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DIAGNOSTIC TOOLS FOR THE MONITORING AND ORGANIZATION OF IN-SITU AIR SPARGING SYSTEMS

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FEBRUARY 1998

FINAL REPORT: SEPT 1996 – DEC 1997

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MATERIALS & MANUFACTURING DIRECTORATE
AIRBASE & ENVIRONMENTAL TECHNOLOGY DIVISION
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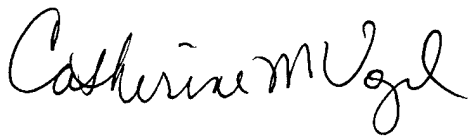

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13. ABSTRACT (Maximum 200 words)

In situ air sparging (IAS) involves injecting air into an aquifer to treat trapped contaminant sources, remediate dissolved contaminant plumes, and mitigate dissolved contaminant plume migration. The injected air also provides a source of oxygen for aerobic biodegradation of contaminants. Although the principle of the technology is simple, the practical aspects of effectively monitoring and optimizing IAS systems remain problematic. Conventional monitoring approaches generally focus on assessing the air distribution within the aquifer. There is a need, however, for methods to measure mass transfer or treatment rates at points within the target treatment zone in order to monitor the system's performance. The goal of this research was to develop diagnostic tools for quantifying mass transfer rates during IAS operation. Experiments have focused on two alternatives: a) a push-pull test using a multi-component tracer solution and b) a continuous ground water pumping test coupled with injecting sulfur hexafluoride through the air injection well. The multi-component tracer solution was developed and tested under controlled experimental conditions in a 3-dimensional tank. Both the multi-tracer solution and the continuous pumping SF6 test were field tested at the US Navy National Test Site at Port Hueneme, California. The 3-dimensional tank and field data indicate that the diagnostic tools are appropriate for assessing mass transfer at IAS sites. Two oxygen transfer rates, one indication oxygen consumption and one indicating oxygen delivery, have been derived from the tracer test data. Key results are that: a) oxygen transfer may be occurring at points of a site that are not within the zone of treatment according to conventional air distribution techniques, b) dissolved oxygen concentrations may not accurately reflect the oxygen transfer occurring at a given point, and c) oxygen transfer rates ranged from 0.00 to 126.58 mg-O2/lL-d in this study.

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PREFACE

This report was submitted as a thesis to the Graduate School at Arizona State University, Phoenix, AZ, in partial fulfillment for the degree of Master of Science. The thesis covers work performed by Ms. Illa Lyn Amerson. The effort was partially funded by the Armstrong Laboratory Environmental Quality Directorate (AL/EQ) (now known as the Air Force Research Laboratory, Materials and Manufacturing Directorate, Airbase and Environmental Division, AFRL/MLQ).

This thesis is being published in its original format because of its interest to the worldwide scientific and engineering community. It covers work performed between September 1996 and December 1997. The AFRL/MLQ Project Manager was Ms. Catherine M. Vogel. The assistance of AFRL support contractor Mr. Richard C. Woodworth, Environmental Systems Engineer, BDM, is acknowledged.

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The research presented in this thesis reflects the advice, support, and expertise of numerous people who have contributed to its development. I would like to thank my research advisor, Paul Johnson, for countless valuable suggestions, for teaching me more than I ever imagined, and for his ongoing support of holiday decorating. Special thanks also go to my thesis committee members Peter Fox and Larry Baker for their questions and suggestions for improving this thesis.

I would like to thank the Strategic Environmental Research and Development Program (SERDP), the Air Force Research Laboratory, Materials and Manufacturing Directorate, Airbase and Environmental Technology Division (AFRL/MLQ), Tyndall AFB, FL, and the Naval Facilities Engineering Support Command (NFESC) at Port Hueneme, CA for providing funding for this project. This project was also funded by the American Petroleum Institute (API) Soil and Ground Water Task Force. I would like to thank Harley Hopkins from API for his numerous contributions. I would also like to acknowledge Ed Payne from Mobil Oil and Tom Peargin from Chevron for their many suggestions which helped guide this project. Special thanks are extended to Cathy Vogel (AFRL/MLQ) for her guidance and Karen Miller and Ernie Lory (NFESC) for key logistical support.

I would like to thank NFESC for providing the field site for this research. As a National Environmental Technology Test Site (NETTS) test site facility, Port Hueneme, CA has been selected for technology demonstrations by SERDP, other governmental agencies, and the private sector.

Several other people contributed time and ideas to improving this project. I would like to acknowledge Richard Johnson from the Oregon Graduate Institute, and Mariush Kemblowski from Utah State University for their contributions to the original proposal and subsequent development of this project. Many thanks to Richard Johnson for contributing suggestions and material which proved to be invaluable during field implementation. I would also like to thank Andrea Leeson, Rob Hinchee, Dave McWhorter, and Mike Marley for In Situ Air Sparging (IAS) project peer review.

I would like to thank my fellow grad students at ASU, my parents, and my husband for their friendship and support throughout years of research, travel, writing, editing, and occasional insanity.

ABSTRACT

In situ air sparging (IAS) involves injecting air into an aquifer to treat trapped contaminant sources, remediate dissolved contaminant plumes, and mitigate dissolved contaminant plume migration. The injected air also provides a source of oxygen for aerobic biodegradation of contaminants. Although the principle of the technology is simple, the practical aspects of effectively monitoring and optimizing IAS systems remain problematic. Conventional monitoring approaches generally focus on assessing the air distribution within the aquifer. There is a need, however, for methods to measure mass transfer or treatment rates at points within the target treatment zone in order to monitor the system's performance.

The goal of this research was to develop diagnostic tools for quantifying mass transfer rates during IAS operation. Experiments have focused on two alternatives: a) a push-pull test using a multi-component tracer solution and b) a continuous ground water pumping test coupled with injecting sulfur hexafluoride through the air injection well. The multi-component tracer solution was developed and tested under controlled experimental conditions in a 3-dimensional tank. Both the multi-tracer solution and the continuous pumping SF_6 test were field tested at the US Navy National Test Site at Port Hueneme, California.

The 3-dimensional tank and field data indicate that the diagnostic tools are appropriate for assessing mass transfer at IAS sites. Two oxygen transfer rates, one indicating oxygen consumption and one indicating oxygen delivery, have been derived from the tracer test data. Key results are that: a) oxygen transfer may be occurring at

points of a site that are not within the zone of treatment according to conventional air distribution techniques, b) dissolved oxygen concentrations may not accurately reflect the oxygen transfer occurring at a given point, and c) oxygen transfer rates ranged from 0.00 to 126.58 mg-O_2/L-d in this study.

TABLE OF CONTENTS

Page

Page

LIST OF TABLES

Table Page

Table Page

LIST OF FIGURES

Figure Page

Figure Page

Figure Page

Figure Page

Figure Page

1. Introduction

Ground water contamination due to petroleum fuel releases, such a gasoline from underground storage tanks (USTs), has become a prevalent environmental problem . When a leak from a UST occurs, fuel seeps through the vadose, or unsaturated zone, leaving residual hydrocarbon in the soil pore spaces. If the spill is large enough, the fuel will continue to the saturated zone and pool on top of the water table (Figure 1.1). This

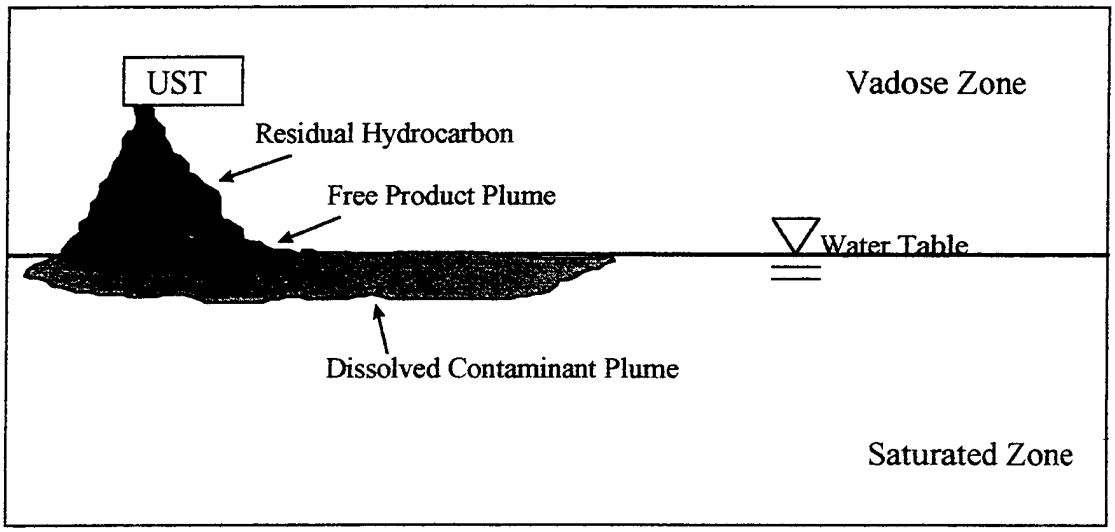

Figure 1.1: Schematic of Subsurface Fuel Spill

hydrocarbon pool is commonly referred to as the light, non-aqueous phase liquid (LNAPL) or free product layer. It serves as the "source" of vapor and dissolved phase contaminants. In addition, as the water table rises and lowers, the free product layer will become smeared over a greater thickness of soil. As gasoline components from the free product layer dissolve in the ground water, a dissolved plume forms and is extended downgradient of the original spill site by ground water movement. Depending on the size of the hydrocarbon spill and aquifer properties, dissolved plumes may continue hundreds or thousands of feet beyond the spill site.

Remediation strategies for contaminated aquifers include ground water pump and treat, soil vapor extraction, natural attenuation, and in situ air sparging (IAS). Pump and treat involves extracting contaminated water, treating it at the surface, and discharging or reinjecting it. It is limited by dissolution and is best used for containment (MacDonald and Kavanaugh 1994). Soil vapor extraction (SVE) works by drawing a vacuum on the subsurface and flushing air through contaminated soils. Volatile compounds then partition into the air stream and are removed by the system. If it is applied to treat aquifer soils, SVE must be used in conjunction with pumping to lower the water table. Since lowering the water table by more than a few feet is impracticable at most sites, SVE is best applied to vadose soils. Natural attenuation is the degradation of dissolved contaminants by instrinsic processes such as biodegradation, adsorption, dispersion, and chemical transformation (McAllister and Chiang 1994). It is currently proposed as a dissolved plume management option, rather than a source zone treatment. IAS involves injecting contaminant free air into the aquifer below the zone of contamination. It is hoped that the air stream will remove volatile organic compounds (VOCs) by volatilization and aerobic biodegradation. It is often coupled with SVE to remove the injected air from the subsurface as shown in Figure 1.2. While all four "technologies" are currently used, this thesis concentrates on IAS and its application to restoring aquifers contaminated with VOCs.

IAS has gained widespread use at field sites due to the apparent simplicity of the technology. The effectiveness of IAS, however, has been variable and it is not clear if

this is an inherent feature of the technology or a result of poor design and operation (Marley 1991). It is becoming clear that there is a lack of appropriate performance

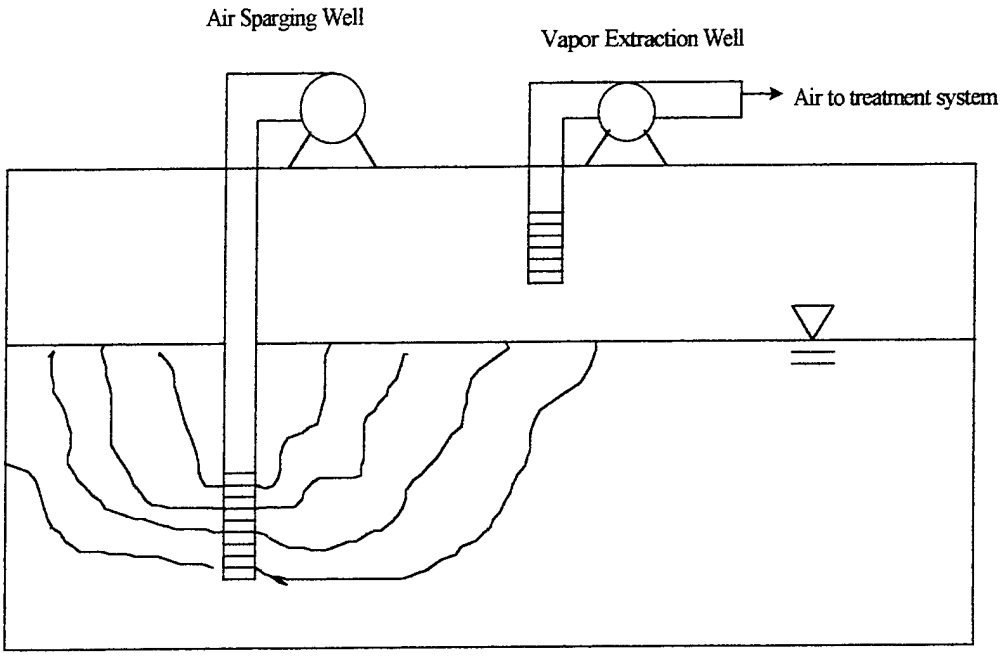

Figure 1.2: Schematic of an Air Sparging System

monitoring methods (Johnson et al. 1997). Common approaches include measuring dissolved oxygen in ground water monitoring wells or piezometers, measuring water pressure changes with transducers, measuring dissolved contaminant concentrations, and monitoring vapor concentrations in associated soil vapor extraction systems. Other methods, such as neutron probe measurements or electrical resistance tomography, have been used to assess the subsurface air distribution but are not commonly employed in practice (Lundegard 1994; Acomb et al. 1995).

While air distribution data are important to understanding IAS operations, mass transfer rates to and from the aquifer are more important measures of long-term remedial

effectiveness. It is necessary, therefore, to be able to assess and monitor these mass transfer rates over the operating life of the system. Furthermore, in order to assess the continued effectiveness of the IAS system, its performance must be compared against the rate of natural degradation of the contaminants.

The research presented in this thesis focused on developing and testing two tracer-based methods for quantifying mass transfer rates during IAS operations. The first involves a multi-tracer solution consisting of a volatile, non-degradable compound, a degradable, non-volatile compound, and a conservative tracer. The second involves continuous ground water pumping while injecting pure SF_6 with the system sparge air.

1.1 Relevant Background on IAS Monitoring and Performance Evaluation:

Several researchers have reported on the use of IAS to treat contaminant sources trapped within water-saturated and capillary zones, remediate dissolved contaminant plumes, and mitigate dissolved contaminant plume migration (Ardito and Billings 1990, Bohler et al. 1990, Griffin et al. 1990, Middleton and Hiller 1990, Marley et al.,\ 1990, Wehrle 1990, Brown and Fraxedas 1991, Brown et al.1991, Kabek et al. 1991, Marley et al. 1991, Ahlfeld et al. 1992, USEPA 1992, Beausoleil et al. 1993, Johnson et al. 1993, Pankow et al. 1993, USEPA 1993, Boersma et al. 1994, Johnson et al. 1995). In addition, IAS can be used to enhance aerobic biodegradation by supplying oxygen to the subsurface. The use of IAS to improve air flow near the capillary fringe for bioventing has been reported as well (Leeson 1993). The results of these studies vary in terms of required system operating time, operating method, radius of influence, and contaminant

removal. Due to these variations, researchers have investigated several aspects of IAS operations in an effort to better understand their influence on the subsurface.

As mentioned briefly above, several efforts have focused on assessing the air distribution in the subsurface. Ji et al. (1993) conducted laboratory air flow visualization studies during IAS simulations. Using glass beads in Plexiglas tank, air flow pathways for several grain sizes and degrees of heterogeneity were observed. Several important findings resulted from this work. Evidence of air flowing in channels, rather than bubbles, was seen in bead sizes less than 2 mm in diameter and the width of the air flow zone and density of the channels increased with increasing air flow rate. The air flow region generally was parabolic for homogeneous media. No increase in the air flow region was observed for pulsed flow conditions. Introducing heterogeneity to the system resulted in greater divergence in the air flow region. This is expected to be the dominant situation in natural systems. In addition, macroscale heterogeneity, such as clay lenses, were shown to cause trapped air pockets to form under fine grain layers. The air spread laterally beneath the lenses, leaving the zones immediately above the lenses untouched by air.

Since the Ji et al. study, several field methods have been employed to assess air distribution at IAS sites and to determine the existence of any preferential pathways. Lundegard (1994) used ERT to determine the air distribution at a field site in western Oregon and compared it to the air flow zone indicated by water table mounding, dissolved oxygen levels in monitoring wells, and water pressure changes. The ERT data indicated a parabolic air flow zone approximately 8 feet in width at the water table with

air flow concentrated around the sparge well. The more conventional measurements (e.g. dissolved oxygen, water pressure) appeared to over-predict the zone of influence by 2 to 8 times. A similar parabolic shape with concentrated air flow around the sparge well was seen in a field test employing a neutron probe (Acomb et al., 1995). The neutron probe responds to changes in moisture content or air saturation. The sparge well was located in a uniform sand. A maximum width of the air flow zone of 15 feet was measured at a flow rate of 16 cubic feet per minute (cfm). Dissolved oxygen readings suggested that the width of the air flow zone was 14 feet. Water pressure increases were detected 69 feet from the sparge well. The results of these studies demonstrate the potential inconsistencies in air distribution measurements based on conventrional monitoring tools.

Leeson et al. (1995) conducted a visual assessment of air distribution using sparge wells placed at different depths in a shallow standing water. Soils were relatively uniform sand. Again, the zone of influence was found to be fairly small, ranging from 4 to 16 feet, with the majority of the air flow exiting only 1-2 feet from the sparge well. As with the findings by Ji et al. (1993), increased flow rate resulted in more air flow channels but not in a greater zone of influence. Pulsed flow, likewise, did not affect the zone of influence.

