DISTRIBUTION OF PETROLEUM HYDROCARBONS AND TOLUENE BIODEGRADATION, KNOX STREET FIRE PITS, FORT BRAGG, NORTH CAROLINA

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Prepared for the
Department of the Army
Fort Bragg, North Carolina

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Raleigh, North Carolina

1996

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

GORDON P. EATON, Director

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CONVERSION FACTORS, VERTICAL DATUM, AND TEMPERATURE

Multiply	By	To obtain
Length		
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
Flow		
foot per day (ft/d)	0.3048	meter per day
Hydraulic conductivity		
foot per day (ft/d)	0.3048	meter per day

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Temperature: In this report temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by the following equation: °F = 1.8 (°C) + 32

Biodegradation rate constant: In this report the biodegradation rate constant is expressed in units of percent of compound degraded per day (%/d). Because percent is dimensionless, this reduces to units of inverse days (d^{-1}).

$^{14}CO_2$: In this report $^{14}CO_2$ refers to carbon dioxide which is labeled with radioactive carbon.

^{14}C-toluene: In this report ^{14}C-toluene refers to toluene which is uniformly ring-labeled with radioactive carbon.

Abbreviations used in this report in addition to those shown above:

bls	below land surface
BTEX	benzene, toluene, ethylbenzene and xylene
GC	gas chromatograph
L	liter
mL	milliliter
moles/L	moles per liter
n	number of samples
ppm	part per million
r	correlation coefficient
TEX	toluene, ethylbenzene, and xylene
µg/L	microgram per liter
α	alpha

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ABSTRACT

An investigation was conducted at the Knox Street fire pits, Fort Bragg, North Carolina, to monitor the distribution of toluene, ethylbenzene, and xylene (TEX) in soil vapor, ground water, and ground-water/vapor to evaluate if total concentrations of TEX at the site are decreasing with time, and to quantify biodegradation rates of toluene in the unsaturated and saturated zones. Soil-vapor and ground-water samples were collected around the fire pits and ground-water/ vapor samples were collected along the ground-water discharge zone, Beaver Creek, on a monthly basis from June 1994 through June 1995. Concentrations of TEX compounds in these samples were determined with a field gas chromatograph. Laboratory experiments were performed on aquifer sediment samples to measure rates of toluene biodegradation by *in situ* microorganisms.

Based on field gas chromatographic analytical results, contamination levels of TEX compounds in both soil vapor and ground water appear to decrease downgradient of the fire-pit source area. During the 1-year study period, the observed temporal and spatial trends in soil vapor TEX concentrations appear to reflect differences in the distribution of TEX among solid, aqueous, and gaseous phases within fuel-contaminated soils in the unsaturated zone. Soil temperature and soil moisture are two important factors which influence the distribution of TEX compounds among the different phases. Because of the short period of data collection, it was not possible to distinguish between seasonal fluctuations in soil vapor TEX concentrations and an overall net decrease in TEX concentrations at the study site.

No seasonal trend was observed in total TEX concentrations for ground-water samples collected at the study site. Although the analytical results could not be used to determine if ground-water TEX concentrations decreased during the study at a specific location, the data were used to examine rate constants of toluene biodegradation. Based on ground-water toluene concentration data, a maximum rate constant for anaerobic biodegradation of toluene in the saturated zone was estimated to be as low as 0.002 d^{-1} or as high as 0.026 d^{-1}.

Based on analyses of ground-water/vapor samples, toluene was the principal TEX compound identified in ground water discharging to Beaver Creek. Observed decreases in ground-water/vapor toluene concentrations during the study period may reflect a decrease in source inputs, an increase in dilution caused by higher ground-water flow, and(or) removal by biological or other physical processes.

Rate constants of toluene anaerobic biodegradation determined by laboratory measurements illustrate a typical acclimation response of microorganisms to hydrocarbon contamination in sediments collected from the site. Toluene biodegradation rate constants derived from laboratory microcosm studies ranged from 0.001 to 0.027 d^{-1}, which is similar to the range of 0.002 to 0.026 d^{-1} for toluene biodegradation rate constants derived from ground-water analytical data. The close agreement of toluene biodegradation rate constants reported using both approaches offer strong evidence that toluene can be degraded at environmentally significant rates at the study site.

INTRODUCTION

The Knox Street fire pits at Fort Bragg, North Carolina (fig. 1), have been used by local fire-fighting personnel for training purposes. The fire pits were filled with petroleum fuel, ignited, and the resulting fire was extinguished by fire-fighting personnel. The burning of fuels at the fire-training pits has resulted in the release of petroleum products to adjacent soils.

The presence of petroleum hydrocarbons in soils surrounding the fire pits is a potentially serious environmental problem. Petroleum compounds in contaminated soils at the site could pose health risks to people who have incidental contact with the contaminated soil. The transport of soluble petroleum hydrocarbons, such as benzene, toluene, ethylbenzene and xylene (BTEX), away from fuel-contaminated soil at the fire pits also represents a potential environmental problem. Soluble petroleum hydrocarbons in the unsaturated zone can migrate into underlying ground water which can be transported considerable distances to a point of contact with humans and wildlife. Some soluble petroleum hydrocarbons, such as BTEX, are hazardous and could pose health risks to humans and wildlife who consume water contaminated with these compounds.

Hydrocarbon transport in ground water can be retarded by sorption to aquifer materials and by biodegradation from microbial organisms. If the rate of biodegradation is fast, relative to rates of contaminant release from the source area and rates of ground-water flow, contaminants might not be transported long distances (Chapelle and others, 1996). Conversely, if rates of biodegradation are slow relative to rates of contaminant release and ground-water flow, and sorption of contaminants to aquifer material is negligible, then the contaminants can be relatively mobile.

Although information about the site is sufficient to document hydrocarbon contamination in unsaturated soils and rates of ground-water flow, there is no information available on rates of microbial degradation of soluble petroleum compounds at the site. In addition, there is insufficient information available to document the presence of soluble petroleum compounds in shallow ground water around the site. The lack of this information is a significant obstacle to designing and implementing potential cleanup strategies at the site.

In 1994, the U.S. Geological Survey began a study at the Knox Street fire pits to examine hydrocarbon contamination of soils and shallow ground water, as well as to examine rates of soluble hydrocarbon biodegradation. The main objectives of the study were (1) to monitor BTEX concentrations in soil vapor, ground water, and ground-water/vapor to determine if concentrations of these compounds at the site are decreasing with time, and (2) to quantify biodegradation rate constants of toluene in the unsaturated and saturated zones. However, benzene could not be rigorously identified or quantified in media sampled during this investigation because of analytical difficulties.

Purpose and Scope

This report describes the results of the study conducted at the Knox Street fire pits, Fort Bragg, North Carolina, to determine the distribution of TEX compounds in the environment, and to evaluate toluene biodegradation rate constants. Field studies were used to determine if concentrations of TEX compounds at the site are decreasing with time, and laboratory measurements were used to determine biodegradation rate constants of toluene. If TEX concentrations decrease with time and these changes can be attributed to biological processes, then toluene biodegradation rate constants can be estimated using field data. In this way, the range of *in situ* toluene biodegradation rate constants can be estimated by comparing field-derived rate constants to laboratory-derived rate constants.

Soil-vapor and ground-water sample extraction points were installed at six locations around the fire pits. Samples of ground-water/vapor were collected at seven locations adjacent to Beaver Creek. The term ground-water/vapor is used to define vapor samples which are collected within the water-table aquifer adjacent to Beaver Creek. Soil-vapor, ground-water, and ground-water/vapor samples were collected monthly from June 1994 to June 1995. Concentrations of TEX in soil-vapor, ground-water, and ground-water/vapor samples were determined with a field portable gas chromatograph (GC).

In March 1995, soil borings were augered at two locations between the fire pits and Beaver Creek to collect soil samples from the unsaturated and saturated zones to examine toluene biodegradation. Rate constants of toluene biodegradation in fuel-contaminated soils were determined by laboratory experiments.

HARNETT
COUNTY

35°15'   MOORE
              COUNTY   Pope Air Force Spring
                             Base   Lake
                                                    Knox Street
   Southern   Fire Pits
   Pines ○

                    Fort Bragg Military
                    Reservation
                                                                    SAMPSON
                                                                    COUNTY

                                             CUMBERLAND
                                    Fayetteville   COUNTY

35°   Raeford ○   Rockfish
                                          Creek
              HOKE
   SCOTLAND   COUNTY
   COUNTY   ROBESON
                                 COUNTY

         0   10   20   30 MILES
         |----------|----------|----------|
         0   10   20   30 KILOMETERS

PIEDMONT   COASTAL PLAIN

BLUE RIDGE
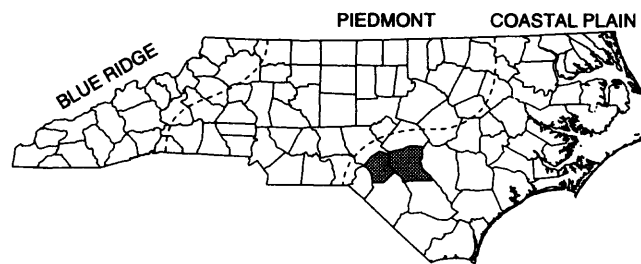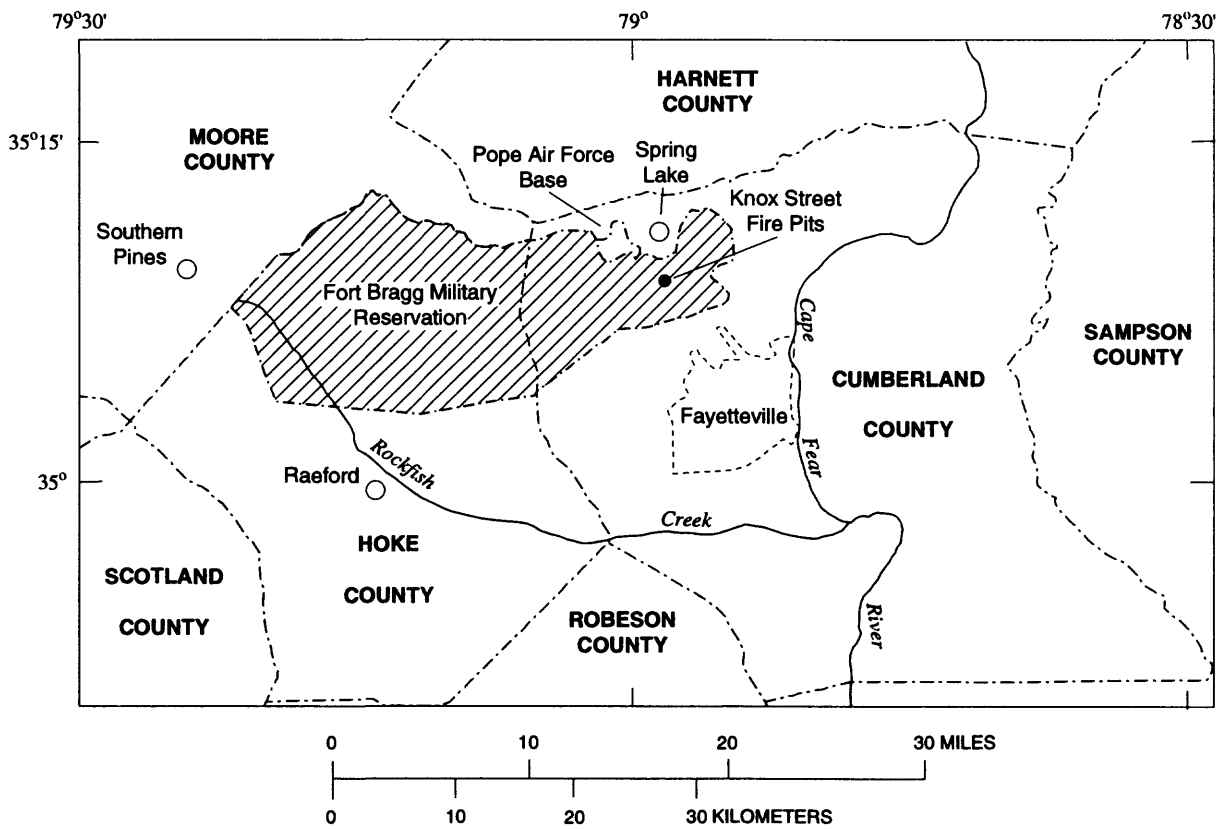
LOCATION OF STUDY AREA IN NORTH CAROLINA

Figure 1.--Location of Fort Bragg, North Carolina (modified from Kessler and others, 1996).

Knox Street Fire Pits

The Knox Street fire pits, hereafter referred to as the fire pits, are located southeast of the intersection of Honeycutt Road and Knox Street at Fort Bragg, North Carolina (fig. 2). The fire-pit study site originally consisted of a sand-lined shallow basin which was constructed in 1966. This shallow basin was located in the area currently occupied by fire pit 1 (fig. 2). For fire-training purposes, the shallow basin was filled with water, and fuel was added, ignited, and extinguished.

The fire pits were redesigned in 1978. A concrete-lined pit (fire pit 1) was constructed over the area previously occupied by the sand-lined basin. Additionally, a second concrete-lined pit (fire pit 2) was constructed immediately south of this area (fig. 2). These two pits are each approximately 70 feet (ft) by 70 ft wide. A 1/2-ft high concrete curb surrounds each pit on all sides. Drains were installed in the center of each fire pit to discharge wastes into a nearby oil/water separator following fire extinguishing activities. At times, unburned fuel was released over the small curb to adjacent soils during fire-training activities. The fire pits were closed to fire-training activities in the fall of 1993.

Hydrologic Setting

The fire pits are located on top of an abandoned landfill which is approximately 10 acres in size. This landfill was active from 1961 to 1966. In the vicinity of the fire pits, the top of the buried landfill materials generally occurs between 2 to 5 ft below land surface (bls). Landfill debris have been encountered at depths of 10 to 11 ft bls. Buried landfill materials observed at the fire pits include pieces of metal, glass, cans, cardboard, and wood. A gravel road encircles both of the fire pits. Beneath the gravel, landfill cover material consists of a fine- to medium-grained silty sand which contains small amounts of clay.

Hydrogeologic units in the vicinity of the fire pits include a shallow aquifer that contains the water table, the Cape Fear confining unit, and the Cape Fear aquifer. The shallow aquifer is about 30 ft thick, and consists of fine to medium sand mixed with clay and silt. The water table is in this aquifer and is generally 7 to 9 ft bls. The Cape Fear confining unit is laterally continuous throughout the area, and consists of clay and silty clay that is at least 9 ft thick. This unit serves to retard the movement of ground water between the shallow aquifer and the Cape Fear aquifer. Immediately below the confining unit is the Cape Fear aquifer, which extends about 155 ft bls to consolidated basement rocks. This aquifer is composed primarily of fine, silty sand with laterally discontinuous beds of clay and silt.

A water-table contour map of the study area (fig. 3) indicates that shallow ground water is moving east to the discharge area at Beaver Creek. Beaver Creek is located approximately 120 ft east of the fire pits. A range in hydraulic gradient of 0.020 to 0.027 feet per feet was observed during the study period based on water-level data collected at wells 4-2 and 4-4. Both of these wells are located approximately parallel to ground-water flow lines at the site (fig. 3). Horizontal hydraulic conductivities in the shallow aquifer range from 1.2 to 10.8 feet per day (ft/d) (Steven Berg, U.S. Geological Survey, written commun., 1994). Minimum and maximum advective ground-water flow velocities of 0.10 to 1.17 ft/d were calculated using these data and an assumed aquifer porosity of 25 percent (Driscoll, 1986).

Acknowledgments

The authors wish to thank Mr. Stephen Mackmull, former Chief of the Environmental Branch, Directorate of Public Works and Environment at Fort Bragg, North Carolina, and all the Environmental Branch Staff for their cooperation and assistance during this investigation.

DATA COLLECTION

This section describes the installation of sampling stations at the fire pits and Beaver Creek, and the procedures used to collect soil-vapor, ground-water, and ground-water/vapor samples for GC analysis. The laboratory procedures used to prepare and analyze soil samples for determination of toluene biodegradation rates also are described.

