United States
Environmental Protection
Agency

Office of Research and
Development
Washington DC 20460

EPA/600/R-96/145
December 1996

EPA

Enhanced Bioremediation of BTEX Using Immobilized Nutrients

Field Demonstration and Monitoring

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Enhanced Bioremediation of BTEX Using Immobilized Nutrients

Field Demonstration and Monitoring

by

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Cooperative Agreement Number
CR820468

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NATIONAL EXPOSURE RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
US ENVIRONMENTAL PROTECTION AGENCY
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The U.S. Environmental Protection Agency (EPA), through its Office of Research and Development (ORD), partially funded and collaborated in the research described here. It has been peer reviewed by the Agency and approved as an EPA publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Abstract

A permeable barrier system was developed for controlling the migration of dissolved contaminant plumes in ground water. The barrier system consisted of a line of closely spaced wells installed perpendicular to the contaminant plume. Each well contained concrete briquets that released oxygen and nitrate at a controlled rate, enhancing the aerobic biodegradation of dissolved hydrocarbons in the downgradient aquifer.

Laboratory batch reactor experiments were conducted to identify concrete mixtures that slowly released oxygen over an extended time period. Concretes prepared with urea hydrogen peroxide were unacceptable while concretes prepared with calcium peroxide and a proprietary formulation of magnesium peroxide gradually released oxygen at a steadily declining rate over a three- to six-month period.

A full-scale permeable barrier system was constructed at a gasoline-spill site near Leland, NC. Initially, increased dissolved oxygen and decreased benzene, toluene, ethylbenzene, and xylene isomer (BTEX) concentrations in the downgradient aquifer indicated that oxygen released from the remediation wells was enhancing biodegradation. Over time, treatment efficiencies declined, suggesting that the barrier system was becoming less effective in releasing oxygen and nutrients to the aquifer. Field tracer tests and soil analyses performed at the conclusion of the project indicated that the aquifer in the vicinity of the remediation wells was being clogged by precipitation of iron minerals.

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Acknowledgment

Regenesis, Inc. and the North Carolina Division of Environmental Management provided partial support for this project. We would like to thank Ms. Linda Mintz for providing access to her property and Rebecca Stager for her assistance in the laboratory.

Section 1
Introduction

Background

The U.S. Environmental Protection Agency (U.S. EPA) is studying the performance of enhanced bioremediation systems to evaluate the effectiveness of the technology. The goal of this study was to design and monitor the field performance of a permeable barrier treatment system for controlling the downgradient migration of dissolved gasoline components. The system operates by enhancing the biodegradation of contaminated ground water that passes through the barrier and could be a less expensive method for treating contaminated ground water than the techniques currently employed. The potential advantages of a permeable barrier treatment system include low maintenance requirements, no above-ground facilities, and in-situ biodegradation of contaminants with no requirement for disposal of contaminated treatment media or ground water.

Contamination of ground-water supplies by gasoline and other petroleum-derived hydrocarbons released from underground storage tanks (USTs) is a serious and widespread environmental problem. Corrosion, ground movement, and poor sealing can cause leaks in the tanks and associated piping. As of 1990, there were about 2 million underground tanks storing gasoline in the United States with 90,000 confirmed releases reported between 1989 and 1990 (OUST, 1990).

In large spills, gasoline may penetrate the soil and reach the saturated zone. Once gasoline comes in contact with ground water, the more water-soluble components, including benzene, toluene, ethylbenzene, and the xylene isomers (BTEX), will dissolve. Benzene has been identified as a carcinogen, and the compounds TEX have been identified as neurotoxins (NIOSH, 1990). Although these aromatic hydrocarbons are relatively water-soluble, they are contained in the immiscible bulk fuel phase that serves as a slow-release mechanism for sustained ground-water contamination.

Biodegradation and irreversible sorption are the two main natural mechanisms that remove organic materials in aquifers. Of these two mechanisms, biodegradation is the major removal mechanism (Major et al., 1988). Biodegradation of organic contaminants within the subsurface results from the activity of microorganisms as they obtain energy and carbon to generate new cells. Microbial degradation of a contaminant can result in mineralization (complete degradation of the parent molecule to inorganic end products) or biotransformation that may yield other organic compounds as end products. Biodegradation rates can vary two to three orders of magnitude between aquifers or over a vertical separation of only 1 or 2 m in the same aquifer (Wilson et al., 1986). These rates are controlled by environmental parameters such as temperature (Thorton-Manning et al., 1987), community interactions (Lewis et al., 1986), pH, electron acceptors (Nakajima et al., 1984), salinity, mineral nutrient availability (Lewis et al., 1986), competing organisms, concentration of primary and secondary compounds (Wilson et al., 1986; Schmidt et al., 1987), and adaptation of microorganisms to the pollutant (Spain and Van Veld, 1983; Lewis et al., 1986).

Under favorable conditions, soil microorganisms will degrade most fuel hydrocarbons. In-situ aerobic bioremediation has been shown to be effective for many fuel spills. Controlled laboratory and field studies have demonstrated that a variety of indigenous microbes can aerobically degrade mixtures of aliphatic and aromatic compounds found in gasoline and distillate fuels. All BTEX components have been found to be biodegradable under aerobic conditions (Wilson et al., 1983; Swindoll et al., 1988; Chiang et al., 1989; Song et al., 1990). Early work on enhanced in-situ bioremediation at contaminated aquifers involved sparging air in a well, but the low solubility (9.2 mg/L at 20°C) of oxygen increased the difficulty and expense of maintaining aerobic conditions in ground water. Using hydrogen peroxide (H_2O_2) to provide oxygen to contaminated ground water can increase the effective solubility of oxygen. However, disadvantages of using H_2O_2 at elevated levels include its toxicity to microorganisms, reactivity with inorganic species, and rapid oxygen-release rate.

One approach for remediation of contaminated aquifers that is attracting increased attention is the installation of permeable reactive zones within the aquifers. As contaminated ground water moves under natural or induced hydraulic gradients through a permeable reactive zone, the contaminants are scavenged or degraded, and uncontaminated ground water emerges downgradient of the permeable zone (Gillham and Burris, 1992).

The full-scale permeable barrier system examined in this study employs concrete prepared with a proprietary formulation of magnesium peroxide (MgO_2). The concrete is loaded into permeable filter socks and placed in fully-screened polyvinyl chloride (PVC) wells (remediation wells) installed perpendicular to the ground-water flow direction. When ground water passes through a line of remediation wells, the MgO_2 in the concrete reacts with water, producing oxygen. Indigenous microorganisms then use the released oxygen to aerobically biodegrade the petroleum hydrocarbons present in the ground water. Sodium nitrate ($NaNO_3$) may also be added to the concrete to provide nitrogen, further enhancing biodegradation.

Laboratory batch experiments were conducted to determine the oxygen-release characteristics of several solid peroxide-concrete mixtures. A full-scale barrier system was then installed at a UST gasoline-spill site near Leland, North Carolina. Monitoring wells were installed upgradient and downgradient of the barrier in the contaminated portion of the aquifer. Ground-water samples were monitored and analyzed for dissolved oxygen (DO), individual BTEX components, and other relevant parameters to assess the effectiveness of the barrier system. According to the system design, high DO and low BTEX concentration should be observed in the remediation wells and downgradient monitoring wells. At some distance downgradient of the barrier, the BTEX concentration should be degraded below regulatory levels.

Previous Studies of Permeable Barrier Systems

Burris and Antworth (1990) and Hatfield et al. (1992) performed bench-scale experiments modeling subsurface sorption systems (SSSs) which are zones of treated soil within an aquifer positioned downgradient of a contamination source. These zones retard the flow of contaminants through the aquifer. Burris and Antworth (1990) performed experiments using cationic organic surfactants to form SSSs. Sorption coefficients for common ground-water contaminants were shown to increase by two to three orders of magnitude through surfactant modification of aquifer sediment. Hatfield et al. (1992) proposed SSSs consist of existing soils or fill soils that contain a residual saturation of a non-toxic sorbing organic phase (SOP) into which hydrophobic ground-water contaminants partition. These researchers performed experiments with aquifer material containing decane at residual saturation and observed increases in retardation factors for common hydrophobic ground-water contaminants of at least two orders of magnitude. These hydrophobic contaminants partition preferentially to organic material and are scavenged from ground water by the SOP.

Starr and Cherry (1994) developed the Funnel-and-Gate concept in which contaminated ground water is forced to pass through a small permeable reactive zone by the installation of low hydraulic conductivity cutoff walls. The advantage of this system, over a system in which the contaminated ground-water plume is not funneled, is a smaller permeable treatment zone may be used. The researchers presented various system configurations including single-gate systems, multiple-gate systems, fully penetrating gates, and hanging gates. They also presented five classes of in-situ reactors that could be employed: 1) an in-situ reactor with material that alters pH or redox potential; 2) a reactor containing a material that dissolves and causes precipitation of a mineral phase that immobilizes the contaminant; 3) a reactor which removes contaminants via sorption; 4) a reactor which supplies nutrients whose normal in-situ availability limits the rate of biodegradation; and 5) a reactor in which a physical removal or transformation of the contaminant occurs. As a result of ground-water modeling, the critical factors in the performance of Funnel-and-Gate systems were determined to be funnel width, gate width, gate hydraulic conductivity, and retention time.

Bianchi-Mosquera et al. (1994) performed a short-term field study of the effectiveness of oxygen-releasing concrete and slurry in the reduction of injected benzene and toluene concentrations. These researchers installed 20% MgO_2 concrete briquets and MgO_2 "pencils" (MgO_2 water slurry) in separate treatment lines and injected benzene and toluene into the aquifer at the Canadian Forces Base Borden to achieve a concentration of 4 mg/L for each contaminant. Contaminant levels in ground water passing through the MgO_2 concrete line were below detection limits in downgradient wells about 18 days after installation. DO levels increased in downgradient monitoring wells after installation of concrete briquets, with peak values of 15 mg/L approximately 0.5 m from the concrete line. The installation of the MgO_2 "pencils" yielded reductions in benzene and toluene levels and increases in DO concentrations but not to the extent observed in the concrete briquet zones. Field testing of the treatment zones was performed over a 39-day period with no major system inefficiencies encountered.

Cohen et al. (1996) proposed the use of peat and nutrient briquets as media in permeable treatment zones. They performed a series of experiments to identify types of peat that had good potential for use in a permeable barrier. High sorption capacity and reasonably high hydraulic conductivity were identified as important characteristics for peats to be used as permeable barrier media. In addition, the researchers developed nutrient briquets to supply nitrate as an electron acceptor for the microbial denitrification in a simulated contaminated ground-water system. In bench scale studies, a combined nutrient (nitrate) briquet and peat barrier removed up to 85% of toluene and 71% of ethylbenzene from the system. Cohen et al. (1996) and Thomson et al. (1990) suggested possible field construction of permeable barriers by trenching and backfilling with treatment media in shallow, contaminated aquifer systems.

Davis-Hoover et al. (1991) reported the use of hydraulic fracturing to create permeable channels that could be filled with granules of slow-dissolving nutrients or oxygen-releasing chemicals. Hydraulic fractures filled with sand act as permeable channels to increase the rate of delivery and the area affected by the injection of nutrient- or oxygen-bearing fluid. Encapsulated sodium percarbonate was suggested as a possible solid oxygen-releasing compound, but this compound has a very short oxygen-release life. The authors suggest that a longer lasting and less toxic oxygen-releasing compound should be developed.

Section 2
Conclusions

1. Portland cement concretes incorporating solid peroxides, which release oxygen at a controlled rate, can be easily prepared. Concretes containing either calcium peroxide or a proprietary formulation of magnesium peroxide (ORC™) have desirable oxygen-release characteristics, including high retention of the original oxygen content and slowly declining oxygen-release rates. Both concretes have useful oxygen-release lives of 100 days or more. Concrete prepared with urea hydrogen peroxide was unacceptable for two reasons: 1) chemical assays revealed that most of the original oxygen was lost during the preparation of the urea hydrogen peroxide concrete; and 2) oxygen-release testing revealed that the oxygen that had been retained by the concrete during preparation was released in less than 10 days.

2. BTEX concentrations decreased and DO concentrations increased during passage through the active side of the permeable barrier system. Reductions in BTEX concentrations were statistically significant but were not sufficient to contain the plume. BTEX reductions on the control side of the barrier were much greater than on the active side of the barrier. The cause of this reduction is unknown. Consequently, it is not possible to determine whether the decline in BTEX was due to the barrier system or due to natural variations in BTEX concentration throughout the site. The modifications made to the barrier during the course of the project did not dramatically improve BTEX removal efficiency.

3. Batch reactor experiments indicated that nitrate addition enhanced the aerobic biodegradation of BTEX in ground water from the site. Incorporating sodium nitrate ($NaNO_3$) into the concrete briquets at 0.5 to 0.7% by weight during the second and third treatment periods, respectively, did not cause regulatory levels for nitrate to be exceeded. The highest nitrate concentration observed downgradient of the barrier was 2.9 mg/L NO_3-N. Nitrate concentration declined to near background level further downgradient.

4. Remediation well clogging had a major impact on oxygen delivery to the aquifer. Tracer tests conducted at the end of the project indicated that the average specific discharge through the control remediation wells (no concrete) was over 4 times higher than in the original remediation wells that received concrete. These results indicated that the active remediation wells clogged over time. Also, soil iron concentrations were significantly higher around the active remediation wells than in upgradient site soils, indicating that the clogging was at least partially due to the precipitation of insoluble iron oxides.

5. The average specific discharge in the original active remediation wells was significantly higher than in the new active remediation wells. This difference is believed to be due to well construction techniques. The new remediation wells were vibrated into place with no filter pack while the original remediation wells were installed with a large diameter hollow stem auger and filter pack.

The vibration may have caused local densification of the soil surrounding the new wells with an accompanying decrease in aquifer permeability.

6. The oxygen-releasing permeable barrier installed near the Leland, NC site was not effective in fully containing the dissolved BTEX plume. Only toluene was reduced to below regulatory standards in monitoring well 25 m downgradient. Benzene, ethylbenzene, and the total xylene concentrations in downgradient monitoring wells were consistently above regulatory levels.

7. The failure of the oxygen-releasing permeable barrier system to meet remediation objectives was primarily due to two factors: 1) high total BTEX concentration entering the barrier, and 2) high dissolved iron concentration entering the barrier. The high total BTEX concentration entering the barrier resulted in a high demand for oxygen, which was difficult to meet with a reasonable number of remediation wells. The high iron concentration entering the barrier caused clogging of the remediation wells and reduced oxygen delivery to the aquifer.

Section 3
Recommendations

1. Future work on oxygen-releasing permeable barriers should focus on sites with lower concentrations of biodegradable organics and dissolved iron. At sites where oxygen demand or dissolved iron concentrations are high, delivery of sufficient oxygen to the aquifer will be very difficult.

2. The tracer test measurements of specific discharge conducted at the completion of this project were very useful in evaluating the performance of the remediation wells. In future work, before construction of the full-scale barrier, field measurements of specific discharge should be combined with laboratory measurements of oxygen and nitrate release to more precisely predict the amount of oxygen and nitrate that will be introduced into the aquifer. These measurements will allow a more rational design of the permeable barrier and significantly improve the probability of success.

3. The nitrate content of the concrete should be increased for further enhancement of aerobic biodegradation and for use as an electron acceptor after the available oxygen is depleted. A small increase in the nitrate content of the concrete generally should not result in any violations of water quality standards since the maximum nitrate concentration observed in the monitoring wells downgradient of the barrier was 2.9 mg/L NO_3-N, a value well below the current ground-water standard of 10 mg/L NO_3-N.

4. Near the end of this project, significant concentrations of DO were reaching wells immediately downgradient of the permeable barrier, yet BTEX was not being biodegraded. The lack of biodegradation could be due to stratification within the aquifer, which reduces mixing of oxygenated- and BTEX-contaminated ground water. In future work, variations in oxygen and contaminant concentration with depth should be examined to evaluate the importance of stratification on mixing and subsequent biodegradation.

Section 4
Methodology

Laboratory Methods: Pre-Barrier Construction

Prior to building the permeable barrier, laboratory studies were conducted to determine the oxygen-releasing characteristics of solid peroxide compounds when incorporated into concrete and to determine the effect of nitrate addition on the aerobic biodegradation of BTEX. Methods used in these analyses follow.

Oxygen Retention in Solid Peroxide Concretes

Three solid peroxide compounds, magnesium peroxide (MgO_2), calcium peroxide (CaO_2), and urea hydrogen peroxide [$CO(NH_2)_2 \bullet H_2O_2$], were analyzed for their oxygen-releasing characteristics when incorporated into concrete. The first part of this analysis involved performing chemical assays on each compound and corresponding concrete mix to determine the amount of available oxygen retained in the concrete.

The oxygen content was determined by adding 75 to 100 mL of 1 M sulfuric acid to a flask containing 0.5 to 0.6 grams of compound or powdered concrete mix and titrating the solution with standardized potassium permanganate (approximately 0.1 N) to a light pink-purple end point (Applied Power Concepts, Inc., 1992). This assay was performed in triplicate on each compound and on each corresponding concrete mix. The amount of oxygen in the compound or concrete mix was calculated as:

$$\frac{mg\ O_2}{g\ sample} = \frac{(N)(V)(7.9997)}{W} \qquad (1)$$

where: N = normality of potassium permanganate solution

V = volume of potassium permanganate solution added (mL)

W = weight of sample assayed (g).

(The factor 7.9997 in Equation 1 is the grams per equivalent of oxygen.)

Oxygen Release Over Time from Solid Peroxide Concretes

A technique based on soil respiration measurement (Page et al., 1982) was used to measure the oxygen-release characteristics of the three concrete mixes. The procedure used an enclosed reactor to measure changes in pressure, which were subsequently related to the amount of oxygen released by the concrete. Figure 1 presents a schematic of a reactor used to measure oxygen-release rates. The reactor consisted of a 500-mL jar and an attached manometer for measuring pressure changes. The reactor was initially filled with a known volume of water, which was subsequently saturated with oxygen. A known mass of concrete was then completely submerged in the oxygenated water, and the reactor was sealed.

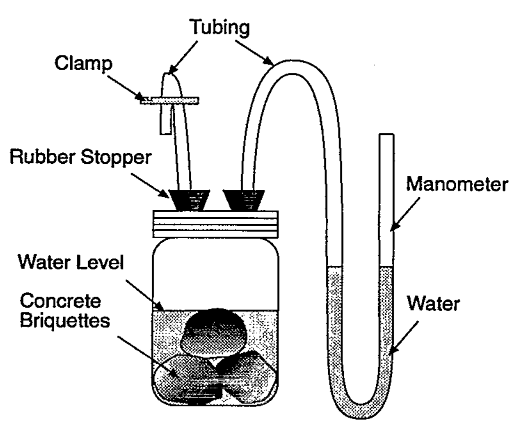

Figure 1. Schematic of reactor used for measuring oxygen-release rates.

One reactor was used for each concrete mix. Measurements of change in the water-column height in the manometers were taken periodically, then the jars were vented. Pressure changes due to oxygen release in the enclosed reactors were measured as changes in water levels of the attached manometer. The number of milligrams of oxygen released was calculated as:

$$O_2 \ released = (k)(\Delta h_{manometer}) \qquad (2)$$

where: k = is the reactor constant
$\Delta h_{manometer}$ = change in water-column height in the manometer.

