallia (finer at the top with increasing gravel towards the bottom of the interval) was noted in some of the boreholes (88G, 83G, 87G, 88G, 89G , 94G). A silt layer within the Gallia at 25 to 27 ft bgs was also observed in boreholes 85G, 88G, 89G, 90G, BH19. Given these observations, vertical and lateral hetrogeneities in hydraulic conductivity are likely within the Gallia. The Sunbury layer consisted of a black, fissile, weathered shale.

3.2.2 TRICHLOROETHYLENE CONTAMINATION

A wide range of TCE concentrations were measured in samples from the Minford, Gallia and Sunbury shale layers. Based on the average TCE concentrations in Table 3.1, there is a significant amount of TCE contamination in both the Gallia and Sunbury and in the Minford layer below 20-ft (contamination at shallower depths can not be confirmed since samples were not collected at depths < 20 ft). Although ISCOR implementation at X-701B is targeted towards removal of TCE from the Gallia water-bearing unit, TCE concentrations were also of interest in the Minford and Sunbury to determine whether ISCOR will affect TCE levels in these layers. TCE concentrations in the Gallia were highest in the central region of the treatment zone (Fig. 3.3), consistent with groundwater measurements made during the ISTR field test (Korte et al., 1997).

Table 3.1 Statistical parameters of trichloroethylene concentrations in the Minford, Gallia and Sunbury shale soil samples collected during the ISCOR pretreatment characterization.

		Trichloroethylene in Soil (µg/kg)**				
Layer	No. of Samples	Average	Std. Dev.	Median	Minimum	Max
Minford *	90	19,493	21,770	10,002	nd	80,471
Gallia	163	53,596	52,713	43,320	nd	302,237
Sunbury	13	132,405	269,791	46,932	32	1,048,174

* Based on samples collected at depths > 20 ft.

** Based on wet soil weights, nd = not detected at an approximate detection limit of 5 µg/kg.

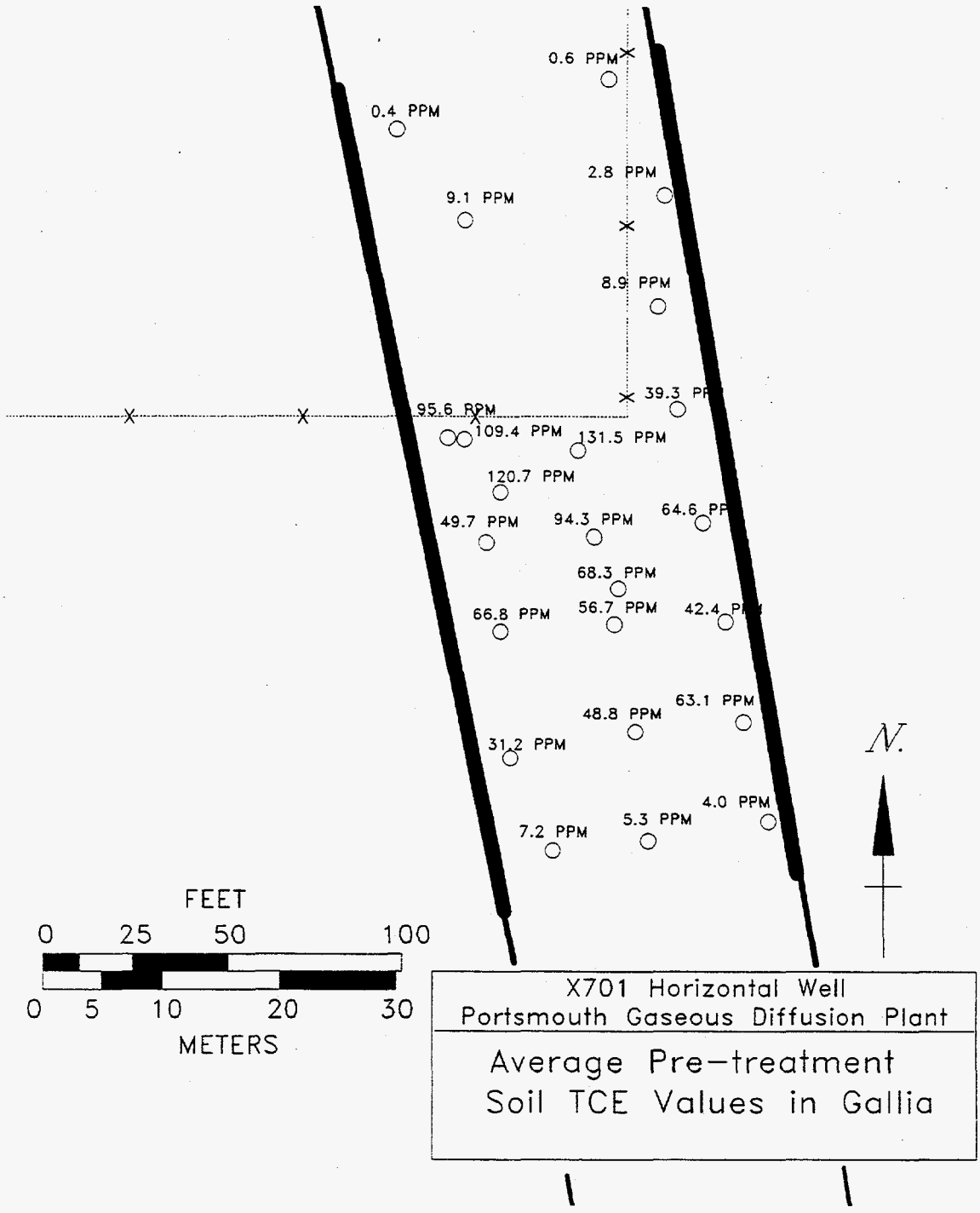


Fig. 3.3 Average TCE concentrations in the Gallia measured in soil samples collected during ISCOR pretreatment characterization.

TCE soil concentrations from corresponding depths in the duplicate boreholes (85G and BH19) are within the same order of magnitude in the Minford and Gallia layers, with a maximum difference of 50% relative to the higher value (e.g., at depth = 28 ft in Fig. 3.4). The large discrepancy between samples from the Sunbury shale (at 30-ft depth) indicates wide variability in the TCE distribution within that layer.

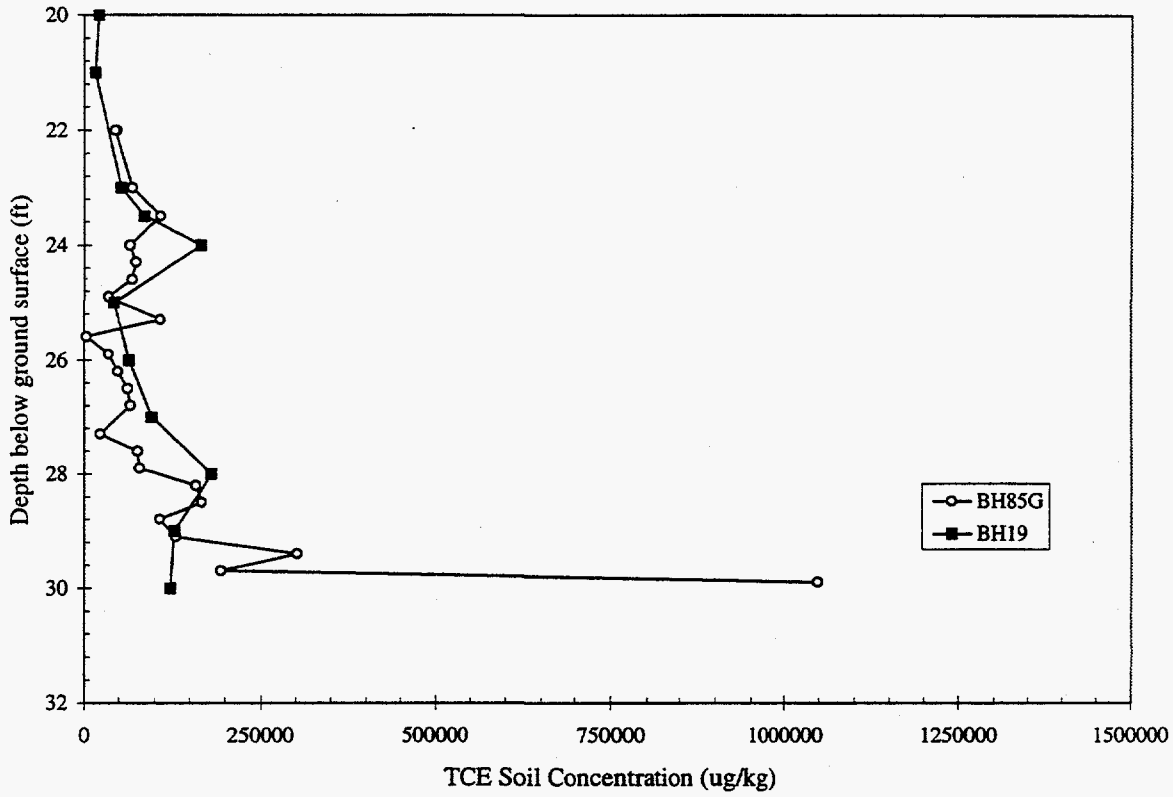


Fig. 3.4 Comparison of TCE soil concentrations (wet soil weight basis) in duplicate boreholes (<5 ft apart) 85G and BH19.

Groundwater samples collected before ISCOR was initiated correlate very well with the average TCE concentrations measured in corresponding boreholes (see Fig. 3.5). Thus, TCE groundwater concentrations under quasi-equilibrium conditions (i.e., normal groundwater flow rates) appear to be a good indicator of residual TCE in the aquifer sediments.

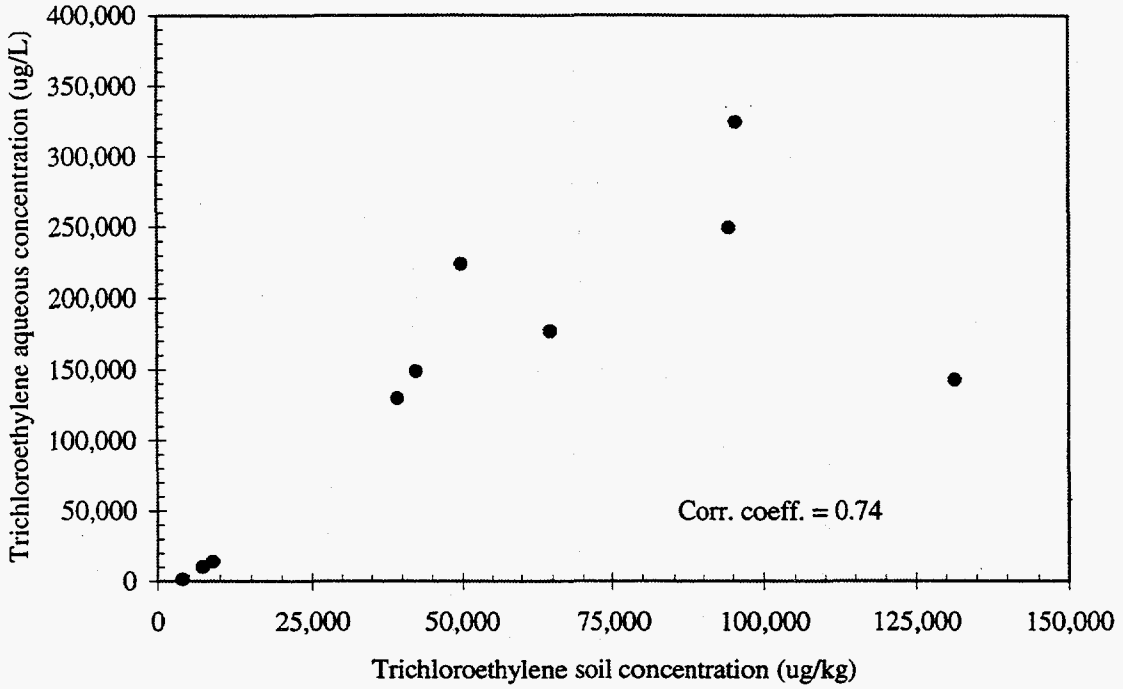


Fig. 3.5 Average TCE concentration in the Gallia from pretreatment boreholes vs TCE concentration in groundwater collected from corresponding monitoring wells before initiation of ISCOR test.

4. ISCOR FIELD TEST OPERATIONS

4.1 DESCRIPTION OF ISCOR IMPLEMENTATION AT X-701B

The schematic for the flow system used during the ISCOR field test is shown in Fig. 4.1. Groundwater was extracted from the upgradient (west) horizontal well and delivered to the X-623 Groundwater Treatment Facility (X-623 GTF). Water for oxidant injection solution was taken from a portion of the X-623 effluent, and mixed with $KMnO_4$ using a solids feeder. The solids feeder consisted of a hopper and auger system that delivered pre-determined amounts of $KMnO_4$ into a mix tank. The oxidant laden water then flowed by gravity into a second mix tank, from which a jet pump pulled and delivered the oxidant laden water into the downgradient (east) horizontal well. Extraction from the west horizontal well was set to ~10 gpm by flow regulators. The target injection flow rate at the east horizontal well was 10 gpm. However, this well could only take in a maximum of 6 gpm; water backed up to the ground surface when higher oxidant injection flow rates were attempted.

The original concept for ISCOR implementation at X-701B involved (1) extraction of groundwater from the west horizontal well, (2) amendment of this extracted groundwater with $KMnO_4$, and (3) re-injection of the oxidant-laden groundwater into the east horizontal well. The X-623 facility was included in the treatment system to comply with a regulatory requirement that TCE in the re-injected groundwater be less than 5 ppb. A screening test of TCE degradation in water from well 73G showed that 1.5% $KMnO_4$ can reduce the initial TCE concentration from 1000 ppm (close to saturation) to 10 ppm in 90 minutes. Although this is a significant reduction in concentration (99%), $KMnO_4$ amendments alone were not adequate to ensure compliance with the 5-ppb injection limit. In the state of OH, it is possible to obtain a permit to re-inject groundwater that does not satisfy drinking water standards. However, an application for this injection permit was not pursued due to time and scheduling constraints.

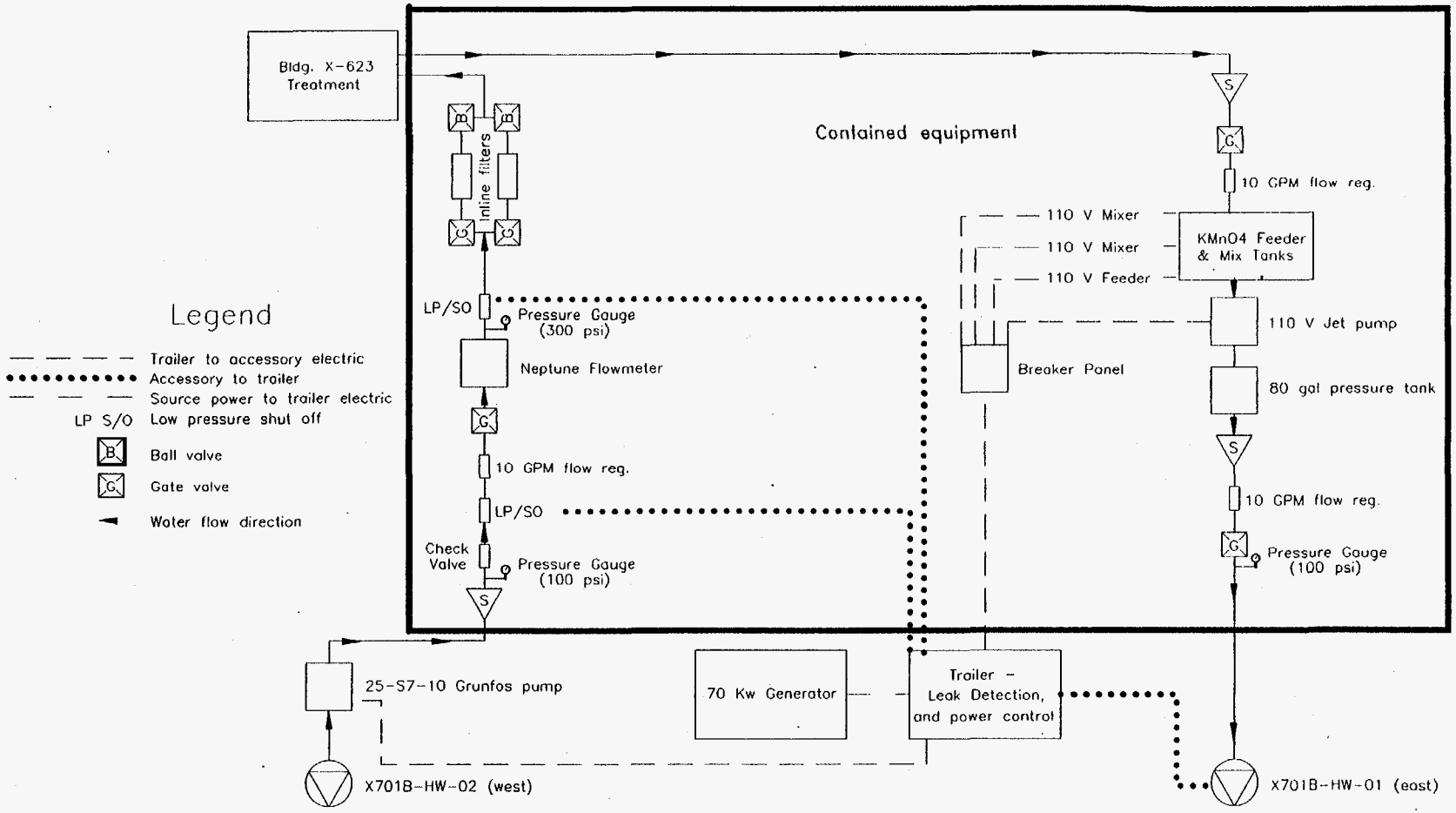


Fig. 4.1 Schematic of ISCOR treatment system

4.2 FIELD OPERATIONS

Before ISCOR recirculation was initiated between the horizontal wells, a shakedown test was conducted in which 500 gal of a 2% KMnO4 solution was injected through well 75G. This test was conducted to identify gross problems (e.g., rapid well clogging) associated with injecting an oxidant solution at high concentrations. No such clogging was encountered during the shakedown test.

After a leak test of the flow system by recirculating water without $KMnO_4$ additions, ISCOR between the horizontal wells began operations on July 26, 1997 and continued through August 21, 1997 (see Fig. 4.2 for cumulative groundwater flows and $KMnO_4$ used). Simultaneous injections in the east horizontal well and well 74G were begun on August 20, 1997. Injection and extraction from the horizontal wells were halted on August 21, 1997 because of increasing amounts of colloidal particles from the extraction well which X-623 GTF was not prepared to handle (see Sect. 4.3 for description of particles). Oxidant injections through well 74G were continued through August 28, 1997. Oxidant injection was attempted through 73G on August 26, 1997 but was only sustained for <12 hours because of excessive pressure build-up in that well.

The recirculation system, designed to run non-stop throughout the duration of the test, was contained and configured with water level sensors, low-pressure detectors and breakers which would shut down the system automatically should leaks occur. During actual operations however, the system was temporarily shut down for each of the following reasons: (1) X-623 shut downs, (2) water backing up in the injection well, (3) heavy rainfall which would trip the leak detectors and (4) repairs of components on the system. Water backing up in the injection horizontal well appeared to be related either to heavy rainfall or clogging of the well screen due to undissolved oxidant or precipitates. Whatever the reason for this apparent clogging, the problem was transient and flow in the injection well resumed within a few days. The overall flow through the recirculation system was relatively steady, as shown by plots of cumulative groundwater flow through the horizontal wells and total $KMnO_4$ injected into the Gallia (see Fig. 4.2). A total of ~12,700 kg of $KMnO_4$ was delivered to the treatment region during the ISCOR field test, 1960 kg of which was introduced through vertical well 74G. Of the 206,000 gallons of oxidant solution injected into the treatment region, 14,000 gallons was delivered through well 74G. The total volume of soil within the Gallia between the horizontal wells is 220 ft x 90 ft x 5 ft ≅ 119,000 cu. ft. Assuming a porosity of 30%, the total pore volume is approximately equal to 267,000 gallons. Thus, the total volume of oxidant solution injected during the ISCOR demo corresponds to ~77% of the total pore volume.

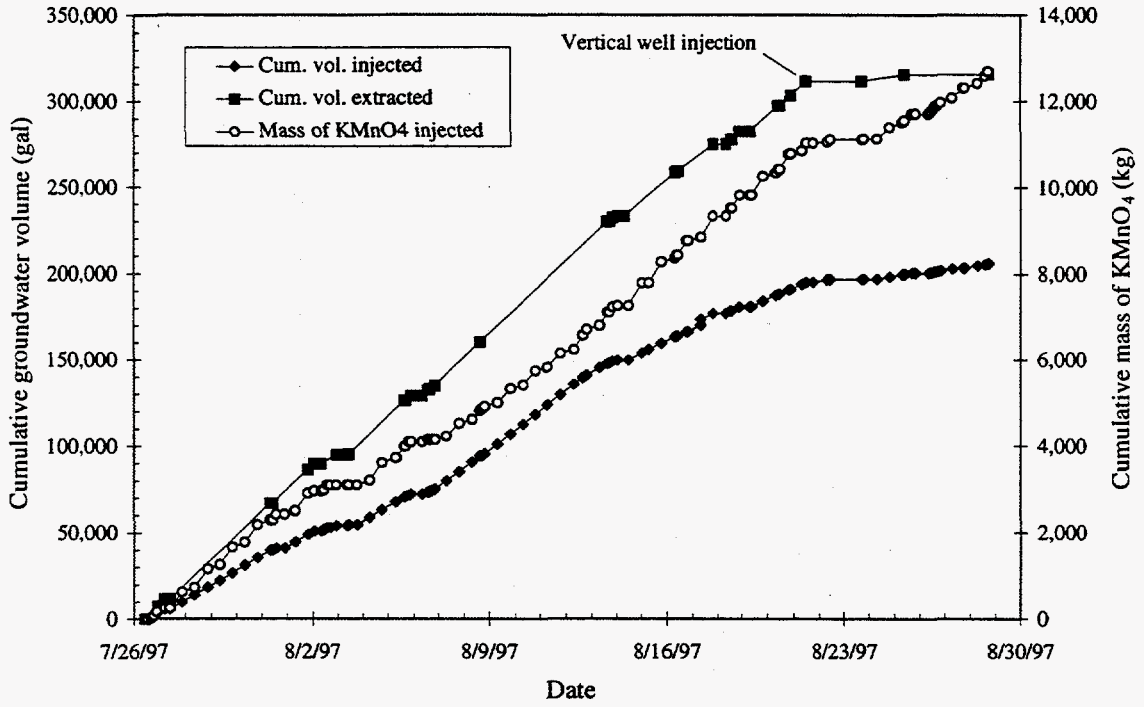


Fig. 4.2 Cumulative groundwater injection and extraction volumes and mass of potassium permanganate delivered ($KMnO_4$) to the treatment region during the ISCOR field test.

4.3 PERFORMANCE MONITORING

4.3.1 METHODS

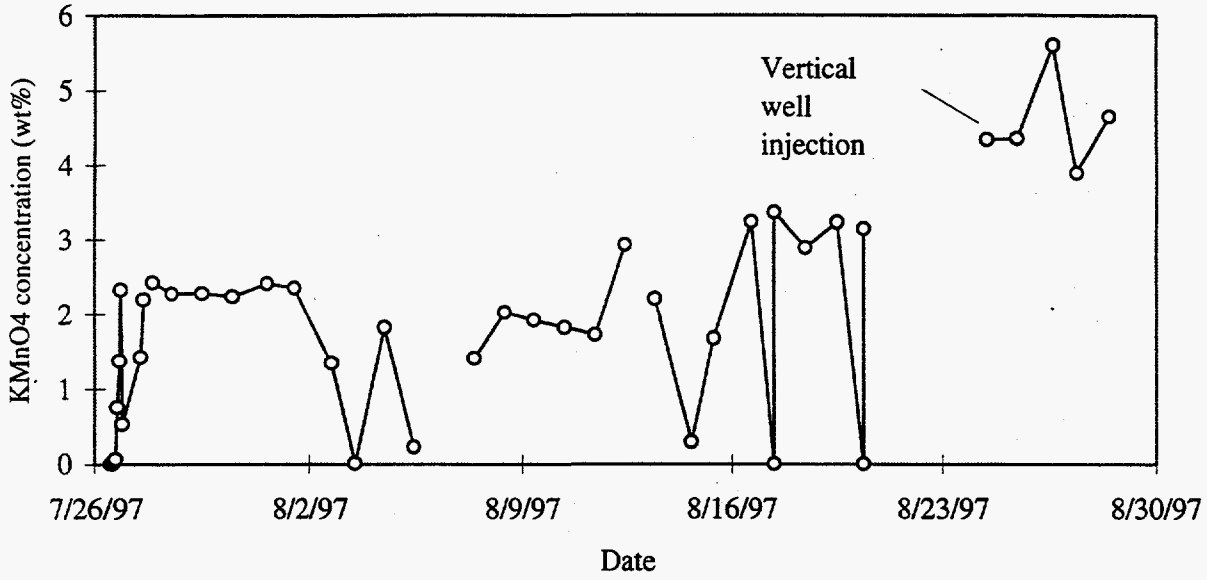
The performance of the ISCOR system was monitored through the collection of water samples from the influent and effluent streams (daily), and from monitoring wells (daily to every three days) in the vicinity of the treatment region. $KMnO_4$ concentration in these water samples was quantified in the field by measuring absorbance by the solution using a Hach DR2000 spectrophotometer at 525 nm. pH, temperature and conductance were also measured in the field. TCE concentrations were quantified by hexane extraction followed by GC/ECD analysis of the extract, the same method used for the pretreatment samples. The TCE analyses were done within 7 days of sample collection.

4.3.2 CHEMICAL CHARACTERISTICS OF INJECTION AND EXTRACTION WATER

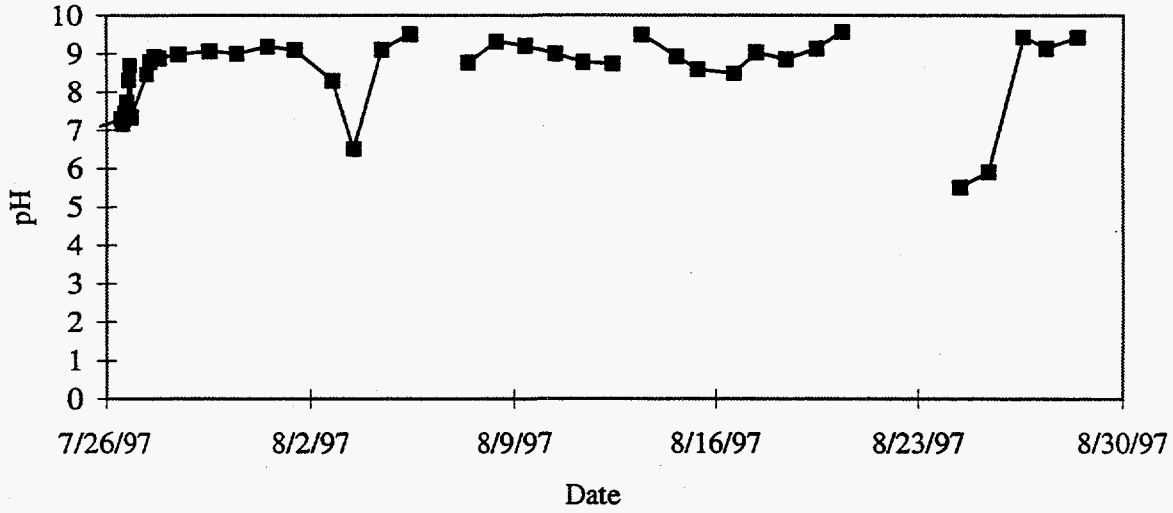
At the beginning of the test, the solids feeder was set to deliver potassium permanganate at a rate that would result in a concentration of 1.5% at a 10 gpm groundwater recirculation rate. Due to the lower flow rate that the X-623 GTF was able to provide (< 8 gpm), the resulting oxidant concentration at the beginning of the test was 2.5%, as measured in injection water samples using the spectrophotometric technique described above (see Fig. 4.3). The solids feeder rate was reduced at night so that enough oxidant was in the hopper (300 lb capacity) to provide a continuous feed for 12 hours while the system was unmanned. Fig. 4.3 shows oxidant concentrations measured during the day, as well as the resulting pH of the oxidant-laden injection water. The target oxidant concentration was increased during the field test; higher oxidant concentrations results in faster delivery of the oxidant and less time required for recirculation. However, because there was concern about clogging at the higher concentration, the oxidant concentration was increased in increments (see Fig. 4.3). The resulting pH of the oxidant-laden groundwater was generally between 8 and 9. The TCE concentration in the injection water before $KMnO_4$ amendments (i.e., X-623 GTF effluent) was less than 5 ppb.

The TCE concentration in the extraction well varied from 50,000 ppb at the beginning of recirculation, to 350,000 ppb (see Fig. 4.4). The extraction well draws water from both upstream and downstream of the treatment region. Thus, even if the mass of TCE were reduced between the horizontal wells, the TCE level in the extraction well can remain elevated from TCE contamination upstream of the west extraction well. The extraction water pH appears to be decreasing with time, as shown in Fig. 4.4, starting at >6 and ending at <5.5. This decrease may be due to oxidation reactions occurring within the treatment region.

The groundwater from the extraction well was initially clear but became increasingly turbid starting on August 10, 1997, approximately 2 weeks after the ISCOR test was begun. The suspended material turned out to be particles that were < 1 μm in size (Fig. 4.5). Elemental analysis of these particles using scanning electron microscopy/energy dispersive x-ray revealed the presence of Mn, with trace amounts of Fe. No crystalline phases were detected by X-ray diffraction of the particles. These particles are probably amorphous manganese oxides which can form with the reduction of MnO_4^- as it reacts with TCE and other oxidizable materials.



(a)



(b)

Fig. 4.3 Potassium permanganate concentration (a) and pH (b) of water injected into east horizontal well during the ISCOR field test.

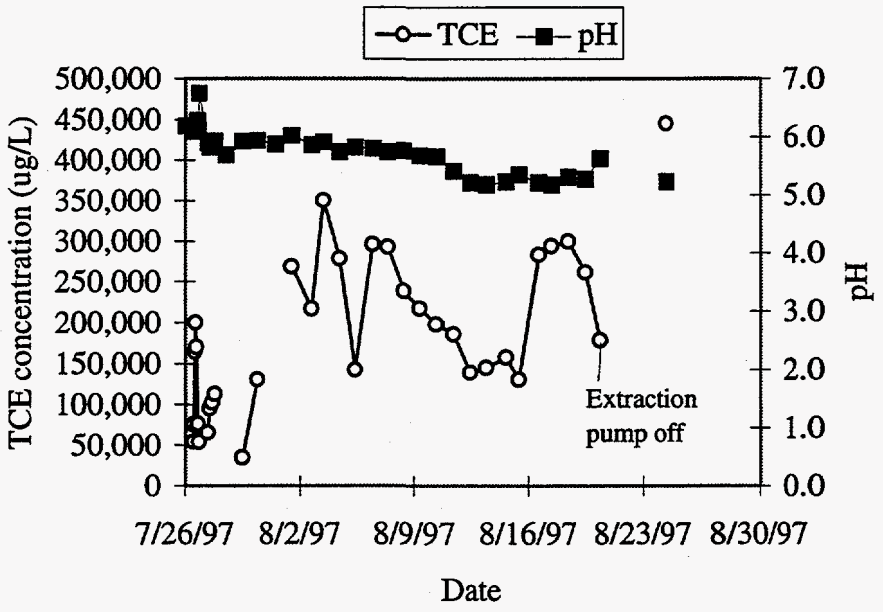


Fig. 4.4 Trichloroethylene concentration and pH of water from extraction (west) horizontal well during the ISCOR field test.