Soil Vapor and Ground Water

Soil-vapor and ground-water sample extraction points were installed at six monitoring stations (FP1, FP2, FP3, FP4, FP5, and FP10) around the fire pits (fig. 4). Monitoring stations FP1 through FP5 are
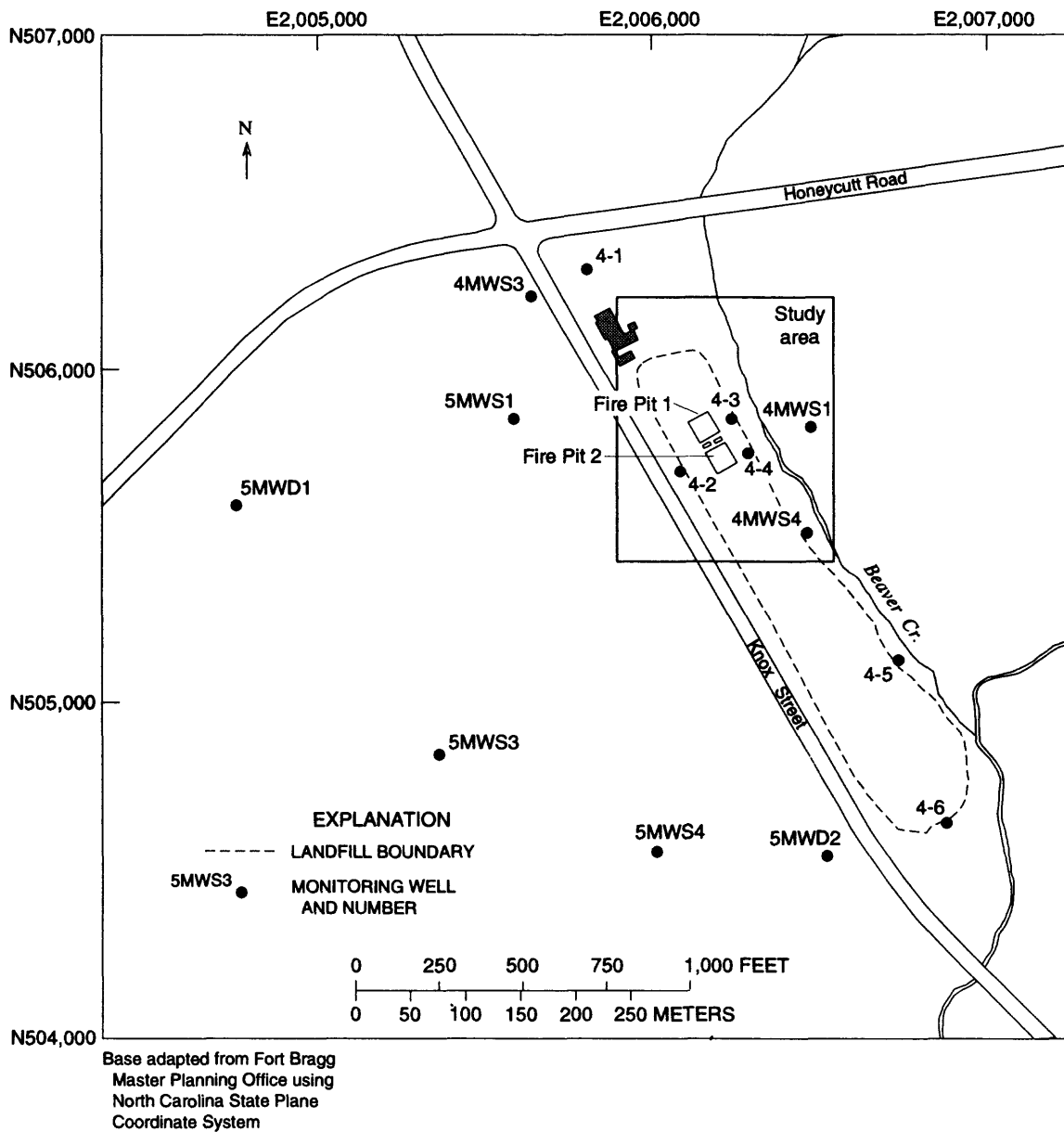
Figure 2.--Location of fire-pit study area, Fort Bragg, North Carolina.

N507,000

N

Honeycutt Road

4-1
227.9

4MWS3
228.5

N506,000

4-3
215.4

5MWS1
226.4

4MWS1
217.3

4-4
214.9

5MWD1
227.9

4-2
220.2

4MWS4
214.4

225

Beaver Cr.

220

4-5
210.9

N505,000

215

5MWS3
211.2

210

4-6
210.2

5MWD2
212.1

5MWS4
208.7

Knox Street

0   250   500   750   1,000 FEET

0   50   100   150   200   250 METERS

N504,000

Base adapted from Fort Bragg
Master Planning Office using
North Carolina State Plane
Coordinate System

EXPLANATION

—210--- WATER-TABLE CONTOUR--Shows altitude
of water table. Dashed where approximately
located. Contour interval 5 feet. Datum is
sea level

——→ GENERALIZED DIRECTION OF GROUND-
WATER FLOW

- - - - LANDFILL BOUNDARY

5MWS3
211.2 • MONITORING WELL AND NUMBER. NUMBER
ON BOTTOM IS ALTITUDE OF MEASURED
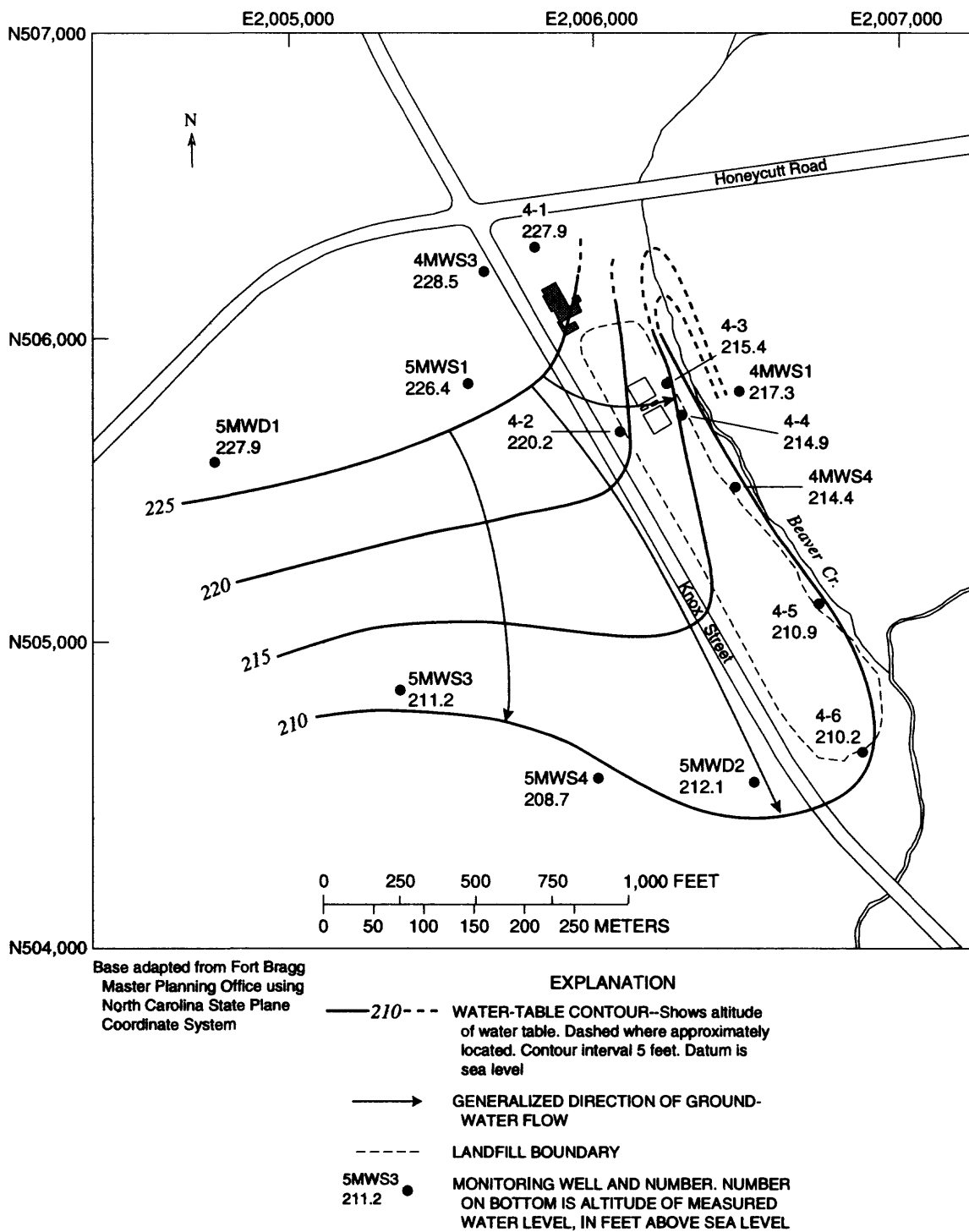WATER LEVEL, IN FEET ABOVE SEA LEVEL

Figure 3.--Water levels in the shallow water-table aquifer at the fire pits, Fort Bragg,
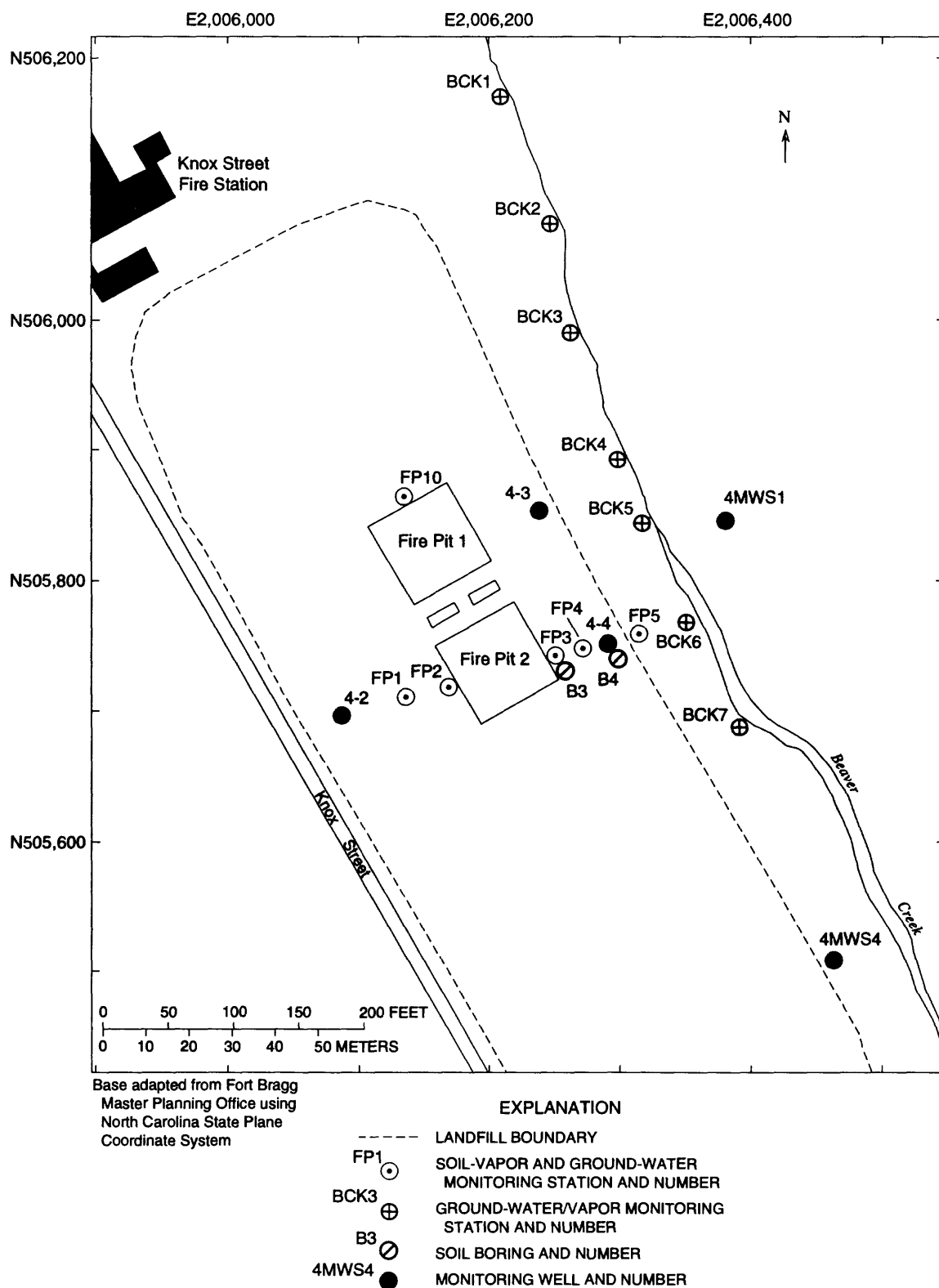North Carolina, April 1995.

Figure 4.--Locations of soil-vapor and ground-water monitoring stations, Beaver Creek monitoring stations, and soil borings for the fire-pit study area, Fort Bragg, North Carolina.

located along a line that transects fire pit 2. The transect approximately parallels ground-water flow lines at the site (fig. 3). Station FP10 is on the north side of fire pit 1. All of these monitoring stations are located within the boundary of the landfill underlying the fire pits except for FP5, which is located between the landfill boundary and Beaver Creek. Soil-vapor samples generally were collected from the unsaturated zone at depths of 2, 4, and 6 ft bls. Ground-water samples typically were collected from depths of 10 and 13 ft bls. An exception to this was station FP5, which has an elevation approximately 5 ft lower than the other sampling stations. Ground-water samples were collected at a depth of 6 ft bls at FP5.

The monitoring stations used for collecting soil-vapor and ground-water samples were constructed following a modified version of the procedure described by Deyo and others (1993). A solid-metal 1/2-inch (in.) diameter bar was used to drive holes to depths of 2, 4, 6, 7, 10, or 13 ft bls. Teflon tubing (3/16-in. diameter) fitted with a stainless-steel point was then inserted into these openings. The upper inch of the stainless-steel point contains 4 inlet holes which allow soil vapor and ground water to be extracted from the subsurface. Sand was filled around the Teflon tubes to within approximately 1 ft of land surface. Several inches of bentonite were then added to seal the hole. The open ends of Teflon tubing were fitted with 3-way valves which were closed between sampling events to prevent gas exchange between the atmosphere and subsurface.

To obtain *in situ* measurements of subsurface soil temperature during soil-vapor sampling, polyvinyl-chloride insulated thermocouple wires were installed to depths of 2, 4, 6, or 7 ft at monitoring stations FP1, FP2, FP3, and FP4. During sampling, the thermocouple wires were connected to a digital thermocouple-thermometer which provided direct measurements of soil temperature with depth. A monitoring-well manhole-cover was fitted, flush with ground surface, over the Teflon extraction tubes and thermocouple wires at each monitoring station to allow passing vehicles to drive over the sampling stations without damaging the equipment.

For soil-vapor sampling, the Teflon extraction tube was connected to a desiccator and purged of ambient air. A Tedlar gas-sample bag was then connected, and the desiccator system was closed. A

peristaltic pump was used to draw a vacuum on the desiccator, which in turn inflated the Tedlar bag with soil vapor drawn from the vapor extraction point. Sample size typically was between 300 to 600 milliliters (mL). Occasionally, saturated soil conditions prevented soil-vapor collection at some monitoring stations. In addition, several samples were lost because of leaky gas-sampling bags.

Ground-water samples were collected by connecting a peristaltic pump directly to the Teflon extraction tube. The tube was purged with approximately 75 to 100 mL of ground water prior to sample collection. After purging, approximately 100 mL of ground water was pumped into a beaker and then a 20 mL sample was pipetted immediately into a 40 mL amber glass vial. The vial was sealed with a cap containing a Teflon lined septum. The sample was then placed on ice. Because of dry conditions or clogged extraction points, water samples could not always be collected at each sampling location.

Ground-Water/Vapor

Ground-water/vapor sampling sites were established at seven locations (BCK1 through BCK7) adjacent to Beaver Creek (fig. 4). All sites were located within several feet of Beaver Creek. A modified version of the technique described by Vroblesky and others (1991) was used to collect ground-water/vapor samples along the western bank of Beaver Creek (fig. 4). A 2-ft deep hole was augered through the creek bank into the saturated zone at each sampling location. An uncapped 40-mL glass vial was sealed inside a polyethylene bag. The vial cap, which has a Teflon-lined septum, was included with the vial. This bag was then sealed inside another polyethylene bag and the sampling vial was placed, open-end down, in the bottom of the hole. The hole was then backfilled with excavated soil. Vapors of volatile organic compounds dissolved in ground water flowing past the buried vial diffused across the polyethylene material into the empty vial headspace. For this report, samples collected in this manner are termed ground-water/ vapor samples. The buried sample vial was retrieved and replaced with a new vial during monthly sampling. Upon sample retrieval, the cap was screwed onto the vial which was then removed from the polyethylene bag. The headspace within the sealed vial was analyzed with a GC to determine TEX concentrations.

Gas Chromatograph Analytical Procedures

Soil-vapor, ground-water, and ground-water/vapor samples were transported to a nearby location for GC analysis. A Photovac 10S55 portable GC was used to analyze samples for the presence of volatile petroleum hydrocarbons. The general procedures used for setting up and calibrating the GC are described by Brock (1990). The GC was equipped with a capillary column (CPSIL5), isothermal oven, photoionization detector, and a self-contained integrator and printer. All samples and standards were analyzed with the GC carrier gas (hydrocarbon-free air) flow rate set at 7 milliliters per minute (mL/min) and the isothermal oven set at 40 °C. An exception was for June 1994 samples and standards which were analyzed at a flow rate of 10 mL/min. Syringe blanks were performed to ensure that the syringes used for injections of standards and samples were not a source of contamination.

For soil-vapor and ground-water/vapor sample analyses, the GC was calibrated with a commercial BTEX gas standard. This standard contained benzene, toluene, ethylbenzene, meta-xylene (m-xylene), para-xylene (p-xylene), and ortho-xylene (o-xylene). For ground-water sample analyses, the GC was calibrated with benzene, toluene, ethylbenzene, m-xylene, and o-xylene by procedures described by Brock (1990). It should be noted that m-xylene and p-xylene co-elute on the CPSIL5 capillary column and therefore cannot be identified separately. Thus, analytical concentrations of m-xylene and p-xylene for soil-vapor and ground-water/vapor samples are reported as a combined concentration which is designated as m,p-xylene.

BTEX compounds in samples were tentatively identified and quantified by comparing individual BTEX chromatographic peaks in the samples to those of the calibration standards. Although the GC was calibrated with benzene, it was not possible to identify the presence or determine the concentration of benzene in samples because of the complex hydrocarbon signature of the sample gas-chromatographs. Therefore, only concentrations of toluene, ethylbenzene, m,p-xylene, and o-xylene (TEX) are presented. For field GC analysis of soil-vapor and ground-water/vapor samples, the data reporting limit for the individual TEX compounds is 0.01 parts per million (ppm). For field GC analysis of ground-water samples, the data reporting limit for the individual TEX compounds is 0.10 microgram per liter (μg/L).