The reactor constant (k) was determined for each reactor based on the physical properties of the reactor and environmental conditions as presented in Equation 3.

$$k = \frac{(V_g)(\frac{273}{T}) + (V_f)(\alpha)}{P_o} \qquad (3)$$

where: k = reactor constant
V_g = volume of total headspace in reactor
V_f = volume of water added to reactor
T = temperature in degrees Kelvin
α = solubility of oxygen at ambient temperature
P_o = standard pressure
= 10,336 mm for distilled water.

Water level changes in the manometers were corrected for barometric pressure fluctuations by subtracting the water-level changes in a controlled reactor constructed without concrete.

The reactors were loaded with different types and sizes of solid peroxide concrete (10-cm-diameter concrete cylinders or 4-cm-diameter briquets). Oxygen-release rates were measured for the following concrete mixes: 21% $CO(NH_2)_2 \bullet H_2O_2$ concrete briquets, 14% CaO_2 briquets, 21% MgO_2 cylinders and briquets, and 37% MgO_2 cylinders and briquets. A lower percentage CaO_2 was used because of the higher percentage available oxygen in CaO_2.

Effect of Nitrate Addition on Bioremediation

A batch biodegradation experiment was performed to assess the influence of nitrate addition on the aerobic biodegradation of BTEX. Gasoline-contaminated ground water from a site in Leland, NC, was collected from a monitoring well upgradient of the concrete permeable barrier (SU7) and transferred to 125-mL serum bottles (100 mL in each). Three bottles were amended with $NaNO_3$ to produce a final concentration of 100 mg/L NO_3-N. To another three bottles, only hydrochloric acid (HCl) was added to reduce the pH to less than 2; these served as controls. The remaining three bottles received neither nitrate nor acid (ambient). All bottles were sealed with an aerobic headspace and incubated at 16°C in the dark. Aqueous samples were periodically taken from each bottle and analyzed for BTEX to determine the effect of the nitrate addition.

Field Monitoring of Permeable Barrier System

Site Description

Soil and ground-water contamination are present at the Jennifer Mobile Home Park near Leland, NC, due to the release of gasoline from a former UST present on an adjoining property. The spill was detected when dissolved hydrocarbons were found in nearby domestic water supply wells. The water table was less than 3 m (10 ft) below grade in the area adjoining the former UST and is shallower in the downgradient aquifer. Ground-water flow has transported the gasoline components at least 150 m (500 ft) downgradient from the UST. The former UST and some petroleum-contaminated soil were removed six months prior to installation of the barrier. Excavation of the contaminated soil was limited by the shallow water table and the foundation of the nearby store.

The geology underlying the site consists mainly of a medium gray-brown silty sand to a depth of 0.6 to 1.2 m (2 to 4 ft). This material changes to an orange-brown clayey silty sand for approximately 0.6 m (2 ft), becoming a medium to very coarse light brown to blond sand at greater depth. This upper sand unit extends 15 m (50 ft) or more below the surface. The medium to very coarse sand layer results in a single, unconfined aquifer within the relevant depth of contamination throughout the site. The average hydraulic conductivity of the aquifer was estimated to be 23 m/d from drawdown and recovery tests (LaTowsky, 1993). The vertical extent of contamination is limited to within approximately 7.6 m (25 ft) of surface grade based on monitoring from clustered wells.

Barrier Design

The permeable barrier intersected the BTEX plume approximately 27 m downgradient from the former UST location and consisted of a series of 15-cm (6-in)-diameter PVC wells installed approximately 1.5 m (5 ft) on center (Figure 2). Each well was designed to release a plume of DO, enhancing biodegradation in the downgradient aquifer. Preliminary modeling indicated that the plumes from each well would mix over a 6- to 15-m distance resulting in complete biodegradation of the BTEX plume. Field delineation of the BTEX plume indicated that the barrier would need to be 40-m wide and extend approximately 3 m below the ground-water table.

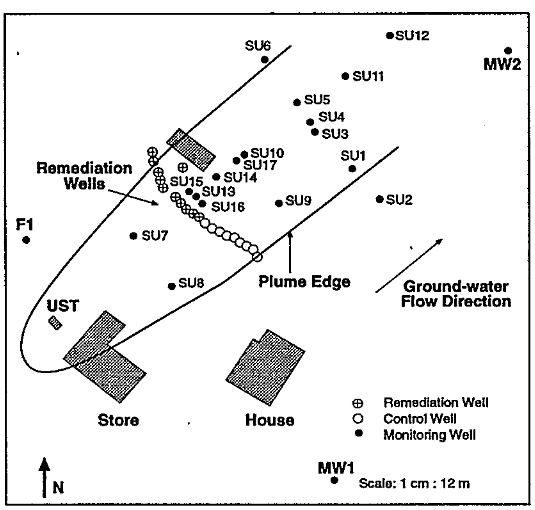

Figure 2. Site map showing permeable barrier and monitoring wells.

Twenty remediation wells were initially installed in the remediation line perpendicular to the plume at a distance of 1.5 m on center (Figure 3). (Ten new remediation wells—NR1 to NR10 —were installed later in the project. See Section 5 for further discussion.) The nine original wells on the eastern half of the plume did not receive concrete and were operated as a control to evaluate the barrier effectiveness. One of the remediation wells (R6) had to be installed downgradient of the other wells due to an overhead power line. A schematic of a remediation well is presented in Figure 4. Originally, 3-m-long concrete columns with 10-cm diameters were encased in filter fabric socks and hung inside remediation wells. This design was modified over the course of the project in an attempt to further enhance the barrier system effectiveness.

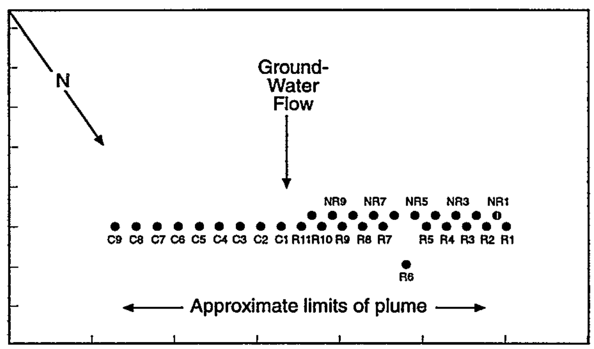

Figure 3. Location of original and added permeable barrier remediation wells (not to scale).

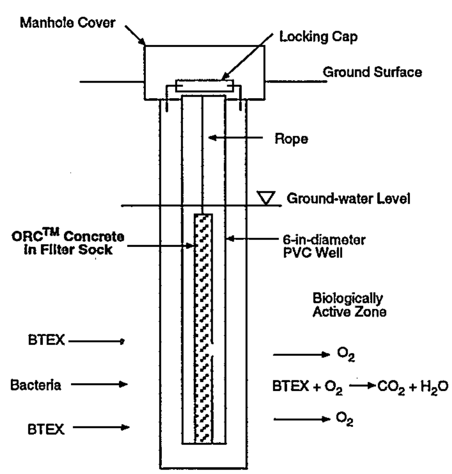

Figure 4. Schematic of remediation well containing oxygen-releasing concrete.

Three different mixes of concrete were used in the operation of the barrier system. The concrete was prepared by blending Portland cement, sand, water, a proprietary formulation of MgO_2 (Plant Research Laboratories, Corona Del Mar, CA), and $NaNO_3$. The compositions (by weight) of the three mixes are presented in Table 1.

Table 1. Mass Ratios of Components in Concrete by Treatment Period

Treatment Period	MgO_2	Portland Cement	Sand	Water	$NaNO_3$
1 (Days 0 to 242)	1	0.694	0.388	0.643	0
2 (Days 242 to 361)	1	0.260	0.470	0.670	0.013
3 (Days 361 to 498)	1	0.330	0.600	0.770	0.020

Well Placement

Twenty monitoring wells (F1, MW1, MW2, and SU1 to SU17) were installed to define the plume, monitor ground-water flow, and aid the permeable barrier system design (Figure 2). North Carolina State University (NCSU) installed the SU wells.

Monitoring wells SU1 to SU6 were used to define the width and depth of the subsurface hydrocarbon plume. They are situated approximately 50 m (175 ft) downgradient (Figure 2) from the former UST along a transect whose center point is roughly in line with the contaminated wells in the study area. Monitoring data (Goin, 1995) indicate that SU2 and SU6 are located at the edges of the plume, and F1 and MW1 are located outside of the plume area. The BTEX plume is reasonably well defined and extends in a northeast direction away from the former UST location and through the central portion of the monitoring wells.

Monitoring wells SU7 and SU8 are 10 m (33 ft) upgradient of the remediation line with SU7 located on the active side 5 m from the plume centerline and SU8 located 5 m from the centerline on the control side. Monitoring wells SU9 and SU10 are similarly located 11 m (36 ft) downgradient of the remediation line. Monitoring well SU10 was damaged during grading of the site and could no longer be sampled after 86 days of barrier operation. Monitoring well SU17 was installed to replace SU10.

Monitoring wells SU13 and SU14 were installed 3 m (10 ft) and 8 m (25 ft), respectively, downgradient from the remediation line along the same stream line as SU7 and SU10. These wells allow for ground-water sampling at positions immediately downgradient of the remediation line. Monitoring wells SU15 and SU16 were installed 0.75 m west and east of SU13, respectively, to evaluate transverse dispersion of oxygen and nutrients away from the remediation wells.

Well Construction

Monitoring and remediation wells were constructed in accordance with the applicable standards of the NC Division of Environmental Management. Monitoring wells were installed with a hollow stem auger and consisted of 5.1-cm (2.0-in) diameter PVC well casing with a 1.5-m (5-ft) long, 0.025-cm slot, PVC screen and end plug. A natural sand pack was placed around the screened interval of the well casing and a bentonite pellet layer was installed above the sand pack to prevent infiltration of surface water into the well. The well was completed with the installation of a locking well cap, metal identification tag, and steel cover set in concrete. A dedicated Waterra™ model D-25 inertial pump attached to a section of high density polyethylene tubing was installed in each monitoring well. Ground-water samples were obtained by vertically oscillating the tubing, thereby advancing a column of ground water to the surface. During sampling, a short section of new vinyl tubing was attached to the surface end of the polyethylene tubing to allow for easier sample collection.

Seventeen of the original 20 remediation wells were installed by a private contractor. These remediation wells consisted of 3 m of Schedule 40 PVC well screen with a 0.050-cm slot size attached to 1.5 m of Schedule 40 PVC casing. The installation procedure was similar to that previously described for the monitoring wells but with a coarse filter pack installed along the entire length of the well screen. A bentonite seal and locking well cover were installed to prevent infiltration of surface water.

NCSU installed three of the original remediation wells (R7, R8 and R9) and the ten new remediation wells by vibrating 4.6 m of 15.2-cm-diameter well screen (0.05-cm slot size) into a pre-augured pilot boring. Due to the nature of the installation, no filter material could be placed around the well screen. All remediation wells were developed by repeated surging with a high capacity pump.

Ground-Water Sampling

Ground-water samples were collected and handled according to the protocol described in Barcelona et al. (1988) with the following sequence of events: 1) well purging; 2) sample collection; 3) field blanks; 4) field determination; 5) preservation/ storage; and 6) transportation.

Prior to sampling, the monitoring well headspace was purged with pre-purified argon gas to prevent the introduction of atmospheric oxygen to the ground water during purging and sampling. A minimum of five well volumes were pumped from the well prior to sample collection. Samples were collected, filtered, labeled, and preserved according to the information shown in Table 2. Field and equipment blanks were collected and treated in the same manner as all other samples. Field samples were stored on ice in insulated ice chests and transported to the NCSU Environmental Engineering Laboratories. Upon arrival at the laboratory, samples were stored in an ignition-safe refrigerator at 4°C and analyzed within 48 hours.

Field analysis of ground-water samples included measurement of DO, temperature, and pH. Ground-water temperature and DO were measured using an Orion Model 840 dissolved oxygen meter. The DO meter probe was introduced into the well and placed approximately mid-height in the existing water column. The probe was slowly oscillated vertically and readings recorded after equilibration. Sample pH was measured using an Orion Model 920 ISE meter with an Orion pH triode.

Table 2. Sample Collection and Preparation Protocol

Analysis	Container	Label ID	Filter	Preserved
Volatile Organics	40-mL VOA Vial	MW-X, GC-1	No	2.0 N HCl added to pH 2
Back-up Volatile Organics	40-mL VOA Vial	MW-X, GC-4	No	2.0 HCl added to pH 2
Metals	40-mL VOA Vial	MW-X, SS-6	Yes - 45 μm	2.0 HCl added to pH 2
Nutrients	40-mL VOA Vial	MW-X, SS-7	Yes - 45 μm	No
Alkalinity	225-mL Polyethyl-ene Jug	MW-X	Yes - 45 μm	No
Field Analysis pH	500-mL Beaker	None	Yes - 45 μm	No

Volatile organic compounds (BTEX) were analyzed using a Perkin-Elmer Model 9000 Auto System Gas Chromatograph fitted with a flame ionization detector, Tekmar Purge-and-Trap Model LSC 2000, and a 75-m DB-624 megabore capillary column. Sample analysis for Cl^-, Br^-, and SO_4^- was conducted on a Dionex Ion Chromatograph. A Perkin-Elmer Plasma II Inductively Coupled Plasma Atomic Emission Spectrometer (ICP-AES) was used for determining soluble concentrations of Na, K, Ca, Mg, Fe, Al, Cu, and Mn. Nitrogen compound analysis was performed using a LACHAT™ auto-analyzer. Alkalinity was determined by titration to pH 4.5 with 0.1 N HCl, and phosphate was determined using the ascorbic acid method (APHA, 1989).

Iron Content of Soil Adjoining Remediation Wells

In addition to collecting ground-water samples, the field team collected soil samples to determine if iron was precipitating next to the remediation wells. Soil samples were collected for iron analysis immediately adjoining three remediation wells (R10, R11, NR10) and three locations 7 m upgradient of the barrier. Soil samples adjoining the wells were taken by inserting a modified 60-mL-syringe barrel horizontally into the soil mass surrounding each well until the screen was encountered, removing the syringe, and placing the soil sample in an air-tight container for transport. Six soil samples (three points spaced 15 cm apart at two different depths) were collected at each well for iron content determination. For comparison purposes, soil samples were collected from two depths at three locations approximately 7 m upgradient of the active remediation wells in the contaminated portion of the aquifer. Upgradient soil samples were obtained by drilling to a depth of approximately 10 cm above the ground-water table with a stainless steel hand auger and placing the soil samples in an air-tight container for transport. After transport to the laboratory, the readily extractable iron was determined by extracting 1-g soil samples with 1.0 N HCl for 3 hours followed by ICP analysis of the filtered extract (Lovely and Phillips, 1986; Goin, 1995). Analyses were performed in triplicate for each soil sample.

Specific Discharge Measurements

Tracer tests were conducted on several of the active and control remediation wells to evaluate the effect of the oxygen-releasing concrete on specific discharge through the well. The tracer tests and specific discharge calculations were performed following the procedure outlined by Hall (1993). The concrete briquets were removed from the wells and the water level allowed to equilibrate before tracer addition. Background specific conductivities and ground-water temperatures were measured at several depths using a YSI Model 33 meter and a YSI 33000 Series probe. The tracer, consisting of a solution of 100 or 250 g of sodium chloride (NaCl) in 1 L of distilled water, was then vigorously mixed into each well. Specific conductivity and temperature readings were taken at the same depths in each of the wells over a two-day period. Specific conductivity was converted to NaCl concentration using a standard curve developed by measuring conductivities of solutions with known NaCl concentrations at the ambient ground-water temperature. The slope of the natural log of the tracer concentration versus time was determined by linear regression. Equation 4 (Hall, 1993) was used to calculate the specific discharge (q) of ground water through the well.

$$q = -\left(\frac{A}{V}\right)\left(\frac{d(\ln(C))}{dt}\right) \qquad (4)$$

where:
- V = volume of the water-filled test interval
- A = cross-sectional area of the test interval normal to flow
- C = tracer concentration
- t = time.

Section 5
Results and Discussion

Laboratory Results: Pre-Barrier Construction

Concretes prepared contained CaO_2, MgO_2, and $CO(NH_2)_2 \bullet H_2O_2$ as potential sources of oxygen to enhance BTEX biodegradation. Urea hydrogen peroxide releases oxygen due to the decomposition of hydrogen peroxide (H_2O_2). Reaction of CaO_2 and MgO_2 with water releases oxygen as shown below:

$$CaO_2 + H_2O \rightarrow Ca(OH)_2 + 0.5O_2$$
$$MgO_2 + H_2O \rightarrow Mg(OH)_2 + 0.5O_2$$

Oxygen Retention in Solid Peroxide Concretes

In the first part of this analysis, different concrete mixes were prepared and analyzed in triplicate to determine the fraction of the original oxygen retained in the final concrete mix. Average oxygen contents for each compound and mix are shown in Table 3.

Table 3. Average Oxygen Contents of CaO_2, MgO_2, and $CO(NH_2)_2 \bullet H_2O_2$ in Original Form and in a Concrete Matrix

Compound or Concrete Mix	Oxygen Content (mg O_2/g of material)	Oxygen Recovery[c] (%)
CaO_2	49.75 ± 1.21	
14%[a] CaO_2 Concrete	7.36 ± 0.64	106
MgO_2 (ORC™)[b]	66.82 ± 1.59	
21% MgO_2 Concrete	14.55 ± 1.08	104
37% MgO_2 Concrete	24.25 ± 1.80	98
$CO(NH_2)_2 \bullet H_2O_2$	64.69 ± 3.54	
21% $CO(NH_2)_2 \bullet H_2O_2$ Concrete	1.67 ± 0.36	12

[a] Percentage of compound by weight in concrete.
[b] A proprietary formulation of magnesium peroxide (Plant Research Laboratories, Corona Del Mar, CA) was used in this study.
[c] Oxygen Recovery = (oxygen content of concrete/percentage of compound in concrete)/(oxygen content of compound); i.e., 14% CaO_2 average oxygen recovery = ((7.36 mg O_2/g mix) / (0.14))/(49.75 mg O_2/g of compound) = 106%.

The oxygen recoveries for MgO_2 and CaO_2 concrete mixes were close to 100% based on the oxygen content of the original compound. In contrast, a large portion of the available oxygen in the original $CO(NH_2)_2 \bullet H_2O_2$ was lost during preparation of this concrete.

Oxygen Release Over Time from Solid Peroxide Concretes

The $CO(NH_2)_2 \bullet H_2O_2$ concrete was highly reactive and released oxygen at rates as large as 2.5 mg per gram of $CO(NH_2)_2 \bullet H_2O_2$ per day. This high release rate, along with the low-oxygen retention for the $CO(NH_2)_2 \bullet H_2O_2$ concrete, resulted in rapid depletion of the available oxygen (Appendix A). After 10 days of operation, no measurable oxygen was being released from the $CO(NH_2)_2 \bullet H_2O_2$ concrete. The rapid decline in oxygen-release rate indicates that $CO(NH_2)_2 \bullet H_2O_2$ concrete would not be acceptable for use in long-term bioremediation activities.

Experimental results for MgO_2 and CaO_2 concrete were modeled assuming the oxygen-release rate declined linearly with time. The modeled linear regression equations for each material are provided in Table 4. Figure 5 shows oxygen-release rates over time for 21% and 37% MgO_2 concrete briquets along with the best fit line. Oxygen-release rates from the 37% MgO_2 briquets and cylinders closely matched the modeled linear regression. However, oxygen-release rates from the 21% MgO_2 and 14% CaO_2 were much more variable, resulting in a much poorer model fit ($r^2 < 0.7$).