Given the results of air distribution studies, it is evident that long-term IAS performance could be a diffusion-limited process and that the rate and extent of contaminant removal will be dependent on mass transfer to and from established air channels. This is particularly important for the transfer of oxygen to the ground water

since air sparging has the potential to stimulate aerobic biodegradation of contaminants as well as strip them from the water. Bulk ground water mixing due to air sparging is a key element to oxygen mass transfer away from the zone of influence. Clayton et al. (1995) offer evidence of non-steady state ground water mixing (advection) using time domain reflectometry (TDR) to assess changes in moisture content in subsurface soils. The TDR data show transient decreases in moisture content as the sparging system is turned on, followed by gradual increase to near pre-startup conditions. In addition, mass removal and TDR data indicate increased mixing during pulsed sparging operation.

The TDR results were confirmed by experiments presented in Johnson et al. (1994). Large experimental tanks equipped with a sparge well and monitoring network were used for these experiments. Rhodamine WT and bromide were used as water flow tracers. Sulfur hexafluoride (SF_6) was used to track air movement. Mixing was not significant during 7 days of steady sparging based on the physical model tracer tests. Ground water movement was indicated by the rhodamine and bromide distributions after pulsed operation.

The indication that ground water mixing and, in theory, mass transfer can be enhanced by pulsed sparging rather than continuous injection has been tested in several laboratory and field comparisons of continuous and pulsed behavior. Field data presented by Payne et al. (1995) show lower ground water concentrations of trichloroethylene (TCE) under pulsed conditions compared to continuous injection for samples taken within a 1.5 meter radius. TCE concentrations at 3.0 meter radius were not significantly different under either circumstance. Das (1996) and Rutherford (1995) both conducted

steady and pulsed sparge tests in a 2-dimensional tank with a homogeneous medium of glass beads. Das investigated the removal of octane and hexane from the tank under various operating conditions. For the case of contaminant removal by volatilization, Das concluded that pulsing improved the volatilization of hydrocarbons. The Rutherford data pertained to oxygen mass transfer as a function of operational parameters. The results of the study indicated that optimum air injection rates may exist, but that pulsing did not significantly increase the oxygen mass transfer rate.

Although there have been many studies of air distribution, ground water mixing, pressure responses, ground water concentrations, and SVE off-gas concentrations, there is still a lack of mass transfer data, especially data which can give an indication of system performance. This is further complicated by the fact that IAS systems are often designed on the basis of pilot test data. Johnson et al. (1997) indicate that data from conventional pilot tests may give a more optimistic picture of long-term performance than what will likely be observed. Moreover, the feasibility of air sparging at a site may vary simply on the basis of the monitoring method. Conventional practice also lacks a way of assessing potential degradation rates and the effect of the IAS system on degradative processes.

1.2 Research Objectives:

The objectives for this project were two-fold. First, the research was to develop and implement innovative approaches for evaluating IAS performance and effectiveness. The second objective was to develop diagnostic tools capable of quantifying the mass transfer or contaminant destruction rate for a give air sparging system. Furthermore, the

tools were to be practical, independent of the stage of system operation, and applicable at both local and large scales.

1.3 Diagnostic Tools:

Two diagnostic tools were focused on in this research. The first is a push-pull test using a multi-tracer solution consisting of acetate, bromide, and sulfur hexafluoride. The solution is injected in the aquifer, left in situ for a pre-determined time, and extracted.

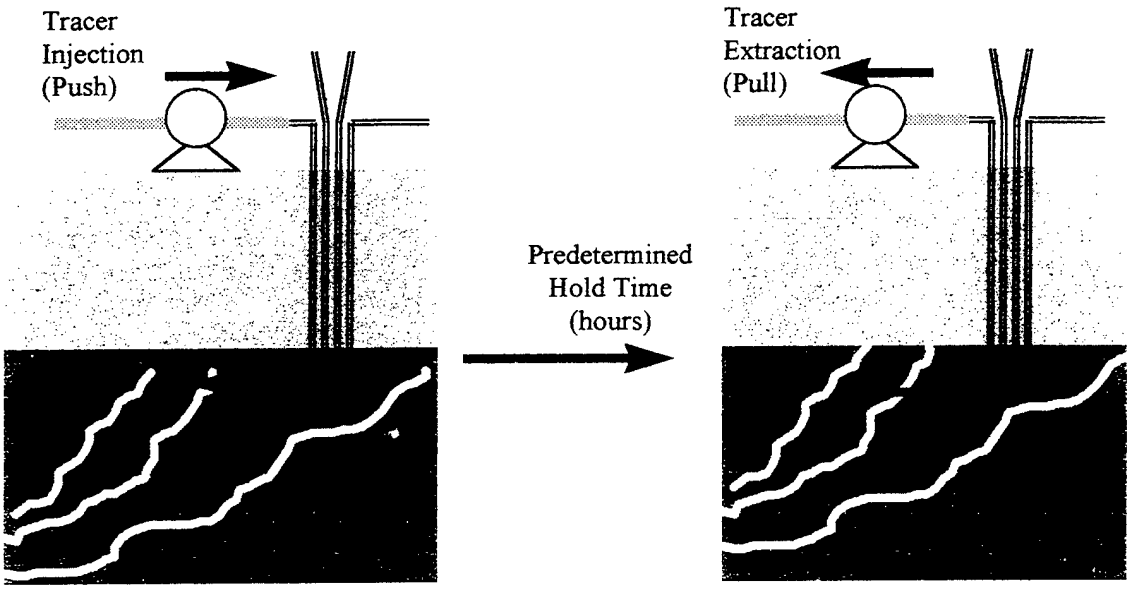

Figure 1.3: Process Schematic of Multi-Tracer Push-Pull Test

The change in acetate mass is then used to calculated an oxygen consumption rate. A schematic of the push-pull test is shown in Figure 1.3.

The second diagnostic tool is a continuous ground water pumping test coupled with injection of sulfur hexafluoride through the air injection well. Aqueous concentrations of SF_6 are used to calculate an oxygen delivery rate. The process schematic for this test is shown in Figure 1.4.

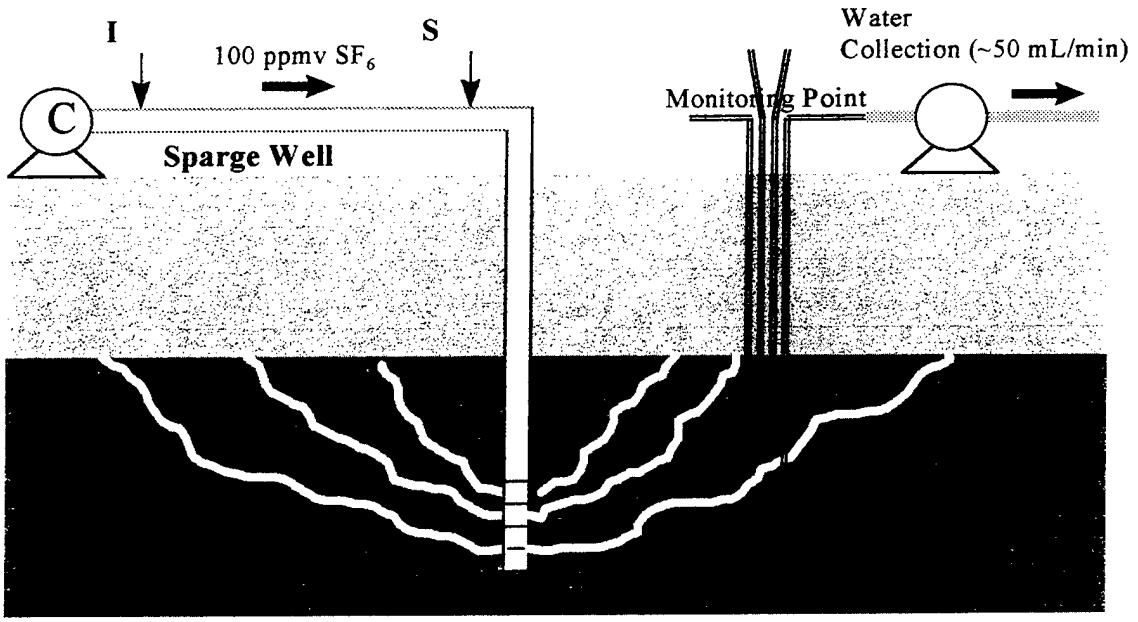

Figure 1.4: Process Schematic of Continuous Ground Water Pumping Test Coupled with SF_6 Injection

The following chapters describe the development process for the diagnostic tools. Data from controlled and field experiments are presented and discussed, and methods for calculating mass transfer rates from the data are detailed. The contents of each chapter are as follows:

- Chapter 2 discusses oxygen mass transfer theory, mathematical models that are commonly used to estimate mass transfer rates, and their applicability to air sparging.

- Chapter 3 focuses on the controlled experiments for the multi-tracer push-pull tests which were conducted in a 3-dimensional physical model including tracer behavior with and without air injection.
- Chapter 4 describes preliminary field work with the multi-tracer push-pull test that was conducted in October 1996.
- Chapter 5 describes the field implementation of the multi-tracer push-pull test conducted from June to September 1997 and describes how oxygen consumption rates are calculated.
- Chapter 6 details the continuous ground water pumping SF_6 tracer tests conducted in July and August 1997 including the method by which oxygen delivery rates are calculated.
- Chapter 7 lists the conclusions drawn from this research
- Appendix A describes several small laboratory experiments conducted during the diagnostic tools development process.
- Appendix B contains the concentration and tracer recovery profiles with extracted volume from the field tests.
- Appendix C contains a hard copy of the spreadsheets used to calculate oxygen delivery rates derived from the continuous ground water pumping SF_6 tracer tests.

2. Mass Transfer Theory

Mass transfer occurs from the air channels to the bulk liquid, from the bulk liquid to the air channels and within the bulk liquid during air sparging. Since fluid velocities are high in the air channel, it is reasonable to assume that air channels are well mixed. Johnson et al (1995) offered evidence that the bulk liquid, however, is not. Therefore, mass transfer across the liquid-gas interface is limited by transfer in the bulk liquid. Two models of oxygen mass transfer that have been commonly used by researchers are unsteady-state diffusion and two-film theory.

2.1 Unsteady-state diffusion:

The unsteady-state diffusion model assumes well mixed air channels and a stagnant bulk liquid. Molecular diffusion, therefore, is the sole mass transfer mechanism considered in this model. Assuming constant air injection, the flux of oxygen into the bulk liquid from air channels can be considered constant with time but not with space. The concentration of oxygen in the liquid phase will decrease with increasing distance from the air channel in this diffusion limited scenario. As time progresses, the oxygen concentration at any given point in the bulk liquid will continue to increase until the concentration at the liquid interface is in equilibrium with the oxygen concentration in the air channel.

Equation 2.1 describes the concentration profile as a function of time and space for one-dimensional unsteady-state diffusion in a semi-infinite medium (Bird et al. 1960, Geankoplis 1972). The solution is based on mass transfer from air to liquid across an

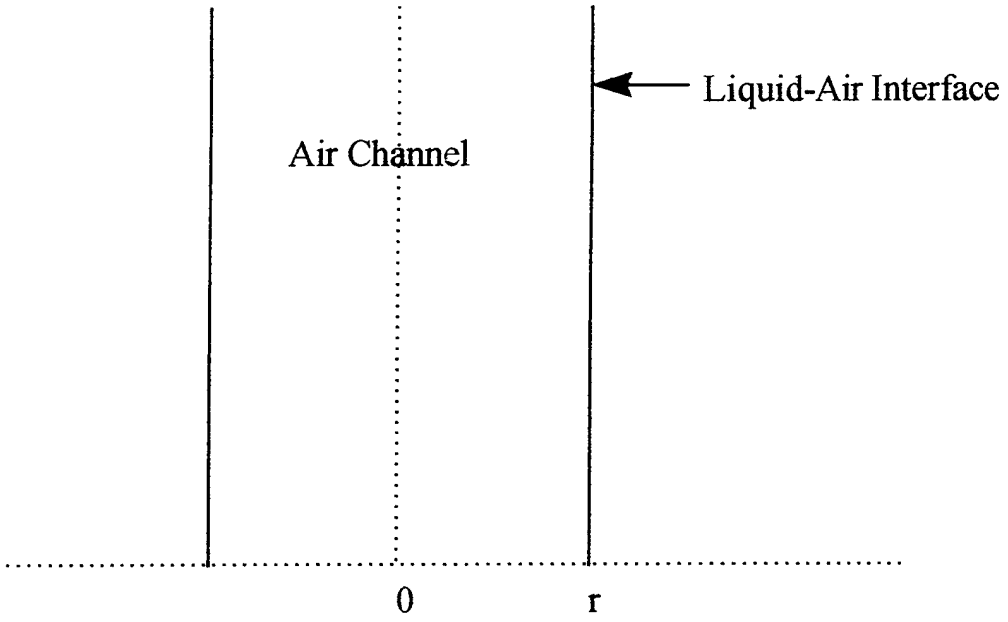

Figure 2.1: Geometry for 1-D Unsteady-State Diffusion Model

infinite plane. Figure 2.1 shows the geometry for the scenario.

$$c(x,t) = c_1 + (c_0 - c_1)erfc\left(\frac{x}{2\sqrt{Dt}}\right) \tag{2.1}$$

c = concentration at a given point in the bulk liquid (M/L^3)

c_1 = initial uniform concentration at all points in the bulk liquid (M/L^3)

c_0 = concentration at the air-liquid interface (M/L^3)

D = effective diffusion coefficient (L^2/T)

Given the generally low concentration of dissolved compounds, Henry's law can be applied to this scenario. The c_0 term can, therefore, be defined as:

$$c_0 = k_H p \tag{2.2}$$

p = partial pressure of compound in the air phase (P)

k_H = Henry's law coefficient (M/L^3-P)

Equation 2.1 can be incorporated into an expression for the mass transfer rate by applying Fick's law since only diffusion is being considered.

$$\frac{J}{A} = D\frac{dc}{dx} \tag{2.3}$$

Substituting (2.2) into (2.1) and using the relationship that erfc ( ) = 1 - erf ( ), the following equation for c(x,t) is derived:

$$c(x,t) = c_1 + B\left[1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)\right] \tag{2.4}$$

where $B = k_H p - c_1$

The result of applying equation 2.3 to equation 2.4 is an expression for the flux at some location x in the bulk fluid.

$$J = -DA\left(\frac{B}{\sqrt{\pi Dt}} e^{-\frac{x^2}{4Dt}}\right) \tag{2.5}$$

where A is the interfacial surface area (L^2)

At the interface (x=0), the flux, J, is equal to:

$$J = \frac{DAB}{\sqrt{\pi Dt}} \tag{2.6}$$

Thus, the flux into or out of the water decreases as $\frac{1}{\sqrt{t}}$ at constant air injection.

The unsteady-state diffusion equations, while sound, are not practical to the application of air sparging for two important reasons. First, the equations assume that properties of the air channels are known. Data such as the interfacial surface area of the air channels are not likely to be known for any air sparging application. Second, the model assumes a stagnant liquid phase. Ground water, however, is a dynamic medium. In addition, induced bulk water movement under sparging conditions, particularly pulsed flow, has demonstrated by Johnson et al. 1994. The assumption of static conditions, therefore, is not valid for sparging conditions.

2.2 Two-Film Theory:

Two-film theory is a widely applied model for industrial applications and may have some relevance to air sparging applications as well. Figure 2.2 shows the two-film model.

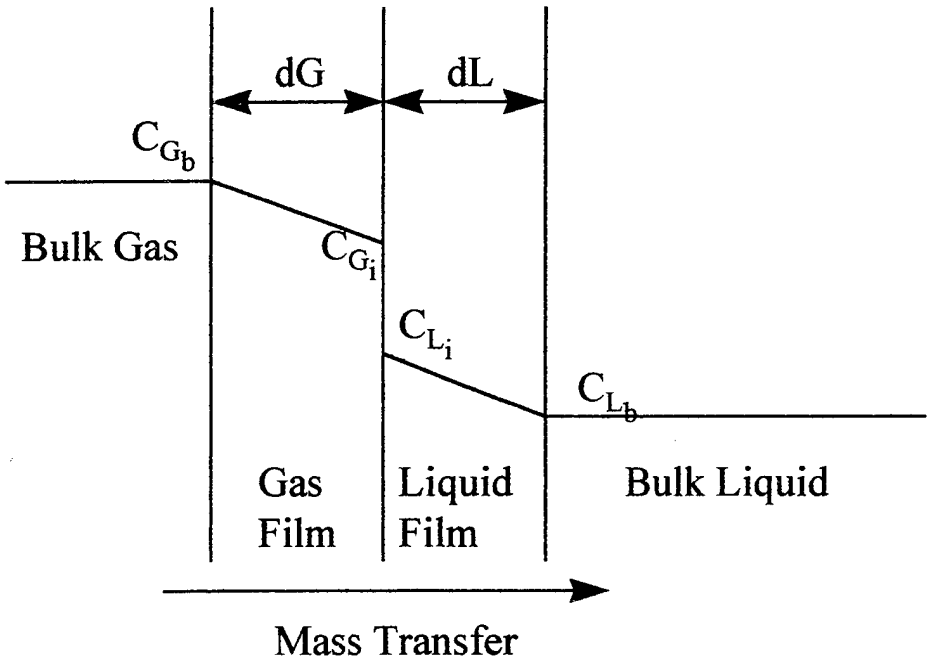

Figure 2.2: Schematic of the Two-Film Mass Transfer Theory

The two-film theory indicates that two immiscible phases in contact will develop a thin transitional film on each side of the interface. Within each film diffusion dominates mass transfer. The bulk liquid beyond the transitional film is assumed to be well mixed in each phase. The phases are considered to be in equilibrium at the interface. Advection will influence the film thickness although it is not explicitly contained in the model.

The rate of mass transfer across the interface is given by the expression:

$$J^* = k_G\left(c_{G_b} - c_{G_i}\right) = k_L\left(c_{L_i} - c_{L_b}\right) \qquad (2.7)$$

J^* = mass flux rate (M/T-L^2)

k_G = gas film mass transfer coefficient (L/T)

c_{G_b} = concentration in bulk gas phase (M/L^3)

c_{G_i} = gas phase concentration at air-liquid interface (M/L^3)

k_L = liquid film mass transfer coefficient (L/T)

c_{L_i} = liquid phase concentration at air-liquid interface (M/L^3)

c_{L_b} = concentration in bulk liquid phase (M/L^3)

It should be noted that mass transfer is considered positive in the direction of gas to liquid.