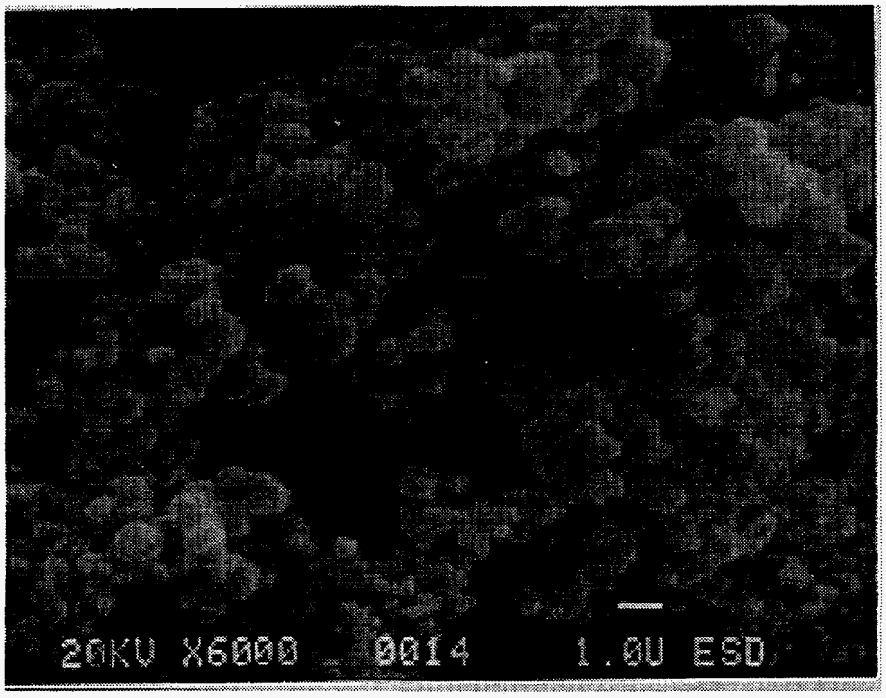


Fig. 4.5 Scanning electron micrograph (SEM) of suspended solids in extraction well samples collected on August 20, 1997.

4.3.3 MIGRATION OF $KMnO_4$ BETWEEN HORIZONTAL WELLS DURING THE ISCOR FIELD TEST

The delivery of oxidant solution through the east horizontal well was not uniform throughout the length of the treatment region, as shown in Figs. 4.6 through 4.9. These figures show the approximate shape of the $MnO4^-$ front based on its detection in the monitoring wells. On Day 7, $MnO4^-$ had broken half-way through the distance between the horizontal wells in the southern end of the treatment zone (see Fig. 4.6). The same trend was observed during the ISTR demo (Korte et al., 1997). The oxidant detected in well 75G on Day 7 and Day 14 is probably from the vertical well test since the oxidant is absent in this well on Day 21. After 21 days, the oxidant had been detected in all the monitoring wells that were ~15-ft from the injection wells except for well 75G (Fig. 4.8). Furthermore, the oxidant had been detected in well 88G, which is the well closest to the extraction well in the southernmost section of the treatment region. The oxidant was detected in the central monitoring wells only after oxidant injections in vertical well 74G (Fig. 4.9).

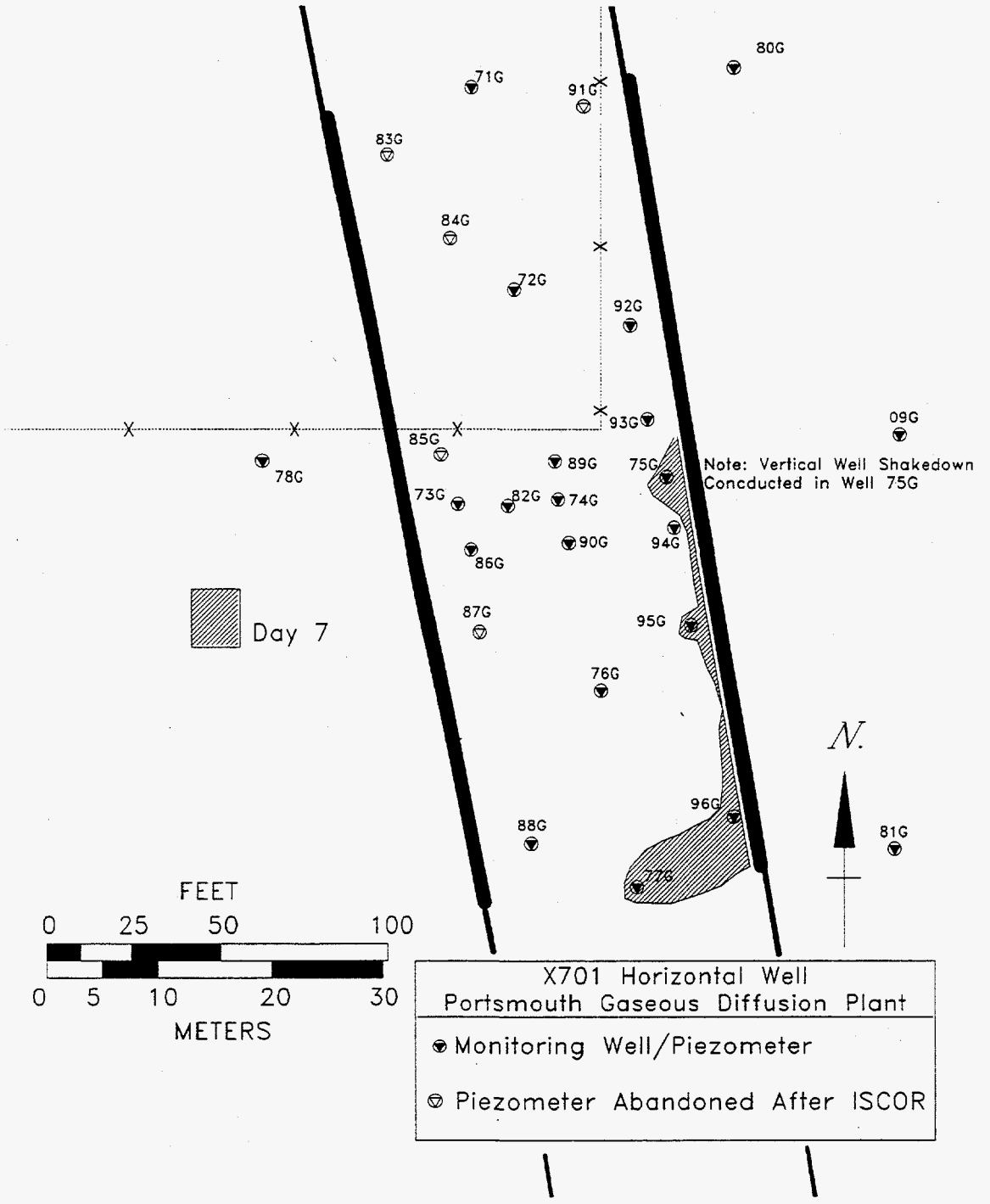


Fig. 4.6 Approximate potassium permanganate front on the 7th day of the ISCOR field test based on detection of oxidant in the monitoring wells.

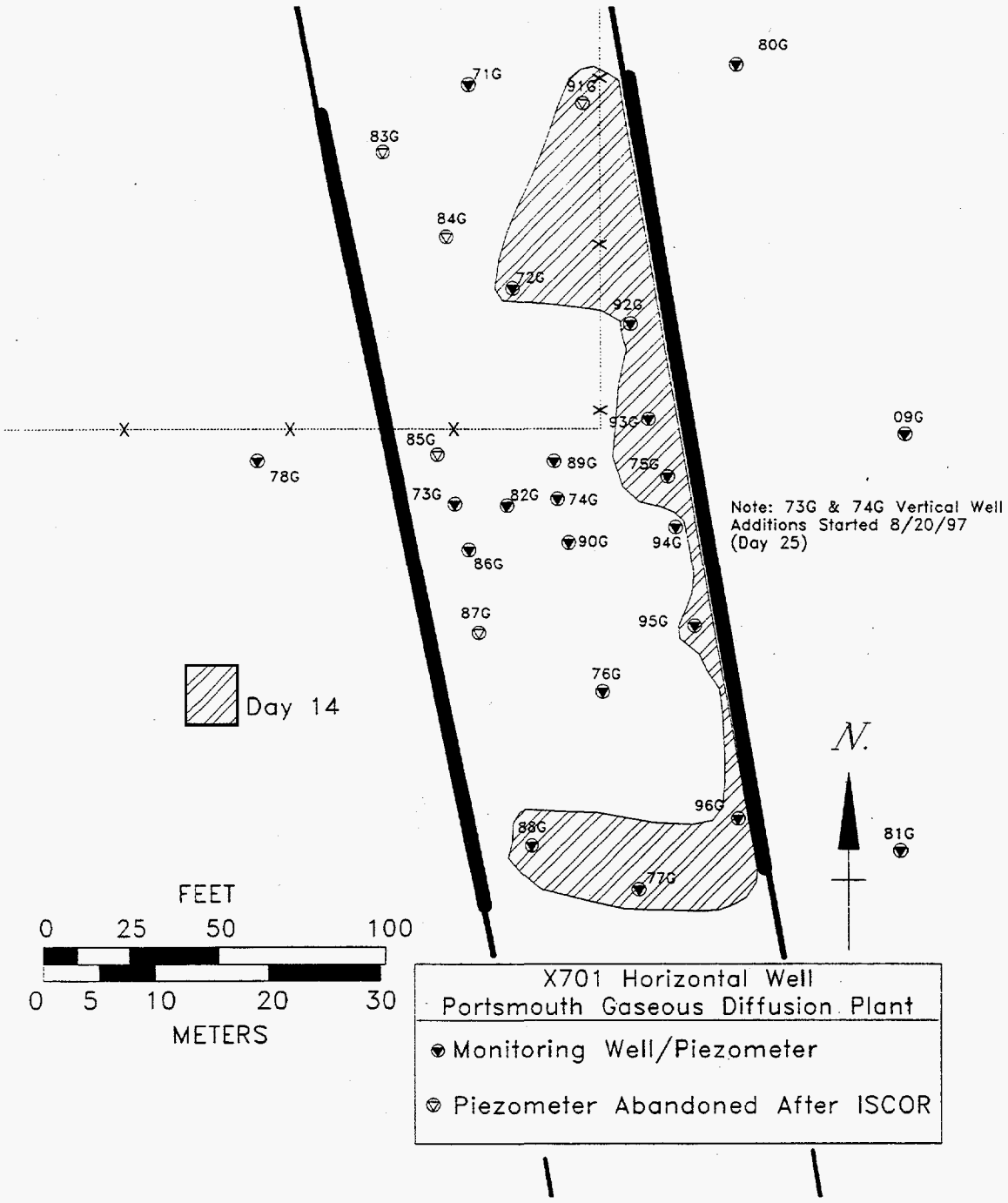


Fig. 4.7 Approximate potassium permanganate front on the 14th day of the ISCOR field test based on detection of oxidant in the monitoring wells.

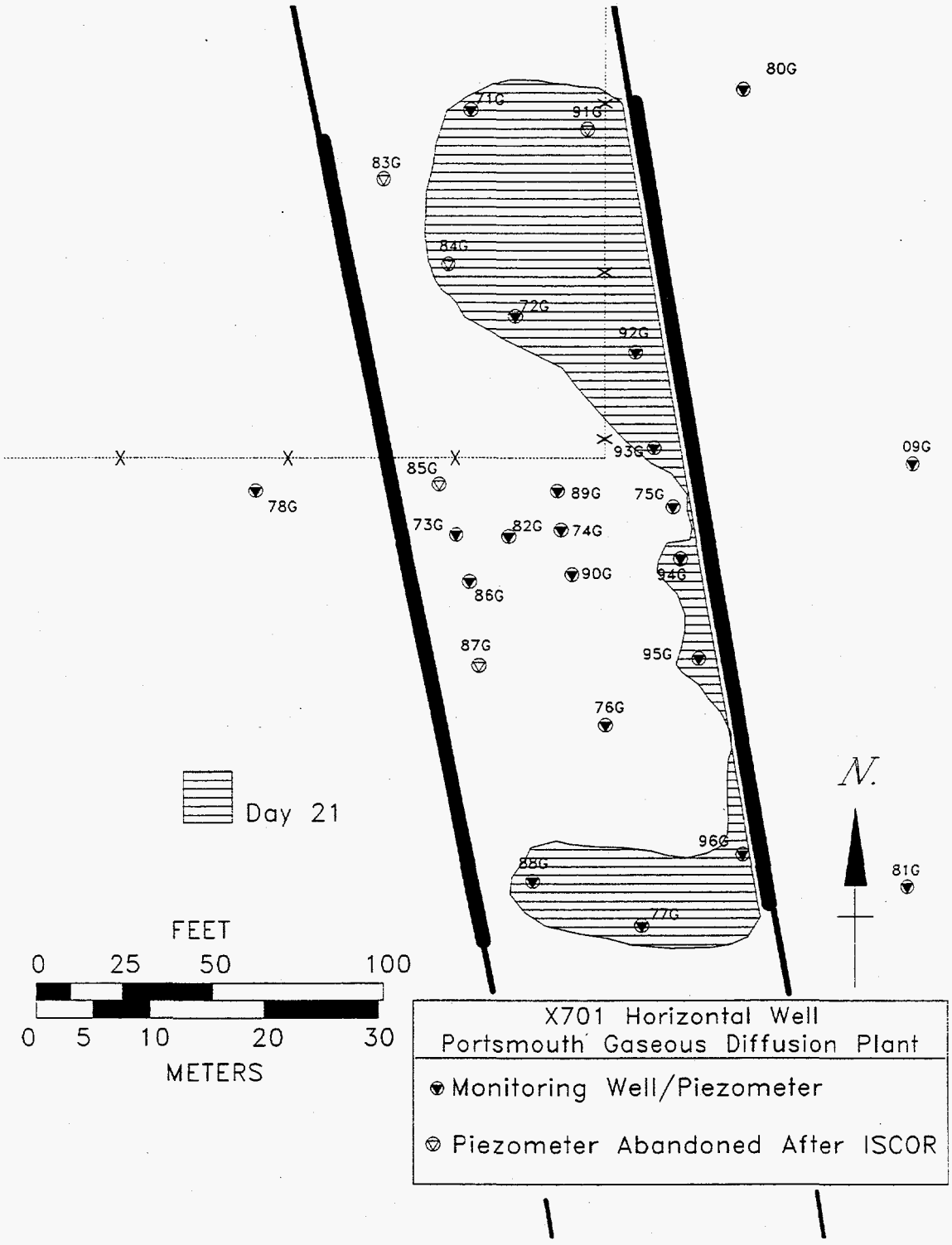


Fig. 4.8 Approximate potassium permanganate front on the 21st day of the ISCOR field test based on detection of oxidant in the monitoring wells.

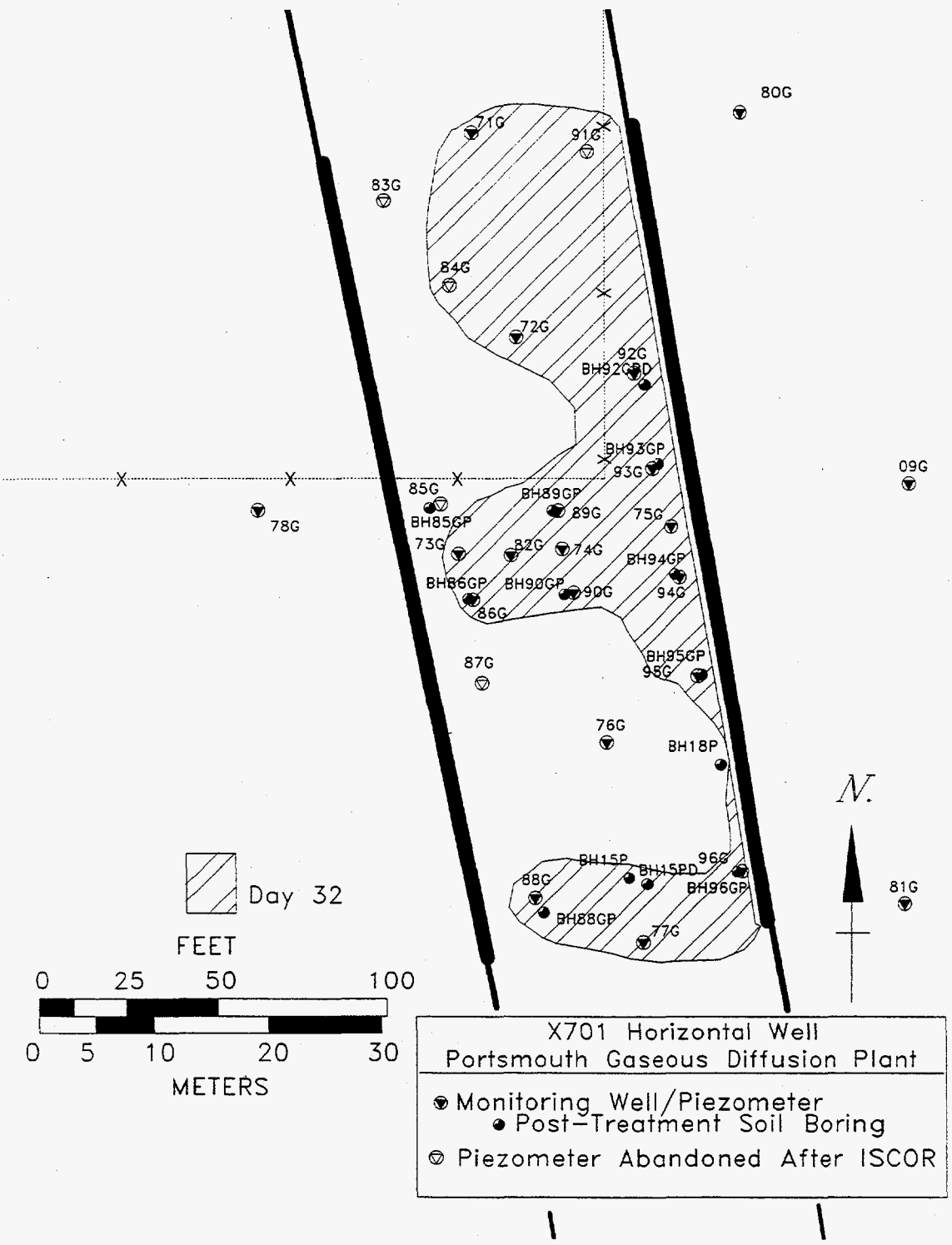
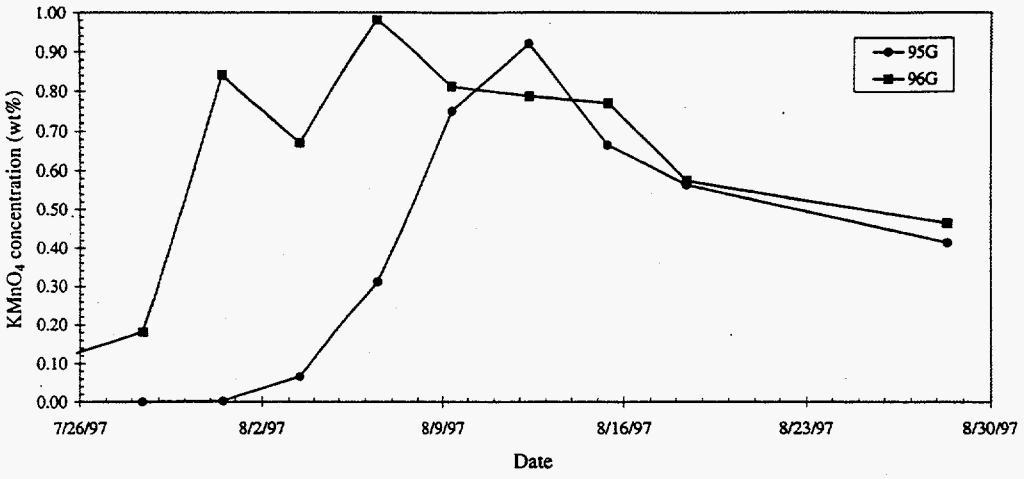


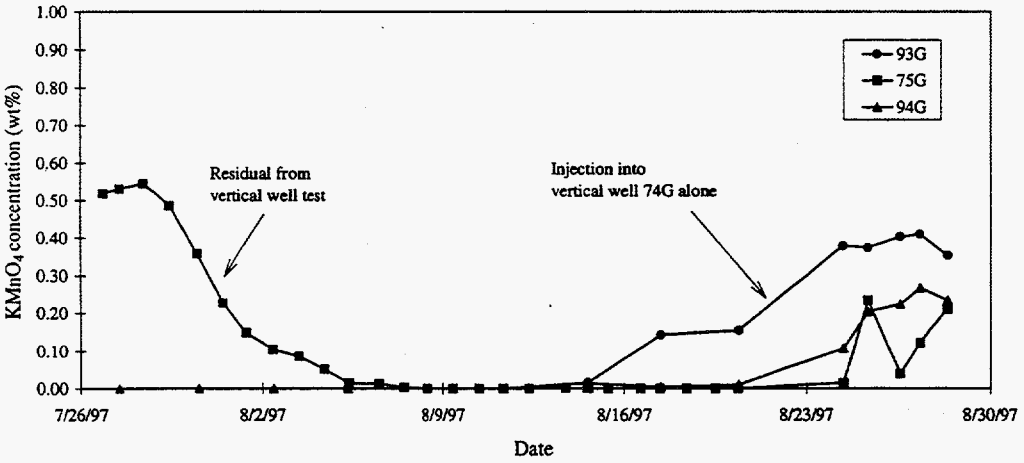
Fig. 4.9 Approximate potassium permanganate front on the 32nd day of the ISCOR field test based on detection of oxidant in the monitoring wells.

Temporal plots of permanganate concentration in the vertical wells immediately adjacent to the east (injection) horizontal well further illustrate that $KMnO_4$ oxidant transport between the horizontal wells was non-uniform along the length of the treatment zone (see. Fig. 4.10). Reasons for this non-uniform flow include: (1) heterogeneous conductivities either due to variable sediment particle size distributions or the presence of a DNAPL phase in the central region of the treatment zone, and/or (2) the horizontal well screen at its mid-section is plugged or inefficient. Significant amounts of oxidant were only detected in well 94G a few days after vertical injection into 74G was initiated. As mentioned previously, the oxidant detected in well 75G during the first 2 weeks of the field test is likely from the shakedown injection into that well. The oxidant level eventually dropped back to non-detectable levels in 75G; it started to rise again a few days after injections into vertical well 74G (see Fig. 4.10b).

During ISCOR in the horizontal wells, the oxidant broke through midway between the horizontal wells only in 71G, 72G, and 77G (see Fig. 4.11), with very low oxidant levels measured in well 71G. The significant rise in oxidant concentration in wells 89G and 90G were due to the oxidant injection into vertical well 74G. In the wells immediately adjacent to the west (extraction) well, the oxidant was detected only in well 88G during ISCOR in the horizontal wells (see Fig. 4.12). The high oxidant level in 73G is due to an attempt to deliver oxidant solutions through this well. The oxidant levels in 86G may be due to vertical injections in 73G and/or 74G.



(a)



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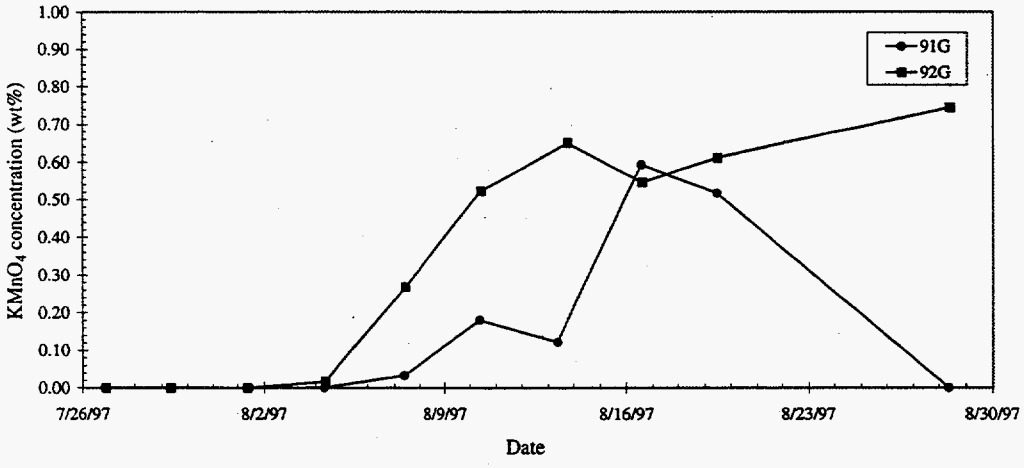
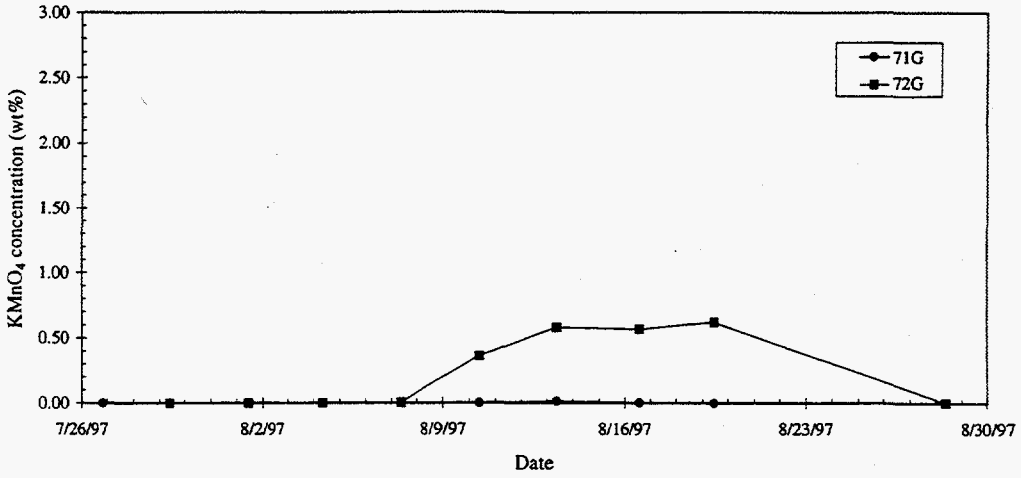
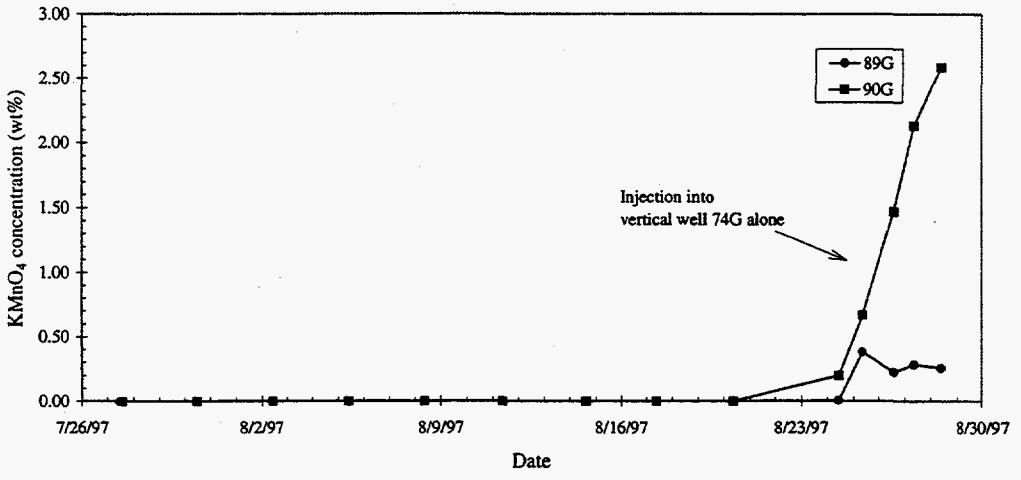


(c)

Fig. 4.10 Potassium permanganate concentrations in groundwater from (a) the southern (wells 96G and 95G), (b) the middle (wells 93G, 75G,and 94G), and (c) the northernmost wells (91G and 92G) adjacent to the east horizontal well.



(a)



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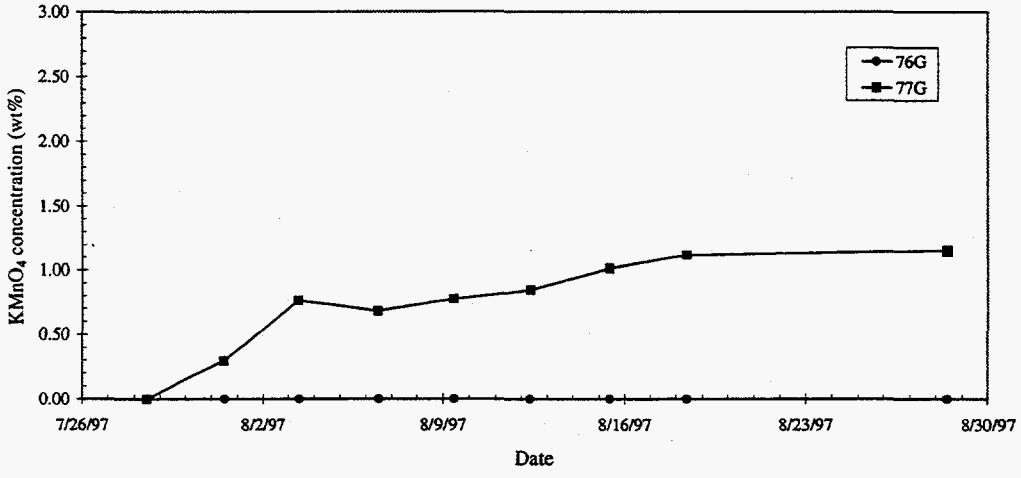

(c)

Fig. 4.11 Potassium permanganate concentrations in groundwater from (a) the northern (71G and 72G), (b) the middle (89G and 90G), and (c) the southern (76G and 77G) wells midway between the west and the east horizontal wells.