Table 4. Model Oxygen-Release Rate Equations for Magnesium Peroxide and Calcium Peroxide Concrete Mixes

Oxygen-releasing Media	Oxygen-Release Equation	r^2
37% MgO_2 Briquets	Rate*= 11.30 - 0.06268 • Time**	0.94
37% MgO_2 Cylinder	Rate = 7.88 - 0.04619 • Time	0.94
21% MgO_2 Briquets	Rate = 3.55 - 0.01065 • Time	0.65
21% MgO_2 Cylinder	Rate = 2.41 - 0.00777 • Time	0.69
14% CaO_2 Briquets	Rate = 27.24 - 0.2853 • Time	0.57

* Rate = units of mg O_2/day/g available O_2.
** Time = days.

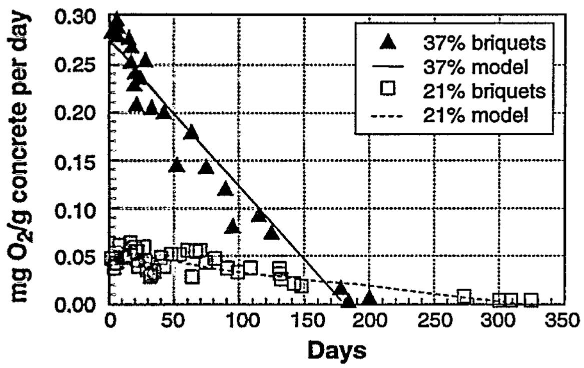

Figure 5. Oxygen release from MgO_2 concrete briquets (1.7-cm diameter).

Figure 6 is a plot of oxygen-release rates over time, estimated using the linear regression equations for different concrete mixtures and sizes. Use of the large cylinders (10-cm diameter) slowed the oxygen-release rate somewhat, presumably due to the slower rate of water entry into the cylinders. The 21% MgO_2 concrete cylinders and briquets released oxygen at measurable rates for up to 300 days, while the 14% CaO_2 briquets were exhausted by 100 days. Where a slow constant release of oxygen is required, the 21% MgO_2 concrete briquets and cylinders will be most useful. When a higher O_2 release rate is needed, the 37% MgO_2 or 14% CaO_2 concretes may be more useful.

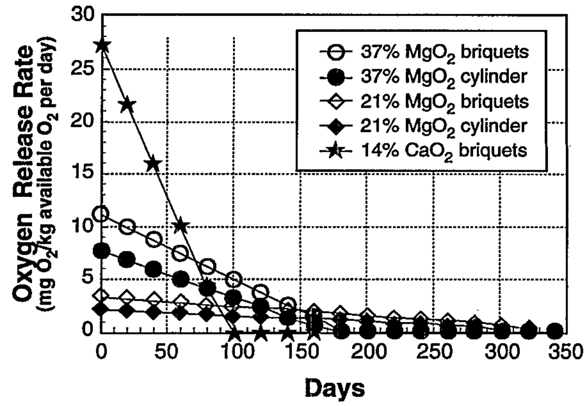

Figure 6. Best fit estimated lines showing variation in oxygen-release rates with time for magnesium peroxide and calcium peroxide concrete mixes.

Effect of Nitrate Addition on Bioremediation

Figure 7 shows the results of the nitrate addition experiments. In the bottles amended with 100 mg/L NO_3-N, significant BTEX degradation was observed after 10 days. Total BTEX concentration dropped from 22.2 mg/L to below 0.035 mg/L after one month of incubation. In the bottles with no added nitrate or acid (ambient), no significant change in BTEX concentrations was observed after 10 days. Significant BTEX degradation was observed only in two of three bottles after 30 days of incubation. Over this period, the average total BTEX concentration dropped from 22.2 to 7.4 mg/L in this comparison group. In the abiotic control bottles, there was a small initial abiotic loss, then BTEX concentrations remained constant. These results indicate that nitrate addition enhanced the rate of aerobic biodegradation. Since an aerobic headspace was maintained, the added nitrate is believed to have enhanced biodegradation by increasing nitrogen to non-limiting levels, thereby increasing biomass synthesis; the increased biomass caused the higher BTEX degradation rate.

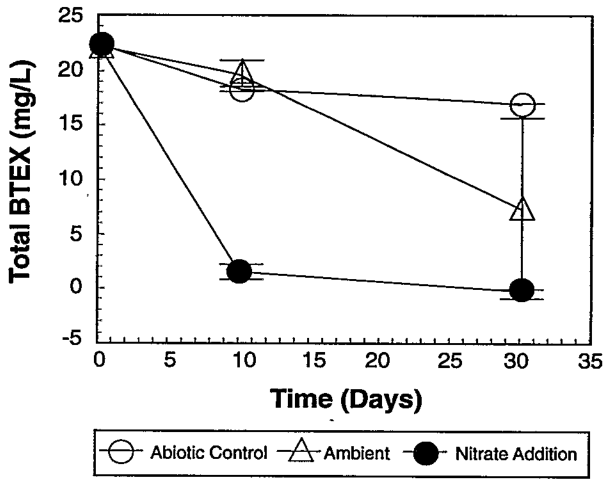

Figure 7. Effect of nitrate addition on BTEX biodegradation in ground water from gasoline-contaminated site near Leland, NC. (Symbols are the mean of three replicates. Error bars are ± one standard deviation.)

Field Monitoring of Permeable Barrier System

Ground water upgradient and downgradient of the full-scale permeable barrier was monitored over an 18-month period to determine the barrier system's effectiveness and to identify areas where the design could be improved. Field monitoring data are on Appendix B. The barrier first built at the site consisted of 20 six-inch-diameter PVC wells screened from 1.5 to 5 m below grade (Figure 2). Oxygen-releasing concrete was installed in the western line of wells (R1-R11). The eastern line of wells (C1-C9) served as a control and did not receive concrete.

Background Ground-Water Quality

Monitoring well MW1 is located outside of the plume and is representative of background ground-water quality. BTEX was consistently below detection in MW1 (<5 μg/L of each component). The average DO and pH were 3.5 mg/L and 5.1, respectively. Average concentrations of nutrients and major ions were 9 mg/L bicarbonate alkalinity, 1.4 mg/L NO_3-N, <0.1 mg/L NH_4 -N, <0.1 mg/L PO_4-P, 9 mg/L SO_4, 9 mg/L Cl, <0.1 mg/L Fe, <0.1 mg/L Mn, 2 mg/L Ca, 1 mg/L Mg, 9 mg/L Na, and 1 mg/L K. These results indicate that the background water quality was somewhat acidic, was very low in dissolved solids, and contained low levels of inorganic nutrients.

Ground-Water Monitoring

Monitoring-well data indicate an average hydraulic gradient of 0.0043 m/m over the project period. Figure 8 presents hydraulic gradients and ground-water flow directions for selected days within the project period. The length of the arrows are proportional to the hydraulic gradient on that day. The hydraulic gradient data indicate that, while there were small fluctuations, the average ground-water flow direction is closely aligned with the row of monitoring wells: SU7, SU13, SU14, SU17, and SU5 (Figure 2).

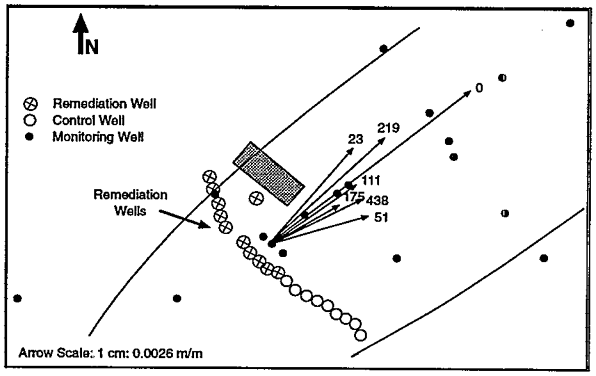

Figure 8. Variation in ground-water flow direction and gradient over the project period. (Monitoring day is shown next to each arrow.)

Ground water upgradient and downgradient of the permeable barrier was monitored from 33 days before startup of the barriers to 498 days after startup. The row of monitoring wells SU7, SU13, SU14, SU17, and SU5 were monitored approximately twice per month. These wells were installed on a single stream line to determine the variation in BTEX, oxygen, and indicator parameters as ground water was transported through the barrier and the downgradient aquifer. Other wells at the site were monitored less frequently.

Over the course of this project, two major modifications were made to the barrier system in an attempt to improve treatment efficiency: 1) use of smaller concrete briquets containing MgO_2 and $NaNO_3$, and 2) installation of additional remediation wells. The smaller concrete briquets were used to increase the oxygen-release rate from the existing wells. Addition of $NaNO_3$ was to enhance bacterial growth and resulting biodegradation rates in the downgradient aquifer. Ten new remediation wells (NR1 to NR10) were added 1.5 m upgradient of the existing barrier to further increase the oxygen supply to the aquifer. Figure 3 shows the placement of the new remediation wells. To evaluate the effect of the original and modified barrier on the contaminant distribution, the monitoring data has been separated into three periods: 1) day 0 to 242 (original barrier cylinders or briquets without $NaNO_3$); 2) day 242 to 361 (original barrier - briquets with $NaNO_3$); and 3) day 361 to 498 (barrier with additional wells - briquets with $NaNO_3$).

Variability in BTEX and Indicator Parameters Upgradient of the Barrier

Monitoring results for wells SU7 and SU8 are shown in Figure 9. These wells are located 10 m (33 ft) upgradient of the active and control sides of the barrier, respectively, and showed an almost identical trend in total BTEX concentration over time. The similarity in concentrations between these two wells indicates that the distribution of total BTEX concentration across the width of the plume is relatively symmetric with respect to the longitudinal axis upgradient of the barrier. BTEX concentration started out very low and increased steadily over the first 100 days of barrier operation. Prior to startup of the barrier, the site experienced a period of very heavy precipitation. The high precipitation is believed to have diluted the contaminants, resulting in lower BTEX concentrations in the aquifer immediately before startup. Over time, the effects of the high recharge diminished, and the BTEX concentrations in both wells returned to the 15 to 40 mg/L range. The low BTEX concentrations observed around days 180 and 390 were also associated with periods of high ground-water recharge and high water table elevation. Dissolved iron concentrations in SU7 and SU8 averaged 19 and 22 mg/L, respectively. The pH values in both wells were approximately 6. The higher pH in the contaminated wells is believed to be due to $Fe(OH)_3$ reduction in the upgradient aquifer. The reduction of the $Fe(OH)_3$ releases OH^- ion and this release increases the ground-water pH.

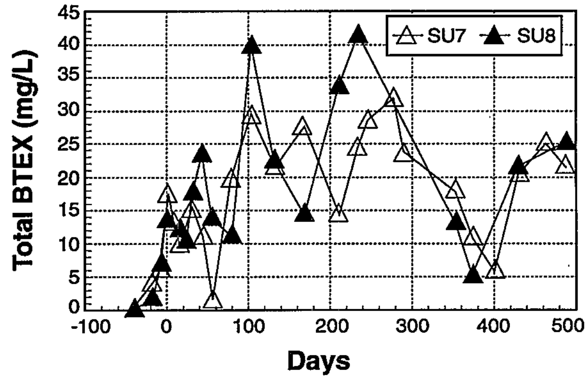

Figure 9. Variation in total BTEX concentration in monitoring wells upgradient of the active (SU7) and control sides (SU8) of the permeable barrier.

Evaluation of Permeable Barrier: Test Period 1 - Day 0 to Day 242

The original barrier system was installed on two different days. The first three remediation wells (R7, R8, R9), which are directly upgradient of SU13, were loaded with 37% MgO_2 concrete on day 0 (1-28-93). The remaining eight active remediation wells were completed and loaded with MgO_2 concrete on day 9. The first treatment period extended from this initial loading of the remediation wells to day 242 when concrete containing $NaNO_3$ was installed. Discussion of monitoring results primarily focuses on data from the row of monitoring wells SU7, SU13, SU14, SU10, and SU5, since information from these wells illustrates the effects of the remediation system. Complete monitoring results for all parameters and wells are reported by Goin (1995).

Monitoring well SU13 is located 3 m (10 ft) downgradient of the active side of the barrier on approximately the same stream line as upgradient well SU7. The total BTEX and DO concentration data for wells SU7 and SU13 are compared in Figures 10a and 10b for the first treatment period. These plots show that total BTEX concentration in SU7 was low initially, then climbed to the 15 to 30 mg/L range after completion of the barrier. DO in SU7 was typically low (<0.5 mg/L) although high oxygen measurements were observed on days 0 and 63 and were associated with periods of high recharge. The average total BTEX and DO concentrations in SU7 from day 0 to day 242 were 17 and 0.4 mg/L, respectively.

On day 0, the total BTEX concentration in wells immediately upgradient (SU7) and downgradient (SU13) of the barrier were similar (~7 mg/L). However, by day 9, the total BTEX concentration had started to decline in SU13 while total BTEX concentration in SU7 continued to increase. After some initial fluctuations, the BTEX concentration in SU13 appeared to have stabilized below 2 mg/L until day 139. During this period, DO in SU13 followed an opposite pattern to BTEX. On day 0, DO concentration in SU13 was low (0.7 mg/L) and then increased to between 1.5 and 3.0 mg/L. On day 139, DO concentration dropped to 0.8 mg/L in SU13 and on the subsequent sampling BTEX increased to 11 mg/L. The drop in oxygen and increase in BTEX concentration in SU13 was probably due to reduced oxygen release from the concrete. At that point, the oxygen-releasing concrete had reached the end of its operating life and was probably not releasing sufficient oxygen. On day 170, the old concrete cylinders were replaced with fresh concrete briquets. Briquets were used in place of cylinders to increase the oxygen-release rate. Replacement of the concrete appeared to improve barrier performance, and on the next sampling event, DO concentration increased and BTEX concentration decreased in SU13.

Figures 11a and 11b show total BTEX and DO concentrations for wells SU14 and SU5 located 8 m (25 ft) and 23 m (75 ft) downgradient of the barrier. Immediately after construction of the barrier, total BTEX concentration in SU14 and SU5 continued to increase following the same pattern as the upgradient well SU7. After day 40, DO concentrations in SU14 began to increase which corresponded to a BTEX decline. The lag in oxygen arrival and BTEX removal in well SU14 is believed to be due to the travel time from the barrier to these wells. Using the non-reactive transport velocity of 0.3 m/day, oxygen released from the barrier would not be expected to arrive at well SU14 until day 25. A small increase in DO and decrease in BTEX was observed in SU5 on day 50. These changes are not believed to be due to the barrier since oxygen released from the barrier would not be expected to arrive at SU5 until day 75.

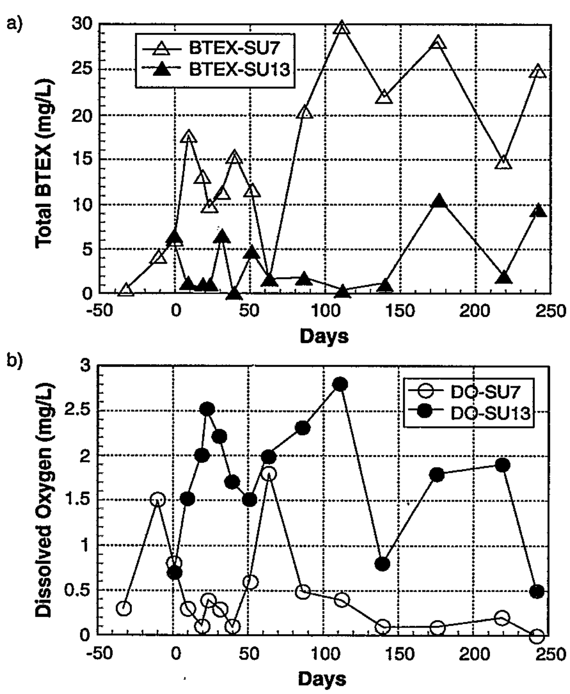

Figure 10. Variation in (a) total BTEX concentrations and (b) dissolved oxygen concentrations during test period 1 (day 0 to day 242) in monitoring wells upgradient (SU7) and downgradient (SU13) of the barrier.

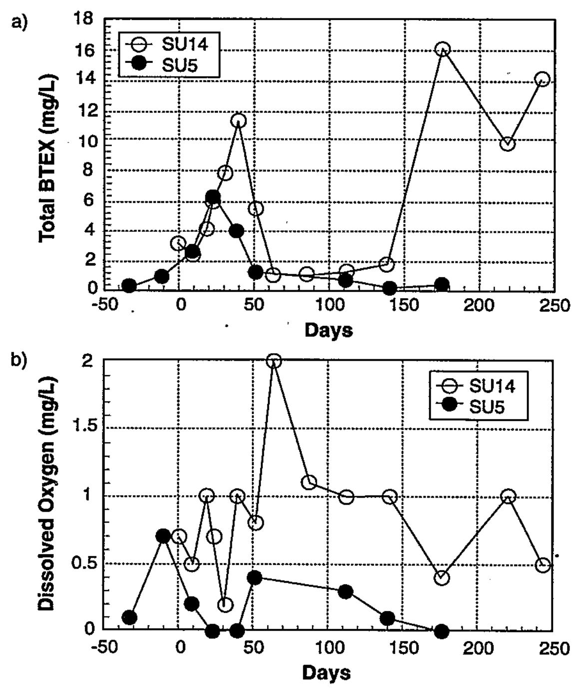

Figure 11. Variation in (a) total BTEX concentrations and (b) dissolved oxygen concentrations during test period 1 (day 0 to day 242) in monitoring wells SU14 and SU5.

On day 115, DO concentrations were 1.0 mg/L in SU14 and only 0.3 mg/L in SU5. These concentrations indicate that whatever oxygen was being released to the aquifer by the permeable barrier, it was essentially depleted before it reached SU5. After 150 days, DO decreased in both SU14 and SU5. After the concrete in the remediation wells was replaced on day 170, the DO increased and BTEX decreased in SU14 as seen by results on day 220.

As part of the original experimental design, monitoring wells were installed 11 m (36 ft) downgradient of both the active (SU10) and control (SU9) sides of the barrier. Figure 12 shows total BTEX concentrations in these two wells for the first 86 days of barrier operation. The total BTEX concentration on the control side (SU9) is much lower than on the active remediation side (SU10). The reason for this difference is not known. The barrier could not be the cause because water released from the barrier should not reach these wells until at least day 50. Regardless, BTEX concentrations are much lower on the untreated (control) side, than on the side which was treated with oxygen-releasing concrete.

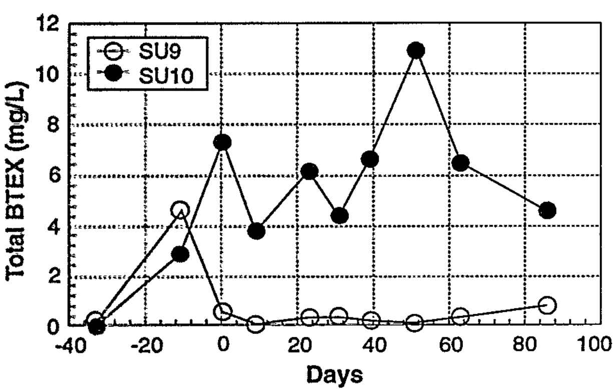

Figure 12. Variation in total BTEX concentrations in monitoring wells downgradient of the active (SU10) and control (SU9) sides of the permeable barrier.