Incorporating Henry's law (equation 2.2) for c_{Li} into equation 2.7 and rearranging yields a mass transfer relationship (equation 2.8) involving an overall mass transfer

coefficient, K_L, and bulk fluid concentrations. Thus, the need to know interfacial concentrations has been eliminated.

$$J^* = K_L\left(k_H p - c_{L_b}\right) \tag{2.8}$$

K_L = overall mass transfer coefficient (L/T)

k_H = Henry's law constant (M/L3-T)

p = partial pressure in the bulk air phase (P)

Given a differential area element on the air-liquid interface, da, the mass transfer rate at that location can be described by equation 2.9

$$J = K_L da\left(k_H p - c_{L_b}\right) \tag{2.9}$$

J = mass transfer rate (M/T)

da = differential surface area element (L^2)

This equation is equivalent to equation 2.7 where K_L is related to k_G and k_L as follows:

$$\frac{1}{K_L} = \frac{k_H}{k_G} + \frac{1}{k_L} \tag{2.10}$$

The overall mass transfer rate can then be found by summing the mass transfer rates at all points on the air-liquid surface.

$$J_{overall} = K_L \int_R \left(k_H p - c_{L_b}\right) da \tag{2.11}$$

The two-film theory has proven very useful for applications where packing and geometry can be easily characterized and controlled (i.e. packed columns). Given the heterogeneity of soils, such characterization is not feasible at sites where IAS has been or is being applied.

It was seen in the above discussion that commonly used mass transfer models do not directly apply to the conditions presented at IAS sites. This research sought to quantify mass transfer rates without knowing the characteristics of the air and water flow rates at any given site by evaluating the behavior of tracers. Two oxygen mass transfer rates were derived from the tracer studies. Oxygen consumption rates can be quantified from the acetate degradation data in the multi-tracer solution tests. Oxygen delivery rates were derived from the continuous pumping SF_6 tests.

2.3 Effects of Trapped Gas on Mass Transfer:

Donaldson et al. (1997) reported on a model of oxygen transport through saturated soils with trapped gas in soil pore spaces. The investigators undertook the research to determined if dissolved oxygen in aerated water injected to stimulate aerobic degradation was being retarded by interacting with trapped air in subsurface soils. The model will be briefly addressed here because the results have implications for aspects of this research.

The dissolved gas transport model was developed using the control volume depicted in Figure 2.3. The mass fluxes between the gas and liquid phases are defined in the same way as those in the two-film model, giving the follow expression for mass flux across the air-liquid interface:

$$\dot{m} = \alpha\left(HC_{aq} - C_g\right) \qquad (2.12)$$

$\dot{m}$ = mass flux rate across the interface (M/T-L^2)

H = dimensionless Henry's law constant

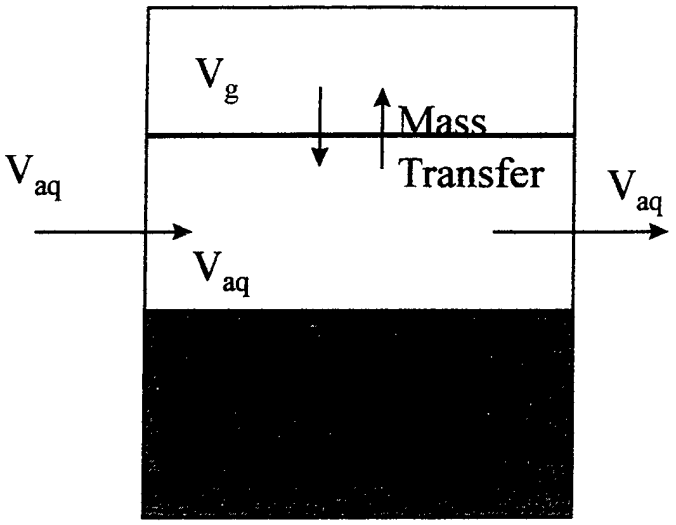

Figure 2.3: Control Volume for Dissolved Oxygen Transport Model

(Donaldson et al. 1997)

C_{aq} = concentration in the aqueous phase

C_g = concentration in the gas phase

$$\alpha = \left[\frac{1}{\frac{1}{k_g} + \frac{H}{k_{aq}}}\right] = \text{overall mass transfer rate (L/T)} \qquad (2.13)$$

Equations 2.12 and 2.13 along with a statement of conservation of mass for the gas phase to yield equation 2.14, the rate of change of mass in the trapped gas phase due to interphase mass transfer.

$$\theta_g = \frac{\partial C_g}{\partial t} = \left(\frac{A_g \alpha}{V}\right)\left(HC_{aq} - C_g\right) \qquad (2.14)$$

θ_g = fraction of total volume occupied by trapped gas

A_g = interfacial area between the trapped gas and aqueous phases (L^2)

V = total volume (L^3)

An equation for aqueous transport of a dissolved gas is derived from a statement of conservation of mass for the control volume with the advection-dispersion equation. The case of steady-state one-dimensional flow of the aqueous phase yields equation 2.15.

$$\theta_g \frac{\partial C_g}{\partial t} + \theta_{aq} \frac{\partial C_{aq}}{\partial t} = \theta_{aq} D \frac{\partial^2 C_{aq}}{\partial x^2} - \theta_{aq} v_{aq} \frac{\partial C_{aq}}{\partial x} \qquad (2.15)$$

D = dispersion coefficient (L^2/T)= δv_{aq}

δ = dispersivity of the porous media (L)

v_{aq} = average aqueous phase velocity (L/T) = q/θ_{aq}

q = aqueous phase flux (L/T)

Equations 2.14 and 2.15 formed the basis of the model. For their purposes, Donaldson et al. made both equations dimensionless to ease obtaining analytical solutions. Several dimensionless groups were defined as a result of dimensional analysis, one of which has important implications to the research presented in this thesis. A retardation factor, R, was defined as follows:

$$R = 1 + H \frac{\theta_g}{\theta_{aq}} \qquad (2.16)$$

This expression is analogous to the case of solute transport with sorption/desorption effects. According to equation 2.16, increasing trapped gas will result in more significant retardation of dissolved gases via aqueous transport. In addition, compounds with high Henry's law constants may be significantly retarded by even small amounts of trapped

gas in aquifer soils. This is an important result to consider in evaluating the behavior of SF_6 in the both the three component tests and the continuous ground water pumping SF_6 tests conducted for this project.

The results of the model were compared to the results of column tests with varying amounts of trapped air. Bromide and dissolved oxygen were used as tracers for the study. Model results correlated well the results of the column study.

3. Three-Dimensional Tank Experiments - Multi-Tracer Solution

3.1 Purpose of Experiments:

Because these tools were newly developed as a part of this research, it was desirable to test the proposed preparation, push-pull, and analytical methods in controlled settings prior to field implementation. To do this a 3-dimensional experimental tank was constructed. The general experimental procedure followed in this research involved injecting the three component tracer solution into the tank, leaving it "in situ" for a predetermined holding time, and extracting an excess amount water from the tank. A process schematic for this process is shown in Figure 1.3. The experimental methods for using the tracer solution could then be tested under conditions of controlled water and air flow. In addition, the controlled experiments allowed an appropriate in situ holding time to be determined. This chapter presents the methods and results of the push-pull tests conducted under controlled conditions in the 3-dimensional tank.

During the development process, several quick laboratory studies were conducted to further understand the behavior of the tracers in the tank experiments. A discussion of these experiments, along with results and the relevance to the tank experiments, can be found in Appendix A.

3.2 Multi-Tracer Push-Pull Test: Description:

The multi-tracer solution push-pull test was designed to provide quantitative assessment of relative losses to degradation and volatilization at selected locations in the target treatment area. The tracer solution used in this research was composed three

components, each with specific chemical properties: 1) a volatile, non-degradable component, 2) a degradable, non-volatile component, and 3) a conservative (non-volatile, non-degradable) component to which the recovery of the other components could be compared. In addition, all tracer components needed to be nontoxic and free from interactions with contaminants likely to be present at IAS field sites.

3.2a Tracer Selection

Bromide (Br^-) has been used previously as a conservative tracer in ground water, surface water, and laboratory scale studies (Johnson et al. 1994, Istok et al. 1997). Since bromide is a dissolved salt, its transport in ground water should be due only to the physical processes of advection, dispersion, and diffusion. Moreover, it is usually found only in trace concentrations in ground water systems, eliminating any difficulty in differentiating the tracer from ground water.

Chemicals considered for degradable, non-volatile component were ethanol and acetate. While ethanol is a readily biodegradable compound, it is widely used as a fuel additive. It, therefore, could be difficult to differentiate the injected tracer solution from the contaminant plume at fuel spill sites. Acetate is a readily degradable compound via both anaerobic and aerobic pathways (Chapelle 1993). Acetate has an advantage over ethanol or other small chain alcohols because it is not a common component fuels.

Several compounds were investigated as potential volatile, non-degradable components. The list of proposed compounds includes hexafluoroethane, octafluoropropane, decafluorobutane, cyclofluorobutane, and sulfur hexafluoride (SF_6). All five compounds exist as gases under common laboratory and field conditions and are

sparingly soluble in water. Available analytical equipment using electron capture detectors is capable of detecting concentrations (for the fluorinated alkanes) in the 1-10 ppbv range reliably. SF_6 had an advantage over the remaining compounds because analytical equipment specific to SF_6 was available, and it has a detection limit in the low pptvv level. In addition, the use of SF_6 as a tracer for ground water and geothermal applications has been well-documented (Wilson and Mackay 1993, Upstill-Goddard and Wilkins 1995, Johnson et al. 1994).

3.2b Preparation of the Multi-Tracer Solution

The multi-tracer solution was prepared in 1 liter (L) volumes for the controlled tank experiments. The tracer solution was prepared using potassium bromide (KBr) and anhydrous sodium acetate ($NaCH_3COO$ or NaAc) salts. Due to its extremely volatile nature, SF_6 required a special incorporation procedure which was carried out after the bromide and acetate solution was prepared. The concentration of acetate and bromide ions in the solution was 50 mg/L. The concentrations of the salts were deliberately kept low to keep the density of the solution close to that of water.

To prepare the ionic solution, 0.0745 grams (g) of KBr and 0.0695 g of NaAc were added to a clean 1 L volumetric flask. Prior to being used for the solution, the flask was washed and triple-rinsed with distilled, deionized water. The flask was filled to approximately 1/3 volume with distilled, deionized water and gently shaken to dissolve the dry chemicals. Once the KBr and NaAc were dissolved, the solution was brought to volume using distilled, deionized water. The flask was covered with Parafilm and shaken to ensure complete mixing of the solution. Generally, 20-35 milliliters (mL) of solution

were reserved for analysis to determine the initial masses of acetate and bromide injected into the tank. The volume of the reserved solution was measured in a clean, triple-rinsed 100 mL graduated cylinder. 900 mL of the remaining solution were then transferred to a clean, triple-rinsed 1 L glass bottle. The solution was sparged with nitrogen gas to deoxygenate the water prior to SF_6 incorporation. Typically, the solution was sparged for 45 minutes to 1 hour, and the resulting dissolved oxygen concentration was <1 mg/L.

SF_6 was incorporated into the solution using the apparatus shown in Figure 3.1. A No. 5 rubber stopper with two holes was used to seal the glass bottle. Stainless steel tubing (1/4" outer diameter) was placed in the stopper holes with one piece reaching to the bottom of the bottle and the other extending only to the 100 mL headspace. Flexible tubing connected to the stainless steel tubing subsequently connected to a peristaltic pump, forming a closed loop. The pump could then be used to circulate the headspace through the solution. Within this loop there was a Swagelok T fitting with a septum through which SF_6 could be injected into the headspace. A 5 mL Hamilton gas-tight syringe was used to inject 1 mL of 1 part per thousand (ppthv) SF_6 in nitrogen into the air stream in the bottle, resulting in an approximate headspace concentration of 10 ppmv SF_6. The headspace was allowed to circulate for 30 to 40 minutes prior to injecting the solution into the tank.

A sample used to determine the initial mass of SF_6 was taken immediately prior to injection into the tank. Headspace circulation was terminated and the flexible tubing was disconnected ahead of the T connection. The pump was operated in reverse to purge

any remaining 10 ppmv SF_6 from the tubing. The tubing was then connected to a prepared 1 L Tedlar bag with a twist-lock closure. The closure was opened and approximately 100 mL of the initial tracer solution was pumped into the bag. The bag was then closed immediately after the pump was shut off to prevent any SF_6 from

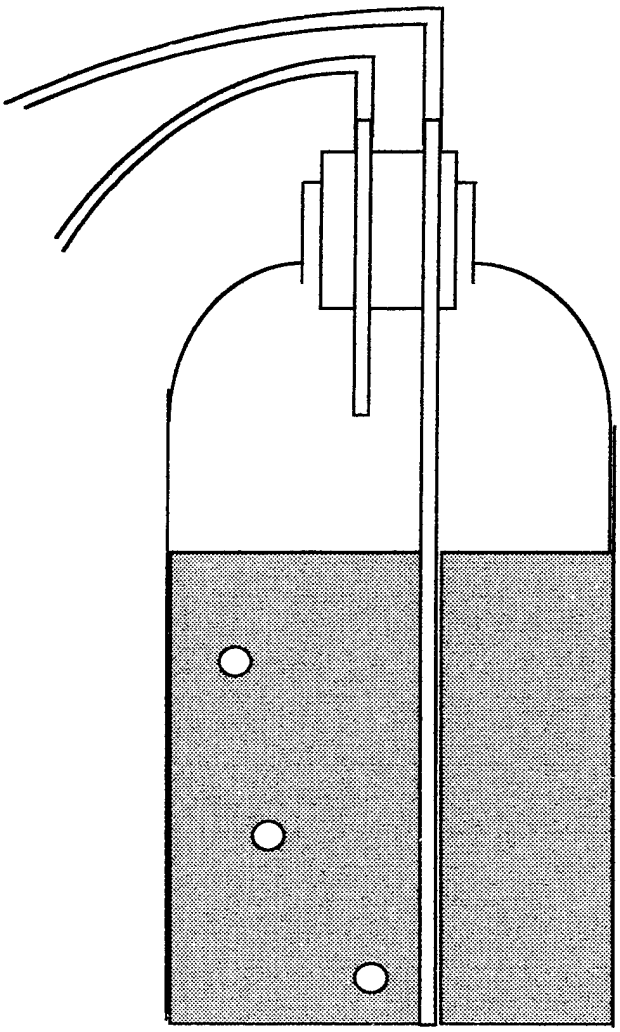

Figure 3.1: SF_6 Incorporation Setup

escaping. To prepare the Tedlar bag for sampling, it was triple-rinsed with either medical air or nitrogen to remove any trace SF_6. The bag was then filled with 100 mL of medical air or nitrogen and sealed until sample collection. This sampling technique is

required because the Henry's law constant for SF_6 is large (150.6 @ 20°C)(dimensionless), and it will readily partition from water into the gas phase. This approach, therefore, assumes that any SF_6 in the water will volatilize into the headspace.

3.2c Analytical Methods for the Multi-Tracer Solution

SF_6 samples were analyzed using a Lagus Applied Technologies Autotrac tracer gas analyzer. The Autotrac is essentially a gas chromatograph an ECD detector. The equipment includes a 1 mL sample loop connected to a stainless steel Mole sieve packed column. An electron conductivity detector (ECD) is used to detect SF_6. Oxygen can be detected by the ECD as well and a large oxygen peak may overlap the SF_6 peak, limiting the ability to quantify SF6. The Autotrac has a backflush mechanism which allows the sample to be washed from the system before the oxygen peak can be detected. The Autotrac has a self calibration feature which allows it to make a one point calibration based on a 4.92 ppbv standard. This feature allows the Autotrac to report a concentration for each analyzed sample instead of a peak area. SF_6 standard concentrations were prepared to check the concentrations reported by the analyzer as well. Standards were prepared in 1-L Tedlar bags using medical air or nitrogen and 100 ppmvv SF_6 (Matheson Gas Products). Standard concentrations of 100, 50, 10, 5, 1, 0.5, and 0.25 ppbvv used.

Acetate and bromide were analyzed on a Dionex DX 500 Ion Chromatograph (IC) equipped with an Ionpac® AS12A analytical column, Ionpac® AG12A guard column, and electrochemical and conductivity detectors. The IC utilizes a 2.7 mM sodium carbonate/0.3 mM sodium bicarbonate eluent. Each time the eluent was changed a new set of three standards (100, 50, and 10 mg/L) was prepared and run to calibrate the

instrument's response. The standards were prepared using the two ions of interest, acetate and bromide, and distilled, deionized water. A response factor was determined by the slope of the linear regression fitted to the three standard analyses and a zero. The calibration was determined to be valid if the r^2 value of the regression was 0.99 or greater.

The acetate and bromide concentrations were calculated from the peak areas. At acetate concentrations near the 1 mg/L level, other trace ions (thought to be fluoride and chlorite) interfere with the acetate peak. Typically, background water chromatographs were used to quantify the interfering peaks.

3.3 Physical Model:

3.3a Tank Specifications

A controlled physical setting was necessary to test the diagnostic tools developed in this research. The experimental design for the 3-dimensional, physical model is shown in plan view and cross-section in Figures 3.2 and 3.3, respectively. The tank is a 4' tall x 8' long x 4' deep and constructed of steel. The tank is welded on all edges to maintain water tightness. The tank is elevated approximately 6" off the ground by steel beams to provide a draining mechanism at the bottom of the tank. An air inlet port is located 3" from the bottom edge of the tank at the center of the outside 4'x8' face of the tank. Water circulation ports are located in the approximate center of the (4'x4') end panels of the tank. The top is sealed with Plexiglas bolted to the top edge of the tank. Rubber stripping and silicon were used to provide an airtight seal at the top of the tank. Since the

tank is located outside, the area is kept covered with a plastic tarp to prevent the Plexiglas cover from being exposed to the sun. Some exposure has occurred, however, and the cover has warped sufficiently to cause the tank to no longer be air tight.