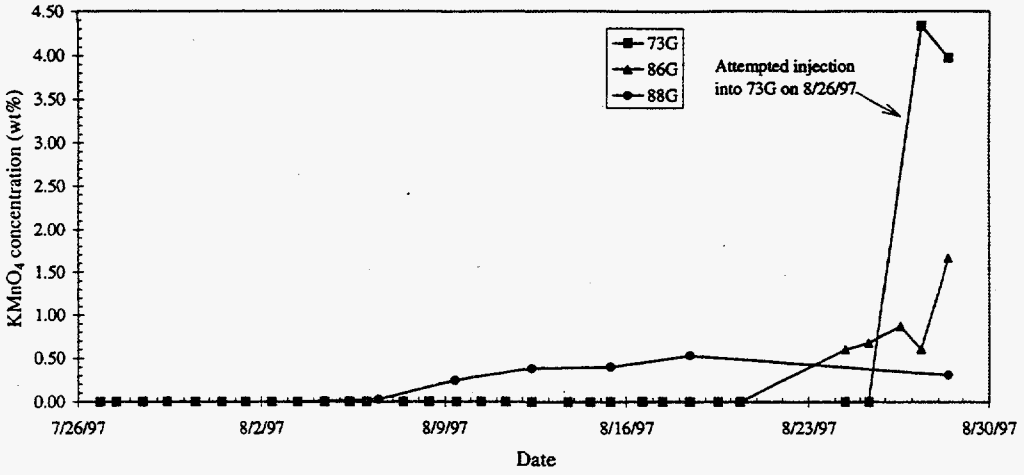

Fig. 4.12 Potassium permanganate concentration in the wells immediately adjacent to the extraction (west) horizontal well. Permanganate was not detected in wells 83G, 85G, and 87G throughout the duration of the ISCOR field test.

4.3.4 TCE Levels in Monitoring Wells during the ISCOR Field Test

Overall, whenever permanganate was detected in the monitoring wells, TCE concentrations dropped to very low levels (non-detect to low ppb range). Figs. 4.13 through 4.15 show TCE vs time trends in monitoring wells immediately adjacent to the injection (east) horizontal well. Complete TCE vs time data from all the monitoring wells are given in the Appendix.

A reduction in groundwater TCE concentration may indicate that (1) TCE from associated sediments has been removed, or (2) clean water has replaced contaminated groundwater in the pore space and TCE in the sediments is not yet in equilibrium with the pore water. The results of post-treatment soil sampling as well as groundwater sampling two weeks after the field test was completed are presented in Sect. 5.

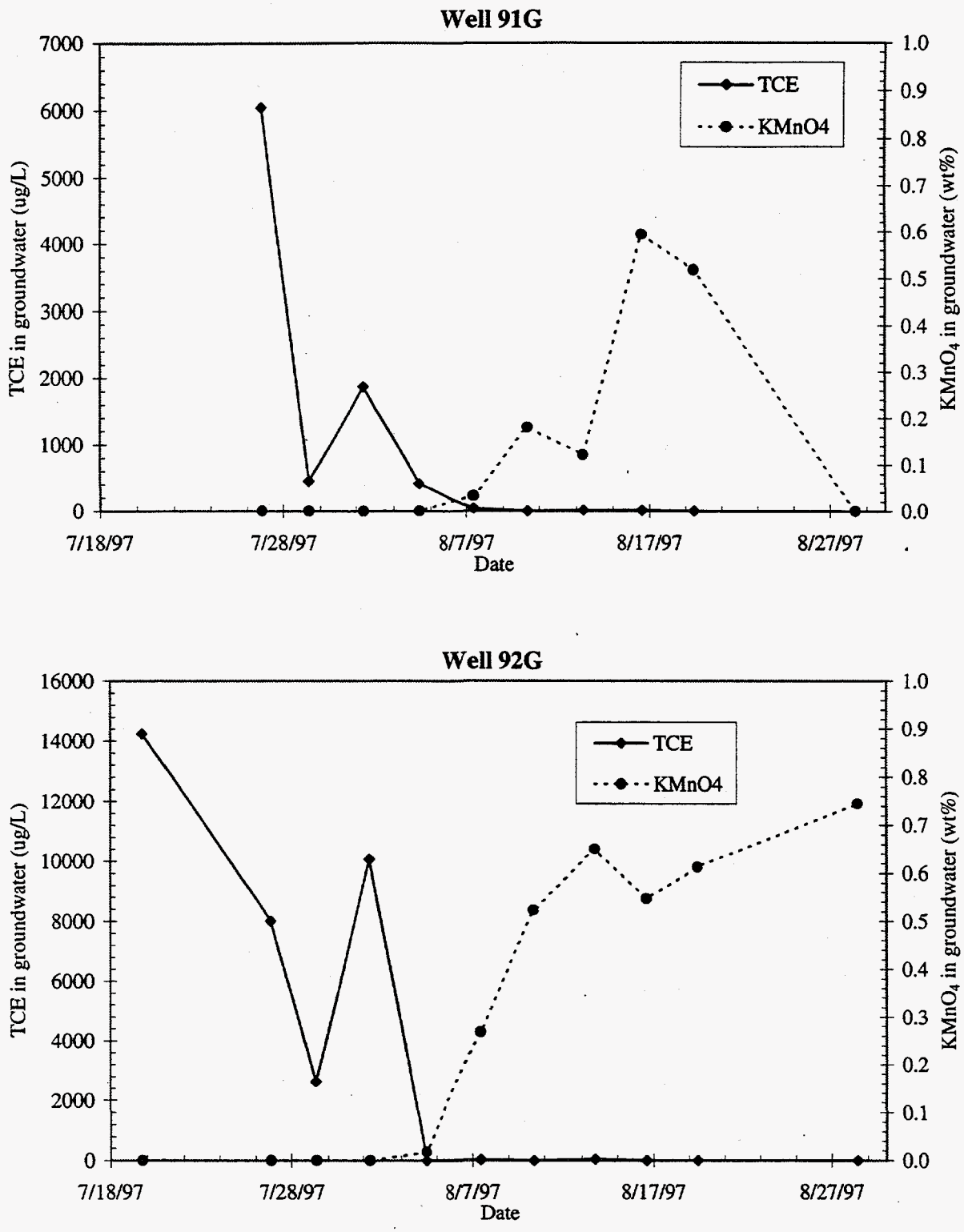

Fig. 4.13 Trichloroethylene and potassium permanganate concentrations in groundwater samples collected from northernmost monitoring wells immediately adjacent to the injection (east) horizontal well.

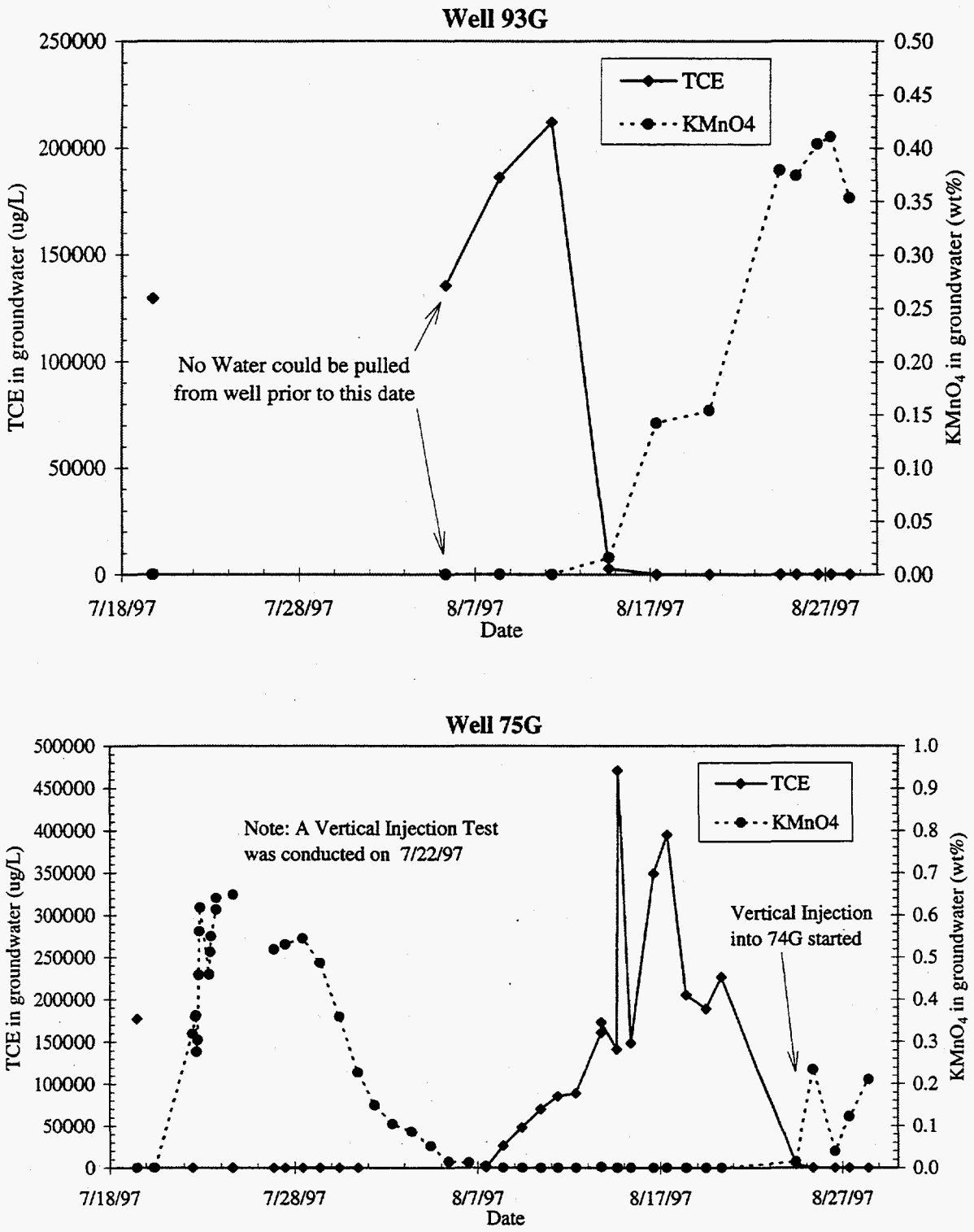

Fig. 4.14 Trichloroethylene and potassium permanganate concentrations in groundwater samples collected from middle-section monitoring wells immediately adjacent to the injection (east) horizontal well. (continued next page)

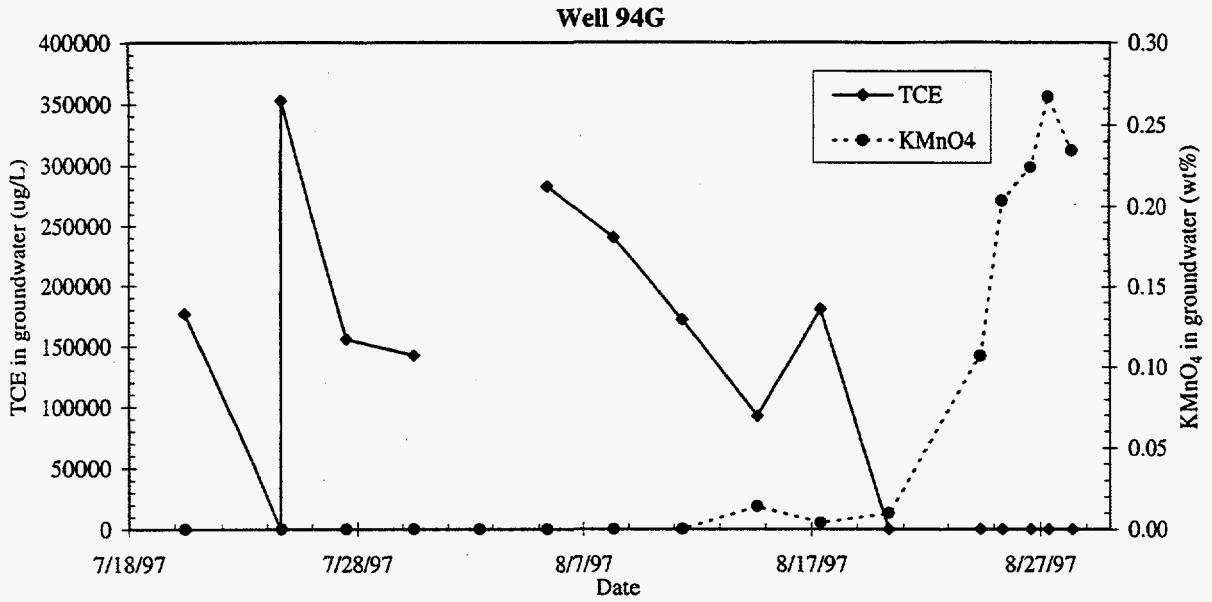

Fig. 4.14 (continued) Trichloroethylene and potassium permanganate concentrations in groundwater samples collected from middle-section monitoring wells immediately adjacent to the injection (east) horizontal well.

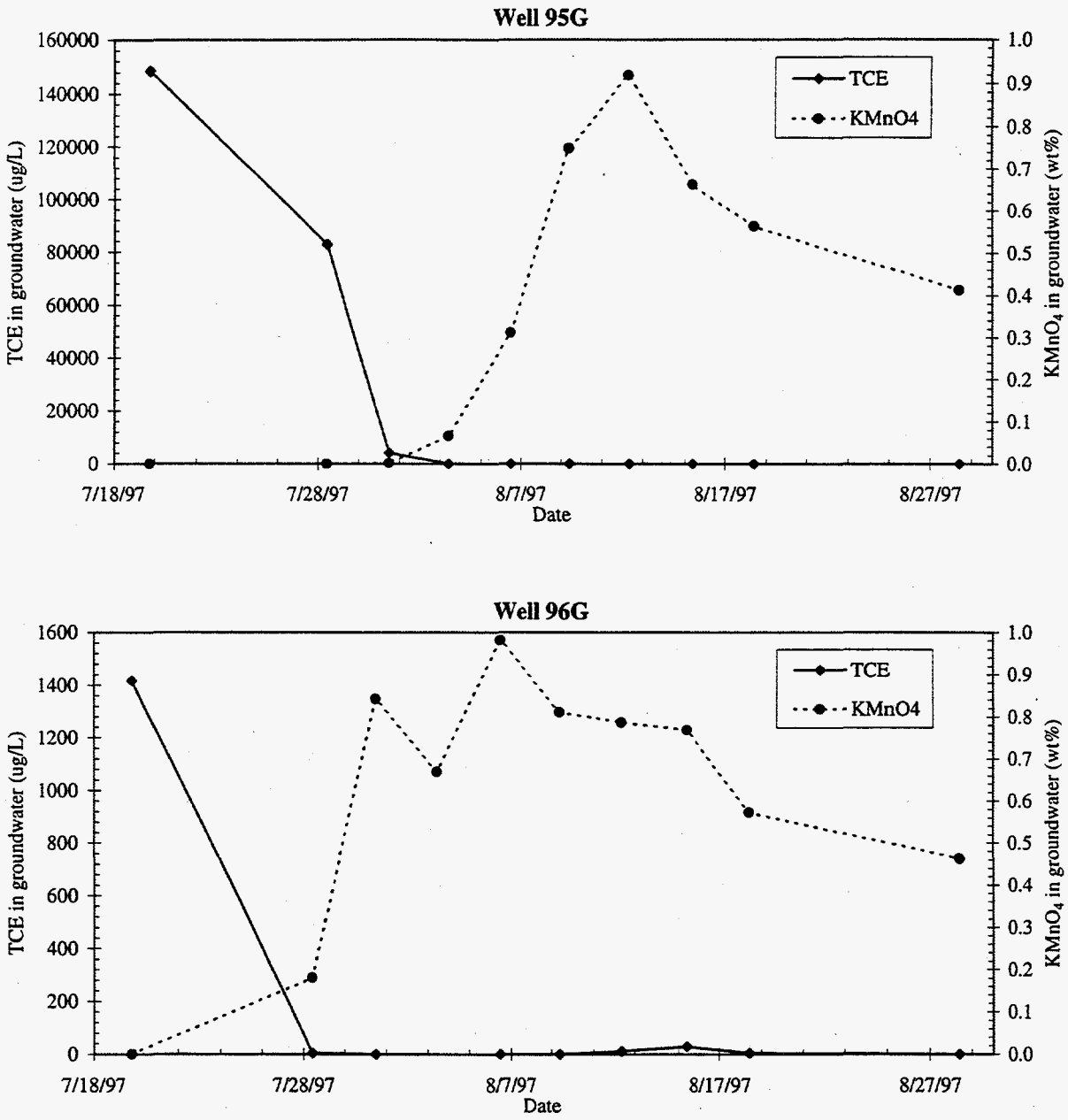

Fig. 4.15 Trichloroethylene and potassium permanganate concentrations in groundwater samples collected from southernmost monitoring wells immediately adjacent to the injection (east) horizontal well.

5. POST-TREATMENT CHARACTERIZATION

5.1 METHODS

Approximately two weeks after the ISCOR field test ended, post-treatment characterization activities were conducted to collect soil and groundwater samples from the treatment region. Fifteen boreholes were drilled in locations shown in Fig. 5.1. TCE analyses of soil samples will indicate whether significant reductions in TCE measured in the monitoring wells were from clean-up of the sediments. Except for borehole 85GP, 15 and 18, all were drilled next to monitoring wells that had detectable oxidant levels at the end of the ISCOR field test and significant reduction in aqueous TCE levels (see Sect. 4.3.3). Boreholes were not drilled within the fenced-in rad area since this zone was found to have less contamination during pre-treatment characterization (see Sect. 3).

5.2 RESULTS

5.2.1 TCE IN SOIL

Reduced TCE levels in groundwater from the monitoring wells appear to be well correlated with reductions in TCE contamination in the sediments (refer to Appendix for pre- and post-treatment TCE levels from all boreholes). In boreholes associated with 92G, 95G, and 96G, no TCE was detected in any of the post-treatment samples collected from the Gallia (see Fig. 5.2). However, the oxidant did not affect TCE levels in the Minford and Sunbury layers. TCE levels in the Minford from post-treatment borehole 96 are higher than pre-treatment levels. This can possibly be due to the ISCOR treatment mobilizing TCE contaminants from the Gallia into the Minford. However, duplicate borings during pretreatment characterization showed that 50% differences in TCE levels is possible within a 5-ft distance (see Sect. 3). Thus, the differences in pre- and post-treatment Minford TCE levels in borehole 96 can be due to heterogeneity.

In monitoring wells where significant levels of oxidant were detected only after oxidant injection into vertical well 74G, TCE reductions in the Gallia to non-detect levels occurred only at the bottom section of the layer. This is illustrated in Fig. 5.3, which compares pre- and post-treatment TCE soil levels in boreholes 86G, 89G, and 90G. Visual observation of the cores from the pretreatment boreholes showed gradations in particle size within the Gallia layer, with finer particles dominating the upper section (see Sect. 3). The post-treatment TCE distribution in boreholes 86G, 89G, and 90G is probably a result of this vertical heterogeneity in hydraulic conductivity within the Gallia.

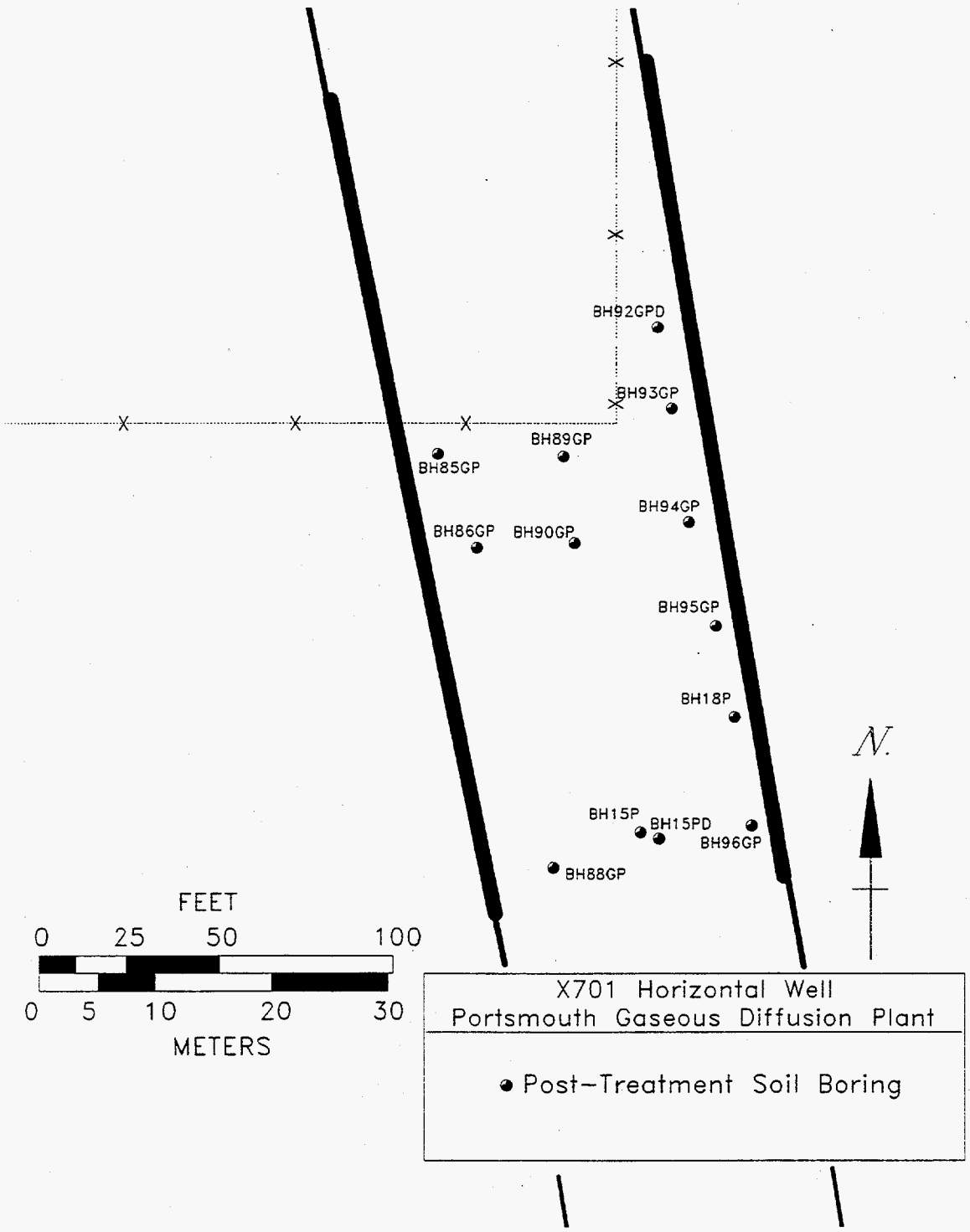

Fig. 5.1 Locations of boreholes drilled two weeks after the ISCOR field test

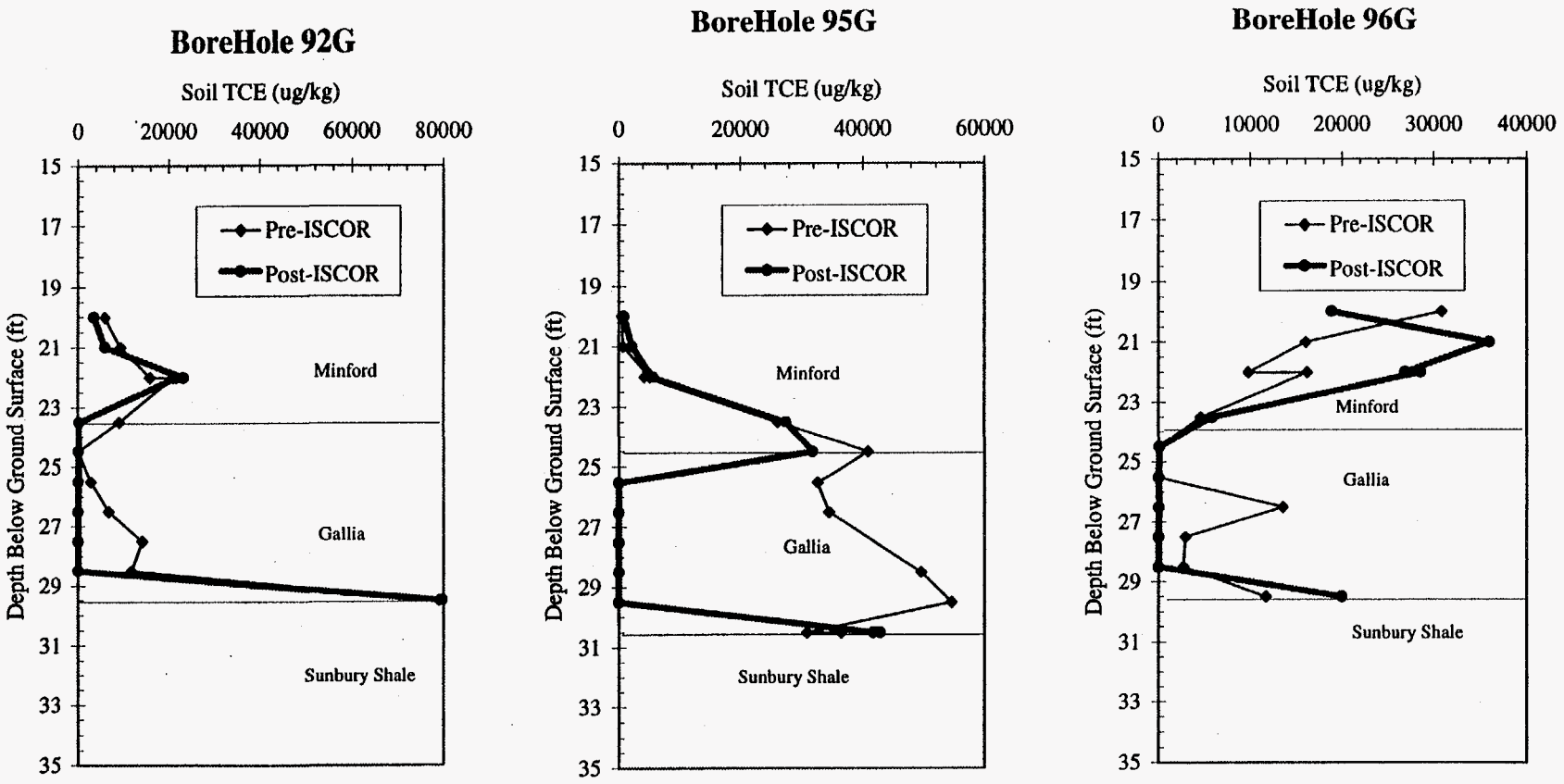

Fig. 5.2 Pre- and post-treatment levels of trichloroethylene in soil samples collected from boreholes associated with monitoring wells 92G, 95G, and 96G.

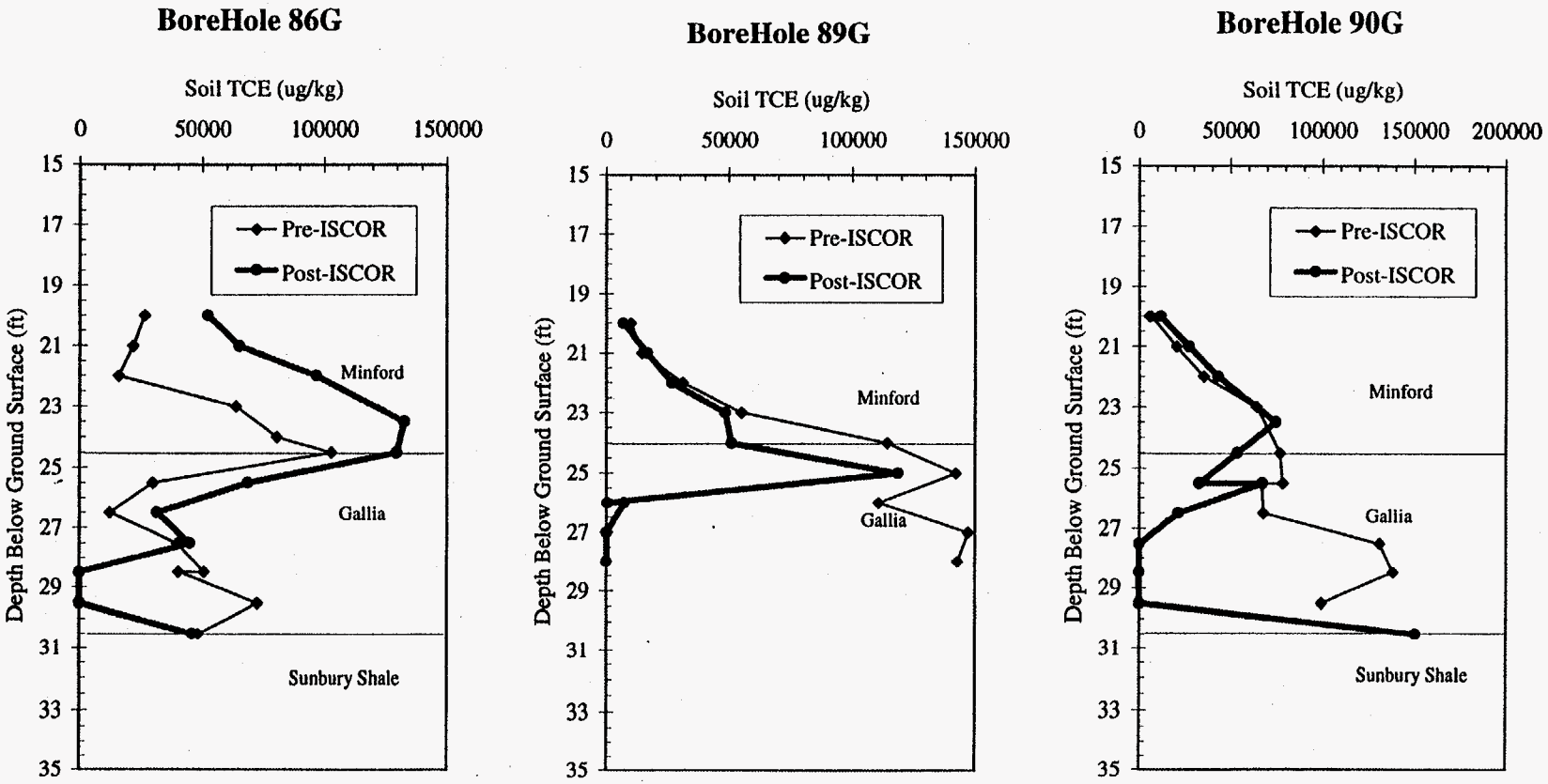

Fig. 5.3 Pre- and post-treatment levels of trichloroethylene in soil samples collected from boreholes associated with monitoring wells 86G, 89G, and 90G. Oxidant levels were detected in these wells after injection into well 74G.

A couple of boreholes were drilled in locations without associated monitoring wells (see Fig. 5.4). Borehole 15G is located within the southern area of the treatment zone where oxidant migrated most rapidly. Non-detectable post-treatment levels of TCE were generally observed in the Gallia in this borehole. Borehole 18 was located midway between monitoring wells 95G and 96G, both of which showed oxidant levels during horizontal well recirculation. TCE reductions in Borehole 18 were not significant and differences in pre- and post-treatment samples could be attributed heterogeneity. During pre-treatment characterization, drilling refusal was met in borehole 18 at ~26.5 ft bgs due to the presence of a hard layer of lithified silty gravel. This layer may have affected the transport of oxidant and its effectiveness for degrading TCE within the vicinity of this borehole.

