Appendix A
Dye Trace Study Report

A.1 Introduction

PRC Environmental Management, Inc. (PRC), received an assignment from the U.S. Environmental Protection Agency (EPA) to conduct a Superfund Innovative Technology Evaluation (SITE) demonstration of the Unterdruck-Verdampfer-Brunnen (UVB) groundwater treatment system at Site 31, March Air Force Base (AFB), California. The demonstration was conducted by Roy F. Weston, Inc. (Weston), in association with IEG Technologies Corporation (IEG). PRC completed field evaluation activities in accordance with the Quality Assurance Project Plan (QAPP) for the UVB demonstration (PRC 1993). One of the primary objectives of the demonstration was to estimate the radius of circulation cell of the UVB technology. However, the UVB system's radius of circulation cell could not be meaningfully estimated under the originally planned demonstration activities due to a lack of contaminant concentration reduction in the aquifer and the inapplicability of the aquifer flow evaluation method (Jacobs straight-line method) proposed in the QAPP. Therefore, EPA instructed PRC to perform a dye trace study to evaluate the UVB technology's area of influence. PRC prepared a dye trace study plan as an amendment to the QAPP to describe the study approach, field procedures, and analytical methods (PRC 1994a).

This report documents the field and analytical procedures, results, and conclusions of the dye trace study drawn to support the Innovative Technology Evaluation Report (ITER) to be prepared for the UVB system.

A.1.1 Background

The UVB technology is an in situ groundwater remediation technology that combines air-lift pumping and air stripping to remediate aquifers contaminated with volatile organic compounds. A UVB system consists of a single well with two hydraulically separated screened intervals installed within a single permeable zone. The air-lift pumping occurs in response to negative pressure introduced at the wellhead by a blower. A mechanical pump draws water into the well through the lower screened portion of the well. Simultaneously, air stripping occurs as ambient air (also flowing in response to the vacuum) is introduced through a sieve plate located within the upper screened section of the well, causing air bubbles to form in the water pulled into the well. The rising air bubbles provide the air-lift pump effect that moves water toward the top of the well and draws water into the lower screened section of the well. This pumping effect is supplemented by a submersible pump which ensures that water flows from bottom to top in the well. As the air bubbles rise through the water column, volatile compounds are transferred from the aqueous to the gas phase. The rising air transports volatile compounds to the top of the well casing, where they are removed by the vacuum blower. The blower effluent is treated before discharge using granular activated carbon.

The transfer of volatile compounds is further enhanced by a fluted and channelized column that increases the contact time between the two phases and minimizes the coalescence of air bubbles.

Once the upward stream of water leaves the stripping reactor, the water falls back through the well casing and returns to the aquifer through the upper well screen. This return flow to the aquifer, coupled with inflow at the well bottom, circulates groundwater around the UVB well. The extent of the circulation pattern is known as the radius of circulation cell, which determines the volume of water affected by the UVB system. A more detailed description of the UVB system is presented in the ITER.

The hydraulic conductivity of the aquifer affects the radius of circulation cell of the UVB system. The UVB system circulation cell includes both untreated and previously treated groundwater, and its radius is directly proportional

to the ratio of the horizontal to vertical hydraulic conductivity (Kh to Kv) of the aquifer. Thus, larger ratio values will result in a greater effective radius. Based on data contained in the draft report "March AFB IRP, Site 31, Aquifer Testing" (TETC 1993), the radius of circulation cell (r_o) was estimated to be 60 feet (18.3 meters [m]) (see Appendix A), and aquifer characteristics values were calculated for transmissivity (T, 6,800 gallons per day per foot [gpd/ft] [9.75 x 10^{-4} meters squared per second {m^2/s}]) and Kh (90.5 gallons per day per foot squared [gpd/ft^2] [4.26 x 10^{-3} centimeters per second {cm/s}]). The calculated value for storativity of the aquifer underlying Site 31 may be several orders of magnitude low based on the data from the short-term pumping tests (TETC estimates a month-long pumping test would be necessary to accurately calculate storativity). Since storativity values calculated from the aquifer test were not considered representative of aquifer conditions, storativity of the unconfined aquifer (specific yield) is approximated by effective porosity (TETC 1994). Storativity can be approximated by effective porosity in unconfined aquifers since storativity of an unconfined aquifer represents an actual dewatering of the soil pores. The average effective porosity at the site is 25 percent (TETC 1994). Because of the heterogeneous and anisotropic nature of the alluvial deposits at the site, the value of Kh is estimated to be an order of magnitude greater than Kv.

In addition to the calculated hydraulic conductivity, information was gathered on the pumping rate and hydraulic gradient to estimate the time required for treated water from the UVB system to travel to the outer perimeter of the circulation cell. The UVB system operated at a pumping rate of about 20 gallons per minute (gpm) (75.7 liters per minute) during demonstration activities. Water level elevations measured before and during the UVB demonstration showed that the potentiometric surface is relatively flat with minor undulations of generally less than 1 foot (0.3 m) across Site 31. Based on the calculated hydraulic conductivity, the pumping rate, and the observed hydraulic gradient, it was estimated that treated water from the UVB system would reach a radial distance of 40 feet in 30 to 45 days.

A.1.2 Purpose and Goals

The overall purpose of the dye trace study was to achieve the second primary objective stated in the UVB QAPP: to estimate the radius of circulation cell of the groundwater treatment system (PRC 1993). To estimate the radius of circulation cell, both primary and secondary dye trace study goals were established. Primary goals were considered critical to evaluate the radius of the UVB system's circulation cell. Secondary goals provided additional information that was useful for understanding aquifer characteristics, but not critical for establishing the radius of circulation cell. These goals were achieved by injecting dyes into the aquifer and subsequently monitoring their movement by collecting groundwater samples.

The primary and secondary goals for the dye trace study are listed below (PRC 1994a).

Primary

- Demonstrate hydraulic interconnection between the UVB system and distant sample locations
- Demonstrate circulation of groundwater within the UVB circulation cell
- Estimate the radius of circulation cell of the UVB system

Secondary

- Estimate maximum and average groundwater velocities produced by the UVB system
- Quantify selected aquifer characteristics

A.1.3 Dye Trace Study Design

The dye trace study used water-soluble dyes that could be detected both visually and by measuring the fluorescent emissions resulting from ultraviolet light excitation. The dye trace study was based on PRC Standard Operating Procedure 98, which was appended to the dye tracer study plan (PRC 1994a). The basic design for the dye trace study was a two-dye approach consisting of injecting one dye into the outlet of the UVB system (diverging test) and injecting a second dye in well PW2 (converging test), the intermediate depth well from the well cluster nearest the UVB system. A two-dye approach was selected to reduce the time required to demonstrate circulation in the zone between the UVB system and wells PW1 and PW2.

Sodium fluorescein (uranine or yellow-green xanthene) was selected as the dye for the diverging test, in which dye was injected in the upper screened interval of the UVB

system and spread radially outward. Rhodamine WT (red-purple xanthene) was selected for the converging test, in which a dye was injected in well PW2 and flowed back to the lower screened interval of the UVB system. Both dyes are considered environmentally safe (EPA 1991).

Fluorescein was selected for the diverging test because greater dilution occurs in a diverging test and this dye can be detected at very low concentrations. Greater dilution occurs in the diverging test because the dye is expected to diverge radially from the injection point with some preferential movement in the downgradient direction (dye in the converging test is expected to travel preferentially toward the convergence point with some dye movement in the downgradient direction). Because fluorescein fluoresces with a higher intensity than rhodamine WT, fluorescein theoretically has a lower limit of detection on a scanning spectrofluorophotometer. (Theoretically, rhodamine WT has a lower limit of detection on a fluorometer because rhodamine WT (1) has a narrower emission bandwidth, and (2) the peak emission frequency is higher than most naturally occurring background fluorescence.) Rhodamine WT dye was selected for its contrasting fluorescent color (bright yellow-orange) as compared to fluorescein (bright green).

The appropriate quantities of dye for this study were determined by assuming a target concentration of 10 micrograms per liter (µg/L) in the circulation cell and dye recovery of only 1 percent. A conservative estimate of dye loss of 99 percent (1 percent recovery) was used to account for adsorption, attenuation, and degradation of dye in the aquifer. The volume of water in the circulation cell was estimated at 448,800 gallons (1,698,708 liters), and the dyes were obtained in 7.5 percent (fluorescein) and 20 percent (rhodamine WT) solutions. The minimum dye quantities at these concentrations were thus calculated as 5.7 gallons (21.6 liters) of fluorescein and 1.89 gallons (7.2 liters) of rhodamine WT (Appendix B). The movement of the dye was monitored by sampling wells three times a week. Monitoring wells within 50 feet (15.2 m) of the UVB system were sampled at a higher frequency during the first week of the study. Wells sampled included: W1, W2, PW1, PW2, PW3, PW4, PW5, PW6, PW7, PW8, 31OW1, 31PW1, and 4MW14 (well locations are shown on Figure A-1). Well construction information on these wells is provided in Table A-1. Wells PW1 through PW6 were installed linearly downgradient of the UVB system well. Wells PW1 and PW4 are shallow (screened 38 to 58 feet [11.6 to 17.7 m] below ground surface [bgs]); wells PW2 and PW5 are intermediate (screened 65 to 75 and 68 to 78 feet [19.8 to 22.9 and 20.7 to 23.8 m] bgs); and wells PW3 and PW6 are deep (screened 90 to 105 and 91 to 106 feet [27.4 to 32.0 and 27.7 to 32.3 m] bgs). The downgradient direction was originally determined to be to the southwest based on a preliminary contour map of November 1992 groundwater elevations at Site 31 (TETC 1994). New data collected after the UVB system was turned off in December 1994 also shows that groundwater flow direction is to the southeast. A detailed discussion of the groundwater gradient is presented in Section 3.3.

Sampling methodology consisted of using dedicated, disposable bailers to collect groundwater samples from the screened portion of each well. Point source bailers were used to collect the samples from wells not screened across the water table. The collected samples were transferred to amber bottles for subsequent quantitative analysis. The quantitative results were confirmed by use of activated carbon units (bugs) installed as passive dye receptors in the screened interval of sampling wells. The bugs were changed weekly and qualitatively analyzed for the presence of dye.

Analytical methodology included both field and laboratory methods. Field analysis consisted of visual examination of water samples using both ambient and ultraviolet lighting to examine for dye presence. At low concentrations (approximately 10 µg/L), both dyes were readily visible with these simple methods. Additionally, a scanning spectrofluorometer was used in the on-site laboratory for the analysis of fluorescent emissions. The scanning spectrofluorometer can detect lower dye concentrations and is not significantly affected by background interferences.

Wells were monitored for dye for 4 months. This period was the maximum duration deemed practical based on conservative estimates of dye travel time from the UVB system to outer perimeter well PW5.

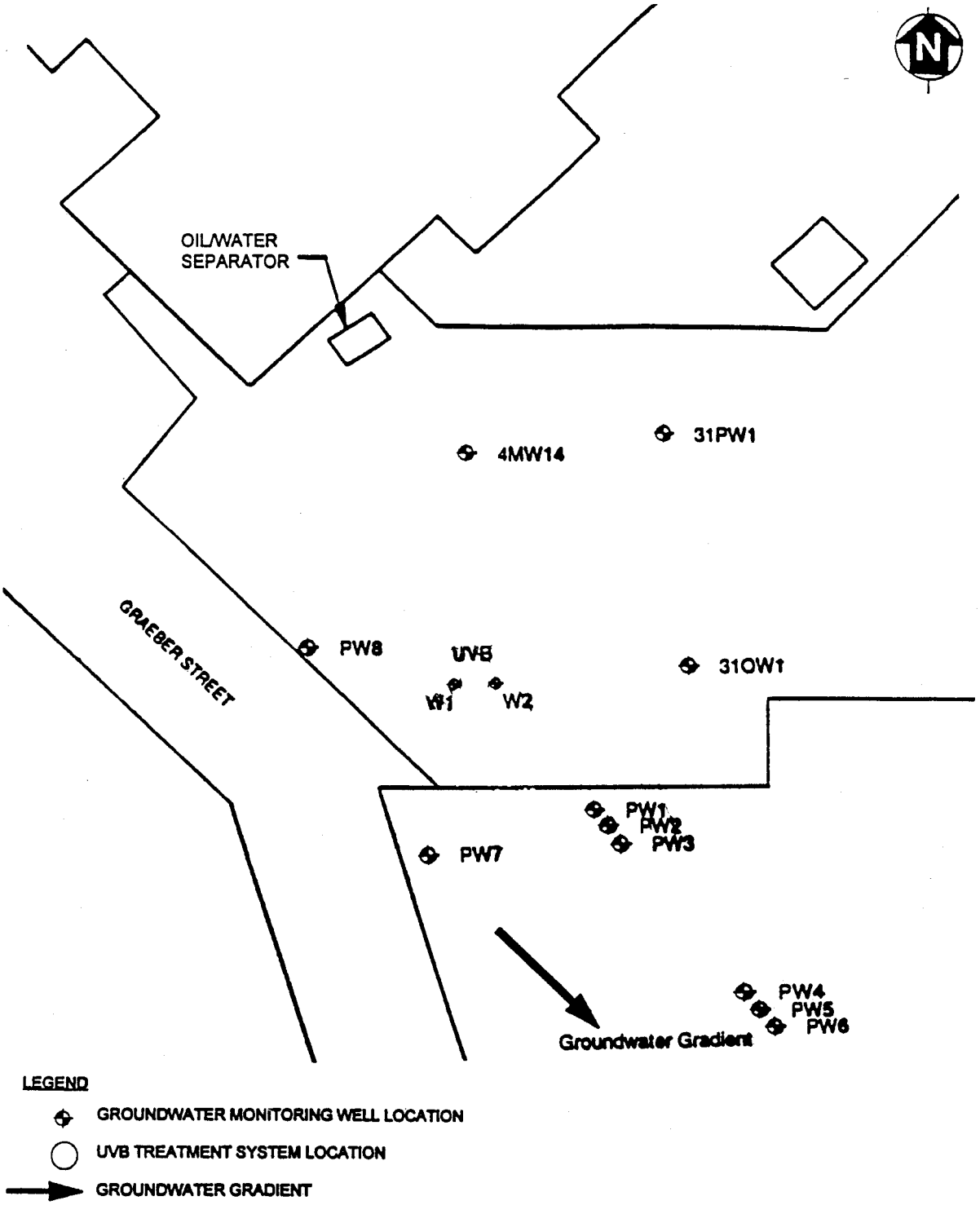


Figure A-1. Well location map.

Table A-1. Well Construction Information and Sample Collection Depths

Well No.	Screen Interval (feet bgs)[a]	Screen Length (feet)[a]	Sand Pack Interval (feet bgs)	Total Depth (feet bgs)[a]	Designation	Sample Depth (feet bgs)	Relative Collection Location
W2	40-55	15	36-58	55	Shallow	40-42	Top of Water Column[b]
PW1	38-58	20	33-58	58	Shallow	40-42	Top of Water Column
PW4	38-58	20	33-59	57	Shallow	40-42	Top of Water Column
PW7	35-55	20	32-55	55	Shallow	40-42	Top of Water Column
PW8	35-55	20	32-55	55	Shallow	40-42	Top of Water Column
4MW14	35-75	40	24-77	75	Shallow	40-42 and 73-75	Top of Screen and Bottom of Screen
31PW1[c]	52-92	40	39-92	92	Intermediate	72-73 and 90-92	Top of Screen and Bottom of Screen
PW2[c]	65-75	10	58-77	75	Intermediate	69-70	Mid-Screen
PW5[c]	68-78	10	57-78	78	Intermediate	72.5-73.5	Mid-Screen
W1[c]	70-80	10	68-82	80	Intermediate	76.5-77.5	Mid-Screen
31OW1[c]	61-81	20	54-82	81	Intermediate	71-72	Mid-Screen
PW3[c]	90-105	15	86-109	105	Deep	97.5	Mid-Screen
PW6[c]	91-106	15	85-106	106	Deep	98.5	Mid-Screen

Notes:

[a] Approximate
[b] Top of water column is approximately 40 feet below ground surface
[c] Well not screened across the water table

A.2 Methodology

This section describes the methods and procedures used for field and analytical activities. An overview of the dye trace study is provided in Section 2.1. The field sampling activities are described in Section 2.2, and the analytical activities are addressed in Section 2.3.

A.2.1 Dye Trace Study

The activities associated with the dye trace study included (1) collecting background samples and evaluating background fluorescence, (2) injecting the dye, (3) collecting carbon bugs and groundwater grab samples, (4) qualitatively analyzing carbon bug samples to determine the presence or absence of dye, (5) quantitatively analyzing groundwater samples to measure dye concentrations, and (6) field and laboratory quality assurance and quality control (QA/QC) samples and calibration checks to measure accuracy, precision, and instrument performance.

Background samples consisted of both carbon bugs from wells PW1, PW2, PW4, and PW5, and grab samples from all monitoring wells. The carbon bugs were analyzed qualitatively, and the grab samples were analyzed both qualitatively and quantitatively. Grab samples of groundwater were collected from the wells three times per week, and the carbon bugs were changed weekly. The grab samples were qualitatively analyzed by observation under visual-ambient light conditions and under visual ultraviolet light. The grab samples also were analyzed on a scanning spectrofluorometer to quantify the dye concentration. The carbon bugs were eluted and visually inspected for the presence of dye. The QA/QC program consisted of field (equipment) and laboratory blank samples, duplicate samples, matrix spike and matrix spike duplicate (MS/MSD) samples, trip blanks (for the carbon bugs), and calibration standards for each type of dye. A more detailed discussion of the field and analytical activities is presented in the following sections.

A chronology of key events is provided in the following summary:

- January 10, 1994: Carbon bugs installed for background fluorescence study
- January 18, 26, and February 2, 1994: Groundwater grab samples collected for background fluorescence study
- January 26, 1994: Carbon bugs collected for background fluorescence study
- January 27, 1994: Method detection limit study conducted
- February 2, 1994: Background fluorescence study conducted (analysis of background groundwater grab samples and carbon bugs)
- February 8, 1994: Dye injected into groundwater monitoring wells PW2 and W2
- February 8, 1994 through February 14, 1994: Groundwater samples collected from wells PW1, PW7, PW8, and 31OW1 at accelerated frequency (see Section 2.2.4 for details)
- February 9, 1994: Groundwater samples collected from wells W1, PW4, PW5, 4MW14, and 31PW1 at normal frequency (three times per week)
- February 9, 1994: Fluorescein detected in well W1
- February 25, 1994: Well PW3 added to sample collection locations

- February 25, 1994: Rhodamine WT detected in well PW3
- March 28, 1994: Fluorescein detected in well PW1
- April 8, 1994: Fluorescein detected in well PW3
- April 27, 1994: Well PW6 added to sample collection locations
- May 4, 1994: Rhodamine WT detected in well W1
- May 27, 1994: Sampling for dye trace study terminated

A.2.2 Field Procedures

This section describes the procedures used for field activities, including dye injection, sample collection (including frequency and location), and the field QA/QC plan.

A.2.2.1 Dye Injection

The liquid forms of fluorescein and rhodamine WT were chosen to avoid potential mixing problems in the field. The dyes were handled separately to avoid cross contamination. The dyes were injected on February 8, 1994. Two gallons (7.6 liters) of rhodamine WT were injected into well PW2 at 0950 hours, and 6 gallons (22.7 liters) of fluorescein were injected into well W2 at 1000 hours. The dyes were injected through dedicated hoses to control the depth of injection and to avoid dye loss on the inside of the well casing. The rhodamine WT was injected into the bottom of the screen in well PW2 at a depth of 74 feet (22.6 m) bgs. The depth for rhodamine WT injection was selected to intercept the converging portion of the circulation cell near the elevation of the UVB system intake. However, subsequent observations showed that the dye was diluted across the entire water column in well PW2, and that the injected dye did not remain in the injection interval. The fluorescein dye was injected at the top of well W2, which was screened across the groundwater table. The depth for fluorescein injection was selected to intercept the diverging portion of the circulation cell near the elevation of the UVB system discharge. Observations of grab samples from W2 also indicate that fluorescein was diluted across the entire water column in the well (40 to 55 feet [12.2 to 16.7 m] bgs). The dilution of dye across the water column in both injection wells (PW2 and W2) does not impact the study goals since no groundwater was removed from either wells during the course of the study with the exception of grab samples.

A.2.2.2 Sample Collection

This section describes the sample collection procedures for grab samples of groundwater and for the carbon bugs.

A.2.2.2.1 Grab Samples

Groundwater samples were collected from 15 locations in 13 wells (see Section A.2.2.4 for frequency and location information). The samples were collected by lowering dedicated, disposable bailers to the required sampling interval of the well screen. To address concerns over the frequency of purging effects on the UVB system flow field and subsequent dye trace study results, purging of monitoring wells was kept to a minimum and was restricted to monthly groundwater sampling as specified in the QAPP (PRC 1993). Therefore, the groundwater samples collected for the dye trace study were collected without purging the wells. Since the wells were not purged before sample collection, the bailers were lowered and retrieved with care to minimize mixing water between the casing and screened sections of the well. This approach did not adversely affect the dye trace study results due to the stability of the selected dyes and the frequency of sampling. On retrieval from each well, the collected groundwater samples were poured into 250 milliliter (mL) amber glass sample containers.

A.2.2.2.2 Carbon Bugs

The dye trace study used activated carbon passive dye receptors known as “bugs” for collecting composite samples for qualitative analysis. The bugs provided visual evidence of the presence of dye by adsorbing dye and then releasing it when washed with an elutriate solution. The bugs accumulate dye even from very low concentrations in the groundwater and, thus, provide confirmation of positive detections at very low concentrations. The bugs were suspended by a teflon-coated wire line in the screened interval of each well in the sample network. The bugs consisted of activated coconut charcoal, size 6 to 14 mesh, contained in packets made of nylon window screen. Before use, the activated charcoal was kept fresh in airtight containers. On retrieval, each bug was sealed separately in a plastic bag with a prelabeled sample tag attached.

A.2.2.3 Background Samples

Groundwater grab samples were collected on January 18 and 26 and February 2, 1994, before dye was injected into the aquifer. In addition, carbon bugs were placed in wells PW1, PW2, PW4, and PW5 for 16 days beginning January 10, 1994. These background samples were collected to evaluate interference from natural or introduced background fluorescence. The samples were collected as described in Section A.2.2.2 and analyzed as described in Section A.2.3. The results of the analysis are presented in Section A.3.1.1.

The background samples also were used to establish the minimum detection limit (MDL) and reportable detection limit (RDL) for the scanning spectrofluorometer used for this study. (A description of this unit is given in Section 2.3.2.) Initial calibration standards ranging from 0.01 µg/L to 100.0 µg/L were analyzed to evaluate the instrument response, and the background samples were checked for fluorescent emissions and interference at low concentrations of dye. Based on the instrument response and analysis of the background samples, the RDL was established at 1 µg/L and the MDL was established at 0.1 µg/L. These threshold limits were sufficiently low to measure the target dye concentration of 10 µg/L. The background samples were stored as described in Section A.2.2.5 for use as reference checks of background fluorescence.