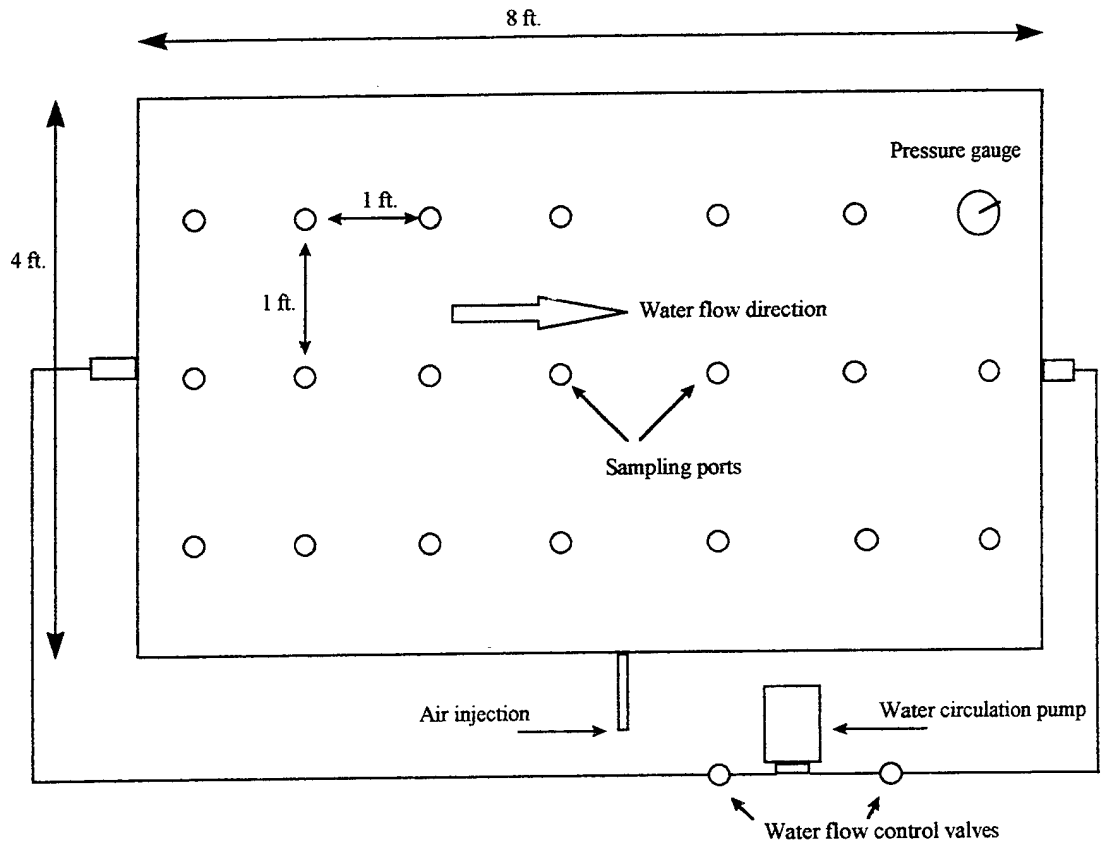

Figure 3.2: Plan View of Experimental Tank

As shown in Figure 3.2, the experimental tank is equipped with several sampling ports through the top of the tank. These ports are set in place through drilled, threaded holes in the Plexiglas cover. The ¼" outer diameter stainless steel sampling ports are held in place with ¼" plastic Swagelok compression fittings. The sampling ports range in depth from 1' to 3' below the surface of the tank. The depths and positions of the ports

were arranged to monitor both affected and unaffected areas of the tank under air sparging conditions.

The tank is filled with approximately 120 ft^3 of soil. The top of the soil layer is located approximately 3" from the top edge of the tank. A wire mesh screen rests on top of the soil layer to keep the soil in place during air injection. A heavier steel screen is then laid over the mesh to keep it in place. In order to effectively distribute water during circulation, 6" of coarse material are packed into each end of the tank as shown in Figure 3.3. All sampling ports used for tracer experiments were located within the finer grained soil in the middle of the tank.

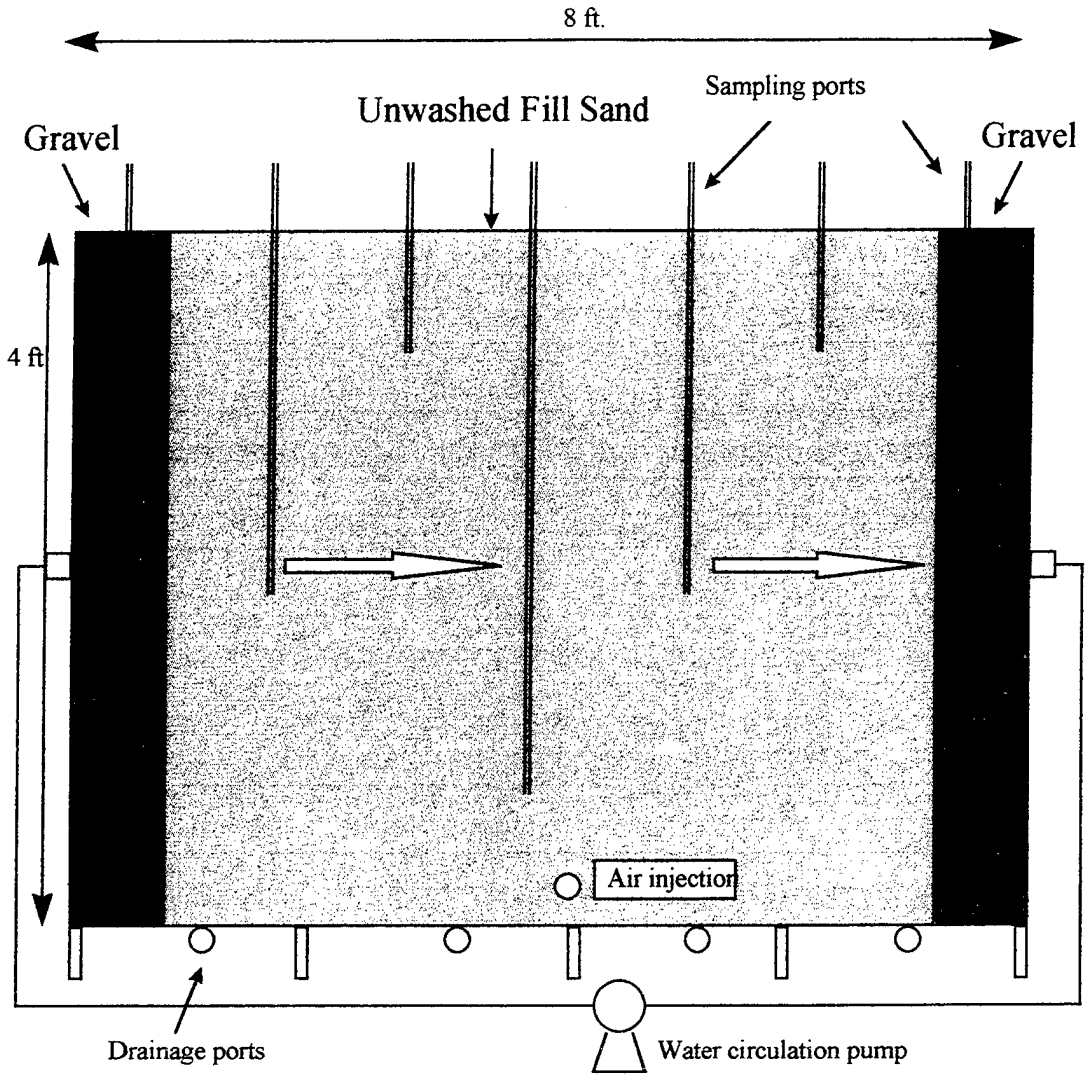

Figure 3.3: Cross-sectional View of the Tank

3.3b Soil Characteristics

In order to simulate field conditions, a soil similar to those at sites thought to be appropriate for air sparging was desired. Target soils were those with a significant sand content and some silts and clays. In addition, it was desirable to attain a water flow rate of at least 0.12 L/min during circulation. This flow rate corresponds to a ground water velocity of 1 ft/day through the tank. ABC composite was selected for the coarse grained

material used for flow distribution. Several soils were considered for the finer grained material including top soil, mortar sand, combinations of top soil and mortar sand, and unwashed fill sand. Unwashed fill sand was selected based on soil column permeability measurements. Two constant head permeability tests were conducted on the unwashed fill. The average hydraulic conductivity was determined to be 3.2 m/day (0.004 cm/s).

Characterization of the grain size distribution for the unwashed fill sand was done using a mechanical sieve. The grain size distribution for the unwashed fill sand is given in Table 3.1 and Figure 3.4.

Sieve No.	Sieve Opening Size (mm)	Mass of Soil (g)	% Retained	% Finer by Weight
3/8	9.50	4.6	0.46	99.54
4	4.75	42.6	4.26	95.28
10	2.00	179.5	17.95	77.33
40	0.425	476.8	47.68	29.65
100	0.150	215.8	21.58	8.07
200	0.075	43.6	4.36	3.71
pan		36.5	3.65	
Initial soil mass = 1000.0 g				

Table 3.1: Grain Size Distribution for Unwashed Fill Sand

A soil moisture retention curve was constructed for the unwashed fill sand. Moisture retention was measured using a Soilmoisture #1400 Tempe Pressure Cell. A saturated soil sample is placed in the Tempe cell and sealed tightly. The saturated weight of the soil is recorded. External pressure was applied to the cell with a regulated air line. Water will drain through the ceramic plate at the bottom of the cell once the air entry pressure of the soil is reached. The pressure is raised in small increments, forcing more water out of the soil. After water stops draining from the cell at each pressure increment,

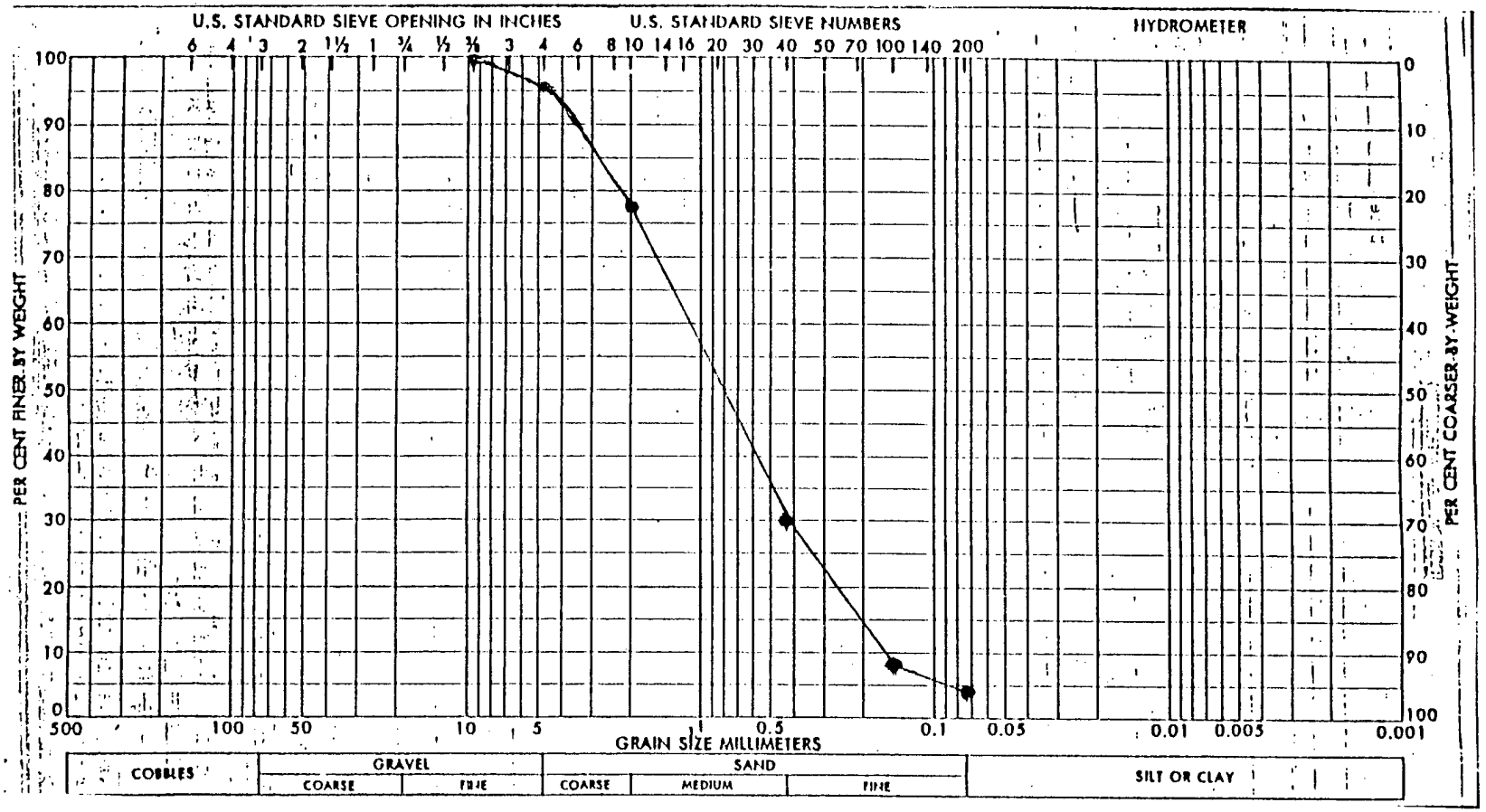

Figure 3.4: Grain Size Distribution for the Unwashed Fill Sand

the cell is weighed again. Eventually, no additional water is forced from the cell with increasing pressure. The remaining water is residual soil moisture that is held in the soil by capillary forces. The soil is then dried and weighed again to determine the amount of residual water. The moisture content can be plotted against the applied pressure to generate a soil moisture retention curve for the soil. The moisture retention curve for the unwashed fill sand is given in Figure 3.5.

The porosity of the ABC composite and ABC composite was calculated using the following equation:

$$(1-\eta)^{*}\rho_{solid} = \frac{M}{V}$$

where:

η = porosity [calculated]

M = mass of soil (g)

V = volume (cm^3)

ρ_{solid} = solid density (g/cm^3) [2.7 assumed]

The porosities of the ABC composite and unwashed fill sand were 0.08 and 0.38, respectively.

3.3c Soil Packing Procedures

The tank was filled with approximately 15 cubic feet of ABC composite soil and 105 cubic feet of unwashed sand. The tank was packed in 6-inch lifts, smoothed across the area of the tank, sprayed with water, and compacted using a 1 ft^2 tamper. A minimum of ten blows per section were used during compaction. Each soil layer was

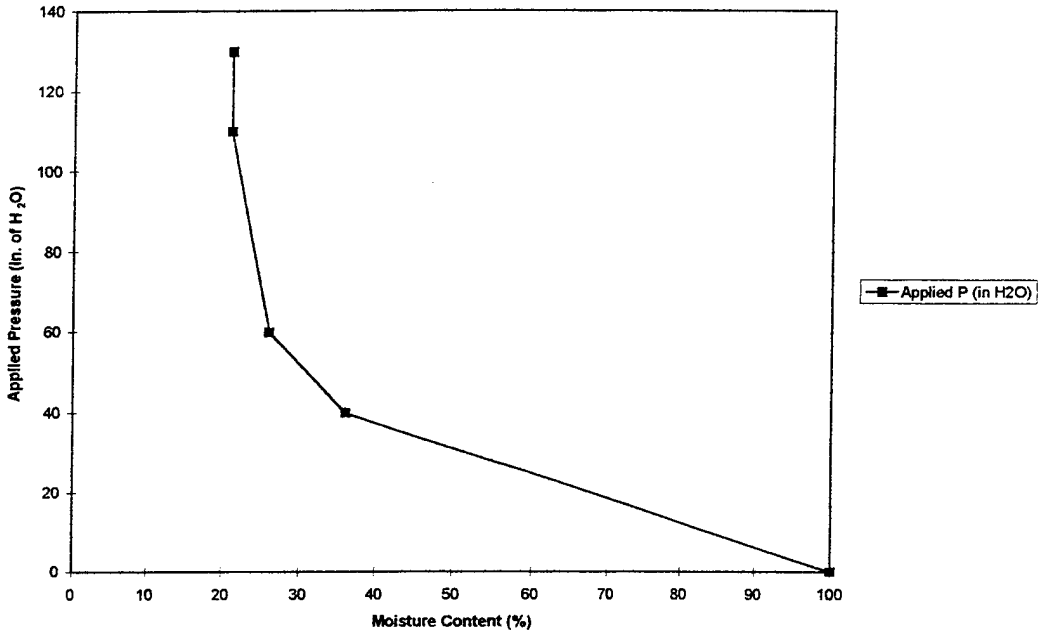

Figure 3.5: Moisture Retention Curve for Unwashed Fill Sand

sprayed a second time with water after compaction. In order to maintain the 6" ABC sections on either side of the tank, two 4' long boards were placed in the tank 6" from each end and roped in place while soil was being added to the tank. The boards were tall enough to allow several lifts to be placed before they were raised. Soil packing continued until the soil layer was within 3 inches of the top of the tank, giving a total depth of 45". After packing was completed and the overlying screens were set in place, the tank was filled with water to a level approximately ¼' above the top of the soil layer.

3.3d Injection Port Development

Injection ports were installed through the Plexiglas cover after the tank was sealed. Consequently, soil that was lodged inside the stainless steel tubing had to be

washed out before the ports could be used for experiments. Ports were developed using tap water and a Spectrum Macroflow peristaltic pump. One gallon bottles were used as water reservoirs and water was alternately pumped into and out of the port being developed to loosen and remove the soil trapped within the tubing.

3.4 Controlled Experiments:

Several experiments were conducted in the 3-dimensional tank to evaluate the experimental method and tracer behavior and gain information for field implementation. In order to characterize the losses of the degradable and volatile components under unsparged and, presumably, anaerobic conditions, two baseline studies were conducted. Once this data had been collected, the compressor was connected to the tank and tracer behavior under sparged conditions was evaluated.