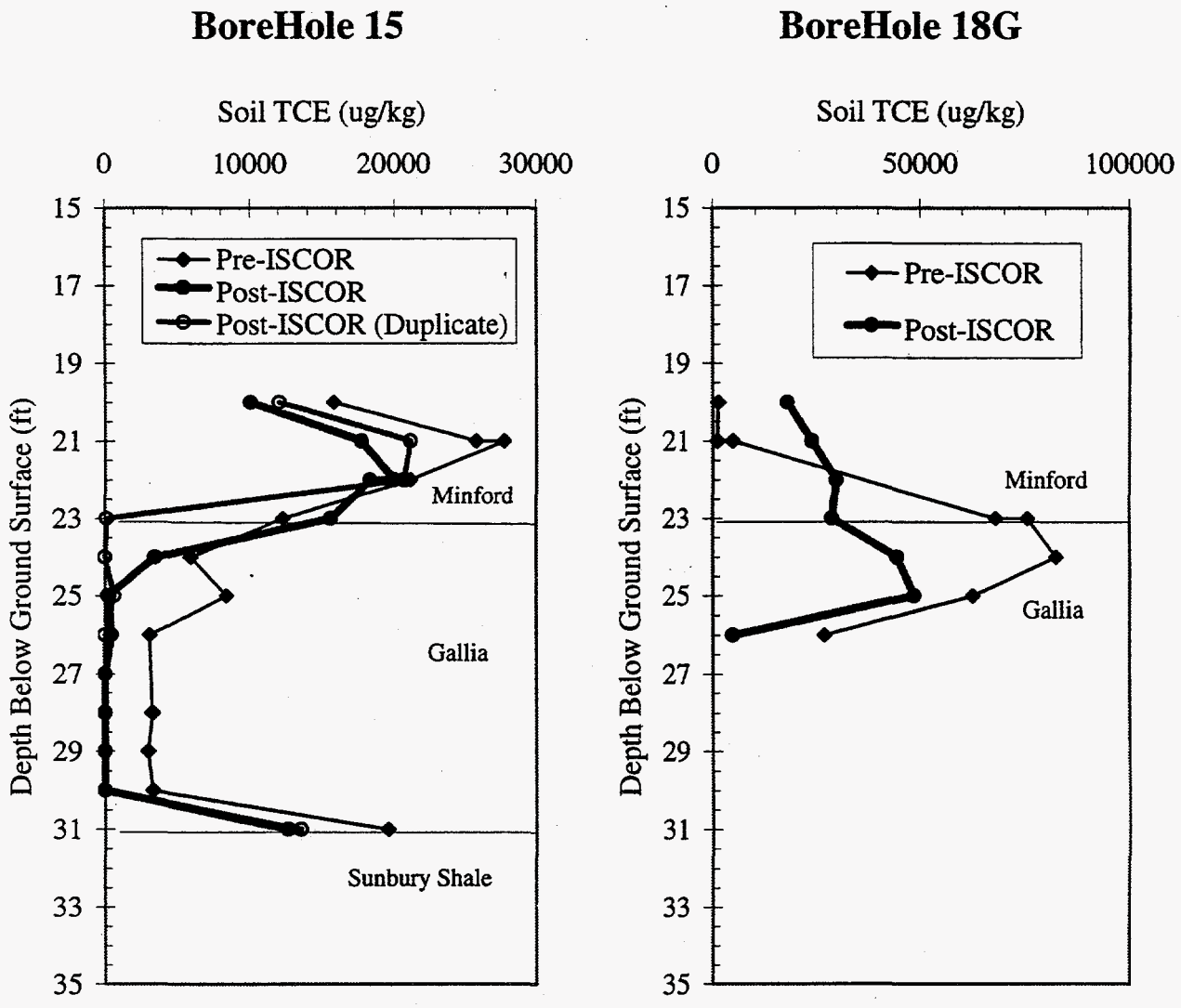

Fig. 5.4 Pre- and post-treatment levels of trichloroethylene in soil samples collected from boreholes without associated monitoring wells. Duplicate post-treatment boreholes (< 5 ft apart) were drilled in borehole location 15.

5.2.2 TCE IN GROUNDWATER

TCE was measured at levels below 1 ppm in wells where it was not detected immediately after the end of the ISCOR field test (Table 5.1, compare 8/28/97 and 9/13/97). This increase stems from residual TCE within the vicinity of the monitoring wells. All the post-treatment boreholes showed that TCE levels in the Sunbury shale were not affected by ISCOR treatment. In some boreholes, TCE was still detected in the upper Gallia even though TCE was down to non-detectable levels in the lower Gallia. This was attributed to a higher percentage of fine particles in the upper Gallia which results in a lower hydraulic conductivity. Residual TCE in the Sunbury shale and upper Gallia, perhaps even from the Minford layer, can still serve as a source for TCE in the groundwater. However, because the residual TCE is present in lower-conductivity zones, its mobility is probably significantly reduced relative to conditions before TCE from the lower Gallia were removed by oxidation.

Table 5.1 Summary of trichloroethylene concentrations in monitoring wells before, immediately after and two weeks after the end of the ISCOR field test.

	Trichloroethylene concentration (µg/L)*		
Well No.	7/18/97 Pre-ISCOR	8/28/97 Immediately after ISCOR	9/13/97 Two weeks after ISCOR
09G	250,948	582,566	147,934
21G	862	4,792	3,059
41G	38	NA	190
42G	0	406	336
71G	28	4,820	1,706
72G	67,645	ND	111
73G	328,924	ND	39
74G	733,527	NA	NA
75G	176,998	ND	83
76G	110,220	273,849	106,080
77G	586	ND	50
78G	820,602	797,746	339,451
80G	NA	NA	NA
81G	NA	NA	NA
83G	3,931	5,555	NA
84G	45,275	7,734	NA
85G	774,541	692,813	179,480
86G	224,119	7	32
87G	168,933	262,911	NA
88G	10,351	11	46
89G	142,736	ND	230
90G	249,461	ND	426
91G	6,051	ND	NA
92G	14,234	ND	NA
93G	129,445	ND	125
94G	176,908	ND	318
95G	148,529	ND	72
96G	1,416	ND	NA

*NA = not analyzed; ND = not detected at an approximate detection limit of 5 ppb.

Long term monthly monitoring of the groundwater in the X-701B area has been initiated. TCE values in the area at 8 and 12 weeks following the ISCOR test are presented in Table 5.2. All monitoring wells in the treatment zone which had $KMnO_4$ present at the end of the field test had TCE concentrations less than 5 ppb. With the exception of Well 88G, these same wells still had very little increase in TCE concentrations after 12 weeks had elapsed. The $KMnO_4$ concentration, however, decreased substantially over the same time period, with an average 40% decrease in the $KMnO_4$ concentration between the 8 and 12 week samples.

Table 5.2 Summary of trichloroethylene concentrations in monitoring Wells 8 and 12 weeks after the end of the ISCOR field test.

	Trichloroethylene concentration (µg/L)*	
Well No.	10/2397 8 weeks after ISCOR	11/20/97 12 weeks after ISCOR
09G	282,708	349,075
21G	7,759	2,591
41G	72	ND
42G	658	ND
71G	4,669	3,394
72G	14	ND
73G	ND	ND
74G	ND	ND
75G	ND	ND
76G	364,582	629,506
77G	ND	ND
78G	621,488	923,260
80G	ND	23
81G	14,092	19,160
83G	Piezometer Removed	Piezometer Removed
84G	Piezometer Removed	Piezometer Removed
85G	Piezometer Removed	Piezometer Removed
86G	138,763	315,867
87G	Piezometer Removed	Piezometer Removed
88G	ND	22,409
89G	ND	7
90G	Piezometer Removed	Piezometer Removed
91G	Piezometer Removed	Piezometer Removed
92G	ND	ND
93G	ND	ND
94G	ND	ND
95G	ND	ND
96G	ND	ND

*NA = not analyzed; ND = not detected at an approximate detection limit of 5 ppb.

6. SUMMARY AND RECOMMENDATIONS

The field test of in situ chemical oxidation through recirculation at the X-701B site has shown the following:

(1) The recirculation concept of introducing potassium permanganate into the subsurface appears to be viable at PORTS. Using this approach, there is more control over oxidant distribution and mobilized contamination is better contained relative to oxidant injection alone. Using groundwater for the oxidant solution is also operationally more convenient in cases where a nearby source of water is not available.

(2) Oxidant injection (without extraction) into the Gallia was also found to be feasible. However, as noted in (1), there is no control in the subsequent movement of the oxidant after its release.

(3) If a recirculation approach is used to deliver $KMnO_4$ to the subsurface, a system for handling MnO_2 particulates in extracted groundwater must be incorporated into the recirculation system.

(4) Lateral and vertical heterogeneity within the Gallia impacted the delivery of oxidants through the horizontal wells. Modeling studies were conducted to compare the efficacy of using horizontal wells vs a series of vertical wells in heterogeneous aquifers. The modeling results, which will be described in the forthcoming expanded report, indicate that vertical wells can be more effective in uniformly dispersing solutions in an aquifer with significant lateral heterogenetics when compared to horizontal wells. In treating large areas, it may be more technically and cost-effective to install a number of vertical wells than to install a few of the more expensive horizontal wells.

(5) Where the oxidant was able to permeate the Gallia, significant reductions in TCE were measured in both groundwater and soil samples. ISCOR did not seem to affect TCE levels in the Minford and Sunbury layers. Nevertheless, reduction of TCE mass within the more conductive media at PORTS leads to a reduction of overall TCE mobility within the X-701B area. This mobility reduction may be enough to reduce risk to acceptable levels. Evaluation of risk is a new approach to establishing clean-up levels that is being advocated by the Environmental Protection Agency. A qualitative measure of reduced TCE mobility can be obtained by continuing to monitor TCE groundwater levels particularly in wells where it was not detected immediately after the ISCOR field test. If TCE levels remain low over a long time period (e.g., a year), then ISCOR at the X-701B site would have achieved a clean-up goal of reduced contaminant mobility.

7. REFERENCES

Korte, N., Muck, M., Kearl, P., Siegrist, R., Houk, T., Schlosser, R., Zutman, J. 1997. *Field Evaluation of a Horizontal Well Recirculation System for Groundwater Treatment: Field Demonstration at X-701B Portsmouth Gaseous Diffusion Plant, Piketon, Ohio.* Oak Ridge National Laboratory, Grand Junction, Colorado.

U.S.DOE. 1994a. *Quadrant II RFI Report for Portsmouth Uranium Enrichment Plant, Piketon, Ohio. Volume 1 (draft).* U.S. Department of Energy, Office of Environmental Restoration and Waste Management. Piketon, Ohio.

U.S.DOE. 1994b. *X-701B Draft Cleanup Alternatives Study/Corrective Measures Study Report for the Portsmouth Gaseous Diffusion Plant, Piketon, Ohio.* U.S. Department of Energy, Office of Environmental Restoration and Waste Management. Piketon, Ohio.

APPENDIX A: LOGS FROM BORINGS DRILLED DURING ISCOR PRETREATMENT CHARACTERIZATION

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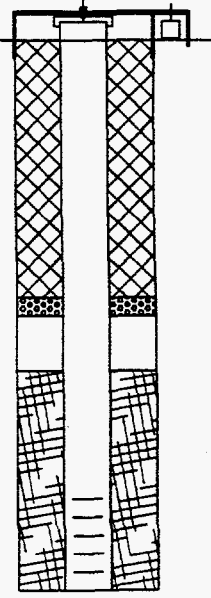
Life Sciences Division
Environmental Technology Section
2597 B 3/4 Road
Grand Junction CO, 81503

Monitoring Well Summary

Project Name: Ports ISCOR	**Site Id:** MW83G
Date: 07/13/97	**State Plane North:** 370694.89 **State Plane East:** 1860800.14
Ground Elevation: 672.29'	**Completed Depth:** 30.00' **Total Depth:** 30.50'
Remarks: 1" OD, 0.10" slotted PVC Screen 25–30' Natural pack 18–30' #4 Sand from 15–18' 1/4" Bentonite pellets 14–15'	**Drilling Method:** Geoprobe macrocore
	Logged By: F.G. Gardner
	Contractor: ORNL

Elevation (ft)	Depth (ft)	Graphic Log	Material Description	Well Construction
670				MP. EL. 673.29
	10		Auger 4" hole to 18'.	
660				
	20		ML SILT: yellowish brown, very moist at 22', some fine grained sand lenses.	
650			GM SILTY GRAVEL: yellowish brown to reddish brown, silty matrix with upward fining sands and gravels to 1", rounded to subangular, wet at 29'.	
	30		SH SHALE: black, weathered Sunbury.	
640				



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Environmental Technology Section
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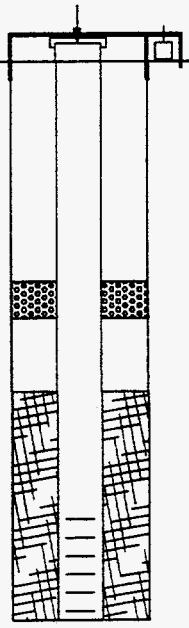
Monitoring Well Summary

Project Name: Ports ISCOR	Site Id: MWB4G
Date: 07/13/97	State Plane North: 370670.17 State Plane East: 1860818.70
Ground Elevation: 672.36'	Completed Depth: 30.50' Total Depth: 30.50'
Remarks: 1" OD, 0.10" Slotted PVC Screen 25-30' #4 Sand 14-18' Natural Pack 18-30.5' 1/4" Bentonite pellets 12-14' WELL ABANDONED, 9/17/97 GROUTED TO SURFACE	Drilling Method: Geoprobe macrocore Logged By: F.G. Gardner Contractor: ORNL

Elevation (ft)	Depth (ft)	Graphic Log	Material Description
670			
	10		Auger 4" hole to 18'
660			
	20		ML SILT: Minford to 23.5'
650			SM SILTY GRAVEL to 29.5'
	30		SH SHALE: Black, fissile Sunbury shale.
640			

Well Construction

MP. EL. 673.36



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Environmental Technology Section
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Grand Junction CO, 81503

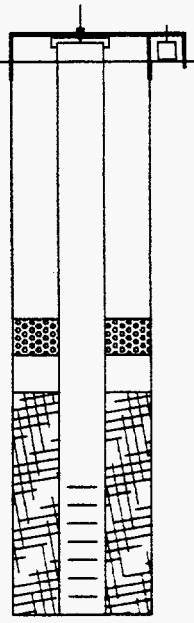
Monitoring Well Summary

Project Name: Ports ISCOR	Site Id: MW85G
Date: 07/11/97	State Plane North: 370605.77 State Plane East: 1860812.94
Ground Elevation: 671.14'	Completed Depth: 30.20' Total Depth: 30.20'
Remarks: 1" OD, 0.10" Slotted PVC screen 23.2-30.2' Natural pack 18-23.2' #4 Sand 16-18' 1/4" Bentonite pellets 14-16' WELL ABANDONED 9/17/97 - GROUTED TO SURFACE	Drilling Method: Geoprobe macrocore Logged By: R.M. Schlosser Contractor: ORNL

Elevation (ft)	Depth (ft)	Graphic Log	Material Description
670			
	10		Auger 4" hole to 18'
660			
	20		ML SILT: Minford
650			GM SILTY GRAVEL: yellowish brown to reddish brown Gallia, very silty. ML SILT: as above with scattered limestone gravel.
			GM SILTY GRAVEL: as above, very wet at 29'.
	30		SH SHALE: black fissile weathered Sunbury Shale
640			

Well Construction

MP. EL. 672.14



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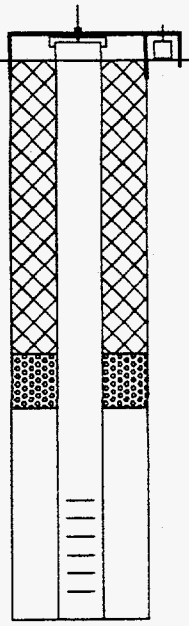
Monitoring Well Summary

Project Name: Ports ISCOR	Site Id: MW86G
Date: 07/11/97	State Plane North: 370578.96 State Plane East: 1860824.95
Grownd Elevation: 672.29'	Completed Depth: 30.50' Total Depth: 30.50'
Remarks: 1" OD, 0.10" slotted PVC screen 24-30.5' #4 sand 19-30.5' 1/4" bentonite pellets, 16'-19' Bentonite grout, surface-16'	Drilling Method: Geoprobe macrocore
	Logged By: R.M. Schlosser
	Contractor: ORNL

Elevation (ft)	Depth (ft)	Graphic Log	Material Description
670	10		Auger 4" hole to 19'
660	20		ML SILT: yellowish brown, moist, wet at 19'
650			GM SILTY GRAVEL: 1/4-1/2" angular limestone gravel very wet at top drier at 25.5', becoming siltier with depth.
	30		SH SHALE: black, fissile Sunbury Shale.
640			

Well Construction

MP. EL. 673.29



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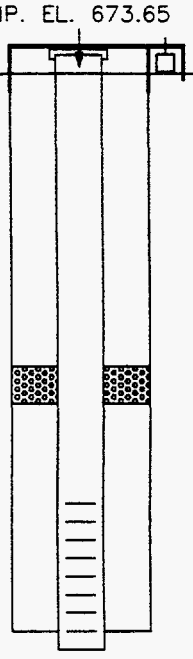
Monitoring Well Summary

Project Name: Ports ISCOR	Site Id: MW87G
Date 07/13/97	State Plane North: 370554.65 State Plane East: 1860827.53
Ground Elevation: 673.31'	Completed Depth: 31.50' Total Depth: 32.00'
Remarks: 1" OD, 0.10" slotted PVC screen, 23.5-31.5 #4 sand 23.5-31.5' 1/4" bentonite pellets, 16-18' WELL ABANDONED 9/17/97 - GROUTED TO SURFACE	Drilling Method: Geoprobe macrocore Logged By: R.M. Schlosser Contractor: ORNL

Elevation (ft)	Depth (ft)	Graphic Log	Material Description
670	10		Auger 4" hole to 18'
660	20		ML SILT: Minford, yellowish brown, occasional gravel.
650			GM SILTY GRAVEL: yellowish brown, gravel in a silt matrix. ML SILT: as above
	30		GM SILTY GRAVEL: 1/4"-1/2" angular limestone gravel, very wet, some fining upward sand from 27-28'.
640			SH SHALE. weathered black Sunbury.

Well Construction



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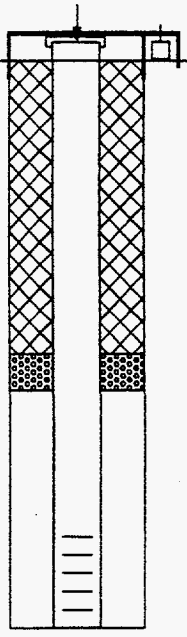
Monitoring Well Summary

Project Name: Ports ISCOR	Site Id: MW88G
Date: 07/12/97	State Plane North: 370492.32 State Plane East: 1860842.91
Ground Elevation: 673.31'	Completed Depth: 31.00' Total Depth: 31.00'
Remarks: 1" OD, 0.10" slotted PVC screen, 26–31' #4 Sand, 18–31' 1/4" bentonite pellets 16–18' Bentonite grout Surface–16'	Drilling Method: Geoprobe macrocore
	Logged By: R.M. Schlosser
	Contractor: ORNL

Elevation (ft)	Depth (ft)	Graphic Log	Material Description
670	10		Auger 4" hole to 18.5'
660	20		ML SILT: Minford, yellowish brown, moist at 21'.
650			GM SILTY GRAVEL: Yellowish to dark yellowish brown, 1/4"–1" rounded to subangular gravels in a silty matrix, trace of sand.
			ML SILT: reddish brown, some scattered gravels.
	30		GM SILTY GRAVEL: appearance as GM above, increasing amount of gravel towards the bottom of interval.
640			SH SHALE: bedrock, weathered black shale.

Well Construction

MP. EL. 674.31



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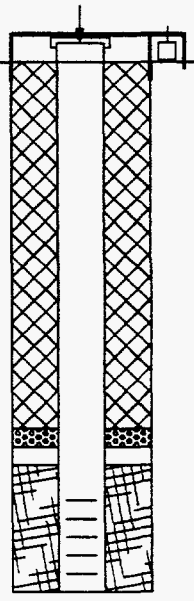
Monitoring Well Summary

Project Name: Ports ISCOR	Site Id: MW89G
Date 07/10/97	State Plane North: 370604.67 State Plane East: 1860849.96
Ground Elevation: 670.85'	Completed Depth: 28.90' Total Depth: 28.90'
Remarks: 1" OD, 0.10 " slotted PVC screen 23.9-28.9' Native pack 22-28.9' #4 sand 21-22' 1/4" Bentonite pellets. 20-21' Bentonite grout Surface-20'	Drilling Method: Geoprobe macrocore Logged By: R.M. Schlosser Contractor: ORNL

Elevation (ft)	Depth (ft)	Graphic Log	Material Description
670			
	10		Auger 4" hole to 18'
660			
	20		ML SILT: strong brown to reddish yellow, (7.5YR6/8) mottled light gray throughout, some scattered chert, sandy with increasing percent with depth, abundant Fe staining.
650			GM SILTY GRAVEL: top 6" of Gallia 1/2-1" angular gravel, becoming siltier with depth
			ML SILT: reddish grown, scattered gravel.
			GM SITY GRAVEL: predominantly silty at top, becoming more gravelly with depth, Fe cemented, silty matrix
	30		
640			

Well Construction

MP. EL. 671.85



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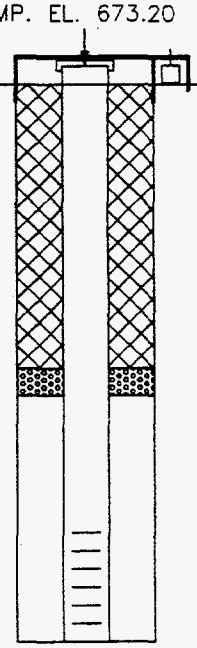
Monitoring Well Summary

Project Name: Ports ISCOR	Site Id: MW90G
Date 07/11/97	State Plane North: 370581.05 State Plane East: 1860854.23
Ground Elevation: 672.20'	Completed Depth: 30.50' Total Depth: 31.00'
Remarks: 1" OD, 0.10" slotted PVC screen 24.5-30.5' #5 sand 17-30.5' 1/4" Bentonite pellets 15.5-17' Bentonite grout, Surface-15.5'	Drilling Method: Geoprobe macrocore
	Logged By: R.M. Schlosser
	Contractor: ORNL

Elevation (ft)	Depth (ft)	Graphic Log	Material Description
670			
	10		Auger 4" hole to 19'
660			
	20		ML SILT: yellowish brown, abundant Fe staining throughout, moist at 21'.
650			GM SILTY GRAVEL: yellowish brown to reddish yellow, gravel to 2", angular to rounded, in a silt matrix, trace of sand.
			ML SILT: reddish brown with scattered gravels.
			GM SILTY GRAVEL: abundant Fe stained and cemented zones, very hard, well cemented in lower part.
	30		SH SHALE: black, fissile weathered Sunbury shale.
640			

Well Construction



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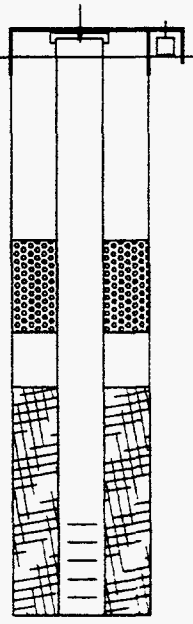
Monitoring Well Summary

Project Name: Ports ISCOR	Site Id: MW91G
Date 07/15/97	State Plane North: 370708.98 State Plane East: 1860858.40
Ground Elevation: 671.35'	Completed Depth: 30.50' Total Depth: 31.00'
Remarks: 1" OD, 0.10" slotted PVC screen 25.5-30.5' Natural pack 18-30.5' #4 Sand 15-18' 1/4" Bentoniote pellets 10-15' WELL ABANDOND 9/17/97- GROUTED TO SURFACE.	Drilling Method: Geoprobe macrocore Logged By: F.G. Gardner Contractor: ORNL

Elevation (ft)	Depth (ft)	Graphic Log	Material Description
670			
	10		Auger 4" hole to 18'
660			
	20		ML SILT: Minford, yellowish brown to light gray, very fine silt, becoming wet at 20.5'
650			GM SILTY GRAVEL: 1/4"-1" rounded to subangular limestone gravels in a reddish brown silt matrix, sandy in part, damp.
			SAMPLE INTERVAL LOST
	30		SH SHALE: black fissile weathered Sunbury Shale.
640			

Well Construction

MP. EL. 672.14



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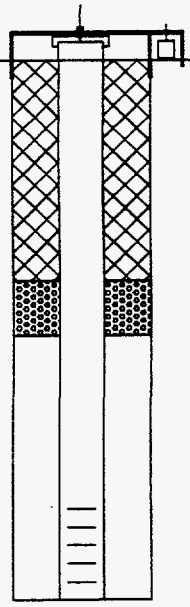
Monitoring Well Summary

Project Name: Ports ISCOR	Site Id: MW92G
Date 07/15/97	State Plane North: 370644.77 State Plane East: 1860872.30
Ground Elevation: 671.17'	Completed Depth: 29.50' Total Depth: 29.50'
Remarks: 1" OD, 0.10" slotted PVC screen 24.5-29.5 #4 sand, 15-29.5' 1/4" Bentonite pellets 12-15' Bentonite grout Surface-12'	Drilling Method: Geoprobe macrocore
	Logged By: F.G. Gardner
	Contractor: ORNL

Elevation (ft)	Depth (ft)	Graphic Log	Material Description
670			
	10		Auger 4" hole to 18'
660			
	20		ML SILT: Minford, yellowish brown (10YR5/8), some mottled strong brown, firm, moist, fine grained sand scattered throughout, limonite staining in part.
650			GM SILTY GRAVEL: moist Gallia with some very dry streaks throughout interval, 1/4-3/4" rounded to subangular limestone and sandstone, matrix is fine grained silty sand with abundant fines, strong red Fe staining from 26.75-27', some yellow limonite staining throughout.
	30		SH SHALE: weathered black fissile Sunbury Shale.
640			

Well Construction

MP. EL. 672.17



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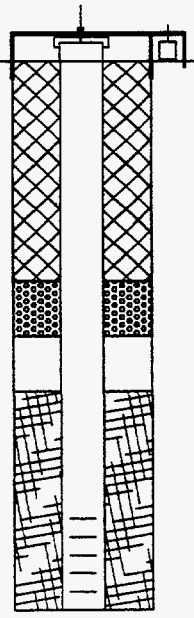
Monitoring Well Summary

Project Name: Ports ISCOR	Site Id: MW93G
Date 07/15/97	State Plane North: 370617.27 State Plane East: 1860877.26
Ground Elevation: 670.60'	Completed Depth: 30.00' Total Depth: 31.00'
Remarks: 1" OD, 0.10 " slotted PVC casing 25-30' Natural pack 18-30' #4 sand 15-18' 1/4" bentonite pellets 12-15' Bentonite grout 0-12'	Drilling Method: Geoprobe macrocore
	Logged By: F.G. Gardner
	Contractor: ORNL

Elevation (ft)	Depth (ft)	Graphic Log	Material Description
670			
			Auger 4" hole to 18'
660	10		
			ML SILT: Minford, abundant fine sand scattered throughout.
650	20		
			GM SILTY GRAVEL: angular to subrounded 1/4-3/4" sandstone and limestome gravels with strong red Fe staining, some scattered black shale partings throughout, some moisture, scattered fines throughout, silty sand matrix, very sandy gravel zone 29-29.5'.
640	30		SH SHALE: black fissile weathered Sunbury Shale.

Well Construction

MP. EL. 671.60



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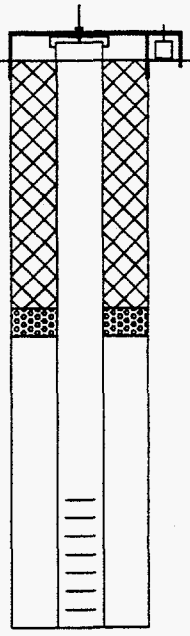
Monitoring Well Summary

Project Name: Ports ISCOR	Site Id: MW94G
Date: 07/11/97	State Plane North: 370585.52 State Plane East: 1860885.30
Ground Elevation: 672.17'	Completed Depth: 31.00' Total Depth: 32.00'
Remarks: 1" OD, 0.10" slotted PVC screen 24-31' #5 sand 15-31' 1/4" Bentonite pellets 13.5-15' Bentonite Grout Surface-13.5'	Drilling Method: Geoprobe macrocore
	Logged By: R.M. Schlosser
	Contractor: ORNL

Elevation (ft)	Depth (ft)	Graphic Log	Material Description
670			
	10		Auger 4" hole to 18.5'
660			
	20		ML SILT: Minford light yellowish brown to yellowish brown (2.5YR-10YR 6/4), yellowsih brown becoming more prominanat with depth, firm, wet at 20.5', scattered fine grained sand and chert.
650			
			GM SILTY CLAY: yellowish brown to strong reddish brown, 1/2-1" angular limestone and sandstone gravels, siltier from 28-29', abundant yellow limonite staining. wet, very hard.
	30		
640			SH SHALE: Sunbury Shale, soft weathered black shale at contact, becoming harder and more fissile with depth.