A.2.2.4 Sample Collection Frequency and Location

The locations at which samples were collected during the dye trace study are shown on Figure A-1. Groundwater grab samples were initially collected from 13 locations in 11 wells, and later from 15 locations in 13 wells after wells PW3 and PW6 were added to the sampling well network. Well PW3 was added on February 25, 1994, and well PW6 was added on April 27, 1994. Wells PW3 and PW6 were added to the sampling program to obtain additional data from the deep portion of the aquifer at Site 31. The sample collection depths are summarized on Table A-1. Samples were collected from the top of the screened interval in shallow wells W2, PW1, PW4, PW7, and PW8. Samples were collected from mid-screen in intermediate wells PW2, PW5, W1, and 31OW1. In wells 4MW14 and 31PW1, which have 40-foot (12.2 m) screen lengths, samples were collected from the top of the screened interval for the diverging trace study and from the bottom of the screened interval for the converging trace study. Wells PW3 and PW6 have 15-foot (4.6 m) screens and are approximately 105 feet (32.0 m) deep. Samples were collected from mid-screen at a depth of about 98 feet (29.9 m) bgs. Wells were sampled by increasing order of anticipated dye concentration, with the anticipated highest concentration wells sampled last. (This approach corresponds to sampling the outer perimeter wells first.)

In general, samples were collected from the sampling well network at a frequency of three times per week on nonconsecutive days. A summary of the sampling and analysis plan is presented in Table A-2.

However, shallow wells PW1, PW7, PW8, and 31OW1, which are all located within 50 feet (15.2 m) of the UVB system well, were sampled at an increased frequency during the first week of the dye trace study. The increased sampling frequency occurred as follows: (1) for the first day, one sample per hour for the first 8-hour period, one sample every 2 hours for the second 8-hour period, and one sample every 4 hours for the third 8-hour period; (2) for the second day, the wells were sampled once every 8 hours for a 24-hour period; (3) for the third through fifth days, the wells were sampled once per day. This increased frequency was used to monitor potential early dye movement during the initial period of the study.

The carbon bugs were suspended at the top of the well screen in shallow wells PW1, PW4, PW7, and PW8 and at mid-screen for intermediate wells PW2, PW5, W1, and 31OW1. Bugs were placed at both the top and bottom of the 40-foot (12.2 m) screens in wells 4MW14 and 31PW1. The bugs were changed on a weekly basis.

A.2.2.5 Field QA/QC

The field QA/QC program consisted of collecting MS/MSD samples, equipment rinsate blanks, and trip blanks. Groundwater grab samples were collected, handled, and transported in accordance with the QAPP (PRC 1993). The MS/MSD samples were collected at a frequency of one pair for every 20 groundwater samples. The equipment rinsate samples were collected at a frequency of one for every groundwater grab sampling event. To minimize the potential for cross contamination between wells, disposable point-source bailers were used to collect the groundwater samples from each monitoring well. Sample integrity requirements outlined in the QAPP (PRC 1993) were followed with additional requirements for sample storage and holding times. Groundwater samples

Table A-2. Summary of Sample Collection and Field Management Program

Well No.	Sample Type	Analytical Parameter	Number of Field and QC Samples (Per Sampling Event)					Field Generated Lab QC Samples	Total Number of Samples
			Number of Field Samples	Field QC Samples			Total Field and QC Samples	MS/MSD Samples	
				Field Blanks	Trip Blanks	Equipment Blanks			
W1, W2, PW1, PW2, PW3, PW4, PW5, PW6, PW7, PW8, 31OW1, 31PW1[a], and 4MW14[a]	Groundwater[b]	Rhodamine WT and Fluorescein	15	0	0	1	16	1	17
W1, PW1, PW2, PW4, PW5, PW7, PW8, 31OW1, 31PW1[a], and 4MW14[a]	Carbon Bug[c]	Rhodamine WT and Fluorescein	12	0	1	0	13	0	13

Notes:

[a] Samples were collected at the top and bottom of well screen
[b] Sample frequency of 3 times per week on nonconsecutive days
[c] Sample frequency was once a week

were placed in 250 mL amber bottles and stored in the dark at 4°C to minimize dye destruction caused by ultraviolet light. In addition, the samples were analyzed within 14 days of collection, usually on the same day as collection.

A carbon bug trip blank was used to evaluate the potential for dye contamination introduced in the field or during transport. The trip blank accompanied the sample carbon bugs during installation and collection, and the trip blank was analyzed in the same manner as the sample carbon bugs.

A.2.3 Analytical Procedures

This section describes the procedures used for qualitative and quantitative analyses of the samples. Qualitative analyses included observation of groundwater samples and of elutriated carbon bugs under visual and ultraviolet light conditions; quantitative analysis provided a measurement of dye concentrations using a scanning spectrofluorometer. All samples were allowed to equilibrate to the same temperature as the calibration standards before analysis.

A.2.3.1 Qualitative Analyses

This section describes the qualitative procedures used for the visual determination of the presence or absence of dye under ambient light and visual-ultraviolet light conditions.

A.2.3.1.1 Visual - Ambient Light

The presence or absence of dye was first evaluated by visual examination of each sample. Visual assessment is possible at low concentrations (about 10 µg/L) of the selected dyes. A sample aliquot was placed in a clear glass container and viewed in a uniformly lighted area. A white backdrop was used to enhance dye identification. Standards of prepared dye concentrations were used for comparison.

A.2.3.1.2 Visual - Ultraviolet Light

The presence or absence of dye was further evaluated by visual examination of each sample under ultraviolet light. Visual assessment is possible at lower concentrations (relative to ambient light) under ultraviolet light. The sample aliquot in the clear glass container was viewed under long wavelength (365 nanometer [nm]) ultraviolet light in a darkroom. A dark backdrop was used to enhance dye identification. Standards of prepared dye concentrations were used for comparison.

A.2.3.1.3 Carbon Bugs

The carbon bugs were analyzed as backup confirmation of the presence or absence of dye in the groundwater samples. The carbon bugs were analyzed by elutriating the charcoal and looking for the presence of dye on and above the surface of the charcoal. For this analysis, the charcoal was placed in clear glass containers and viewed in a dark room against a dark backdrop. The elutriated charcoal was viewed under both white light (by shining a focused beam through the elution) and under ultraviolet light. Because the carbon bugs accumulate dye over time, very low concentrations can be detected using this procedure.

For this study, the presence of absorbed dye on the charcoal was determined using two types of elutriant: KOH and Smart solutions. The KOH solution consisted of 6 to 7 grams of potassium hydroxide dissolved in 100 mL of 70 percent isopropyl alcohol. The Smart solution consisted of 38 percent ammonium hydroxide, 43 percent 1-propanol, and 19 percent distilled water. The solutions were prepared weekly as needed.

A.2.3.2 Quantitative Analysis

This section describes the procedures used for quantitative analysis of groundwater samples to measure dye concentrations. The type of instrument used is described, as well as calibration and QA/QC procedures.

A.2.3.2.1 Scanning Spectrofluorometer

A scanning spectrofluorometer was used to measure dye concentrations in terms of degree of fluorescence. For this study, an Aminco SPF-500 was used. An on-site building was designated as an analytical laboratory during the study. A scanning bandwidth separation of 5 nm between 400 and 700 nm was selected for this study. An excitation bandwidth of 5 nm and an emission bandwidth of 10 nm were used to produce and measure fluorescent emissions. The maximum excitation frequency is 490 nm for fluorescein and 555 nm for rhodamine WT, and the peak emission frequency is 520 nm for fluorescein and 580 nm for rhodamine WT.

A.2.3.2.2 Calibration Procedures

Calibration of the spectrofluorometer required preparation of known concentration solutions of the respective dyes using distilled water. Concentration steps did not exceed an order of magnitude and were prepared for the expected range of sample concentrations. Using dye from the test lot, a working solution of 100 µg/L was prepared for each dye in accordance with published procedures (EPA 1988; Wilson, et al. 1986). From the working solutions, initial calibration standards were prepared in the following concentrations: 0.01 µg/L, 0.1 µg/L, 1.0 µg/L, 10.0 µg/L, and 100.0 µg/L. Calibration curves were generated for comparison to sample measurements to obtain the sample's dye concentration. The temperatures of the samples and of the calibration standards were allowed to equilibrate before equipment calibration and subsequent analysis to minimize potential variations in fluorescent intensity.

A.2.3.2.3 Laboratory QA/QC

The laboratory QA/QC program included MS/MSD analyses and continuing calibration checks consisting of laboratory blanks, laboratory blank spikes, and laboratory blank spike duplicates. Continuing calibration checks were run at a frequency of 1 per every 10 samples and at the end of each sample batch. The continuing calibration check samples consisted of distilled water and a spike of both dyes at a concentration of 10 µg/L. The acceptance criteria was plus or minus 20 percent of the true value. The dye tracer study plan (PRC 1994a) required instrument recalibration in the event the calibration verification fell outside the acceptance criteria. After each batch of samples was analyzed, calibration of the instrument was verified by a final calibration check. In the event that the final calibration check failed to meet the 20 percent acceptance criteria, the instrument was recalibrated and any samples analyzed since the previous acceptable calibration check were reanalyzed. All equipment calibrations were made at the same sample temperature as the groundwater samples.

Analytical accuracy was assessed by measuring the percent recovery (%R) of MS samples. Precision was measured by comparing the results of the MS sample with the MSD sample. The calculation of the accuracy and precision data quality indicators was performed in accordance with the QAPP for the UVB demonstration (PRC 1993). There are no established quality assurance objectives (QAO) for quantitative analysis of dye traces; however, for this study, QAOs of 50 to 150 percent for %R and 50 percent for relative percent difference (RPD) of MS and MSD analyses were used (PRC 1994a). These acceptance criteria are based on similar QAOs established for organic compounds under EPA's contract laboratory program.

The frequency of MS/MSD analyses was 1 pair per 20 groundwater samples. Corrective action was implemented when an analytical error was discovered or the established acceptance criteria were not met. Corrective actions included: recalibrating the instrument, reanalyzing the samples (if within holding time), resampling and reanalyzing the new samples, evaluating and amending analytical procedures, or accepting the data with an acknowledged level of uncertainty.

A.3 Results and Data Interpretation

This section provides a summary of qualitative and quantitative analytical results for the dye trace study, including QA/QC results. An assessment of conformance with the QAOs is presented by evaluation of %R and RPD. The data are interpreted by qualitative and quantitative evaluation methods.

A.3.1 Summary of Results

This section summarizes (1) qualitative and quantitative results for the background fluorescent study, (2) qualitative results for the carbon bugs and visual examination of groundwater grab samples, (3) quantitative results of spectrofluorometric analysis, and (4) QA/QC results.

A.3.1.1 Background Results

Grab samples and carbon bugs were collected from select groundwater monitoring wells before injecting dye into the aquifer. The results of the qualitative and quantitative analyses of these samples are presented in Table A-3. These results indicate that there were no detected interferences from natural or introduced background fluorescence.

A.3.1.2 Qualitative Results

After dye injection, grab samples of the groundwater were collected for qualitative analysis with each carbon bug. The qualitative analysis results were found to be the same for visual observation of grab samples under ambient and ultraviolet light and for elution of the carbon bugs. These results are summarized in Table A-4. The results show that rhodamine WT was visible in samples from well PW2 for the duration of the study. Rhodamine WT was not observed in samples from any other wells monitored with carbon bugs. Fluorescein was visible in samples from the UVB system well (W1) for the duration of the study, and fluorescein was visible in samples from well PW1 beginning April 4, 1994, for the remainder of the study duration. Quantitative analysis showed that fluorescein was detected in samples from well PW1 on March 28, 1994 (one week prior to detection by the carbon bugs). It is believed that dye breakthrough in well PW1 occurred on March 26 or 27, and that the concentration of dye adsorbed onto the charcoal at the time of collection on March 28 had not reached the visible threshold.

Different solutions were used to elute the carbon bugs for fluorescein and rhodamine WT, as described previously in Section A.2.3.1.3. Throughout the study period, the ability of both solutions to release both dyes from the charcoal was visually compared to contrast the relative performance of the KOH solution to release rhodamine WT and of the Smart solution to release fluorescein. Based on a review of literature, the KOH solution was expected to be more effective for releasing fluorescein, and the Smart solution was expected to be more effective for releasing rhodamine WT. However, no qualitative difference was observed between the effectiveness of either solution in releasing either type of dye. Both solutions worked well for releasing both types of dye.

A.3.1.3 Quantitative Results

The results of quantitative analyses are summarized in Table A-5. The results show positive determination of fluorescein in UVB system wells W1 and W2, and in monitoring wells PW1 and PW3. Rhodamine WT was detected in wells PW3 and W1. The samples from all other wells were below detection limits for both dyes.

Fluorescein was detected in samples from well PW1 on March 28, 1994, the 48th day of the study. The dye was detected in samples from well PW3 on April 8, 1994, the 59th day of the study. Rhodamine WT was detected in

Table A-3. Qualitative and Quantitative Analysis of Background Grab Samples and Carbon Bugs

Sampling Date	Sample Type	Well Location										
		W1	W2	PW1	PW2	PW4	PW5	PW7	PW8	31PW1	31OW1	4MW14
		Qualitative Results										
January 10-26, 1994	Carbon Bug	NA	NA	-	-	-	-	NA	NA	NA	NA	NA
January 18, 1994	Grab Sample	NA	NA	-	-	-	-	NA	NA	NA	NA	NA
January 26, 1994	Grab Sample	-	-	-	-	-	-	NA	NA	NA	NA	NA
February 2, 1994	Grab Sample	-	-	-	-	-	-	-	-	-	-	-
		Quantitative Results (µg/L)										
January 18, 1994	Grab Sample	NA	NA	<1	<1	<1	<1	NA	NA	NA	NA	NA
January 26, 1994	Grab Sample	<1	<1	NA	<1	<1	<1	NA	NA	NA	NA	NA
February 2, 1994	Grab Sample	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1

Notes:

- Negative result for qualitative fluorescence
NA Not analyzed

Table A-4. Qualitative Analysis of Grab Samples and Carbon Bugs

Sampling Date	W1	PW1	PW2	PW4	PW5	PW7	PW8	4MW14 T[1]	4MW14 B[2]	31OW1	31PW1 T[1]	31PW1 B[2]	BLANK[3]
2/14/94	+F	-	+R	-	-	-	-	-	-	-	-	-	-
2/21/94	+F	-	+R	-	-	-	-	-	-	-	-	-	-
2/28/94	+F	-	+R	-	-	-	-	-	-	-	-	-	-
3/7/94	+F	-	+R	-	-	-	-	-	-	-	-	-	-
3/14/94	+F	-	+R	-	-	-	-	-	-	-	-	-	-
3/21/94	+F	-	+R	-	-	-	-	-	-	-	-	-	-
3/28/94	+F	-	+R	-	-	-	-	-	-	-	-	-	-
4/4/94	+F	+F	+R	-	-	-	-	-	-	-	-	-	-
4/11/94	+F	+F	+R	-	-	-	-	-	-	-	-	-	-
4/18/94	+F	+F	+R	-	-	-	-	-	-	-	-	-	-
4/25/94	+F	+F	+R	-	-	-	-	-	-	-	-	-	-
5/4/94	+F	+F	+R	-	-	-	-	-	-	-	-	-	-
5/13/94	+F	+F	+R	-	-	-	-	-	-	-	-	-	-
5/20/94	+F	+F	+R	-	-	-	-	-	-	-	-	-	-
5/27/94	+F	+F	+R	-	-	-	-	-	-	-	-	-	-

Notes:

Carbon bugs were not installed in wells W2, PW3, and PW6

1	Top of screen	+F	Positive result for fluorescein
2	Bottom of screen	-	Negative result for both dyes
3	Carbon bug trip blank	+R	Positive result for rhodamine WT

Table A-5. Quantitative Analysis of Grab Samples

Sampling Date/Time	Dye Concentration (μg/L)[a]														
	W1	W2	PW1	PW2	PW3	PW4	PW5	PW6	PW7	PW8	31OW1	4MW14[t]	4MW14[b]	31PW1[t]	31PW1[b]
2/8/94 (1st hr)	<1	NA	<1	*2,900,000*	NA	NA	NA	NA	<1	<1	<1	NA	NA	NA	NA
2/8/94 (2nd hr)	NA	NA	<1	NA	NA	NA	NA	NA	<1	<1	<1	NA	NA	NA	NA
2/8/94 (3rd hr)	NA	NA	<1	NA	NA	NA	NA	NA	<1	<1	<1	NA	NA	NA	NA
2/8/94 (4th hr)	NA	NA	<1	NA	NA	NA	NA	NA	<1	<1	<1	NA	NA	NA	NA
2/8/94 (5th hr)	NA	NA	<1	NA	NA	NA	NA	NA	<1	<1	<1	NA	NA	NA	NA
2/8/94 (6th hr)	NA	NA	<1	NA	NA	NA	NA	NA	<1	<1	<1	NA	NA	NA	NA
2/8/94 (7th hr)	NA	NA	<1	NA	NA	NA	NA	NA	<1	<1	<1	NA	NA	NA	NA
2/8/94 (8th hr)	NA	NA	<1	NA	NA	NA	NA	NA	<1	<1	<1	NA	NA	NA	NA
2/8/94 (10th hr)	NA	NA	<1	NA	NA	NA	NA	NA	<1	<1	<1	NA	NA	NA	NA
2/8/94 (12th hr)	NA	NA	<1	NA	NA	NA	NA	NA	<1	<1	<1	NA	NA	NA	NA
2/9/94 (14th hr)	NA	NA	<1	NA	NA	NA	NA	NA	<1	<1	<1	NA	NA	NA	NA
2/9/94 (16th hr)	NA	NA	<1	NA	NA	NA	NA	NA	<1	<1	<1	NA	NA	NA	NA
2/9/94 (20th hr)	NA	NA	<1	NA	NA	NA	NA	NA	<1	<1	<1	NA	NA	NA	NA
2/9/94 (24th hr)	**12,500**	NA	<1	*3,500,000*	NA	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
2/9/94 (32nd hr)	NA	NA	<1	NA	NA	NA	NA	NA	<1	<1	<1	NA	NA	NA	NA
2/10/94 (40th hr)	NA	NA	<1	NA	NA	NA	NA	NA	<1	<1	<1	NA	NA	NA	NA
2/10/94 (48th hr)	NA	NA	<1	NA	NA	NA	NA	NA	<1	<1	<1	NA	NA	NA	NA
2/11/94	**25,000**	**540,000**	<1	*930,000*	NA	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
2/12/94	NA	NA	<1	*210,000*	NA	NA	NA	NA	<1	<1	<1	NA	NA	NA	NA
2/13/94	NA	NA	<1	*160,000*	NA	NA	NA	NA	<1	<1	<1	NA	NA	NA	NA
2/14/94	**27,000**	**290,000**	<1	*150,000*	NA	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
2/16/94	**80,000**	**290,000**	<1	*97,000*	NA	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
2/18/94	**52,000**	**210,000**	<1	*67,000*	NA	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
2/21/94	**110,000**	**135,000**	<1	*58,000*	NA	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
2/23/94	**150,000**	**100,000**	<1	*84,000*	NA	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
2/25/94	**160,000**	**120,000**	<1	*40,000*	*13*	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
2/28/94	**83,000**	**75,000**	<1	*25,000*	*92*	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
3/2/94	**89,000**	**83,000**	<1	*26,000*	NA	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1

Table A-5. Quantitative Analysis of Grab Samples (continued)

Sampling Date/Time	Dye Concentration (μg/L)[a]														
	W1	W2	PW1	PW2	PW3	PW4	PW5	PW6	PW7	PW8	31OW1	4MW14[t]	4MW14[b]	31PW1[t]	31PW1[b]
3/4/94	**55,000**	**110,000**	<1	*26,000*	*360*	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
3/7/94	**47,000**	**45,000**	<1	*13,000*	*96*	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
3/9/94	**18,000**	**18,000**	<1	*9,900*	*86*	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
3/11/94	**43,000**	**36,000**	<1	*15,000*	*120*	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
3/14/94	**30,000**	**25,000**	<1	*10,000*	*120*	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
3/16/94	**29,000**	**18,000**	<1	*3,800*	*120*	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
3/18/94	**65,000**	**33,000**	<1	*6,400*	*150*	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
3/21/94	**14,000**	**6,400**	<1	*4,300*	*200*	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
3/23/94	**17,000**	**10,000**	<1	*1,800*	*210*	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
3/25/94	**8,000**	**1,800**	<1	*1,600*	*270*	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
3/28/94	**6,100**	**2,100**	**230**	*1,100*	*340*	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
3/30/94	**4,400**	**3,600**	**220**	*1,300*	*320*	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
4/1/94	**4,200**	**3,200**	**40**	*450*	*350*	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
4/4/94	**2,200**	**1,400**	**11**	*1,500*	*270*	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
4/6/94	**1,800**	**1,200**	**6.7**	*650*	*390*	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
4/8/94	**2,800**	**2,300**	**4.9**	*750*	*610*/**28**	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
4/11/94	**4,900**	**2,100**	**69**	*670*	*330*/**6.7**	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
4/13/94	**4,200**	**2,000**	**180**	*630*	*310*/**6.8**	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
4/15/94	**3,600**	**1,700**	**380**	*570*	*600*/**34**	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
4/18/94	**3,000**	**1,200**	**470**	*540*	*490*/**20**	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
4/20/94	**2,400**	**1,200**	**560**	*500*	*420*/**9.3**	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
4/22/94	**2,100**	**1,100**	**920**	*470*	*580*/**32**	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
4/25/94	**3,300**	**1,700**	**1,700**	*480*	*600*/**48**	<1	<1	NA	<1	<1	<1	<1	<1	<1	<1
4/27/94	**1,900**	**1,200**	**1,400**	*450*	*630*/**36**	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
4/29/94	**870**	**1,300**	**3,100**	*570*	*640*/**33**	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
5/4/94	**1,200**/*21*	**1,500**	**5,300**	*460*	*500*/**25**	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1

Table A-5. Quantitative Analysis of Grab Samples (continued)

Sampling Date/Time	Dye Concentration (μg/L)[a]														
	W1	W2	PW1	PW2	PW3	PW4	PW5	PW6	PW7	PW8	31OW1	4MW14[t]	4MW14[b]	31PW1[t]	31PW1[b]
5/6/94	**1,200**/*8*	**1,500**	**4,900**	*440*	*630*/**42**	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
5/13/94	**930**	**890**	**7,600**	*460*	*620*/**48**	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
5/20/94	**1,000**	**950**	**12,000**	*440*	*590*/**41**	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
5/27/94	**700**	**500**	**18,000**	*330*	*640*/**49**	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1

Notes:

NA Not analyzed
[a] All fluorescein results are considered estimated due to matrix interference
[t] Top of screen
[b] Bottom of screen
300 Fluorescein
500 Rhodamine WT

deep well PW3 on February 25, 1994, the 17th day of the study, when the well was sampled for comparison with the sampling well network results. Wells PW3 and PW6 were not included with the original sampling locations because the deep wells were not expected to yield critical results for evaluation of the circulation cell in the upper portion of the aquifer. Deep wells PW3 and PW6 were added to the sampling well network after rhodamine WT was detected in samples from well PW3. Rhodamine WT was detected in samples from UVB system well W1 on May 4, 1994, the 85th day of the study. The rhodamine WT dye in UVB system well W1 was detectable only during one other sampling event (on May 6, 1994).