In general, concentrations of inorganic nutrients (NO_3-N, NH_4-N, PO_4 -P) and ions, as well as pH, upgradient and downgradient of the barrier were very similar. The average pH in SU7, upgradient of the barrier, and in SU13, immediately downgradient of the barrier, was 5.9 and 6.1, respectively. Concentrations of PO_4-P and NO_3-N were below detection (<0.5 mg/L) both upgradient and downgradient of the barrier. Ammonia (NH_4-N) decreased slightly from 1.8 mg/L to less than 0.5 mg/L during passage from SU7 to SU13. Two notable exceptions to this trend were Ca and Mg. On the first sampling date after the concrete installation, there was an abrupt increase in Ca and Mg immediately downgradient of the barrier (SU13); but by the second sampling date, both Ca and Mg had returned to background levels. The temporary increase in Ca and Mg is believed to be due to the dissolution of fine powder produced during handling of the concrete. Once this powder was depleted, the rate of Ca and Mg release returned to background levels. The only inorganic parameter which was consistently affected by the barrier was dissolved iron. From day 0 to 242, the average concentrations of dissolved iron upgradient (SU7) and downgradient (SU13) of the barrier were 19 and 7 mg/L, respectively.

Evaluation of Permeable Barrier: Test Period 2 - Day 242 to Day 361

After the completion of the first treatment period, it was apparent that while the oxygen-releasing barrier was having some beneficial effects, the existing barrier was not fully effective in containing the contaminant plume. Field monitoring had shown that dissolved nitrogen and phosphorus concentrations in the ground water were very low (PO_4-P < 0.5 mg/L, NH_4-N < 0.5 mg/L). Based on this initial work, laboratory batch experiments were conducted to evaluate the effect of nitrate addition on the BTEX biodegradation rate (see page 19). Results of these experiments indicated that nitrate addition could potentially increase the BTEX biodegradation rate. In test period 2, concrete briquets were prepared from a mixture of 41% MgO_2 and 0.5% $NaNO_3$ and installed in the existing remediation wells. This formulation was selected to provide sufficient nitrogen for bacterial growth but to be low enough in nitrogen to ensure that the ground-water quality standard of 10 mg/L NO_3-N was not violated.

Total BTEX and oxygen concentrations in monitoring wells SU7, SU13, and SU14 are shown in Figures 13a and 13b for the second treatment period. Total BTEX concentration in the upgradient well (SU7) was relatively consistent during this period, ranging from 18 to 32 mg/L with an average of 26 mg/L. BTEX levels in SU13 and SU14 were lower than in SU7, but were much higher than in the previous treatment period. At this point, there was no clear explanation for the drop in BTEX removal efficiency. Oxygen levels in SU13 were somewhat lower than in the previous treatment period, indicating that oxygen was not penetrating the aquifer in sufficient quantities to biodegrade the plume. In contrast to the disappointing results with BTEX and oxygen, nitrate concentrations behaved as expected. Average nitrate concentrations in SU13 and SU14 were 0.88 and 0.91 mg/L, respectively. In comparison, the average nitrate concentration in SU7 upgradient of the barrier was less than 0.5 mg/L. The maximum nitrate concentration detected in any well was 2.9 mg/L NO_3-N, which is well below the ground-water quality standard of 10 mg/L NO_3-N. Sodium (Na) release from $NaNO_3$ present in the concrete was negligible. During test period 1, the average Na concentration in SU13 was 5 mg/L, while in test period 2 the average concentration was 7 mg/L.

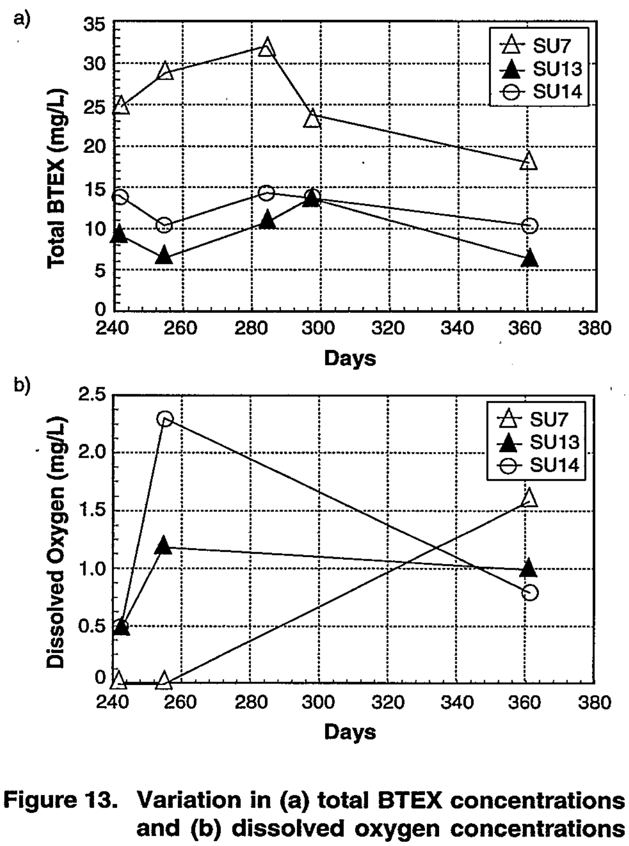

Figure 13. Variation in (a) total BTEX concentrations and (b) dissolved oxygen concentrations during test period 2 (day 242 to day 361) in monitoring wells SU7, SU13, and SU14.

As previously observed, there were no significant changes in pH or most dissolved ions during transport through the barrier. Dissolved iron concentrations were consistently lower in wells downgradient of the barrier than in wells upgradient of the barrier.

Evaluation of Permeable Barrier: Test Period 3 - Day 361 to Day 498

During the first two test periods, BTEX concentrations were reduced by approximately 12 to 16 mg/L over an 18-m distance. While this result was promising, significant concentrations of BTEX persisted downgradient of the barrier. Since the DO levels in downgradient wells were low, availability of oxygen was believed to be limiting further biodegradation of BTEX. Ten new remediation wells were installed at the beginning of the third treatment period to provide additional oxygen and further enhance BTEX biodegradation.

The new wells were installed between the existing wells just upgradient (~1.5 m) of the active side of the barrier. The net effect of this installation was that oxygen-releasing wells were spaced approximately 0.75 m on center over the western half of the BTEX plume. Both the new remediation wells and the original active remediation wells were loaded with fresh concrete briquets prepared with 37% MgO_2 and 0.7% $NaNO_3$ on day 361. Two additional monitoring wells (SU15 and SU16) were installed directly adjoining SU13 to evaluate oxygen and nutrient transport transverse to the direction of flow.

Total BTEX and DO concentrations in wells SU7 to SU17 are shown in Figures 14a and 14b for the third treatment period. SU17 replaces SU10, which was damaged during site grading. Due to the proximity of monitoring wells SU13, SU15, and SU16, the BTEX and oxygen concentrations in these three wells are averaged to represent contaminant levels immediately downgradient of the barrier.

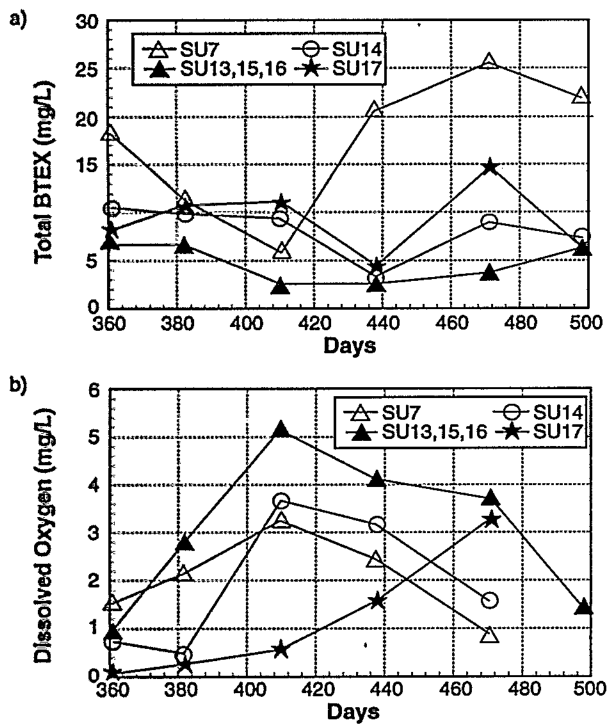

Figure 14. Variation in (a) total BTEX concentrations and (b) dissolved oxygen concentrations during test period 3 (day 361 to day 498) in monitoring wells SU7, SU14, SU17 and the average of SU13, SU15, and SU16.

Total BTEX concentration upgradient of the barrier (SU7) was 19 mg/L at the beginning of the third treatment period and then decreased to 6.1 mg/L on day 410 before rebounding to over 20 mg/L for the remainder of the treatment period. DO followed an inverse trend in SU7, increasing from 1.6 mg/L on day 361 to 3.3 mg/L on day 410 and then gradually declining. The high DO and low BTEX concentrations on day 410 were associated with a period of high water-table elevation.

DO concentrations in all wells downgradient of the barrier increased after the installation of MgO_2-nitrate briquets in the new remediation wells. The average of the oxygen concentrations in wells SU13, SU15, and SU16 increased from 1.0 mg/L on day 361 to 5.2 mg/L on day 410, indicating that oxygen released from the barrier was being transported through the aquifer. Farther downgradient in wells SU14 and SU17, oxygen also increased after a lag period. DO levels in the active remediation wells were high, ranging from 7 to 30 mg/L more than 100 days after the beginning of the third treatment period.

One surprising observation was that BTEX levels remained fairly constant in the wells downgradient of the barrier even though DO concentrations increased. While there was a measurable decline in total BTEX concentrations in wells SU13, SU15, and SU16 when oxygen increased on day 410, substantial concentrations of BTEX persisted. This trend continued when the data from individual wells were examined. Figures 15a and 15b show total BTEX and oxygen concentrations in the individual wells SU13, SU15, and SU16. All of these wells were located 3 m downgradient of the barrier and were spaced 0.75 m apart perpendicular to the ground-water flow direction. Total BTEX and DO concentrations were similar in these three wells with no consistent differences. This similarity indicates that oxygen was being distributed laterally through the ground water. While high concentrations of oxygen were reaching these wells, high concentrations of BTEX continued to persist. For the period from day 382 to 438, the average DO and total BTEX concentrations in well SU16 were 6.7 and 2.3 mg/L, respectively.

We hypothesize that the continued presence of high concentrations of both DO and BTEX in several of the monitoring wells may be due to inadequate mixing between layers in the aquifer. If high oxygen concentrations were present in one layer and high BTEX concentrations were present in an adjoining layer, there would be little opportunity for biodegradation, yet monitoring wells screened over the two layers would show high concentrations of both oxygen and BTEX.

Nutrient and indicator parameter concentrations followed the same general trends as observed in the second treatment period. Nitrate concentrations in downgradient wells ranged from 0.7 to 2.9 mg/L NO_3-N, indicating that small amounts of nitrate were being transported into the downgradient aquifer. Dissolved iron concentrations continued to be somewhat lower in wells downgradient of the barrier than upgradient. The pH and other dissolved ion concentrations were similar to values observed in the second treatment period.

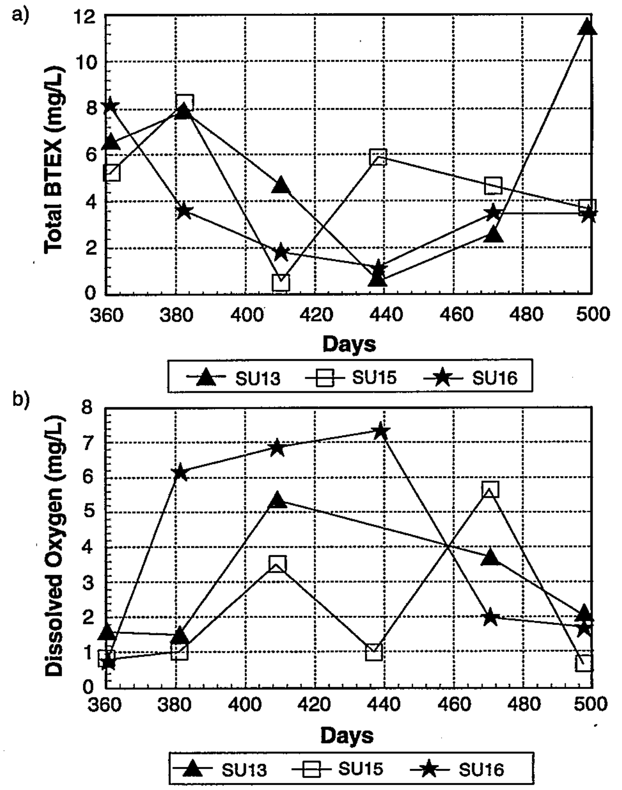

Figure 15. Variation in (a) total BTEX concentrations and (b) dissolved oxygen concentrations during test period 3 (day 361 to day 498) in monitoring wells SU13, SU15, and SU16.

Remediation Well Clogging

A preliminary review of the field monitoring results was performed to determine if dissolved iron concentrations were being reduced during passage through the barrier. Dissolved iron concentrations in SU7 were used to represent upgradient conditions. Before day 382, iron concentrations in SU13 were used to represent downgradient conditions. After day 382, the average of SU13, SU15, and SU16 was used. Results of a Student's t-test indicated that the iron concentration in SU7 was statistically greater than the iron concentrations in the downgradient location at the 99% confidence level. The mean difference in concentrations was 12.1 mg/L with a standard error of 3.0 mg/L.

The observed decline in iron concentration during passage through the barrier could be due to oxidation of soluble iron (Fe^{+2}) by oxygen released from the remediation wells and precipitation as insoluble iron oxides (Fe^{+3}). If the iron oxides precipitated near the active remediation wells, the aquifer could become clogged resulting in large reductions in aquifer permeability and reduced barrier efficiency. Brown and Norris (1994) observed that elevated dissolved iron concentrations are often found in conjunction with hydrocarbon plumes. These authors indicate that oxygen from all sources causes iron precipitation and subsequent plugging around oxygen injection points. Heersche et al. (1994) reported that iron hydroxide precipitation reduced the withdrawal rate in a pumping system at a gasoline-contaminated site when using hydrogen peroxide as the oxygen source in a bioremediation system. Brown and Norris (1994) suggested the use of tripolyphosphate as both a phosphorous source and to reduce the impact of iron precipitation on bioremediation system operations.

Specific Discharge Measurements

The potential for iron clogging of the remediation wells in the permeable barrier system was investigated by conducting tracer tests and specific discharge measurements on the remediation wells after the end of test period 3. Several wells were then excavated to visually examine the aquifer material and collect samples for iron analysis.

The mean and standard deviation for the specific discharges (q) of the original active remediation wells, the new active remediation wells, and the control wells are presented in Table 5. Tracer test data for individual wells are reported by Goin (1995). Regression coefficients (r^2) for all wells were greater than 0.85 indicating a strong correlation between changes in tracer concentration and time.

Table 5. Specific Discharges for Remediation Well Groups Estimated from Tracer Tests

Well Group	Number of Wells Tested	Mean q (m/day)	Std. Deviation (m/day)
Control Wells	5	0.2233	± 0.0362
Original Active Wells	9	0.0476	± 0.0164
New Active Wells	6	0.0174	± 0.0032

The mean specific discharge of the control well group was significantly greater than the specific discharges of both the original active well group and the new active well group at the 99% level using a one-tailed Student's t-test. The mean specific discharge of the original active remediation well group was also significantly larger than the new active well group at the 99% confidence level.

The difference in specific discharge between the control remediation well group and the two active remediation well groups was hypothesized to be the result of iron precipitation around the active remediation wells. The difference in the specific discharges of the original active remediation wells and the new active remediation wells is believed to be partially due to differences in well construction techniques. With the exception of remediation wells R7, R8, and R9, the original active remediation wells were installed in an oversized augered borehole with a coarse sand pack placed along the full length of the well screen. The new remediation wells were installed by vibrating the well screen into place without an artificial sand pack. The vibratory method of installing the new remediation wells may have caused localized densification of the aquifer material with an accompanying reduction in permeability.

Iron Content of Soil Adjoining Remediation Wells

Ferrous iron (Fe^{+2}) will rapidly precipitate in the presence of DO forming an insoluble ferric hydroxide $Fe(OH)_3$ according to the equation:

$$Fe^{+2} + 0.25O_2 + 0.5H_2O + 2OH^- \longrightarrow Fe(OH)_3 \text{ (solid)}$$

We hypothesized that this reaction occurred in the immediate vicinity of the barrier, resulting in a loss of permeability and lower specific discharge through the remediation wells. To evaluate this hypothesis, the aquifer adjoining two of the original active remediation wells (R10 and R11) and one new active remediation well (NR10) was excavated to a depth of approximately 10 cm above the ground-water table and visually examined for evidence of clogging.

There was no apparent change in color between the soils upgradient and directly adjoining the barrier. The lack of distinct color change is not surprising. Soils in the saturated zone are a very coarse light brown to blond sand. Minor red or brown staining due to iron hydroxide cement would probably be obscured by the existing soil color.

While there was no apparent change in color, there was a distinct change in the cohesive strength of the soil. Soils upgradient of the barrier flowed easily with essentially no cohesive strength. Soils immediately adjoining and downgradient of the barrier had considerable cohesive strength and formed a vertical face immediately adjoining the active remediation wells. Upon drying, soils collected adjoining the remediation wells retained this cohesive strength although they could be easily crumbled by hand. This indicates that some type of cement had formed binding the soil particles.

The moisture contents of the soil samples were calculated in conjunction with the iron content analyses so that the iron contents could be expressed in terms of soil dry weight. Extractable iron concentrations for each location sampled are presented in Table 6.

Table 6. Extractable Iron Content in Soils Adjoining the Remediation Wells and Upgradient of the Barrier

Sample Location[a]	Iron Concentration (mg Fe/g of dry soil)	Standard Deviation (mg Fe/g of dry soil)
R10	0.415	0.091
R11	0.272	0.080
NR10	0.254	0.071
Upgradient[b]	0.159	0.110

[a] Soil samples were taken in triplicate at two depths for each sample location.
[b] Upgradient refers to soil samples obtained approximately 7 m upgradient of the permeable barrier.

The soil iron contents around the three remediation wells were compared with the upgradient soil iron content using a one-tailed Student's t-test. The iron contents adjoining all three remediation wells were significantly greater than the upgradient soil iron content ($p < 0.01$). The mean differences between soil iron contents around R10, R11, and

NR10 and upgradient soil iron content were 0.256, 0.113, and 0.095 mg/g, respectively, with corresponding standard errors of 0.034, 0.032, and 0.031 mg/g.

As a rough check on the horizontal extent of the iron precipitation, the mass of iron precipitated by the barrier was estimated using the mean difference in upgradient and downgradient dissolved iron concentrations (12 mg/L), the specific discharge, and the time the barrier has been in place. This mass was then converted to a volume of clogged soil using the maximum difference between the upgradient and remediation well soil iron contents (0.256 mg/g). Following this procedure, the iron-clogged zone was estimated to be 1.5 m wide. This distance seems reasonable, suggesting that iron precipitation is the probable cause for low specific discharges in active remediation wells.

Overall Evaluation of Permeable Barrier System

The permeable barrier system examined in this project was designed to control the migration of dissolved gasoline components by enhancing the aerobic biodegradation of these compounds in the aquifer immediately downgradient of the barrier. Ideally, all contaminants would be degraded to below regulatory limits before reaching the furthest downgradient monitoring wells. The permeable barrier examined in this project did not achieve this objective. Table 7 lists average concentrations of BTEX in monitoring wells immediately downgradient of the barrier over the entire treatment period and current North Carolina ground-water quality standards. While the average concentration of all BTEX components decreased substantially with distance downgradient, none of the BTEX components met ground-water quality standards 8 m downgradient of the barrier. Farther downgradient at well SU5 (25 m), only toluene met water quality standards.