Well Construction



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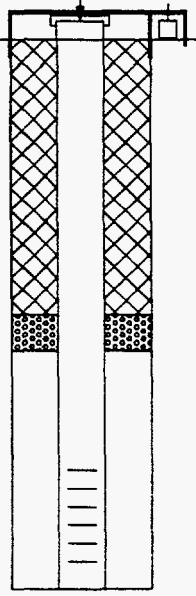
Monitoring Well Summary

Project Name: Ports ISCOR	Site Id: MW95G
Date 07/12/97	State Plane North: 370556.83 State Plane East: 1860890.56
Ground Elevation: 671.69'	Completed Depth: 30.00' Total Depth: 30.00'
Remarks: 1" OD, 0.10" slotted PVC screen set 23.5–30' #4 Sand 17–30' 1/4" Bentonite pellets 15–17' Bentonite grout Surface–15'	Drilling Method: Geoprobe macrocore Logged By: R.M. Schlosser Contractor: ORNL

Elevation (ft)	Depth (ft)	Graphic Log	Material Description
670			
	10		Auger 4" hole to 18.5'
660			
	20		ML SILT: lower Minford, yellowish brown (10YR5/8), mottled strong brown, firm, moist, mottling from limonite staining some scattered very fine grained sand throughout.
650			GM SILTY GRAVEL: yellowish brown to strong brown, angular to subangular 1/4"–3/4" limestone and sandstone gravels, very wet in upper 8–12", becoming drier at 25', wet at 26'.
	30		SH SHALE: weathered black Sunbury Shale.
640			

Well Construction

MP. EL. 672.69



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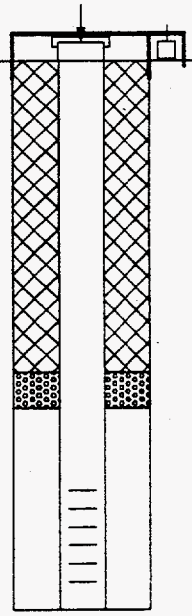
Monitoring Well Summary

Project Name: Ports ISCOR	Site Id: MW96G
Date 07/12/97	State Plane North: 370500.16 State Plane East: 1860902.96
Ground Elevation: 671.51'	Completed Depth: 30.00' Total Depth: 30.00'
Remarks: 1" OD, 0.10" slotted PVC screen 23.5-30' #2 sand 19'-30'. 1/4" Bentonite Pellets 17-19' Bentonite Grout Surface-17'	Drilling Method: Geoprobe macrocore Logged By: R.M. Schlosser Contractor: ORNL

Elevation (ft)	Depth (ft)	Graphic Log	Material Description
670			
	10		Auger 4" hole to 18.5'
660			
	20		ML SILT: light yellowish brown (7.5YR6/4) with abundant limonite staining throughout, moist to wet at 19.5, soft.
650			GM SILTY GRAVEL: yellowsih brown, Gallia, very hard limestone gravel in a yellowish brown silt matrix.
	30		SH SHALE: weathered black shale, Sunbury.
640			

Well Construction

MP. EL. 672.51



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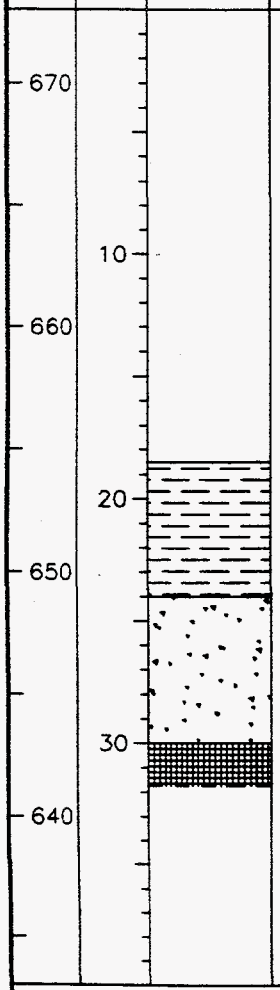
Borehole Summary

Project Name: Ports ISCOR	Site Id: BH08
Date(s): 07/13/97	Total Depth: 31.75'
Contractor: ORNL	Borehole Dia.: 2.00"
Ground Elevation: 673.00'	Drilling Method: Geoprobe macrocore
State Plane North: 370518.32	Logged By: R.M. Schlosser
State Plane East: 1860829.91	Certified By: F.G. Gardner



Material Description

Auger 4" hole to 18.5'

ML SILT: Minford silt.

GM SILTY GRAVEL: Gallia

Lost 23–26.5, Sampler didn't open.

GM SILTY GRAVEL: very hard, appears lithified with Fe cement, wet, abundant chert nodules throughout.

SH SHALE: Sunbury shale, black, weathered, becoming very hard and dry.

Borehole backfilled with 1/4" Bentonite pellets to 18', remainder backfilled with soil from above the water table.

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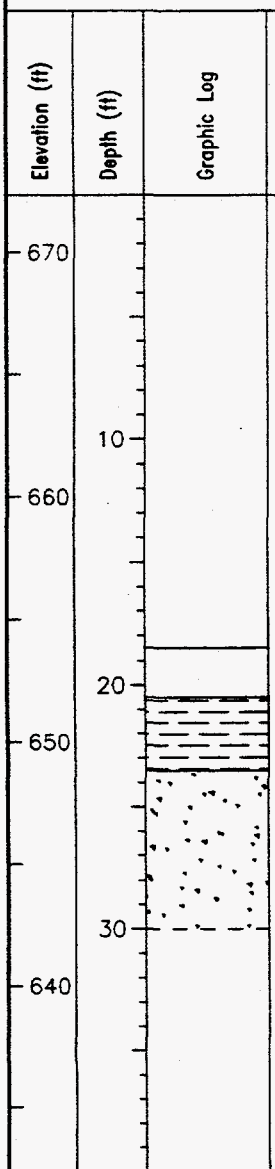
Borehole Summary

Project Name: Ports ISCOR	Site Id: BH13
Date(s): 07/14/97	Total Depth: 30.00'
Contractor: ORNL	Borehole Dia.: 2.00"
Ground Elevation: 672.35'	Drilling Method: Geoprobe macrocore
State Plane North: 370555.94	Logged By: R.M. Schlosser
State Plane East: 1860860.19	Certified By: F.G. Gardner



Material Description
Auger 4" hole to 18.5'
SP SAND: light gray, semi-lithofied
ML SILT: yellowish brown, soft, moist.
GM SILTY GRAVEL: very large cobb;es form 26-30', limestone, very hard, semi-lithified gravels form 28-30'
Borehole backfill with 1/4" Bentonite to 15', remainder backfilled with cuttings from above the water table.

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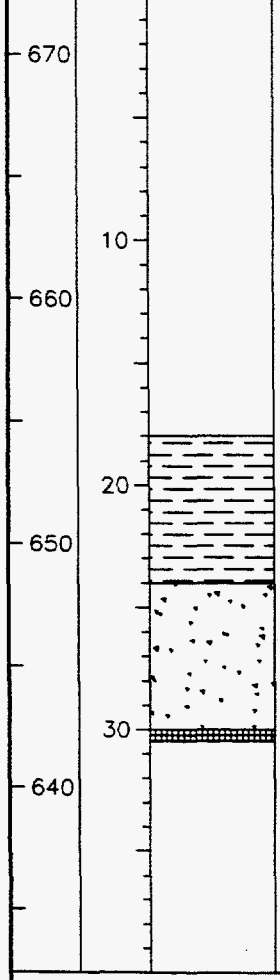
Borehole Summary

Project Name: Ports ISCOR	Site Id: BH14
Date(s): 07/03/97	Total Depth: 30.50'
Contractor: ORNL	Borehole Dia.: 2.00"
Ground Elevation: 672.40'	Drilling Method: Geoprobe macrocore
State Plane North: 370525.87	Logged By: R.M. Schlosser
State Plane East: 1860865.64	Certified By: F.G. Gardner



Material Description

Auger 4" hole to 18'

ML SILT: Minford

GM SILTY GRAVEL: Gallia

GM SILTY GRAVEL: as above, very very hard.

SH Shale: Sunbury, black, weathered.

Borehole backfilled with 1/4" bentonite pellets to 14', remainder backfilled with soil from above the water table.

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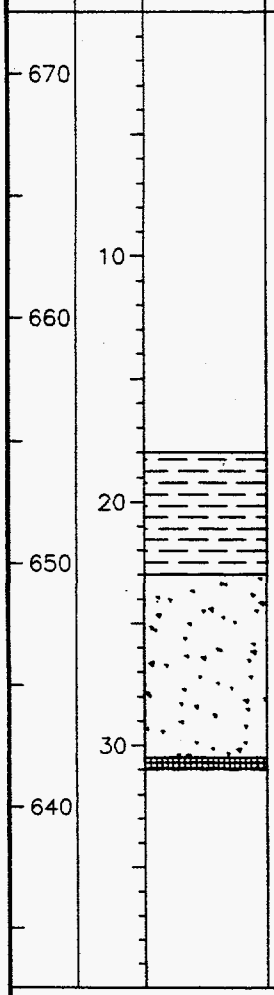
Borehole Summary

Project Name: Ports ISCOR	Site Id: BH15
Date: 07/13/97	Total Depth: 31.00'
Contractor: ORNL	Borehole Dia.: 2.00"
Ground Elevation: 672.51'	Drilling Method: Geoprobe macrocore
State Plane North: 370494.90	Logged By: R.M. Schlosser
State Plane East: 1860869.32	Certified By: F.G. Gardner



Material Description

Auger 4" to 18.5'

ML SILT: yellowish brown, soft, moist at 19.5'.

GM SILTY GRAVEL: yellowish red, grown, silty matrix, some very fine sand at 29', very wet at 29'.

SH SHALE: Sunbury, black, weathered.

Borehole backfilled with 1/4" bentonite chips to 21', remainder backfilled with soil cuttings taken from above the water table.

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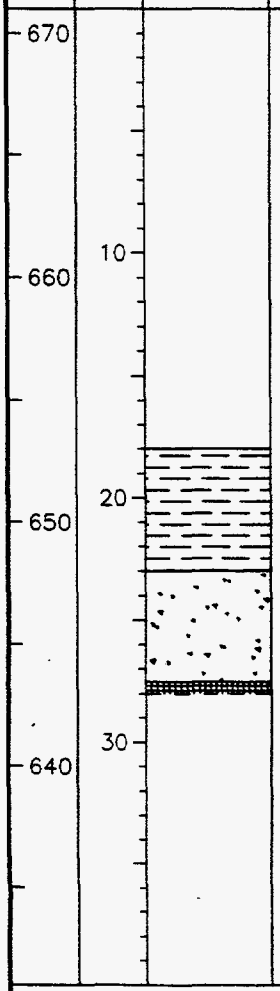
Borehole Summary

Project Name: Ports ISCOR	Site Id: BH16
Date: 07/14/97	Total Depth: 28.00'
Contractor: ORNL	Borehole Dia.: 2.00"
Ground Elevation: 671.00'	Drilling Method: Geoprobe macrocore
State Plane North: 370676.83	Logged By: R.M. Schlosser
State Plane East: 1860874.58	Certified By: F.G. Gardner



Material Description

Auger 4" hole to 18'.

ML SILT: Minford, yellowish brown mottled light gray, damp, abundant Fe and limonite staining throughout.

GM SILTY GRAVEL: reddish brown, 1/2"–1" limestone and sandstone gravels in a silty sandy matrix, becoming very silty at 27', hard from 26.5–27'.

SH SHALE: black weathered Sunbury Shale.

Borehole backfilled with 1/4" bentonite pellets to 15', remainder of boring backfilled with cuttings from above the water table.

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Borehole Summary

Project Name: Ports ISCOR	Site Id: BH17
Date(s): 07/14/97 - 07/14/97	Total Depth: 30.50'
Contractor: ORNL	Borehole Dia.: 2.00"
Ground Elevation: 672.25'	Drilling Method: Geoprobe macrocore
State Plane North: 370565.96	Logged By: R.M. Schlosser
State Plane East: 1860861.68	Certified By: F.G. Gardner

Elevation (ft)	Depth (ft)	Graphic Log	Material Description
670	10		Auger 4" hole to 18'
660	20		ML SILT: Minford, yellowish brown, abundant Fe staining and common limonite staining on laminations, soft to firm, moist, becoming wet at 20.5', occassional chert nodule, some scattered gravel in lower 3'.
650	30		GM SILTY GRAVEL: Yellowish to reddish brown, up to 1" angular to subrounded limestone and scattered sandstone gravels in a reddish brown silt matrix, soft throughout entire interval, poorly lithified, abundant Fe oxides and limonite staining.
640			SH SHALE: black weathered fissile Sunbury Shale.
			Borhole backfilled to 16' with 1/4" bentonite pellets, remainder of hole backfilled with cuttings from above the water table.

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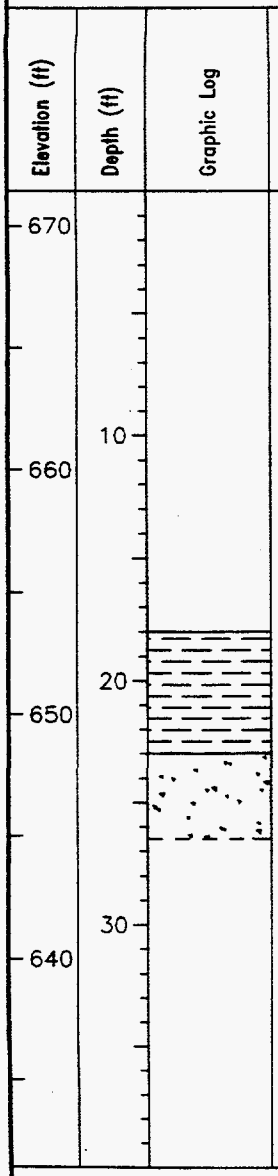
Borehole Summary

Project Name: Ports ISCOR	Site Id: BH18
Date: 07/14/97	Total Depth: 26.50'
Contractor: ORNL	Borehole Dia.: 2.00"
Ground Elevation: 671.40'	Drilling Method: Geoprobe macrocore
State Plane North: 370528.74	Logged By: R.M. Schlosser
State Plane East: 1860896.21	Certified By: F.G. Gardner



Material Description

Auger 4" hole to 18'.

ML SILT: Minford yellowish brown, mottled occassionally light gray, sandy in part wet at 21'.

GM SILTY CLAY: Gallia, 1/4–3/8" limestone and sandstone gravels, predominantly angular in a yellow brown silt matrix, very hard.

GM SILTY CLAY: color as above, very hard litofed silty gravel. REFUSAL at 26.5'.

Borehole backfilled with 1/4" bentonite pellets to 17', remainder of hole backfilled with soil cuttings from above the water table.

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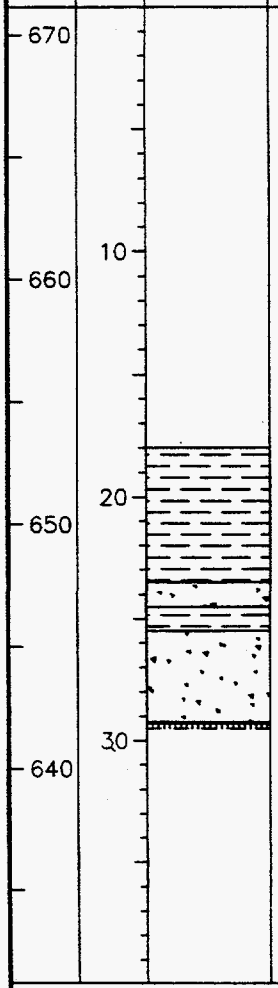
Borehole Summary

Project Name: Ports ISCOR	Site Id: BH19
Date: 07/10/97	Total Depth: 29.50'
Contractor: ORNL	Borehole Dia.: 2.00"
Ground Elevation: 671.14'	Drilling Method: Geoprobe macrocore
State Plane North: 370606.95	Logged By: R.M. Schlosser
State Plane East: 1860817.70	Certified By: M.E. Mumby



Material Description

Auger 4" hole to 18'.

ML SILT: light yellowish brown to yellowish brown (2.5YR6/4–10YR6/4), slightly sandy to very sandy from 20–21'. Fe stained pebbles occasionally, common Fe staining on laminations.
ML SILT: abundant chert.

SILTY GRAVEL: yellowish brown as above, 1/4–1" Fe stained limestone and sandstone gravels.
ML SILT: yellowish brown with scattered gravels.

GM SILTY GRAVEL: as above, very wet.

SH SHALE: black weathered fissile Sunbury shale.

Borehole backfilled with 1/4" bentonite pellets to 15', remainder of hole backfilled with soil cuttings from above the water table.

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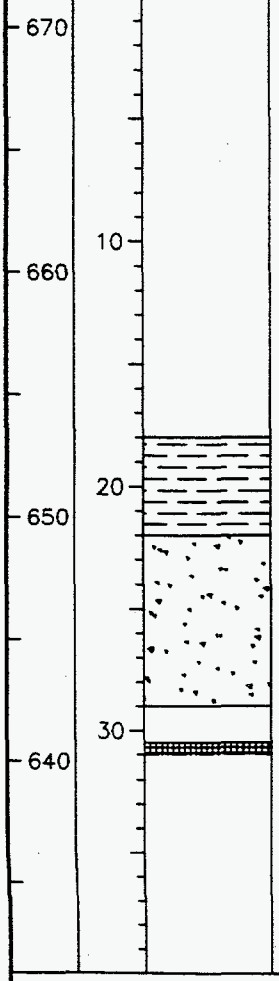
Borehole Summary

Project Name: Ports ISCOR	Site Id: BH20
Date: 07/16/97	Total Depth: 31.00'
Contractor: ORNL	Borehole Dia.: 2.00"
Ground Elevation: 671.25'	Drilling Method: Geoprobe macrocore
State Plane North: 370594.55	Logged By: F.G. Gardner
State Plane East: 1860828.72	Certified By: M.E. Mumby



Material Description

Auger 4" hole to 18'

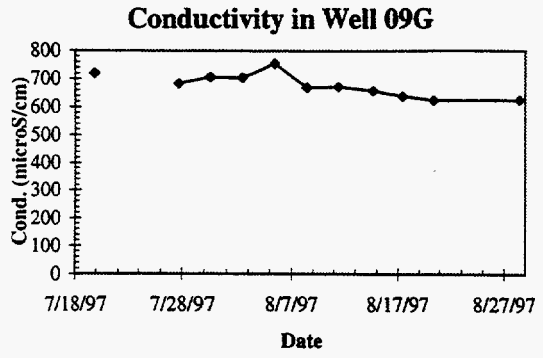
ML SILT: Minford, yellow brown silt with scattered fine grained sand, moist.

GM SILTY GRAVEL: yellowish to dark yellowish brown, 1/4"–1" limestone and sandstone gravels in a silt and sand matrix.

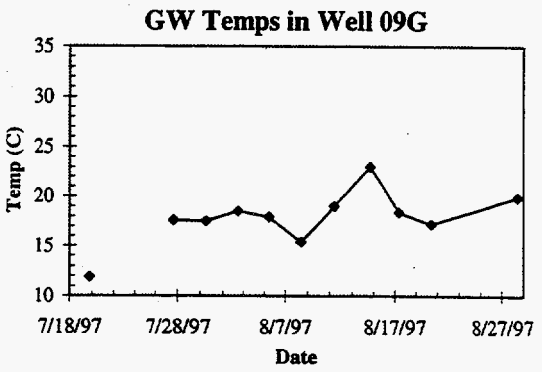
SW SAND: very fine to fine grained sand, saturated from 29–29.5', strong solvent odor in sand.
SH SHALE: black fissile weathered Sunbury shale.

Borehole backfilled with 1/4" bentonite chips to 17' remainder backfilled with soil cuttings from above the water table.

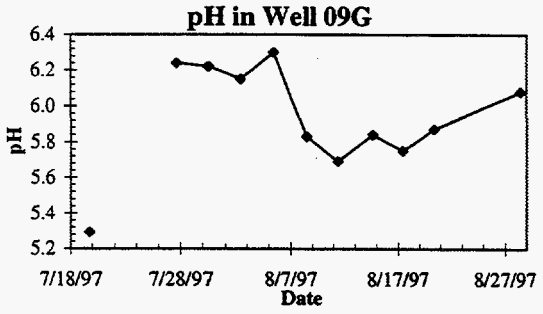
APPENDIX B: SOIL AND GROUNDWATER CHEMICAL CHARACTERISTICS FROM SOIL BORINGS AND GROUNDWATER WELLS MONITORED DURING THE ISCOR FIELD TEST



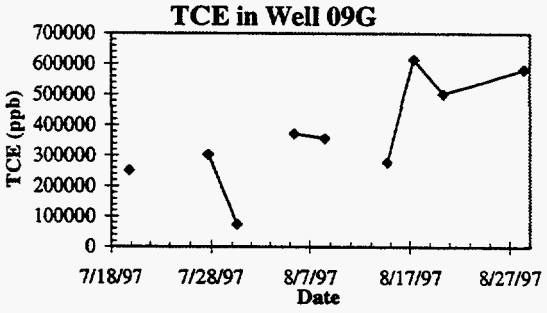
(a)



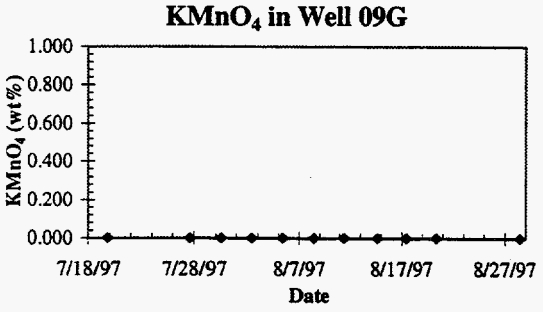
(b)



(c)



(d)



(e)

Fig. B-1 Values of (a) conductance, (b) temperature, (c) pH, (d) trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from Well 09G during the ISCOR field test.

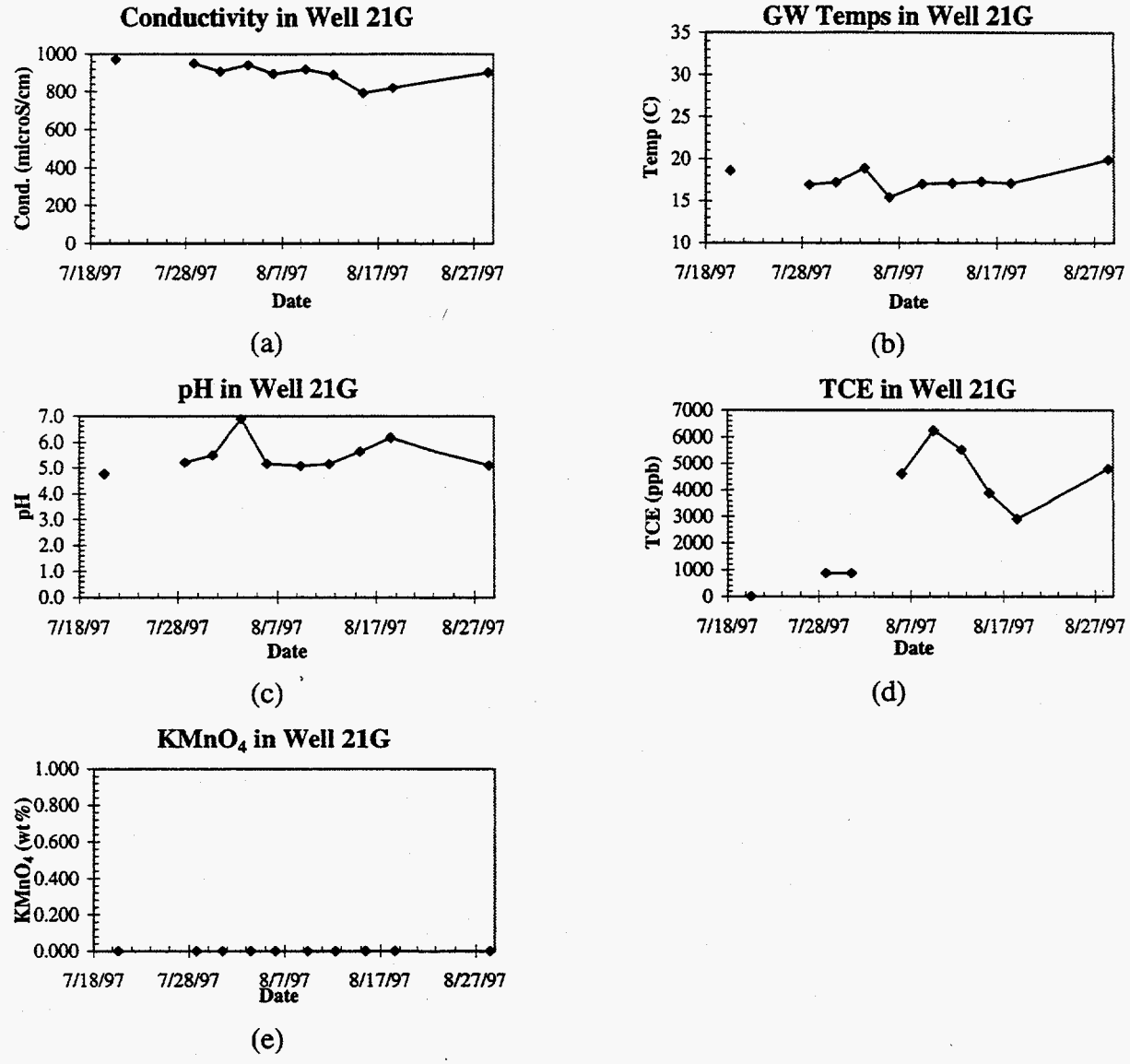


Fig. B-2 Values of (a) conductance, (b) temperature, (c) pH, (d) trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from Well 21G during the ISCOR field test.

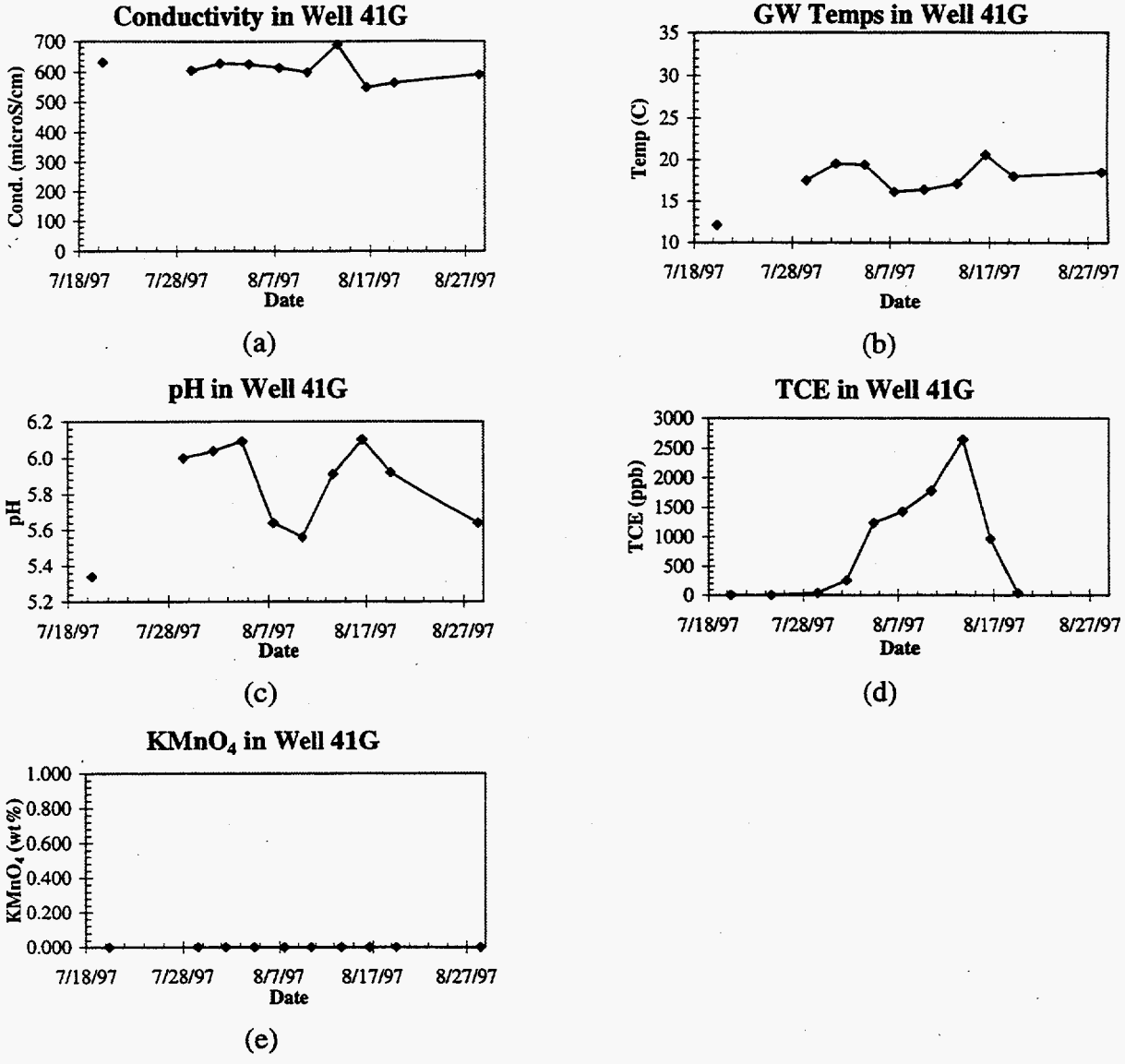


Fig. B.3 Values of (a) conductance, (b) temperature, (c) pH, (d) trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from Well 41G during the ISCOR field test.

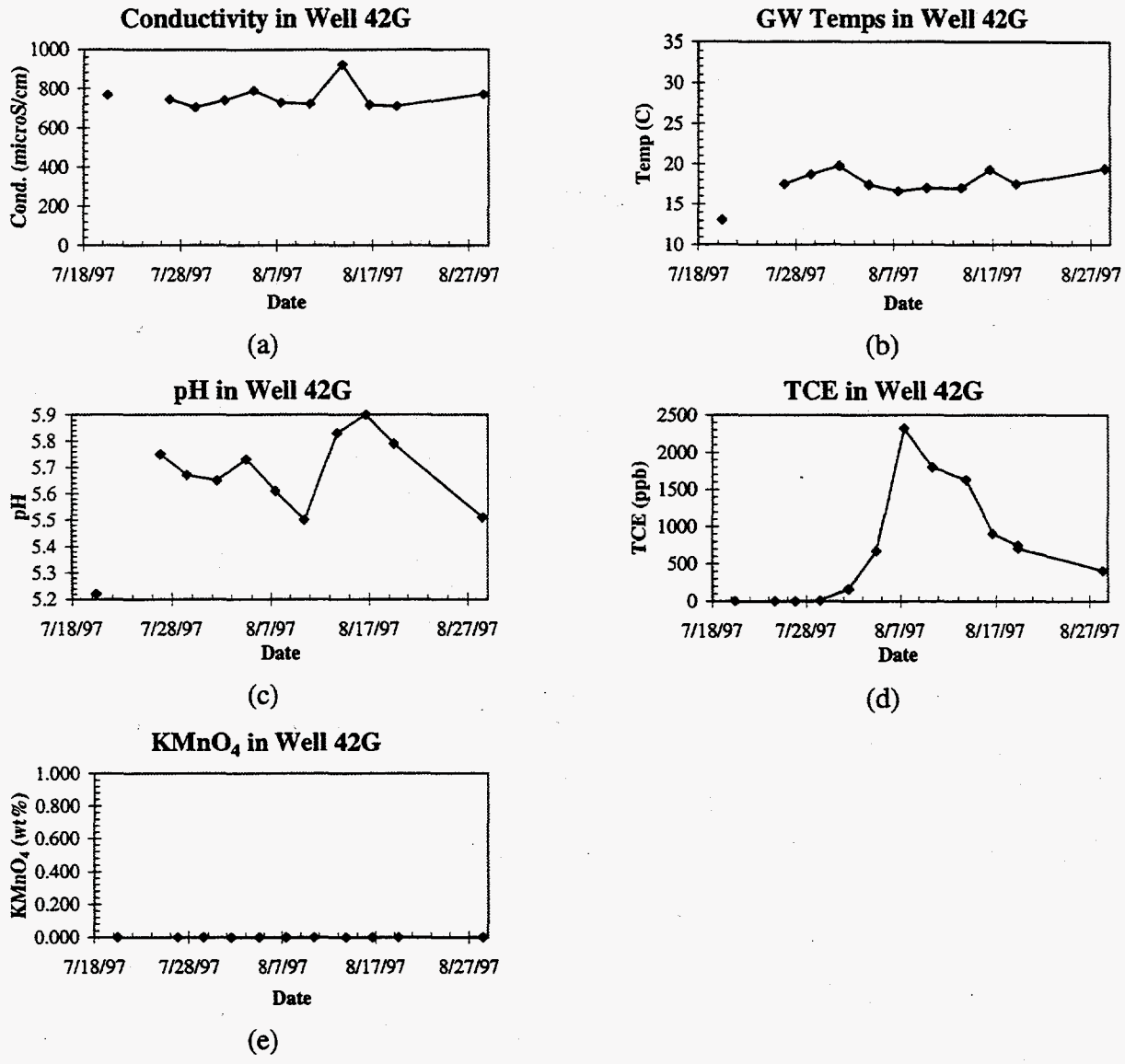


Fig. B-4 Values of (a) conductance, (b) temperature, (c) pH, (d) trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from Well 42G during the ISCOR field test.