A.3.2 Data Quality

The scanning spectrofluorometer was initially calibrated with five standards of each dye (0.01, 0.10, 1.0, 10.0, and 100.0 µg/L). Calibration records are included in the laboratory logbook notes provided in the Technology Evaluation Report (TER) for UVB SITE demonstration (PRC 1995). Daily calibrations consisted of an 8-point curve for fluorescein (1.0, 2.0, 5.0, 8.0, 10.0, 20.0, 50.0, and 100.0 µg/L) and a 5-point curve for rhodamine WT (1.0, 10.0, 20.0, 50.0, and 100.0 µg/L). Calibration and continuing calibration checks included blanks, blank spikes (BS), and blank spike duplicates (BSD). Continuing calibration checks were performed at a frequency of 1 per 10 samples and at the end of each sample batch. Records of continuing calibration checks also are included in TER (PRC 1995). The results of continuing calibration checks for both dyes show an average instrument response difference from true concentration of 5.4 percent for rhodamine WT and 16.7 percent for fluorescein. These ranges are within the established acceptable range of 20 percent. The following calculation was used to measure the instrument response difference for the continuing calibration checks:

$$IRD = \frac{C_{rs} - C_{cc}}{C_{rs}} \times 100\%$$

Where:

IRD = Instrument response difference
C_{rs} = Measured concentration in reference standard during calibration
C_{cc} = Measured concentration in continuing calibration sample (spiked at the same concentration as reference standard)

The accuracy and precision of quantitative analysis was tested by analyzing an MS sample and an MSD sample at a frequency of 1 per 20 samples. These results are shown in Tables A-6 and A-7. Due to laboratory error, MS/MSD analysis did not begin until March 7, 1994. On analysis, matrix interference was found for fluorescein. The average %R for fluorescein was 245.5 percent, which is outside the established acceptance range of 50 to 150 percent. The high fluorescein %R range (between 99 and 360 percent) is attributed to either matrix interference in the groundwater or instrument error, as discussed below. The %R for rhodamine WT averaged 96.6 percent; none of the rhodamine WT %R values fell outside the acceptance range. The RPD for fluorescein was 5.6 percent and was 2.7 percent for rhodamine WT. The RPD for both dyes was within the established acceptable range of 50 percent.

Instrument performance was checked by BS/BSDs. The %R for fluorescein was found to range between 15 and 170 percent with an average of 83.9. The RPD for fluorescein was found to range between 0 and 57.1 percent, with an average of 14.0. The fluorescein %R data for the BS/BSD fell outside the acceptable range of 50 to 150 percent on 10 occasions; the fluorescein RPD data fell outside the acceptable range of 50 percent only once. The accuracy deviations for fluorescein may not be entirely attributed to instrument performance since the instrument calibration and continuing calibration checks were within acceptable limits. In addition, the difference between fluorescein average %R for MS/MSD (245.5) and BS/BSD (83.9) data indicates a large influence due to matrix interference.

The rhodamine WT data BS/BSD results show that the %R ranged between 77 and 110 percent with an average of 96.7, and the RPD ranged between 0 and 22.7 percent with an average of 2.9. The rhodamine WT BS/BSD data are all within acceptable limits.

Corrective actions were implemented to identify and correct the cause for the high fluorescein %R readings. First, the instrument was recalibrated, and the samples were reanalyzed. However, no problems were found with instrument calibration. The sampling and analytical procedures were evaluated for technical adequacy and to identify potential deficiencies in the sampling and analysis program. The program was found to be technically adequate, and no deficiencies were identified. Therefore, the accuracy variance is attributed to matrix interference in the groundwater (possibly from the volatile organic compound [VOC] contamination). Although background samples did not show fluorescence from the VOCs in the

Table A-6. Fluorescein Quality Assurance/Quality Control Results

SAMPLING EVENT (DATE)	SAMPLE ID	FIELD BLANK RESULT	MS/MSD						BS/BSD				
			SAMPLE RESULT	SPIKE CONC	SPIKED SAMPLE RESULT	DUP. SPIKED SAMPLE RESULT	% R	RPD	METHOD BLANK RESULT	BLANK SPIKE RESULT	DUP. BLANK SPIKE RESULT	% R	RPD
3/7/94	PW7	<1	<1	10	30	30	300	0	<1	5.4	5.0	54	7.7
3/9/94	PW7	<1	<1	10	17	18	165	8.7	<1	9.1	9.1	91	0
3/11/94	PW7	<1	<1	10	33	31	330	6.3	<1	16	18	160	11.8
3/14/94	PW7	<1	<1	10	30	29	300	3.4	<1	8.6	8.6	86	0
3/16/94	PW4	<1	<1	10	35	36	350	1.4	<1	15.5	17.5	155	12.1
3/18/94	PW1	<1	<1	10	19	18	190	5.4	<1	9.1	9.2	91	1.1
3/21/94	31OW1	<1	<1	10	18	19	180	5.4	<1	5.4	5.0	54	7.7
3/23/94	31OW1	<1	<1	10	36	38	360	5.4	<1	13	13	130	0
3/25/94	PW1	<1	<1	10	33	32	330	3.1	<1	17	17	170	0
3/28/94	PW8	<1	<1	10	28	30	280	6.9	<1	16	17	160	6.1
3/30/94	PW7	<1	<1	10	31	30	310	3.3	<1	13	14	130	7.4
4/1/94	PW4	<1	<1	10	24	26	240	8.0	<1	14.5	9.6	145	40.7
4/4/94	PW4	<1	<1	10	16	13	160	20.7	<1	10.8	7.8	108	32.3
4/6/94	31OW1	<1	<1	10	15	20	150	28.6	<1	10.0	7.5	100	28.6
4/8/94	PW7	<1	<1	10	23	24	230	4.3	<1	1.5	2.7	15	57.1
4/11/94	PW7	<1	<1	10	25	26	250	3.9	<1	5.3	6.9	53	26.2
4/13/94	PW8	<1	<1	10	28	24	280	15.4	<1	3.8	5.4	38	34.8
4/15/94	31OW1	<1	<1	10	28	28	280	0	<1	4.3	4.2	43	2.4
4/18/94	31OW1	<1	<1	10	21	22	210	4.7	<1	3.7	5.0	37	29.9
4/20/94	31OW1	<1	<1	10	25	25	250	0	<1	3.1	4.4	31	34.7
4/22/94	31OW1	<1	<1	10	24	25	240	4.1	<1	3.1	2.8	31	10.2
4/25/94	31OW1	<1	<1	10	32	32	320	0	<1	6.0	4.9	60	20.2

Table A-6. Fluorescein Quality Assurance/Quality Control Results (continued)

SAMPLING EVENT (DATE)	SAMPLE ID	FIELD BLANK RESULT	MS/MSD						BS/BSD				
			SAMPLE RESULT	SPIKE CONC	SPIKED SAMPLE RESULT	DUP. SPIKED SAMPLE RESULT	% R	RPD	METHOD BLANK RESULT	BLANK SPIKE RESULT	DUP. BLANK SPIKE RESULT	% R	RPD
4/27/94	PW7	<1	<1	10	21	21	210	0	<1	9.8	9.8	98	0
4/29/94	31OW1	<1	<1	10	24	24	240	0	<1	7.4	7.9	74	6.5
5/4/94	31OW1	<1	<1	10	21	22	210	4.7	<1	5.3	5.4	53	1.9
5/6/94	31OW1	<1	<1	10	23	23	230	0	<1	5.3	5.4	53	1.9
5/13/94	31OW1	<1	<1	10	20	21	200	4.9	<1	8	9.7	80	19.2
5/20/94	31OW1	<1	<1	10	21	20	210	4.9	<1	6.8	6.8	68	0
5/27/94	31OW1	<1	<1	10	20	21	200	4.9	<1	6.5	6.9	65	6.0

Notes:

% R Percent recovery = (spike sample result - sample result)/spike concentration X 100
RPD Relative percent difference = (spiked sample result - duplicate spike sample result)/average of spiked sample X 100
DUP Duplicate
ID Identification
CONC Concentration

Table A-7. Rhodamine WT Quality Assurance/Quality Control Results

SAMPLING EVENT (DATE)	SAMPLE ID	FIELD BLANK RESULT	MS/MSD						BS/BSD				
			SAMPLE RESULT	SPIKE CONC	SPIKED SAMPLE RESULT	DUP. SPIKED SAMPLE RESULT	% R	RPD	METHOD BLANK RESULT	BLANK SPIKE RESULT	DUP. BLANK SPIKE RESULT	% R	RPD
3/7/94	PW7	<1	<1	10	10	9.7	100	3.0	<1	7.7	7.9	77	2.6
3/9/94	PW7	<1	<1	10	10	11	100	9.5	<1	9.7	9.8	97	1.0
3/11/94	PW7	<1	<1	10	10	10	100	0	<1	8.8	8.7	88	1.1
3/14/94	PW7	<1	<1	10	8.0	11	80	31.6	<1	8.0	9.4	80	16.1
3/16/94	PW4	<1	<1	10	8.7	8.7	87	0	<1	9.6	9.5	96	1.0
3/18/94	PW1	<1	<1	10	9.4	9.5	94	0.5	<1	9.8	7.8	98	22.7
3/21/94	31OW1	<1	<1	10	7.6	7.8	76	2.6	<1	7.7	7.9	77	2.6
3/23/94	31OW1	<1	<1	10	7.9	7.7	79	2.6	<1	8.1	8.5	81	4.8
3/25/94	PW1	<1	<1	10	9.5	9.6	95	1.0	<1	9.8	9.8	98	0
3/28/94	PW8	<1	<1	10	9.6	9.6	96	0	<1	10	9.9	100	1.0
3/30/94	PW7	<1	<1	10	9.9	9.9	99	0	<1	10	9.9	100	1.0
4/1/94	PW4	<1	<1	10	9.6	9.3	96	3.2	<1	9.0	9.8	90	8.5
4/4/94	PW4	<1	<1	10	9.7	9.7	97	0	<1	9.9	9.8	99	1.0
4/6/94	31OW1	<1	<1	10	9.4	9.4	94	0	<1	9.4	9.4	94	0
4/8/94	PW7	<1	<1	10	9.8	10	98	2.0	<1	9.8	9.8	98	0
4/11/94	PW7	<1	<1	10	9.7	9.9	97	2.0	<1	9.9	10	99	1.0
4/13/94	PW8	<1	<1	10	9.6	9.6	96	0	<1	9.7	9.7	97	0
4/15/94	31OW1	<1	<1	10	9.6	9.8	96	2.1	<1	9.7	9.6	97	1.0
4/18/94	31OW1	<1	<1	10	10	10	100	0	<1	10	10	100	0
4/20/94	31OW1	<1	<1	10	10	10	100	0	<1	10	10	100	0
4/22/94	31OW1	<1	<1	10	10	10	100	0	<1	11	11	110	0
4/25/94	31OW1	<1	<1	10	10	10	100	0	<1	10	10	100	0

Table A-7. Rhodamine WT Quality Assurance/Quality Control Results (continued)

SAMPLING EVENT (DATE)	SAMPLE ID	FIELD BLANK RESULT	MS/MSD						BS/BSD				
			SAMPLE RESULT	SPIKE CONC	SPIKED SAMPLE RESULT	DUP. SPIKED SAMPLE RESULT	% R	RPD	METHOD BLANK RESULT	BLANK SPIKE RESULT	DUP. BLANK SPIKE RESULT	% R	RPD
4/27/94	PW7	<1	<1	10	10	10	100	0	<1	10	11	100	9.5
4/29/94	31OW1	<1	<1	10	11	11	110	0	<1	11	11	110	0
5/4/94	31OW1	<1	<1	10	9.9	10	99	1.0	<1	10	10	100	0
5/6/94	31OW1	<1	<1	10	9.6	10	96	4.1	<1	10	11	100	9.5
5/13/94	31OW1	<1	<1	10	11	10	110	9.5	<1	11	11	110	0
5/20/94	31OW1	<1	<1	10	11	11	110	0	<1	11	11	110	0
5/27/94	31OW1	<1	<1	10	9.9	9.9	99	0	<1	9.9	10	99	1.0

Notes:

% R Percent recovery = (spiked sample result - sample result)/spiked concentration X 100
RPD Relative percent difference = (spiked sample result - duplicate spike sample result)/average of spiked sample X 100
DUP. Duplicate
ID Identification
CONC Concentration

emission range of fluorescein, the reaction of VOCs with the dye may exaggerate the measured fluorescence. Therefore, all fluorescein concentration values shown in Table A-5 are considered estimated due to matrix interference. The matrix interference does not affect any of the study goals since all the primary and secondary goals are based on detection of the presence or absence of dye rather than accurate measurement of dye concentration.

A.3.3 Data Interpretation

This section presents the results of the dye trace study. An overview of the hydrogeologic conditions affecting the dye trace study results is provided in Section A.3.3.1. Interpretation of the qualitative and quantitative results of the dye trace study is addressed in Section A.3.3.2.

A.3.3.1 Hydrogeologic Conditions

Data collected during the dye trace study indicate that hydrogeologic conditions at Site 31 exert a controlling influence over the movement of groundwater and likely the subsequent distribution of dye during the dye trace study. The primary hydrogeologic factors affecting the dye trace study results are groundwater flow direction and anisotropy and heterogeneity of the aquifer.

A.3.3.1.1 Groundwater Flow Direction

The downgradient direction of groundwater flow was originally determined to be to the southeast based on a preliminary contour map of the November 1992 groundwater elevations at Site 31 (TETC 1994). This flow direction corresponds to the general groundwater gradient over the majority of the base, gently sloping to the southeast. After heavy rains during the winter of 1992-93, an apparent change in groundwater flow direction was observed at the site (TETC 1994). This change was interpreted to be in response to recharge along Heacock Storm Drain, located along the eastern boundary of the base. Recharge from the storm drain appears to have caused localized groundwater mounding, which in turn locally affects the direction of groundwater flow. The mounding of groundwater in response to the recharge appears to have temporarily redirected the groundwater flow toward the west-southwest along the eastern portion of the base, which includes Site 31. However, wells west of Site 31 appear not to have been affected by groundwater recharge from Heacock Storm Drain, and data from these wells continue to indicate a groundwater flow direction to the southeast.

Groundwater level elevations were collected before and during the UVB demonstration. Based on contouring of the groundwater elevations, the potentiometric surface appears relatively flat with generally less than 1 foot (0.3 m) change of gradient across the entire area of Site 31. Due to the relatively flat gradient and the linear distribution of groundwater monitoring wells at the site, the groundwater flow direction could not be precisely determined. However, groundwater levels measured during operation of the UVB system suggest that wells PW1 through PW6 are downgradient (southeast) of the treatment system. Since startup of the UVB system, additional wells screened across the groundwater table have been installed in the immediate vicinity of the treatment system. These additional wells will allow an accurate measurement of the groundwater gradient once the UVB system has been shut down. The UVB system was turned off on December 4, 1994 and the groundwater elevation was subsequently measured over a 7-day period until the measurements stabilized. The results of the December 9 measurements indicate that groundwater flow is to the southeast. Modeling of groundwater flow at March AFB by Tetra Tech, Inc., suggests that the site is located at the convergence of the two flow directions (PRC 1994c). This convergence appears to have caused a trough in the groundwater gradient. Several interpretations for the change in gradient direction at the site have been proposed, including shallow bedrock and structural discontinuity (PRC 1994c). However, boring log data from the site suggest that the depth to weathered bedrock on site averages 100 feet or more, it is unlikely that bedrock topography has significantly affected the groundwater gradient direction at the site. In addition, more recent data show that temporary changes in groundwater flow direction may result from precipitation and subsequent recharge.

A.3.3.1.2 Anisotropy and Heterogeneity

In addition to the natural groundwater gradient direction, the anisotropy and heterogeneity of the aquifer plays a significant roll in controlling the movement of groundwater and subsequent distribution of dye. These factors are magnified especially when an induced flow, such as the UVB circulation cell, is placed on the aquifer. Induced groundwater flow resulting from the UVB system is influenced by the anisotropy and heterogeneity of the

aquifer and locally may not flow in the normal downgradient flow direction.

Since the aquifer consists of alluvial deposits, anisotropic conditions are likely present. The value of Kh at the site is estimated to be an order of magnitude greater than Kv (TETC 1994). In addition to anisotropic conditions in the alluvial deposits, structural controls, such as fractures and faults, may significantly affect groundwater flow in the aquifer.

During the UVB demonstration, a seismic reflection survey was conducted at Site 31 by Tetra Tech, Inc. A fault was interpreted from the reflection data at a depth of about 100 feet (30.5 m) bgs trending northwest/southeast, parallel to Graeber Street (Figure A-1). The trend of this feature roughly parallels the downgradient direction and may influence groundwater flow. The specific effects caused by this feature were not investigated during the dye trace study. Additional information concerning the identified feature can be found in the seismic reflection survey prepared by Tetra Tech, Inc. (1993).

Recent unpublished geophysical investigative results from March AFB support the presence of a fault at the base (PRC 1994b). Preliminary data from this investigation appear to correlate with the seismic reflection survey conducted at Site 31 by Tetra Tech, Inc. This correlation suggests that a well-developed fracture zone parallel to Graeber Street (southeast trending) may be present. If present, this fault could provide a preferential conduit for groundwater flow. An interpreted zone of higher conductivity is currently being used by Tetra Tech, Inc., for its base-wide groundwater modeling and appears to provide the best match for the observed groundwater data collected at the base (PRC 1994c). This interpretation may also explain the observed distribution of rhodamine WT and fluorescein during the dye trace study. A detailed discussion of the interpreted linear discontinuity and site anisotropy and heterogeneity is provided in the ITER

A.3.3.2 Interpretation of Dye Trace Study Results

The results of the dye trace study provide both qualitative and quantitative information. This information provides data that are used to demonstrate the hydraulic interconnection between the UVB system and wells PW1, PW2, and PW3, calculate aquifer characteristics and groundwater velocities, and estimate of the radius of circulation cell of the UVB circulation cell.

A.3.3.2.1 Interconnection of Groundwater Flow

The presence of fluorescein dye in samples from wells PW1 and PW3 shows interconnection between these points and UVB system well W2. Likewise, the presence of rhodamine WT in samples from well PW3 shows interconnection with well PW2. The presence of rhodamine WT in samples from UVB system well W1 indicates that a circulation cell has developed between the UVB system and well PW2. The absence of dye in any of the surrounding wells, however, suggests that groundwater movement is in the southwest direction, downgradient, rather than within a well developed, symmetrical circulation cell around the system.

The absence of rhodamine WT in samples from well PW1 and the absence of fluorescein in samples from well PW2 indicates an uneven distribution of dye within the UVB circulation cell. The uneven distribution of dye may reflect different flow regimes due to heterogeneous, anisotropic deposits, or the linear discontinuity discussed above. The screened intervals of wells W1, PW2, and PW5 are in well-graded, fine to coarse sand with little fine to medium gravel and no silt or clay-sized particles. The over- and underlying intervals are finer sands with some silt. The lack of dye mixing within the screened intervals of wells PW1 and PW2 may be due to variable lithologies in the aquifer system. The presence of both dyes in samples from well PW3 indicates that the flow regimes mix in the deeper interval. Because fluorescein was detected in samples from well PW1 but not in samples from well PW2, the fluorescein probably mixes into the deeper interval between the UVB system and well PW1. The mixing phenomenon in the deeper interval may be due to the specific gravity of the dyes (fluorescein = 1.050, rhodamine WT = 1.19). Because the dyes are slightly heavier than water, they may tend to sink under Site 31 conditions. Also, because of the lack of dye mixing in well PW2 (and the presence of rhodamine WT in UVB system well W1), UVB system well W1 appears to draw water from the intermediate interval, but not from the upper interval. The study results do not indicate whether groundwater is drawn from the deeper interval.

Fluorescein breakthrough from UVB system well W2 to well W1 occurred within 24 hours after dye injection,

indicating a high degree of groundwater circulation within the system (Figure A-2). The concentration of dye in samples from UVB system well W1 continued to increase over the next 14 days until equilibrium was reached between the UVB system wells (W1 and W2). Using an estimated Kv of approximately 9.05 gpd/ft2 (1.40 x 10^{-5} feet per second; 4.26 x 10^{-4} cm/s) (one order of magnitude less than Kh), it is unlikely that fluorescein dye traveled a minimum distance of approximately 8.8 feet (2.7 m) vertically through the saturated sediments between wells W1 and W2 within 24 hours. This suggests that a preferential pathway of groundwater flow likely exists. Three potential preferential pathways were identified: bridging of grout during well completion, leakage around the packer, and conduits of flow in the aquifer.

Review of well completion logs suggests that during grouting an adequate seal was emplaced between the two well screens. However, it is possible that conduits in the seal (bridging) may have occurred during emplacement of the bentonite chips. The packer used to separate the upper and lower screen intervals consisted of an inflatable rubber tire with a hole in the center of the steel rim to house the educter pipe. The seal between the steel rim and educter pipe is loose to allow the internal components of the UVB system to move freely within the treatment well. This seal is a likely source of groundwater recirculation. The third possible source of groundwater recirculation is from effects of the interpreted fault. Conduits of flow, such as fractures, may be associated with the fault. These conduits may be continuous between the upper and lower screened sections of the UVB system well, causing a high degree of groundwater circulation to occur.

A.3.3.2.2 Groundwater Velocities

The groundwater maximum velocity was estimated by dividing the horizontal distance between the injection and sampling point by the first arrival time of the dye at the sampling point. Dye breakthrough curves were drawn to estimate first arrival and maximum concentration times and to show the decline of dye concentration in the injection wells (Figures A-2, A-3, and A-4). The dye breakthrough curves shown on Figures A-3 and A-4 do not display typical bell-shaped patterns. The shape of the curves may reflect the nature of groundwater flow in the porous aquifer (rather than channelized or conduit flow), or the curves may become more typical with an extended monitoring period. (The dye concentration in well PW1 was rising at the end of the study period.)

Fluorescein breakthrough in well PW1 is shown on Figure A-3. The breakthrough occurred between March 25, 1994 (concentration < 1 µg/L) and March 28, 1994 (concentration = 230 µg/L). Based on a travel time of 46 to 47 days and the distance between wells W2 and PW1 (35.18 feet [10.7m]), an estimate of the maximum groundwater velocity is between 0.75 and 0.76 feet per day (feet/day) (2.65 x 10^{-4} and 2.68 x 10^{-4} cm/s). Based on the shape of the breakthrough curve, the travel time for maximum concentration is believed to extend beyond the monitoring period of the study. Because the average groundwater velocity is calculated based on the travel time for the maximum dye concentration, the average groundwater velocity was not estimated. The maximum concentration travel time may be prolonged due to the recirculation within the UVB system between wells W2 and W1, as indicated on Figure A-2.