For this report, the identification of individual TEX compounds in samples analyzed with the portable field GC are considered tentative and the reported concentrations are considered to be semiquantitative.

Sample analysis by an independent laboratory would be required for quantitative verification.

Laboratory Measurements of Toluene Biodegradation Rate Constants

Sediment samples from the water-table aquifer were collected from borings B3 and B4 (fig. 4) in March 1995 for biodegradation experiments. Samples were collected from the unsaturated zone (2.0-3.0 ft), partially saturated zone (7.5-8.5 ft), and saturated zone (9.0-10.0 ft) at boring B3 adjacent to fire pit 2. A saturated sample (10.0-11.0 ft) was collected downgradient of boring B3 in a less-contaminated area at boring B4.

The microbial degradation of toluene (a monoaromatic compound representative of TEX) was determined by quantifying the production rate of radiolabeled $^{14}CO_2$ from a known amount of radiolabeled ^{14}C-toluene added to microcosms containing aquifer sediment. Triplicate 40-mL glass microcosms were sterilized by autoclaving (121 °C for 1 hour) and contained 5 mL of a sediment (about 5 grams)/ground-water slurry from boring B3 and B4 samples. Anaerobic microcosm conditions were created to reflect *in situ* conditions by purging the microcosms with helium for 3 minutes after capping each microcosm with a thick rubber stopper. Approximately 1,000,000 disintegrations per minute of ^{14}C-toluene (specific activity of 9.7 milliCuries per millimole) was added to each microcosm. Dead controls to account for abiotic evolution of $^{14}CO_2$ were prepared for each triplicate sampling-time point by sterilizing each microcosm containing aquifer sediment by autoclaving (121 °C for 1 hour) and the addition of 8-millimolar mercuric chloride. At specified times during the experiment (t = 0, 1, 5, and 23 weeks), vials were sacrificed by acidification with 45 percent phosphoric acid, and the evolved $^{14}CO_2$ captured in a 10 molar potassium hydroxide solution (0.4 mL) suspended in the microcosm in a plastic bucket assembly. The $^{14}CO_2$ activity in the base solution was measured through liquid scintillation counting after addition to scintillation cocktail (Ultima Gold, Packard Instrument Corporation) using a 1600TR liquid scintillation counter (Packard Instrument Corporation). The ^{14}C activities were corrected for production in dead controls, background radiation, activity at time point t=0, and counting efficiency. Activities in ^{14}C are reported as a percentage of the added radiolabel activity.

DISTRIBUTION OF TOLUENE, ETHYLBENZENE, AND XYLENE

Soil-vapor, ground-water, and ground-water/vapor samples were collected and analyzed monthly from June 1994 to June 1995. Individual concentrations of toluene, ethylbenzene, m,p-xylene, and o-xlyene determined with the field GC for the soil-vapor, ground-water, and ground-water/vapor samples collected during this study are presented in Appendix A, Appendix B, and Appendix C, respectively.

For this report, total TEX concentrations, equal to the cumulative sum of the individual TEX compounds, for soil-vapor and ground-water samples were used to examine spatial and temporal trends. The total TEX concentrations for the soil-vapor and ground-water samples are reported in Appendix A and Appendix B, respectively. Total TEX concentrations were not determined for the ground-water/vapor samples collected at Beaver Creek because toluene commonly was the only TEX compound identified for these samples.

This section first discusses the spatial and temporal distribution of TEX in soil-vapor samples, and then ground-water samples, collected at monitoring stations FP1, FP2, FP3, FP4, FP5, and FP10. A discussion of the spatial and temporal distribution of toluene in ground-water/vapor samples at Beaver Creek monitoring stations BCK1 through BCK7 is then presented.
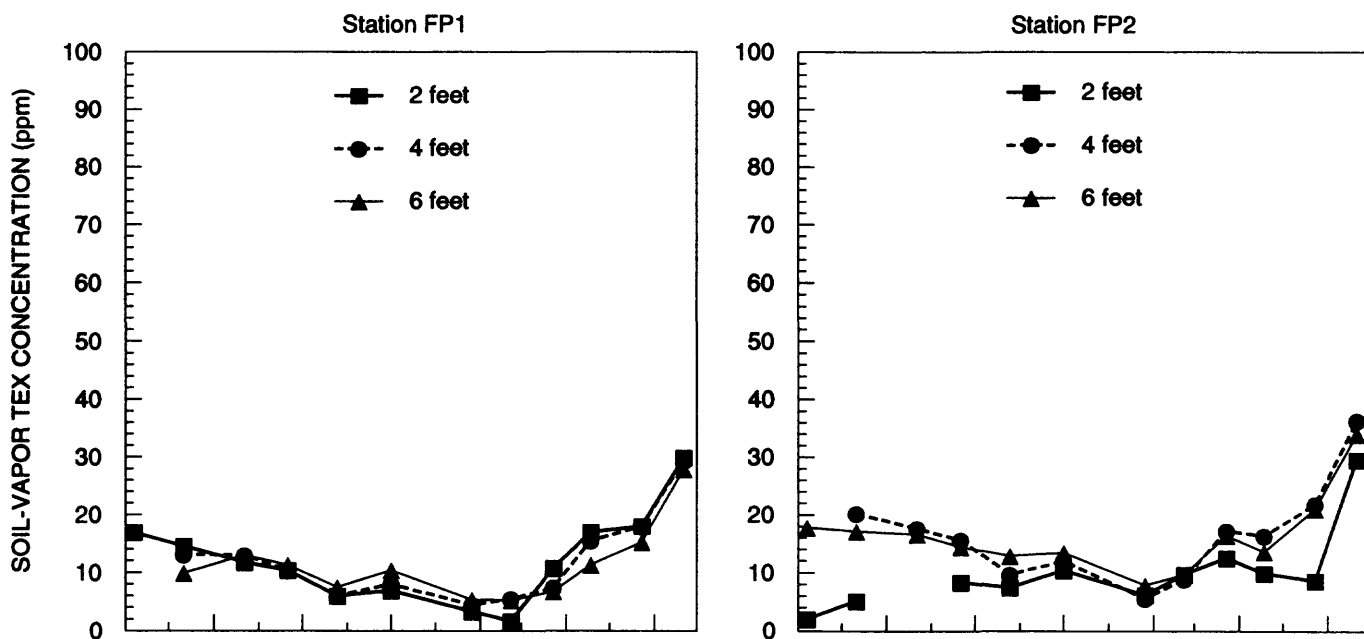
Soil Vapor

Field GC analyses were used to examine the spatial and temporal distribution of total TEX concentrations for soil-vapor samples collected at monitoring stations FP1-FP5 and FP10. As mentioned previously, stations FP1 through FP5 are located along a line which transects fire pit 2 (fig. 4). There is a slightly higher concentration of TEX in soil vapor at FP2 on the western side of fire pit 2 relative to FP1 (fig. 5). The highest TEX concentrations in soil vapor along the transect line occur at FP3 on the eastern edge of fire pit 2. Soil-vapor TEX concentrations decrease moving downgradient of fire pit 2 from FP3 to FP5. The highest soil-vapor TEX concentrations (typically higher than 100 ppm) were measured for samples collected at FP10 on the northern edge of fire pit 1. The higher soil-vapor TEX concentrations at FP10, relative to FP1 through FP5, may reflect a higher degree of past

fuel input to the unsaturated zone in this area because of fuel releases associated with the sand-lined basin (operated from 1966 to 1978) and the concrete-lined fire pit 1 (operated from 1978 to 1993).

The higher soil-vapor TEX concentrations at monitoring stations located adjacent to the fire pits (FP2, FP3, and FP10), relative to stations located away from the fire pits (FP1, FP4, and FP5), indicate that petroleum contamination in unsaturated zone soils at the site originated from the fire pits. Differences in soil-vapor TEX concentrations between sampling depths further suggest that fuel infiltrated the unsaturated zone from land surface. The highest TEX concentrations for a given monitoring station generally were observed for those samples collected at depths of 6 ft or less. Deeper soil-vapor samples, such as those collected at 7 ft at FP4 and 10 ft at FP10 (fig. 5), usually had lower TEX concentrations relative to samples collected at shallower depths.

In general, there appears to be a seasonal influence on the observed patterns in soil-vapor TEX concentrations. The TEX concentrations generally decreased from June 1994 until approximately January and February 1995. The trend then reversed and the TEX concentrations increased until June 1995 when the study ended. This seasonal pattern in TEX concentration is similar for most sampling depths at the different monitoring stations (fig. 5). For example, the seasonal pattern in soil-vapor TEX concentration is basically the same for each depth at FP1. This same overall pattern also is observed at FP2, FP3, FP4, and FP10. There is no noticeable seasonal pattern at FP5 where minimal concentrations of TEX (< 0.5 ppm) were measured for soil-vapor samples.

For the first two months at FP2 and the last five months at FP3 there is poor agreement between the seasonal pattern in TEX concentration at the 2-ft depth, relative to the 4- and 6-ft depths (fig. 5). One possible explanation is that the upper soils at FP2 and FP3 were more susceptible to water saturation from rain events relative to the other monitoring stations. Significant amounts of liquid water commonly were mixed in with the soil-vapor samples collected from the 2-ft extraction points at FP2 and FP3. The only vapor samples collected from depths of 2 ft at FP2 and FP3 that did not contain water were those collected during August, September, April, and May. The departure of the seasonal TEX concentration profile at 2 ft from the 4 ft and 6 ft TEX concentration profiles at FP2 and FP3 is likely due to water-saturated soil conditions. The

Figure 5.--Monthly soil-vapor and ground-water total TEX concentrations at monitoring stations FP1 through FP5 and FP10, June 1994 through June 1995, Fort Bragg, North Carolina.

Note: Breaks in the graphs represent sampling dates with no data.
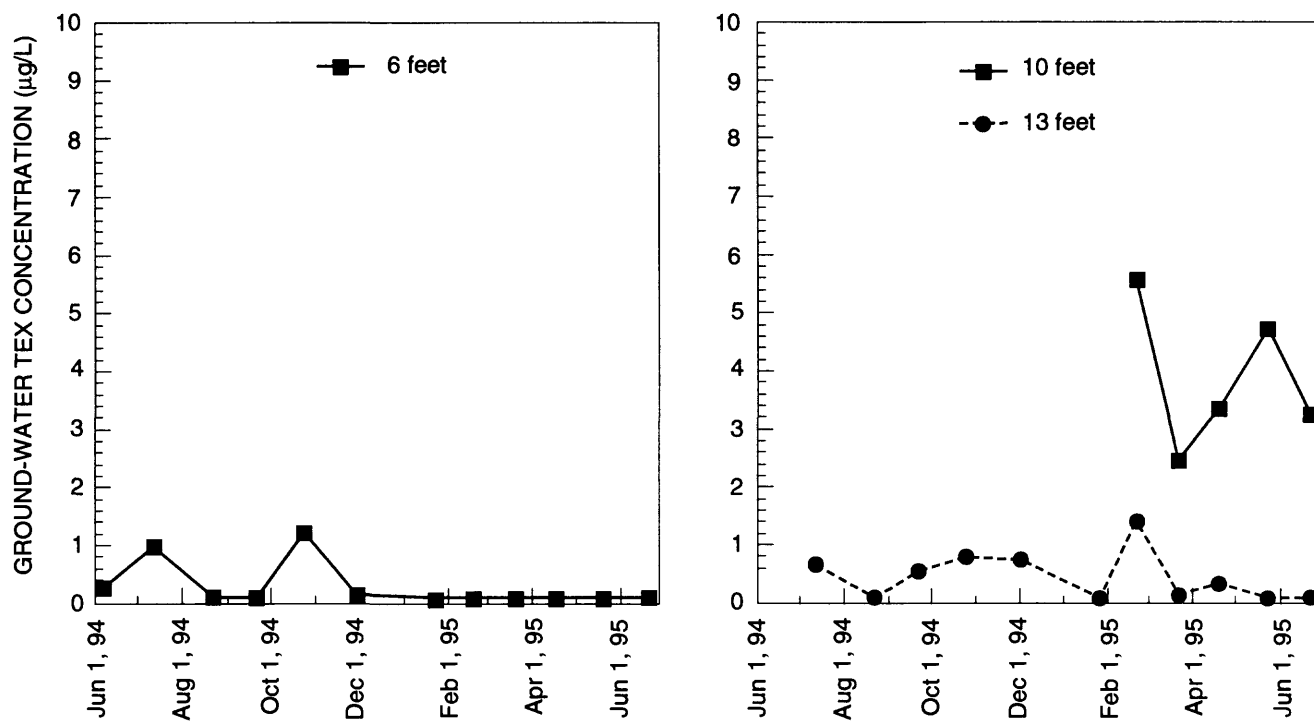
Figure 5--Continued. Monthly soil-vapor and ground-water total TEX concentrations at monitoring stations FP1 through FP5 and FP10, June 1994 through June 1995, Fort Bragg, North Carolina.