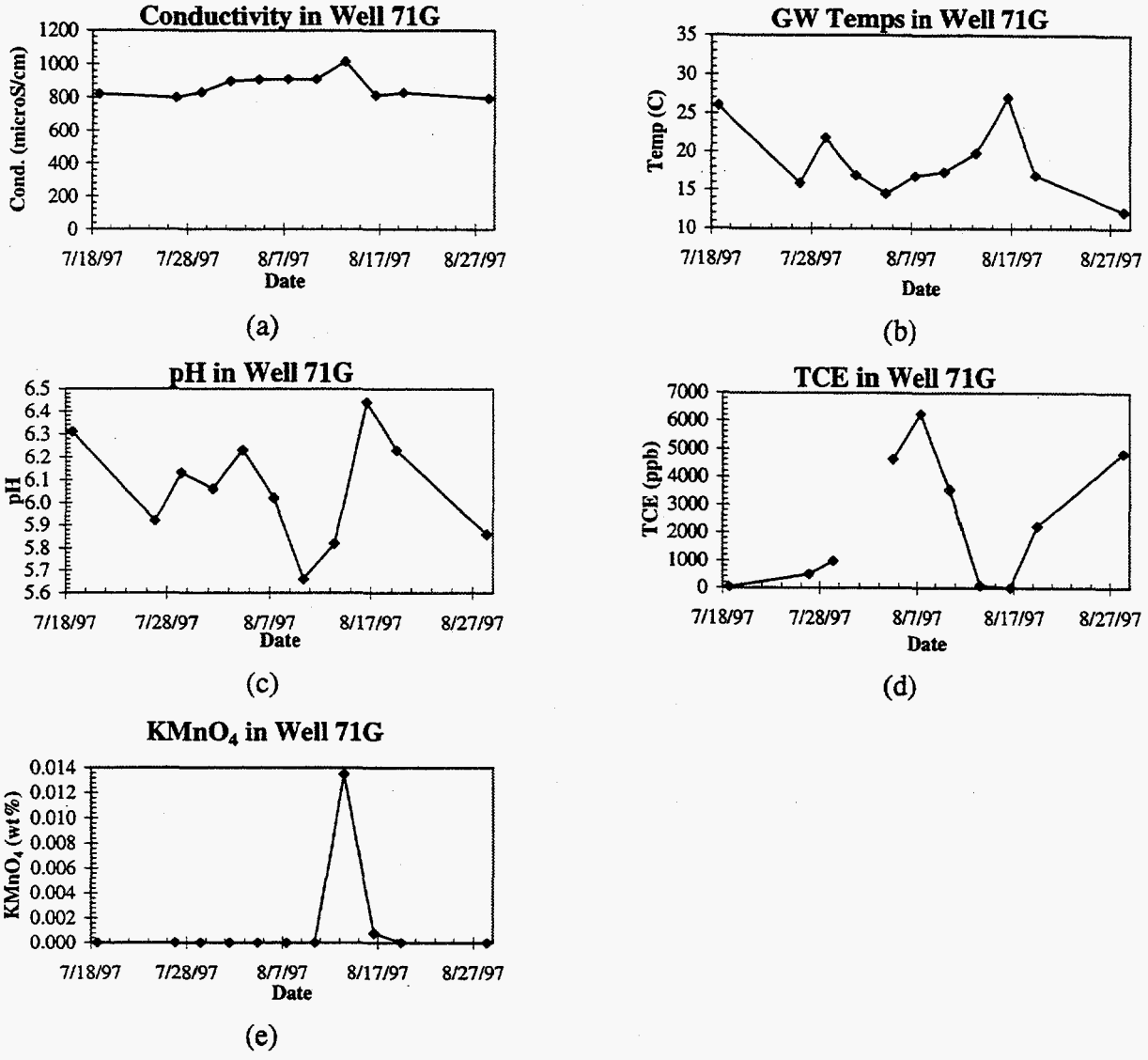
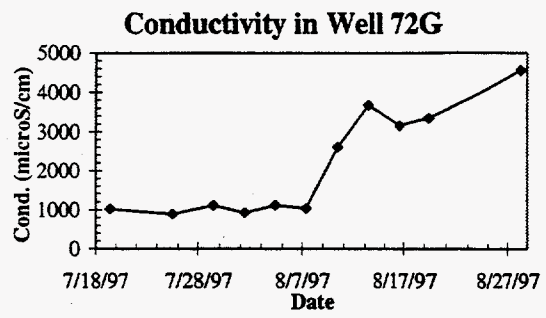
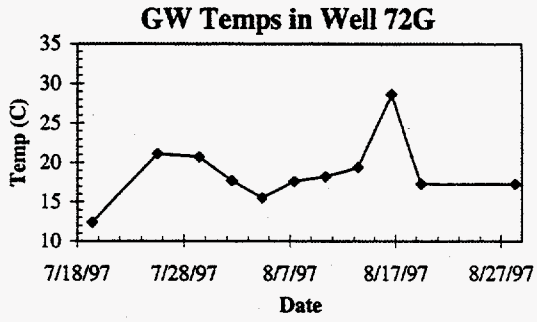


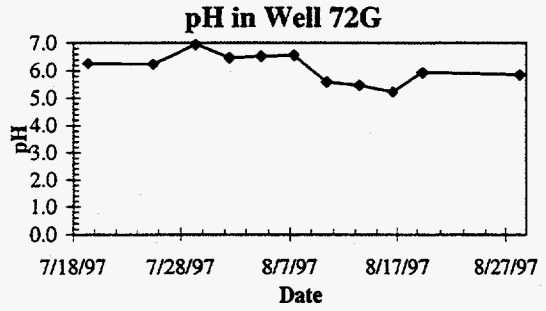
Fig. B-5 Values of (a) conductance, (b) temperature, (c) pH, (d) trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from Well 71G during the ISCOR field test.



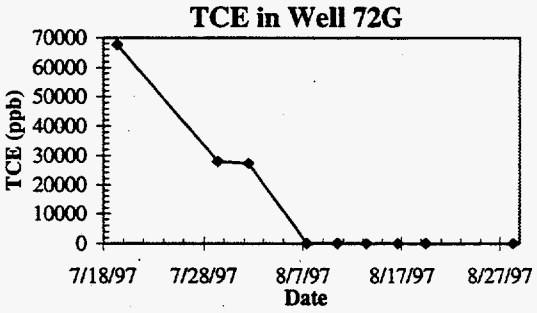
(a)



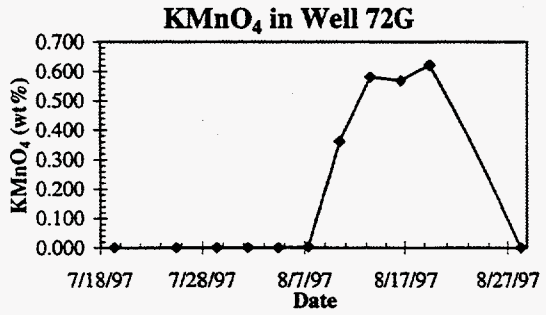
(b)



(c)

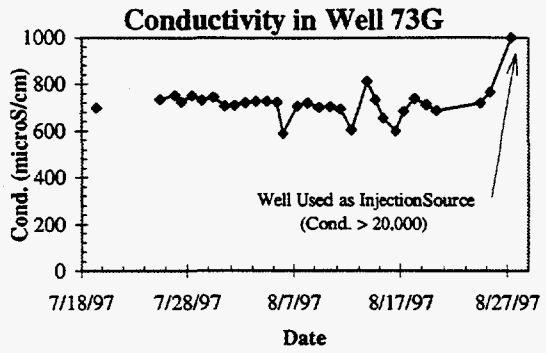


(d)

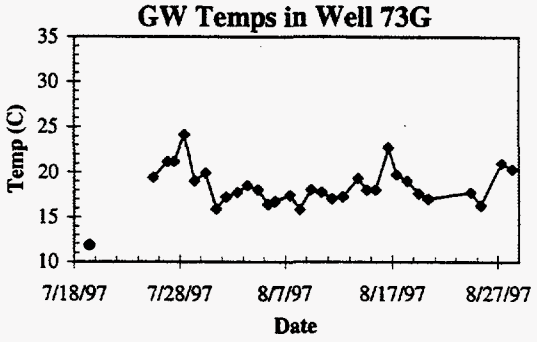


(e)

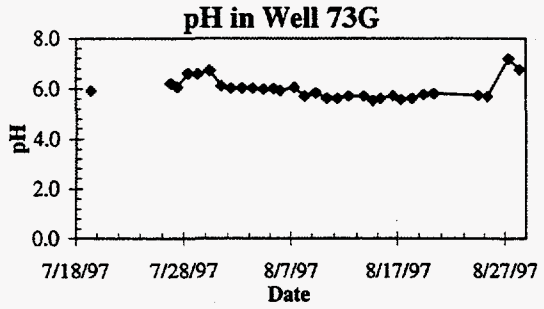
Fig. B.6 Values of (a) conductance, (b) temperature, (c) pH, (d) trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from Well 72G during the ISCOR field test.



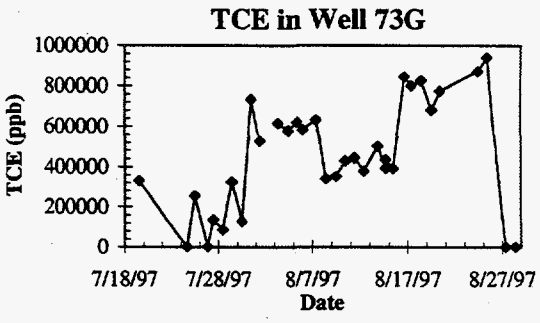
(a)



(b)



(c)



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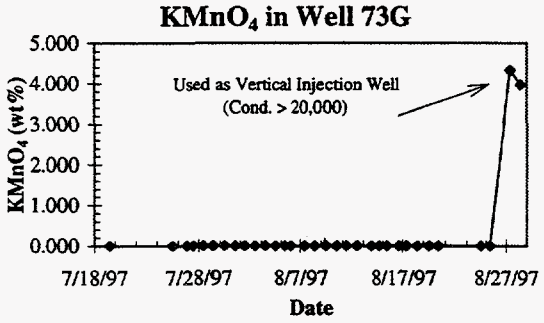
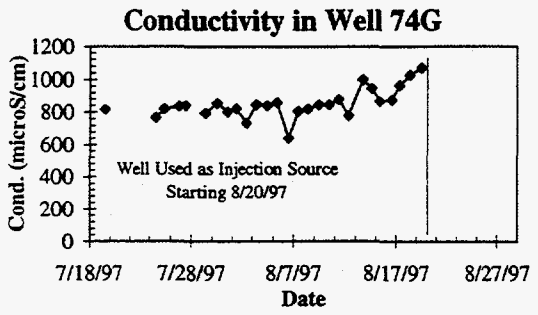
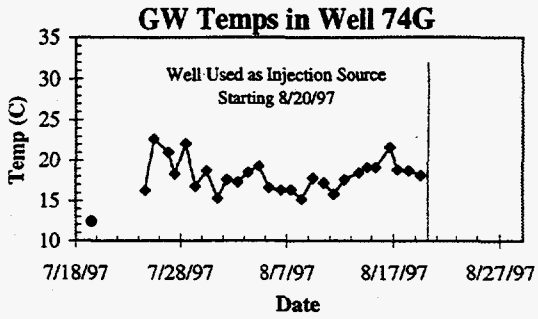


(e)

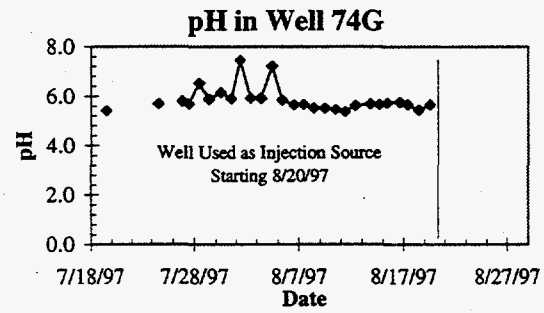
Fig. B-7 Values of (a) conductance, (b) temperature, (c) pH, (d) trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from Well 73G during the ISCOR field test.



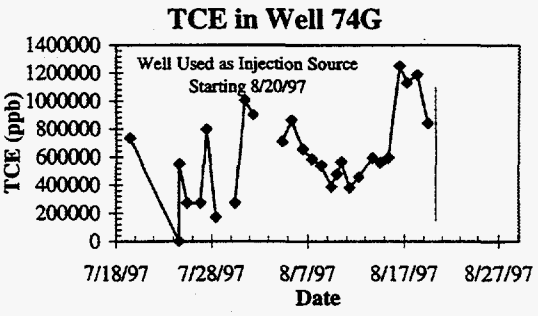
(a)



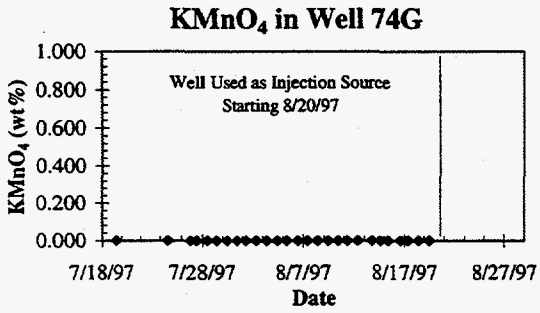
(b)



(c)



(d)



(e)

Fig. B-8 Values of (a) conductance, (b) temperature, (c) pH, (d) trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from Well 74G during the ISCOR field test.

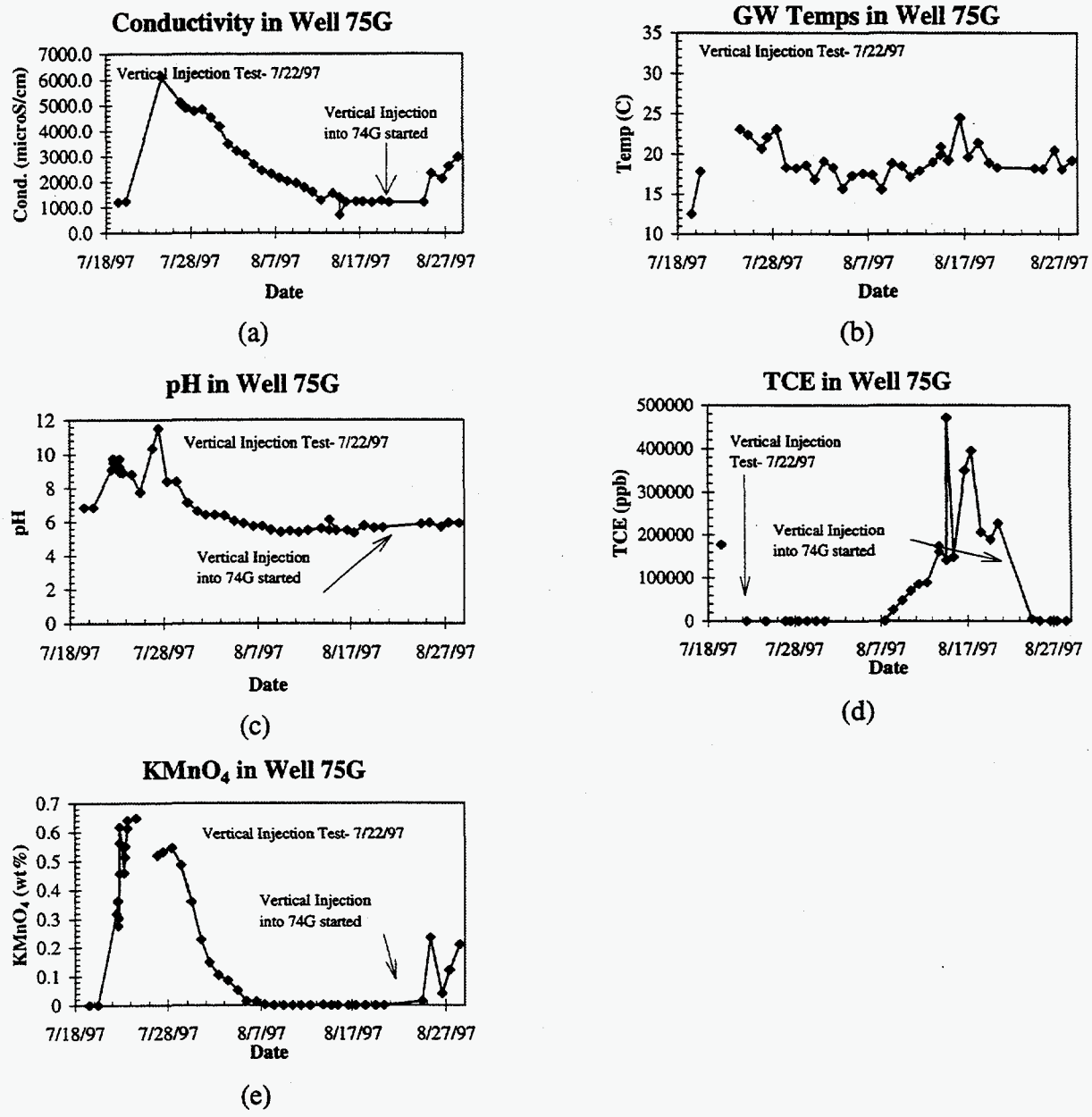
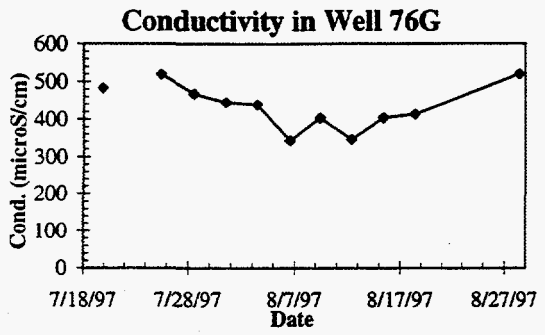
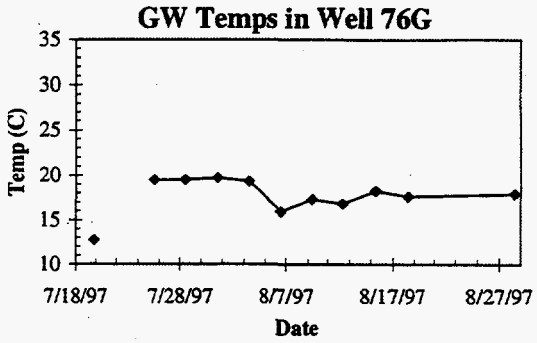


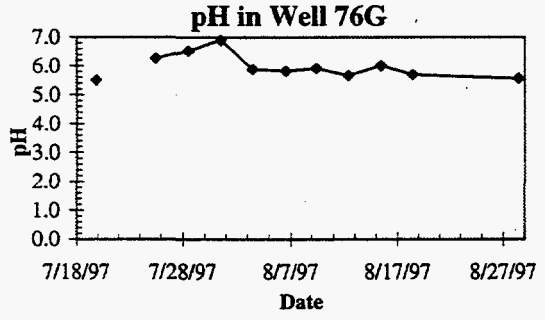
Fig. B-9 Values of (a) conductance, (b) temperature, (c) pH, (d) trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from Well 75G during the ISCOR field test.



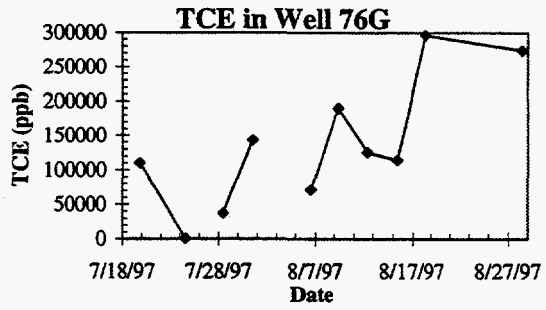
(a)



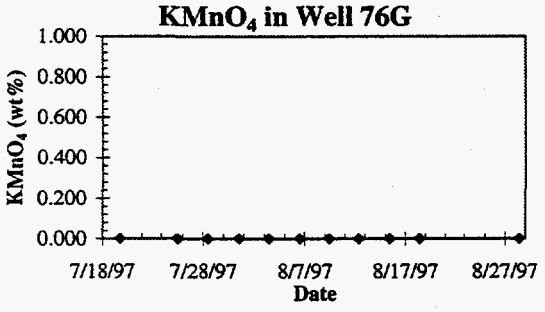
(b)



(c)



(d)



(e)

Fig. B-10 Values of (a) conductance, (b) temperature, (c) pH, (d) trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from Well 76G during the ISCOR field test.

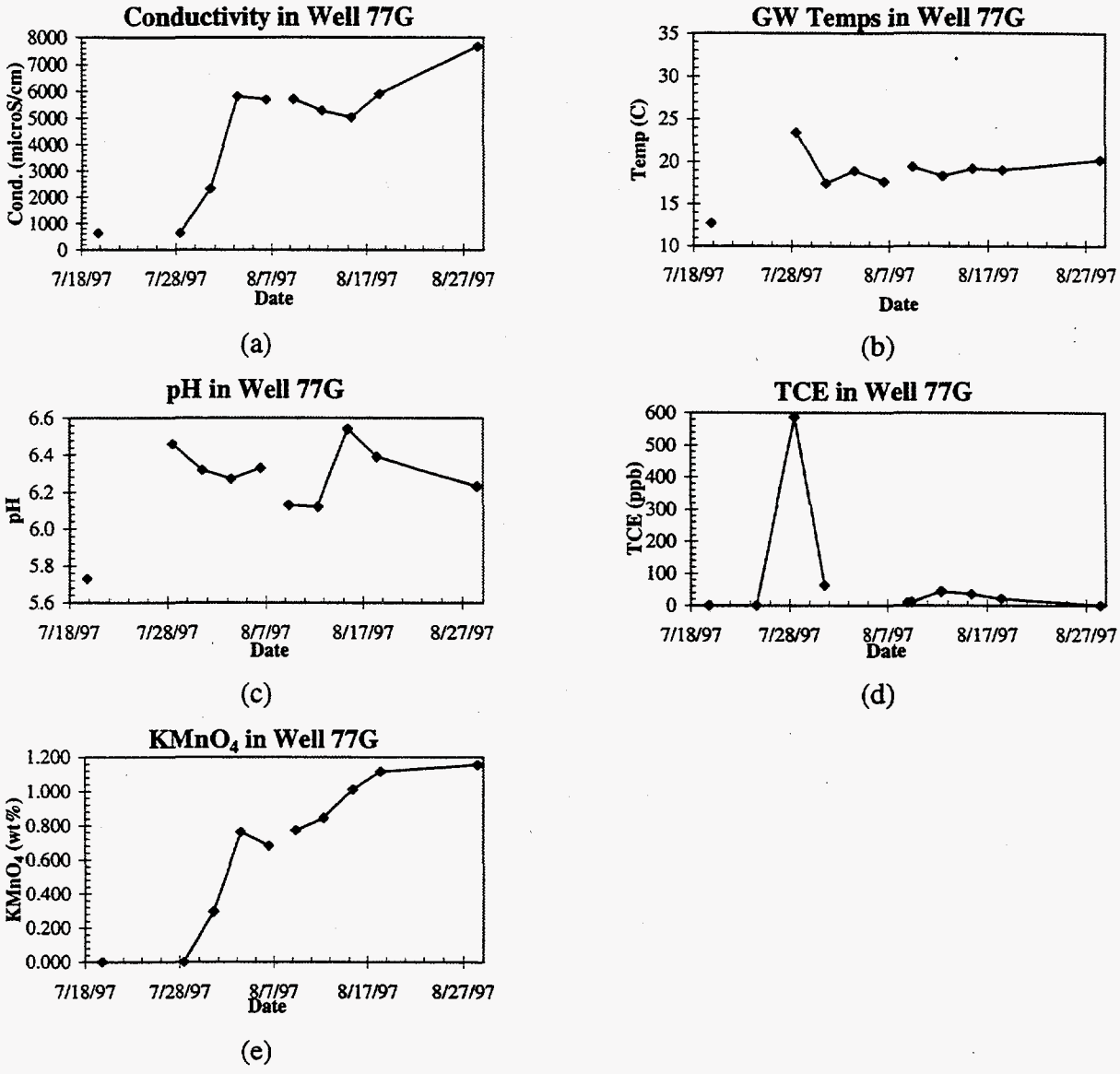
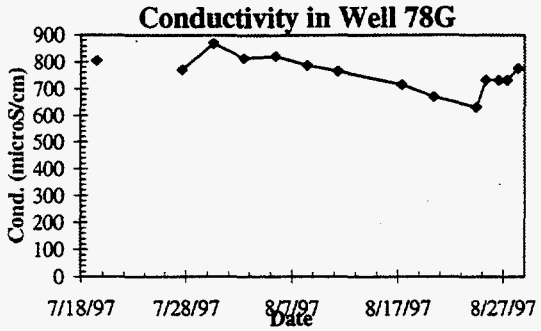
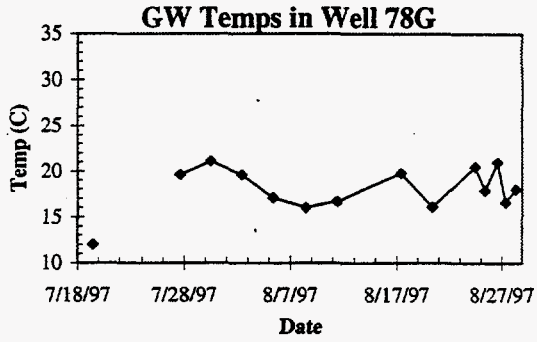


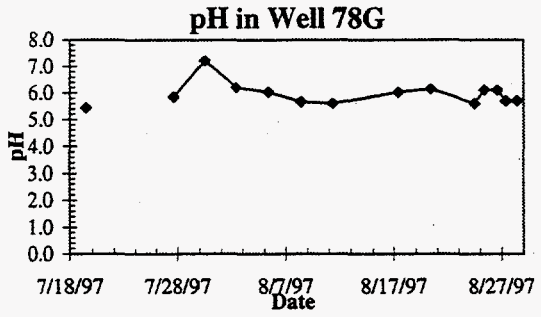
Fig. B-11 Values of (a) conductance, (b) temperature, (c) pH, (d) trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from Well 77G during the ISCOR field test.



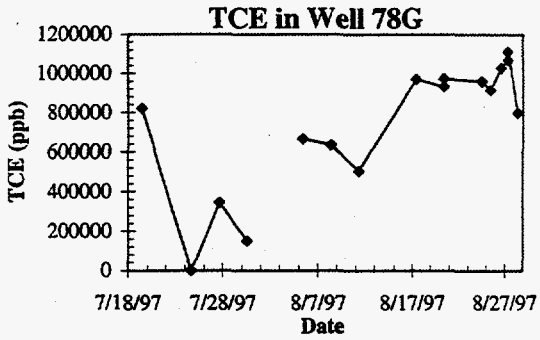
(a)



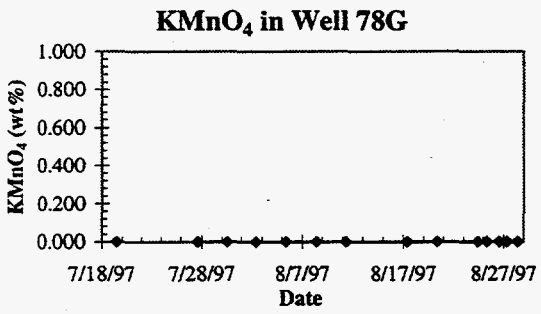
(b)



(c)

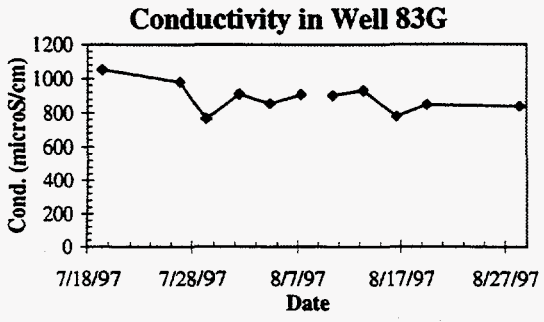


(d)

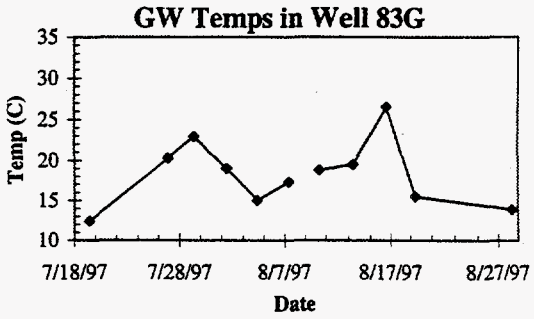


(e)

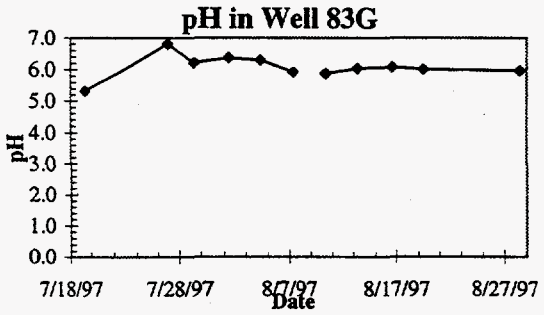
Fig. B-12 Values of (a) conductance, (b) temperature, (c) pH, (d) trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from Well 78G during the ISCOR field test.