The breakthrough curves shown on Figure A-4 represent fluorescein and rhodamine WT concentrations in samples from well PW3. Because rhodamine WT was found in samples from well PW3 on the first sampling event (February 25, 1994), these data were not used to estimate first time of arrival. The appearance of fluorescein in well PW3 on April 8, 1994, however, confirmed the maximum groundwater velocity estimate provided by sample results from well PW1 (45.3 feet/59 days = 0.77 feet/day [13.8 m/ 59 days = 0.2339 m/day or 2.72 x 10^{-4} cm/s]). The graphs of dye concentrations in samples from well PW3 appear to have leveled off, but the concentrations did not appear to be declining at the end of the monitoring period. Therefore, the well PW3 data do not provide a firm estimate of the maximum concentration time or the average groundwater velocity.

A.3.3.2.3 Radius of Circulation Cell

The results show that an elongated circulation cell developed between wells W1 and PW2 over a distance of about 40 feet (12.2 m). Hydraulic interconnection was demonstrated between wells W2 and PW3 over a distance of about 45 feet (13.7 m); however, the results do not indicate whether this interconnection is primarily due to UVB system circulation or to groundwater flow in the downgradient direction. The absence of dye in wells other than those installed in the downgradient direction (southeast) shows that the circulation cell developed less than 40 feet (12.2 m) in all other directions. Furthermore, the results may indicate that the circulation cell did not develop at all in the other directions. Thus, the area of

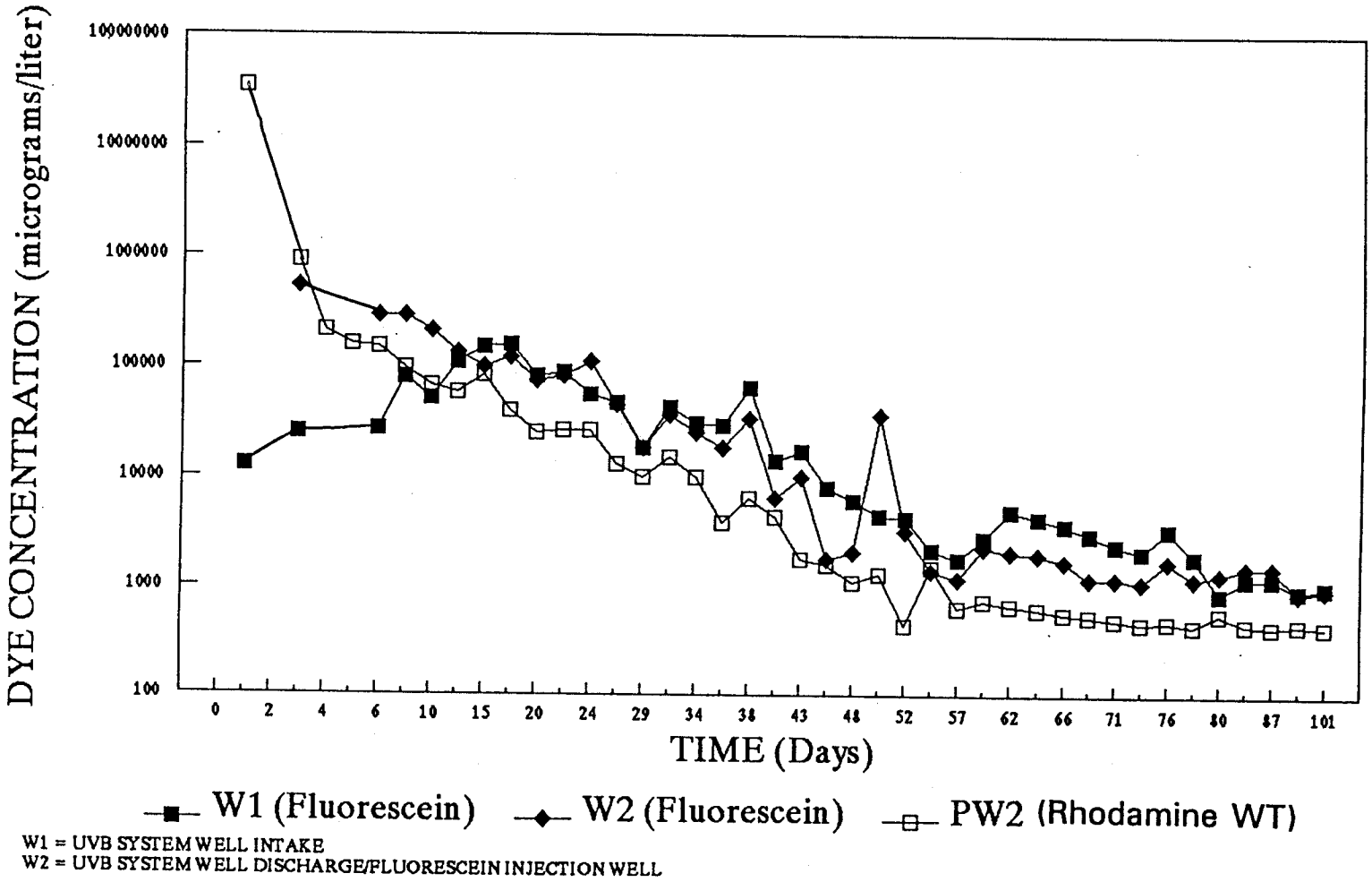


Figure A-2. Dye study results, system and injection wells.

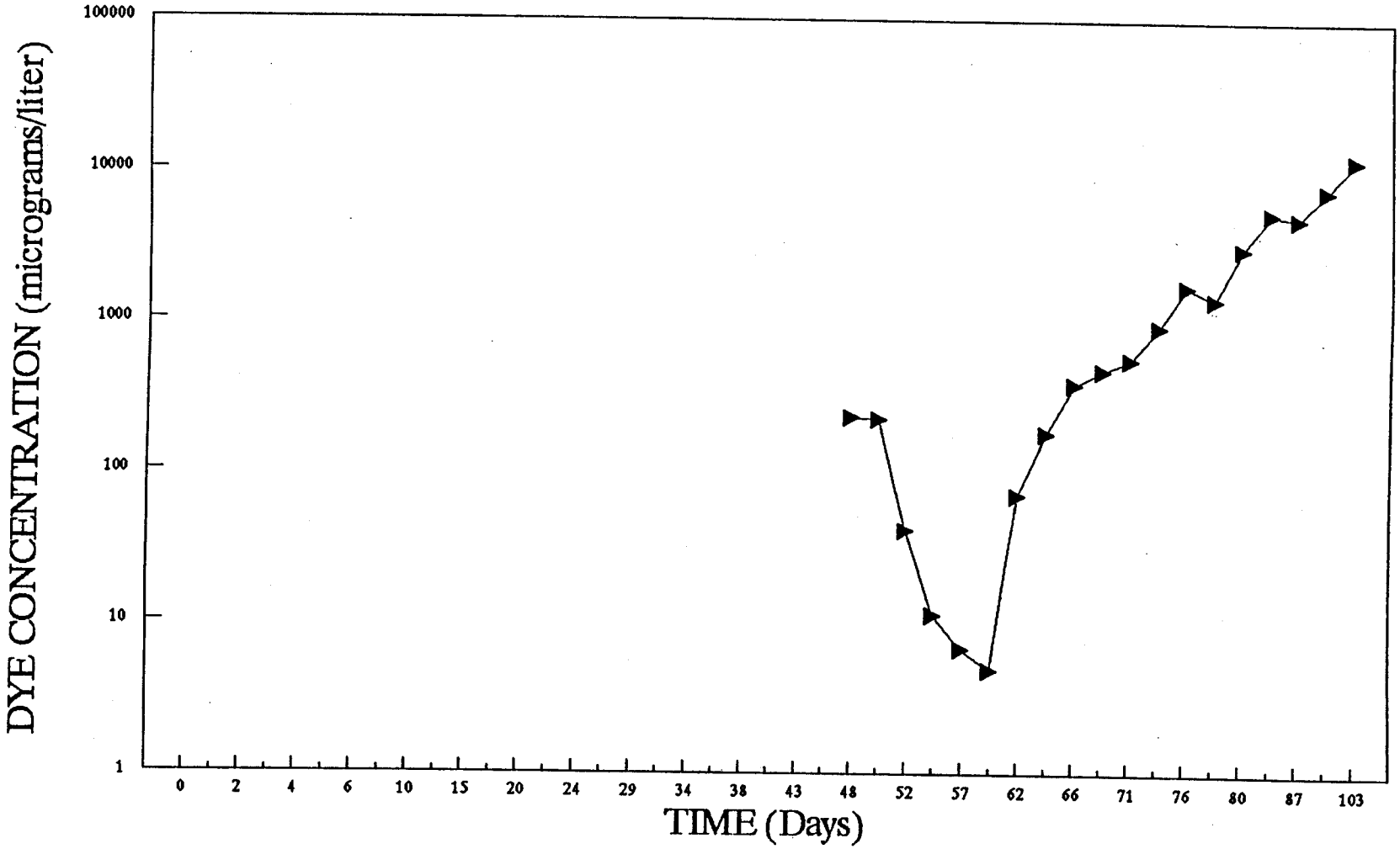
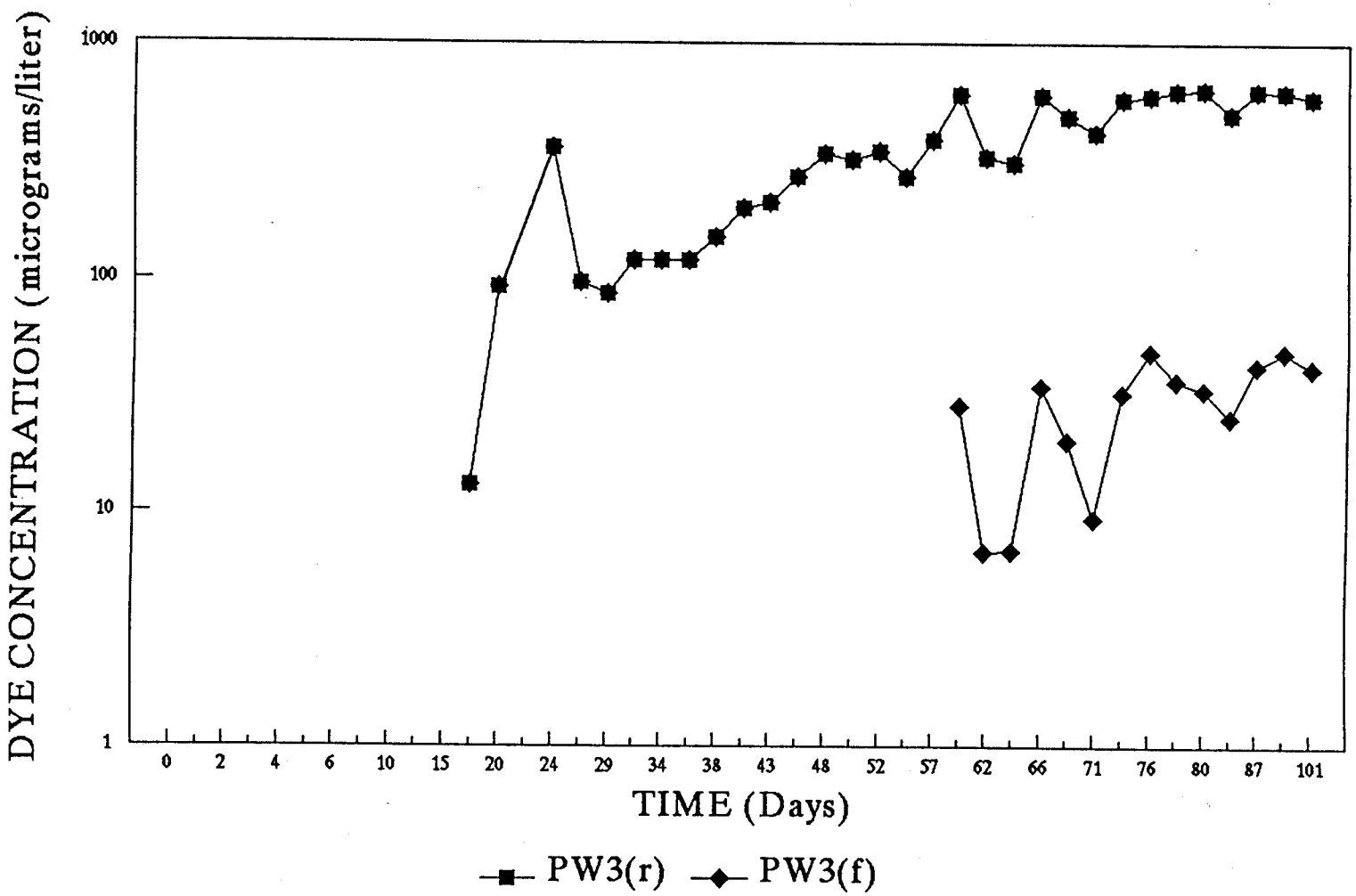


Table A-3. Dye study results, well PW1.



r = Rhodamine WT
f = Fluorescein

Table A-4. Dye study results, well PW3.

influence of the UVB circulation cell was shown to be at least 40 feet (12.2 m) in the downgradient (southeast) direction and less than 40 feet (12.2 m) in all other directions.

A.4 Conclusions

This section presents the conclusions regarding the primary and secondary goals.

Primary Goals (PG)

- *PG-1: Demonstrate hydraulic interconnection between the UVB system and distant sample locations*

This goal was achieved by analyzing passive receptors and groundwater samples for fluorescein and rhodamine WT from wells W1, W2, PW1, PW2, PW3, PW4, PW5, PW6, PW7, PW8 31OW1, 31PW1, and 4MW14. The results show interconnection between the UVB system and wells PW1, PW2, and PW3. These wells are believed to be downgradient of the UVB system. The results show the presence of a short-circuit circulation pattern between wells W2 and W1, and an elongated circulation cell between the UVB system and wells PW1, PW2, and PW3. Although dye was not detected in the outer cluster wells (PW4, PW5, and PW6) during the study period, it is believed that dye movement will follow natural groundwater flow in the downgradient direction toward the outer cluster wells. However, dye was not visibly apparent in the outer cluster wells on February 1 and 2, 1995.

- *PG-2: Demonstrate circulation of groundwater within the UVB circulation cell*

Confirmation of hydraulic interconnection between the UVB system and wells PW1, PW2, and PW3 shows that the UVB system is producing an elongated circulation pattern in a downgradient direction. Circulation of the groundwater within the UVB system was verified by the detection of fluorescein in samples from well PW1 and of rhodamine WT in samples from UVB system well W1. There is no indication, however, of a well-developed circulation cell between the UVB system and remote wells that are not downgradient of the system. The uneven distribution of dye within the aquifer suggests different flow regimes in heterogenous, anisotropic deposits.

Based on the dye trace study results, it appears that a narrow and elongated circulation cell may have developed to a distance of at least 40 feet (12.2 m) in a downgradient direction and less than 40 feet (12.2 m) in all other directions. However, the mixing aspect of the circulation cell does not appear to be well developed. In addition, the movement of the groundwater appears to be driven in a downgradient direction, rather than within a well-developed circulation cell.

Secondary Goals (SG)

- *SG-1: Estimate maximum and average groundwater velocities produced by the UVB system*

The maximum groundwater velocity was calculated between wells W2 and PW1 and between wells W2 and PW3. The average groundwater velocity could not be calculated because the maximum dye concentration peak did not occur during the study period. The prolonged period of dye breakthrough is probably due to attenuation of the dye in the aquifer. Dye breakthrough occurred between wells W2 and PW1 (a distance of 35.18 feet [10.7 m]) in 46 or 47 days. The maximum groundwater velocity is thus calculated to be between 0.75 and 0.76 feet/day (2.65×10^{-4} and 2.68×10^{-4} cm/s). Dye breakthrough between wells W2 and PW3 confirms the maximum groundwater velocity estimate. The maximum groundwater velocity between W2 and PW3 (a distance of 45.30 [13.8 m] feet in 59 days) is 0.77 feet/day (2.72×10^{-4} cm/s).

- *SG-2: Quantify selected aquifer characteristics*

The hydraulic conductivity between wells W2 and PW1 (Kh1) and between wells W2 and PW3 (Kh2) is calculated in the following equation:

$$K = \frac{ve}{i}$$

Where:

K = hydraulic conductivity
v = groundwater velocity (0.75 and 0.77 feet/day [2.65 x 10^{-4} and 2.72 x 10^{-4} cm/s] from SG-1)
e = formation porosity (25 percent [TETC 1994])
i = hydraulic gradient (0.014 April 1993 average gradient [TETC 1994])

For wells W2 and PW1:

K_{h1} = (0.75 feet/day [2.65 x 10^{-4} cm/s])(0.25)/(0.014)
K_{h1} = 13.39 feet/day or 100.4 gpd/ft^2 (4.72 x 10^{-3} cm/s)

For wells W2 and PW3:

K_{h2} = (0.77 feet/day [2.72 x 10^{-4} cm/s])(0.25)/(0.014)
K_{h2} = 13.75 feet/day or 103.1 gpd/ft^2 (4.85 x 10^{-3} cm/s)

These measured values are only slightly higher than the previously calculated average site Kh value of 90.5 gpd/ft^2 (4.26 x 10^{-3} cm/s) (TETC 1993), and the measured values compare favorably within the same order of magnitude estimate. The higher conductivity value obtained in this study may reflect preferential flow in the downgradient direction. An estimate of the aquifer transmissivity is calculated for a saturated thickness of 75 feet (22.9 m) using the following equation:

T = Kb

Where:

T = transmissivity
K = hydraulic conductivity (100.4 and 103.1 gpd/ft^2 [4.72 x 10^{-3} and 4.85 x 10^{-3} cm/s] from SG-2)
b = saturated thickness (75 feet [22.9 m])

For wells W2 and PW1:

T = (100.4 gpd/ft^2 [4.72 x 10^{-5} m/s])(75 feet [22.9 m])
T = 7,530 gpd/ft (1.08 x 10^{-3} m^2/s)

For wells W2 and PW3:

T = (103.1 gpd/ft^2 [4.85 x 10^{-5} m/s])(75 feet [22.9 m])
T = 7,732.5 gpd/ft (1.11 x 10^{-3} m^2/s)

These estimates are close to the previous calculations average site value of 6,800 gpd/ft (9.75 x 10^{-4} m^2/s) (TETC 1993). The previous estimates based on the pump test of well 31OW1 may reflect the average transmissivity of the aquifer. The estimates obtained under the dye trace study may reflect preferential flow in the downgradient direction.

A.5 References

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Appendix AA
Estimation of Aquifer Characteristics

The MARCH AFB, SITE 31, AQUIFER TESTING (TETC 1993) report contained data for a pumping test in observation well 31OW1. Well 31OW1 was pumped at a constant rate of 8 gallons per minute (gpm) (30.3 liters per minute). After 1,212 minutes of pumping, well 31OW1 went dry at approximately 32 feet (9.8 meters) of drawdown. Within that time frame, identifiable drawdown was observed in adjacent wells 31PW1 (50 feet (15.2 meters) north of the pumped well) and 4MW14 (almost 64 feet (19.5 meters) northwest of the pumped well).

Using the hydrogeologic parameters from the pump test conducted at Site 31 and the distance-drawdown method, the radius of circulation cell was estimated to be about 60 feet (18.3 meters). The distance-drawdown method is a modification of the Jacob straight line method to determine the distance at which a pumping well does not affect the water level. This method is based on the Theis equation and is valid for long pumping times and nearby wells.

The distance-drawdown method averages the differences of hydraulic conductivity measured in the wells due to aquifer anisotropy and provides an estimate of the radius of circulation cell under average conditions in the aquifer. A distance-drawdown plot was drawn based on drawdown and recovery data from the pump test of well 31OW1 and using wells 4MW14 and 31PW1 as observation wells (TETC 1993). Using the distance-drawdown method, the observed drawdown was plotted on an arithmetic scale with distance plotted on a logarithmic scale. A best fit straight line was drawn through the data points until it intercepted the zero drawdown line. The 60-foot (18.3-meter) estimate is considered approximate due to variations in the observed drawdown data caused by aquifer anisotropy.

Appendix AB
Dye Concentration Calculations

The equation for calculation of dye volume is:

Dye Volume=
(Final Concentration)Water Volume to be Dyed)
(Dye Concentration)(Dye Specific Gravity)

Assume volume of water to be dyed is 60.000 cubic feet (ft3) (1,699.2 cubic meters).

60,000 ft^3 x 7.48 gallons/ft^3=448.800 gallons
(1,699.2 cubic meters x 1,000 liters per cubic meter= 1,699,200 liters)

Assume final concentration is 10 micrograms per liter= 1 X 10^{-8}

The specific gravity of rhodamine WT, 20 percent solution, is 1.19; the specific gravity of fluorescein, 7.5 percent solution, is 1.050.

For rhodamine WT, 20 percent solution:

Dye Volume=
(1 x 10^{-8})(448,800 gallons [1,699,200 liters])
(0.20)(1.19) =

0.0189 gallons (0.0714 liters)

Assume only 1 percent is recovered; 100 x dye volume = 1.89 gallons (7.1 liters)

For fluorescein, 7.5 percent solution:

Dye Volume=
(1 x 10^{-8})(448,800 gallons [1,699,200 liters])
(0.075)(1.050) =

0.0570 gallons (0.2158 liters)

Assume only 1 percent is recovered: 100 x dye volume = 5.7 gallons (21.6 liters)

Appendix B1
In Situ Groundwater Remediation: Pilot Study of the UVB-Vacuum Vaporizer Well, March Air Force Base, California

INTRODUCTION -

The Unterdruck-Verdampfer-Brunnen (UVB) technology (roughly translated to Vacuum Vaporizer Well) is an in-situ system for groundwater remediation, particularly for aquifers contaminated with volatile organic compounds (VOC). The UVB system was developed and patented by IEG mbH, Reutlingen, Germany, and is now being demonstrated and used in the United States.

In conjunction with the technology developer (IEG Technologies Corporation), Roy F. Weston, Inc. (WESTON) has completed an 18-month demonstration program of the UVB system at March Air Force Base (AFB), Riverside, California under subcontract to Black & Veatch Waste Science, Inc. The system has been demonstrated for March AFB, the U.S. Environmental Protection Agency, Office of Research and Development (USEPA ORD) under the Superfund Innovative Technology Evaluation (SITE) Program, and the U.S. Army Corps of Engineers, Omaha District who is administering the innovative technology program for March AFB. This is the first application of the UVB system at a federal facility.

STUDY OBJECTIVES

March AFB is committed to the testing of innovative technologies for remediation of contaminants found on the base. The primary objective of the study was to evaluate the feasibility of the UVB system for removal of chlorinated hydrocarbons (primarily trichloroethene (TCE)) from the groundwater, and to evaluate cost effectiveness of the treatment.

SITE DESCRIPTION

March AFB is located east of the City of Riverside, Riverside County, California, approximately 60 miles east of Los Angeles. The study was conducted at Site 31 (Unconfirmed Solvent Disposal), Operable Unit 1 (Figure 1).