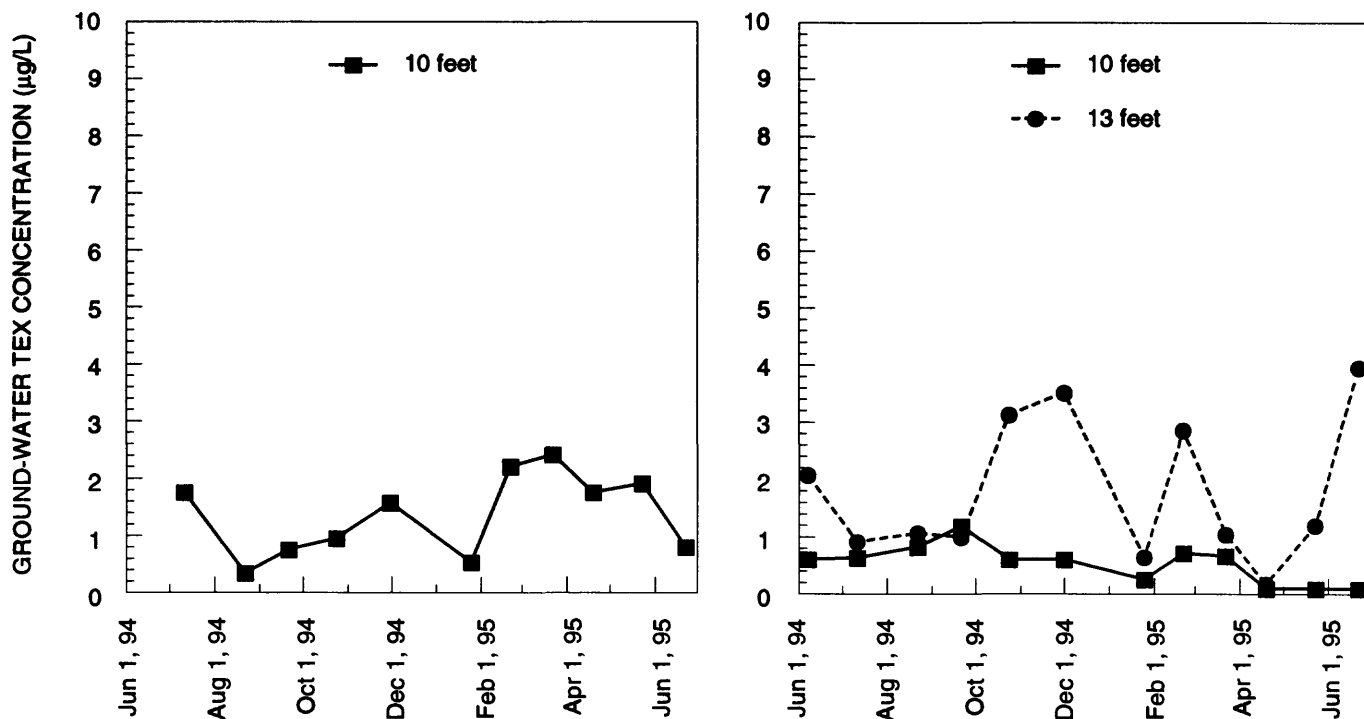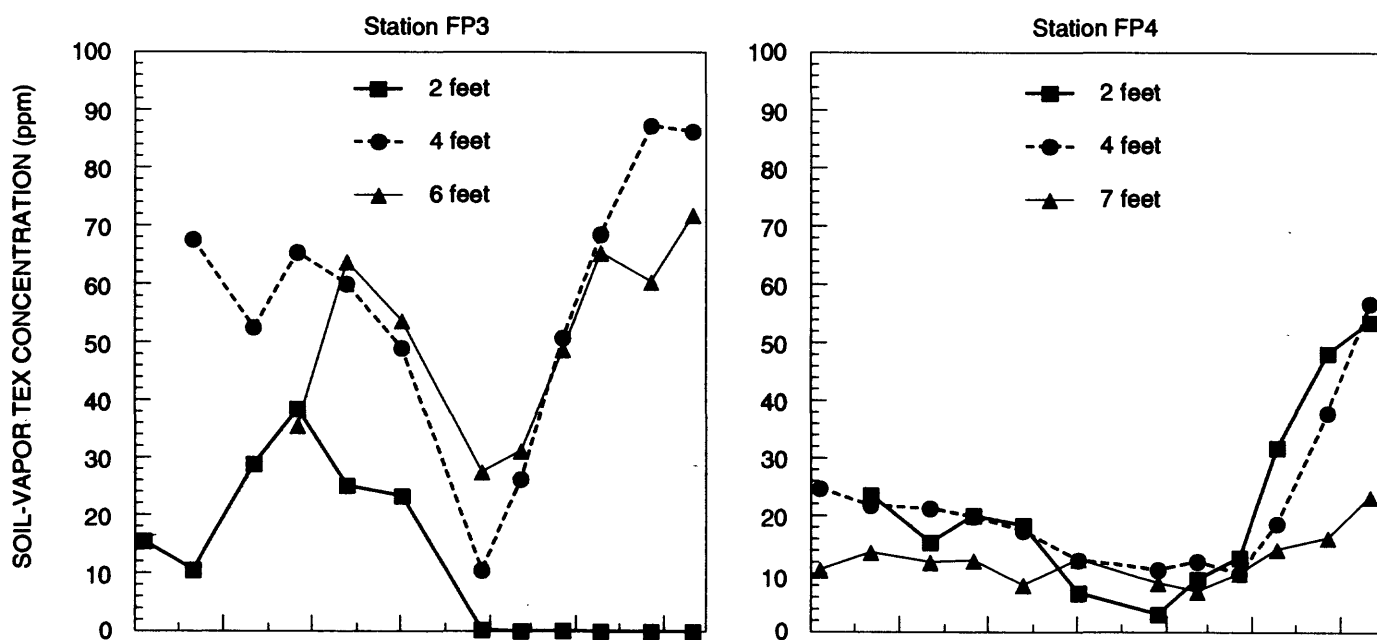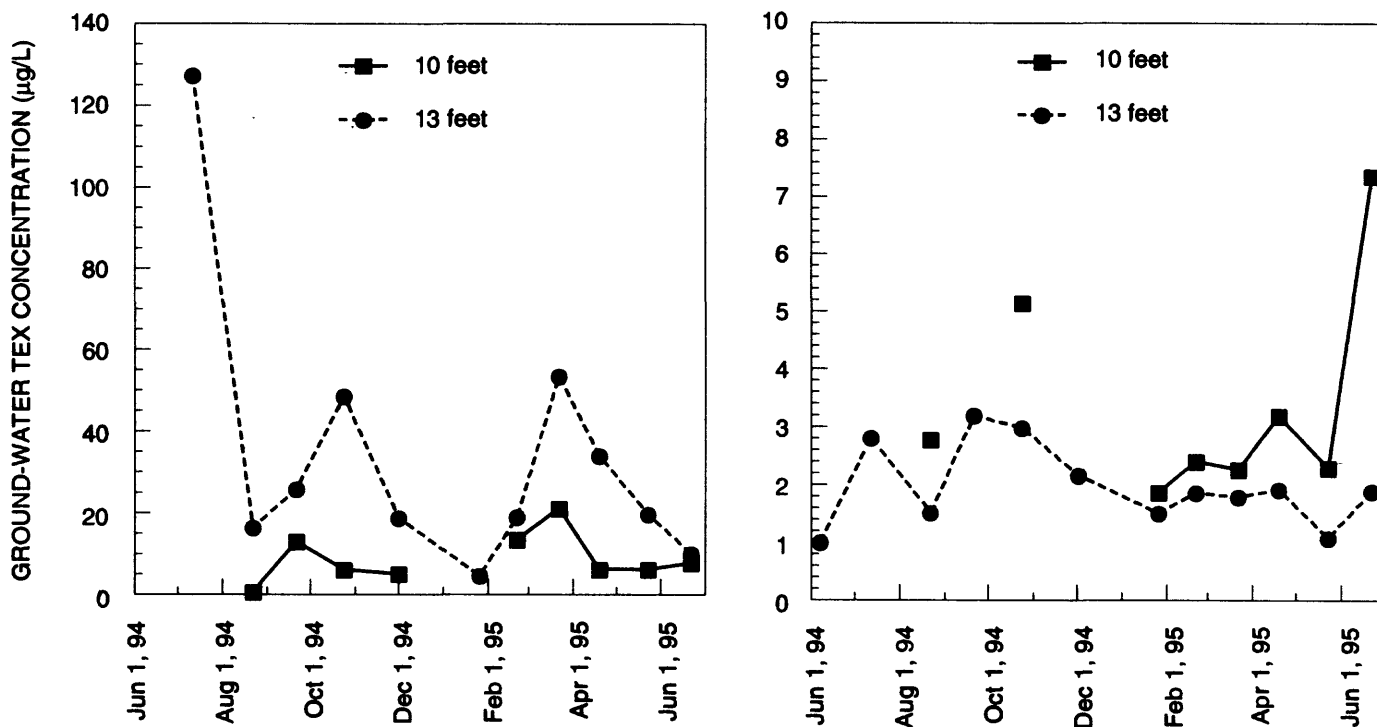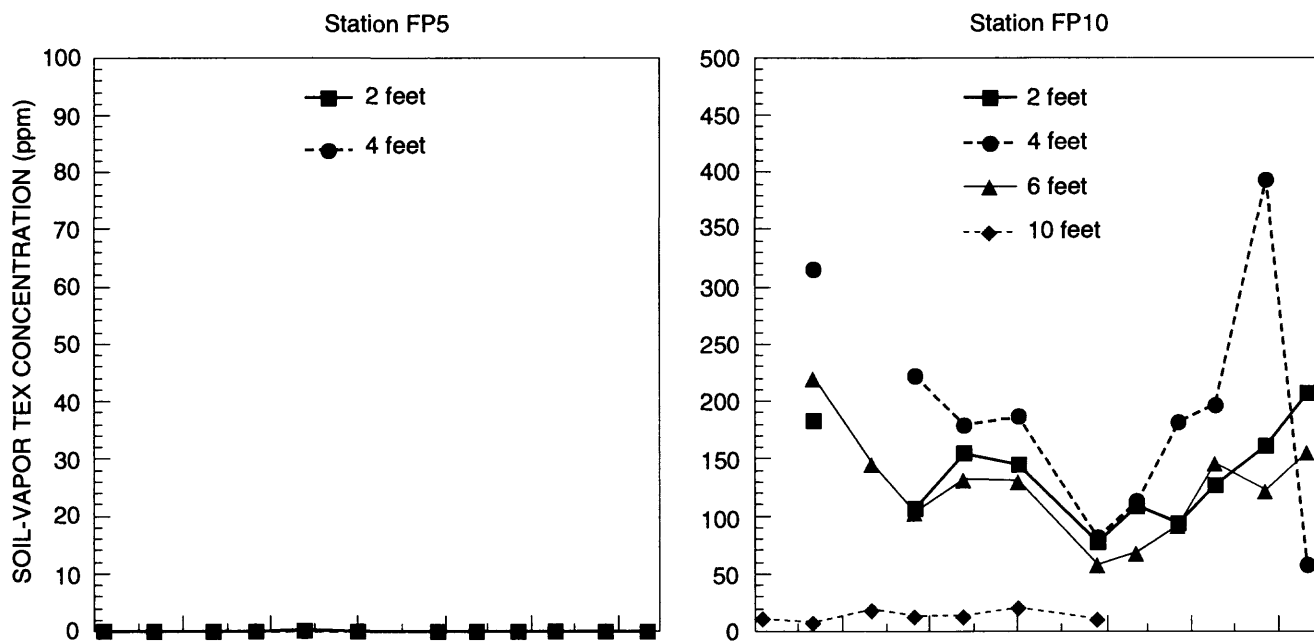Figure 5--Continued. Monthly soil-vapor and ground-water total TEX concentrations at monitoring stations FP1 through FP5 and FP10, June 1994 through June 1995, Fort Bragg, North Carolina.

large drop in soil-vapor TEX concentrations for the June 1995 sample collected at 4 ft for FP10 (fig. 5) also is attributed to saturated soil conditions. During a soil-gas survey of trichloroethylene contamination, Marrin and Thompson (1987) measured anomalously low trichloroethylene concentrations in soil-vapor samples collected from highly saturated soils. They indicated that water-filled pore spaces associated with saturated soils may have inhibited contaminant diffusion and extraction of a representative soil-vapor sample. They further indicated that increased solubilization of trichloroethylene within water-saturated soils may have lowered the vapor concentrations. These same factors influenced TEX concentrations in soil-vapor samples collected from water-saturated soils at the fire pits.

There also were seasonal differences in soil-vapor TEX concentrations with depth depending on the month of sample collection. For instance, the 4- and 6-ft depths at FP1 and the 4- and 7-ft depths at FP4 generally had higher TEX concentrations in the colder months (December through February) relative to the 2-ft depths (fig. 5). In the warmer months, the 2- and 4-ft depths at these locations typically had higher TEX concentrations. An examination of the 4- and 6-ft depths at FP2 and FP3 indicates that the 6-ft depth has higher TEX concentrations in the colder months, whereas the 4-ft depth has higher concentrations in the warmer months. This information, coupled with the observed seasonal pattern in soil-vapor TEX concentrations described above, suggests that soil-vapor TEX concentrations are influenced by temperature.

Temperature data collected at stations FP1, FP2, FP3, and FP4 also indicate a seasonal pattern in subsurface soil temperatures. A representative example of the seasonal trend observed for soil temperatures is shown for FP1 in figure 6. Soil temperature at all depths decreased from July and August 1994 until approximately January and February 1995 (fig. 6). The trend then reversed, and soil temperatures increased through June 1995. This same general pattern also was observed for soil-vapor TEX concentrations (fig. 5). Additionally, the data indicate that from approximately October through March soil temperature increased with depth, whereas, from April through September, soil temperature decreased with depth (fig. 6). Some of the spatial and temporal differences in soil-vapor TEX concentrations observed at the study site may be related to seasonal changes in subsurface soil temperatures.
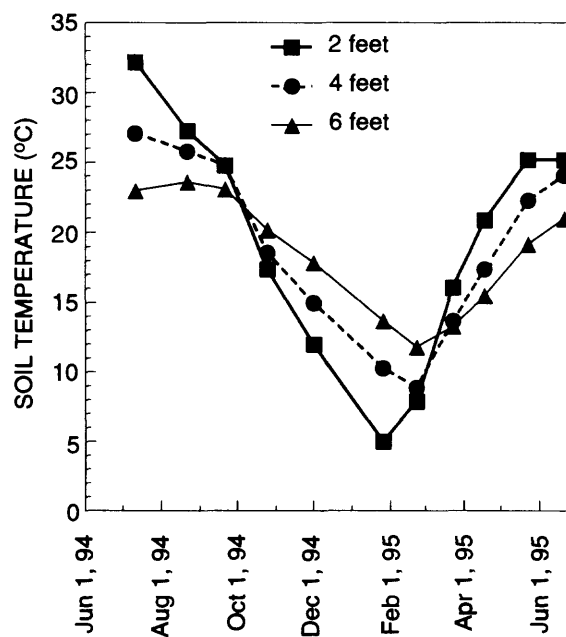
Figure 6.--Monthly measurements of soil temperature at station FP1, June 1994 through June 1995, Fort Bragg, North Carolina.

Some of the major factors that influence the distribution of a volatile organic compound between the solid, aqueous, and gaseous phases in soil include volatilization, dissolution, gaseous diffusion, soil porosity, soil-moisture content, sorption to minerals, partioning into organic matter, and microbial and chemical degradation (Chiou and Shoup, 1985; Marrin and Thompson, 1987; Marrin and Kerfoot, 1988; Li and Voudrias, 1992; Ong and others, 1992). The occurrence of volatile organic compounds, such as TEX, in soil vapor associated with petroleum contaminated soils is largely a function of volatilization. The most important chemical properties that influence the volatilization of a compound are vapor pressure and aqueous solubility. Temperature is an important physical process which can influence the volatilization of a compound because vapor pressure and aqueous solubility are temperature dependent. For the individual TEX compounds, toluene has the highest vapor pressure and aqueous solubility.

At a temperature of 25 °C, the vapor pressures of toluene, ethylbenzene, o-xylene, and p-xylene are 0.038, 0.013, 0.009, and 0.012 atmospheres, respectively (Schwarzenbach and others, 1993). The aqueous solubilities for toluene, ethylbenzene, o-xylene, and p-xylene at a temperature of 25 °C are

0.006, 0.002, 0.002, and 0.002 moles per liter (moles/L) respectively. The analytical data for soil-vapor samples in Appendix A indicate that concentrations of toluene typically are much higher than concentrations of ethylbenzene, m,p-xylene, and o-xylene, which may be due in part to the higher vapor pressure of toluene relative to the other TEX compounds.

To determine if there is a relation between soil-vapor TEX concentration and soil temperature, soil-vapor TEX concentrations were plotted as a function of soil temperature for all sampling depths at monitoring stations FP1, FP2, FP3, and FP4; an example is provided in figure 7 for station FP1. A least-squares linear regression was applied to each data set to provide a best fit line and a correlation coefficient (r). To test the null hypothesis that the correlation coefficient between soil-vapor TEX concentration and soil temperature is equal to zero, a t-test with n-2 (where n is the number of sample pairs) degrees of freedom was employed to determine the significance of r at the 5 percent level, or α=0.05, (Rohlf and Sokal, 1981). The results for stations FP1, FP2, FP3, and FP4 are provided in table 1. A significant correlation exists when r is greater than or equal to the critical value, and conversely, the correlation is not significantly different from zero when r is less than the critical value.
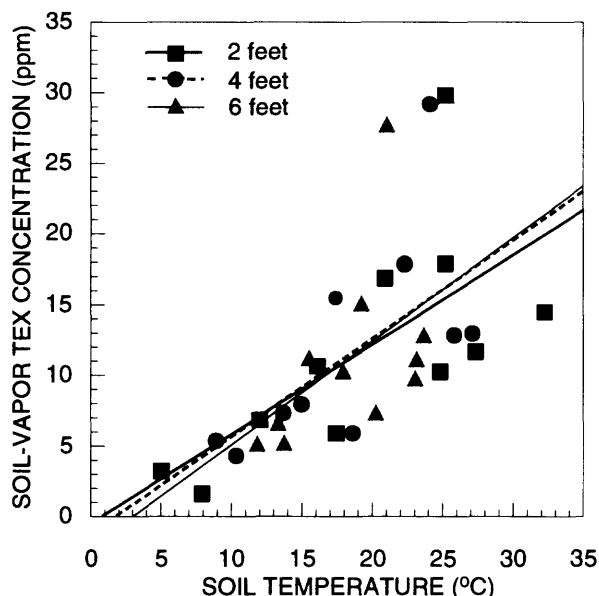
Figure 7.--Scatter plot of total TEX concentration and soil temperature for data collected at station FP1 from June 1994 through June 1995, Fort Bragg, North Carolina.

Table 1. Correlations between soil-vapor TEX concentration and soil temperature

[shading reflects those locations where a significant correlation exists; ft, feet; α, alpha]

Monitoring station (fig. 4)	Depth (ft)	Number of samples, n	Correlation coefficient, r	Critical value for α=0.05
FP1	2	11	0.682	0.602
FP1	4	11	.612	.602
FP1	6	11	.492	.602
FP2	2	11	.039	.602
FP2	4	11	.677	.602
FP2	6	12	.419	.576
FP3	2	11	.237	.602
FP3	4	11	.776	.602
FP3	6	9	.512	.666
FP4	2	11	.662	.602
FP4	4	12	.582	.576
FP4	7	12	.345	.576

For half of the monitoring stations, r is less than the critical value; thus, the correlation between soil-vapor TEX concentration and soil temperature is not significant (table 1). The poor correlation between TEX concentration and soil temperature at depths of 2 ft at FP2 and FP3 was expected because of the water-saturated soil conditions which were commonly encountered at these locations. For the 2-ft sampling depths at FP1 and FP4 and all of the 4-ft sampling depths, a significant correlation between soil-vapor TEX concentration and soil temperature is observed (table 1). For those sites where a significant correlation exists, TEX concentrations in soil vapor tend to increase as soil temperatures increase, as illustrated in figure 7. This correlation between higher total TEX concentration and higher temperature likely reflects an increase in volatilization of TEX compounds from fuel-contaminated soils into soil vapor because of associated increases in vapor pressures of the individual TEX compounds. Although this information indicates that soil temperature is an important factor which influences TEX concentrations, other factors, such as soil moisture, also appear to influence TEX concentrations in soil vapor at the fire pits.

Based on the field GC analyses, there is residual fuel contamination entrained within unsaturated zone soils at the study site. The observed temporal and spatial changes in soil-vapor TEX concentrations may reflect differences in the distribution of TEX compounds among solid, aqueous, and gaseous phases within the contaminated soils during the 1-year study period. Soil temperature and soil moisture are important factors which influence the distribution of TEX compounds among the different phases. The TEX concentrations for soil-vapor samples collected during the study cannot be used to determine if TEX compounds in the unsaturated zone at the site are decreasing with time because of the seasonal pattern observed during the 1-year study period.

Ground Water

Spatial and temporal trends in total TEX concentrations for ground-water samples also were examined for monitoring stations FP1-FP5 and FP10. Total TEX concentrations are less than 5 μg/L for ground-water samples collected from stations FP1 and FP2 on the western side of fire pit 2 (fig. 5). Total TEX concentrations in ground-water samples from FP10 also were generally less than 5 μg/L, which was not expected because the highest soil-vapor TEX

concentrations (typically > 100 ppm) were observed for this location. The lack of data from June 1994 to January 1995 for the 10-ft sampling depth at FP10 is because ground water was not present at this depth, and therefore, soil-vapor samples were collected instead. The highest ground-water TEX concentrations (typically between 5 to 50 μg/L) were for samples collected at FP3 on the eastern side of fire pit 2 (fig. 4). From FP3 at fire pit 2 downgradient toward Beaver Creek, there is an overall decrease in TEX concentration levels from FP3 (generally 5 to 50 μg/L), to FP4 (generally < 4 μg/L), and then FP5 (generally < 1 μg/L). Similar spatial changes between stations FP1 through FP5 also were observed in soil-vapor TEX concentrations. Total TEX concentrations in both ground-water and soil-vapor samples appear to decrease downgradient of the fire-pit source area.