3.4a Baseline Experiments

Baseline experiments were conducted to observe the tracer behavior and recovery under unsparged, anaerobic conditions. These experiments were expected to yield information on the degradation of acetate under anaerobic conditions and potential loss of SF_6 to trapped air in the tank. Before the baseline experiments were performed, a dissolved oxygen measurement was taken from the injection port to be used to confirm that anaerobic conditions existed in the tank. The measured dissolved oxygen level was <1 mg/L. The 3' below ground surface (BGS) port at the center of the tank near the air injection point was selected for all baseline studies. It was anticipated that this port would yield the greatest contrast in unsparged and sparged behavior.

The first set of baseline experiments was performed using only acetate and bromide. SF_6 was neglected from this set of experiments because the Lagus SF_6 detector was being used for field work at Port Hueneme. Since the SF_6 incorporation procedure was not required for these tests, the tracer solution was pumped directly from a 1 L glass bottle into the tank after being deoxygenated. Typically, injection and extraction took 5 to 10 minutes per liter of fluid. Five separate push-pull tests were conducted with in situ hold times of 5 minutes, 1 hour, 4 hours, 24 hours, and 48 hours. The 5-minute test was conducted to provide an indication of tracer recovery based on the push-pull method with essentially no tank contact time. The water temperature in the tank during the first baseline study ranged from 29 to 33°C.

After the designated holding time, 7 to10 L of solution were extracted in approximately 1 L increments. As each liter was extracted from tank, a dissolved oxygen (D.O.) measurement was taken immediately. To prevent an inaccurately low D.O. measurement, the extracted water was stirred continuously. D.O. measurements were made using a YSI dissolved oxygen probe in the 4-h, 24-h, and 48-h experiments. The D.O. concentrations were measured using an Orion dissolved oxygen probe for the 5-min and 1-h tests. The D.O. measurements are higher for these runs. The YSI meter results are thought to be more representative of conditions in the tank because the response of the Orion probe was slow, and the measured D.O. level varied continuously ($\pm$ 0.8 ppm) rather than reaching a steady reading. The YSI probe response was almost immediate, and fluctuations in the reading were minor ($\pm$ 0.1 ppm).

The actual volume extracted in each bottle was measured using a 1 L graduated cylinder marked in ten mL increments. A subsample of each liter was transferred to a Nalgene 60 mL or 100 mL bottle and reserved for analysis on the ion chromatograph. Injection and extraction volumes for the first baseline study are shown in Table 3.2.

Test #	Hold Time (hrs)	Injected Volume (L)	Total Extracted Volume (L)
1	0.083	0.941	9.745
2	1	0.948	9.720
3	4	0.967	6.900
4	24	0.977	6.890
5	48	0.964	7.825

Table 3.2: Injected and Extracted Volumes for the First Baseline Tracer Study (September 1996)

Test #	Hold Time (hrs)	Volume Extracted (L)	Acetate Recovery (%)	Adj. Acetate Recovery (%)	Bromide Recovery (%)
1	0.083	9.745	107.6	107.4	100.2
2	1	9.720	93.2	96.8	96.3
3	4	6.900	90.6	89.4	101.3
4	24	6.890	45.5	46.3	98.3
5	48	7.825	0.5	0.5	95.7

Table 3.3: Recovery Data for the First Baseline Tracer Study (September 1996)

The results of the first baseline study are presented in Table 3.3. Typically, recovery of >90% of the bromide was achieved within the first 4 to 5 liters of water

extracted. Adjusted acetate recoveries reflect the percentage of acetate recovered normalized to a bromide recovery of exactly 100%.

Bromide recovery exceeds 90% in all five push-pull tests. Based on this behavior, the bromide appears to exhibit the conservative behavior desired in this research. The acetate is recovered completely in the 5-min experiment. The appearance of recovering excess acetate may be attributed to interference from trace ions in the analytical method. As the holding time in the tank increased, the maximum recoverable amount of acetate decreased. Based on the data, the half-life of acetate in the tank is just under 24 hrs under unsparged, anaerobic conditions. The dissolved oxygen concentrations in the tank water remained in the range of 1.2 to 1.6 mg/L throughout the experiments. The first baseline study offered considerable encouragement that each of the two tracers exhibited behavior appropriate to its intended function.

The second baseline study was conducted with the full tracer solution. The tracer solution was prepared and an initial mass sample collected as described in Section 3.2b. The resulting headspace was analyzed on a Lagus Applied Technologies tracer gas analyzer. The initial mass of SF_6 dissolved in the tracer solution varied with each test and ranged from 6×10^{-8} to 2×10^{-7} g/L. Immediately after the initial mass sample was collected, the tubing was connected to the same 3' injection port used in the first baseline study and the solution was injected. Care was taken not to inject any of the high concentration headspace as the liquid level neared the bottom of the bottle.

Five tests were conducted with the full tracer solution. In situ hold times for the second baseline study were 1 hour, 4 hours, 12 hours, 24 hours, and 48 hours. Once again

dissolved oxygen in the tank was measured to confirm that anaerobic conditions existed at the port of interest. The measured D.O. concentration prior to each test was <1 mg/L. The temperature during the second baseline study ranged from 15 to 18°C. Injection and extraction volumes for the second baseline study are given in Table 3.4.

Test #	Hold Time (hrs)	Injected Volume (L)	Extracted Volume (L)
1	1	0.760	7.160
2	4	0.750	8.305
3	12	0.760	11.105
4	24	0.780	8.555
5	48	0.750	11.53

Table 3.4: Injection and Extraction Volumes for Second Baseline Tracer Study (January 1997)

Extracted sample collection was done in 10-L Tedlar bags. Bags were triple-rinsed with pure medical air prior to sample collection. The headspace volume in each 10-L bag was 1-L of medical air. The target volume of water collected in the bags was 1-L, although volumes generally exceeded this value. The samples were allowed to equilibrate before headspace analysis. After the last consecutive sample was collected in the 1-h, 4-h, 12-hr, and 48-h runs, the tank was allowed to sit undisturbed for a minimum of 3 hrs before a final sample was collected. This was done to determine whether or not an SF_6 "spike" occurs after a resting period. Time constraints prevented this procedure from being done after the 24-hour run.

The Tedlar bag headspace was analyzed using the Lagus tracer gas analyzer. Samples were removed from the bags using a 5 mL Hamilton gas-tight syringe and

injected directly to the front sampling port. After the headspace had been analyzed on a given bag, the water was drained into a 1-L graduated cylinder to measure the volume collected. A sample of the water from each bag was reserved for bromide and acetate analysis on the IC. Results for the second baseline study are given in Table 3.5. Data from the 12-h tank experiment show results for SF_6 only. Due to a malfunction of the IC autosampler, several samples from the 12-h test were lost. Reliable recovery data could not be obtained from the remaining samples.

Test #	Hold Time (hrs)	Volume Extracted (L)	SF_6 Recovery (%)	Adj. SF_6 Recovery (%)	Acetate Recovery (%)	Adj. Acetate Recovery (%)	Bromide Recovery (%)
1	1	7.160	17.2	18.9	81.3	89.4	90.9
2	4	8.305	43.0	45.9	73.5	78.5	93.6
3	12	11.105	50.7	Data not available			
4	24	8.555	37.9	40.9	64.9	70.1	92.6
5	48	11.530	13.6	16.0	0.0	0.0	84.9

Table 3.5: Recovery Data for Second Baseline Tracer Study (January 1997)

As in the first baseline study, the majority of the bromide is recovered in the first few liters of water. Between 85 and 95% of the initial mass of bromide is recovered in the second set of baseline tank experiments. This is somewhat lower than previous recovery results for bromide, particularly for the 1-hour and 48-hour experiments. The recovery data, however, confirms the use of bromide as a conservative tracer in this research.

As the holding time in the tank increased, the maximum recoverable amount of acetate decreased as in previously reported results. The recoverable acetate at 1-h and 4-h holding times is significantly lower in the more recently completed runs. Given the low

recovery of bromide in these runs, it is hard to distinguish whether these results are from biodegradation or a lowered response in the analytical equipment. The maximum recoverable acetate after 24 hrs was 70.1% (adjusted) in this data set. The previous study determined that only 46.3% (adjusted) of the initial mass of acetate was recoverable at the same holding time. This discrepancy may be explained by a much lower water temperature and corresponding decrease in reaction kinetics. The water temperature dropped from 30° C in September to 18° C in January.

The SF_6 data remain somewhat scattered even under controlled conditions. Recoverable amounts of SF_6 vary from 17.2% in the 1-h run to 50.7% in the 12-h run. The 1-h run has an unusually low recovery and is probably not representative of the actual SF_6 behavior. This may be due to a small amount of the 10 ppmv SF_6 solution used in the incorporation procedure reaching the initial mass sample bag. This would result in an overestimated initial mass value. This seems likely given the results of the other 3 tests. The range in recovery excluding the 1-h run is 37.9% to 50.7%. The SF_6 data seem to imply that the final amount recovered is not necessarily linked to the holding time since the 12-h run has the highest recovery. Recovery may, instead, be influenced by trapped air in the model aquifer and inherent method errors from run to run.

3.4b Tracer Experiments with Air Injection

Following the baseline experiments, the air compressor was connected to the tank at the air inlet valve for sparging experiments. The compressor is a DeVilbiss Model F5020 with a 20 gallon air tank. An onboard pressure regulator allows control of the

exiting air pressure. A plastic hose rated for use with compressors was used to connect the compressor to the tank. In order to regulate flow to the tank, a Dwyer 50 scfm flow meter was placed in line between the compressor and the tank.

Initially, tank experiments were planned at several flow rates to determine what effect, if any, the flow rate had on tracer behavior. Once the compressor was connected, however, significant variations in flow rate were observed. Setting the flow to approximately 5 scfm resulted in fluctuations between 2 and 8 scfm within a few minutes of start up. Adjustments to both the pressure regulator and the flow meter were made in attempt to better control the flow but did not produce noticeable improvements. Raising the flow rate above the range of fluctuation caused the compressor to cycle at a frequency exceeding the manufacturer's recommendation. Consequently, the flow was reduced and held at 5 $\pm$ 3 scfm.

Dissolved oxygen (D.O) was measured at several sampling ports prior to air injection to determine the background D.O. throughout the tank. All measurements were <2 mg/L. After air injection had begun, D.O. was monitored periodically at several points to identify areas of the tank that were influenced by the injected air. Dissolved oxygen measurements leveled off within 6 hours of starting air injection. One point with high (>6 mg/L) D.O. and another with low (<1 mg/L) D.O. were selected to test the multi-tracer solution. The chosen sampling points are shown in Figure 3.6.

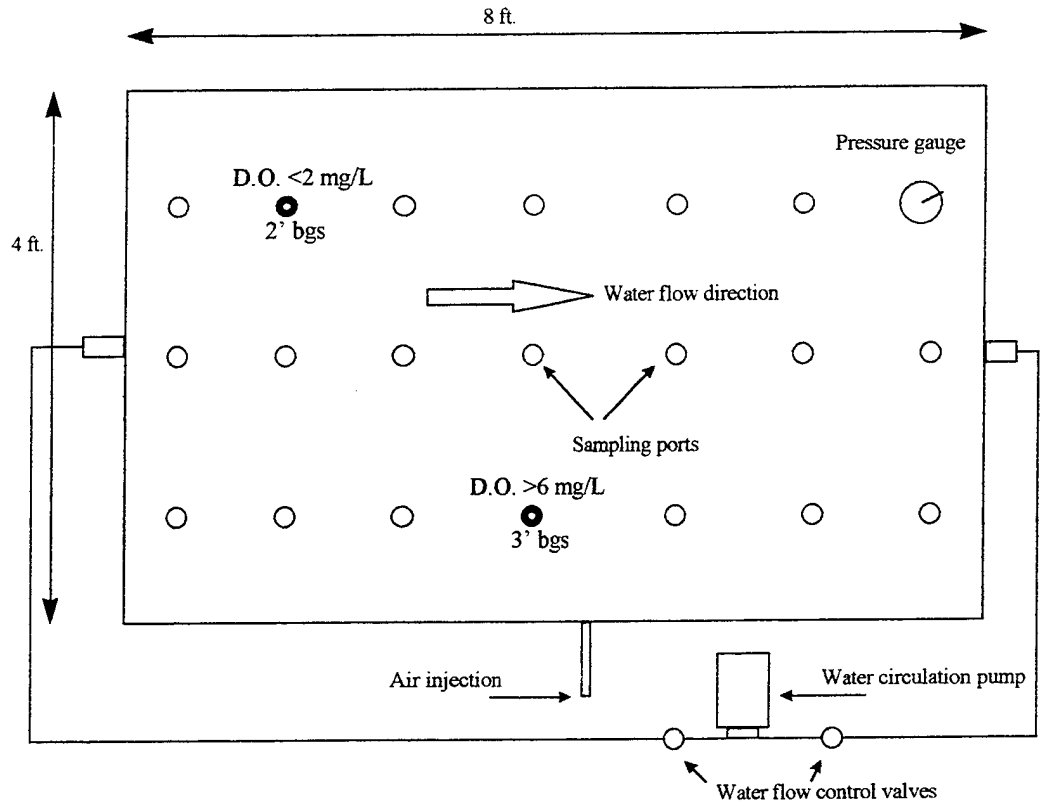

Figure 3.6: Plan View of Sampling Points Utilized for Air Injection Experiments

The solution preparation and push-pull methods for the air injection tests were identical to those used in the baseline studies. In situ hold times for these tests were 1 hour, 4 hours, 24 hours, and 48 hours. The water temperature in the tank ranged from 27°C to 33°C during these tests. The initial solution for each sampling point was prepared separately. A lag time between the two injections was desired because it allowed time to extract several liters from the first port before extraction from the second port started. Injection and extraction volumes for the each test are given in Tables 3.6 and 3.7.

Test #	Hold Time (hrs)	Injected Volume (L)	Total Extracted Volume (L)
1	1	0.760	8.325
2	4	0.750	8.565
3	24	0.740	8.750
4	48	0.770	8.660

Table 3.6: Injection and Extraction Volumes for Affected Sampling Point

Test #	Hold Time (hrs)	Injected Volume (L)	Total Extracted Volume (L)
1	1	0.770	7.885
2	4	0.740	8.050
3	24	0.760	9.030
4	48	0.740	9.035

Table 3.7: Injection and Extraction Volumes for Unaffected Sampling Point

SF_6 analysis of these samples was done on an SRI 8610C gas chromatograph (GC) equipped with an ECD as well as the Lagus SF_6 detector. The use of the Lagus instrument for field work at Port Hueneme at the same time necessitated the use of the GC. Standards were prepared using medical air and the 100 ppmv SF_6 standard to achieve concentrations of 100 ppbv, 50 ppbv, 10 ppbv, 1 ppbv, and 0.25 ppbv. A blank was used to complete the standard curve. The reliable detection limit for the GC is approximately 1 ppbv, although the 0.25 ppbv standard consistently yielded a response. Concentrations lower than 1 ppbv were recorded and included in calculating the % SF_6 recovered but are not likely to be as accurate as results from the Lagus detector in this range.

The results of the multi-tracer experiments with air injection are given in Tables 3.8 and 3.9. These tables list in situ hold time, volume extracted, and the tracer recovery. Adjusted recoveries are shown for both SF_6 and acetate. Recall that adjusted recovery is the percentage of SF_6 or acetate normalized to a bromide recovery of 100%. The concentration and recovery profiles are also shown graphically in Figures 3.7 through 3.22.

Test #	Hold Time (hrs)	Volume Extracted (L)	SF_6 Recovery (%)	Adj. SF_6 Recovery (%)	Acetate Recovery (%)	Adj. Acetate Recovery (%)	Bromide Recovery (%)
1	1	8.325	56.2	55.9	81.0	80.5	100.6
2	4	8.565	21.5	22.6	52.4	55.0	95.3
3	24	8.750	35.1	36.6	23.6	24.6	96.0
4	48	8.660	16.2	17.9	0.0	0.0	90.3

Table 3.8: Recovery Data for the Affected Sampling Point

Test #	Hold Time (hrs)	Volume Extracted (L)	SF_6 Recovery (%)	Adj. SF_6 Recovery (%)	Acetate Recovery (%)	Adj. Acetate Recovery (%)	Bromide Recovery (%)
1	1	7.885	48.5	49.6	88.1	90.1	97.8
2	4	8.050	39.6	33.9	83.5	71.6	116.7
3	24	9.030	38.6	41.5	50.5	54.3	93.0
4	48	9.035	43.2	40.9	0.0	0.0	105.6

Table 3.9: Recovery Data for the Unaffected Sampling Point

As in the baseline studies, bromide recovery is high for all tests at both points. In three cases the bromide recovery exceeds 100%. This likely is due to a combination of inherent experimental error and residual bromide remaining in the tank from previous

experiments. The fact that bromide recoveries are >90% at the point affected by the sparge air as well as the one which is not affected confirms the use of bromide as a conservative tracer for the multi-tracer push-pull method.

Acetate recovery again decreases as the in situ hold time is increased at the unaffected point, confirming the results of the previous baseline studies. The decrease in recovered acetate at the unaffected point seems to be similar to that in the first baseline study (Table 3.3). The decrease in acetate within the first 24 hours in situ was much slower in the second baseline test. The water temperature in the tank during the air injection tests was in the same range as it was during the first baseline test so this behavior is not surprising. The change in the rate of acetate degradation with temperature indicates that monitoring the ground water temperature during push-pull tests in the field is necessary. While large fluctuations in ground water temperature are not expected, the data should be available when evaluating multi-tracer push-pull results from different times of the year.

Comparison of the acetate recoveries obtained at the affected and unaffected points indicates that degradation is indeed occurring faster within the air flow zone. This behavior was seen on smaller scale during laboratory experiments (Appendix A). At a 1 hour in situ hold time the difference in recoveries was only 10%. After 24 hours in the tank, however, recoveries differed by roughly 30% between the affected and unaffected ports. The 48 hour in situ hold time was too long to distinguish between the affected and unaffected regions of the tank. The results suggest two things. First, acetate appears to a reasonable component for distinguishing conditions inside and outside the air flow zone.

Second, an in situ hold time between 4 and 24 hours (approximately) should be appropriate for assessing mass transfer rates at points affected and unaffected by an IAS well. This large window allows the tracer solution to be used for short term (e.g. pilot test) applications where a fast test is desired as well as long term monitoring applications where more time may be preferable.