Site 31 is underlain by fine-grained sediment dominated by fine-grained sand and silt. As is typical of alluvial and fluvial deposits, individual lithologic units tend not to be laterally continuous. Based on lithologic logs available from this and previous site studies, the following generalized alluvial sequence underlies Site 31: fine sandy silt to clayey silt and silty fine sand to depths of about 40-50 feet below ground surface (bgs); relatively continuous interval of clean sand (i.e., containing few fines) to about 50-60 feet bgs; interbedded silt, sand and minor clay extending to weathered granitic basement rock.

The first occurrence of saturated soil is reported in most boring logs between approximately 45-55 feet bgs. Dry to slightly moist conditions were reported between approximately 100-120 feet bgs in 31MW1. This fine-grained interval is considered a barrier to the vertical flow of groundwater in this location and, at least locally, appears to separate the alluvial aquifer into two zones. This interpretation is further supported by a groundwater elevation head differential between 31MW1 and adjacent 4MW14 of approximately 4.5 feet. The depth to weathered granitic basement rock is irregular, ranging from approximately 30-160 feet bgs across the site.

The hydrogeologic conditions at Site 31 are fairly complex and hydraulic parameters appear to vary widely in both vertical and horizontal directions. Depth to groundwater in developed wells is approximately 40 feet bgs. Groundwater flow direction across the site is predominately toward the south at an average gradient of approximately 0.007 feet/foot. Based on aquifer test results conducted on

monitoring wells 31OW1 and 31PW1, the following average hydraulic parameters are calculated (Earth Technologies Corporation, 1994):

- Hydraulic conductivity (k) — 90.5 gpd/ft^2 (average Site 31 value)
- Hydraulic gradient (i) — 0.007 (December 1994 average condition)
- Effective porosity (n_e) — 27.2%
- Transport velocity (V) — 0.31 ft/day

TECHNOLOGY DESCRIPTION

The UVB technology uses a system of chemical, physical, and biological processes to treat VOC-contaminated groundwater and subsurface soils. The UVB system consists of a specially adapted groundwater treatment well, a negative pressure stripping reactor, an aboveground vacuum extraction blower, and an off-gas treatment system if necessary (e.g., activated carbon adsorption units)(Figure 2). The UVB treatment well is constructed with two screened zones: one section which is placed at the bottom of the treatment interval, and one section which straddles the groundwater interface. The borehole annulus between the two screened zones is sealed with bentonite. A packer is installed in the treatment well between the two screened zones to ensure one directional flow of the groundwater through the treatment well. A pipe is placed through the packer and connected to a pump which provides groundwater from the lower zone to the upper zone where the stripper reactor is situated. The upper end of the pipe terminates at the reactor.

The upper, closed part of the well, is maintained at below atmospheric pressure by a centrifugal blower. The air for the in-situ stripping is drawn in through a 3-inch diameter fresh air pipe: the upper end is open to the atmosphere, and the lower end terminates in a pinhole plate (diffuser) located in the reactor. Soil air is also drawn into the treatment well from the vadose zone through the upper well screen. The negative pressure within the upper part of the well also causes a water level rise within the treatment well.

The stripper reactor is balanced below the groundwater level within the treatment well and is free-floating to allow for changing water levels. The location of the reactor with respect to the water level in the well determines the ratio of air that is drawn from the atmosphere through the air intake pipe, to the air that is drawn into the well from the vadose zone through the upper screen. This also controls the air to water ratio within the stripper reactor since only the air drawn from the surface through the air intake pipe is directed to the pinhole plate in the stripper reactor. Balancing of the system within the well is achieved by installing buoyancy tanks below the pump.

The zone within the well between the pinhole plate and the water surface is the stripping zone, in which an air bubble flow develops and strips VOCs from the groundwater. The rising air bubbles produce an air lift pumping effect, which moves the water, and causes a suction effect at the bottom of the well. Stripped air from the groundwater, and extracted soil gas, is transported up through the casing and blower, for treatment, if necessary, before venting to the atmosphere.

The upward-streaming, stripped groundwater leaves the well casing through the upper screen section of the treatment well. The mass of flowing groundwater leaving the upper screen is counterbalanced by the flow of groundwater toward the lower screened section, thereby setting up a three-dimensional groundwater circulation cell around the UVB well. Contaminated groundwater flows toward the well

through the lower screen and is moved up in the treatment well to the stripping zone by the action of the pump as well as the air lift effect. The water is stripped of VOCs, and is returned to the groundwater flow regime through the upper screen. The artificial groundwater circulation cell established by the UVB system is superimposed over the natural groundwater flow surface, and results in a three-dimensional flow regime around the UVB well.

Treatment Well Construction

Prior to installation of the UVB treatment well, a pilot soil boring was installed using the dual-tube percussion drill rig to a depth of 118.5 ft bgs to collect soil samples and obtain lithologic information. The pilot boring was partially sealed with bentonite upon completion. The UVB treatment well was then drilled at the location of the pilot boring to a total depth of 87.5 feet using a 26 inch bucket-auger drill rig.

Figure 2 shows the construction details of the UVB treatment well. The well is 16 inches in diameter and consists of two screened sections separated by blank mild steel casing. The lower (influent) screen section is comprised of 12 ft of steel bridge-slot casing, while the upper (effluent) screen section is comprised of three feet of bridge-slot casing with an additional 12 ft of double-cased stainless steel screen which is filled with 3/8-inch Teflon beads.

Within the annulus of the borehole, three 2-inch PVC monitoring wells with stainless steel screens were installed. One well (W1) is screened at approximately the same interval as the influent portion of the treatment well, to allow collection of groundwater samples specific to the influent portion of the treatment cell. The two remaining monitoring wells within the annulus (W2 and W3) are both screened between 40-55 feet bgs. These wells were installed to allow collection of groundwater samples specific to the effluent portion of the treatment well. Wells W2 and W3 were installed at the same depths and at 180° from each other.

Treatment Well Internal Components

Virtually all of the down-hole components of the UVB treatment well including the double-wall stripper reactor, pinhole (diffuser) plate, internal centralizers, and piping are made of high density polyethylene (HDPE), with the exception of the upper 40 feet of the 3-inch diameter fresh air intake pipe, which is made of aluminum. The use of HDPE minimizes the number of metal pieces that would corrode while being submerged in groundwater over extended periods of time.

The pump used in the UVB treatment well is a Grundfos KP 300 MI submersible pump equipped with a 15 mm orifice flow restrictor to provide a consistent upward flow within the well. The calculated pump rate is approximately 22 gpm. The entire set of UVB down-hole components (except for the packer) is free-floating and can adjust to fluctuations in groundwater elevations.

Aboveground Treatment System Components

Figure 3 shows the layout of the aboveground UVB system installed at Site 31. The entire system is enclosed by a chain-link fence equipped with a locking gate. The blower is located adjacent to the UVB well-head and the suction side of this blower is connected to the 16-inch well casing via a 4-inch HDPE pipe to create a vacuum in the casing. The blower is mounted on a moisture knockout drum. No accumulation of liquid has occurred during the study. Four-inch diameter PVC pipe is used to connect the discharge side of the blower to two 1800-lb vapor phase carbon canisters. Four sampling/monitoring ports (V1 through V4) are installed within the aboveground airstream piping network (Figure 3).

"CAPTURE ZONE" COMPUTATION

The UVB creates a complex, three-dimensional groundwater circulation cell with a flow pattern having a vertical component in addition to horizontal flow. The UVB "capture zone" and size of the three-dimensional groundwater circulation cell have been estimated using equations and graphical solutions developed over several years by Dr. Bruno Herrling of the Groundwater Research Group, Hydromechanics Institute, University of Karlsruhe, Germany. A discussion of the geometry created around a UVB and the assumptions used in the model is provided in Herrling, et al. (1991).

Based on the following hydraulic parameters and well specifications, the upstream and downstream stagnation points, the distances B_B and B_T and cross-sectional UVB "capture zone" area, and the spacing requirements for additional UVB's have been estimated.

i	=	0.007	(hydraulic gradient)
k_H	=	4.3×10^{-5} m/s	(horizontal hydraulic conductivity)
k_V	=	4.3×10^{-6} m/s	(vertical hydraulic conductivity)
V	=	3×10^{-7} m/s	(Darcian velocity)
H	=	13.72 m	(thickness of treatment zone)
Q	=	5 m^3/hr	(discharge through the UVB)
a_T	=	4.2 m	(length of upper screen section)
a_B	=	3.6 m	(length of lower screen section)

Using the corresponding dimensioning diagrams from Herrling et al., the following values were obtained for the UVB at Site 31:

S	=	34.3m (112 ft.)	(distance to the upstream and downstream stagnation points from the well axis)
B_T	=	27.4m (90 ft.)	(capture width at the top of the aquifer)
B_B	=	106.3m (349 ft.)	(capture width at the bottom of the aquifer)
A	=	1,176m^2 (12,660 $ft.^2$)	(cross sectional area of UVB "capture zone")
D	=	72m (236 ft.)	(predicted spacing distance between UVBs for most efficient plume capture)

The width at the top and bottom of the capture zone is calculated for a distance five times the stagnation point upstream of the UVB. In plan view, the radial distance of the circulation cell perpendicular to flow is calculated using the equation $B_T+B_B/4$. This equation yields a plan view radial distance for the circulation cell of approximately 110 feet. The result of this analysis is shown on Figure 4.

MONITORING AND SAMPLING PROGRAM

The monitoring and sampling program designed to generate data necessary for evaluating the treatment effectiveness consisted of the following major elements:

- Pilot boring and soil sampling.
- Baseline (pre-startup) groundwater sampling.
- Operational monitoring.
  - Air monitoring and sampling.

- Treatment well groundwater sampling.
- Perimeter wells groundwater sampling.

Sampling and analytical procedures were performed following stringent methods outlined in the Quality Assurance/Quality Control Plan and Sampling and Analysis Plan developed and approved for this project.

Pilot Boring and Soil Sampling
The pilot boring was drilled using a dual-tube percussion drill rig equipped with a down-hole hammer and California-modified split-spoon samplers. Soil samples were collected virtually continuously for the following objectives:

- Geotechnical analysis.
- Chemical analysis.
- Microbiological analysis.
- Lithologic description and field screening.

Baseline Groundwater Sampling
Groundwater samples were collected prior to system startup from wells scheduled to be used for the long-term monitoring to establish baseline chemical conditions. A wide range of chemical analyses were performed including VOC, metals, general minerals and water quality parameters. Baseline samples were not collected from 31PW1, PW7, or PW8 which were added to the monitoring network after startup.

Operational Monitoring
The 18-month operational monitoring consisted of air monitoring and sampling, treatment well groundwater sampling, and perimeter wells groundwater sampling.

Air Monitoring and Sampling. The primary objectives of the air monitoring, sampling and analysis program were to monitor the system operating parameters, to evaluate the removal rates of VOC's from the groundwater, and to evaluate the efficiency of the off-gas treatment units. This consisted of recording air flow parameters including linear flow velocity, relative humidity, temperature, vacuum/pressure, and relative VOC concentrations at the air intake pipe and at four ports installed in the above-ground airstream piping. Air samples were also collected primarily from port V2 and V3 (Figure 3) for laboratory analysis of VOC concentrations.

Treatment Well Groundwater Sampling. Groundwater samples were collected frequently (approximately 165 rounds) from the two-inch diameter monitoring wells affixed to the UVB treatment well. Concentrations in these wells (W1 and W3) are considered to represent the influent and effluent groundwater conditions, respectively. Initially, sampling frequency was very rapid at startup, reducing to twice per week months 2-6, and finally to biweekly for the following 12 months.

Analysis consisted of VOC's on every sample, as well as six rounds for alkalinity, nitrogen, phosphate, BOD, COD and carbon dioxide, and three rounds for microbiological analysis. Field parameters (temperature, specific conductance, pH and dissolved oxygen) were also recorded on each sample round.

Perimeter Wells Groundwater Sampling. Perimeter wells were sampled for VOC analysis monthly for the first six months, and bimonthly for the following 12 months. Field parameters (temperature, specific conductance, pH and dissolved oxygen) were also recorded on each sample round.

RESULTS AND DISCUSSION

Pilot Boring and Soil Sampling

The most significant results of the pilot boring and soil sampling was the lithologic logging. The identification of very low permeability sediments below approximately 85 feet bgs within what is still considered the upper water zone influenced the well construction. The ability of the UVB to drive vertical circulation through a thick interval of low hydraulic conductivity sediments is limited. Therefore, the well was constructed above 85 feet to ensure that a circulation cell would be created.

Although the results of the geotechnical and chemical analyses assisted in further defining site soil characteristics, these results did not contribute significantly to the evaluation of the UVB groundwater treatment and are not presented here.

Baseline Groundwater Sampling

The VOC analyses showed TCE concentrations ranging from 3.4 μg/l to 1,000 μg/l in samples obtained from the perimeter wells. Except for monitoring well 31MW1 (3.4 μg/l), the TCE concentrations ranged between 160 μg/l and 940 μg/l (Table 1). The presence of a relatively lower TCE concentration in monitoring well 31MW1 supports the earlier finding that the groundwater within the alluvial aquifer at Site 31 occurs in two zones. TCE concentrations of 6.4 μg/l and 33.0 μg/l, respectively, were found in the groundwater samples collected from the monitoring wells attached to the treatment well (W1 and W3). A possible explanation for relatively low TCE concentrations (compared to perimeter wells) in these samples is that water was used during well installation, which may have contributed to temporary dilution of actual groundwater concentrations.

Operational Monitoring - Air Monitoring and Sampling

System Operating Parameters. Figure 5 is a graphical representation of the airstream flow data measured at sample ports INTAKE and V2 as a function of time. These points represent the volume of air entering the treatment well and used in air stripping (INTAKE), and the volume of air being discharged by the blower (V2), which is a combination of intake air and air removed from the unsaturated zone through soil vapor extraction.

The fluctuation in flow rates recorded in a few rounds in the first few days after start-up is attributed to equipment malfunction or operator error and are not considered to represent actual flow conditions. The very low flow rates measured at the INTAKE in the initial seven weeks is attributed to the method used for measuring air flow. Following modification to the INTAKE air monitoring port as shown on Figure 5, the air flows at port V2 correlate very closely with air flows at the INTAKE port, indicating that little to no air flow was occurring from the vadose zone. Since the UVB well is not located within an area of soil contamination, soil vapor extraction was not performed during this pilot study.

Air Sampling Results. Air samples were collected from the four sample ports located on the aboveground components of the system. The compounds detected in the air samples included: acetone, benzene, 2-butanone, carbon disulfide, carbon tetrachloride, chloroethane, chloromethane, dichloromethane, ethylbenzene, styrene, toluene, trichloroethane, trichloroethene, tetrachloroethene, tetrachlorofluoromethane (F-11), and xylenes. The following trends were observed in the air analytical data:

- Total VOC concentrations in the airstream peaked at 825.6 μg/cu.m a few days following startup,

then stabilized at low concentrations between 1.3 to 75.7 μg/cu.m after approximately one month of operation.

- The chlorinated compounds chloroethane, chloromethane, dichloromethane, PCE, 1,1,1-TCA, and TCE were detected in the groundwater and in the airstream.

- The overall concentrations of VOCs within the air stream are much lower than was calculated based upon anticipated removal rates from the groundwater.

- The highest VOC concentrations were from BTEX compounds which are not thought to be associated with the groundwater at Site 31. Since the treatment well is located near an active runway, the elevated BTEX concentrations most likely reflect ambient conditions.

- Sample ports V1 and V2 showed consistent results for sampling rounds where both samples were collected, indicating that samples collected from either sample port are indicative of the air concentrations being extracted from the UVB well.

Operational Monitoring - Treatment Well Groundwater Sampling

The TCE analytical results for groundwater sampling performed at the UVB treatment well are plotted on Figure 6. Samples from well W1 are representative of the groundwater conditions in the lower, or influent well screen, and samples from well W3 are representative of treated groundwater exiting the UVB well in the upper well screen.

Influent TCE concentrations, as measured at well W1, have varied between non-detect and 320 μg/l throughout the pilot study. The highest influent concentrations, as well as the highest variability in influent concentrations, occurred during the first five months of operation. This time frame corresponds to the highest concentrations in the adjacent monitoring wells. The influent concentration peaks observed during the 19-month pilot study probably reflect the inhomogeneity in the distribution of TCE entering the treatment cell from upgradient areas.

For the most part, the effluent concentrations, as measured at well W3, have varied between non-detect and 15 μg/l throughout the study. Eight anomalous peaks in the effluent concentrations are exceptions (Figure 6). These peaks in the effluent concentrations are explained as follows:

- Peaks 1, 2, and 3 are single sample occurrences corresponding to low concentrations in monitoring well W1. It is suspected that the samples collected during these sample rounds were inadvertently switched between wells W1 and W3.

- Peaks 4 and 5 are suspected to be a response to system maintenance performed prior to those sampling events. This interpretation is based solely on the coincident occurrence of the maintenances and anomalous peaks, and not on a predicted theoretical basis. Unlike the single sample anomalies discussed above, the concentration data for these two peaks are comprised of several sampling rounds conducted over 1-2 weeks.

- Peaks 6 and 7 occurred following the development of a hole in one of the buoyancy tanks of the UVB system. This occurrence caused the system to ride lower in the water thereby reducing, or eliminating, intake air flow and subsequent air stripping. Based on the groundwater sample data

- and air flow data, the hole developed sometime following the maintenance conducted on January 10/11, 1994, but prior to the February 3, 1994 sample round. The damaged buoyancy tank was discovered and replaced on 17 May 1995.

- Peak 8 occurred in early November 1994, following the system being shut down from October 26, 1994 to November 3, 1994 to allow for drilling beneath the power lines.

Disregarding the data from these anomalous peaks in the effluent concentrations, a comparison of influent TCE concentrations to the effluent TCE concentrations for the stripper unit indicates that a TCE removal percentage of greater than 90% was achieved in 95% of the sample rounds and a TCE removal percentage of greater than 95% was achieved in approximately 77% of the sample rounds. It is evident from this data that the UVB vacuum vaporization well is effectively treating the groundwater (removing TCE) across the system. The UVB system effluent TCE concentrations as measured at monitoring well W3 were below the Federal MCL of 5 µg/l in 85% of the samples.

Operational Monitoring - Perimeter Wells Groundwater Sampling

Results of the groundwater TCE analyses for both the treatment and perimeter monitoring wells are shown on Figure 7. For monitoring wells PW1 through PW6, data generated by PRC Environmental Management, Inc. is also plotted. PRC was retained by the EPA SITE Program to perform field sampling and technical analysis for this project.

Several important trends are evident from review of the TCE plots and the summary concentration data on Table 1.

- The final TCE concentrations in wells that are both within the treatment cell, and have sufficient data available to establish a trend, are lower than their initial concentrations. These wells include PW1, PW2, PW4, PW5, 4MW14, and 31OW1.

- The concentrations in wells considered most affected by the UVB (PW1, PW2, PW4, PW5, 4MW14, and 31OW1) showed a marked increase following startup, followed by decrease after several months of operation. Similar trends have been observed in previous UVB groundwater remediation programs and have been attributed to mobilization of contaminants from the pore spaces, particularly in the capillary fringe (Herrling et al., 1991). The increase and subsequent decrease is delayed from PW1 to PW4 (and from PW2 to PW5) which reflects the increased travel time as the treatment cell expands over time.

- Wells screened deeper than the treatment interval (PW3, PW6, and 31MW1) do not appear to be affected by the UVB.

- Well 31MW4 is considered laterally outside of the capture zone as evident by fairly consistent TCE concentrations.

- The monitoring well data is generally consistent with the capture zone model computation results. Based on a comparison of Figures 4 and 7, it is evident that monitoring wells PW1, PW2, PW4, PW5, PW7, PW8, 4MW14, 31PW1, and 31OW1 are located within the treatment zone. Monitoring wells PW3, PW6, and 31MW1, are screened below the treatment interval. Monitoring well 31MW4 is laterally outside of the treatment zone.

- An average TCE reduction of greater than 60% occurred in the monitoring wells which have data available prior to system startup and are within the treatment zone (Table 1).

Mass Removals - The Mass Balance

The mass of VOCs removed from the groundwater was estimated by comparing the UVB well groundwater influent concentrations to the effluent groundwater concentrations. The concentration of VOCs removed multiplied by the average water flow through the stripping reactor (based on the pump performance) resulted in an average removal rate for TCE from the groundwater to be on the order of 10 grams per day. The mass of VOCs collected in the air stream was determined by multiplying the air sample concentrations by the average air flow rate, assuming that all the air flow was from the ambient air intake pipe and no air flow was from the vadose zone. This resulted in an average removal rate for TCE, as collected in the air stream, to be on the order of 0.1 grams per day.

This mass balance estimate shows at least an order-of-magnitude difference between the water and the air side of the mass balance equation. That is, the mass balance estimate shows that the amount of TCE entering and not leaving the UVB system through the water side, can not be accounted for by detailed monitoring of the TCE being removed on the air side of the system. The assumption associated with this analysis is that there are only two compartments to the mass balance. Based on these results, it is suspected that the simple two-compartment conceptual model for TCE removal by air stripping as the primary treatment mechanism may be overly simplified and should be further evaluated.

CONCLUSIONS

An 18-month demonstration project of the UVB Vacuum Vaporizer Well technology has been completed at Site 31, March AFB. The primary objective of the study was to evaluate the feasibility of the UVB system for removal of chlorinated hydrocarbons from the groundwater. The monitoring and sampling program designed to generate data necessary for evaluating the system effectiveness consisted of soil sampling, baseline groundwater sampling, air monitoring and sampling, and treatment and perimeter groundwater monitoring well sampling. Conclusions derived from analysis of the data are as follows:

- Except for the scheduled maintenances, the system operated without interruption for the entire 18 months.
- During normal operating conditions, TCE removal of greater than 95% was achieved.
- Effluent TCE concentrations were below the Federal MCL in 85% of the samples.
- Final perimeter well TCE concentrations for those wells within the treatment zone are lower than their initial concentrations.
- Perimeter well TCE concentrations for those wells within the treatment zone showed a marked increase in the first few months of operation. These results are attributed to mobilization of contaminants from the pore spaces, particularly in the capillary fringe.
- Capture zone evaluation using Herrling's model estimated the radius of the treatment cell at approximately 110 feet.
- Perimeter well results validated the calculated treatment cell size.
- The calculated mass of contaminants removed from the groundwater and from the air samples is at least an order-of-magnitude off. It is suspected that additional treatment mechanisms other than air stripping may be performing a significant role in TCE removal.