Although a seasonal pattern was observed for soil-vapor TEX concentrations, no similar pattern was evident for the ground-water TEX concentrations. Monthly changes in TEX concentrations for the ground-water samples collected at the fire pits were variable. For example, several peaks in TEX concentration were observed for ground-water samples collected at depths of 13 ft at FP2 and FP3; however, these same peaks were either non-existent or subdued for samples collected at 10 ft from the same locations (fig. 5). Furthermore, there were variations in ground-water TEX concentrations with depth between some of the monitoring stations. Ground-water samples collected at 13 ft at FP2 and FP3 typically had higher TEX concentrations relative to the samples collected at 10 ft, whereas the reverse was true at FP4 and FP10.

The variations in ground-water TEX concentrations at the fire pits likely is due to a combination of factors. Some factors, such as volatilization, advection, dilution, and sorption, which can influence the partioning of TEX compounds among different phases within the unsaturated zone also can affect concentration levels of TEX compounds dissolved in ground water. For instance, changes in recharge can affect the amount of ground water flowing into the study area from an upgradient source. An increase in the amount of water flowing into the study area can dilute ground water TEX concentrations if the input of TEX compounds to ground water from the contaminated soils is constant. Conversely, changes in local recharge also can increase or decrease the downward flux of TEX compounds from the unsaturated zone to underlying ground water. The

sorption of TEX compounds to organic matter within aquifer sediments can influence ground water TEX concentrations. Degradation of TEX compounds by microbial organisms can decrease concentrations of these compounds dissolved in ground water.

Furthermore, differences in the aqueous solubilities of the individual TEX compounds can influence the distribution of these compounds in ground water. The higher aqueous solubility of toluene (0.006 moles/L at 25 °C), relative to the aqueous solubility of 0.002 moles/L, at 25 °C, for ethylbenzene, o-xylene, and p-xylene, may explain why toluene concentrations were higher than concentrations of ethylbenzene and xylenes in ground-water samples collected at stations FP1 and FP4 (Appendix B). However, toluene concentrations generally were lower than ethylbenzene and xylene concentrations at FP2 and FP3 (Appendix B), which implies that other factors may be important at these locations.

Because of the variability in ground-water TEX concentrations observed during the study period, it is not possible to determine if concentrations of TEX compounds in ground water at a given monitoring station are decreasing with time. However, an examination of ground-water data collected at all of the monitoring stations along the transect indicates that TEX concentrations decrease downgradient of the fire-pit source area.

The field GC analytical results also were used to examine rate constants of hydrocarbon degradation in ground water by biological processes. Concentrations of toluene in ground water were used to estimate toluene biodegradation rate constants for the saturated zone. Toluene in ground water was chosen because toluene is the predominant TEX compound observed in the unsaturated zone, and ground water is the primary media which can transport toluene away from the site. The biodegradation rate constant is calculated by dividing the percent change in toluene along a given distance by the time required for ground water to travel the same distance. This calculation assumes that the source of toluene to the ground water is at a steady state and that the decrease in ground-water toluene concentration along the flow path is due solely to biodegradation. It is further assumed that ground-water toluene concentrations are not influenced by volatilization, dilution, and sorption processes. The biodegradation rate constants estimated in this manner are considered to be a maximum. Neglecting those

processes, such as dilution and sorption, that can lower concentrations of toluene dissolved in ground water, may overestimate the calculated biodegradation rate constant. Additionally, the biodegradation rate constant is considered to be an anaerobic biodegradation rate constant because ground water at the site occurs under anaerobic conditions. This rate constant (in inverse days) is used when the total mass of contaminant at the site is unknown. Whereas, the actual biodegradation rate (in millimoles per liter per day) can be calculated when the contaminant mass is known.

Ground-water toluene data for FP4 and FP5 were used for estimating the biodegradation rate constants because these were the only locations where ground-water toluene concentrations decreased downgradient of fire pit 2. The percent decrease in ground-water toluene concentrations from FP4 to FP5 are listed in table 2. It should be noted that for FP4, an average concentration was presented in table 2 in those cases where duplicate values or values for more than one depth were listed in Appendix B. In addition, ground-water toluene concentrations for FP5 typically were less than the data reporting limit of 0.10 µg/L (table 2). When the FP5 toluene concentration is reported to be <0.10 µg/L, the actual concentration may be as high as 0.099 µg/L, or as low as 0 µg/L. Therefore, a range in percent decrease between FP4 and FP5 was determined by using toluene concentrations of 0.099 µg/L and 0 µg/L for FP5 when the reported value was less than the reporting limit.

An overall range of 85 to 100 percent is observed for the percent decrease in ground-water toluene concentration from FP4 to FP5 (table 2). FP5 is located 45 ft downgradient of FP4, which when divided by the range in advective ground-water flow velocities of 0.10 to 1.17 ft/d at the site, yields a range of 38.5 to 450 days as the time required for ground water to flow from FP4 to FP5. Dividing 0.85 (or 85 percent) as the percent toluene decrease from FP4 to FP5 by ground-water travel times of 38.5 and 450 days, yields biodegradation rate constants of 0.022 d^{-1} and 0.002 d^{-1}, respectively. Similarly, dividing 1 (or 100 percent) by 38.5 and 450 days yields biodegradation rate constants of 0.026 d^{-1} and 0.002 d^{-1}, respectively. Because of the range of numbers used in the above calculations, the maximum toluene biodegradation rate constant may be as low as 0.002 d^{-1} or as high as 0.026 d^{-1}.

Table 2. Percent decrease in ground-water toluene concentration from FP4 to FP5

[mg/L, micrograms per liter]

Sample date	FP4 Ground-water toluene concentration (µg/L)	FP5 Ground-water toluene concentration (µg/L)	Percent decrease in toluene concentration from FP4 to FP5 (percent)
6-7-94	0.67	<0.10	[a](85 - 100)
7-12-94	1.33	<.10	[a](93 - 100)
8-22-94	1.45	<.10	[a](93 - 100)
9-21-94	1.29	<.10	[a](92 - 100)
10-24-94	2.67	.16	94
11-30-94	1.29	<.10	[a](92 - 100)
1-26-95	1.38	<.10	[a](93 - 100)
2-21-95	1.51	<.10	[a](93 - 100)
3-22-95	1.52	<.10	[a](93 - 100)
4-19-95	1.86	<.10	[a](95 - 100)
5-23-95	2.58	<.10	[a](96 - 100)
6-22-95	3.60	<.10	[a](97 - 100)

[a] A range in percent decrease was calculated for those sampling dates when the FP5 ground-water toluene concentration was less than the data reporting level of 0.10 µg/L. The range was based on calculations assuming a FP5 ground-water toluene concentration of 0.099 µg/L and 0.0 µg/L.

Ground-Water/Vapor

Samples of ground-water/vapor were collected at stations BCK1-BCK7 (fig. 4) along Beaver Creek to determine if TEX compounds were present in ground water at the point of discharge. With the exception of three samples, toluene was the only TEX compound detected at or above the reporting limit of 0.01 ppm (Appendix C). The lack of ethylbenzene and xylenes in ground-water/vapor samples at Beaver Creek may reflect a lower degree of mobility of these compounds in ground water at the site as compared to toluene. As indicated previously, ethylbenzene and xylenes are less soluble than toluene. Furthermore, ethylbenzene and xylenes have higher octanol-water partition coefficients than toluene, which indicates that these compounds are more likely to sorb to organic materials within the aquifer sediments than toluene. At a temperature of 25 °C, the octanol-water partition coefficients, in units of (moles/L octanol)/(moles/L water), for toluene, ethylbenzene, o-xylene, and p-xylene are 490, 1,413, 1,318, and 1,514, respectively (Schwarzenbach and others, 1993). Because of the lower solubilities and higher octanol-water partition coefficients for ethylbenzene and xylenes, the transport

of these compounds in ground water flowing from the fire-pit source area toward Beaver Creek may be retarded to a higher degree than the ground-water transport of toluene.

Toluene was detected in ground-water/vapor samples collected from all sites; however, the concentrations of toluene at BCK3 and BCK6 were minimal (< 0.1 ppm) relative to toluene concentrations (up to 33 ppm) at the other locations (fig. 8). Toluene concentrations in the ground-water/vapor samples peaked between July and August 1994 (fig. 8). This peak in toluene concentrations was observed at sampling sites BCK1, BCK2, BCK4, BCK5, and BCK7. After November and December 1994, toluene in the ground-water/vapor samples were detected at low concentrations (< 1 ppm) or at concentrations less than the reporting limit of 0.01 ppm. The observed peak in toluene concentrations for the ground-water/vapor samples represents a pulse of ground water enriched with toluene that moved through the sampling sites during that time period. The subsequent decrease in toluene concentrations may reflect a decrease in source inputs, an increase in dilution caused by higher ground-water flow, and(or) removal by biological or other physical processes.
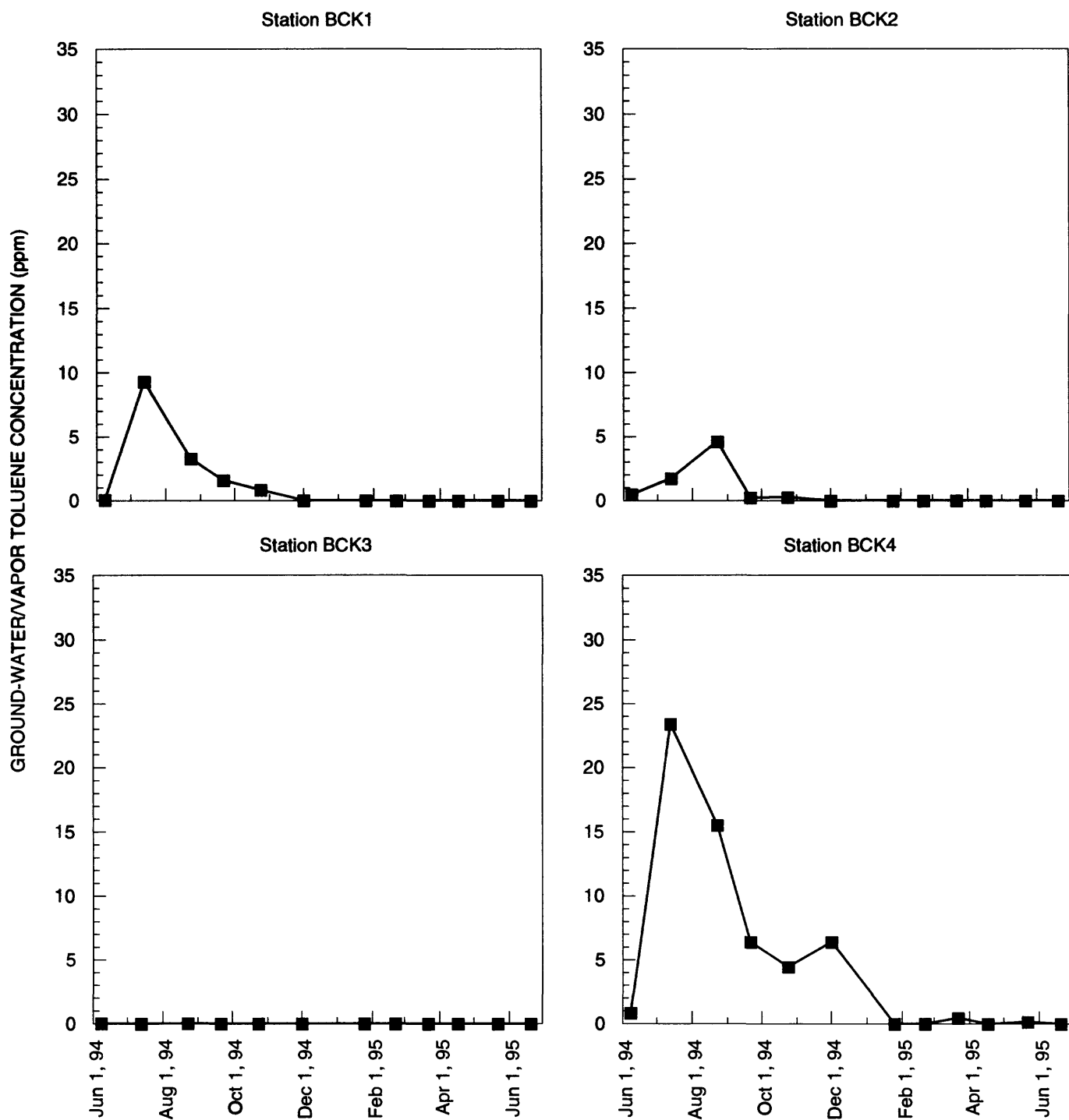
Figure 8.--Monthly ground-water/vapor total TEX concentrations at monitoring stations BCK1 through BCK7, June 1994 through June 1995, Fort Bragg, North Carolina.
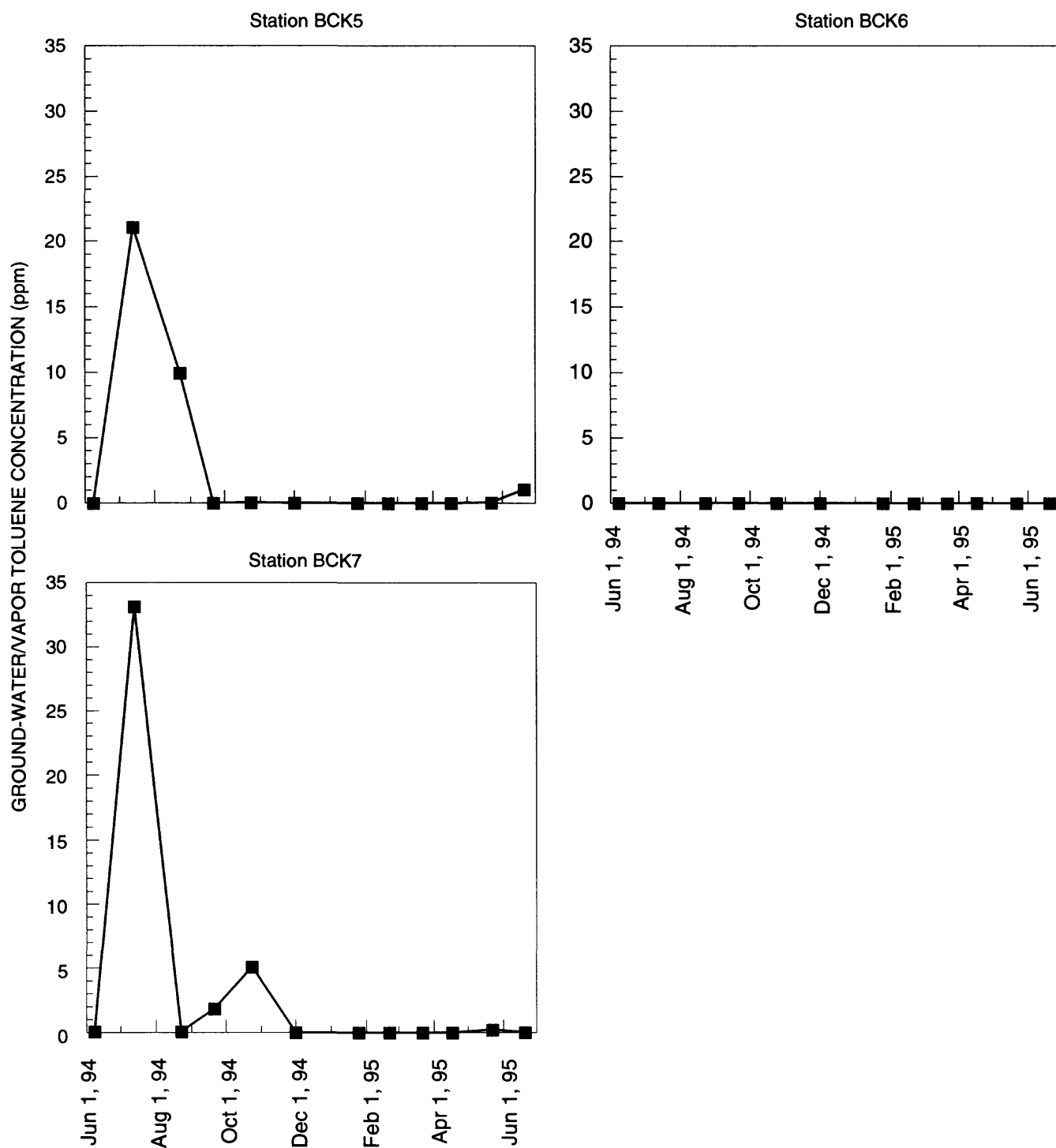
Figure 8--Continued. Monthly ground-water/vapor total TEX concentration at monitoring stations BCK1 through BCK7, June 1994 through June 1995, Fort Bragg, North Carolina.

Based on the field GC analysis of TEX compounds in ground-water/vapor samples, it appears that toluene was the principal TEX compound present in ground water reaching Beaver Creek, and concentrations of toluene in ground water reaching Beaver Creek decreased during the study period. It is uncertain if the toluene detected in ground-water/vapor samples collected at Beaver Creek is due solely to fuel-burning activities at the fire pits. Based on the water-table contour map (fig. 3), the upstream Beaver Creek sampling sites BCK1 and BCK2 are not located hydraulically downgradient of the fire pits. Thus, fuel-contaminated soils adjacent to the fire pit would not be expected to influence the quality of ground water passing through BCK1 and BCK2. Another potential source of petroleum contamination that may be unrelated to the fire pits includes buried landfill materials which are present in the northern portion of the study area (fig. 4). Although there may be more than one source of toluene at the creek sampling sites, the highest toluene concentrations occurred in those ground-water/vapor samples collected at BCK4, BCK5, and BCK7, which are downgradient of the fire pits.