SF_6 recoveries under sparged conditions varied as in the baseline tests. SF_6 recoveries at the unaffected point seem to have a narrower range than what was seen in the baseline tests. Since a different point was used for these tests, this behavior may be attributable to the soil characteristics, such as trapped air, at the unaffected point. By comparison, the SF_6 recoveries at the affected point appeared to vary unpredictably. The recovery of a volatile compound would be expected to decrease as the length of time that it is exposed to air flow increases. This trend is seen in the data overall, but the results from point to point vary. Such variation may indicate that SF_6 is better suited as a qualitative tool. The fact that the SF_6 recoveries at the affected point are generally lower than those at the unaffected point confirm this conclusion.

Figures 3.7 through 3.22 show typical behavior for the individual components of the multi-tracer solution. The concentration profiles show that the first liter of water extracted contains a relatively high concentration of all three components. Concentrations in subsequent volumes drop off quickly for acetate and bromide and somewhat slower for SF_6. An associated increase in dissolved oxygen is seen as water which was not impacted by the tracer solution is extracted from the affected point.

The tracer recovery profiles show the corresponding rise in % recovered with each extracted volume. Acetate and bromide are seen to be recovered within the first 2-3 liters of solution, after which the tracer recovery curve flattens off. The SF_6 curve, however, rises slowly and does not reach an asymptotic level. This behavior may be due to the retardation effect of trapped air in the subsurface on dissolved gas transport as discussed by Fry et al. (1995) and Donaldson et al. (1997).