Table 7. Average Concentrations of BTEX in Monitoring Wells Over the Entire Treatment Period

Well	Distance from Barrier[a]	Benzene (mg/L)	Toluene (mg/L)	Ethyl-benzene (mg/L)	Total Xylenes (mg/L)
SU7	-10 m	2.419	8.326	1.391	6.060
SU13	+3 m	0.757	2.406	0.383	1.627
SU14	+8 m	1.123	3.469	0.595	2.366
SU5	+25 m	0.877	0.853	0.272	0.745
NC Standards		0.001	1.000	0.029	0.400

[a] Negative distances are upgradient of the barrier; positive distances are downgradient.

Figures 16a and 16b show average concentrations of total BTEX and DO concentrations in monitoring wells SU7, SU13, SU14, and SU5 for the three treatment periods and for the total project.

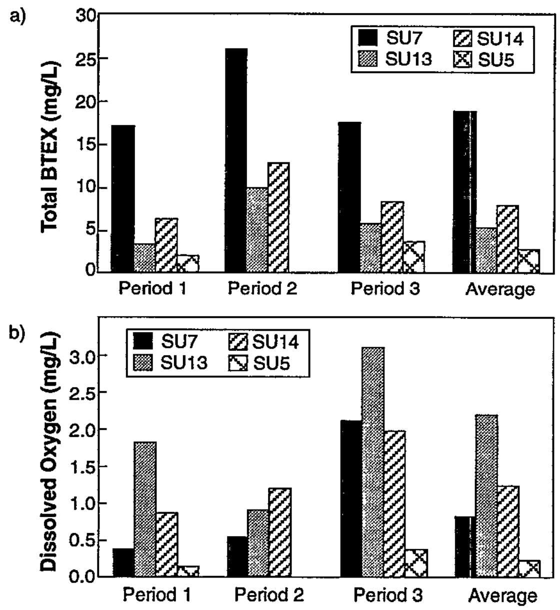

Figure 16. Mean (a) total BTEX concentrations and (b) dissolved oxygen concentrations in monitoring wells for individual treatment periods and entire barrier operational period. (Note: SU5 not included in period 2 graph because only one measurement was taken.)

Total BTEX concentrations in wells downgradient of the barrier are significantly lower than upgradient of the barrier for each treatment period at the 95% confidence level, indicating that some biodegradation is occurring. The barrier also appears to be effective at increasing the DO concentration in the wells immediately downgradient of the barrier. The increase in DO was most notable during the third treatment period when the average oxygen concentration in SU16 was over 4 mg/L.

One possible cause of the poor barrier performance is inadequate delivery of DO to the aquifer. The total mass of BTEX passing through the active side of the barrier was estimated to be approximately 80 grams per day, using the background specific discharge and the average BTEX concentration in SU7 during the third treatment period (17.5 mg/L total BTEX concentration). Samples collected directly from the remediation wells indicated that essentially all of the BTEX compounds that actually entered the remediation wells were biodegraded. This would result in a net loss of 5.6 g of BTEX/day. The total oxygen delivered to the aquifer on day 459 from R1 to R11 and NR1 to NR10 was estimated to be 6.24 grams of oxygen per day. This release rate was estimated, using the measured specific discharges and the oxygen concentration in the remediation wells on day 459 (Tables 8 and 9). Assuming complete mineralization of BTEX (3 to 1 mass ratio of oxygen delivered to BTEX biodegraded), the delivered oxygen should be sufficient to biodegrade an additional 2.1 g of BTEX/day in the downgradient aquifer. This would result in a total BTEX biodegradation of 7.7 g/day or 10% of the total BTEX load. While there is considerable uncertainty in these calculations, they do clearly illustrate the problem in delivering sufficient oxygen to the aquifer using oxygen-releasing wells. This problem was only partially due to clogging of the remediation wells. Assuming an average DO concentration in the remediation wells of 20 mg/L and no reduction in specific discharge, the total maximum BTEX concentration that this barrier could effectively treat is 6 mg/L.

Table 8. Mass of Oxygen Released from Original Remediation Wells on Day 459

Well	Specific Discharge (m/day)	Oxygen Concentration (mg/L)	Oxygen Release[a] (mg/day)
R1	0.045	26.5	542
R2	0.038	26.4	458
R3	0.052	20.2	476
R4	0.079	7.4	269
R5	0.034	18.0	276
R6	0.055	29.5	739
R7	0.059	22.6	609
R8	0.045	26.3	542
R10	0.022	26.0	264
Mean	0.048	22.5	464
C. V.	34%	30%	36%

[a] Oxygen Release = (q)(DO concentration)(well cross-sectional area) with normal well area = (diameter of well)(3 m saturated thickness).

Table 9. Mass of Oxygen Released from New Remediation Wells on Day 459

Well	Specific Discharge (m/day)	Oxygen Concentration (mg/L)	Oxygen Release[a] (mg/day)
NR1	0.023	12.7	132
NR2	0.015	18.3	125
NR3	0.017	12.5	97
NR4	0.020	11.3	101
NR7	0.016	12.3	91
NR10	0.014	21.5	139
Mean	0.0175	14.8	114
C. V.	19%	28%	18%

[a] Oxygen Release = (q)(DO concentration)(well cross-sectional area) with normal well area = (diameter of well)(3 m saturated thickness).

In summary, the permeable barrier constructed in this project was not fully effective in containing the hydrocarbon plume. This was due to two factors: 1) the high concentrations of BTEX entering the barrier, and 2) the clogging of the barrier wells by oxidized iron precipitates.

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APPENDIX A
Laboratory Studies: Oxygen Release Over Time from Solid Peroxide Concretes

Day	37% MgO_2 briquets	37% MgO_2 cylinder	21% MgO_2 briquets	21% MgO_2 cylinder	14% CaO_2 briquets
0	0.2740	0.1910	0.05170	0.03510	0.20052
5	0.2664	0.1854	0.05093	0.03454	0.19002
10	0.2588	0.1798	0.05015	0.03397	0.17952
15	0.2512	0.1742	0.04938	0.03341	0.16902
20	0.2436	0.1686	0.04860	0.03284	0.15852
25	0.2360	0.1630	0.04783	0.03228	0.14802
30	0.2284	0.1574	0.04705	0.03171	0.13752
35	0.2208	0.1518	0.04628	0.03115	0.12702
40	0.2132	0.1462	0.04550	0.03058	0.11652
45	0.2056	0.1406	0.04473	0.03002	0.10602
50	0.1980	0.1350	0.04395	0.02945	0.09552
55	0.1904	0.1294	0.04318	0.02889	0.08502
60	0.1828	0.1238	0.04240	0.02832	0.07452
65	0.1752	0.1182	0.04163	0.02776	0.06402
70	0.1676	0.1126	0.04085	0.02719	0.05352
75	0.1600	0.1070	0.04008	0.02663	0.04302
80	0.1524	0.1014	0.03930	0.02606	0.03252
85	0.1448	0.0958	0.03853	0.02550	0.02202
90	0.1372	0.0902	0.03775	0.02493	0.01152
95	0.1296	0.0846	0.03698	0.02437	0.00102
100	0.1220	0.0790	0.03620	0.02380	
105	0.1144	0.0734	0.03543	0.02324	
110	0.1068	0.0678	0.03465	0.02267	
115	0.0992	0.0622	0.03388	0.02211	
120	0.0916	0.0566	0.03310	0.02154	
125	0.0840	0.0510	0.03233	0.02098	
130	0.0764	0.0454	0.03155	0.02041	
135	0.0688	0.0398	0.03078	0.01985	
140	0.0612	0.0342	0.03000	0.01928	
145	0.0536	0.0286	0.02923	0.01872	
150	0.0460	0.0230	0.02845	0.01815	
155	0.0384	0.0174	0.02768	0.01759	
160	0.0308	0.0118	0.02690	0.01702	
165	0.0232	0.0062	0.02613	0.01646	
170	0.0156	0.0006	0.02535	0.01589	
175	0.0080		0.02458	0.01533	
180	0.0004		0.02380	0.01476	
185			0.02303	0.01420	
190			0.02225	0.01363	
195			0.02148	0.01307	
200			0.02070	0.01250	
205			0.01993	0.01194	
210			0.01915	0.01137	
215			0.01838	0.01081	
220			0.01760	0.01024	
225			0.01683	0.00968	
230			0.01605	0.00911	
235			0.01528	0.00855	
240			0.01450	0.00798	
245			0.01373	0.00742	
250			0.01295	0.00685	

APPENDIX B
Field Monitoring Data

MONITORING WELL F1

TEST PERIOD	Day	Benzene ug/L	Toluene ug/L	Ethyl-benzene ug/L	(m+p)-Xylene ug/L	o-Xylene ug/L	Total BTEX ug/L	Depth to Water	DO mg/L	Eh mv	pH	Temp °C	Alk mg/L	NO_3-N mg/L
	-33	6	0	2	6	2	17	7'2.75"	0.8	86	4.8	18.3	6	<0.5
	-11	10	0	5	10	3	28	5'0.75"	4.4	191	5.4	15.4	6	<0.5
1	9	0	0	0	0	0	0	6'9"	3	207	5	16.2		
	23	2	1	1	1	0	5	7'1"	3.5	140	5.06	16.2	4	<0.5
	39	8	34	67	0	40	149	7'2.5"	2.7	61	5.16	15.9		
	51	3	5	2	0	3	13	6'7.75"	3.9	116	5.25	16	4	<0.5
	111	3	6	0	1	0	9	9'1.75"	1.7	88	4.95	17.7	2	<0.5
	219	9	4	5	15	5	37	9'6"	0.5	65	5.2	22		
	242	29	15	18	68	74	203		0	55.2	5.38	18.2		
2	361	7	1	2	8	1	19	8'11"	2.4	90	4.97	16.3		0.22
3	382	40	13	13	44	25	135	8'8"	1.9	205	5.21	15.1		<0.1
	410	26	1	8	22	10	67	7'7"	4.7	241	5.94	15		<0.1
	438	0	1	0	0	1	2	7'3"	2.3			16		<0.1
	471	0	1	0	1	0	2		1.1	7	5.5	17.6		
	498	111	40	83	266	156	656	11'2"		10				0.71

TEST PERIOD	Day	NH_4-N mg/L	PO_4-P mg/L	SO_4 mg/L	Cl mg/L	Br mg/L	Fe mg/L	Cu mg/L	Mn mg/L	Ca mg/L	Mg mg/L	Na mg/L	Al mg/L	K mg/L
	-33	<0.5	<0.5	8.9	7.5	<0.5	4.2	<0.05	0.02	1.99	0.81	6.3	0.2	2
	-11	<0.5	<0.5	8.5	8.4	<0.5	1.9	0.03	0.04	31.1	1.32	7.2	0.2	<0.5
1	9													
	23	<0.5	<0.5	7.5	6.5	<0.5	0.3	<0.05	2.57	230	4.65	5.2	0.1	0.7
	39													
	51	<0.5	<0.5	7.8	5	<0.5	1.4	<0.05	0.02	2.09	0.67	3.8	0.2	1
	111	<0.5	<0.5	9.6	6.5	<0.5	3	<0.05	0.03	2	0.7	5.6	0.2	0.8
	219													
	242													
2	361	<0.1	<0.1	6.9	8.1	<0.5	1.1	<0.05	0.01	1.91	0.89	6.6	0.2	0.9
3	382	<0.1	<0.1	7.6	9.6	<0.5	1.1	<0.05	0.02	1.76	0.68	6.4	0.2	0.5
	410	<0.1	<0.1	7	6.2	<0.2	1.4	<0.05	0.01	2.04	0.47	6.2	0.2	0.6
	438	<0.1	<0.1	8.2	2.7	<0.2	0.2	<0.05	0.01	2.56	0.47	6.6	<0.1	0.8
	492	<0.1	<0.1	6.4	11	<0.2	5.6	<0.05	0.04	1.81	0.71	5.9	0.2	0.5

Original barriers were installed in 3 remediation wells on day 0.
Original barriers were installed in 8 more remediation wells on day 9.
Original barriers were replaced on day 242.
Barriers were replaced again on day 361.
Alk: alkalinity

MONITORING WELL MW1

TEST PERIOD	Day	Benzene ug/L	Toluene ug/L	Ethyl-benzene ug/L	(m+p)-Xylene ug/L	o-Xylene ug/L	Total BTEX ug/L	Depth to Water	DO mg/L	Eh mv	pH	Temp °C	Alk mg/L	NO_3-N mg/L
	-33	0	1	0	0	0	2	9'3.6"	4.4	57	5.10	18.5	11	1.1
	-11	0	0	0	0	0	0	7'2.75"	4.2	172	5.00	16.6	10	<0.5
	9	0	0	0	0	0	0	9'9.75"	2.9	450	4.93	17.8		
1	39	1	5	6	0	7	19	7'1"	3.5	140	5.06	16.2		
	51	0	4	0	0	0	4	8'6"	3.3	125	5.11	16.6	10	1.52
	111	1	2	0	0	0	3	11'2"	3.6	145	5.10	16.8	6	1.81
2	361	0	0	0	0	0	0	10'9"	4.2	166	5.02	17.9		1.8
3	382	0	0	0	0	0	0	9'10.5"	2.3	260	5.20	17.3		1.68

TEST PERIOD	Day	NH_4-N mg/L	PO_4-P mg/L	SO_4 mg/L	Cl mg/L	Br mg/L	Fe mg/L	Cu mg/L	Mn mg/L	Ca mg/L	Mg mg/L	Na mg/L	Al mg/L	K mg/L
	-33	<0.5	<0.5	3.6	12	2.6	<0.1	0.07	0.75	144	5.53	7.7	<0.1	1
	-11	<0.5	<0.5	23	8.7	<0.5	<0.1	<0.05	<0.01	2	0.93	8.5	<0.1	1.3
	9													
1	39													
	51	<0.5	<0.5	14	10	<0.5	<0.1	<0.05	0.01	2.81	1.23	10.1	0.5	1.5
	111	<0.5	<0.5	<0.5	0.5	<0.5	3.9	<0.05	0.02	2.75	1.31	10.7	<0.1	1.4
2	361	<0.1	<0.1	4.7	8.5	<0.5	<0.1	<0.05	0.01	2.16	1.14	9.1	<0.1	1.1
3	382	<0.1	<0.1	4.9	18	<0.5	<0.1	<0.05	0.01	2.34	1.12	9.3	<0.1	0.7

MONITORING WELL MW2

TEST PERIOD	Day	Benzene ug/L	Toluene ug/L	Ethyl-benzene ug/L	(m+p)-Xylene ug/L	o-Xylene ug/L	Total BTEX ug/L	Depth to Water	DO mg/L	Eh mv	pH	Temp °C	Alk mg/L	NO_3-N mg/L
	-33	37	0	7	5	2	51	3'6.25"	1.2	210	6.57	16.3	72	<0.5
	-11	1411	25	141	213	78	1868	2'2.5"	1.1	-26	6.60	15.4	94	<0.5
1	9	379	15	80	125	69	667	3'2.75"	0.5	1	6.55	15.3		
	39	367	34	87	125	89	701	3'5.5"	0.2	-50	6.50	15.3		
	51	62	7	15	23	18	124	2'11.25"	0.8	-29	6.39	14.4	48	<0.5
	111	508	1	93	21	7	630	5'4.5"	0.2	-10	6.41	15.9	34	<0.5
	175	62	6	5	4	9	87	8'1"	0	-49	6.53	18.6		<0.5
2	361	438	115	120	210	121	1004	5'0.5"	1.3	71	6.12	15.5		0.12
3	382	672	22	178	393	218	1483	7'3"	1.4	52	6.16	13.4		0.11
	498	474	12	119	88	45	738	7'3"		5				0.67

TEST PERIOD	Day	NH_4-N mg/L	PO_4-P mg/L	SO_4 mg/L	Cl mg/L	Br mg/L	Fe mg/L	Cu mg/L	Mn mg/L	Ca mg/L	Mg mg/L	Na mg/L	Al mg/L	K mg/L
	-33	<0.5	<0.5	7.9	6.5	<0.5	3.7	<0.05	0.06	69.8	1.83	5.8	<0.1	1.9
	-11	<0.5	<0.5	6.4	10	<0.5	41.2	<0.05	0.33	48.2	1.86	9.6	<0.1	1.8
1	9													
	39													
	51	<0.5	<0.5	14	10	<0.5	5.5	<0.05	0.01	8.1	0.26	3.9	0.2	2.3
	111	<0.5	<0.5	7.4	5.4	<0.5	12.1	<0.05	0.03	16	1.1	5.7	<0.1	1.4
	175	<0.5	<0.1	11	4.6	<0.5	11.1	<0.05	0.04	19.5	1.02	1.5	<0.1	
2	361	0.14	<0.1	6.7	7.3	<0.5	10.5	<0.05	0.03	11.8	1.21	6.9	0.1	2.6
3	382	<0.1	<0.1	6.3	7.9	<0.5	15.5	<0.05	0.03	12.2	1.11	6.3	0.1	1.3
	498	<0.1	<0.02	8.8	7.4	<0.2	23.5	<0.05	0.04	11.8	1.2	6.2	<0.1	2.7

MONITORING WELL SU1

TEST PERIOD	Day	Benzene ug/L	Toluene ug/L	Ethyl-benzene ug/L	(m+p)-Xylene ug/L	o-Xylene ug/L	Total BTEX ug/L	Depth to Water	DO mg/L	Eh mv	pH	Temp °C	Alk mg/L	NO_3-N mg/L
	-33	1084	137	325	760	441	2747	2'1.1"	0.3	-336	6.25	15.2	22	<0.5
	-11	21	12	7	15	9	64	6"	0	-29	6.30	14.0	84	<0.5
1	9	2338	155	680	1524	845	5542	1'10"	0.5	-3	6.28	14.5		
	23	1261	50	365	685	387	2748	2'0.5"	0	-61	6.34	15.6	46	<0.5
	39	590	23	175	301	166	1254	2'1"	0	-86	6.37	15.0		
	51	333	14	124	271	146	888	2'6"	0.5	-72	6.18	14.5	32	<0.5
	111	159	22	41	96	54	371	4'0.3"	0.1	-62	6.26	16.7	28	<0.5
	175	1645	68	545	1240	686	4185	5'10"	0	-38	6.20	23.0		<0.5
3	382	813	33	439	890	428	2603	2'10"	0.3	48	6.11	14.0		0.2
	438	382	135	2933	526	340	4316	2'2.5"	0.9			15.7		0.27
	498	1298	1487	514	1116	541	4956	5'10"		-41				0.81