TOLUENE BIODEGRADATION RATE CONSTANTS

Field measurements of soil-vapor, ground-water, and ground-water/vapor samples indicated that toluene is the predominant TEX compound present at the study area. Laboratory experiments were performed on sediment samples collected from the study site to determine if *in situ* microorganisms are capable of degrading toluene. The production of $^{14}CO_2$ from ^{14}C-toluene in laboratory microcosms during the 23-week time period is shown in figure 9. The general trend of $^{14}CO_2$ production was one of rapid production during the first week and slower production up to 23 weeks. This is a common phenomena observed in laboratory microcosm studies. The initial production of $^{14}CO_2$ reflects the true oxidation of ^{14}C-toluene by microorganisms; this amount was used to determine biodegradation rate constants. After one week of incubation, however, microorganisms that had oxidized ^{14}C-toluene to $^{14}CO_2$ (and had incorporated some of the ^{14}C-toluene into their biomass) have died. Subsequent generations of microorganisms then had two pools of radiolabel to oxidize; the added substrate and the biomass of dead microbial cells. Such "cell turnover" was not included in determination of the rate constant.
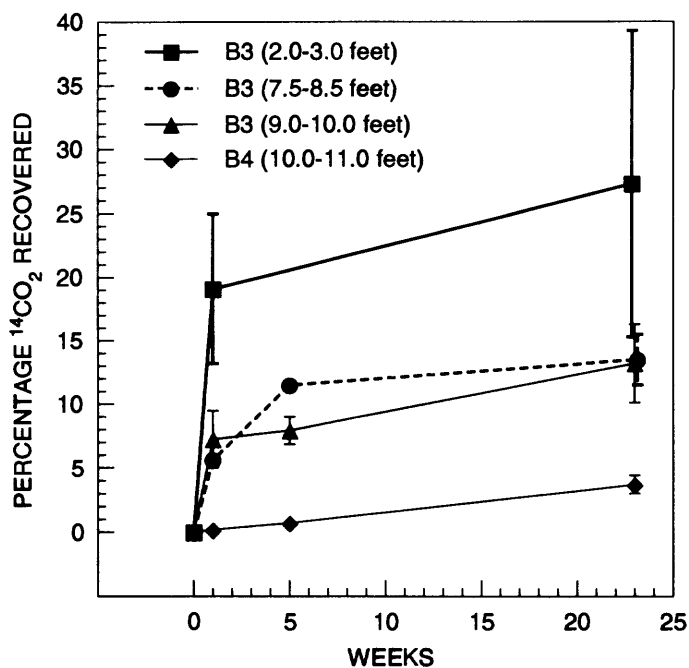
Figure 9.--Percent $^{14}CO^2$ recovery from ^{14}C-toluene during a 23-week incubation period in laboratory microcosms containing sediment from borings B3 and B4, Fort Bragg, North Carolina.

In one week of incubation, aquifer sediments from the unsaturated zone of B3 mineralized approximately 19 percent of the added ^{14}C-toluene to ^{14}CO$_2$ (fig. 9). A first-order anaerobic biodegradation rate constant can be calculated (0.19/7 days), or 0.027 d^{-1}. In the same time period, partially saturated and saturated sediment from B3 mineralized about 5.5 and 7 percent, respectively, of the added ^{14}C-toluene to ^{14}CO$_2$. Anaerobic biodegradation rate constants for these sediments are 0.007 d^{-1} (0.055/7 days) and 0.010 d^{-1} (0.07/7 days), respectively. Saturated sediments from B4 mineralized less than 1 percent of the radiolabeled toluene into radiolabeled CO$_2$ within one week, for a first-order biodegradation rate constant of 0.001 d^{-1} (0.01/7 days).

The production of ^{14}CO$_2$ shown in figure 9 illustrates a typical acclimation response of microorganisms to hydrocarbon contamination in sediments collected from B3 and B4. The highest anaerobic respiration rate observed is in the most hydrocarbon contaminated area (unsaturated sediment from B3 that received recharge entrained with unburned fuel), and the lowest rate is seen in the saturated sediments from B4, downgradient from the contaminant source. This type of acclimation to contamination in ground-water systems has been observed widely (Wilson and others, 1985; Madsen and others, 1991).

At B3, the unsaturated sediments produced three times the amount of ^{14}CO$_2$ from ^{14}C-toluene as sediments from the partially saturated zone and saturated zone in the first week of incubation. Not only does this indicate an acclimation response, but also suggests that biodegradation processes are faster in the unsaturated zone than in the saturated zone. Because microbes need a carbon source, electron acceptor, and water for metabolism, it follows that the variable in least amount will determine the rate of degradation. In the saturated zone, the primary rate-limiting step in the degradation of petroleum hydrocarbons is the diffusion of oxygen into the water column. In the unsaturated zone, however, this constraint is considerably reduced. These results imply that an active community of aromatic hydrocarbon degrading microorganisms exist in the unsaturated zone at this, and probably other, landfills with fuel-contaminated soils at Fort Bragg.

The determination of petroleum hydrocarbon biodegradation rate constants using field and laboratory data provides a powerful approach to estimate the effect of accidental releases on the environment. A reasonable agreement of rate-constant determinations derived from both areas provides a higher degree of confidence that the data reflect actual in situ conditions, than if these constants were reported separately. Although toluene biodegradation rate constants derived from ground-water analytical data are considered to be a maximum, the calculated range of 0.002 to 0.026 d^{-1} based on field data is similar to the range of 0.001 to 0.027 d^{-1} for toluene biodegradation rate constants measured by laboratory microcosm studies. The close agreement of toluene biodegradation rate constants reported using both approaches offers strong evidence that toluene can be degraded at environmentally significant rates at the study site.

SUMMARY AND CONCLUSIONS

From June 1994 through June 1995, an investigation was conducted at the Knox Street fire pits, Fort Bragg, North Carolina, to monitor toluene, ethylbenzene, and xylene (TEX) concentrations in soil vapor, ground water, and ground-water/vapor to determine if total concentrations of TEX at the site are decreasing with time, and to quantify biodegradation rate constants of toluene in the unsaturated and saturated zones. The original fire pit was a shallow, sand-lined basin that was used for fire-training purposes in which various fuels were ignited and extinguished. Later fire pits were redesigned with concrete linings. Unburned fuel seeped directly into the soil beneath the sand-lined pit, or was at times, released over a shallow curb of the concrete-lined pits. The focus of this report is on the distribution of TEX compounds and the evaluation of toluene biodegradation rate constants at the study site.

Hydrogeologic units beneath the fire pits consist of a shallow sandy aquifer, a clay confining unit below the shallow aquifer, and the Cape Fear aquifer below the confining unit. The water table is 7 to 9 ft bls in the shallow aquifer.

There were 6 monitoring stations installed around the fire pits to collect samples of soil vapor and ground water at depths up to 13 ft bls. Also, there were 7 sites located along and within several feet of Beaver Creek at which ground-water/vapor samples were collected. Samples were collected monthly at each site during the investigation. All samples were transported to a nearby location where they were analyzed using a portable field GC. Measurements of toluene biodegradation rate constants were made in a laboratory.

Based on the field GC analysis of soil-vapor and ground-water samples collected at monitoring stations FP1 through FP5 on the fire pit 2 transect line, contamination levels of TEX compounds in soil and ground-water decrease downgradient of the fire-pit source area. Along the transect, soil-vapor and ground-water TEX concentrations were highest at FP3 on the east side of fire pit 2. The lowest total TEX concentrations observed for soil vapor and ground water were for samples collected at FP5, which is hydraulically downgradient of FP3.

Soil-vapor TEX concentrations at the study site are seasonally influenced. Soil-vapor TEX concentrations generally decreased from June 1994 until January and February 1995. The trend then reversed, and the TEX concentrations increased until June 1995. Soil-vapor TEX concentrations also varied with depth at some locations depending on the month of sample collection. For some monitoring stations, soil-vapor TEX concentrations generally were higher for samples collected from deeper depths during December through February. Conversely, soil-vapor TEX concentrations generally were higher for samples collected at shallower depths during warmer months. Similar trends also were observed for subsurface soil temperatures.

An examination of both soil-vapor TEX concentrations and seasonal soil temperature indicated that there was a statistically significant correlation between TEX concentration and soil temperature at some of the sampling locations. This correlation, where total TEX concentrations increase as soil temperatures increase, likely reflects more volatilization of TEX compounds from the fuel-contaminated soils into the vapor phase as temperatures increase because of associated increases in the vapor pressure of the individual TEX compounds. Although temperature is one factor that influences the soil-vapor TEX concentrations, other factors, such as soil-moisture content, also appear to be important.

During the 1-year study period, the observed temporal and spatial changes in soil-vapor TEX concentrations reflect differences in the distribution of TEX compounds among solid, aqueous, and gaseous phases within soils of the unsaturated zone that contain a pool of residual fuel contamination. To distinguish between seasonal fluctuations in TEX concentrations during a given year and an overall long-term net decrease in TEX concentrations at the site, additional

sample collection and analysis would be needed over a period of years.

Unlike soil-vapor TEX concentration data, no seasonal pattern was evident for ground-water TEX concentrations at the study site. The ground-water TEX concentrations for samples collected at a given monitoring station varied during the 1-year study period, which may be due to a combination of factors, such as changes in source inputs, dilution, volatilization, sorption, and biological degradation.

Although the ground-water sample analyses could not be used to determine if concentrations of TEX compounds in ground water decreased with time at a specific location, an examination of the data indicated that concentration levels of TEX compounds were lower in ground water downgradient of the fire-pit source area. In addition, ground-water analytical results were used to examine potential rates of toluene biodegradation for anaerobic saturated zone conditions. Based on ground-water analytical data, the maximum rate constant for anaerobic biodegradation of toluene in the saturated zone is estimated to range from 0.002 to 0.026 d^{-1}. The actual rate constants of biodegradation will be lower if other processes, such as volatilization, dilution, and sorption, contribute to observed decreases in ground-water toluene concentrations.

Samples of ground-water/vapor collected adjacent to Beaver Creek were analyzed with a field GC to determine if TEX compounds were present in ground water at the point of discharge. Toluene generally was the only TEX compound detected in these samples. The presence of toluene and absence of ethylbenzene and xylenes in the ground-water/vapor samples may reflect differences in the transport mobility of these compounds. The transport of ethylbenzene and xylenes in ground water flowing from the fire pits to Beaver Creek may be retarded to a higher degree than toluene because of their lower aqueous solubilities and higher sorption to aquifer materials.

A peak in ground-water/vapor toluene concentrations, with values up to 33 ppm, was observed at stations BCK1, BCK2, BCK4, BCK5, and BCK7 between July and August 1994. After December 1994, toluene in ground-water/vapor samples was detected at concentrations less than 1 ppm. The decrease in ground-water/vapor toluene concentrations

during the study period may reflect a decrease in source inputs, an increase in dilution caused by higher ground-water flow, and(or) removal by biological or other physical processes. Based on analyses of ground-water/vapor samples collected adjacent to Beaver Creek, it appears that toluene was the principal TEX compound present in ground water reaching Beaver Creek and that concentrations of toluene in ground water reaching Beaver Creek decreased during the study period. When the analytical results of the ground-water/vapor samples are examined with respect to the ground-water flow system, it is unclear whether the toluene observed at Beaver Creek sites is derived from more than one source. Other potential sources of toluene include landfill materials that are buried in the vicinity of the fire pits. To more quantitatively define the distribution and concentrations of fuel constituents present in ground water discharging to Beaver Creek, direct chemical analysis of ground water and surface-water samples from Beaver Creek would be needed.

Laboratory experiments were performed on sediment samples collected from borings B3 and B4 at the fire pits to measure biodegradation rate constants of toluene by *in situ* microorganisms. A first-order anaerobic biodegradation rate constant of 0.027 d^{-1} was determined for the unsaturated zone sample collected from B3. Anaerobic biodegradation rate constants of 0.007 and 0.010 d^{-1} were determined for the partially saturated zone sample and the saturated zone sample collected at B3, respectively. At boring B4, a first-order biodegradation rate constant of 0.001 d^{-1} was measured. The data illustrate a typical acclimation response of microorganisms to hydrocarbon contamination in sediments collected from B3 and B4. The results also suggest that biodegradation processes are faster in the unsaturated zone than in the saturated zone.

At the fire-pit study site, toluene anaerobic biodegradation rate constants determined from field data and laboratory measurements are similar. Biodegradation rate constants derived from ground-water analytical data ranged from 0.002 to 0.026 d^{-1}, and laboratory derived rate constants ranged from 0.001 to 0.027 d^{-1}. The close agreement of toluene biodegradation rate constants reported using both approaches offer strong evidence that toluene can be degraded at environmentally significant rates at the study site.

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APPENDIX

26

Appendix A - Field GC analytical results for soil-vapor samples

[Field GC results are rounded to two decimal places; ft, feet; ppm, parts per million; nd, no data; <0.01, analytical result is less than reporting limit of 0.01 ppm]

Soil-Vapor Samples

Site	Depth (ft)	Date	Toluene (ppm)	Ethylbenzene (ppm)	m,p-xylene (ppm)	o-xylene (ppm)	[1]Total TEX (ppm)
FP1	2	6/7/94	12.00	1.21	0.83	2.85	16.89
FP1	4	6/7/94	nd	nd	nd	nd	nd
FP1	6	6/7/94	nd	nd	nd	nd	nd
FP1	2	7/11/94	12.15	0.59	0.63	1.20	14.57
FP1	4	7/11/94	10.48	0.63	0.67	1.30	13.08
FP1	6	7/11/94	8.79	0.45	0.34	0.31	9.89
FP1	2	8/22/94	10.18	0.64	0.42	0.51	11.75
FP1	4	8/22/94	11.35	0.66	0.46	0.49	12.96
FP1	6	8/22/94	11.18	0.73	0.51	0.51	12.93
FP1	2	9/21/94	9.38	0.46	0.28	0.23	10.35
FP1	4	9/21/94	9.53	0.42	0.19	0.20	10.34
FP1	6	9/21/94	9.65	0.58	0.37	0.67	11.27
FP1	2	10/25/94	5.30	0.26	0.16	0.27	5.99
FP1	4	10/25/94	5.30	0.23	0.15	0.33	6.01
FP1	6	10/25/94	6.12	0.56	0.25	0.56	7.49
FP1	2	12/1/94	6.69	0.12	0.07	0.04	6.92
FP1	4	12/1/94	7.78	0.13	0.07	0.04	8.02
FP1	6	12/1/94	9.25	0.57	0.27	0.29	10.38
FP1	2	1/26/95	2.59	0.69	0.03	<0.01	3.31
FP1	4	1/26/95	4.38	0.01	0.05	<0.01	4.44
FP1	6	1/26/95	5.00	0.25	0.09	<0.01	5.34
FP1	2	2/22/95	1.60	0.03	0.01	0.06	1.70
FP1	4	2/22/95	5.25	0.08	0.03	0.11	5.47
FP1	6	2/22/95	5.06	0.09	0.03	0.08	5.26
FP1	2	3/23/95	9.65	0.34	0.14	0.59	10.72
FP1	4	3/23/95	7.28	0.07	0.03	0.03	7.41
FP1	6	3/23/95	6.25	0.15	0.08	0.27	6.75
FP1	2	4/18/95	15.41	0.49	0.20	0.89	16.99
FP1	4	4/18/95	13.89	0.52	0.22	0.87	15.50
FP1	6	4/18/95	9.90	0.44	0.20	0.77	11.31
FP1	2	5/23/95	14.28	0.90	0.51	2.31	18.00
FP1	4	5/23/95	14.35	0.87	0.50	2.24	17.96
FP1	6	5/23/95	12.08	0.77	0.46	1.91	15.22
FP1	2	6/21/95	22.28	1.60	0.89	5.13	29.90
FP1	4	6/21/95	21.82	1.67	1.01	4.78	29.28
FP1	6	6/21/95	20.64	1.57	0.98	4.64	27.83

Appendix A - Field GC analytical results for soil-vapor samples--Continued

[Field GC results are rounded to two decimal places; ft, feet; ppm, parts per million; nd, no data; <0.01, analytical result is less than reporting limit of 0.01 ppm]