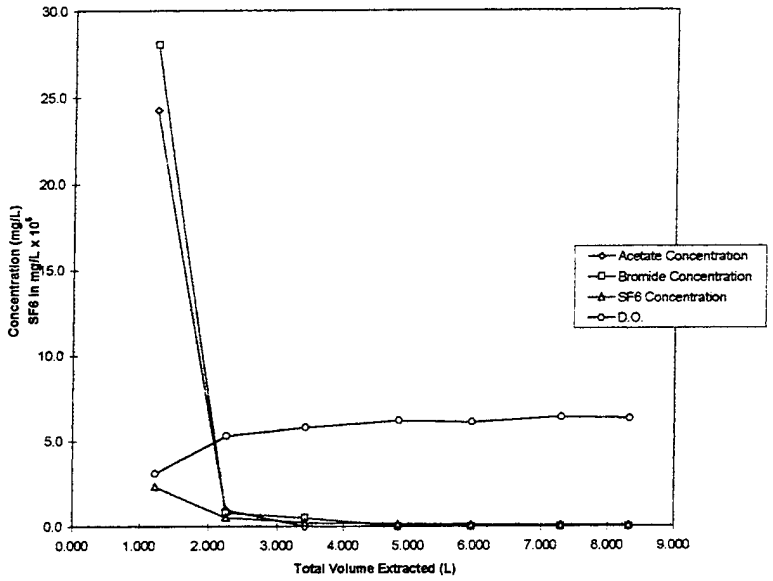

Figure 3.7: Concentration Profile at Affected Point - 1 Hour

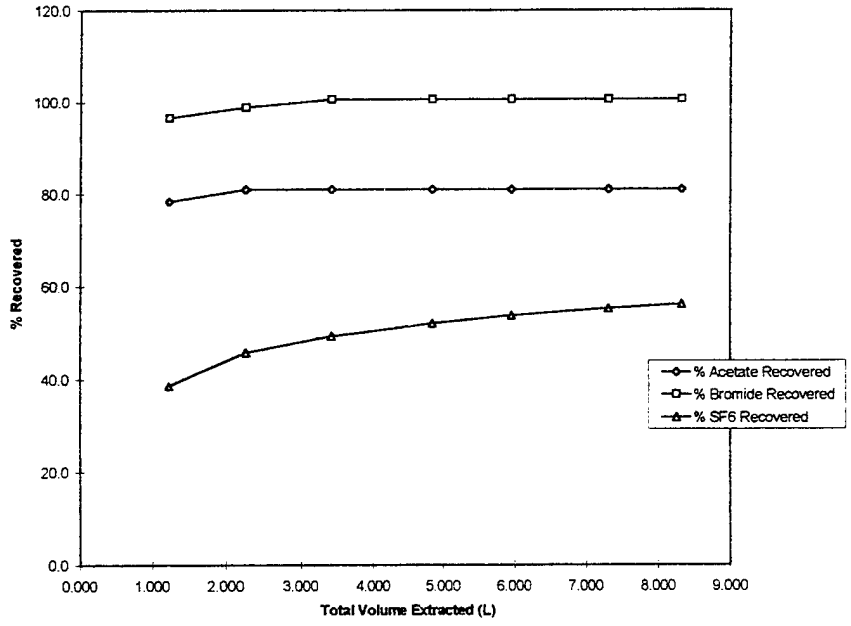

Figure 3.8: % Tracer Recovered at Affected Point - 1 Hour

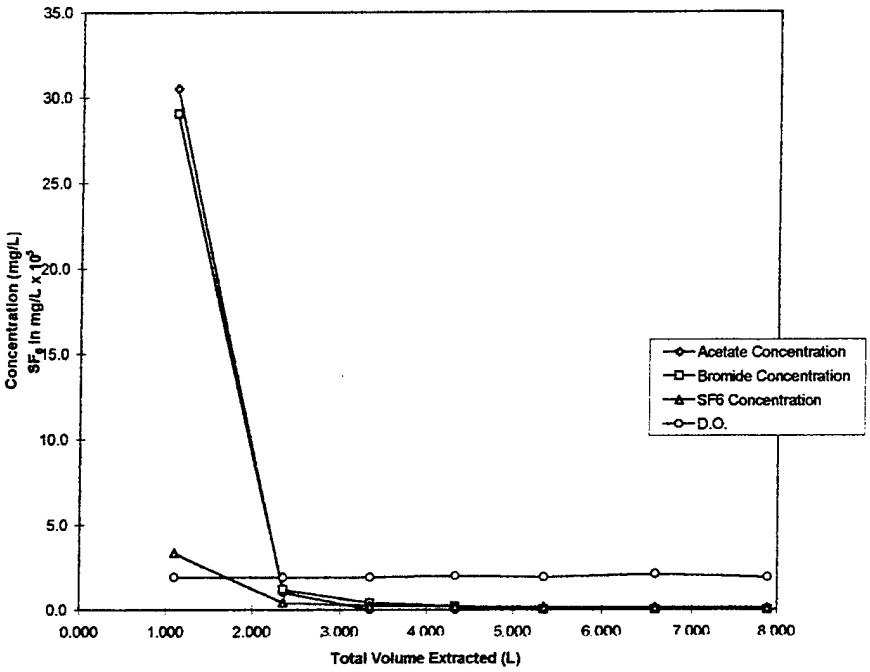

Figure 3.9: Concentration Profile at Unaffected Point - 1 Hour

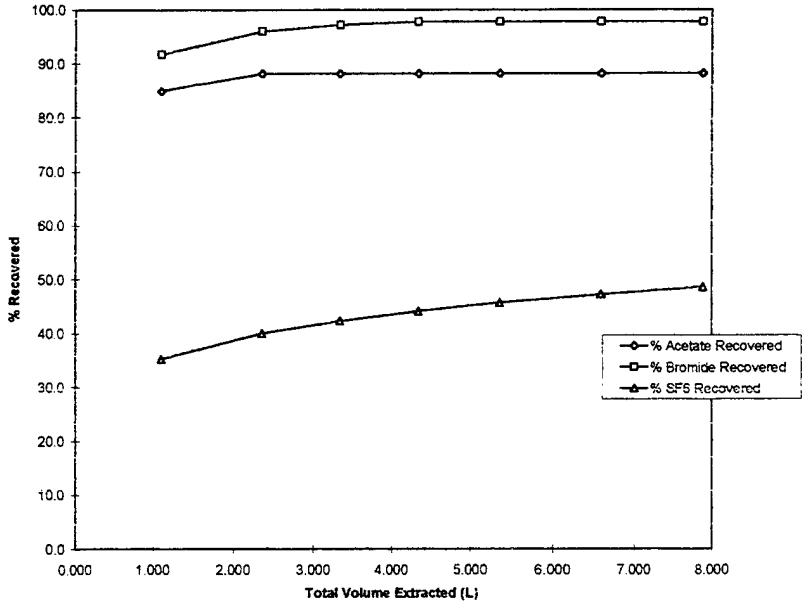

Figure 3.10: % Tracer Recovered at Unaffected Point - 1 Hour

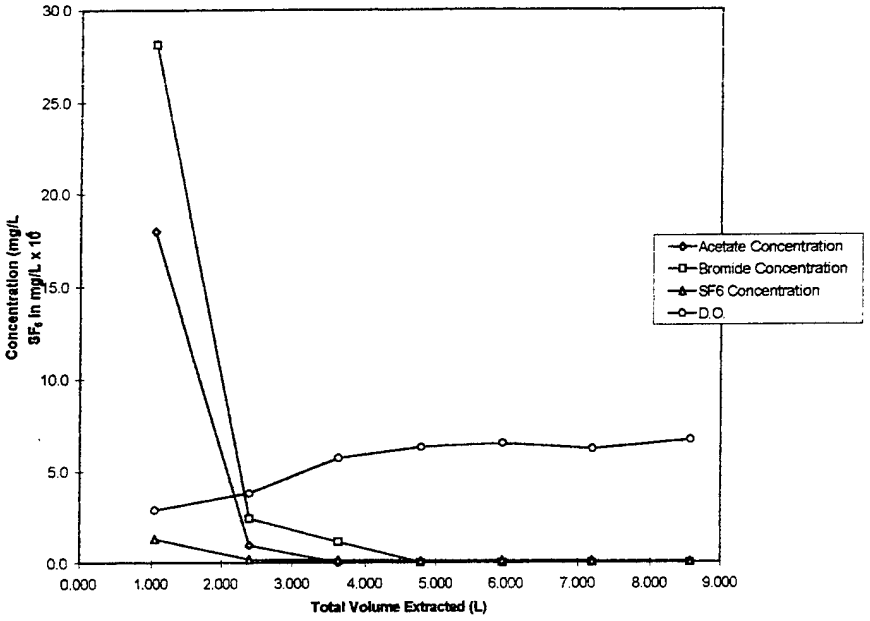

Figure 3.11: Concentration Profile at Affected Point - 4 Hours

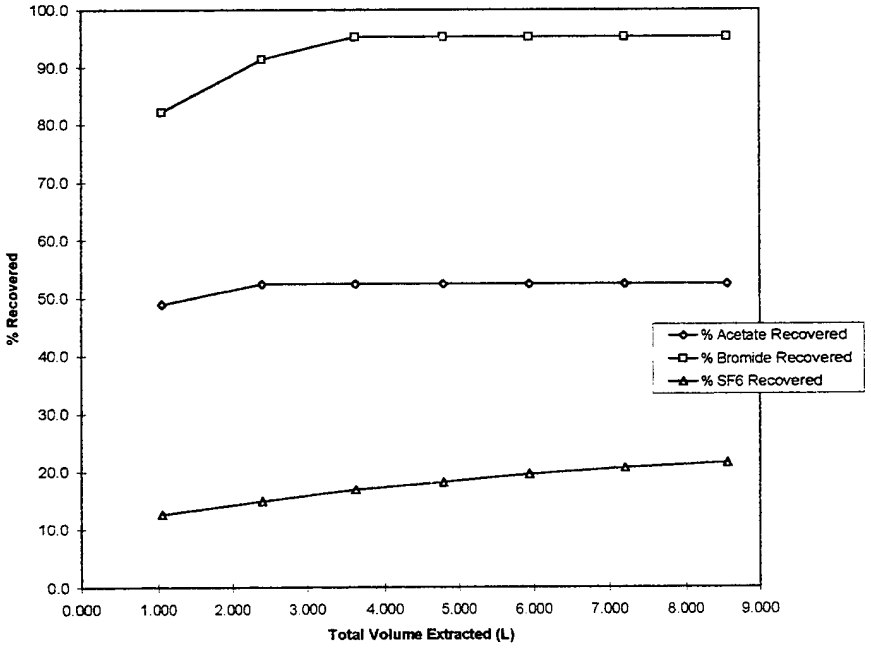

Figure 3.12: % Tracer Recovered at Affected Point - 4 Hours

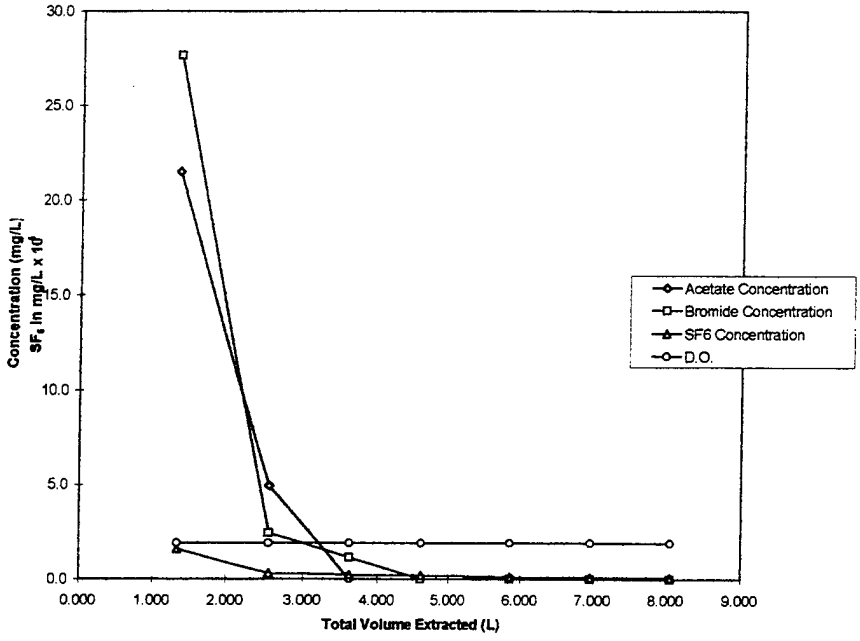

Figure 3.13: Concentration Profile at Unaffected Point - 4 Hours

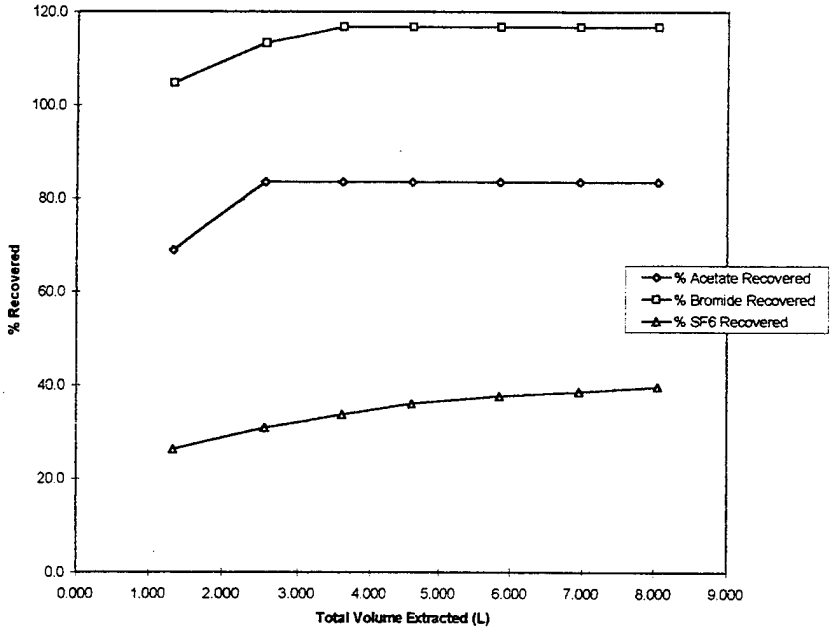

Figure 3.14: % Tracer Recovered at Unaffected Point - 4 Hours

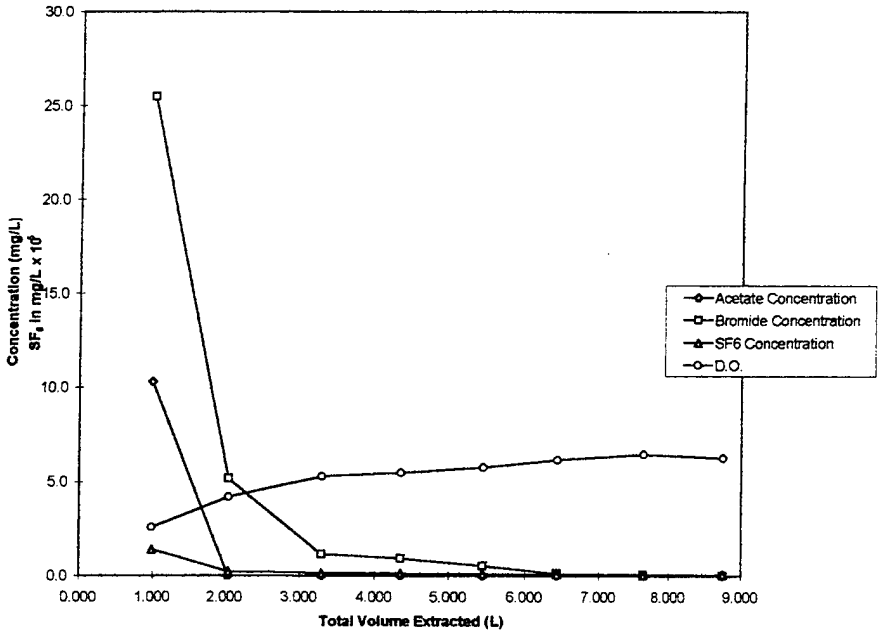

Figure 3.15: Concentration Profile at Affected Point - 24 Hours

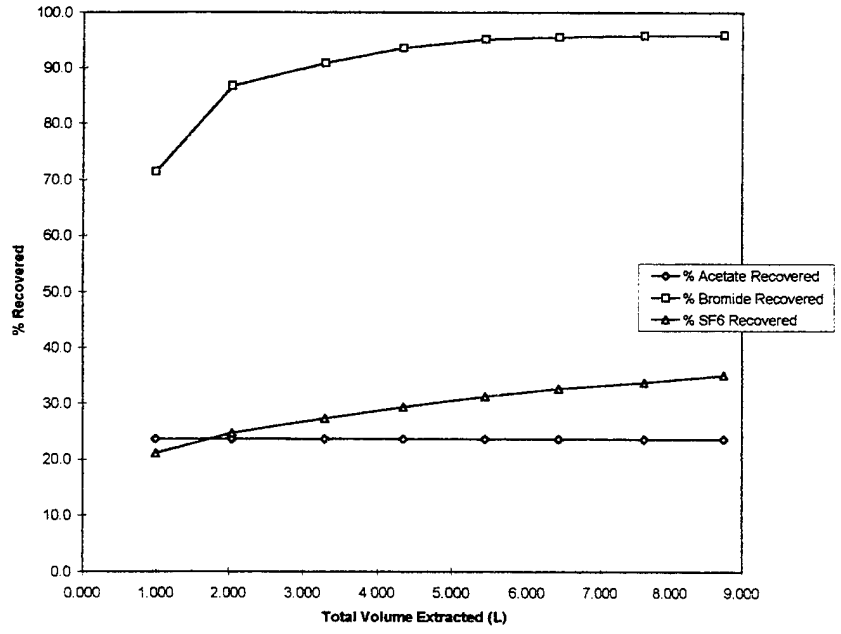

Figure 3.16: % Recovered at Affected Point - 24 Hours

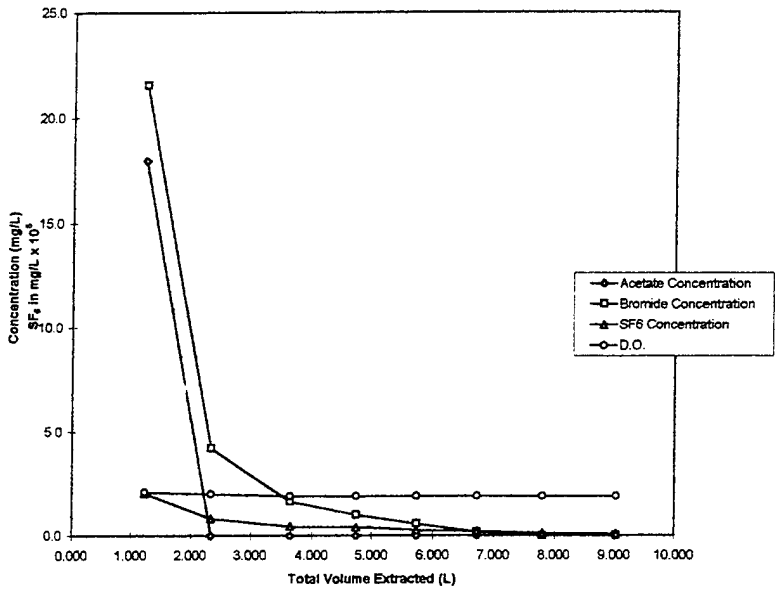

Figure 3.17: Concentration Profile at Unaffected Point - 24 Hours

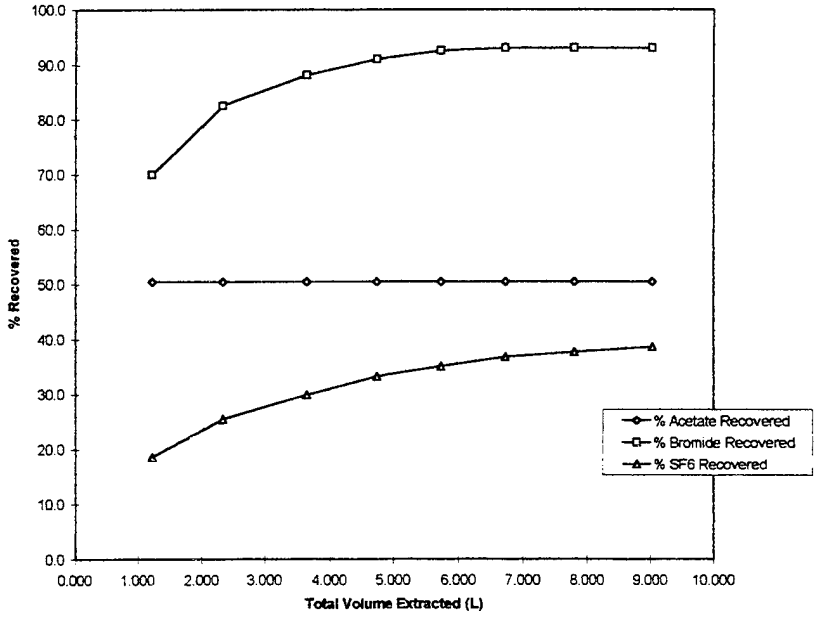

Figure 3.18: % Tracer Recovered at Unaffected Point - 24 Hours

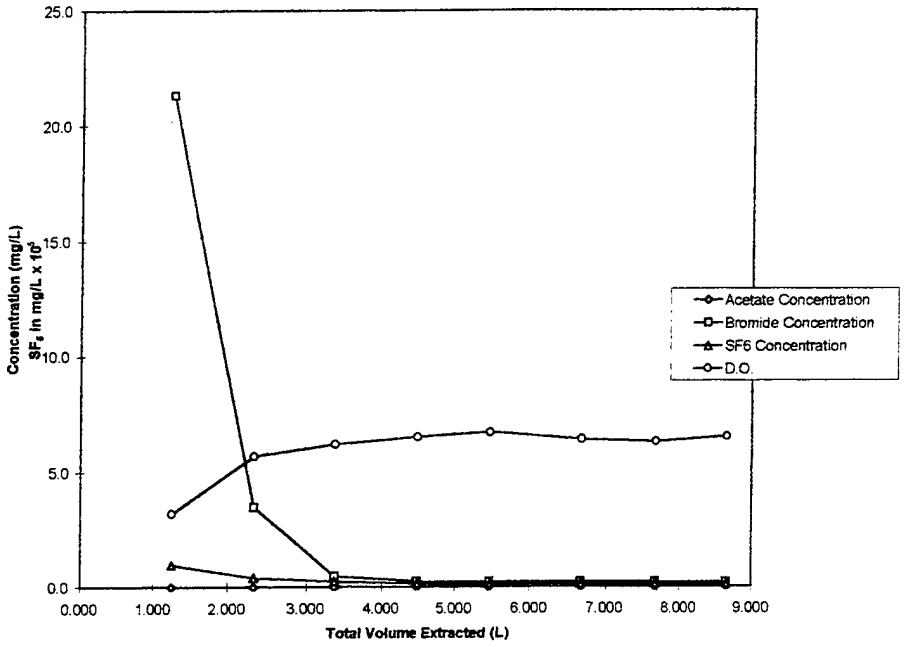

Figure 3.19: Concentration Profile at Affected Point - 48 Hours

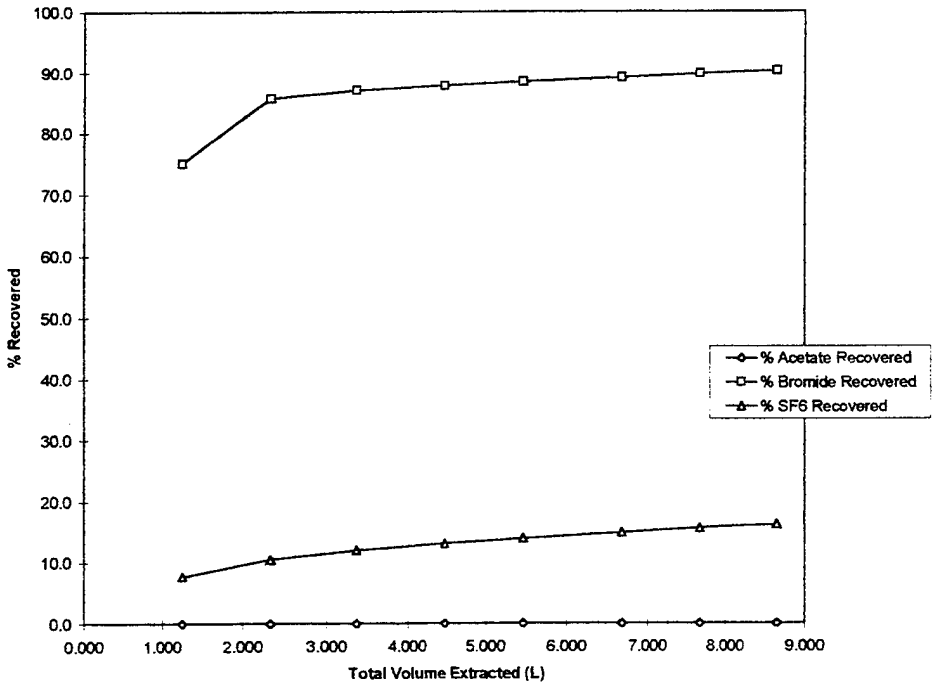

Figure 3.20: % Tracer Recovered at Affected Point - 48 Hours

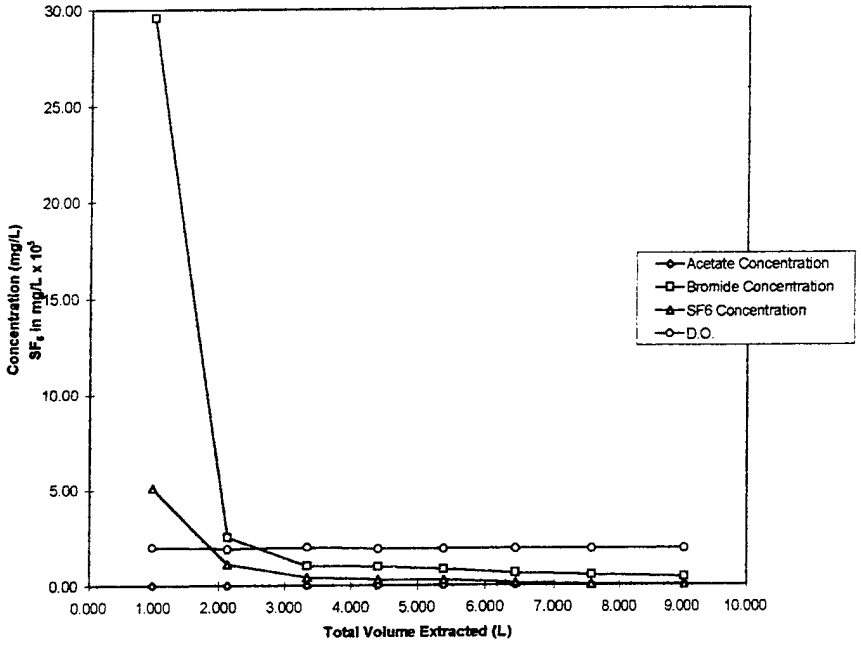

Figure 3.21: Concentration Profile at Unaffected Point - 48 Hours

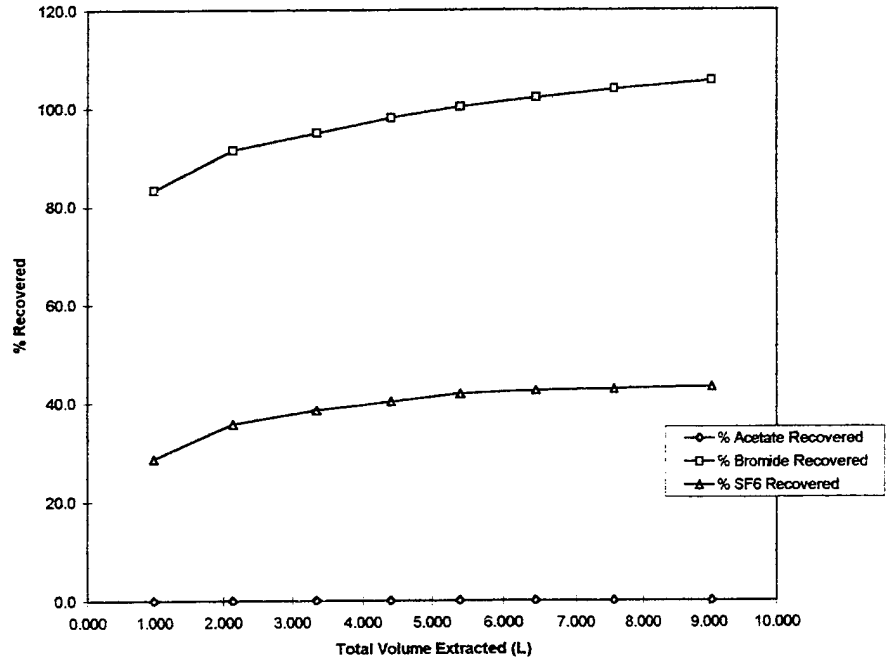

Figure 3.22: % Tracer Recovered at Unaffected Point - 48 Hours

4. Preliminary Field Tests - Multi-Tracer Solution

Field tests of the tracer solutions were conducted at the United States Naval Base at Port Hueneme, California. The field site is a National Environmental Test Site and offers significant logistical support for research projects. Two sites at the base are currently being used for research involving IAS systems. Site 1 is the former location of the Navy Exchange (NEX) gasoline station and has been impacted by petroleum hydrocarbons. Residual non-aqueous phase gasoline continues to be a source of dissolved phase contaminants at Site 1. Site 2 is downgradient of Site 1 and is contaminated with dissolved phase hydrocarbons only. The constituents of concern at both sites are benzene, toluene, ethylbenzene, total xylenes, and methyl tert butyl ether. Tests discussed in this thesis were conducted in the source zone at Site 1.

The field site was chosen because it has been well characterized and has an extensive vadose zone and saturated zone monitoring network in place. Ground water at the site is approximately 10 feet below ground surface and flows in a southwesterly direction. There are 6 conventional monitoring wells and 12 monitoring points installed at Site 1. Each monitoring point contains a bundle of 15 monitoring ports with one port every foot between 10' and 19' BGS and one port every 2 feet from 2' to 8' BGS, inclusive. These ports are constructed of 1/8" stainless steel tubing and color coded according to depth. Stainless steel 1/8" Swagelok compression fittings at the top of each port allow connections to be made with a peristaltic pump. As shown in Figure 4.1, the IAS well is located approximately in the center of the site and is screened from 13' to 19' BGS.

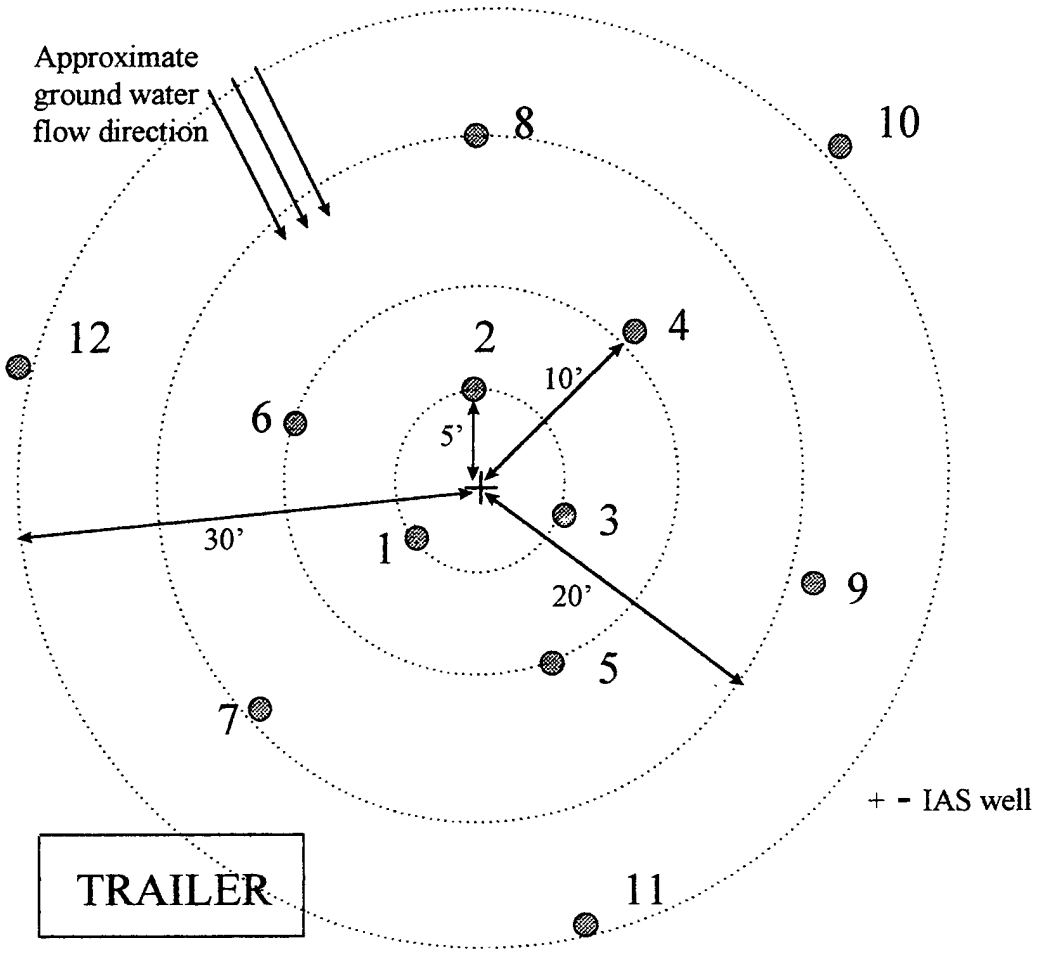

Figure 4.1: Monitoring Point Layout at Port Hueneme Site 1

Field tests were conducted at Port Hueneme at four separate times. The first set of tests, conducted in October 1996, was limited in scope and the results are considered to be preliminary data. They are discussed in this chapter. Full field implementation was done between June and September 1997 and is described in Chapter 5.

4.1 Preliminary Field Data:

The opportunity to conduct some preliminary, limited scope field experiments with the multi-tracer solution presented itself in fall 1996. The preliminary tests were conducted to assess the tracer solution's behavior in regions inside and outside the air flow zone and to compare the acquired data to that collected thus far in the tank. The resulting data were used to refine test methods and conditions for subsequent tank experiments. In addition, valuable insight into scaling up experimental procedures for field implementation was gained.