TEST PERIOD	Day	NH_4-N mg/L	PO_4-P mg/L	SO_4 mg/L	Cl mg/L	Br mg/L	Fe mg/L	Cu mg/L	Mn mg/L	Ca mg/L	Mg mg/L	Na mg/L	Al mg/L	K mg/L
	-33	<0.5	<0.5	9	28	<0.5	23.4	<0.05	0.3	103	2.82	7.6	<0.1	2.2
	-11	<0.5	<0.5	8.4	9.6	0.52	29.4	<0.01	0.04	11.6	0.99	11.9	0.1	2
1	9													
	23	<0.5	<0.5	10	6.5	<0.5	<0.1	<0.05	<0.05	14.7	4.52	16.3	<0.1	7.5
	39													
	51	<0.5	<0.5	4.2	7.2	<0.5	23.1	<0.05	0.03	8	0.7	6.3	<0.1	2.2
	111	<0.5	<0.5	6.7	5.4	<0.5	15.6	<0.05	0.03	8.7	0.6	7	0.4	1.8
	175	<0.5	<0.1	6.7	6.4	<0.5	23	<0.05	0.03	9.19	0.76	7.6	<0.1	2.4
2	361	0.22	<0.1	5.1	13	<0.5	30.8	<0.05	0.04	10.2	1.39	12	0.1	1.9
3	382	0.1	<0.1	2.1	11	<0.5	35	<0.05	0.04	10.5	1.37	11.7	<0.1	1.6
	438	0.11	<0.1	8.4	7.9	<0.2	22.3	<0.05	0.03	9.29	1.07	10.6	0.1	2.1
	498	0.12	0.035	6.5	8.1	1.44	19.4	<0.05	0.03	6.91	0.92	8.7	<0.1	2.2

MONITORING WELL SU2

TEST PERIOD	Day	Benzene ug/L	Toluene ug/L	Ethyl-benzene ug/L	(m+p)-Xylene ug/L	o-Xylene ug/L	Total BTEX ug/L	Depth to Water	DO mg/L	Eh mv	pH	Temp °C	Alk mg/L	NO_3-N mg/L
	-33	54	0	5	0	1	60	2'1.1"	1.3	-22	5.50	14.7	36	1.6
	-11	363	5	91	81	35	574	6"	2.4	105	5.30	14.3	16	1.2
1	9	224	5	71	39	7	346	1'10.5"	0.4	200	5.33	14.8		
	23	2431	36	867	460	100	3894	2'2"	0.1	55	5.15	16.0	20	1.7
	39	254	3	81	9	2	349	2'1"	0.2	-5	5.83	15.5		
	51	175	4	47	5	1	232	1'6.5"	1.2	54	5.20	14.4	22	1.4
	111	14	4	0	0	0	18	4'2.5"	0.9	65	5.66	16.5	18	2
	175	107	4	3	2	2	119	5'10"	0.4	11	5.70	21.0		0.97
2	361	117	2	55	31	4	209	3'8"	0.2	126	5.71	15.0		0.73
3	382	208	3	6	1	2	220	2'10"	0.2	139	5.88	14.4		0.88
	438	68	4	1	1	3	77	2'3"				15.2		0.9
	498	86	2	6	1	1	96	5'10"		13				1.1

TEST PERIOD	Day	NH_4-N mg/L	PO_4-P mg/L	SO_4 mg/L	Cl mg/L	Br mg/L	Fe mg/L	Cu mg/L	Mn mg/L	Ca mg/L	Mg mg/L	Na mg/L	Al mg/L	K mg/L
	-33	<0.5	<0.5	12	17	2.1	2.2	<0.05	0.04	14.9	1.49	10.8	<0.1	2.5
	-11	<0.5	<0.5	14	17	<0.5	2.4	0.02	0.02	6.05	1.36	15.4	0.2	2.1
1	9													
	23	<0.5	<0.5	11	15	<0.5	6.2	<0.05	0.03	7.88	2.04	12.4	<0.1	2.4
	39													
	51	<0.5	<0.5	17	15	<0.5	7.9	<0.05	0.03	7.23	2.1	16.1	<0.1	2.4
	111	<0.5	<0.5	10.2	13.1	<0.5	7.7	<0.05	0.03	6	1.7	11.4	0.4	3.1
	175	<0.5	<0.1	16	11	<0.5	6.1	<0.05	0.03	4.85	1.23	12.5	<0.1	2.2
2	361	<0.1	<0.1	14	15	<0.5	15.5	<0.05	0.03	5.07	1.58	16	<0.1	1.5
3	382	<0.1	<0.1	13	17	<0.5	15.9	<0.05	0.03	6.48	1.95	16.9	0.1	1.5
	438	0.16	<0.1	15	17	<0.2	16.7	<0.05	0.03	5.74	1.58	17.6	0.1	1.8
	498	<0.1	<0.02	15	18	0.3	13.1	<0.05	0.03	4.54	1.15	15.9	0.1	1.9

MONITORING WELL SU3

TEST PERIOD	Day	Benzene ug/L	Toluene ug/L	Ethyl-benzene ug/L	(m+p)-Xylene ug/L	o-Xylene ug/L	Total BTEX ug/L	Depth to Water	DO mg/L	Eh mv	pH	Temp °C	Alk mg/L	NO_3-N mg/L
	-33	470	1499	305	743	429	3447		0	-350	6.23	15.1	40	<0.5
	-11	39	109	19	48	28	243	3.5"	0.8	-40	6.24	14.3	46	<0.5
1	9	4654	7886	1476	3823	2170	20010	1'7.5"	0	-72	6.11	13.8		
	19	2249	4789	846	2039	1166	11089	1'7"	0	-121	6.21	15.0		
	23	1570	2900	506	1146	679	6801	1'9.5"	0.1	-86	6.20	14.2	36	<0.5
	39	856	1833	392	809	486	4375	1'10"	0	-86	6.20	14.4		
	51	459	951	227	420	250	2308	1'3"	0.8	-75	6.26	13.8	32	<0.5
	63	465	988	231	391	277	2353	1'5"	0.6	-77	6.50	14.8		
	86	493	890	231	338	284	2235	1'6"	0	-55	6.60	15.1		
	111	389	736	198	488	327	2138	3'9"	0.3	-35	6.16	17.3	20	<0.5
	139	132	257	102	164	124	779	5'5"	0	-98	6.10	19.6		
	175	245	237	149	189	140	961		0	-42	6.10	21.5		<0.5
	219	891	2606	692	1463	814	6466	4'2"	0.2	-30	6.10	22.0		
	242	2175	7725	1307	3302	1729	16238		0.3	-19	6.06	23.3		
	255	1603	5142	953	2293	1208	11199	4'10"	2.8	-34	6.08	21.9		<0.5
2	298	1511	3748	778	2291	978	9305	4'5"						
	361	1117	2506	510	964	661	5758	3'5.5"	0.1	-61	5.86	15.0		0.24
	382	3737	9467	1425	3489	1976	20094	2'7"	0.1	-58	6.08	13.7		0.17
3	438	1376	3076	507	1116	778	6853	1'11"	0.2			16.1		0.1
	498	848	3204	575	1125	800	6552	5'7"		-34				0.68

TEST PERIOD	Day	NH_4-N mg/L	PO_4-P mg/L	SO_4 mg/L	Cl mg/L	Br mg/L	Fe mg/L	Cu mg/L	Mn mg/L	Ca mg/L	Mg mg/L	Na mg/L	Al mg/L	K mg/L
	-33	<0.5	<0.5	2.3	7.3	<0.5	15.6	<0.05	0.54	124	5	7.6	<0.1	1.2
	-11	<0.5	<0.5	0.95	5.6	<0.5	15.8	<0.01	0.04	7	0.9	6.7	<0.1	1.3
1	9													
	19													
	23	<0.5	<0.5	3.5	4	<0.5	12.8	<0.05	0.04	7.2	0.76	4.9	0.3	1
	39													
	51	<0.5	<0.5	3.8	5	<0.5	12.9	<0.05	0.04	4.8	0.67	4.9	<0.1	1.2
	63													
	86													
	111	<0.5	<0.5	3.5	5	<0.5	10.3	<0.05	0.03	3.82	0.6	5.5	0.3	1
	139													
	175	<0.5	<0.1	5.4	5.5	<0.5	10.4	<0.05	0.03	4.37	0.94	7.1	<0.1	2.4
	219													
	242													
	255	<0.5	<0.5	2.4	8.9	<0.5	23.1	<0.05	0.06	9.15	1.63	8.8	<0.1	2.1
2	298													
	361	0.38	<0.1	2.3	19	<0.5	20.2	<0.05	0.06	11.4	2.1	9.9	<0.1	3
	382	0.69	<0.1	2.9	25	<0.5	30.1	<0.05	0.11	21.5	4.19	11.5	0.1	3.7
3	438	0.64	<0.1	7.9	7.9	<0.2	15.8	<0.05	0.07	13.25	2.29	10.3	0.1	3.9
	498	0.37	0.03				9.6	<0.05	0.04	7.33	1.66	7.6	0.2	3.3

MONITORING WELL SU4

TEST PERIOD	Day	Benzene ug/L	Toluene ug/L	Ethyl-benzene ug/L	(m+p)-Xylene ug/L	o-Xylene ug/L	Total BTEX ug/L	Depth to Water	DO mg/L	Eh mv	pH	Temp °C	Alk mg/L	NO_3-N mg/L
	-33	1090	1380	364	668	446	3950	1'10"	0	-310	6.11	15.4	42	<0.5
	-11	95	47	12	23	14	191	4"	1.2	32	5.80	14.0	36	0.57
1	9	1297	2185	498	1004	606	5590	1'8"	0.1	-51	5.98	13.2		
	23	557	650	186	312	225	1930	1'11"	0	-44	5.99	15.2	44	<0.5
	39	443	442	138	226	166	1414	1'10.5"	0.1	-43	6.01	15.5		
	51	630	749	220	365	250	2214	1'3.5"	0.6	-55	6.12	15.1	42	<0.5
	111	1417	2466	483	914	615	5895	3'9"	0.2	-10	6.00	16.5	38	<0.5
	175	507	545	246	382	305	1984	5'7"	0	-6	5.90	22.0		<0.5
	242	99	50	32	39	47	267		0.2	44	5.93	22.8		
2	251	738	1014	328	567	318	2965	4'10"	2.8	-60	6.08	21.2		<0.5
	298	309	367	126	169	133	1104	4'5"						
	361	880	1134	317	550	403	3284	3'6"	0.3	-18	5.72	13.6		0.21
3	382	680	1086	283	474	330	2853	2'7.5"	0.4	-40	5.81	13.9		0.19
	438	763	1093	245	394	340	2835	2'0"	0.2			16.1		0.15
	498	555	657	208	295	89	1804	5'7"		3				0.75

TEST PERIOD	Day	NH_4-N mg/L	PO_4-P mg/L	SO_4 mg/L	Cl mg/L	Br mg/L	Fe mg/L	Cu mg/L	Mn mg/L	Ca mg/L	Mg mg/L	Na mg/L	Al mg/L	K mg/L
	-33	<0.5	<0.5	5.2	10	<0.5	19.2	<0.05	0.09	38	1.45	13.4	<0.1	1.2
	-11	<0.5	<0.5	12	7.8	<0.5	13.2	0.02	0.44	63.4	2.2	13.2	<0.1	1.1
1	9													
	23	<0.5	<0.5	8	8	<0.5	13.3	<0.05	0.65	56	2	13.7	<0.1	1.3
	39													
	51	<0.5	<0.5	17	15	<0.5	7.9	<0.05	0.03	7.23	2.1	16.1	<0.1	2.4
	111	<0.5	<0.5	9	8	<0.5	14.6	<0.05	0.05	4.2	0.74	14.4	0.2	1
	175	<0.5	<0.1	12	6.9	<0.5	8.2	<0.05	0.06	5.33	0.43	12.7	<0.1	1.8
	242													
2	255	<0.5	<0.5	8.3	7.1	<0.5	10.1	<0.05	0.03	8.06	1.49	12.2	<0.1	1
	298													
	361	0.31	<0.1	11	9.8	<0.5	15.6	<0.05	0.07	5.41	0.95	14.4	0.1	1.5
3	382	0.37	<0.1	8.1	36	<0.5	17.9	<0.05	0.05	6.24	1.08	13.3	0.1	1.2
	438	0.47	<0.1	11	9.7	<0.2	15.9	<0.05	0.07	8.66	1.57	14.1	0.3	1.9
	498	0.68	0.085	8.5	8.9	<0.2	20.8	<0.05	0.07	6.44	1.18	13.9	0.2	1.2

MONITORING WELL SU5

TEST PERIOD	Day	Benzene ug/L	Toluene ug/L	Ethyl-benzene ug/L	(m+p)-Xylene ug/L	o-Xylene ug/L	Total BTEX ug/L	Depth to Water	DO mg/L	Eh mv	pH	Temp °C	Alk mg/L	NO_3-N mg/L
	-33	119	77	25	33	26	280	1'9.5"	0.1	-353	6.22	15.8	10	<0.5
	-11	462	198	106	85	67	918	4.5"	0.7	-8	6.30	13.8	36	<0.5
1	9	839	845	244	334	289	2551	1'6"	0.2	-69	6.20	14.2		
	23	1871	2313	519	886	668	6257	1'8.5"	0	-77	6.25	13.8	36	<0.5
	39	1249	1401	322	533	411	3916	1'1.85"	0	-55	6.13	14.1		
	51	484	295	135	118	114	1147	1'3"	0.4	-68	6.29	13.8	26	<0.5
	111	331	97	77	79	63	646	3'8"	0.3	-20	5.99	17.5	16	<0.5
	139	34	19	8	8	5	74	5'4.5"	0.1	-94	6.06	19.7		
	175	321	5	55	17	11	408	5'6.5"	0	-36	6.10	21.5		<0.5
2	361	629	81	107	113	94	1024	3'5"	0.1	-51	5.90	14.9		0.36
3	382	847	364	217	215	195	1838	2'6.5"	0.7	114	5.70	13.8		0.24
	410	1993	2640	803	1412	1074	7922	1'1"	0.4	-30	5.77	13.7		0.18
	438	1625	2129	707	1298	929	6688	2'0"	0.3			15.8		0.15
	498	303	52	65	44	27	491	5'7"		-66				0.68

TEST PERIOD	Day	NH_4-N mg/L	PO_4-P mg/L	SO_4 mg/L	Cl mg/L	Br mg/L	Fe mg/L	Cu mg/L	Mn mg/L	Ca mg/L	Mg mg/L	Na mg/L	Al mg/L	K mg/L
	-33	<0.5	<0.5	4.3	8.8	<0.5	20	<0.05	1.21	111	3.12	7	<0.1	0.8
	-11	<0.5	<0.5	7	6	<0.5	17.2	0.04	0.78	102	3.4	7.5	<0.1	0.9
1	9													
	23	<0.5	<0.5	2.4	5.5	<0.5	19	<0.05	0.9	43	1.74	7.2	<0.1	1.3
	39													
	51	<0.5	<0.5	10	7	<0.5	15	<0.05	0.04	3.26	1.08	6.7	0.3	2.1
	111	<0.5	<0.5	9	8	<0.5	12.7	<0.05	0.03	2.4	1	7.5	0.3	2
	139													
	175	<0.5	<0.1	13	6.6	<0.5	17.9	<0.05	0.04	3.02	0.95	8.3	<0.1	1.7
2	361	0.19	<0.1	5.5	9.5	<0.5	24.3	<0.05	0.05	3.92	1.36	8.4	0.1	2.4
3	382	0.17	<0.1	6.5	10	<0.5	19.5	<0.05	0.04	3.73	1.39	9	0.1	1.7
	410	0.31	<0.1	2.1	18	<0.2	39.4	<0.05	0.08	6.39	1.7	12.2	<0.1	1.8
	438	0.31	<0.1	3.3	14	<0.2	29.7	<0.05	0.06	5.01	1.63	11.1	0.2	2.6
	498	0.13	0.028	12	7.4	<0.2	13.2	<0.05	0.02	2.29	0.74	8.5	0.2	1.8

MONITORING WELL SU6

TEST PERIOD	Day	Benzene ug/L	Toluene ug/L	Ethyl-benzene ug/L	(m+p)-Xylene ug/L	o-Xylene ug/L	Total BTEX ug/L	Depth to Water	DO mg/L	Eh mv	pH	Temp °C	Alk mg/L	NO_3-N mg/L
	-33	0	0	0	0	0	0	1'7.75"	1.2	-4	4.9	15.8	12	<0.5
	-11	0	0	0	0	0	0	1'1"	2.7	211	4.9	14.1	4	<0.5
1	9	0	0	0	0	0	0	1'3.75"	1.8	118	5.18	13.9		
	23	4	12	2	5	3	26	1'6"	1.9	162	4.93	13.9	4	<0.5
	39	0	19	2	0	2	22	1'6.5"	1.9	82	4.82	13.5		
	51	0	59	0	0	0	59	2'0.5"	2.4	97	5.01	13.3	2	<0.5
	111	4	2	0	0	0	6	3'4.75"	1.5	115	4.75	17.2	2	0.7
	175	0	3	0	0	0	3	5'3"	0.4	39	4.7	22		1.4
2	361	1	0	0	1	0	2	3'1.5"	1.2	157.1	5.05	14.2		1.9
3	382	0	0	0	0	0	0	2'3"	2.1	215	5.04	12.9		1.6
	438	0	3	0	0	1	4	1'7"	5.1			16.4		1.7
	498	0	1	0	0	0	1	5'3"		44				2.3

TEST PERIOD	Day	NH_4-N mg/L	PO_4-P mg/L	SO_4 mg/L	Cl mg/L	Br mg/L	Fe mg/L	Cu mg/L	Mn mg/L	Ca mg/L	Mg mg/L	Na mg/L	Al mg/L	K mg/L
	-33	<0.5	<0.5	13	8.7	<0.5	<0.1	<0.05	.1	55	2.35	6	<0.1	1.3
	-11	<0.5	<0.5	7	6	<0.5	<0.1	0.03	0.02	83	3	7.8	<0.1	1.3
1	9													
	23	<0.5	<0.5	16	4.2	<0.5	<0.1	<0.05	0.53	66.4	3.4	3.6	0.2	2
	39													
	51	<0.5	<0.5	15	5.2	<0.5	0.1	<0.05	0.01	4.6	1.8	4.2	0.1	1.8
	111	<0.5	<0.5	13	6	<0.5	<0.1	<0.05	0.02	4.44	1.7	4.5	0.2	1.3
	175	<0.5	<0.1	11	8.1	<0.5	<0.1	<0.05	0.02	3.35	1.28	7	0.2	2.7
2	361	<0.1	<0.1	11	8.7	<0.5	0.2	<0.05	0.01	4.37	1.64	8.1	0.2	1.7
3	382	0.1	<0.1	13	8.3	<0.5	<0.1	<0.05	0.01	4.54	1.68	7.7	0.1	1.3
	438	<0.1	<0.1	11	13	<0.2	<0.1	<0.05	0.01	4.47	1.65	7.4	0.2	1.9
	498	<0.1	<0.02	9.4	8.9	<0.2	<0.1	<0.05	0.01	4.75	1.61	7.8	0.1	2.2