Table 5-4 Summary of Monitoring Well Results

Well Number	Screened Interval (ft. bgs)	Initial TCE Conc. (ug/L)	TCE Conc. Range During Study (ug/L)	Final TCE Conc. (ug/L)	Percent Reduction (%)
31MW1	150-160	3.4	3.4-34	17[1]	-
31MW4	75-95	170	110-610	190	-
31OW1	60-80	940	150-1,000	150	84%
31PW1	50-90	[2]	48-140	64	-
4MW14	34-75	160	94-1,800	94	41%
PW1	37.5-57.5	400	45-1,500	45	89%
PW2	64.5-74.5	1,000	240-2,000	270	73%
PW3	90-105	130	130-310	250[1]	-
PW4	37-57	480	170-1,600	170	65%
PW5	68.25-78.25	270	210-760	210	22%
PW6	91-106	130	92-150	150[1]	-
PW7	35-55	[2]	58-120	58	-
PW8	35-55	[2]	67-98	67	-

Figure 1 - Site Layout Map

95-WP103.05

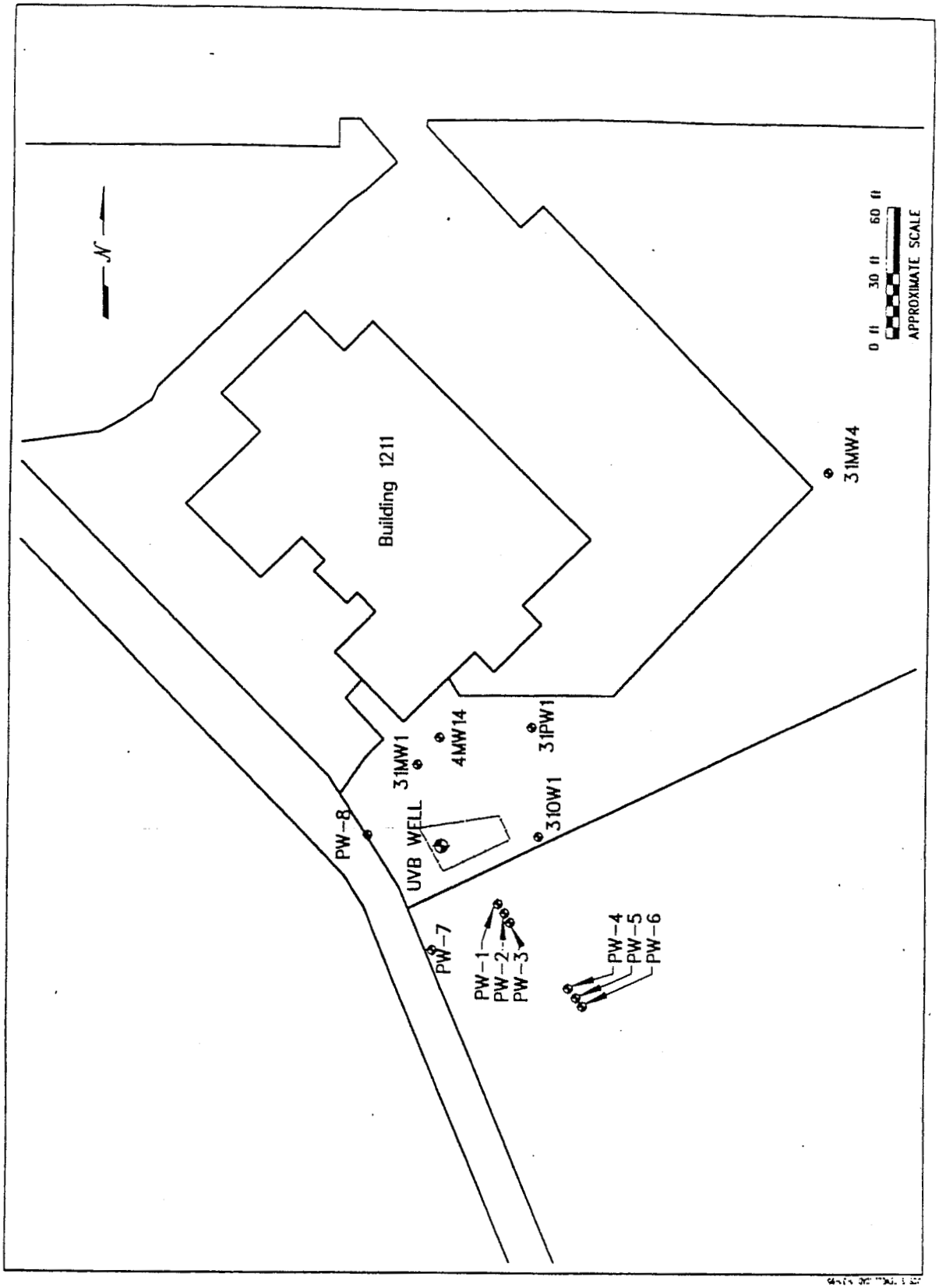


Figure 2 - UVB Vacuum Vaporizer Well Cross-Section.

95-WP103.05

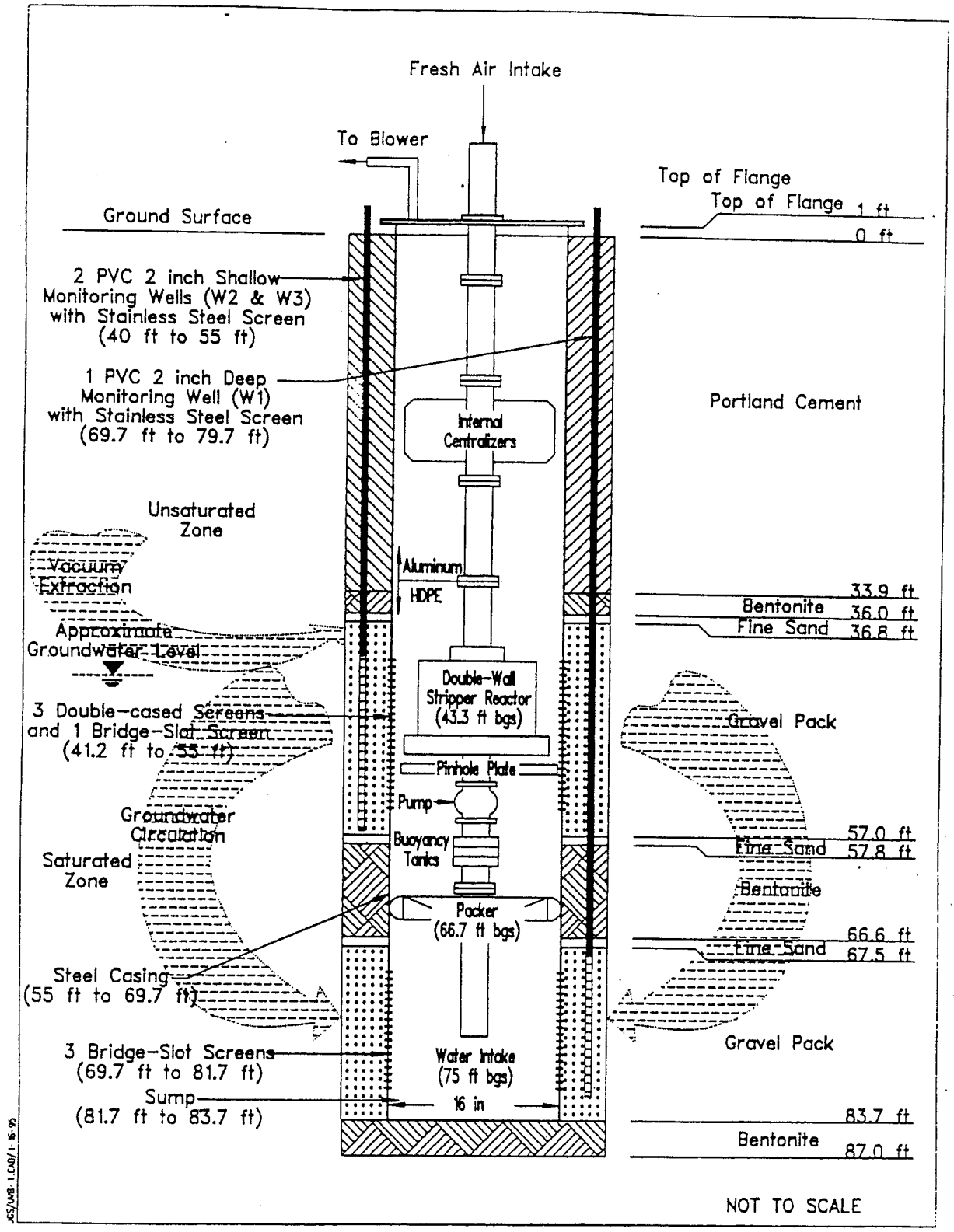


Figure 3 - UVB Vacuum Vaporizer Well System.

95-WP103-05

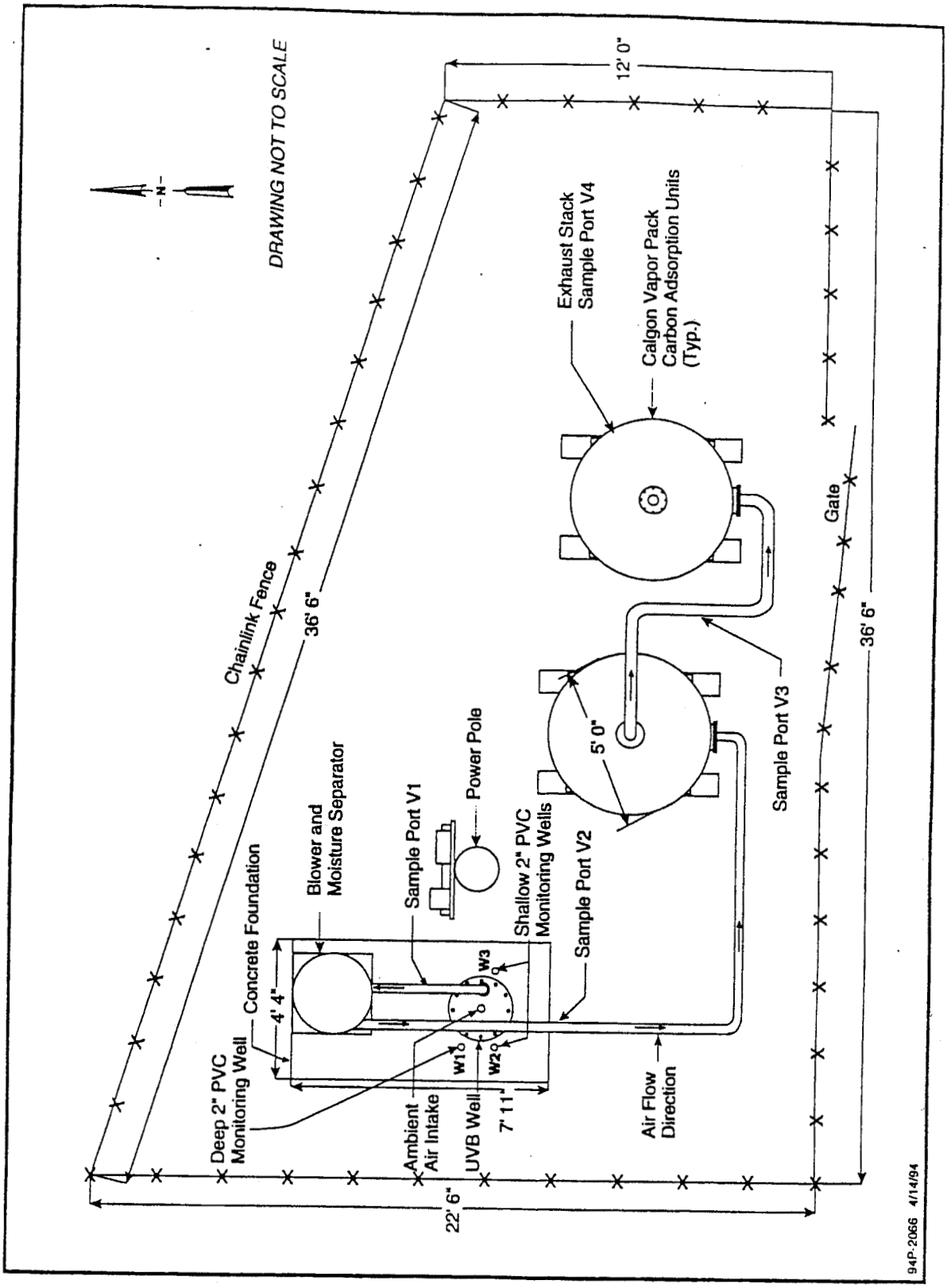


Figure 4 - UVB "Capture Zone" at Site 31.

95-WP103 05

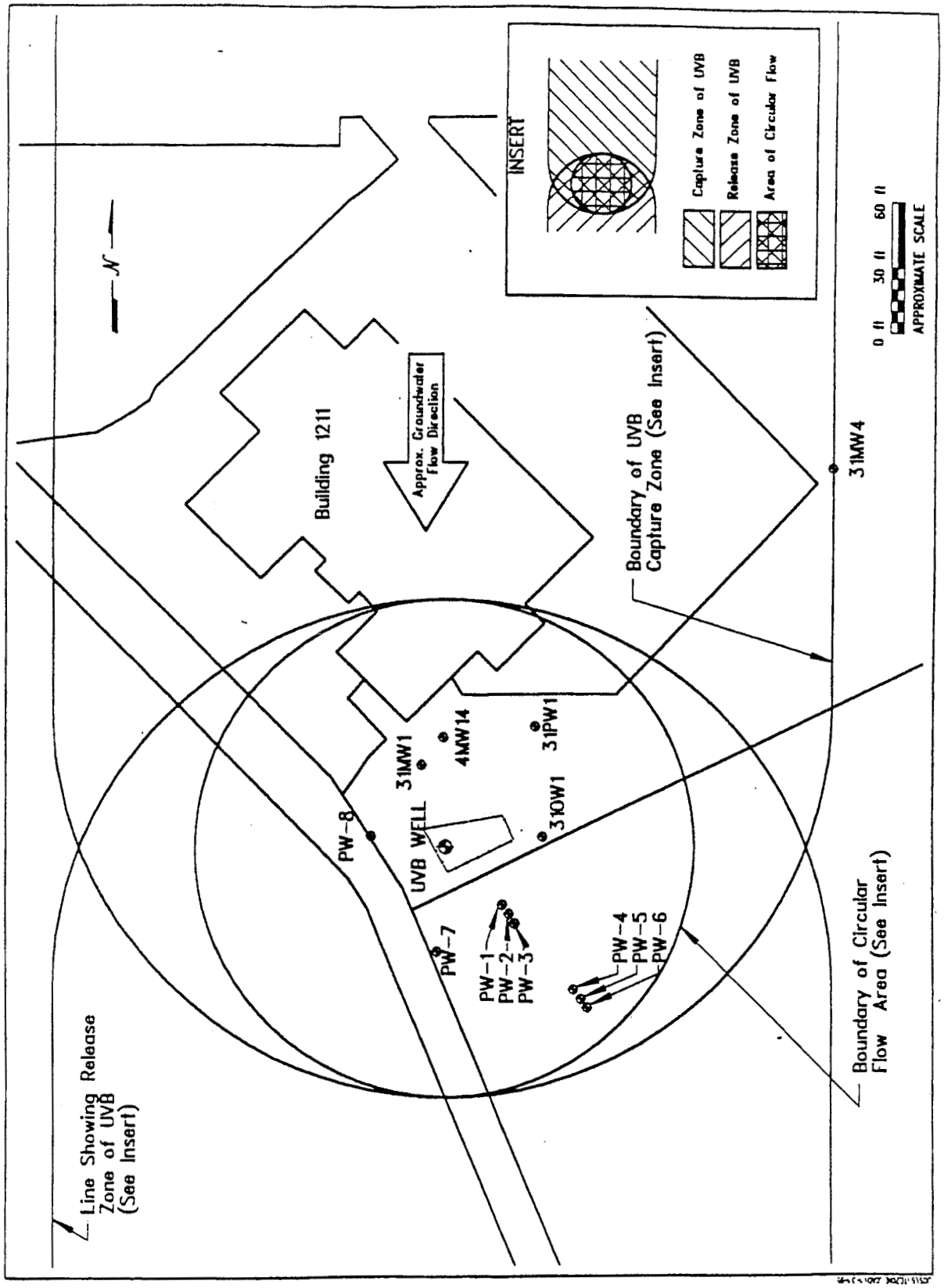


Figure 5 - Comparison of Air Flow Rates.

95-WP103-05

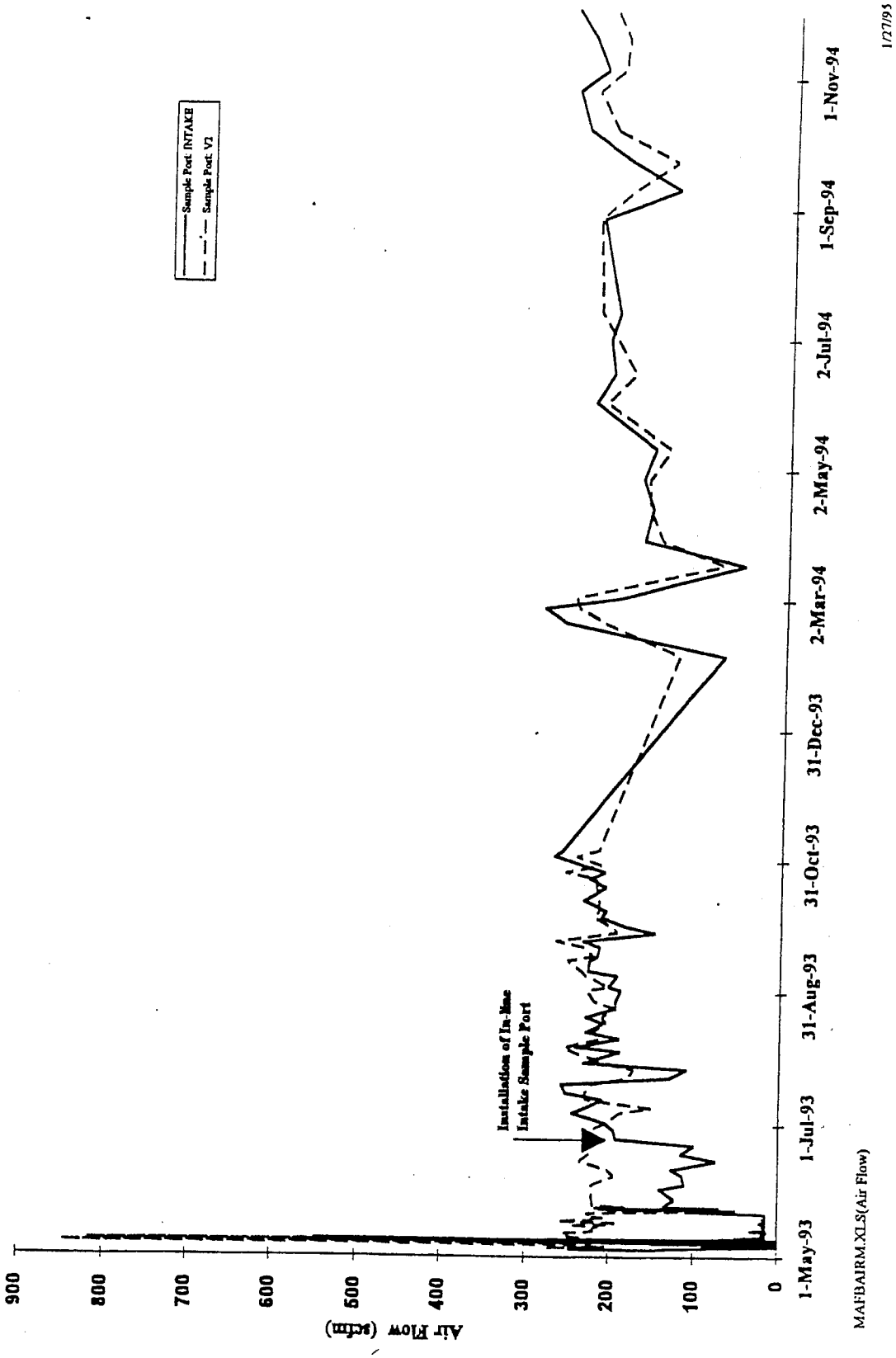


Figure 6 - Concentration of TCE During 18-Month Study in Wells W1 and W3. 95-WP103.