Soil-Vapor Samples

Site	Depth (ft)	Date	Toluene (ppm)	Ethylbenzene (ppm)	m,p-xylene (ppm)	o-xylene (ppm)	[1]Total TEX (ppm)
FP2	2	6/7/94	1.89	0.09	0.02	0.09	2.09
FP2	4	6/7/94	nd	nd	nd	nd	nd
FP2	6	6/7/94	14.6	1.28	1.01	0.92	17.81
FP2	2	7/11/94	4.46	0.37	0.15	0.19	5.17
FP2	4	7/11/94	16.95	1.04	0.83	1.40	20.22
FP2	6	7/11/94	13.94	0.74	0.86	1.62	17.16
FP2	2	8/22/94	nd	nd	nd	nd	nd
FP2	4	8/22/94	12.66	1.61	1.19	2.19	17.65
FP2	6	8/22/94	14.69	0.74	0.53	0.67	16.63
FP2	2	9/21/94	7.79	0.24	0.13	0.22	8.38
FP2	4	9/21/94	13.95	0.61	0.41	0.70	15.67
FP2	6	9/21/94	12.84	0.55	0.39	0.68	14.46
FP2	2	10/25/94	6.71	0.28	0.17	0.32	7.48
FP2	4	10/25/94	7.98	0.54	0.35	0.84	9.71
FP2	6	10/25/94	10.83	0.61	0.42	1.03	12.89
FP2	2	12/1/94	10.13	0.12	0.06	0.10	10.41
FP2	4	12/1/94	11.25	0.30	0.20	0.26	12.01
FP2	6	12/1/94	12.34	0.50	0.24	0.34	13.42
FP2	2	1/26/95	5.45	0.69	0.04	0.01	6.19
FP2	4	1/26/95	5.41	0.14	0.05	<0.01	5.60
FP2	6	1/26/95	7.55	0.25	0.09	<0.01	7.89
FP2	2	2/22/95	9.44	0.11	0.07	0.14	9.76
FP2	4	2/22/95	8.64	0.09	0.06	0.13	8.92
FP2	6	2/22/95	9.04	0.20	0.14	0.30	9.68
FP2	2	3/23/95	12.04	0.21	0.14	0.17	12.56
FP2	4	3/23/95	16.56	0.26	0.16	0.28	17.26
FP2	6	3/23/95	15.57	0.45	0.22	0.16	16.40
FP2	2	4/18/95	9.65	0.12	0.03	0.12	9.92
FP2	4	4/18/95	14.23	0.64	0.38	1.12	16.37
FP2	6	4/18/95	11.75	0.52	0.34	1.00	13.61
FP2	2	5/23/95	8.38	0.11	0.03	0.14	8.66
FP2	4	5/23/95	18.28	1.10	0.68	1.80	21.86
FP2	6	5/23/95	17.27	1.00	0.70	2.08	21.05
FP2	2	6/21/95	25.40	1.53	0.64	2.05	29.62
FP2	4	6/21/95	28.20	2.17	1.45	4.57	36.39
FP2	6	6/21/95	25.65	2.04	1.45	4.87	34.01

Appendix A - Field GC analytical results for soil-vapor samples--**Continued**

[Field GC results are rounded to two decimal places; ft, feet; ppm, parts per million; nd, no data; <0.01, analytical result is less than reporting limit of 0.01 ppm]

Soil-Vapor Samples

Site	Depth (ft)	Date	Toluene (ppm)	Ethylbenzene (ppm)	m,p-xylene (ppm)	o-xylene (ppm)	[1]Total TEX (ppm)
FP3	2	6/7/94	12.32	1.99	0.38	0.79	15.48
FP3	4	6/7/94	nd	nd	nd	nd	nd
FP3	6	6/7/94	nd	nd	nd	nd	nd
FP3	2	7/11/94	9.71	0.72	0.04	0.05	10.52
FP3	4	7/11/94	51.90	6.66	4.51	4.59	67.66
FP3	6	7/11/94	nd	nd	nd	nd	nd
FP3	2	8/22/94	21.17	4.44	1.18	2.05	28.84
FP3	4	8/22/94	42.38	4.67	2.72	2.80	52.57
FP3	6	8/22/94	nd	nd	nd	nd	nd
FP3	2	9/21/94	33.09	2.89	1.15	1.33	38.46
FP3	4	9/21/94	52.72	5.33	3.43	3.96	65.44
FP3	6	9/21/94	29.70	2.51	1.69	1.66	35.56
FP3	2	10/25/94	19.85	2.69	0.88	1.67	25.09
FP3	4	10/25/94	41.79	6.71	4.09	7.44	60.03
FP3	6	10/25/94	45.82	6.99	4.75	6.32	63.88
FP3	2	12/2/94	18.48	2.58	0.89	1.33	23.28
FP3	4	12/1/94	33.38	6.05	3.84	5.72	48.99
FP3	6	12/1/94	36.45	6.98	4.85	5.46	53.74
FP3	2	1/26/95	0.13	0.19	<0.01	<0.01	0.32
FP3	4	1/26/95	7.87	1.81	0.73	0.11	10.52
FP3	6	1/26/95	25.84	1.48	0.17	<0.01	27.49
FP3	2	2/22/95	0.06	0.01	<0.01	<0.01	0.07
FP3	4	2/22/95	20.02	3.02	1.22	1.94	26.2
FP3	6	2/22/95	23.43	3.57	2.00	2.14	31.14
FP3	2	3/23/95	0.18	0.01	<0.01	<0.01	0.19
FP3	4	3/23/95	34.69	7.47	4.42	4.23	50.81
FP3	6	3/23/95	33.35	6.31	4.03	5.09	48.78
FP3	2	4/18/95	0.04	<0.01	<0.01	<0.01	0.04
FP3	4	4/18/95	47.08	8.97	4.87	7.62	68.54
FP3	6	4/18/95	40.72	8.79	6.15	9.77	65.43
FP3	2	5/23/95	0.02	<0.01	<0.01	<0.01	0.02
FP3	4	5/23/95	55.08	12.79	7.58	11.82	87.27
FP3	6	5/23/95	45.82	7.30	3.78	3.56	60.46
FP3	2	6/21/95	0.01	<0.01	<0.01	<0.01	0.01
FP3	4	6/21/95	68.54	9.11	3.86	4.76	86.27
FP3	6	6/21/95	59.87	6.08	3.30	2.62	71.87

Appendix A - Field GC analytical results for soil-vapor samples--Continued

[Field GC results are rounded to two decimal places; ft, feet; ppm, parts per million; nd, no data; <0.01, analytical result is less than reporting limit of 0.01 ppm]

Soil-Vapor Samples

Site	Depth (ft)	Date	Toluene (ppm)	Ethylbenzene (ppm)	m,p-xylene (ppm)	o-xylene (ppm)	[1]Total TEX (ppm)
FP4	2	6/7/94	nd	nd	nd	nd	nd
FP4	4	6/7/94	21.16	1.75	0.93	0.88	24.72
FP4	7	6/7/94	9.19	0.74	0.35	0.42	10.70
FP4	2	7/12/94	20.26	1.40	0.93	1.04	23.63
FP4	4	7/12/94	19.08	1.28	0.71	0.69	21.76
FP4	7	7/12/94	12.45	0.60	0.25	0.40	13.70
FP4	2	8/22/94	14.56	0.53	0.33	<0.01	15.42
FP4	4	8/22/94	17.12	1.92	1.17	1.06	21.27
FP4	7	8/22/94	10.41	0.68	0.46	0.47	12.02
FP4	2	9/21/94	18.66	0.70	0.33	0.32	20.01
FP4	4	9/21/94	18.50	0.67	0.34	0.32	19.83
FP4	7	9/21/94	11.60	0.31	0.19	0.21	12.31
FP4	2	10/25/94	16.59	0.82	0.38	0.55	18.34
FP4	4	10/25/94	15.74	0.76	0.40	0.52	17.42
FP4	7	10/25/94	7.40	0.26	0.16	0.31	8.13
FP4	2	12/2/94	6.47	0.17	0.05	0.09	6.78
FP4	4	12/2/94	11.15	0.53	0.35	0.37	12.40
FP4	7	12/2/94	12.27	0.12	0.05	0.08	12.52
FP4	2	1/26/95	3.12	0.01	<0.01	<0.01	3.13
FP4	4	1/26/95	10.30	0.39	0.07	<0.01	10.76
FP4	7	1/26/95	7.34	1.13	0.01	<0.01	8.48
FP4	2	2/22/95	8.92	0.10	0.03	0.07	9.12
FP4	4	2/22/95	11.88	0.13	0.05	0.09	12.15
FP4	7	2/22/95	6.88	0.08	0.03	0.07	7.06
FP4	2	3/23/95	10.95	0.93	0.38	0.56	12.82
FP4	4	3/23/95	8.58	0.71	0.33	0.47	10.09
FP4	7	3/23/95	9.83	0.14	0.07	0.11	10.15
FP4	2	4/18/95	29.72	0.98	0.43	0.69	31.82
FP4	4	4/18/95	17.05	0.66	0.32	0.65	18.68
FP4	7	4/18/95	13.38	0.39	0.18	0.34	14.29
FP4	2	5/23/95	44.32	1.99	0.76	1.14	48.21
FP4	4	5/23/95	35.16	1.20	0.61	0.90	37.87
FP4	7	5/23/95	14.92	0.59	0.27	0.47	16.25
FP4	2	6/21/95	44.49	3.93	1.93	3.30	53.65
FP4	4	6/21/95	48.63	3.85	1.64	2.7	56.82
FP4	7	6/21/95	20.69	1.09	0.55	0.97	23.30

Appendix A - Field GC analytical results for soil-vapor samples--Continued

[Field GC results are rounded to two decimal places; ft, feet; ppm, parts per million; nd, no data; <0.01, analytical result is less than reporting limit of 0.01 ppm]

Soil-Vapor Samples

Site	Depth (ft)	Date	Toluene (ppm)	Ethylbenzene (ppm)	m,p-xylene (ppm)	o-xylene (ppm)	[1]Total TEX (ppm)
FP5	2	6/7/94	0.02	0.06	<0.01	<0.01	0.08
FP5	4	6/7/94	nd	nd	nd	nd	nd
FP5	2	7/12/94	<0.01	<0.01	<0.01	<0.01	0.01
FP5	4	7/12/94	<0.01	<0.01	<0.01	<0.01	0.01
FP5	2	8/22/94	<0.01	<0.01	<0.01	<0.01	0.01
FP5	4	8/22/94	<0.01	<0.01	<0.01	<0.01	0.01
FP5	2	9/21/94	0.05	0.01	<0.01	<0.01	0.06
FP5	4	9/21/94	0.04	<0.01	<0.01	<0.01	0.04
FP5	2	10/25/94	0.16	0.01	0.01	0.01	0.19
FP5	4	10/25/94	0.09	<0.01	<0.01	<0.01	0.09
FP5	2	12/1/94	0.03	<0.01	<0.01	<0.01	0.03
FP5	4	12/1/94	0.03	<0.01	<0.01	<0.01	0.03
FP5	2	1/26/95	0.04	<0.01	<0.01	<0.01	0.04
FP5	4	1/26/95	0.03	<0.01	<0.01	<0.01	0.03
FP5	2	2/22/95	0.05	<0.01	<0.01	<0.01	0.05
FP5	4	2/22/95	0.02	<0.01	<0.01	<0.01	0.02
FP5	2	3/23/95	0.02	<0.01	<0.01	<0.01	0.02
FP5	4	3/23/95	0.01	<0.01	<0.01	<0.01	0.01
FP5	2	4/18/95	0.06	0.01	0.01	<0.01	0.08
FP5	4	4/18/95	0.04	0.01	<0.01	<0.01	0.05
FP5	2	5/23/95	0.04	<0.01	<0.01	<0.01	0.04
FP5	4	5/23/95	0.03	<0.04	<0.01	<0.01	0.03
FP5	2	6/21/95	0.03	<0.01	<0.01	0.01	0.04
FP5	4	6/21/95	nd	nd	nd	nd	nd
FP10	2	6/7/94	nd	nd	nd	nd	nd
FP10	4	6/7/94	nd	nd	nd	nd	nd
FP10	6	6/7/94	nd	nd	nd	nd	nd
FP10	10	6/7/94	7.70	2.05	0.65	1.25	11.65
FP10	2	7/12/94	114.26	26.72	13.32	29.28	183.58
FP10	4	7/12/94	195.00	33.92	27.98	58.52	315.42
FP10	6	7/12/94	121.20	36.67	22.96	39.67	220.50
FP10	10	7/12/94	4.63	1.39	0.87	1.28	8.17
FP10	2	8/22/94	nd	nd	nd	nd	nd
FP10	4	8/22/94	nd	nd	nd	nd	nd
FP10	6	8/22/94	85.90	23.55	13.29	23.44	146.18
FP10	10	8/22/94	11.50	3.57	1.31	2.75	19.13

Appendix A - Field GC analytical results for soil-vapor samples--Continued

[Field GC results are rounded to two decimal places; ft, feet; ppm, parts per million; nd, no data; <0.01, analytical result is less than reporting limit of 0.01 ppm]

Soil-Vapor Samples

Site	Depth (ft)	Date	Toluene (ppm)	Ethylbenzene (ppm)	m,p-xylene (ppm)	o-xylene (ppm)	[1]Total TEX (ppm)
FP10	2	9/21/94	92.10	6.63	2.84	5.16	106.73
FP10	4	9/21/94	161.25	26.76	14.00	19.92	221.93
FP10	6	9/21/94	85.70	9.00	2.69	6.32	103.71
FP10	10	9/22/94	11.18	1.25	0.35	0.89	13.67
FP10	2	10/25/94	123.25	14.69	5.09	12.20	155.23
FP10	4	10/25/94	133.15	20.52	9.06	16.60	179.33
FP10	6	10/25/94	109.86	11.16	3.14	8.24	132.40
FP10	10	10/25/94	8.91	2.43	0.64	1.55	13.53
FP10	2	12/2/94	117.98	10.61	5.22	11.41	145.22
FP10	4	12/2/94	145.30	17.70	7.20	16.85	187.05
FP10	6	12/2/94	101.44	13.44	4.57	11.30	130.75
FP10	10	12/2/94	14.91	2.92	0.93	2.41	21.17
FP10	2	1/26/95	74.15	3.53	<0.01	<0.01	77.68
FP10	4	1/26/95	62.04	7.00	3.09	9.63	81.76
FP10	6	1/26/95	49.00	5.87	1.53	2.17	58.57
FP10	10	1/26/95	8.16	1.40	0.40	1.17	11.13
FP10	2	2/22/95	87.16	8.04	3.56	10.42	109.18
FP10	4	2/22/95	85.08	9.85	4.52	14.15	113.60
FP10	6	2/22/95	51.16	7.35	2.36	7.75	68.62
FP10	2	3/23/95	79.08	7.37	2.18	5.28	93.91
FP10	4	3/23/95	111.20	31.16	11.45	28.36	182.17
FP10	6	3/23/95	73.10	9.80	2.01	7.70	92.61
FP10	2	4/18/95	102.94	12.07	2.51	9.92	127.44
FP10	4	4/18/95	134.50	28.60	9.69	24.22	197.01
FP10	6	4/18/95	109.48	17.31	4.37	15.88	147.04
FP10	2	5/23/95	118.08	20.88	4.63	18.13	161.72
FP10	4	5/23/95	210.65	73.37	38.36	71.08	393.46
FP10	6	5/23/95	84.30	17.80	5.30	15.26	122.66
FP10	2	6/21/95	154.95	28.32	4.98	19.55	207.80
FP10	4	6/21/95	46.06	5.99	0.69	5.28	58.02
FP10	6	6/21/95	104.80	23.22	6.42	22.26	156.70

[1] In determining total TEX concentration, a value of zero was used for individual TEX compounds having concentrations <0.01 ppm. However, when all TEX compounds for a sample had concentrations less than the reporting limit, the total TEX concentration was arbitrarily assigned a value of 0.01 ppm.

Appendix B - Field GC analytical results for ground-water samples

[Field GC results are rounded to two decimal places; ft, feet; μg/L, micrograms per liter; nd, no data; DUP, duplicate sample; <0.10, analytical result is less than reporting limit of 0.10 μg/L]

Ground-Water Samples

Site	Depth (ft)	Date	Toluene (μg/L)	Ethylbenzene (μg/L)	p-xylene (μg/L)	o-xylene (μg/L)	[1]Total TEX (μg/L)
FP1	10	6/7/94	nd	nd	nd	nd	nd
FP1	10	7/11/94	0.88	0.23	0.16	0.49	1.76
FP1	10	8/22/94	0.25	<0.10	<0.10	0.10	0.35
FP1	10	9/21/94	0.37	0.10	0.11	0.18	0.76
FP1	10	10/24/94	0.56	<0.10	0.13	0.27	0.96
FP1	10	11/30/94	0.83	0.13	0.19	0.43	1.58
FP1	10	1/25/95	0.54	<0.10	<0.10	<0.10	0.54
FP1	10	2/21/95	1.40	0.36	0.23	0.22	2.21
FP1	10	3/22/95	1.16	<0.10	0.15	1.11	2.42
FP1	10	4/19/95	1.02	0.16	0.22	0.36	1.76
FP1	10	5/23/95	1.24	0.21	<0.10	0.47	1.92
FP1	10	6/22/95	0.81	<0.10	<0.10	<0.10	0.81
FP2	10	6/7/94	0.21	0.11	0.11	0.18	0.61
FP2	13	6/7/94	<0.10	0.57	0.24	1.27	2.08
FP2	10	7/11/94	0.17	0.14	0.19	0.14	0.64
FP2	13	7/11/94	<0.10	0.39	0.28	0.25	0.92
FP2	10	8/22/94	0.17	0.20	0.19	0.27	0.83
FP2	13	8/22/94	<0.10	0.43	0.28	0.36	1.07
FP2	10	9/21/94	0.10	0.37	0.43	0.29	1.19
FP2	13	9/21/94	<0.10	0.30	0.16	0.54	1.00
FP2	10	10/24/94	0.19	<0.10	0.15	0.27	0.61
FP2	13	10/24/94	0.12	0.53	0.41	2.07	3.13
FP2	10	12/1/94	0.17	<0.10	0.18	0.26	0.61
FP2	13	12/1/94	<0.10	0.91	0.69	1.92	3.52
FP2	10	1/25/94	<0.10	<0.10	0.13	0.13	0.26
FP2	13	1/25/94	<0.10	<0.10	0.41	0.24	0.65
FP2	10	2/21/95	0.12	0.13	0.16	0.31	0.72
FP2	13	2/21/95	<0.10	1.04	0.49	1.33	2.86
FP2	10	3/22/95	<0.10	0.14	0.13	0.40	0.67
FP2	13	3/22/95	<0.10	0.22	0.20	0.63	1.05
FP2	10	4/19/95	<0.10	<0.10	<0.10	<0.10	0.10
FP2	13	4/19/95	<0.10	0.18	<0.10	<0.10	0.18
FP2	10	5/23/95	<0.10	<0.10	<0.10	<0.10	0.10
FP2	13	5/23/95	<0.10	0.31	0.22	0.68	1.21