MONITORING WELL SU7

TEST PERIOD	Day	Benzene ug/L	Toluene ug/L	Ethyl-benzene ug/L	(m+p)-Xylene ug/L	o-Xylene ug/L	Total BTEX ug/L	Depth to Water	DO mg/L	Eh mv	pH	Temp °C	Alk mg/L	NO_3-N mg/L
	-33	61	194	30	85	44	414	4'10"	0.3	-43	6.08	17	33	<0.5
	-11	739	1907	293	817	434	4189	2'11.5"	1.5	25	5.9	14	34	<0.5
1	0	1142	2149	673	1515	1035	6515	3'8"	0.8	22	5.86	15.9		
	9	2418	7484	1442	4132	2199	17675	4'6.5"	0.3	-36	5.97	15.9		
	19	1641	5842	1093	3061	1638	13276	4'7.5"	0.1	-61	5.98	15.1		
	23	1341	4762	749	2046	1149	10046	4'10.25"	0.4	-25	5.93	15	48	<0.5
	31	1580	5228	896	2450	1306	11459	5'4"	0.3	-37	5.95	15		
	39	2218	6794	1139	3507	1793	15452	4'9.5"	0.1	-9	5.81	15.3		
	51	1521	5585	822	2547	1273	11749	4'3.5"	0.6	-25	5.96	14.7	44	<0.5
	63	241	808	95	404	203	1751		1.8	84.1	5.78	15.4		
	86	3760	7939	1573	4781	2443	20495	4'5.2"	0.5	72	5.57	15.7		
	111	3201	14846	2117	6381	3320	29865	6'10"	0.4	18	5.92	17.4	66	<0.5
	139	3070	8000	2006	5767	3021	21865	8'5.5"	0.1	-35	5.88	19.5		
	175	4684	9777	2775	6611	4286	28134	8'9"	0.1	-21	6.1	22.8		<0.5
	219	1705	6982	1115	3188	1577	14567	7'1.5"	0.2	-21	6.1	24		
	242	3754	12070	1801	4931	2560	25116		0	-29.3	5.84	23.3		
2	255	4108	14166	2140	5845	3055	29313	7'8"	0	-67.2	6.02	23		<0.5
	285	4009	16135	2334	6654	3321	32453							
	298	3089	11989	1677	4844	2467	24066	7'6"						
	361	2517	9379	1215	3670	1825	18606		1.6	-29.6	6.01	16.1		0.3
3	382	1380	5711	776	2282	1164	11313	5'6"	2.2	36	6.2	14.5		0.13
	410	631	2910	452	1381	746	6120	4'0"	3.3	-41	6.2	14.7		0.14
	438	2209	9762	1602	4724	2556	20853	5'0"	2.5			15.8		0.53
	471	3077	12379	1887	5331	3010	25684		0.9	11	5.86	17.8		
	498	2338	10801	1626	5021	2365	22151	8'8"		9				0.73

TEST PERIOD	Day	NH_4-N mg/L	PO_4-P mg/L	SO_4 mg/L	Cl mg/L	Br mg/L	Fe mg/L	Cu mg/L	Mn mg/L	Ca mg/L	Mg mg/L	Na mg/L	Al mg/L	K mg/L
	-33	<0.5	<0.5	5.6	6	<0.5	18	<0.05	0.06	6.7	0.93	5.3	<0.1	1
	-11	<0.5	<0.5	6.8	7	<0.5	18.5	0.02	1	68	2.6	5.7	<0.1	1.2
1	0													
	9													
	19	0.57												
	23		<0.5	6.6	6.7	<0.5	12	<0.05	0.4	62	3.3	7	0.3	2.2
	31													
	39	<0.5												
	51		<0.5	7.3	8.6	<0.5	10	<0.05	0.05	10.4	1.53	7.4	0.2	1.9
	63													
	86	0.95												
	111		<0.5	8.7	13.1	<0.5	13.7	<0.05	0.09	16.6	2.68	11	0.1	2.8
	139	3.8												
	175		<0.1	15	15	0.61	39.8	<0.05	0.3	56.7	10.4	13	0.1	9.7
	219													
	242	1.7												
2	255		<0.5	13	15	<0.5	27.7	<0.05	0.16	27.5	4.34	12.9	<0.1	3.9
	285													
	298	1.8												
	361	1	<0.1	4.9	13	<0.5	20	<0.05	0.18	29.7	3.8	10.3	0.2	4.4
3	382	1.9	<0.1	5.2	13	<0.5	13.1	<0.05	0.13	22.6	2.81	8.2	0.1	3
	410	2.1	<0.1	6	10	<0.2	10.2	<0.05	0.1	19.9	2.52	7.6	0.1	2.6
	438	4	<0.1	9.5	14	0.46	16.3	<0.05	0.14	24.8	4.14	10.9	0.2	5.6
	498		<0.02	9.4	14	0.4	28.6	<0.05	0.24	34.7	7.2	13.7	0.1	8.3

MONITORING WELL SU8

TEST PERIOD	Day	Benzene ug/L	Toluene ug/L	Ethyl-benzene ug/L	(m+p)-Xylene ug/L	o-Xylene ug/L	Total BTEX ug/L	Depth to Water	DO mg/L	Eh mv	pH	Temp °C	Alk mg/L	NO_3-N mg/L
	-33	52	107	16	41	23	239	5'3"	1	-3	6.05	17	38	<0.5
	-11	419	954	176	426	216	2191	3'4.75"	0.5	16	6	14	2.5	<0.5
1	0	1701	3159	539	1342	706	7447	4'2.5"	0.5	-28.8	6.04	15.1		
	9	3192	5942	991	2522	1306	13953	5'0.75"	0.4	-46	6.02	15.6		
	23	3055	5165	879	2232	1187	12518	5'4"	0.3	-53	6.07	14.6	40	<0.5
	31	2802	4548	727	1858	1014	10948	5'11"	0.2	-60	6.14	14.5		
	39	4632	7061	1239	3536	1800	18269	5'3.75"	0	-44	6.07	14.7		
	51	6282	8400	1784	5024	2644	24135	4'10.5"	0.2	-47	6.08	15.5	42	<0.5
	63	3427	6323	852	2473	1244	14318	4'10"	0.4	-47	6.05	15		
	86	2627	5293	714	1999	1011	11644	4'7"	0	-25	5.88	15.8		
	111	8916	19150	2274	6598	3330	40268	7'4"	0.2	-33	6.15	18.3	38	<0.5
	139	5805	8338	1626	4748	2512	23029	8'11.5"	0	-75	6.27	19.3		
	175	2140	6396	1259	3367	1732	14893	9'3"	0	-13	6.45	22.6		<0.5
	219	7139	17156	2001	5289	2900	34486	7'7.5"	0.4	-19	6.2	23		
	242	9609	20483	2351	6597	3397	42437		0.1	-13	6.09	23		
2	361	1409	6069	1333	3407	1423	13641	6'11"	0.3	-90.4	5.96	15.6		0.23
3	382	454	2238	613	1536	664	5505	6'1.5"	0.3	-24	6.1	14.2		0.14
	438	4558	9459	1548	4299	2196	22060	5'7"	0.4			16.2		0.12
	498	5186	12551	1505	4393	2141	25776	9'2"		-14				0.71

TEST PERIOD	Day	NH_4-N mg/L	PO_4-P mg/L	SO_4 mg/L	Cl mg/L	Br mg/L	Fe mg/L	Cu mg/L	Mn mg/L	Ca mg/L	Mg mg/L	Na mg/L	Al mg/L	K mg/L
	-33	<0.5	<0.5	2.6	8.4	<0.5	17.7	<0.05	0.02	10	0.6	8	<0.1	0.6
	-11	<0.5	<0.5	1.3	9	<0.5	23.4	0.01	0.02	22.4	1	9	0.3	0.6
1	0													
	9													
	23	<0.5	<0.5	2.5	6.7	<0.5	21	<0.05	0.03	12.4	0.75	7.6	<0.1	0.9
	31													
	39													
	51	<0.5	<0.5	3.6	7	<0.5	24	<0.05	0.02	3.73	0.9	7.7	0.2	1.2
	63													
	86													
	111	<0.5	<0.5	2.8	7.2	<0.5	30	<0.05	0.02	4.6	0.92	9.7	<0.1	1
	139													
	175	<0.5	<0.1	0.86	10	<0.5	19.3	<0.05	0.02	7.49	1.06	13.6	<0.1	1.4
	219													
	242													
2	361	0.23	<0.1	<0.5	8.3	<0.5	22.3	<0.05	0.02	4.97	0.95	10.2	<0.1	0.6
3	382	0.17	<0.1	0.98	8.3	<0.5	19.9	<0.05	0.02	4.8	0.85	9.7	0.1	0.6
	438	0.26	<0.1	1.5	8.6	<0.2	20.3	<0.05	0.02	4.39	0.95	8.2	<0.1	1.1
	498	1.2	<0.02	2.5	10	<0.2	24.7	<0.05	0.08	19.2	2.59	11.8	0.2	2.6

MONITORING WELL SU9

TEST PERIOD	Day	Benzene ug/L	Toluene ug/L	Ethyl-benzene ug/L	(m+p)-Xylene ug/L	o-Xylene ug/L	Total BTEX ug/L	Depth to Water	DO mg/L	Eh mv	pH	Temp °C	Alk mg/L	NO_3-N mg/L
	-33	60	93	18	47	26	245	2'6.5"	0.4	-32	6.10	14.7	31	<0.5
	-11	1545	1011	441	1013	559	4569	10.3"	1	17	6.03	14.0	42	<0.5
1	0	249	17	90	166	83	604	1'7"	0.3	1	5.94	14.5		
	9	19	2	11	18	9	58	2'4"	0.3	-38	5.81	14.5		
	23	176	32	44	67	40	358	2'7"	0.2	-49	5.86	13.5	14	<0.5
	31	119	53	46	75	36	329	3'1.5"	0.2	-48	6.22	13.8		
	39	27	56	29	77	31	220	2'7"	0.6	5	5.63	13.2		
	51	73	5	13	11	4	106	2'	1.9	9	5.70	12.6	12	1
	63	216	6	42	48	28	341	2'1.5"	0.8	-4	5.84	14.0		
	86	258	142	92	193	102	787	2'3"	0.7	-24	5.79	15.0		
	111	18	2	5	5	3	32	4'6"	1	20	5.60	17.8	4	1.7
	139	213	56	44	85	52	449	6'2.75"	0.8	-45	5.80	20.0		
	175	627	295	125	208	140	1396	6'4.5"	0.2	-15	6.00	23.0		
	219	2338	3631	708	1816	975	9467	4'11"	0.3	14	6.00	23.0		
	242	1925	964	634	1551	804	5878		0.1	-2	5.91	22.8		
2	361	630	14	202	415	192	1453	4'2"	1.6	-70	6.02	13.8		0.49
3	382	72	8	44	83	41	248	3'4"	1.3	88	6.08	12.7		0.24
	438	265	24	109	161	92	651	2'9"	4			15.8		0.16
	498	720	26	250	475	215	1686	6'5"		-52				0.68

TEST PERIOD	Day	NH_4-N mg/L	PO_4-P mg/L	SO_4 mg/L	Cl mg/L	Br mg/L	Fe mg/L	Cu mg/L	Mn mg/L	Ca mg/L	Mg mg/L	Na mg/L	Al mg/L	K mg/L
	-33	<0.5	<0.5	6	4.4	<0.5	14	<0.05	0.05	193	4.37	4.8	0.2	2.1
	-11	<0.5	<0.5	3	6	<0.5	21	0.04	0.02	41	1.5	5	<0.1	1.1
1	0													
	9													
	23	<0.5	<0.5	18	7	<0.5	6.9	<0.05	0.12	119	3.4	5	0.2	6.4
	31													
	39													
	51	<0.5	<0.5	22	9.2	<0.5	2	<0.05	0.01	7	1	11.8	0.3	19.2
	63													
	86													
	111	<0.5	<0.5	29	15	<0.5	1.7	<0.05	0.02	12	1.6	7.7	0.3	10.2
	139													
	175													
	219													
	242													
2	361	0.17	0.12	17	24	<0.5	7.6	<0.05	0.01	5.91	0.99	8.3	0.3	6.4
3	382	<0.1	0.1	11	5.9	<0.5	8.3	<0.05	0.01	4.72	0.79	5.6	0.3	5
	438	<0.1	<0.1	24	9.9	<0.2	5.8	<0.05	0.01	7.81	1.39	7.1	0.3	8.8
	498	<0.1	0.037	33	15	<0.2	5.4	<0.05	0.01	8.91	1.57	11.5	0.2	8.7

MONITORING WELL SU10

TEST PERIOD	Day	Benzene ug/L	Toluene ug/L	Ethyl-benzene ug/L	(m+p)-Xylene ug/L	o-Xylene ug/L	Total BTEX ug/L	Depth to Water	DO mg/L	Eh mv	pH	Temp °C	Alk mg/L	NO_3-N mg/L
	-33	2	4	1	2	1	10	2'2.5"	0.2	-151	6.1	17.2	32	<0.5
	-11	417	1221	246	640	347	2871	7"	2.5	98	5.9	13.9	20	<0.5
1	0	1249	3160	577	1452	813	7252	1'2"	0.3	-36	6	15.7		
	9	650	1682	287	777	425	3820	1'11.5"	0.4	-61	6.03	15.1		
	23	1156	2806	440	1091	651	6144	2'2.5"	0.1	-57	6.09	14		<0.5
	31	713	1941	358	867	500	4379	2'9"	0	-66	6.23	14.6	26	
	39	1023	3201	461	1218	706	6610	2'2"	0.1	-70	6.02	14.3		
	51	1571	5253	774	2134	1170	10901	1'7"	0.2	-52	6.02	15	22	<0.5
	63	772	3044	498	1390	732	6436	1'9"	0.7	-51	6.04	14.4		
	86	460	2042	390	1117	574	4582	1'9.5"	0.7	23	5.67	15.4		

TEST PERIOD	Day	NH_4-N mg/L	PO_4-P mg/L	SO_4 mg/L	Cl mg/L	Br mg/L	Fe mg/L	Cu mg/L	Mn mg/L	Ca mg/L	Mg mg/L	Na mg/L	Al mg/L	K mg/L
	-33	<0.5	<0.5	5	5.4	<0.5	9.4	<0.05	0.04	154	4	7	<0.1	1.4
	-11	<0.5	<0.5	3	6	<0.5	21	0.04	0.02	41	1.5	5	<0.1	1.1
1	0													
	9													
	23	<0.5	<0.5	5.8	5.3	<0.5	8.6	0.02	1.5	101	3	5.8	0.1	1.5
	31													
	39													
	51	<0.5	<0.5	5.3	5.5	<0.5	13	<0.05	0.04	5.6	1	6	0.1	1.8
	63													
	86													

MONITORING WELL SU11

TEST PERIOD	Day	Benzene ug/L	Toluene ug/L	Ethyl-benzene ug/L	(m+p)-Xylene ug/L	o-Xylene ug/L	Total BTEX ug/L	Depth to Water	DO mg/L	Eh mv	pH	Temp °C	Alk mg/L	NO_3-N mg/L
	-33	25	5	5	4	4	43	1'5"	0.3	-230	5.74	14.9	12	<0.5
	-11	1	0	0	0	0	1	1.5"	1.8	75	5.92	13.2	6	<0.5
1	9	85	85	40	36	21	267	1'3"	0.2	-18	5.67	13.7		
	23	126	118	63	52	40	399	1'6"	0.5	-11	5.49	13.1	8	<0.5
	39	2	5	4	2	1	13	1'6.5"	1	54	5.10	13.0		
	51	16	126	48	134	55	379	2'	1.7	86	5.08	12.4	10	<0.5
	111	3	2	1	0	1	8	3'11"	0.9	63	5.09	17.5	4	<0.5
	175	60	13	21	12	12	117	5'3.5"	0.8	20	5.00	23.0		<0.5
2	361	42	0	6	0	0	48	3'2"	0.3	116	4.96	13.4		0.41
3	382	26	3	8	4	3	44	2'3"	0.9	160	5.02	12.4		0.46
	498	3	1	1	0	0	5	5'3"		30				1.2

TEST PERIOD	Day	NH_4-N mg/L	PO_4-P mg/L	SO_4 mg/L	Cl mg/L	Br mg/L	Fe mg/L	Cu mg/L	Mn mg/L	Ca mg/L	Mg mg/L	Na mg/L	Al mg/L	K mg/L
	-33	<0.5	<0.5	17	3.5	<0.5	9	<0.05	1.9	90	2.7	5	<0.1	1.5
	-11	<0.5	<0.5	19	4	<0.5	4.5	0.02	0.32	35	1.72	3	<0.1	1.6
1	9													
	23	<0.5	<0.5	18	3	<0.5	3.2	<0.05	2.65	184	5.36	2.5	<0.1	1.8
	39													
	51	<0.5	<0.5	19	3.2	<0.5	1.9	<0.05	0.01	6	1.64	2.3	<0.1	1.7
	111	<0.5	<0.5	18	3.6	<0.5	1.1	0.07	0.02	5.5	1.7	3	0.2	1.5
	175	<0.5	<0.1	15	5.2	<0.5	1.5	<0.05	0.01	4.81	1.25	3.9	<0.1	2.4
2	361	<0.1	<0.1	15	5.9	<0.5	1.9	<0.05	0.01	4.6	1.27	5.8	0.1	1.4
3	382	<0.1	<0.1	17	5.7	<0.5	0.8	<0.05	0.01	4.82	1.43	5.6	0.1	1.9
	498	<0.1	0.02	14	4.3	<0.2	0.2	<0.05	0.01	5.28	1.35	5	<0.1	1.5

MONITORING WELL SU12

TEST PERIOD	Day	Benzene ug/L	Toluene ug/L	Ethyl-benzene ug/L	(m+p)-Xylene ug/L	o-Xylene ug/L	Total BTEX ug/L	Depth to Water	DO mg/L	Eh mv	pH	Temp °C	Alk mg/L	NO_3-N mg/L
	-33	99	15	14	18	11	157	1'10.5"	0.1	-281	5.94	16.8	26	<0.5
	-11	12	1	2	2	0	16	8"	0.9	-18	5.8	15.1	20	<0.5
1	9	308	160	82	80	82	712	1'8"	0.1	-50	5.69	14.6		
	23	2489	656	657	533	534	4870	1'11.2"	0	-31	5.75	14.1	22	<0.5
	39	219	32	62	59	37	409	1'11"	0.2	-10	5.73	13.8		
	51	85	58	53	13	6	215	1'5"	0.9	-4	5.46	13.5	16	<0.5
	111	7	3	1	1	1	14	3'10"	0.1	-41	5.69	16.3	12	<0.5
	175	30	4	0	4	1	39		0.2	-1.2	5.9	20		<0.5
2	361	10	0	0	0	0	10	3'5.5"	0.7	-45.6	5.36	15		0.11
3	382	2	0	0	0	0	2	2'7.5"	0.5	132	5.28	13.8		<0.1
	498	41	1	3	0	2	47	5'8"		-43				0.67

TEST PERIOD	Day	NH_4-N mg/L	PO_4-P mg/L	SO_4 mg/L	Cl mg/L	Br mg/L	Fe mg/L	Cu mg/L	Mn mg/L	Ca mg/L	Mg mg/L	Na mg/L	Al mg/L	K mg/L
	-33	<0.5	<0.5	20	10	1.1	14	<0.05	0.3	50	2.3	5.2	<0.1	1.4
	-11	<0.5	<0.5	23	10	<0.5	10.7	<0.05	1.2	129	3.6	7	<0.1	1.5
1	9													
	23	<0.5	<0.5	20	7.3	<0.5	10	<0.05	0.03	33	2.5	6.5	0.3	2.3
	39													
	51	<0.5	<0.5	25	9	<0.5	8	<0.05	0.01	5.6	1.8	6.4	<0.1	1.4
	111	<0.5	<0.5	23	6	<0.5	7.8	<0.05	<0.01	5	1.54	5.7	<0.1	1.9
	175	<0.5	<0.1	19	4.7	<0.5	7.8	<0.05	0.01	4.87	1.36	4.1	<0.1	1.8
2	361	0.13	<0.1	18	8.3	<0.5	6.9	<0.05	<0.01	4.94	1.55	6.6	0.1	1.5
3	382	0.14	<0.1	22	13	<0.5	4.1	<0.05	0.01	5.25	1.85	9.6	0.1	2
	498	0.12	<0.02	15	6.5	<0.2	8.4	<0.05	0.01	3.91	1.29	6.6	0.2	1.9