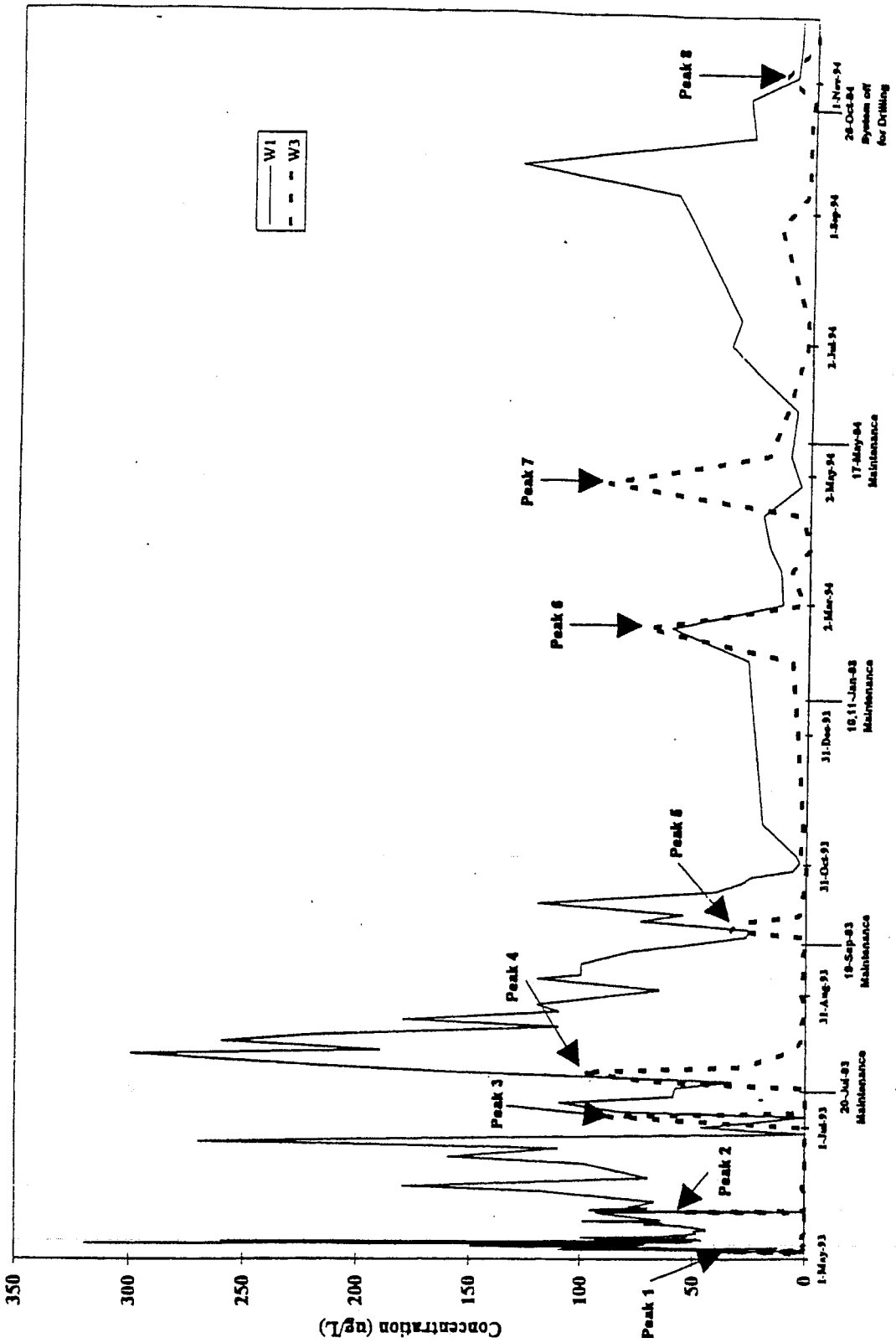
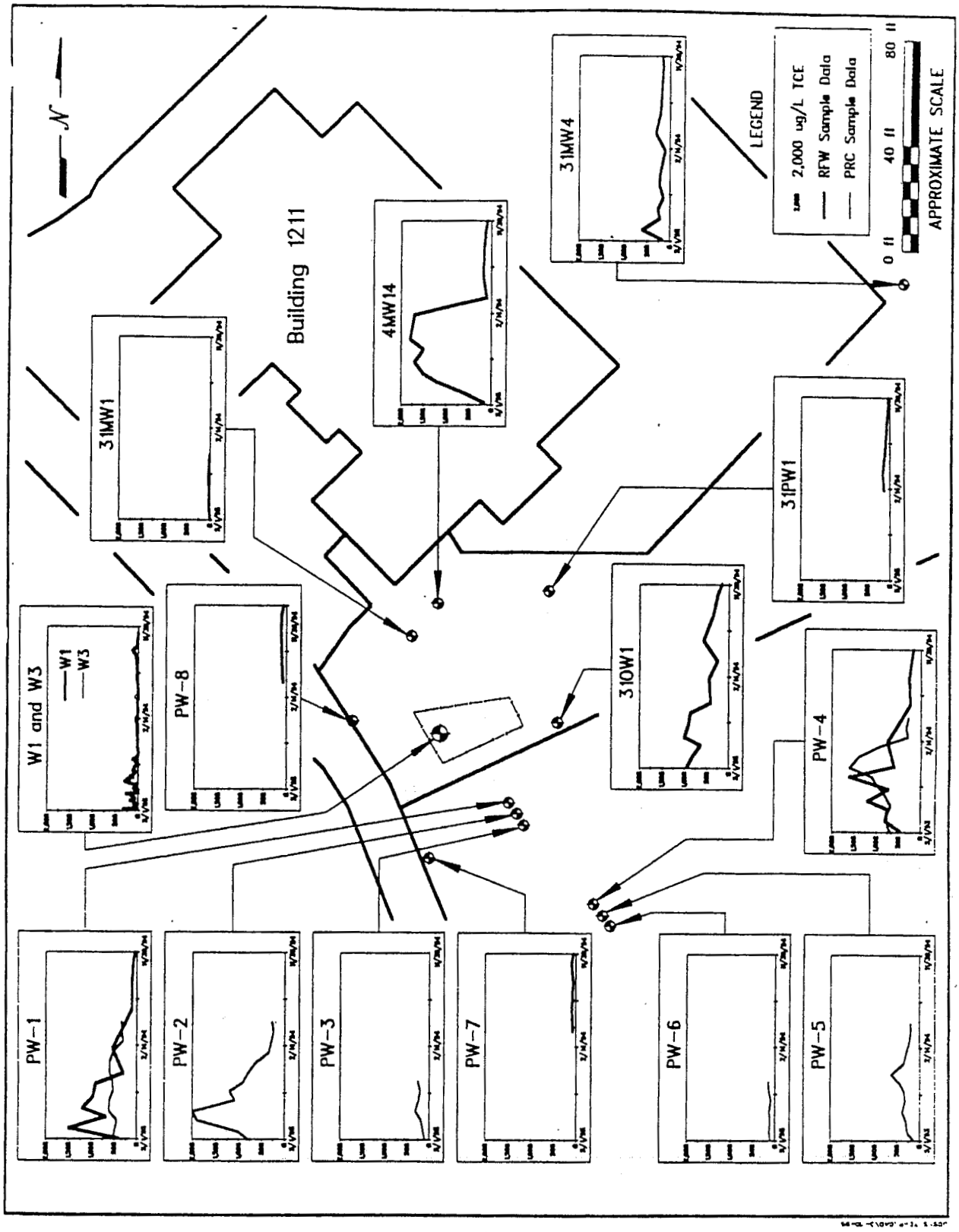


Figure 7 - Results of TCE Analysis in Treatment and Perimeter Wells.

95-WP103 05



Appendix B2
Case History of Hydrocarbon Remediation Using the UVB Technology at a UST Site in Troutman, North Carolina

CASE HISTORY OF HYDROCARBON REMEDIATION USING THE UVB TECHNOLOGY AT A UST SITE IN TROUTMAN, NC

by

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Abstract

UVB (German acronym for "Vacuum Vaporizer Well") is a patented in-situ remediation technology for the restoration of aquifers, the vadose zone, and the capillary fringe. The UVB technology can be applied to treat single- or multi-phase volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs). The UVB system uses a combination of physical and biological processes for the removal of organic contaminants. The UVB can be configured to simultaneously treat the saturated zone, capillary fringe, and/or vadose zone. The UVB is a true in-situ process in that there is no above-ground water treatment or discharge. Only the off air stream is vented at the surface.

Since its inception in 1986, the UVB technology has been applied at some eighty sights in Europe. The technology has achieved regulatory acceptance in the U.S. at both the state and federal levels. A UVB system was first installed at a U.S. site in September 1992. Currently, there are twenty-two UVBs installed and operating in eight states in the U.S. This paper describes the remediation progress using the UVB at an underground storage tank (UST) site in Troutman, North Carolina. After twenty-five months of operating the UVB at this site, the magnitude and extent of the dissolved petroleum hydrocarbon (BTEX) plume has been significantly reduced.

Introduction

UVB (Unterdruck Verdamfer Brunnen - German for Vacuum Vaporizer Well) is a patented technology that offers a number of variations for the treatment of adsorbed, dissolved, and free phase VOCs and SVOCs. (Patent held by IEG mbH, D-72770, Reutlingen, Germany.) It is highly adaptable to varying hydrogeologic conditions including confined and unconfined aquifers, and aquitards. Simultaneous treatment of the vadose zone, capillary fringe, and saturated zone is possible. At the present time in the U.S., twenty-two UVBs are operating in eight states.

Following a brief narrative on the basic system concept, a description of the treatment zone and monitoring results are presented for a UVB which has been operating for twenty-five months at a UST site in Troutman, North Carolina.

Basic System Concept

As shown in Figure 1, the UVB system consists of a specially adapted groundwater well with two separate screen sections, a groundwater treatment unit located inside the well casing (typically a "stripping reactor"), an above-ground mounted blower, and an optional off-air treatment system. The blower creates a reduced pressure within the air-tight well casing. Atmospheric air is introduced to the system, by virtue of the pressure differential, via a fresh air pipe which is open at the ground surface and connected to the stripping reactor located in the well casing. Fresh air is drawn through the fresh air pipe into the stripping reactor where it is directed to a sieve plate. As air bubbles migrate upward from the sieve plate, they strip the VOCs dissolved in groundwater passing through the stripping reactor. The off-air stream, which now includes vapor-phase contaminants, is brought to the surface by the blower and treated as necessary.

The rapidly expanding and rising air bubbles produce an air-lift pump effect which, together with the vacuum in the well casing, elevates the groundwater in the well and causes suction at the lower well screen. The subsequent fall of groundwater along the walls of the well produces an oscillating hydraulic pressure which forces the water horizontally through the upper screen into the aquifer. A portion of the treated groundwater eventually migrates from the upper screen to the lower screen by means of an extensive three-dimensional groundwater flow field. In the presence of a natural groundwater flow, a portion of the flow entering the well casing will be new upstream waters which have entered through the upstream capture zone. An equal portion leaving the well casing will exit the circulation cell through the downstream release zone. These flows and the dimensions of the capture zone, circulation cell, and release zone can be calculated using design aids based on numerical simulations of the groundwater hydraulics.

Aerobic biodegradation of organic contaminants is enhanced by the recirculation of oxygenated groundwater into the aquifer. The vadose zone and capillary fringe are remediated by virtue of their exposure to the upper screened section of the UVB well by soil flushing and soil vapor extraction mechanisms.

Case History: Troutman, North Carolina

A UVB 400 mm system (16 inch diameter well casing) was installed in September 1992 at a former retail gasoline facility in the Piedmont physiographic province in west central North Carolina. A site map depicting well locations and isopleths of total BTEX concentrations prior to UVB activation appear in Figure 2. The saturated regolith consists of saprolite from a depth of about 45 feet from land surface to the top of weathered rock at about 65 feet from land surface. The saprolite is heterogeneous and varies in grain size from medium to fine sand, to silt with clay, and is derived from the bedrock, a quartz-biotite gneiss.

A diagram showing the construction details of the UVB well is given as Figure 3. Depth to water at this site is 45 feet below ground surface. Groundwater flow is to the south and the approximate hydraulic conductivity is 1.9×10^{-4} cm/sec. A 20 foot interval of the saturated zone is being addressed by the UVB system.

Prior to initiation of active remedial measures, dissolved petroleum hydrocarbon constituents historically were present in all five original monitoring wells (MW-1 through MW-5, Figure 2). Additional monitoring wells (MW-6 and DW-1) were installed after UVB system activation to better define both the lateral and vertical extent of petroleum hydrocarbon contamination. The lateral extent of dissolved BTEX in groundwater has been interpreted from analytical data gathered prior to activation of the UVB and after system start-up. Vertical hydrocarbon extent is being monitored through the Type III monitoring well DW-1 completed in bedrock and located cross gradient to the UVB system.

The UVB system was activated on September 17, 1992. The capture zone, circulation cell, and release zone were calculated to encompass the areas shown in Figure 4. The capture zone is defined by the width Bt at the top of the aquifer and the width Bb at the bottom of the aquifer. The initial hydrocarbon removal rate in the off-air stream was estimated to be 34.3 lbs/day (Table 1). Since a portion of the upper screen is open to the vadose zone, soil vapor extraction is occurring. However, about 95% of the initial removal rate was attributed to hydrocarbon removal from the saturated zone and capillary fringe. One day after start-up, the removal rate was 23 lbs/day. Since operating day 58 to the present (operating day 796), the removal rate has remained below 1.3 lbs/day. Prior to the most recent sampling event the stripping reactor efficiency has ranged from 58% to 100% for BTEX and from 95% to 100% for IPE, based on the analytical results for the shallow and deep UVB annulus wells (Table 2). Results from the most recent sampling event (operating day 796) revealed that the BTEX concentrations were higher in the shallow annulus well than in the deep annulus well, which is a reversal of the normal trend. This was likely due to the fact that sampling occurred only a few hours after restarting the system following a shut-down. Hydrocarbon removals and reductions are summarized in Tables 1 and 2, and Figures 5 and 6.

A significant decrease in the concentration of dissolved BTEX near the center of the plume at MW-3 (10 ft from the UVB well) has been observed since the first round of sampling after start-up through the most recent sampling event on operating day 796 (Table 2). At startup, dissolved BTEX was 1719 ug/l at MW-3. All post start-up dissolved BTEX concentrations at MW-3 have been less than 254 ug/l. Also, comparing dissolved constituent concentrations in the other monitoring wells, the lateral extents of the dissolved BTEX plume (Figures 2 and 6, Table 2) and dissolved IPE plume (Table 2) have diminished.

In addition to the physical removal of VOCs which takes place within the stripping reactor, the UVB also introduces dissolved oxygen (DO) into the circulating groundwater. As expected, there is a characteristic increase in DO between the deep and shallow annulus wells of the UVB (Figure 7). Moving out into the aquifer, there is a rapid decrease with distance from the UVB as evidenced by the DO measurements in MW-3 (Table 4). This decrease is likely due to dilution, mixing, and biodegradation of hydrocarbons in the aerobic zone surrounding the UVB well.

Table 1. Offgas data from the UVB site at Troutman, NC

Operating Day (Date)	Volatile Hydrocarbon Concentration (ppm)	Air Flow Rate (cfm)	Estimated Removal Rate (lb/day)
1	371.46	350	34.3
2	296.06	300	23.4
9	164.80	350	15.2
16	45.38	444	4.8
23	84.93	250	5.6
30	64.19	243	4.1
44	50.01	235	3.1
58	14.00	267	0.99
79	3.71	247	0.24
93	16.61	284	1.24
273	0.13*	300	0.01
352	12.53	270	1.25
473	1.47	250	0.14
609	11.90	250	1.10
733	9.35	200	0.69
761	13.09	200	0.97

* Sample analyzed by laboratory. All other samples analyzed by portable GC.

Table 2. Concentrations (ug/l) of petroleum hydrocarbon compounds in groundwater at UVB site, Troutman, NC

Operating Day	Well Number	Benzene (1 ug/l)*	Toluene (1000 ug/l)	Ethyl-benzene (29 ug/l)	Total Xylenes (530 ug/l)	Total BTEX	MTBE (200 ug/l)	IPE (DL)
-307 **	MW-1	8	11	BQL	12	31	BQL	160
1	(44'-54') ***	BQL	BQL	BQL	2	2	BQL	120
58	BQL	BQL	BQL	BQL	BQL	BQL	BQL	BQL
148	BQL	BQL	BQL	BQL	BQL	BQL	130	BQL
273	BQL	BQL	BQL	BQL	BQL	BQL	130	77
352	BQL	BQL	BQL	BQL	BQL	BQL	BQL	110
473	BQL	BQL	BQL	BQL	BQL	BQL	BQL	10
609	BQL	BQL	BQL	BQL	BQL	BQL	BQL	20
796	BQL	BQL	BQL	BQL	BQL	BQL	BQL	71

* North Carolina 2L Standards. DL - Detection limit.
** Negative values are days before UVB start-up. BQL - Below quantitation limit.
*** Screened interval.

Table 2. Continued.

Operating Day	Well Number	Benzene (1 ug/l)*	Toluene (1000 ug/l)	Ethyl-benzene (29 ug/l)	Total Xylenes (530 ug/l)	Total BTEX	MTBE (200 ug/l)	IPE (DL)
-307	MW-2	BQL	BQL	BQL	BQL	BQL	BQL	74
1	(44'-54')	BQL	BQL	BQL	BQL	BQL	BQL	56
58		BQL	BQL	BQL	BQL	BQL	BQL	56
148		BQL	BQL	BQL	BQL	BQL	BQL	BQL
273		BQL	BQL	BQL	BQL	BQL	BQL	BQL
609		BQL	BQL	BQL	BQL	BQL	BQL	BQL
733		BQL	BQL	BQL	BQL	BQL	BQL	BQL
796		BQL	BQL	BQL	BQL	BQL	BQL	BQL
-307	MW-3	840	15	BQL	69	924	BQL	2600
1	(47.5'-57.5')	1600	63	3	53	1719	BQL	2000
58		18	2.5	1	2.7	23.2	BQL	850
148		55	1.3	1	2.9	60.2	BQL	1100
273		9.3	BQL	BQL	BQL	9.3	BQL	590
352		2.5	BQL	BQL	1.2	3.7	BQL	480
473		98	4.2	BQL	3.9	106	BQL	1200
609		39	BQL	BQL	BQL	39	BQL	690
733		237	BQL	BQL	17	254	BQL	2000
796		32	3	BQL	6	41	BQL	663
-307	MW-4	BQL	BQL	BQL	BQL	BQL	BQL	BQL
1	(44'-54')	BQL	BQL	2	13	15	BQL	BQL
148		BQL	BQL	BQL	BQL	BQL	BQL	BQL
273		BQL	BQL	BQL	BQL	BQL	BQL	BQL
796		BQL	BQL	BQL	BQL	BQL	BQL	BQL
-307	MW-5	BQL	BQL	BQL	BQL	BQL	BQL	BQL
1	(42'-52')	BQL	BQL	BQL	BQL	BQL	BQL	BQL
148		BQL	BQL	BQL	BQL	BQL	BQL	BQL
273		BQL	BQL	BQL	BQL	BQL	BQL	BQL
796		BQL	BQL	BQL	BQL	BQL	BQL	BQL

* North Carolina 2L Standards. ** Negative values are days before UVB start-up. *** Screened interval.
DL - Detection limit. BQL - Below quantitation limit.

Table 2. (continued)

Operating Day	Well Number	Benzene (1 ug/l)*	Toluene (1000 ug/l)	Ethyl-benzene (29 ug/l)	Total Xylenes (530 ug/l)	Total BTEX	MTBE (200 ug/l)	IPE (DL)
148	MW-6	1	1.3	BQL	BQL	2.3	BQL	10
273	(40.5'- 50.5')	BQL	1	BQL	BQL	1	BQL	21
352		BQL	BQL	BQL	BQL	BQL	BQL	13
473		BQL	BQL	BQL	BQL	BQL	BQL	10
609		BQL	BQL	BQL	BQL	BQL	BQL	BQL
733		BQL	BQL	BQL	BQL	BQL	BQL	BQL
796		BQL	BQL	BQL	BQL	BQL	BQL	BQL
148	DW-1	BQL	BQL	BQL	BQL	BQL	BQL	BQL
273	(87'-97')	BQL	BQL	BQL	BQL	BQL	BQL	BQL
352		6.2	BQL	BQL	BQL	6.2	BQL	BQL
473		BQL	BQL	BQL	BQL	BQL	BQL	BQL
609		BQL	BQL	BQL	BQL	BQL	BQL	BQL
733		BQL	BQL	BQL	BQL	BQL	BQL	BQL
796		2	BQL	BQL	BQL	2	BQL	BQL
58	UVB-Shallow	6.5	7.6	BQL	3	17.1	BQL	10
148	(40'-49')	9.4	13	BQL	2.5	24.9	BQL	25
273		11	26	1.8	6.8	45.6	BQL	40
352		24	61	4.1	16	105	BQL	41
473		2.9	7.4	BQL	3.1	13.4	BQL	18
609		2	8	BQL	4	14	BQL	BQL
733		BQL	BQL	BQL	BQL	BQL	BQL	BQL
791		6	22	2	14	44	BQL	12
1	UVB-Deep	18	6	3	11	38	BQL	600
58	(60.8'-64.8')	71	5	1.1	8.7	85.8	BQL	1400
148		660	22	BQL	53	735	BQL	1100
273		140	4.4	1.1	30	176	BQL	1000
352		220	3.3	1.2	25	250	BQL	960
473		50	3	BQL	3.9	56.9	BQL	780
609		334	BQL	BQL	BQL	334	BQL	110
733		41	BQL	BQL	3	44	BQL	434
796		6	2	BQL	4	12	BQL	300

* North Carolina 2L Standards. ** Negative values are days before UVB start-up. *** Screened interval.
DL - Detection limit. BQL - Below quantitation limit.

Table 3. Dissolved oxygen concentrations (mg/l) in groundwater at the UVB site in Troutman, NC

Operating Day	MW-1	MW-2	MW-3	MW-4	MW-5	UVB A Deep	UVB B Shallow
-6	3.20	5.20	NS	6.40	4.70	0.95	NS
1	1.75	3.70	NS	NS	NS	0.95	8.80
1.1	1.44	3.55	NS	NS	NS	1.20	9.00
2	1.10	3.15	NS	5.15	NS	0.82	8.30
9	1.00	2.20	1.50	3.25	0.80	0.80	5.50
16	1.20	2.50	1.00	4.50	1.30	0.75	7.80
23	1.25	3.27	2.00	6.10	3.25	1.40	9.60
30	1.30	3.55	1.70	5.90	1.10	0.75	8.90
44	1.30	2.95	0.75	5.40	1.00	0.90	8.90
58	1.90	3.30	2.30	5.90	0.90	0.80	10.50
79	1.65	3.55	0.80	6.40	1.40	0.60	8.10
273	0.79	7.30	1.11	8.39	6.60	NS	8.79
352	1.60	NS	0.20	NS	NS	0.20	7.80
473	NS	NS	NS	NS	NS	NS	NS
609	3.20	4.20	0.10	7.50	0.20	0.30	8.40
733	NS	6.50	0.20	8.10	6.80	3.30	8.80
796	1.50	7.00	0.50	7.80	7.00	0.60	9.30

NS - Not sampled.