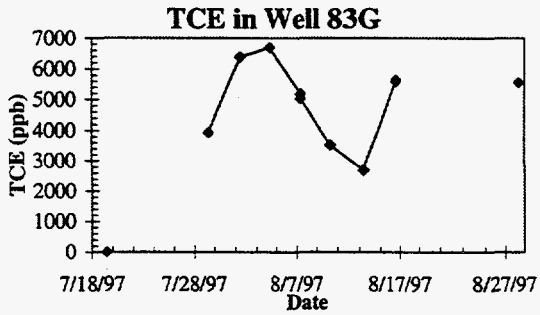
(a)



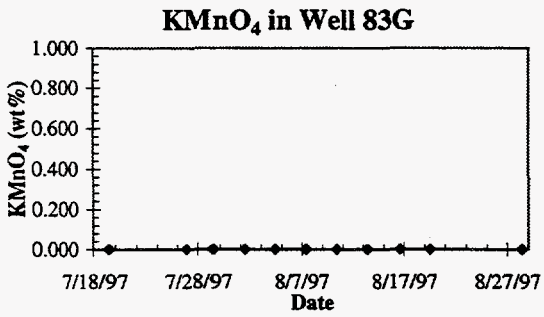
(b)



(c)

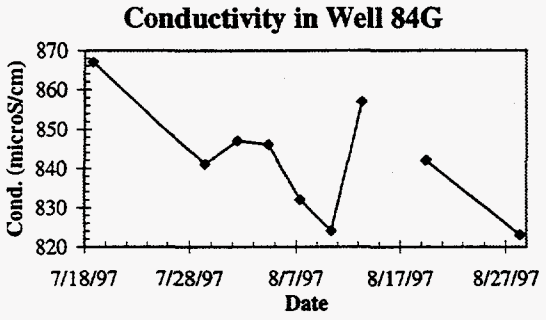


(d)

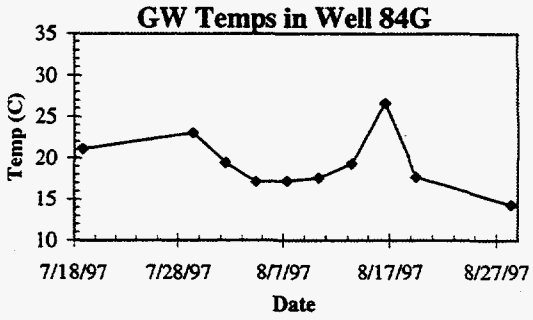


(e)

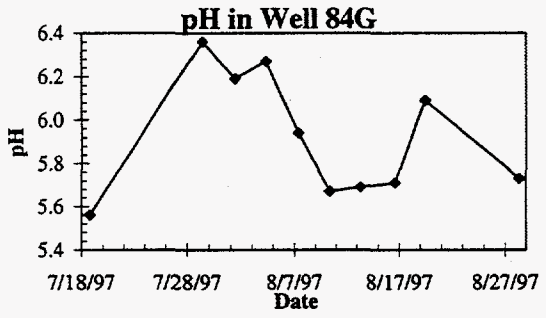
Fig. B-13 Values of (a) conductance, (b) temperature, (c) pH, (d) trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from Well 83G during the ISCOR field test.



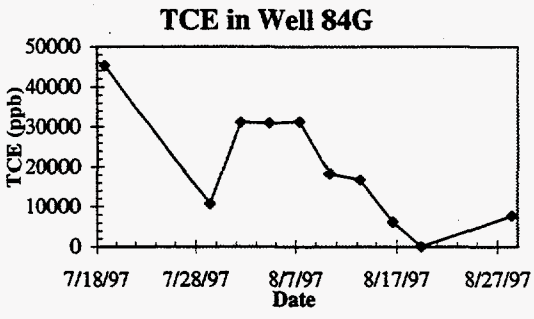
(a)



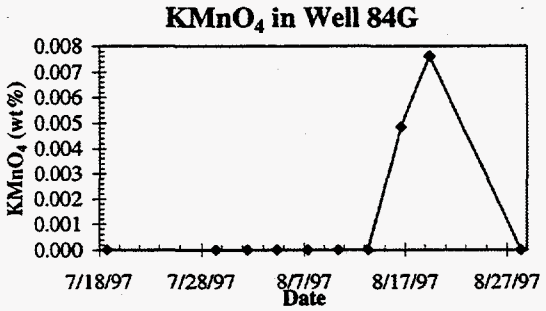
(b)



(c)

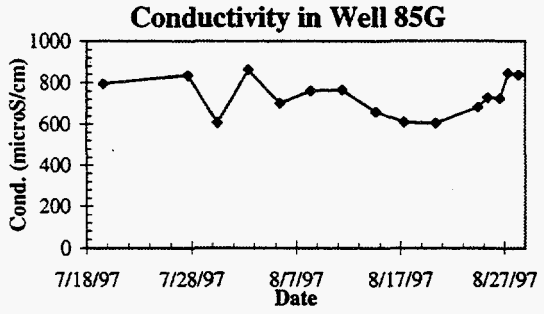


(d)

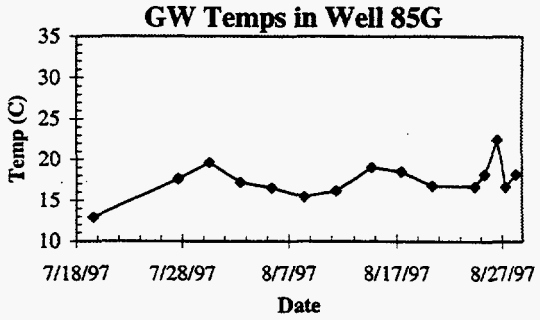


(e)

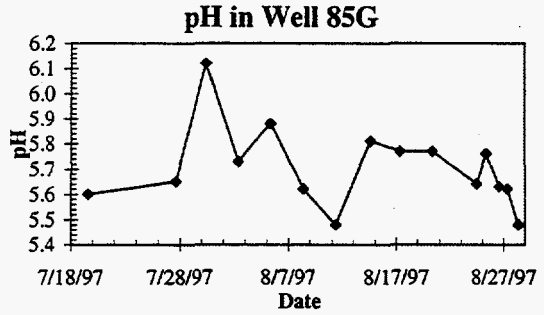
Fig. B-14 Values of (a) conductance, (b) temperature, (c) pH, (d) trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from Well 84G during the ISCOR field test.



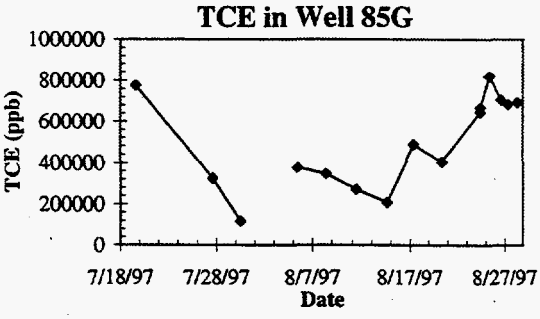
(a)



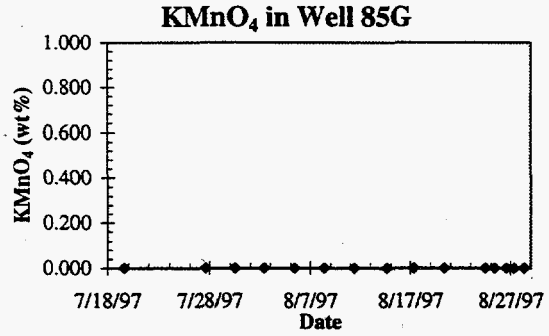
(b)



(c)

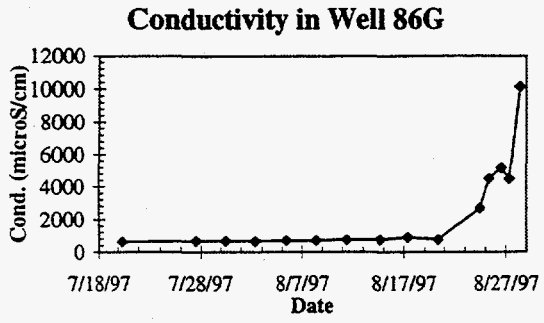


(d)

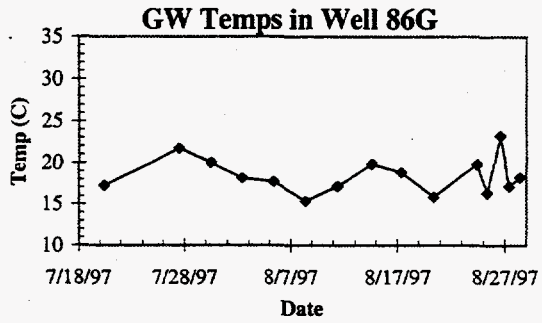


(e)

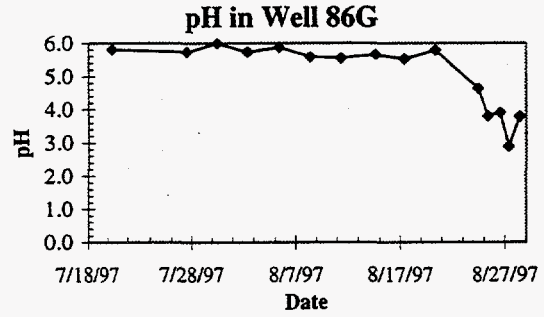
Fig. B-15 Values of (a) conductance, (b) temperature, (c) pH, (d) trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from Well 85G during the ISCOR field test.



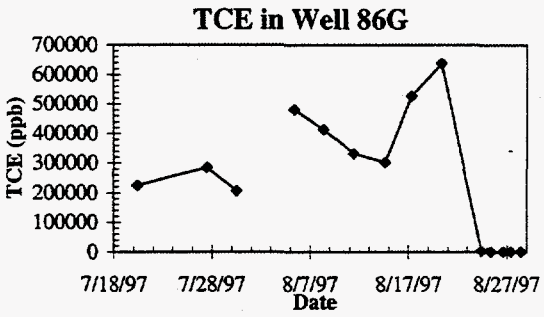
(a)



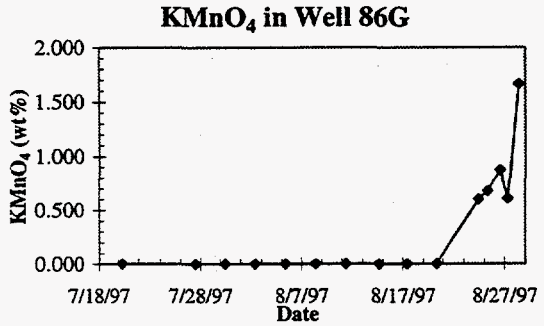
(b)



(c)

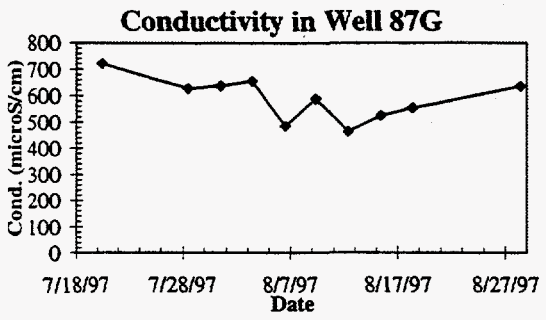


(d)

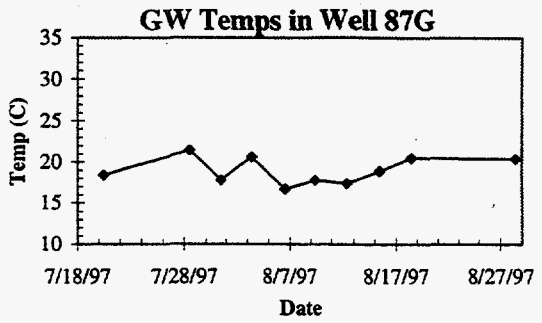


(e)

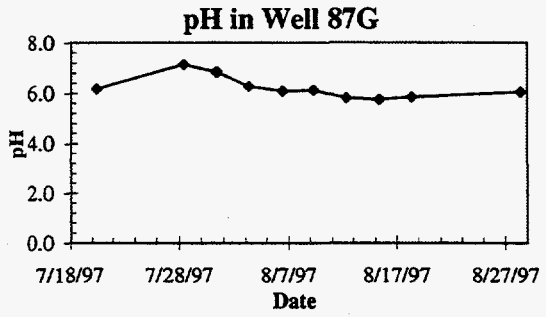
Fig. B-16 Values of (a) conductance, (b) temperature, (c) pH, (d) trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from Well 86G during the ISCOR field test.



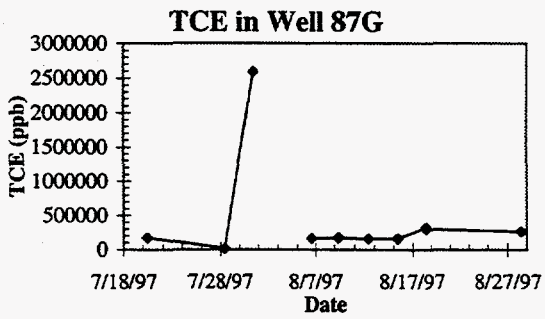
(a)



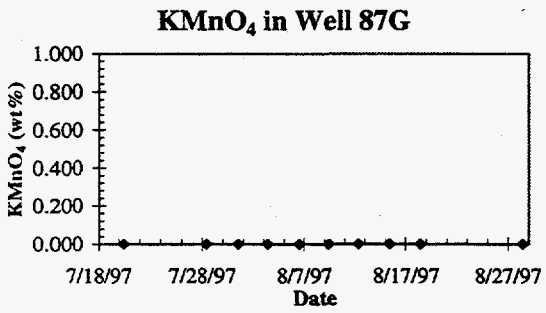
(b)



(c)

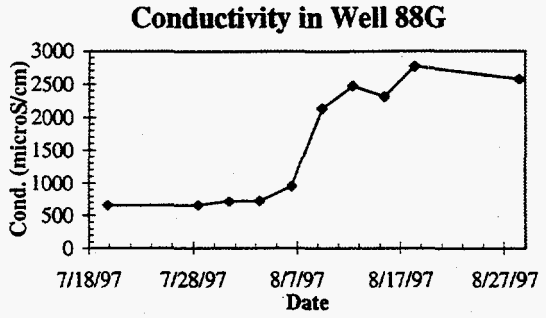


(d)

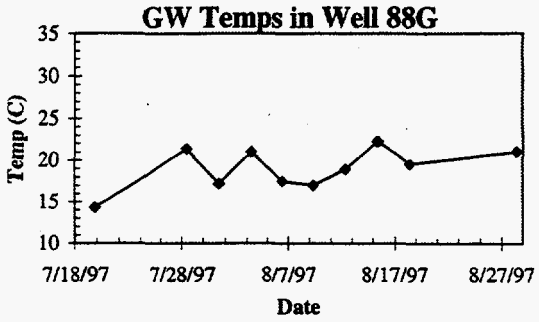


(e)

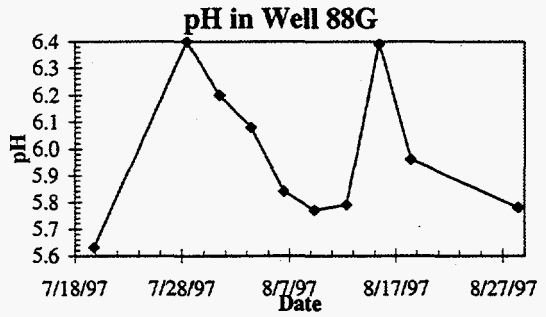
Fig. B-17 Values of (a) conductance, (b) temperature, (c) pH, (d) trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from Well 87G during the ISCOR field test.



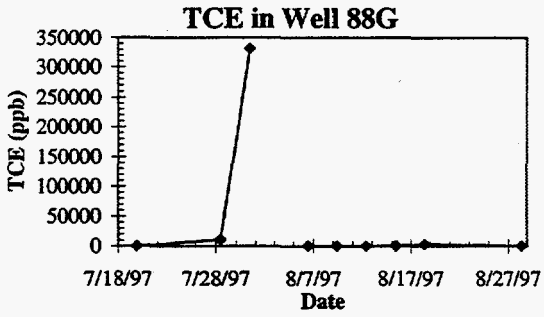
(a)



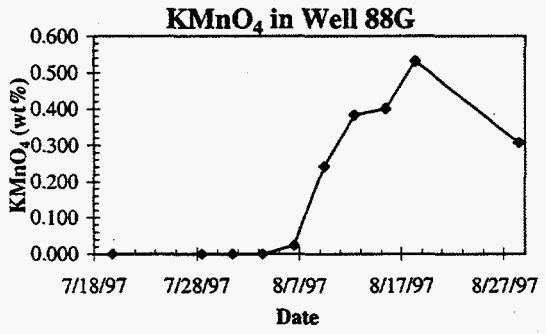
(b)



(c)



(d)



(e)

Fig. B-18 Values of (a) conductance, (b) temperature, (c) pH, (d) trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from Well 88G during the ISCOR field test.

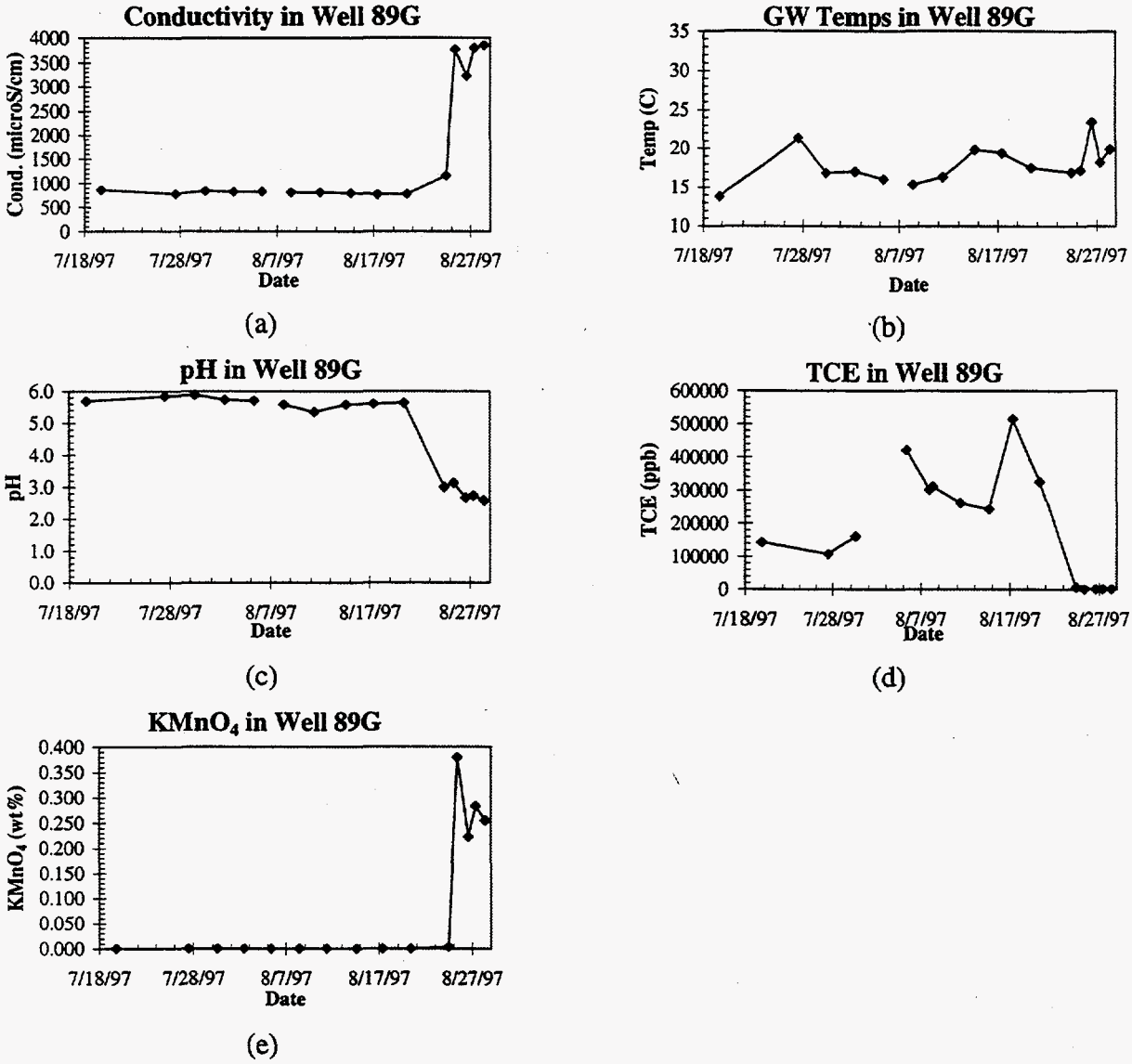
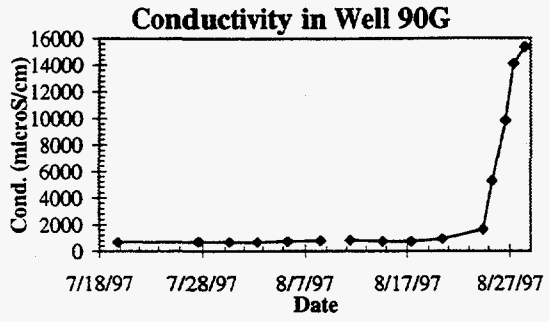
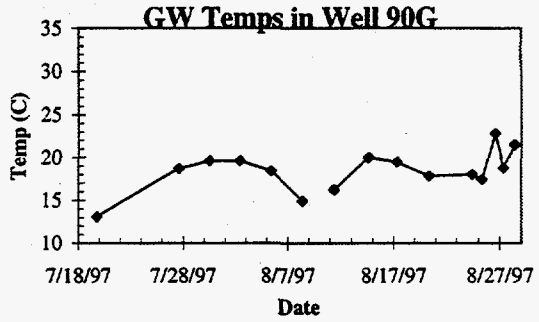


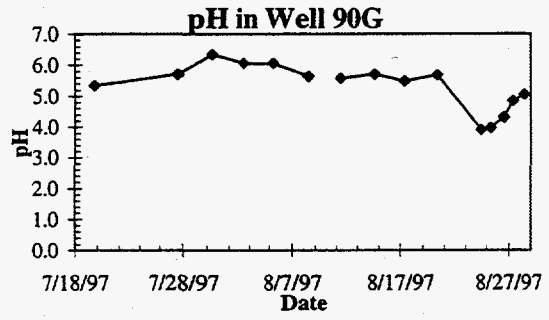
Fig. B-19 Values of (a) conductance, (b) temperature, (c) pH, (d) trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from Well 89G during the ISCOR field test.



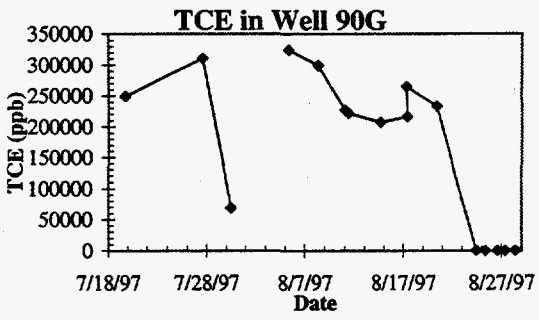
(a)



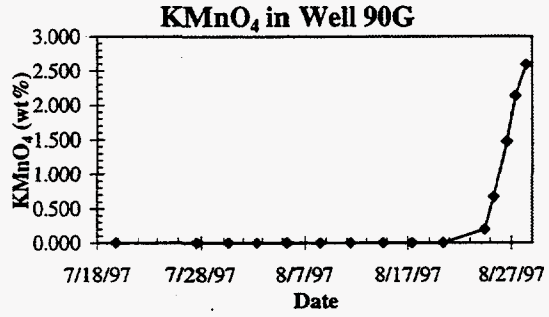
(b)



(c)

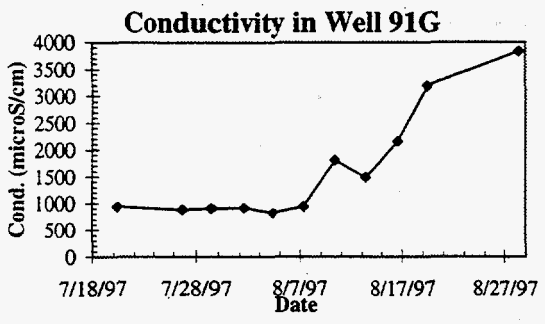


(d)

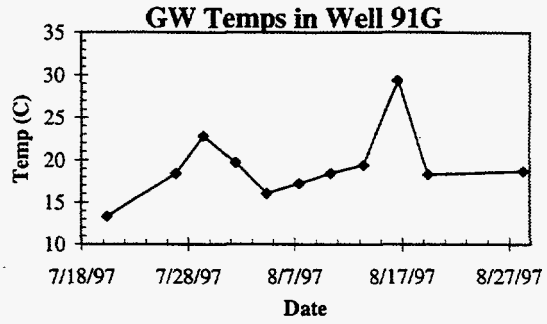


(e)

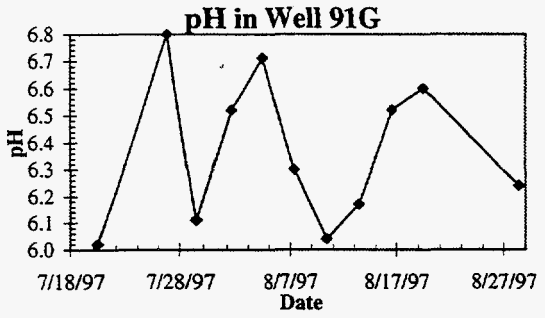
Fig. B-20 Values of (a) conductance, (b) temperature, (c) pH, (d) trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from Well 90G during the ISCOR field test.



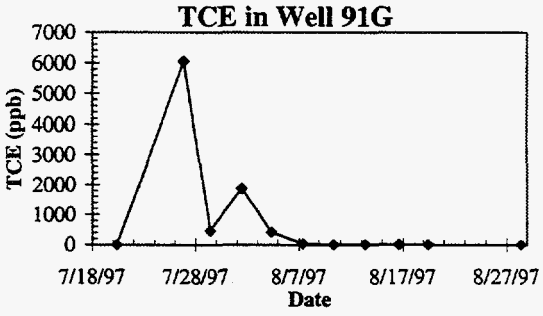
(a)



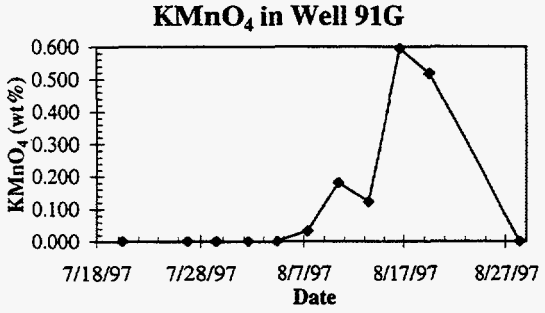
(b)



(c)

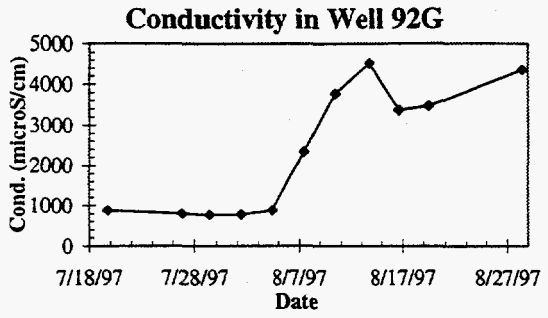


(d)

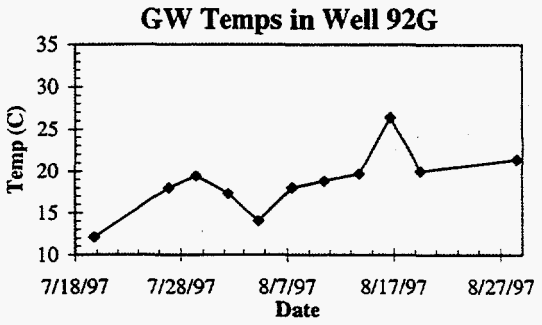


(e)

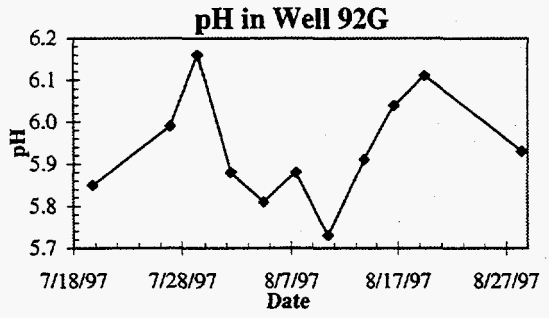
Fig. B-21 Values of (a) conductance, (b) temperature, (c) pH, (d) trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from Well 91G during the ISCOR field test.



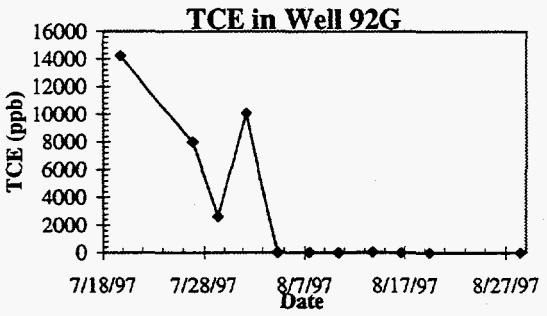
(a)



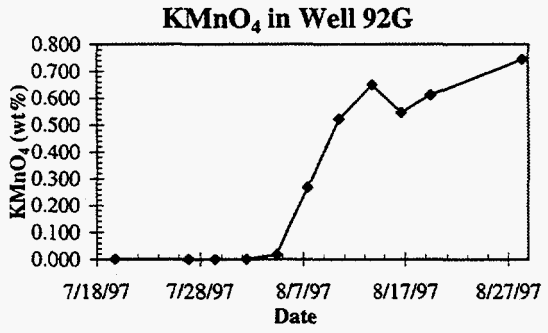
(b)



(c)

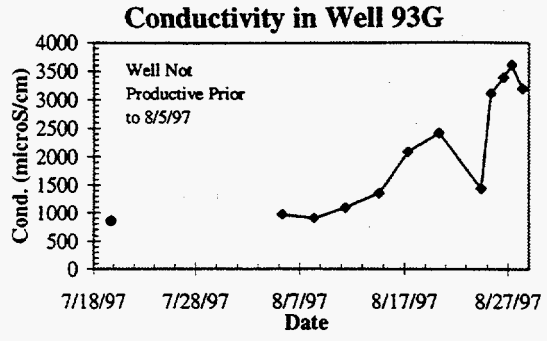


(d)

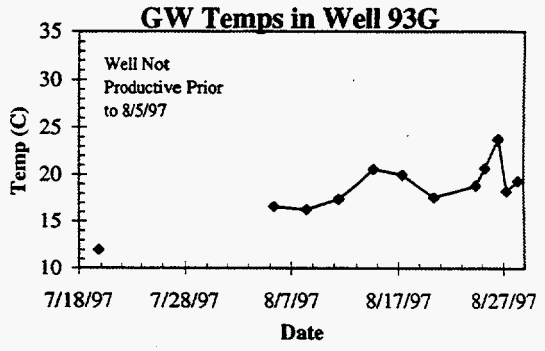


(e)

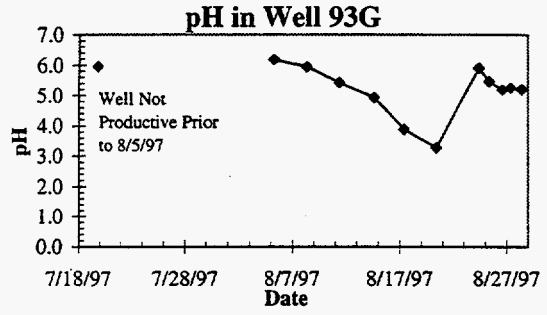
Fig. B-22 Values of (a) conductance, (b) temperature, (c) pH, (d) trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from Well 92G during the ISCOR field test.