MONITORING WELL SU13

TEST PERIOD	Day	Benzene ug/L	Toluene ug/L	Ethyl-benzene ug/L	(m+p)-Xylene ug/L	o-Xylene ug/L	Total BTEX ug/L	Depth to Water	DO mg/L	Eh mv	pH	Temp °C	Alk mg/L	NO_3-N mg/L
1	0	1272	3059	478	1267	690	6765	2'6"	0.7	-17	5.91	16.4	12	<0.5
	9	217	596	112	305	164	1394	3'3"	1.5	-52	5.90	15.8		
	19	206	550	95	248	140	1238	3'4"	2	-66	6.20	14.7		
	23	220	583	94	249	141	1287	3'6.75"	2.5	44	6.40	13.9	24	<0.5
	31	1173	3194	530	1406	439	6742	4'1.5"	2.2	-30	6.80	15.0		
	39	46	116	47	106	48	363	3'6.5"	1.7	-13	6.12	14.6		
	51	553	2340	348	1118	571	4929	3'	1.5	-28	6.07	14.8	8	<0.5
	61	234	827	130	389	207	1787	3'1"	2	-6	5.87	14.5		
	86	274	940	136	378	208	1936	3'2.5"	2.3	21	5.65	15.4		
	111	73	246	38	107	58	523	5'5.75"	2.8	25	5.67	17.6	6	<0.5
	139	197	680	105	210	125	1317	7'2.5"	0.8	-35	6.09	18.9		
	175	1422	4848	820	2397	1295	10783		1.8	18	6.20	23.0		<0.5
	219	295	1049	147	420	269	2180	5'11"	1.9	26	6.10	23.0		
	242	1383	4476	752	1954	1014	9579		0.5	46	5.82	23.3		
2	255	1044	3156	540	1366	722	6828	6'7"	1.2	114	6.00	22.8		1.1
	285	1734	5163	842	2270	1190	11199							
	298	2220	7441	1195	3246	1703	15804	6'3.5"						
	361	1118	3228	396	1212	603	6557	5'4"	1.6	-77	5.85	16.0		0.66
3	382	1315	3875	442	1497	788	7917	4'4.5"	1.5	33	6.14	14.3		1.4
	410	779	2241	317	923	504	4764	2'10"	5.3	39	6.10	14.3		0.61
	438	109	329	59	169	105	771	3'9.5"				15.7		0.59
	471	249	1175	237	659	379	2699		3.7	2	6.02	17.4		
	498	1273	5227	959	2793	1360	11612	7'5"	2.1	60				1.3

TEST PERIOD	Day	NH_4-N mg/L	PO_4-P mg/L	SO_4 mg/L	Cl mg/L	Br mg/L	Fe mg/L	Cu mg/L	Mn mg/L	Ca mg/L	Mg mg/L	Na mg/L	Al mg/L	K mg/L
1	0	<0.5	<0.5	7	3.8	<0.5	13	0.02	0.24	33.4	1.5	3.8	<0.1	1.2
	9													
	19													
	23	<0.5	<0.5	9.2	3.6	<0.5	1.5	<0.05	2.16	246	6.5	3.7	<0.1	5.2
	31													
	39													
	51	<0.5	<0.5	5.7	5.5	<0.5	7.7	<0.05	0.03	9	1.2	5.3	<0.1	4.7
	61													
	86													
	111	<0.5	<0.5	5.5	4.4	<0.5	1.3	<0.05	0.02	2.43	0.9	4	0.2	1.7
	139													
	175	<0.5	<0.1	7.6	8.7	<0.5	12.5	<0.05	0.06	24.5	1.64	8.4	<0.1	5.6
	219													
	242													
2	255	<0.5	<0.5	7.1	6.4	<0.5	8	<0.05	0.04	8.63	1.65	6.8	<0.1	4.3
	285													
	298													
	361	0.48	<0.1	5	60	<0.5	11.2	<0.05	0.06	10.7	2.22	6.8	0.1	1.5
3	382	0.42	<0.1	11	8.7	<0.5	13.4	<0.05	0.07	11.7	2.8	9.9	0.1	7.7
	410	0.51	<0.1	6.4	7	<0.2	9.4	<0.05	0.06	9.85	2.36	6.7	0.1	3.2
	438	0.27	<0.1	7.6	5.8	0.79	2.8	<0.05	0.03	6.03	5.87	6.2	0.1	2.2
	498	0.25	<0.02	526	7.1	<0.2	4.5	<0.05	0.03	4.68	2.29	5	0.1	1.1

MONITORING WELL SU14

TEST PERIOD	Day	Benzene ug/L	Toluene ug/L	Ethyl-benzene ug/L	(m+p)-(Xylene ug/L	o-Xylene ug/L	Total BTEX ug/L	Depth to Water	DO mg/L	Eh mv	pH	Temp °C	Alk mg/L	NO_3-N mg/L
1	0	607	1343	241	595	331	3118	1'10.5"	0.7	-11	5.80	15.9	14	<0.5
	9	440	1071	174	446	257	2388	2'6"	0.5	-43	6.10	15.7		
	19	839	1527	345	847	501	4058	2'6.75"	1	-68	5.98	14.4		
	23	1036	2724	452	1123	646	5980	2'9"	0.7	-40	6.05	14.6	22	<0.5
	31	1409	3647	559	1378	839	7832	3'4"	0.2	-50	6.54	15.0		
	39	1579	5509	775	2262	1230	11355	2'9"	1	-22	5.87	14.2		
	51	721	2670	365	1076	585	5417	2'2"	0.8	-30	5.99	15.0	10	<0.5
	61	121	452	75	218	124	989	2'3.5"	2	-8	5.95	14.4		
	86	151	423	117	205	120	1017	2'5"	1.1	68	5.42	15.8		
	111	190	588	106	238	155	1278	4'9"	1	-13	5.94	18.3	12	<0.5
	139	241	838	141	309	211	1740	6'4.5"	1	-51	5.93	20.2		
	175	2105	6642	1364	3883	2083	16077	6'6"	0.4	-12	6.00	21.0		<0.5
	219	1324	4218	897	2120	1180	9739	5'1.5"	1	31	6.00	23.0		
	242	1912	6489	1143	2984	1549	14077		0.5	-6	6.04	22.8		
2	255	1484	4824	894	2284	1221	10706	5'11"	2.3	101	6.13	22.3		1.4
	285	2149	6499	1179	3129	1615	14571							
	298	2106	6455	1065	2838	1491	13956	5'4"						
	361	1680	5171	713	2024	991	10579	4'5"	0.8	-88	5.94	15.6		0.42
3	382	1662	4710	657	1931	998	9958	3'7"	0.5	39	6.11	14.7		5.5
	410	2087	5244	753	227	1159	9470	2'0"	3.7	-61	6.00	14.1		0.52
	438	409	1431	254	641	395	3130	3'0"	3.2			16.2		0.39
	471	950	4031	755	2002	1166	8904		1.6	-18	5.91	18.1		
	498	627	3292	671	1863	954	7407	7'8"		-50				1.1

TEST PERIOD	Day	NH_4-N mg/L	PO_4-P mg/L	SO_4 mg/L	Cl mg/L	Br mg/L	Fe mg/L	Cu mg/L	Mn mg/L	Ca mg/L	Mg mg/L	Na mg/L	Al mg/L	K mg/L
1	0	<0.5	<0.5	7.6	4.2	<0.5	15	0.01	1	78.3	2.7	3.7	0.3	1.2
	9													
	19													
	23	<0.5	<0.5	6.7	4.6	<0.5	7.2	<0.05	0.03	6.2	0.9	5	0.1	1.4
	31													
	39													
	51	<0.5	<0.5	6.3	5.8	<0.5	10	<0.05	0.03	5.36	1	7	0.1	2.5
	61													
	86													
	111	<0.5	<0.5	7	4.6	<0.5	4.2	<0.05	0.02	3.25	0.9	5.7	<0.1	1.8
	139													
	175	<0.5	<0.1	3.4	9.9	<0.5	22.1	<0.05	0.07	11.5	1.85	9.8	0.1	3.1
	219													
	242													
2	255	0.56	<0.5	14	9	<0.5	13.1	<0.05	0.07	16.5	2.46	8.7	<0.1	4.1
	285													
	298													
	361	0.71	<0.1	4.7	31	<0.5	15	<0.05	0.08	14.2	4.88	8.7	<0.1	3.4
3	382	0.85	<0.1	30	11	<0.5	22.9	<0.05	0.11	18.8	4.03	23.3	0.1	3.5
	410	0.51	<0.1	5.4	8.9	<0.2	9.3	<0.05	0.07	11.8	3.17	7.9	<0.1	5.5
	438	0.56	<0.1	11	9.7	3.81	6.4	<0.05	0.04	7.02	2.86	8.4	0.1	3.8
	498	0.45	<0.02	5.9	9	<0.2	6.5	<0.05	0.05	7.95	2.84	6.2	0.2	3.3

MONITORING WELL SU15

TEST PERIOD	Day	Benzene ug/L	Toluene ug/L	Ethyl-benzene ug/L	(m+p)-Xylene ug/L	o-Xylene ug/L	Total BTEX ug/L	Depth to Water	DO mg/L	Eh mv	pH	Temp °C	Alk mg/L	NO_3-N mg/L
2	298	2446	8049	1445	4017	1985	17942	6'2"						
	361	797	2393	414	1104	544	5252	5'1.5"	0.8	-51	5.96	15.9		
3	382	1245	3909	615	1630	853	8252	4'4"	1	93	6.16	14.5		2.9
	410	80	258	52	124	72	586	2'9"	3.5	-45	5.94	14.6		0.79
	438	634	2980	458	1162	702	5936	3'9"	1			15.8		0.53
	471	475	1843	453	1271	680	4722		5.6	8	6.02	18.1		
	498	277	1366	432	1125	582	3782	7'4"	0.7	46				1.1

TEST PERIOD	Day	NH_4-N mg/L	PO_4-P mg/L	SO_4 mg/L	Cl mg/L	Br mg/L	Fe mg/L	Cu mg/L	Mn mg/L	Ca mg/L	Mg mg/L	Na mg/L	Al mg/L	K mg/L
2	298													
	361													
3	382	0.23	<0.1	8.8	7.6	<0.5	2.6	<0.05	0.03	7.05	6	11.2	0.2	14
	410	0.29	<0.1	4.9	6.4	<0.2	5.4	<0.05	0.03	5.44	1.93	6.2	0.1	1.7
	438	0.5	<0.1	8.9	6.8	0.79	4.9	<0.05	0.04	5.76	1.63	6.9	0.2	3.6
	498	0.49	<0.02	6.6	8	<0.2	9.1	<0.05	0.04	5.99	1.91	6.1	0.1	2.4

MONITORING WELL SU16

TEST PERIOD	Day	Benzene ug/L	Toluene ug/L	Ethyl-benzene ug/L	(m+p)-Xylene ug/L	o-Xylene ug/L	Total BTEX ug/L	Depth to Water	DO mg/L	Eh mv	pH	Temp °C	Alk mg/L	NO_3-N mg/L
2	298	1140	3590	576	1532	825	7663	62.5"						
	361	1400	3892	554	1552	768	8166	5'2"	0.6	-61	5.85	15.9		
3	382	700	1681	234	676	356	3647	43.5"	6.1	108	6.26	14.5		2
	410	357	852	135	367	192	1903	2'10"	6.8	12	6.23	14.5		0.9
	438	311	263	149	310	191	1224	3'8"	7.3			15.7		0.24
	471	344	1567	329	886	480	3606		2	7	5.90	17.4		
	498	513	1584	318	757	426	3598	7'7"	1.7	82				0.86

TEST PERIOD	Day	NH_4-N mg/L	PO_4-P mg/L	SO_4 mg/L	Cl mg/L	Br mg/L	Fe mg/L	Cu mg/L	Mn mg/L	Ca mg/L	Mg mg/L	Na mg/L	Al mg/L	K mg/L
2	298													
	361													
3	382	0.42	<0.1	22	11	<0.5	11.4	<0.05	0.06	8.8	2.56	9.9	0.1	3.4
	410	0.19	<0.1	9.6	6.6	<0.2	1.7	<0.05	0.03	6.3	6.76	7	0.1	3.7
	438	0.2	<0.1	6.8	5.9	<0.2	4.9	<0.05	0.02	3.68	1.83	5.5	0.1	2.2
	498	0.43	<0.02	4.8	8.7	<0.2	11.3	<0.05	0.04	6.25	2.22	6.6	0.1	2.2

MONITORING WELL SU17

TEST PERIOD	Day	Benzene ug/L	Toluene ug/L	Ethyl-benzene ug/L	(m+p)-Xylene ug/L	o-Xylene ug/L	Total BTEX ug/L	Depth to Water	DO mg/L	Eh mv	pH	Temp °C	Alk mg/L	NO_3-N mg/L
2	298	2233.	7127	1264	3266	1775	15665	4'10"						
	361	1222	3805	577	1592	869	8065	3'9"	0.1	-92	5.90	14.7		
3	382	1599	5093	758	2021	1028	10499	3'0"	0.3	83	6.10	13.6		0.21
	410	1841	5155	795	2142	1202	11135	1'5"	0.6	-60	6.04	14.3		0.25
	438	593	2036	329	870	520	4348	2'4"	1.6			16.4		0.39
	471	1938	6933	1081	2931	1645	14528		3.3	12	5.82	18.1		
	498	815	2907	482	1251	673	6128	6'1"		-41				0.91

TEST PERIOD	Day	NH_4-N mg/L	PO_4-P mg/L	SO_4 mg/L	Cl mg/L	Br mg/L	Fe mg/L	Cu mg/L	Mn mg/L	Ca mg/L	Mg mg/L	Na mg/L	Al mg/L	K mg/L
2	298													
	361													
3	382	0.84	<0.1	5.3	10	<0.5	19.7	<0.05	0.09	15.6	3.13	8.3	0.1	3.6
	410	1.1	<0.1	8.3	9.8	<0.2	17.2	<0.05	0.08	14.3	4.3	9.5	0.1	7.3
	438	0.87	<0.1	9.1	7.9	<0.2	8.9	<0.05	0.05	8.34	2.19	7.8	0.1	5.4
	498	0.72	0.022	7.9	8	<0.2	10.8	<0.05	0.06	10.7	2.38	8.9	0.1	3.8

REMEDIATION WELL RW1

TEST PERIOD	Day	Benzene ug/L	Toluene ug/L	Ethyl-benzene ug/L	(m+p)-Xylene ug/L	o-Xylene ug/L	Total BTEX ug/L	Depth to Water	DO mg/L	Eh mv	pH	Temp °C	Alk mg/L	NO_3-N mg/L
1	9	0	0	0	0	0	0	3'6"	16	-20	11.3	14.7		<0.5
	23	46	170	29	81	45	371	3'7.5"	13	65	10.5	14.5	116	<0.5
	51	1	4	0	1	1	7		19	-46	10.11		78	
	111	0	1	0	0	0	1	5'9"	17	87	8.78	17.3	38	<0.5
	139								17	-62	11.1	20		
2	255								33.5					
	361								25.8					
3	382								19					
	410								19.2			14.2		0.96
	438								29.6					1.6

TEST PERIOD	Day	NH_4-N mg/L	PO_4-P mg/L	SO_4 mg/L	Cl mg/L	Br mg/L	Fe mg/L	Cu mg/L	Mn mg/L	Ca mg/L	Mg mg/L	Na mg/L	Al mg/L	K mg/L
1	9	<0.5	<0.5	12	3.9	<0.5	<0.1	<0.05	0.72	55	0.67	21	50	0.2
	23	<0.5	<0.5	5.5	2.9	<0.5	1.4	<0.05	0.02	2.1	0.67	3.8	0.2	1
	51													
	111	<0.5	<0.5	3.6	3.1	<0.5	<0.1	<0.05	<0.01	17	0.5	4	0.1	1.5
	139													
2	255													
	361													
3	382													
	410	0.11	<0.1	17	3.9	<0.2	<0.1	<0.05	<0.01	4.4	20.1	9	0.1	2.2
	438	0.13	<0.1	22	448	6.2	<0.1	<0.05	<0.01	4.31	19.4	19.2	0.1	2.4

REMEDIATION WELL RW1

TEST PERIOD	Day	Benzene ug/L	Toluene ug/L	Ethyl-benzene ug/L	(m+p)-Xylene ug/L	o-Xylene ug/L	Total BTEX ug/L	Depth to Water	DO mg/L	Eh mv	pH	Temp °C	Alk mg/L	NO_3-N mg/L
1	9	0	0	0	0	0	0	3'6"	16	-20	11.3	14.7		<0.5
	23	46	170	29	81	45	371	3'7.5"	13	65	10.5	14.5	116	<0.5
	51	1	4	0	1	1	7		19	-46	10.11		78	
	111	0	1	0	0	0	1	5'9"	17	87	8.78	17.3	38	<0.5
	139								17	-62	11.1	20		
2	255								33.5					
	361								25.8					
3	382								19					
	410								19.2			14.2		0.96
	438								29.6					1.6

TEST PERIOD	Day	NH_4-N mg/L	PO_4-P mg/L	SO_4 mg/L	Cl mg/L	Br mg/L	Fe mg/L	Cu mg/L	Mn mg/L	Ca mg/L	Mg mg/L	Na mg/L	Al mg/L	K mg/L
1	9	<0.5	<0.5	12	3.9	<0.5	<0.1	<0.05	0.72	55	0.67	21	50	0.2
	23	<0.5	<0.5	5.5	2.9	<0.5	1.4	<0.05	0.02	2.1	0.67	3.8	0.2	1
	51													
	111	<0.5	<0.5	3.6	3.1	<0.5	<0.1	<0.05	<0.01	17	0.5	4	0.1	1.5
	139													
2	255													
	361													
3	382													
	410	0.13	<0.1	17	3.9	<0.2	<0.1	<0.05	<0.01	4.4	[illegible]	9	0.1	[illegible]
	438	0.13	<0.1	[illegible]	[illegible]	[illegible]	<0.1	<0.05	<0.01	[illegible]	[illegible]	[illegible]	0.1	[illegible]

APPENDIX C

Summary of Tracer Test Results

Well I.D.	Date	d(ln(C))/dt	Specific Discharge (m/day)	R^2
C-1	12-Mar-94	-0.09322	0.26778	0.98
C-2	12-Mar-94	-0.07114	0.20437	0.97
C-3	10-Jun-94	-0.06085	0.17480	0.96
C-4	10-Jun-94	-0.08600	0.24704	0.95
C-5	10-Jun-94	-0.07746	0.22252	0.99
NR-1	10-Jun-94	-0.00791	0.02271	0.96
NR-2	10-Jun-94	-0.00519	0.01492	0.97
NR-3	10-Jun-94	-0.00589	0.01693	0.85
NR-4	10-Jun-94	-0.00682	0.01959	0.98
NR-7	10-Jun-94	-0.00565	0.01624	0.95
NR-10	10-Jun-94	-0.00493	0.01417	0.87
R-1	24-Jun-94	-0.01558	0.04477	0.99
R-2	24-Jun-94	-0.01320	0.03792	0.90
R-3	24-Jun-94	-0.01794	0.05155	0.97
R-4	24-Jun-94	-0.02765	0.07943	0.95
R-5	24-Jun-94	-0.01169	0.03358	0.99
R-6	24-Jun-94	-0.01907	0.05478	0.98
R-7	24-Jun-94	-0.02050	0.05890	0.95
R-8	24-Jun-94	-0.01570	0.04509	0.99
R-10	24-Jun-94	-0.00775	0.02225	0.94

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