Appendix B - Field GC analytical results for ground-water samples--Continued

[Field GC results are rounded to two decimal places; ft, feet; µg/L, micrograms per liter; nd, no data; DUP, duplicate sample; <0.10, analytical result is less than reporting limit of 0.10 µg/L]

Ground-Water Samples

Site	Depth (ft)	Date	Toluene (µg/L)	Ethylbenzene (µg/L)	p-xylene (µg/L)	o-xylene (µg/L)	[1]Total TEX (µg/L)
FP2	10	6/22/95	<0.10	<0.10	<0.10	<0.10	0.10
FP2	13	6/22/95	<0.10	1.10	0.43	2.43	3.96
FP3	10	6/7/94	nd	nd	nd	nd	nd
FP3	13	6/7/94	nd	nd	nd	nd	nd
FP3	10	7/11/94	nd	nd	nd	nd	nd
FP3	13	7/11/94	51.61	26.05	18.22	31.54	127.42
FP3	10	8/22/94	0.38	0.18	<0.10	0.14	0.70
FP3	13	8/22/94	<0.10	3.06	1.83	11.58	16.47
FP3	10	9/21/94	0.32	2.37	1.52	8.86	13.07
FP3	13	9/21/94	0.19	4.31	2.55	18.78	25.83
FP3	10	10/24/94	0.26	1.07	0.58	4.27	6.18
FP3	13	10/24/94	0.40	6.90	4.27	36.93	48.50
FP3	10	12/1/94	0.31	1.06	0.76	2.78	4.91
FP3	10.DUP	12/1/94	0.27	0.92	0.59	3.45	5.23
FP3	13	12/1/94	0.49	4.47	2.83	11.05	18.84
FP3	10	1/26/95	nd	nd	nd	nd	nd
FP3	13	1/26/95	0.30	1.60	0.71	2.00	4.61
FP3	10	2/21/95	0.29	3.48	3.06	6.71	13.54
FP3	13	2/21/95	0.41	5.28	3.25	10.08	19.02
FP3	10	3/22/95	0.19	2.64	1.83	16.54	21.20
FP3	13	3/22/95	0.16	6.93	4.10	42.30	53.49
FP3	10	4/19/95	0.15	1.48	0.49	4.16	6.28
FP3	13	4/19/95	<0.10	4.60	2.93	26.49	34.02
FP3	10	5/23/95	<0.10	0.71	0.42	5.11	6.24
FP3	13	5/23/95	0.11	2.57	1.60	15.49	19.77
FP3	10	6/22/95	0.22	2.03	1.49	4.09	7.83
FP3	13	6/22/95	0.15	1.41	0.49	8.07	10.12
FP4	10	6/7/94	nd	nd	nd	nd	nd
FP4	13	6/7/94	0.77	<0.10	0.12	0.13	1.02
FP4	13.DUP	6/7/94	0.57	0.10	0.16	0.14	0.97
FP4	10	7/12/94	nd	nd	nd	nd	nd
FP4	13	7/12/94	1.33	0.52	0.37	0.59	2.81
FP4	10	8/22/94	2.08	0.22	0.28	0.20	2.78
FP4	13	8/22/94	0.82	0.23	0.23	0.24	1.52
FP4	10	9/21/94	nd	nd	nd	nd	nd

Appendix B - Field GC analytical results for ground-water samples--**Continued**

[Field GC results are rounded to two decimal places; ft, feet; μg/L, micrograms per liter; nd, no data; DUP, duplicate sample; <0.10, analytical result is less than reporting limit of 0.10 μg/L]

Ground-Water Samples

Site	Depth (ft)	Date	Toluene (μg/L)	Ethylbenzene (μg/L)	p-xylene (μg/L)	o-xylene (μg/L)	[1]Total TEX (μg/L)
FP4	13	9/21/94	1.17	0.52	0.61	0.38	2.68
FP4	13.DUP	9/21/94	1.40	0.36	0.43	1.50	3.69
FP4	10	10/24/94	3.49	0.54	0.65	0.47	5.18
FP4	13	10/24/94	1.85	0.29	0.33	0.51	2.98
FP4	10	11/30/94	nd	nd	nd	nd	nd
FP4	13	11/30/94	1.29	0.19	0.28	0.40	2.16
FP4	10	1/26/95	1.65	<0.10	0.22	<0.10	1.87
FP4	13	1/26/95	1.10	0.16	0.15	0.10	1.51
FP4	10	2/21/95	1.75	0.21	0.23	0.21	2.40
FP4	10.DUP	2/21/95	1.61	0.19	0.18	0.13	2.11
FP4	13	2/21/95	1.16	0.31	0.19	0.20	1.86
FP4	10	3/22/95	1.81	0.16	0.16	0.26	2.39
FP4	13	3/22/95	1.22	0.39	0.18	<0.10	1.79
FP4	10	4/19/95	2.45	0.20	0.23	0.31	3.19
FP4	13	4/19/95	1.26	0.16	0.17	0.33	1.92
FP4	10	5/23/95	2.33	0.16	<0.10	<0.10	2.49
FP4	10.DUP	5/23/95	1.92	0.16	<0.10	<0.10	2.08
FP4	13	5/23/95	0.91	0.17	<0.10	<0.10	1.08
FP4	10	6/22/95	5.30	0.45	0.21	1.41	7.37
FP4	13	6/22/95	1.89	<0.10	<0.10	<0.10	1.89
FP5	6	6/7/94	<0.10	0.12	0.15	<0.10	0.27
FP5	6	7/12/94	<0.10	0.17	0.12	0.69	0.98
FP5	6	8/22/94	<0.10	<0.10	<0.10	0.11	0.11
FP5	6	9/21/94	<0.10	<0.10	<0.10	<0.10	0.10
FP5	6	10/24/94	0.16	0.39	0.49	0.18	1.22
FP5	6	11/30/94	<0.10	<0.10	0.10	0.05	0.15
FP5	6	1/26/95	<0.10	<0.10	<0.10	<0.10	0.10
FP5	6	2/21/95	<0.10	<0.10	<0.10	<0.10	0.10
FP5	6	3/22/95	<0.10	<0.10	<0.10	<0.10	0.10
FP5	6	4/19/95	<0.10	<0.10	<0.10	<0.10	0.10
FP5	6	5/23/95	<0.10	<0.10	<0.10	<0.10	0.10
FP5	6	6/22/95	<0.10	<0.10	<0.10	<0.10	0.10
FP10	10	6/7/94	nd	nd	nd	nd	nd
FP10	13	6/7/94	nd	nd	nd	nd	nd
FP10	10	7/12/94	nd	nd	nd	nd	nd

Appendix B - Field GC analytical results for ground-water samples--Continued

[Field GC results are rounded to two decimal places; ft, feet; μg/L, micrograms per liter; nd, no data; DUP, duplicate sample; <0.10, analytical result is less than reporting limit of 0.10 μg/L]

Ground-Water Samples

Site	Depth (ft)	Date	Toluene (μg/L)	Ethylbenzene (μg/L)	p-xylene (μg/L)	o-xylene (μg/L)	[1]Total TEX (μg/L)
FP10	13	7/12/94	0.18	0.23	0.17	0.11	0.69
FP10	10	8/22/94	nd	nd	nd	nd	nd
FP10	13	8/22/94	0.12	<0.10	<0.10	<0.10	0.12
FP10	10	9/22/94	nd	nd	nd	nd	nd
FP10	13	9/22/94	0.11	0.14	0.16	0.16	0.57
FP10	10	10/25/94	nd	nd	nd	nd	nd
FP10	13	10/25/94	0.48	0.13	0.21	<0.10	0.82
FP10	10	12/2/94	nd	nd	nd	nd	nd
FP10	13	12/2/94	0.21	0.10	0.24	0.22	0.77
FP10	10	1/26/95	nd	nd	nd	nd	nd
FP10	13	1/26/95	<0.10	<0.10	<0.10	<0.10	0.10
FP10	10	2/21/95	3.64	0.97	<0.10	1.02	5.63
FP10	13	2/21/95	0.19	1.10	0.44	<0.10	1.73
FP10	13.DUP	2/21/95	0.26	0.35	0.53	<0.10	1.14
FP10	10	3/22/95	1.33	0.56	0.16	0.45	2.50
FP10	13	3/22/95	<0.10	<0.10	<0.10	0.15	0.15
FP10	10	4/19/95	1.80	0.49	0.12	0.98	3.39
FP10	13	4/19/95	<0.10	0.14	0.21	<0.10	0.35
FP10	10	5/23/95	1.90	1.12	0.27	1.49	4.78
FP10	13	5/23/95	<0.10	<0.10	<0.10	<0.10	0.10
FP10	10	6/22/95	2.54	0.75	<0.10	<0.10	3.29
FP10	13	6/22/95	0.12	<0.10	<0.10	<0.10	0.12

[1] In determining total TEX concentration, a value of zero was used for individual TEX compounds having concentrations <0.10 μg/L. However, when all TEX compounds for a sample had concentrations less than the reporting limit, the total TEX concentration was arbitrarily assigned a value of 0.10 μg/L.

Appendix C - Field GC analytical results for ground-water/vapor samples

[Field GC results are rounded to two decimal places; ft, feet; ppm, parts per million; DUP, duplicate sample; <0.01, analytical result is less than reporting limit of 0.01 ppm]

			Ground-Water/Vapor Samples			
Site	Depth (ft)	Date	Toluene (ppm)	Ethylbenzene (ppm)	m,p-xylene (ppm)	o-xylene (ppm)
BCK1	2	6/8/94	0.06	<0.01	<0.01	<0.01
BCK1	2	7/13/94	9.32	<0.01	<0.01	<0.01
BCK1	2	8/23/94	3.31	<0.01	<0.01	<0.01
BCK1	2	9/21/94	1.58	<0.01	<0.01	<0.01
BCK1	2	10/24/94	0.83	<0.01	<0.01	<0.01
BCK1	2	12/1/94	0.02	<0.01	<0.01	<0.01
BCK1	2	1/25/95	0.03	<0.01	<0.01	<0.01
BCK1	2	2/21/95	<0.01	<0.01	<0.01	<0.01
BCK1	2	3/22/95	<0.01	<0.01	<0.01	<0.01
BCK1	2.DUP	3/22/95	<0.01	<0.01	<0.01	<0.01
BCK1	2	4/17/95	<0.01	<0.01	<0.01	<0.01
BCK1	2	5/22/95	<0.01	<0.01	<0.01	<0.01
BCK1	2	6/20/95	<0.01	<0.01	<0.01	<0.01
BCK2	2	6/8/94	0.48	<0.01	<0.01	<0.01
BCK2	2	7/13/94	1.75	<0.01	<0.01	<0.01
BCK2	2	8/23/94	4.64	<0.01	<0.01	<0.01
BCK2	2	9/21/94	0.25	<0.01	<0.01	<0.01
BCK2	2	10/24/94	0.27	<0.01	<0.01	<0.01
BCK2	2	12/1/94	0.01	<0.01	<0.01	<0.01
BCK2	2	1/25/95	<0.01	<0.01	<0.01	<0.01
BCK2	2	2/21/95	<0.01	<0.01	<0.01	<0.01
BCK2	2	3/22/95	0.03	<0.01	<0.01	<0.01
BCK2	2	4/17/95	<0.01	<0.01	<0.01	<0.01
BCK2	2	5/22/95	<0.01	<0.01	<0.01	<0.01
BCK2	2	6/20/95	<0.01	<0.01	<0.01	<0.01
BCK3	2	6/8/94	0.05	0.10	0.01	0.19
BCK3	2	7/13/94	0.01	<0.01	<0.01	<0.01
BCK3	2.DUP	7/13/94	<0.01	<0.01	<0.01	<0.01
BCK3	2	8/23/94	0.05	<0.01	<0.01	<0.01
BCK3	2	9/21/94	0.01	<0.01	<0.01	<0.01
BCK3	2	10/24/94	0.01	<0.01	<0.01	<0.01
BCK3	2	12/1/94	<0.01	<0.01	<0.01	0.01
BCK3	2.DUP	12/1/94	<0.01	<0.01	<0.01	<0.01

Appendix C - Field GC analytical results for ground-water/vapor samples--Continued

[Field GC results are rounded to two decimal places; ft, feet; ppm, parts per million; DUP, duplicate sample; <0.01, analytical result is less than reporting limit of 0.01 ppm]

			Ground-Water/Vapor Samples			
Site	Depth (ft)	Date	Toluene (ppm)	Ethylbenzene (ppm)	m,p-xylene (ppm)	o-xylene (ppm)
BCK3	2	1/25/95	<0.01	<0.01	<0.01	<0.01
BCK3	2	2/21/95	<0.01	<0.01	<0.01	<0.01
BCK3	2	3/22/95	<0.01	<0.01	<0.01	<0.01
BCK3	2	4/17/95	<0.01	<0.01	<0.01	<0.01
BCK3	2.DUP	4/17/95	<0.01	<0.01	<0.01	<0.01
BCK3	2	5/22/95	<0.01	<0.01	<0.01	<0.01
BCK3	2	6/20/95	<0.01	<0.01	<0.01	<0.01
BCK4	2	6/8/94	0.85	<0.01	<0.01	<0.01
BCK4	2	7/13/94	23.42	<0.01	<0.01	<0.01
BCK4	2	8/23/94	15.54	<0.01	<0.01	<0.01
BCK4	2	9/21/94	6.41	<0.01	<0.01	<0.01
BCK4	2	10/24/94	4.57	<0.01	<0.01	<0.01
BCK4	2.DUP	10/24/94	4.32	<0.01	<0.01	<0.01
BCK4	2	12/1/94	6.42	<0.01	<0.01	<0.01
BCK4	2	1/25/95	<0.01	<0.01	<0.01	<0.01
BCK4	2	2/21/95	<0.01	<0.01	<0.01	<0.01
BCK4	2	3/22/95	0.47	<0.01	<0.01	<0.01
BCK4	2	4/17/95	<0.01	<0.01	<0.01	<0.01
BCK4	2	5/22/95	0.18	<0.01	<0.01	<0.01
BCK4	2	6/20/95	0.02	<0.01	<0.01	<0.01
BCK5	2	6/8/94	0.02	<0.01	<0.01	<0.01
BCK5	2	7/13/94	21.09	<0.01	<0.01	<0.01
BCK5	2	8/23/94	9.97	<0.01	<0.01	<0.01
BCK5	2	9/21/94	0.02	<0.01	<0.01	<0.01
BCK5	2	10/24/94	0.06	<0.01	<0.01	<0.01
BCK5	2	12/1/94	<0.01	<0.01	<0.01	<0.01
BCK5	2	1/25/95	<0.01	<0.01	<0.01	<0.01
BCK5	2	2/21/95	0.01	<0.01	<0.01	<0.01
BCK5	2.DUP	2/21/95	0.01	<0.01	<0.01	<0.01
BCK5	2	3/22/95	<0.01	<0.01	<0.01	<0.01
BCK5	2	4/17/95	0.01	<0.01	<0.01	<0.01
BCK5	2	5/22/95	0.06	<0.01	<0.01	<0.01
BCK5	2	6/20/95	1.06	<0.01	<0.01	<0.01

Appendix C - Field GC analytical results for ground-water/vapor samples--Continued

[Field GC results are rounded to two decimal places; ft, feet; ppm, parts per million; DUP, duplicate sample; <0.01, analytical result is less than reporting limit of 0.01 ppm]

			Ground-Water/Vapor Samples			
Site	Depth (ft)	Date	Toluene (ppm)	Ethylbenzene (ppm)	m,p-xylene (ppm)	o-xylene (ppm)
BCK6	2	6/8/94	<0.01	<0.01	<0.01	<0.01
BCK6	2	7/13/94	<0.01	<0.01	<0.01	<0.01
BCK6	2	8/23/94	0.02	<0.01	<0.01	<0.01
BCK6	2	9/21/94	0.04	<0.01	<0.01	<0.01
BCK6	2	10/24/94	0.01	<0.01	<0.01	<0.01
BCK6	2	12/1/94	<0.01	<0.01	<0.01	<0.01
BCK6	2	1/25/95	<0.01	<0.01	<0.01	<0.01
BCK6	2.DUP	1/25/95	<0.01	<0.01	<0.01	<0.01
BCK6	2	2/21/95	<0.01	<0.01	<0.01	<0.01
BCK6	2	3/22/95	<0.01	<0.01	<0.01	<0.01
BCK6	2	4/17/95	0.03	<0.01	<0.01	<0.01
BCK6	2	5/22/95	0.01	<0.01	<0.01	<0.01
BCK6	2	6/20/95	<0.01	<0.01	<0.01	<0.01
BCK7	2	6/8/94	0.10	<0.01	<0.01	<0.01
BCK7	2	7/13/94	33.17	<0.01	<0.01	<0.01
BCK7	2	8/23/94	0.09	<0.01	<0.01	<0.01
BCK7	2	9/21/94	1.86	<0.01	<0.01	<0.01
BCK7	2	10/24/94	5.09	0.01	<0.01	<0.01
BCK7	2	12/1/94	<0.01	<0.01	<0.01	<0.01
BCK7	2	1/25/95	<0.01	<0.01	<0.01	<0.01
BCK7	2	2/21/95	0.01	<0.01	<0.01	<0.01
BCK7	2	3/22/95	<0.01	<0.01	<0.01	<0.01
BCK7	2	4/17/95	<0.01	<0.01	<0.01	<0.01
BCK7	2	5/22/95	0.24	<0.01	<0.01	<0.01
BCK7	2	6/20/95	0.04	<0.01	<0.01	<0.01