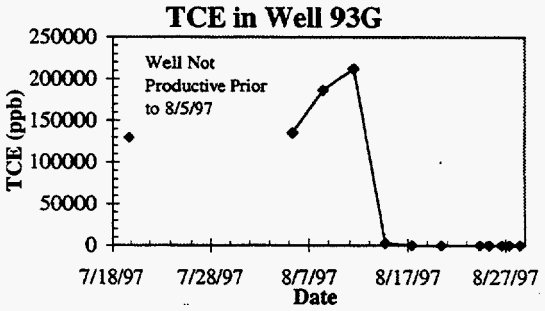
(a)



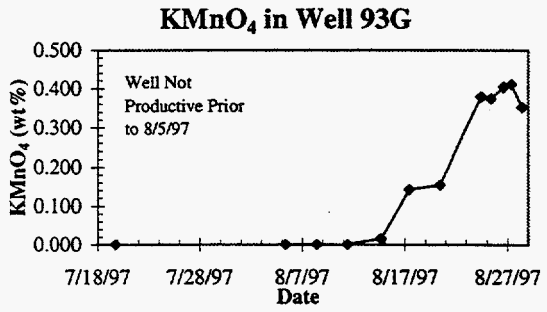
(b)



(c)

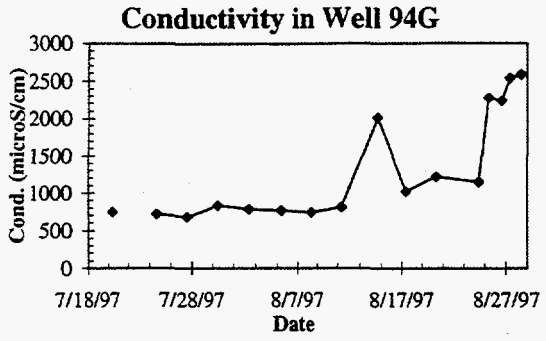


(d)

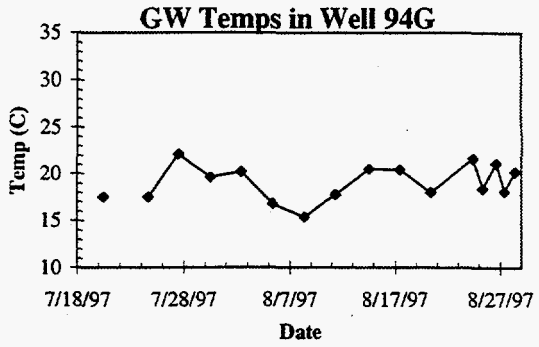


(e)

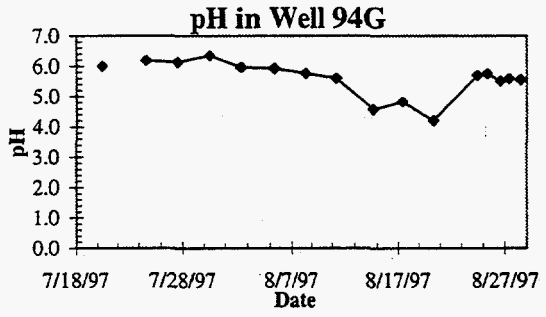
Fig. B-23 Values of (a) conductance, (b) temperature, (c) pH, (d) trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from Well 93G during the ISCOR field test.



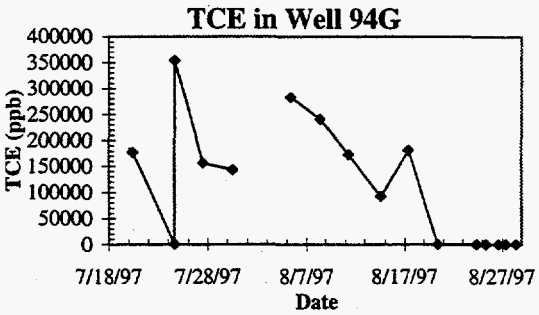
(a)



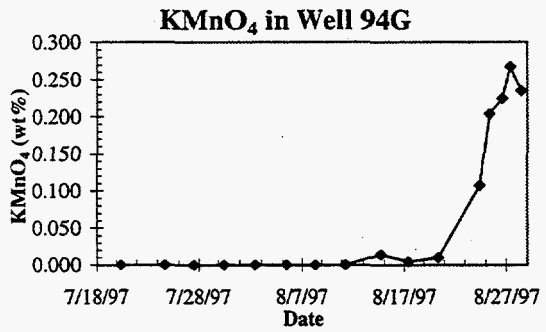
(b)



(c)



(d)



(e)

Fig. B-24 Values of (a) conductance, (b) temperature, (c) pH, (d) trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from Well 94G during the ISCOR field test.

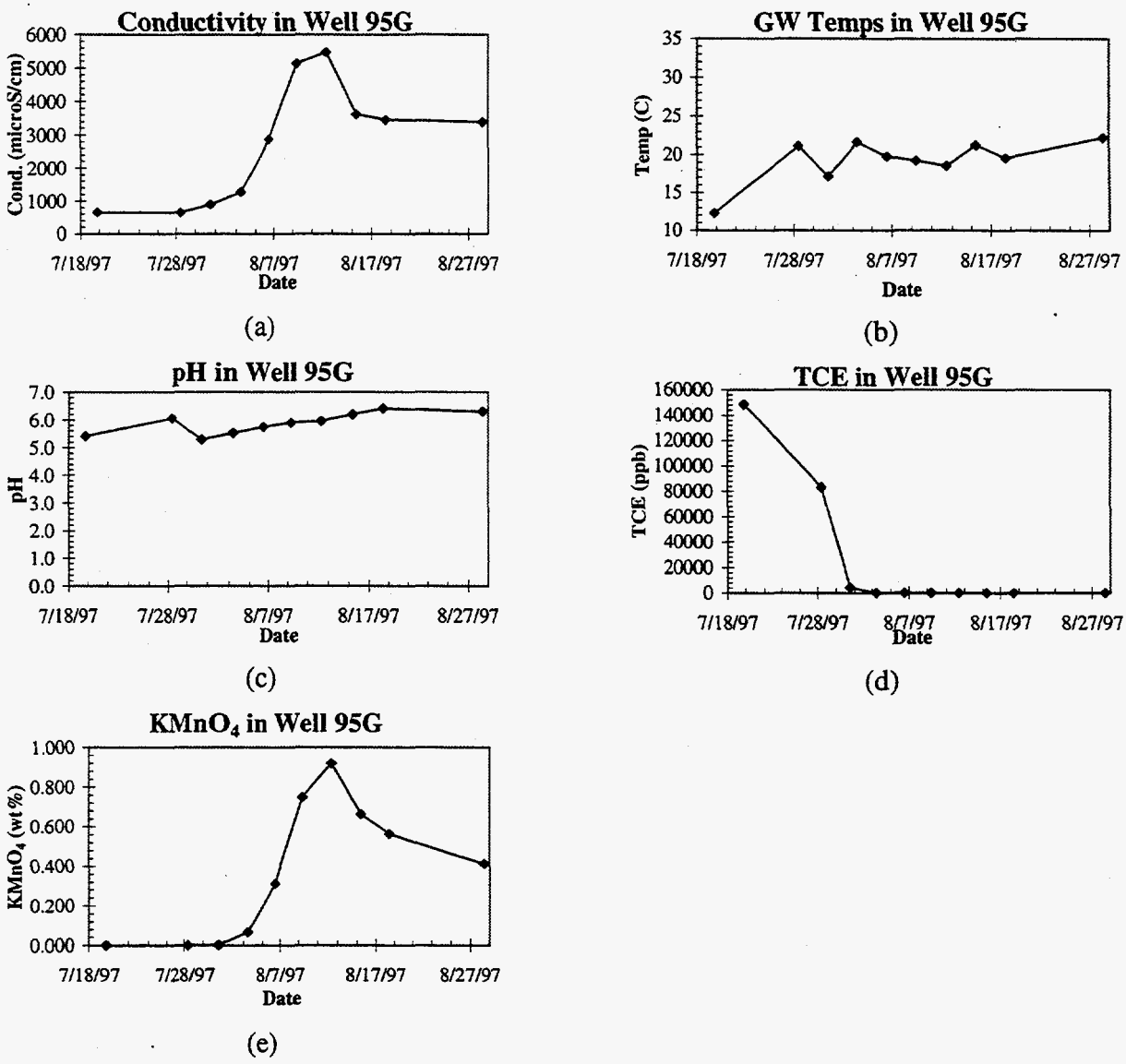
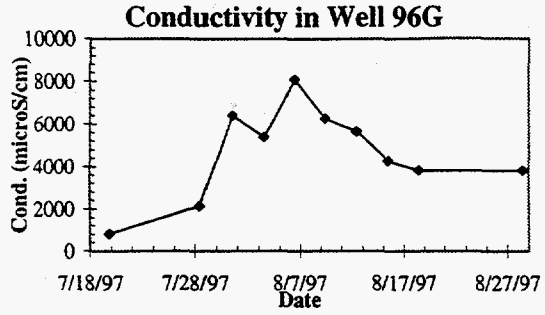
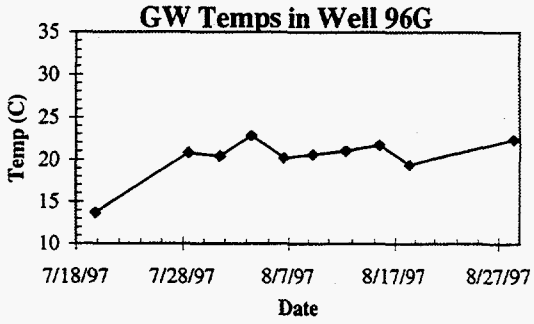


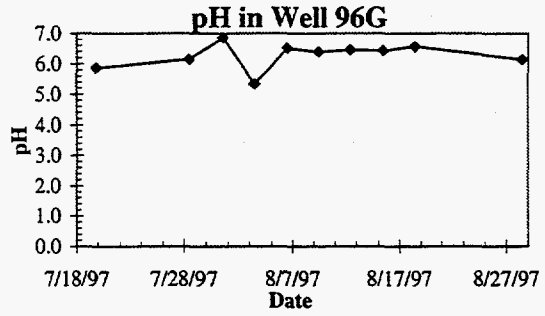
Fig. B-25 Values of (a) conductance, (b) temperature, (c) pH, (d) trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from Well 95G during the ISCOR field test.



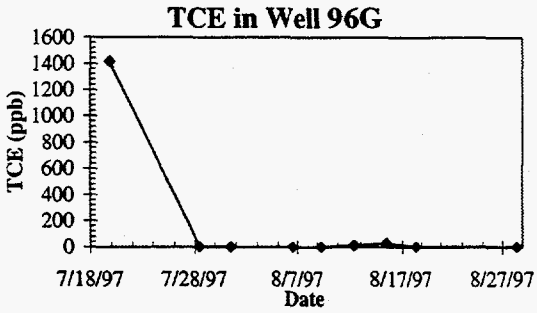
(a)



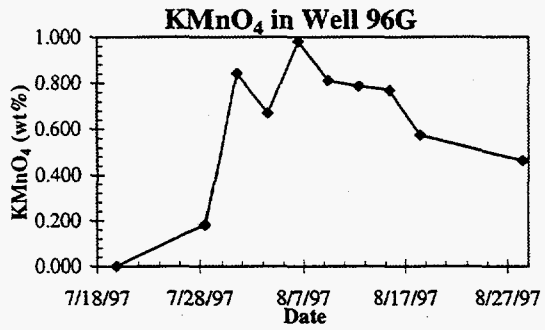
(b)



(c)

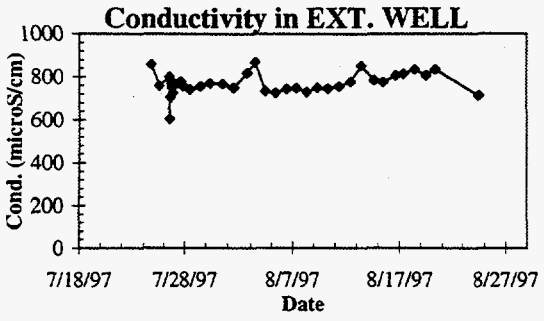


(d)

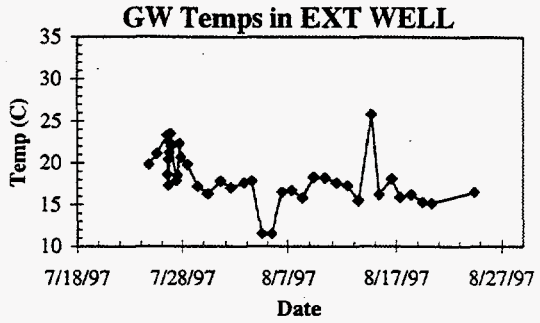


(e)

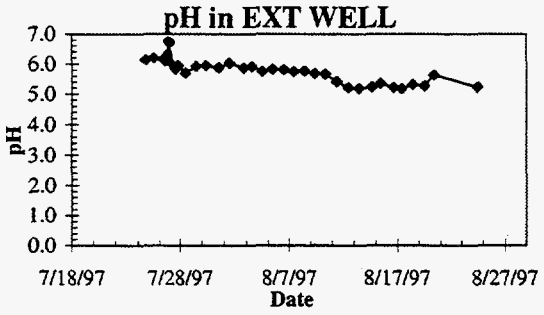
Fig. B-26 Values of (a) conductance, (b) temperature, (c) pH, (d) trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from Well 96G during the ISCOR field test.



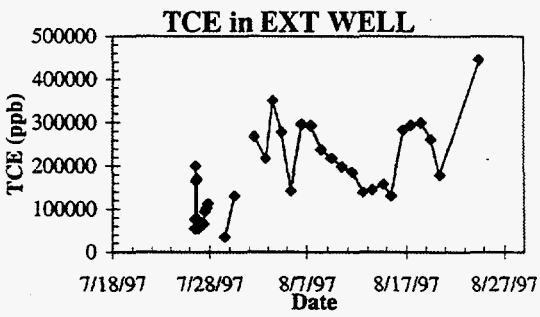
(a)



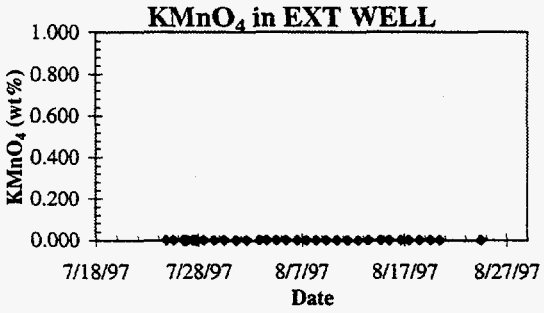
(b)



(c)

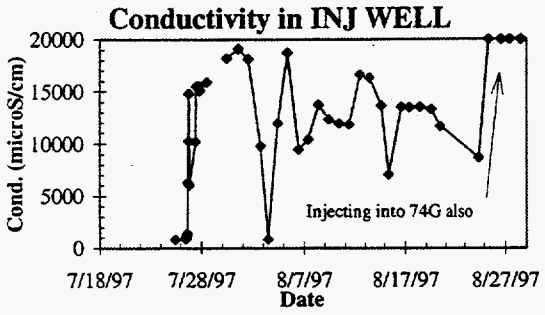


(d)

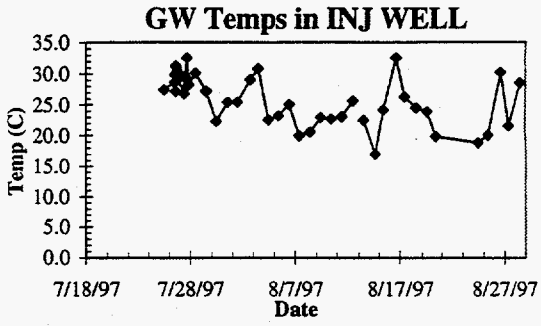


(e)

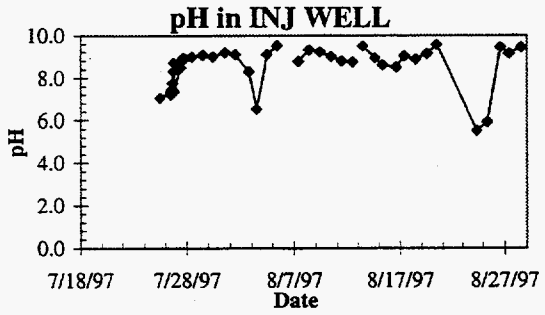
Fig. B-27 Values of (a) conductance, (b) temperature, (c) pH, (d) Trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from the horizontal extraction well during the ISCOR field test.



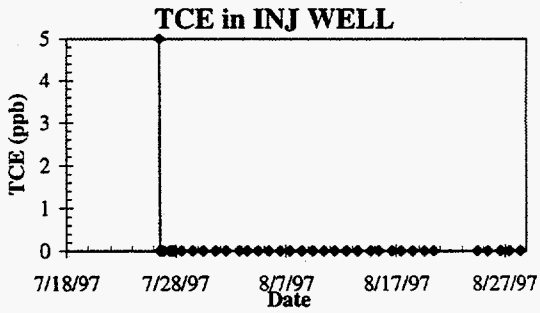
(a)



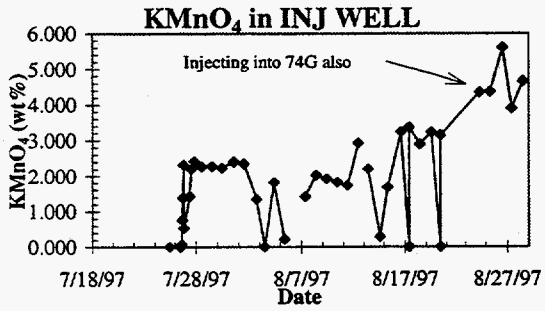
(b)



(c)



(d)



(e)

Fig. B-28 Values of (a) conductance, (b) temperature, (c) pH, (d) Trichloroethylene, and (e) $KMnO_4$ in the groundwater samples collected from the horizontal injection well during the ISCOR field test.

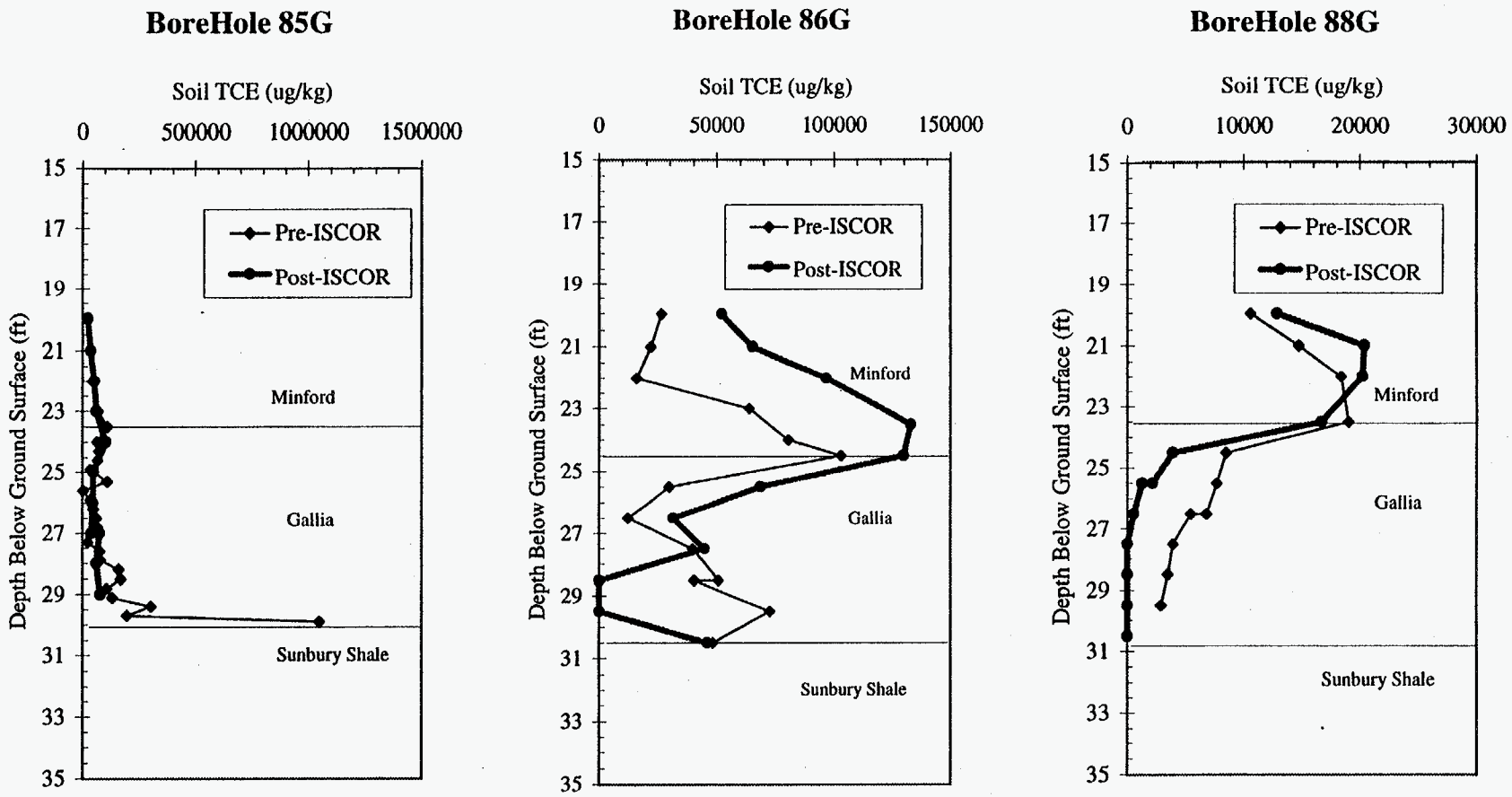


Fig. B-29 Pre- and post-treatment levels of trichloroethylene in soil samples collected from boreholes associated with monitoring wells 85G, 86G, and 88G.

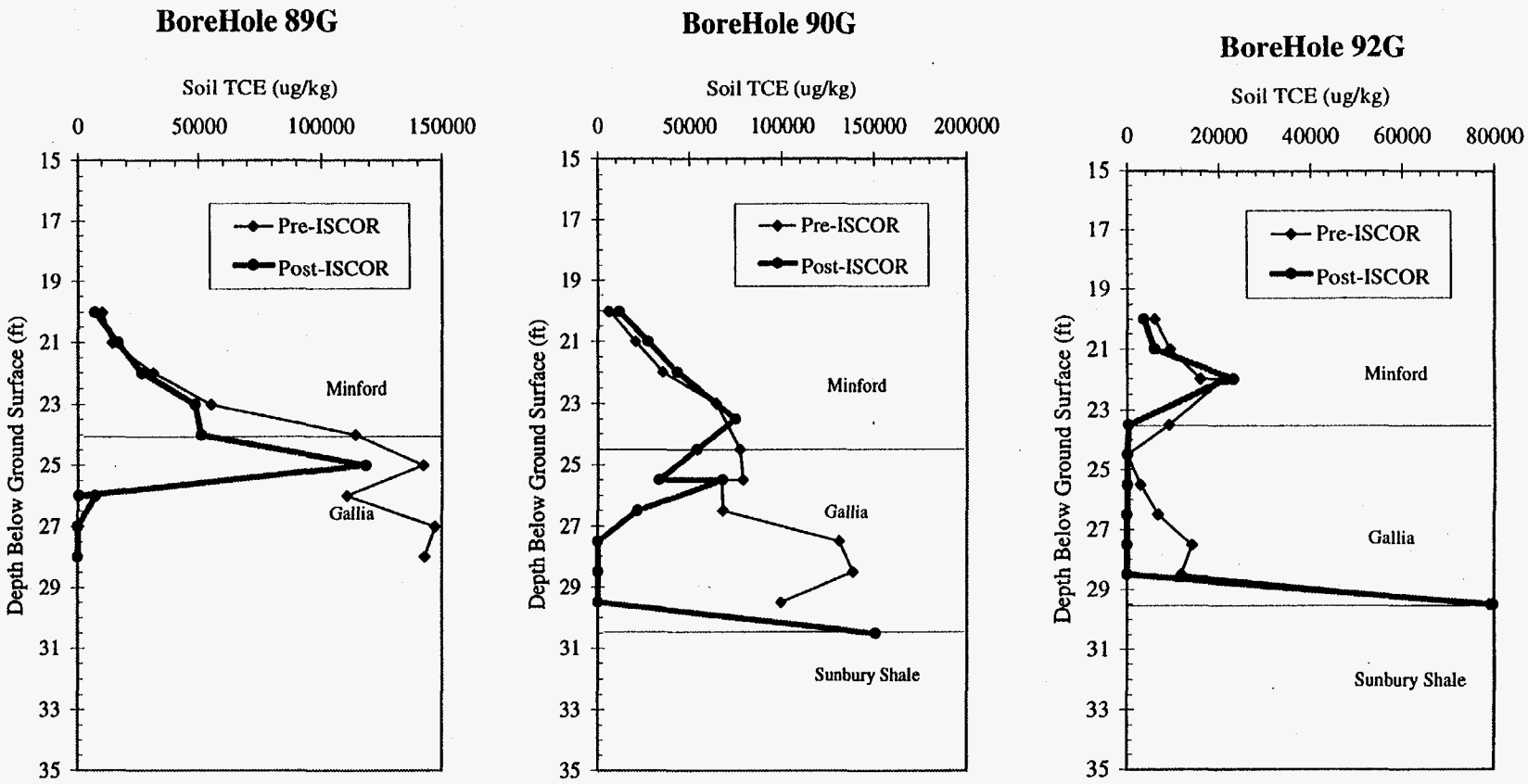


Fig. B-30 Pre- and post-treatment levels of trichloroethylene in soil samples collected from boreholes associated with monitoring wells 89G, 90G, and 92G.

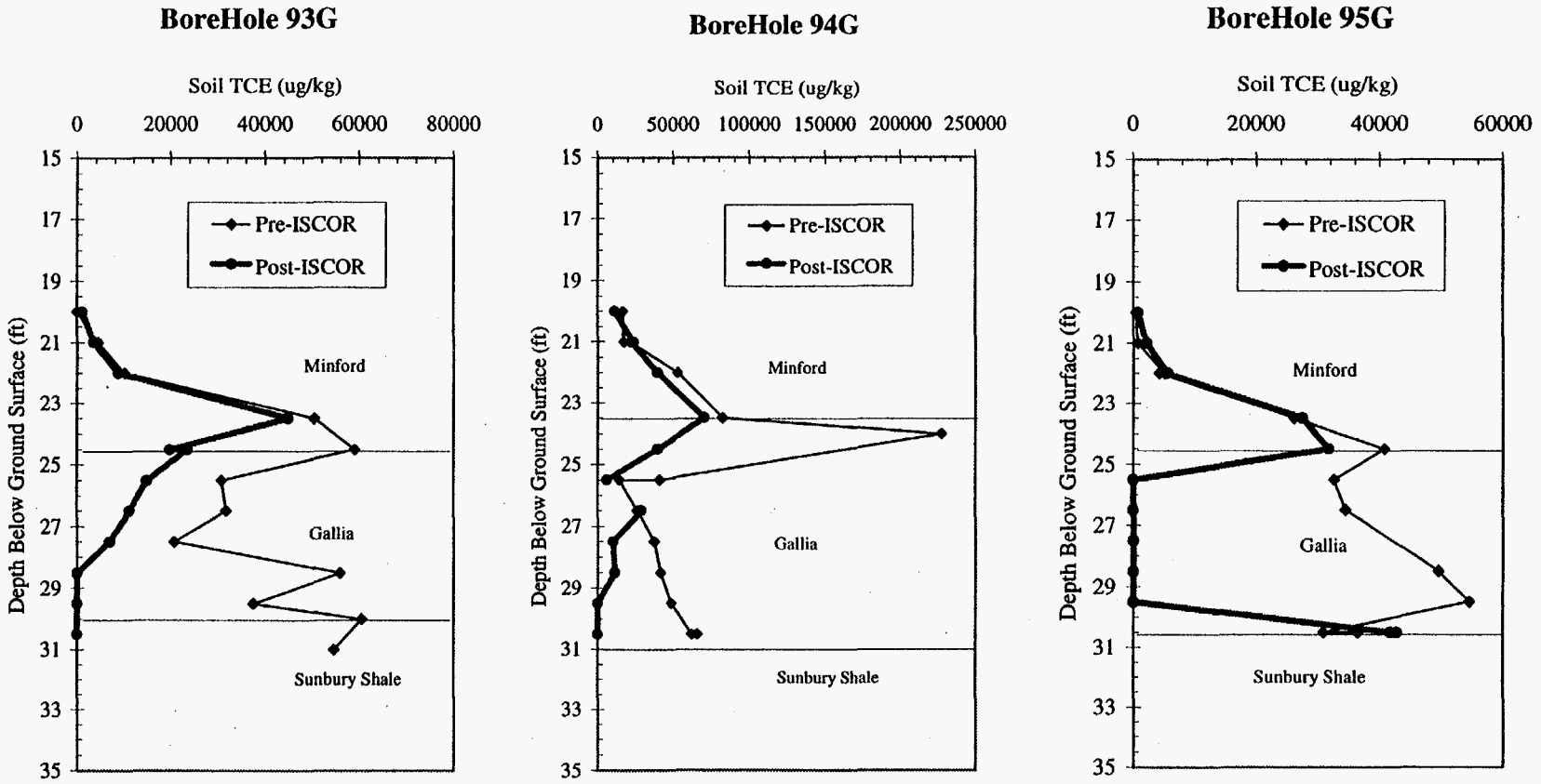


Fig. B-31 Pre- and post-treatment levels of trichloroethylene in soil samples collected from boreholes associated with monitoring wells 93G, 94G, and 95.

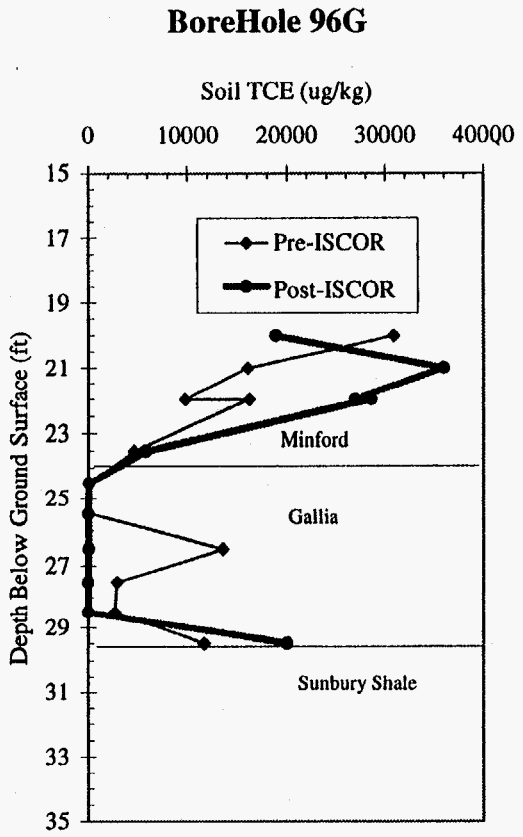


Fig. B-32 Pre- and post-treatment levels of trichloroethylene in soil samples collected from boreholes associated with monitoring well 96G.

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