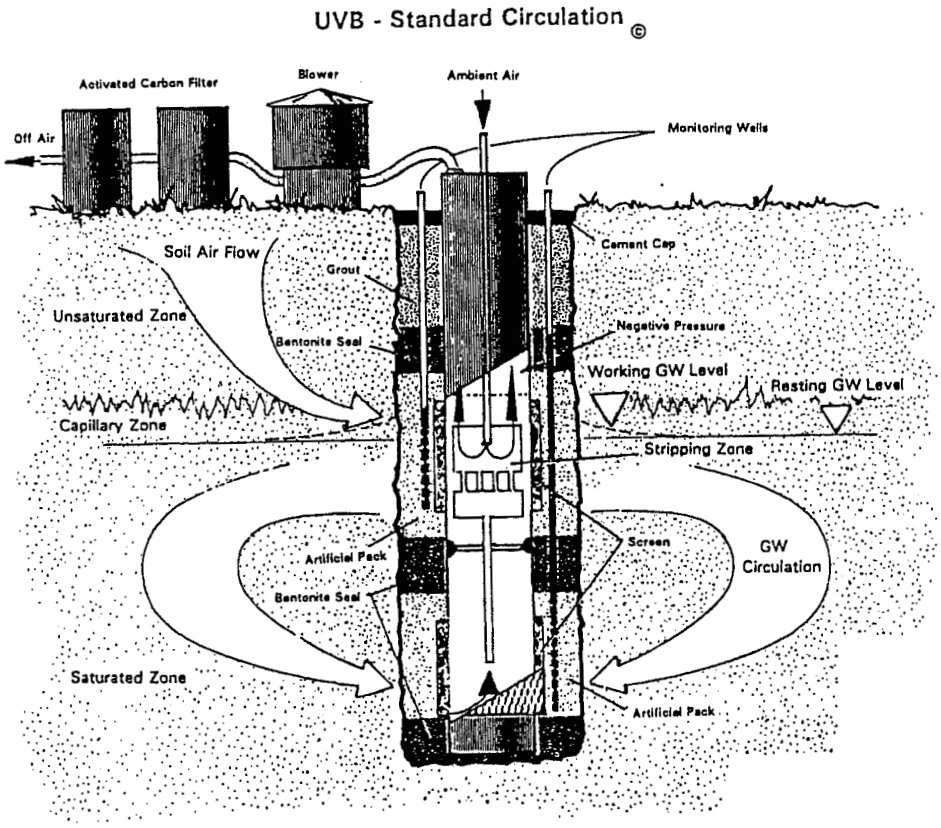

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FIGURE 1. UVB (VACUUM VAPORIZER WELL) STANDARD CIRCULATION

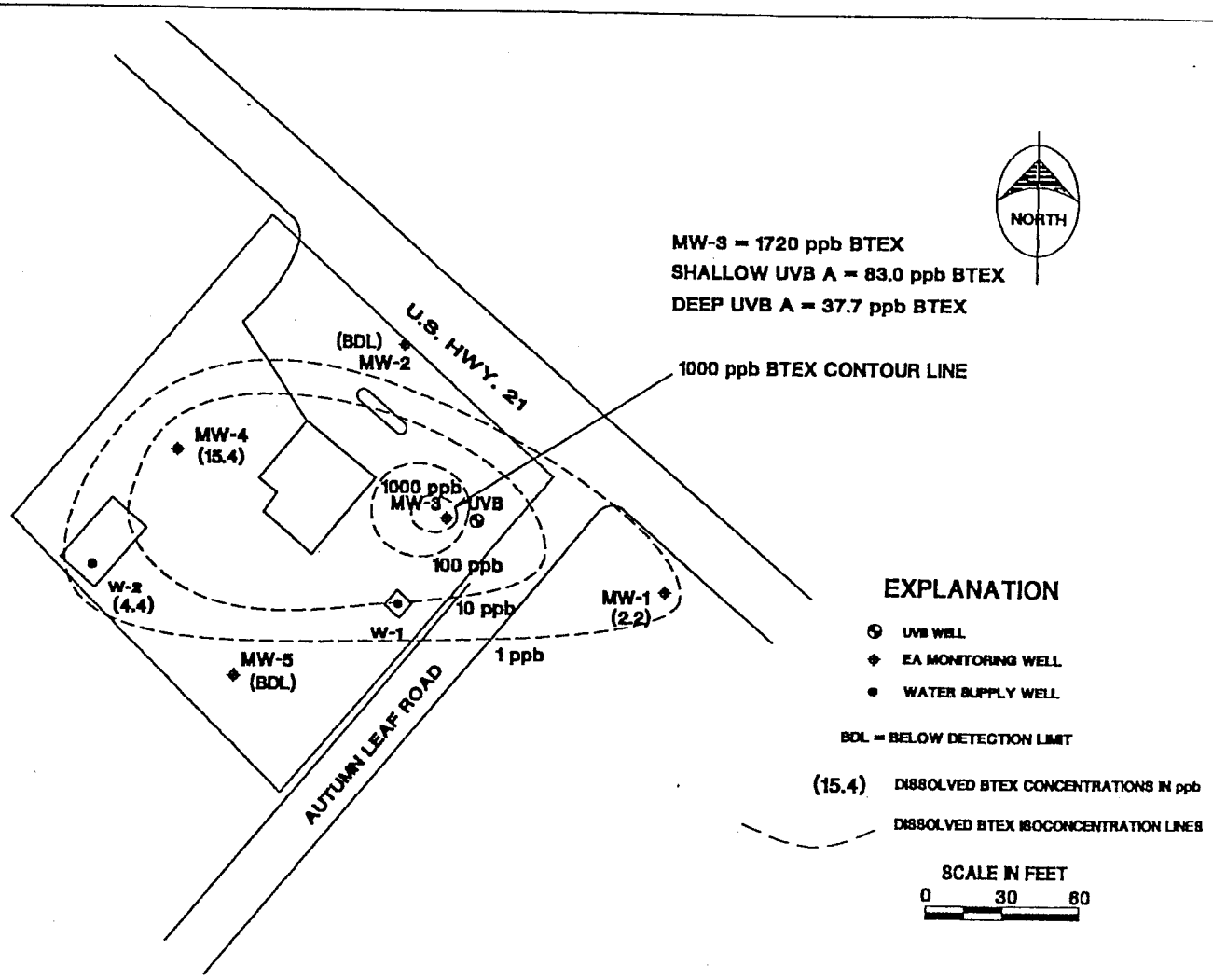

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FIGURE 2. LATERAL EXTENT OF DISSOLVED BTEX IN GROUNDWATER (PRE UVB START-UP)
FORMER RETAIL GASOLINE FACILITY, TROUTMAN, NC
(9/92 ANALYTICAL DATA)

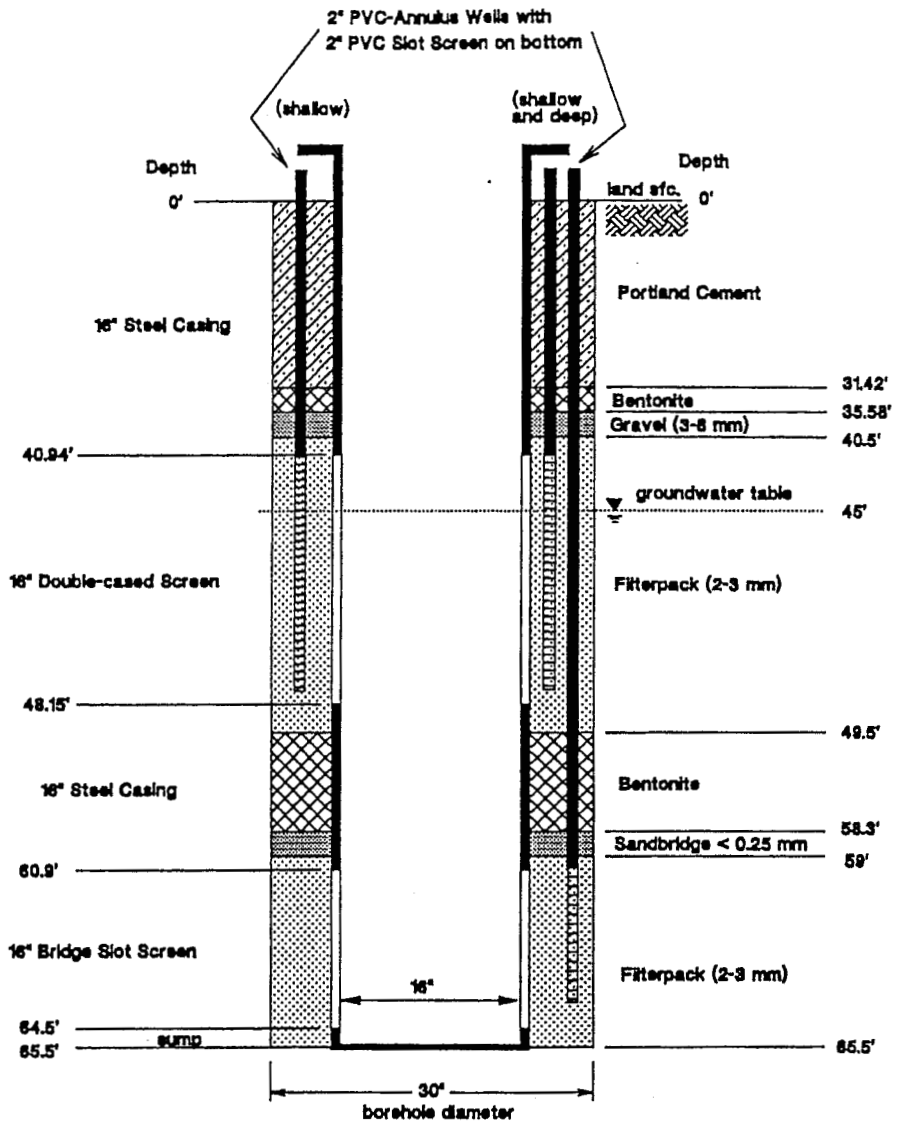

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Figure 3. Well Construction Diagram
UVB Installation
Troutman, NC

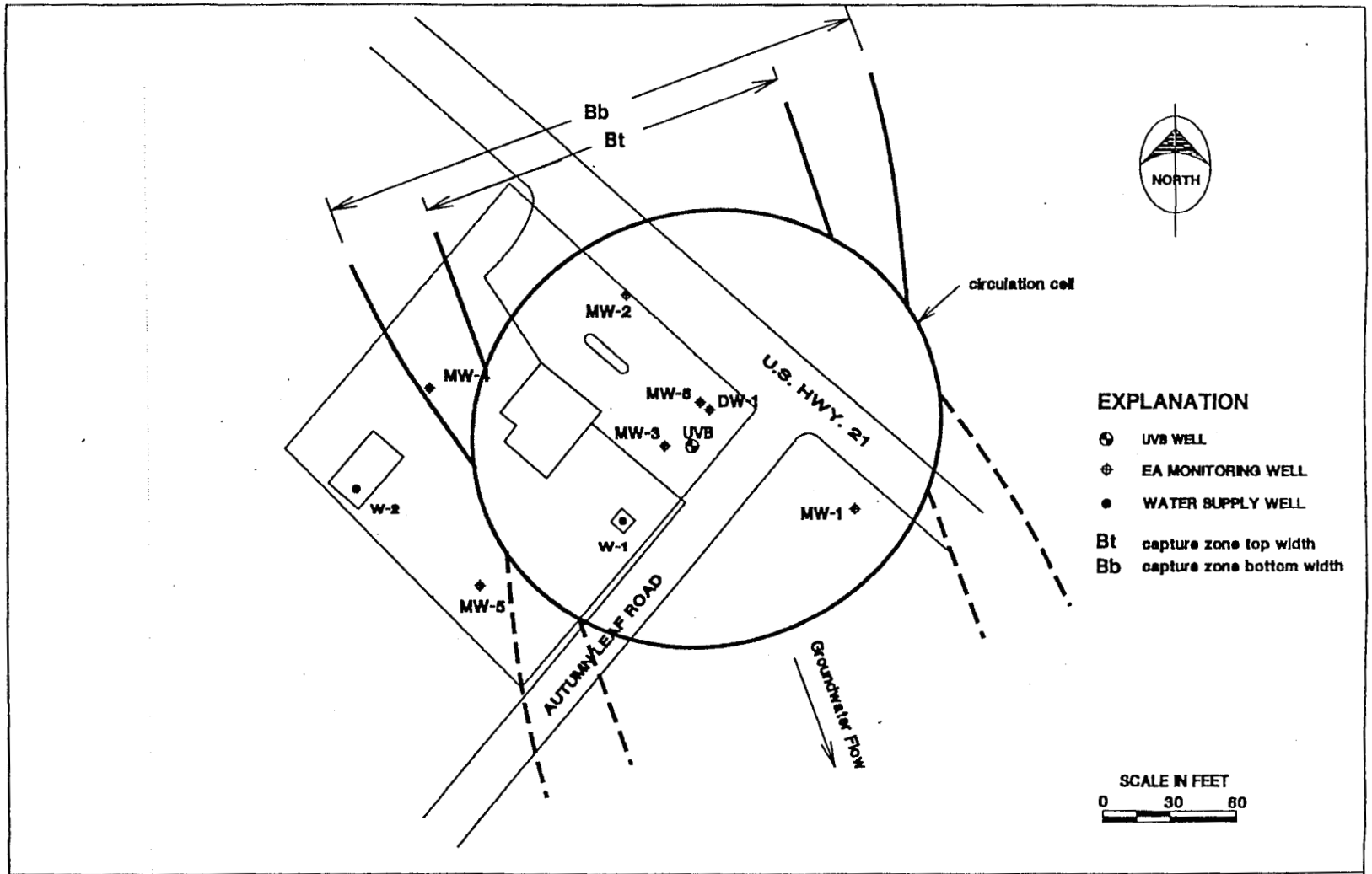

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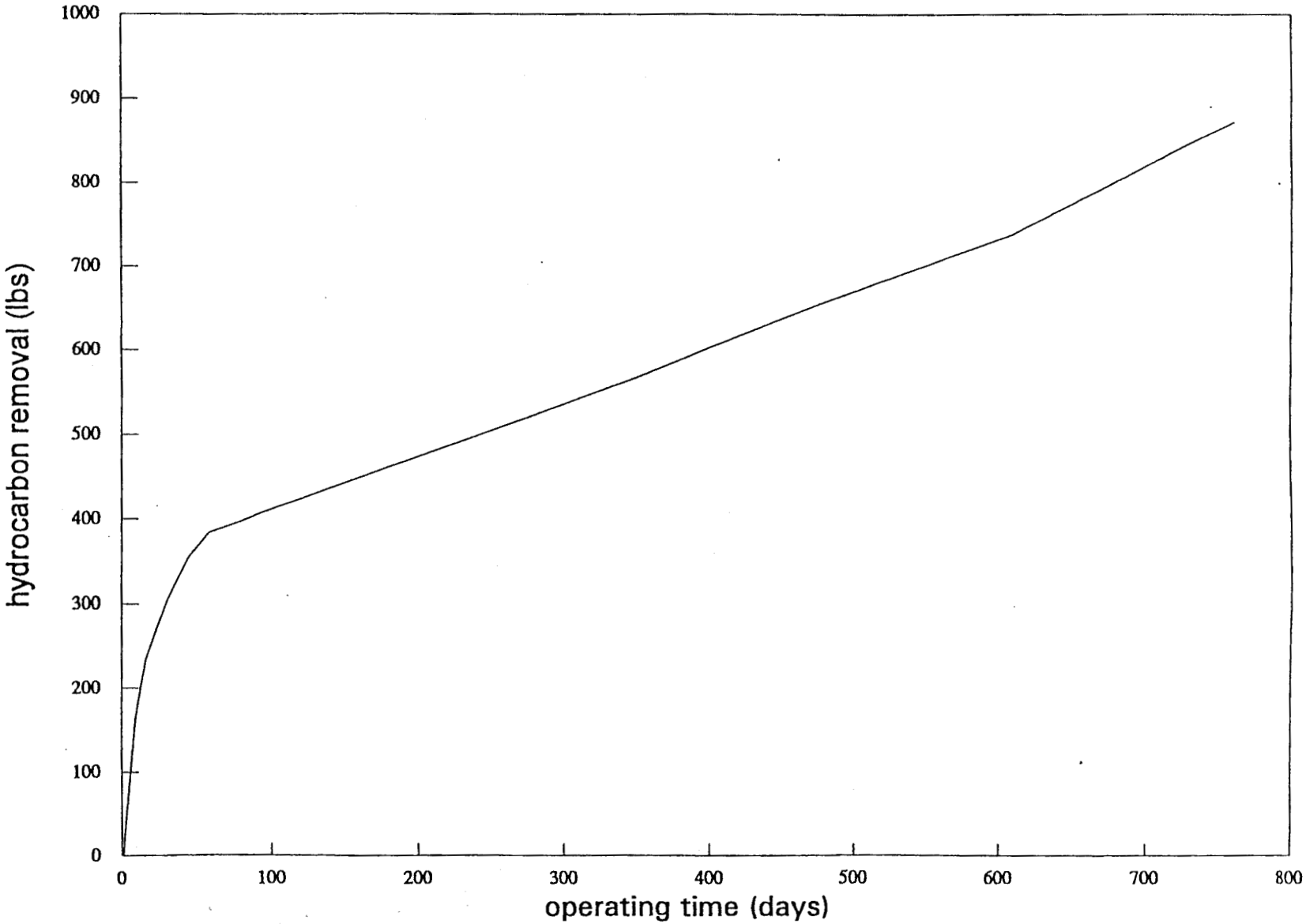
FIGURE 4. UVB CAPTURE ZONE AND CIRCULATION CELL
FORMER RETAIL GASOLINE FACILITY
TROUTMAN, NORTH CAROLINA

Figure 5. Cumulative Hydrocarbon Removal in Offair UVB Site, Troutman, NC



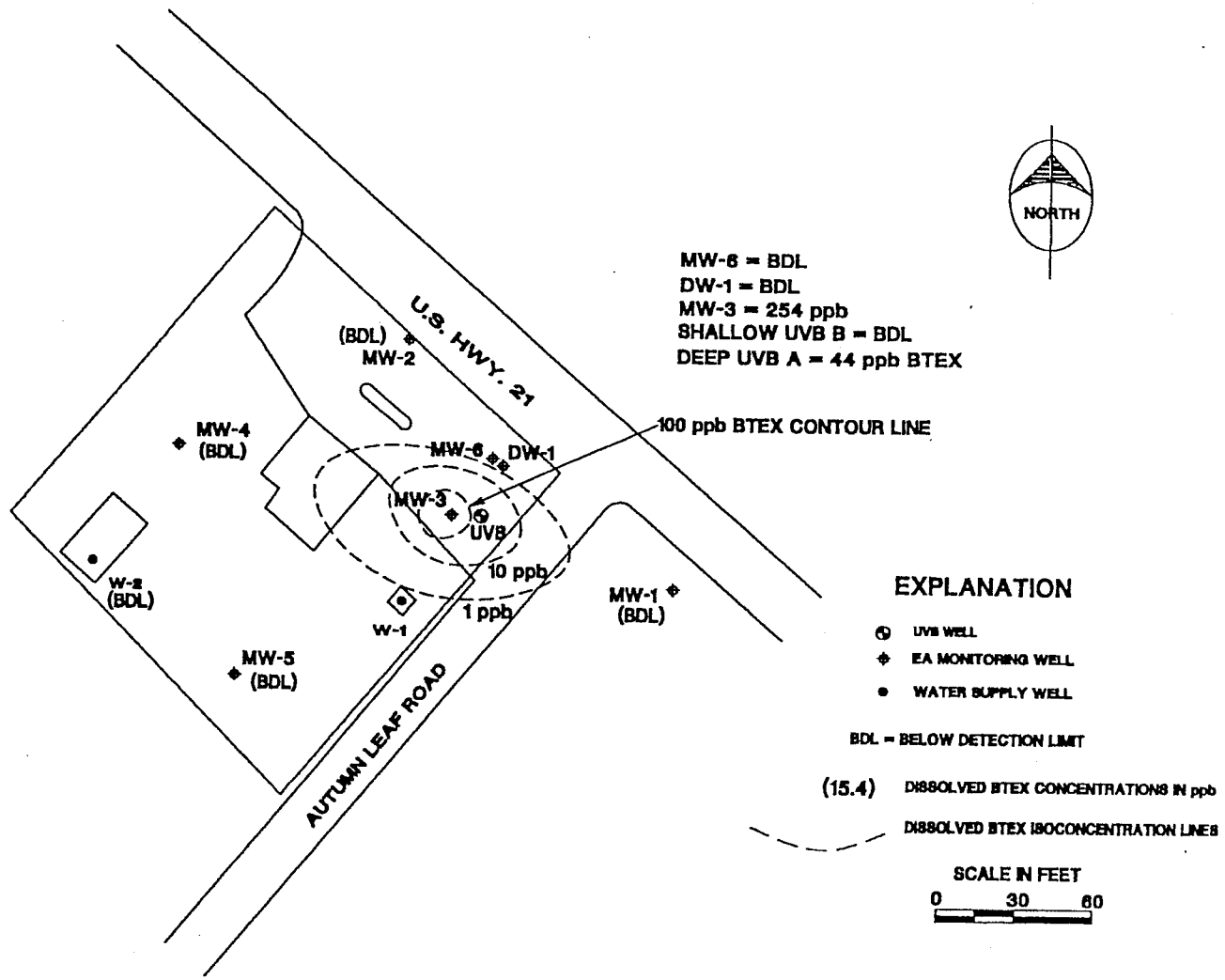


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FIGURE 6. LATERAL EXTENT OF DISSOLVED BTEX IN GROUNDWATER (POST UVB START-UP)
FORMER RETAIL GASOLINE FACILITY, TROUTMAN, NC
9/94 Analytical Data (Operating day 733)
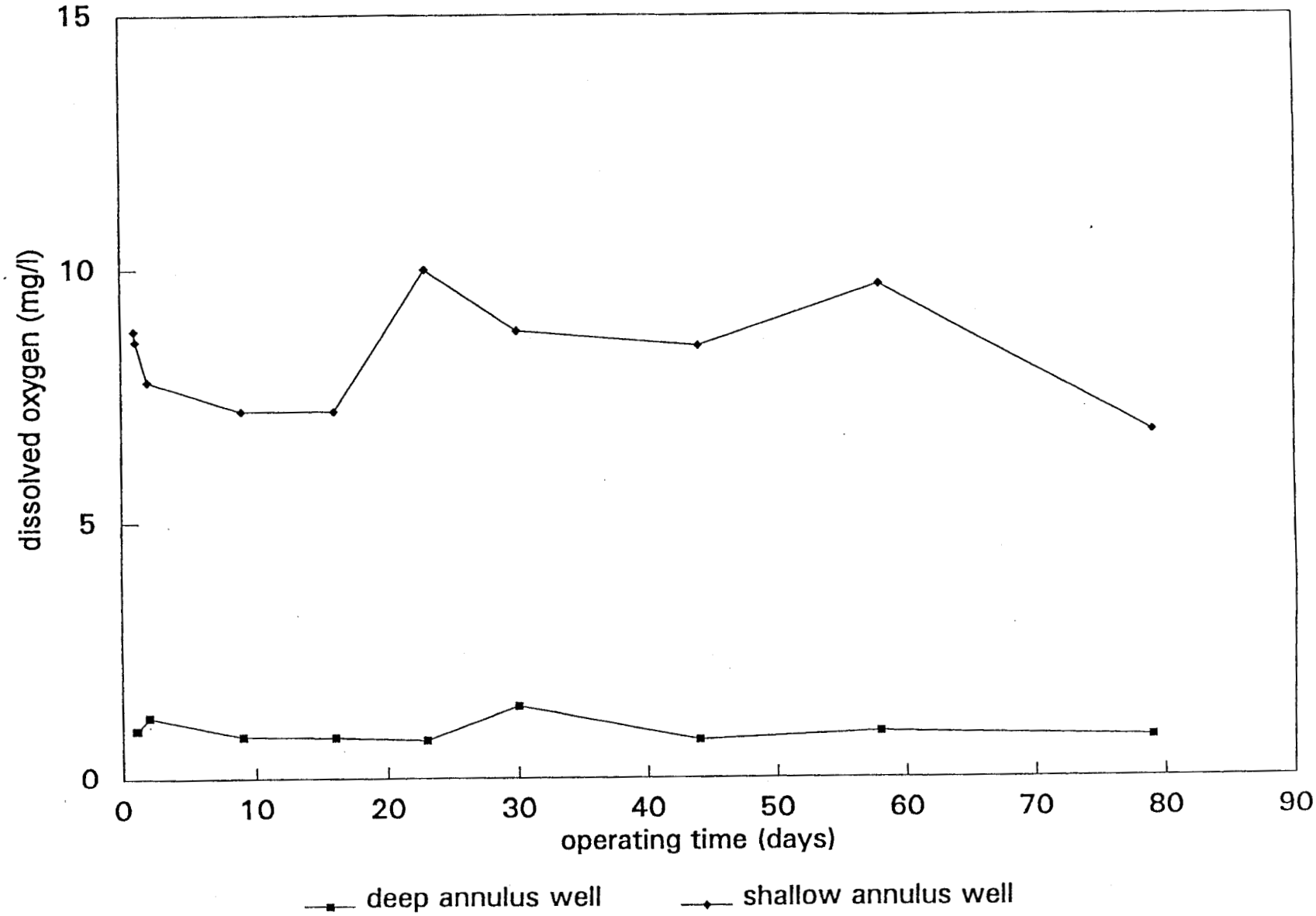
Figure 7. Dissolved Oxygen Concentrations in UVB annulus wells