The multi-tracer push-pull field experiments were conducted October 19-20, 1996 and October 24-28, 1996. Experiments were conducted using the 10' BGS and 17' BGS ports of monitoring point 10 (MP-10-10 and MP-10-17), the 12' BGS port of monitoring point 3 (MP-3-12), and the 15' BGS port of monitoring point 4 (MP-4-15). Three experiments were conducted during preliminary activities: 1) baseline tracer recovery at several *in situ* hold times prior to system startup, 2) SF_6 recovery at two depths to assess the impact of trapped air on recovery, and 3) tracer recovery under deoxygenated and oxygenated conditions following system startup. MP-10 is a peripheral point and was chosen for the tracer recovery studies prior to the IAS system start up. MP-10-10 and MP-10-17 were selected to observe the effect of subsurface trapped air on SF_6 recovery. The MP-10-17 injection consisted only of SF_6 dissolved in distilled water. The in situ hold time for the test was 5 minutes. MP-3-12 and MP-4-15 were chosen for tests under deoxygenated and oxygenated groundwater conditions, respectively, after system startup. The ports were selected on the basis of dissolved oxygen readings taken before and after

system startup. With the exception of the SF_6 recovery experiment, the full multi-tracer solution was injected into the subsurface. The acetate and bromide ion concentrations were approximately 50 mg/L. The initial mass of SF_6 was generally on the order of 10^{-7} g total.

4.1a Procedures

In order to facilitate solution preparation, 50 g/L acetate and bromide ion stock solutions were prepared at ASU and diluted in the field. The bromide and acetate stock solutions were prepared with 14.89 g of KBr and 13.90 g of NaAc, respectively. Each chemical was added separately to a clean 200 mL volumetric flask which had been triple-rinsed with distilled, deionized (DDI) water. The flask was filled to approximately 1/3 volume with DDI water and gently shaken to dissolve the dry chemicals. Once the KBr and NaAc were dissolved, the solution was brought to volume with DDI water. The flask was covered with Parafilm® and shaken to ensure complete mixing of the solution. The acetate stock solution was kept in several individual 40 mL VOA vials with septa. A new vial was used each day to prepare the tracer solution. The bromide was stored in a 250 mL Nalgene bottle. The acetate and bromide stock solutions were diluted for each push-pull experiment by adding 0.9 mL of each stock solution to 900 mL of distilled water, giving the desired concentration of 50 mg/L (approximate). The bromide and acetate stock solutions were extracted using a 2 mL glass syringe and attached needle and added to a 1 L graduated cylinder marked in 10 mL intervals . The syringe was triple-rinsed with distilled water between stock solutions. The solution was brought to volume in the graduated cylinder with distilled water and then transferred to a 1 L glass bottle. Four

drops of fluorescein dye were added to the tracer solution in the experiments conducted between October 24 and October 28, 1996 to give a visual indication of the recovery of the tracer solution.

SF_6 was incorporated into the tracer solution using the apparatus shown in Figure 3.2. A peristaltic pump was used to circulate air through the bottle. A 5 mL Hamilton gas-tight syringe was used to inject 1 mL of 1 ppthv SF_6 into the air stream in the bottle, resulting in an approximate headspace concentration of 10 ppmv SF_6. The air and SF_6 headspace was allowed to circulate for 30 to 40 minutes in each run. After adequate circulation of the headspace air, the pump was stopped and the tubing disconnected ahead of the T connection. The pump was operated in the reverse direction to purge the remaining10 ppmv SF_6 vapor from the tubing. The tubing was then connected to a 1-L Tedlar bag with 100 mL medical air headspace to collect a sample of the tracer solution for determining the initial mass of each component. Approximately 80 mL of the initial tracer solution was collected for this purpose.

After collecting the initial mass sample, the tubing from the SF_6 incorporation apparatus was connected to the selected injection port and the tracer was pumped into the ground. The volume of tracer injected ranged from 800 mL to 830 mL. After a predetermined in situ hold time, the pump was reversed and several liters of water were extracted at discrete increments. In situ hold times for each monitoring point utilized were as follows:

Monitoring Point	Injection Port Depth	In Situ Hold Times
MP-10	10'	5-min, 1-h, 4-h
MP-10	17'	5-min
MP-3	12'	1-h
MP-4	15'	1-h

Both 10-L and 1-L Tedlar bags were used for sample collection. Bags were triple-rinsed with pure medical air prior to sample collection. The headspace volumes in the 10-L and 1-L bags were 1-L and 500 mL of medical air, respectively. The target volume of water collected in the larger bags was 1-L. The target volume in the smaller bags was 500 mL. The samples were allowed to equilibrate for a minimum of 30 minutes before headspace analysis.

The Tedlar bag headspace was analyzed in the field using a Lagus Applied Technologies Autotrac tracer gas analyzer. Samples were removed from the bags using a 5 mL Hamilton gas-tight syringe and injected directly to the front sampling port on the Autotrac. After the headspace had been analyzed on an individual bag, the twist-lock fitting on the bag was removed and the water drained into the 1-L graduated cylinder to measure the volume collected. A sample of the water from each bag was reserved for bromide and acetate analysis on the ion chromatograph.

Acetate and bromide were analyzed on the Dionex DX 500 Ion Chromatograph equipped with an Ionpac® AS12A analytical column, Ionpac® AG12A guard column, and electrochemical and conductivity detectors. Each time the eluent was changed a new set of standards was prepared and a three point standard curve run to calibrate the instrument's response. The standards are prepared using the two ions of interest, acetate and bromide. A response factor is determined by the slope of a linear regression line

fitted to the three standard analyses and a zero. The calibration was determined to be valid if the R^2 value of the regression was 0.99 or greater.

The subsamples of the extracted volumes were analyzed beginning with sample 1 and continuing until the acetate and bromide had disappeared or reached insignificant levels with respect to the mass recovered. Trace ions interfere with the acetate peak at low (<1 mg/L) concentrations. The acetate peak area was adjusted for these peaks using the average peak areas of the interfering ions in samples of unaffected groundwater.

4.1b Preliminary Field Results

The first set of field tests was similar to the anaerobic baseline study conducted in the 4'x 4'x 8' experimental tank. Dissolved oxygen levels at this monitoring point were <2 mg/L. The tests were conducted to gain information on the maximum recovery of the tracers at several *in situ* holding times prior to system start up. These push-pull tests were conducted in MP-10-10. The tracer recovery data are tabulated in Tables 4.1 through 4.3. The same data are presented graphically in Figures 4.2 through 4.4.

SAMPLE	Tot. Vol. Ext. (L)	SF_6 Recovery (%)	Ac Recovery (%)	Br Recovery (%)	SF_6 adj (%)	Ac adj (%)
MP10-10-5-init						
MP10-10-5-1	0.865	11.1	18.2	46.8		
MP10-10-5-2	1.860	15.0	18.2	61.4		
MP10-10-5-3	2.815	17.5	18.2	71.7		
MP10-10-5-4	3.250	18.7	18.2	76.2		
MP10-10-5-5	3.660	21.8				
MP10-10-5-6	4.145	22.7	18.2	80.9		
MP10-10-5-7	4.640	23.7	18.2	85.4		
MP10-10-5-8	5.125	24.6	18.2	89.5		
MP10-10-5-9	5.545	25.3	18.2	93.0	27.3	19.5

Table 4.1: Tracer Recovery Data for a 5-Minute In Situ Hold Time - MP10 at 10' BGS

SAMPLE	Tot. Vol. Ext. (L)	SF_6 Recovery (%)	Ac Recovery (%)	Br Recovery (%)	SF_6 adj (%)	Ac adj (%)
MP10-10-1-init						
MP10-10-1-1	0.820	8.1	1.9	49.2		
MP10-10-1-2	1.810	11.5	9.0	67.8		
MP10-10-1-3	2.780	13.9	9.0	76.0		
MP10-10-1-4	3.695	15.8	9.0	82.0		
MP10-10-1-5	4.125	16.3	9.0	84.6		
MP10-10-1-6	4.540	16.8	9.0	87.0		
MP10-10-1-7	4.970	17.4	9.0	89.4		
MP10-10-1-8	5.430	18.2	9.0	92.0	19.8	9.8

Table 4.2: Tracer Recovery Data for a 1-Hour In Situ Hold Time - MP10 at 10' BGS

SAMPLE	Tot. Vol. Ext. (L)	SF_6 Recovery (%)	Ac Recovery (%)	Br Recovery (%)	SF_6 adj (%)	Ac adj (%)
MP10-10-4-init						
MP10-10-4-1	0.950	24.6	19.2	39.4		
MP10-10-4-2	1.950	32.9	19.2	51.3		
MP10-10-4-3	2.780	37.2	19.2	58.8		
MP10-10-4-4	3.700	39.8	19.2	66.1		
MP10-10-4-5	4.180	41.7	19.2	69.5		
MP10-10-4-6	4.640	43.1	19.2	72.6		
MP10-10-4-7	5.140	44.7	19.2	75.9		
MP10-10-4-8	5.585	46.0	19.2	78.6	58.5	24.4

Table 4.3: Tracer Recovery Data for a 4-Hour In Situ Hold Time - MP10 at 10' BGS

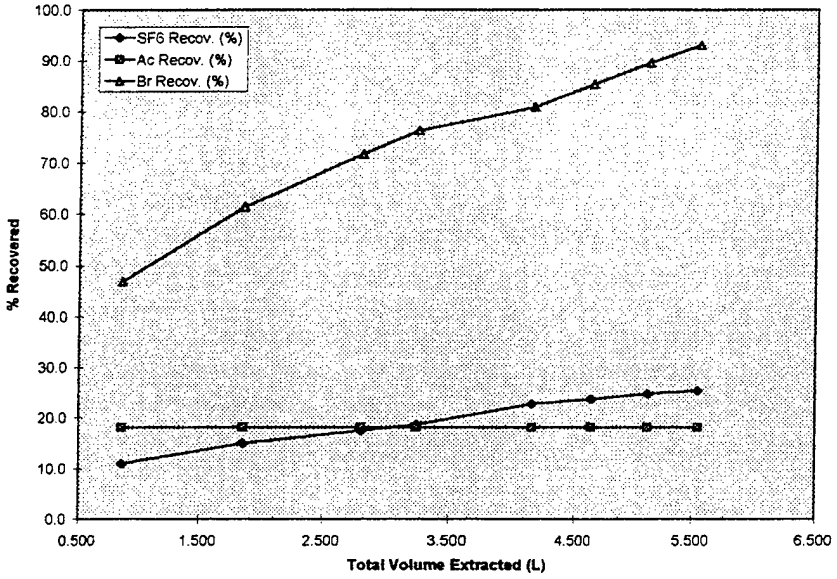

Figure 4.2: % Tracer Recovered vs. Volume Extracted for a 5-Minute In Situ Hold Time - MP10 at 10' BGS

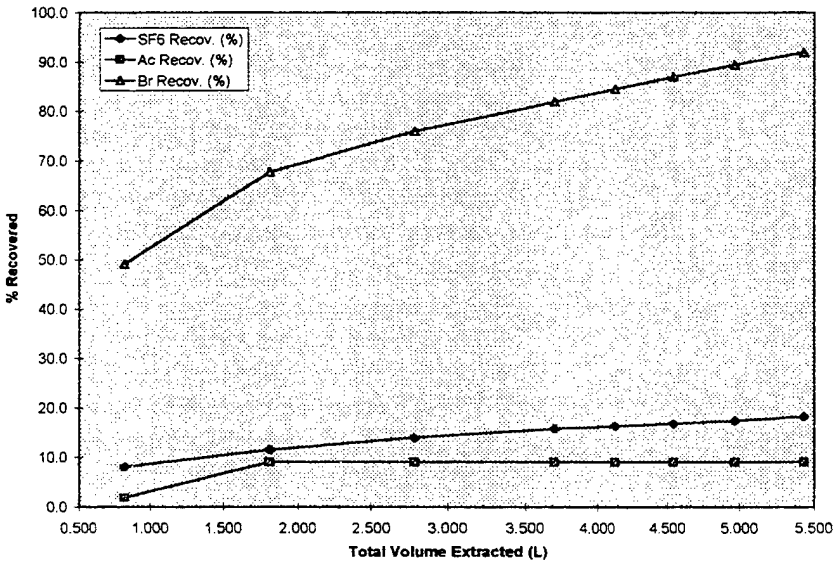

Figure 4.3: % Tracer Recovered vs. Volume Extracted for a 1-Hour In Situ Hold Time - MP10 at 10' BGS

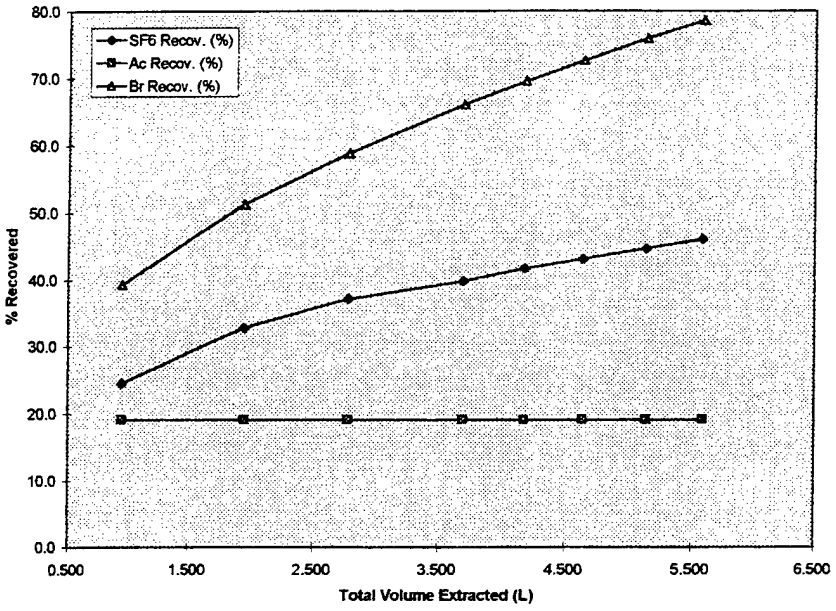

Figure 4.4: % Tracer Recovered vs. Volume Extracted for a 4-Hour In Situ Hold Time - MP10 at 10' BGS

The results of these experiments were somewhat surprising in comparison to the data collected in the experimental tank. The bromide recoveries in the 5-min, 1-h, and 4-h push-pull tests were 93.0 %, 92.0 %, and 78.6 %, respectively. The recoveries in the first two tests were as expected. The recovery in the 4-h test was unexpectedly low. This is likely due to an inadequate volume of water being extracted. Although the fluorescein dye indicator appeared to be recovered, low concentrations of fluorescein are difficult to see without a black light to show fluorescence. This was an important result from the preliminary field tests and one which led to a procedural adjustment prior to full scale field testing.

The acetate data show a decrease in recovery between the 5-minute and 1-hour tests and subsequent increase between the 1-hour and 4-hour test. The tank data

presented in Chapter 3 indicate that a steady decrease in acetate recovery should occur as the in situ hold time is increased. The poor bromide recovery in the 4-hour test, however, makes the comparison of the preliminary field data to the tank data questionable. In addition, several days passed before the ionic analysis could be done. It is likely that acetate degraded in the sample vials between collection and analysis.

The SF_6 recovery decreased from the 5-min to the 1-h push-pull test as expected. The 4-h test, however, resulted in a 27.8 % increase in SF_6 recovery over the 1-h test. This behavior is representative of SF_6 recoveries throughout this research. Because small differences in incorporation method, initial sample collection, injection rate, or soil pore space all contribute to differences in SF_6 recovery, SF_6 results were subsequently considered qualitative data rather than concrete quantitative data. The acetate data from these were considered questionable due to an excessive holding time between sample collection and analysis.

The second study involved injecting dissolved SF_6 into MP10-10-17 for a 5-min in situ holding time to assess the effect of trapped air on the recoverable mass of SF_6. The underlying assumption was that the amount of trapped air in the deeper 17-ft port was less than that near the water table in the 10-ft port. The recovery profile from this test is shown in Figure 4.5.

The recoverable SF_6 from the 10-ft port was 25.3% of the initial mass injected. By comparison, the recovery from the deeper port was 32.5%. While the recovery from the deeper well was greater, the low recoveries from both ports indicate that the presence of any trapped air will lead to rapid partitioning of SF_6 into the gas phase. The

preliminary field data concur with the tank data in the tendency for SF_6 to continue to be recovered slowly and at low concentration in each sample, rather than tapering off.

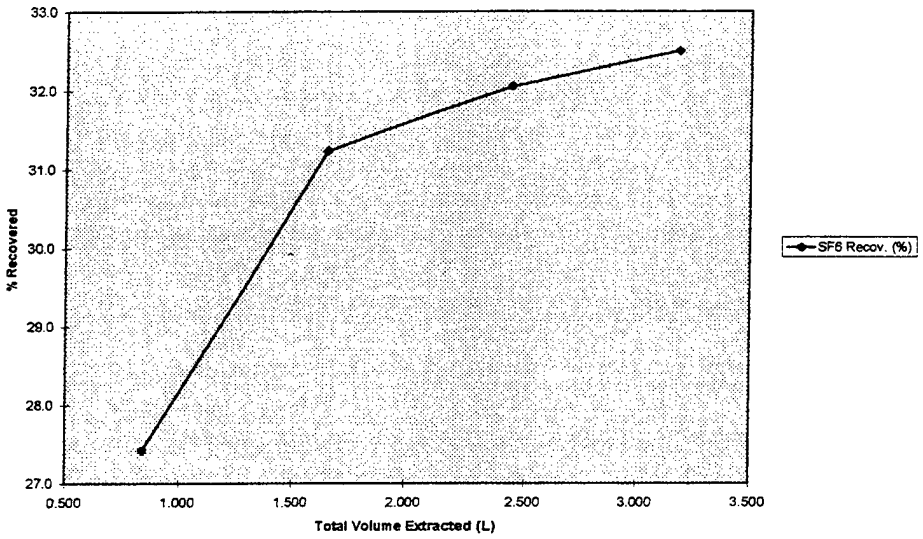

Figure 4.5: % SF_6 Recovered vs. Volume Extracted for a 5-Minute In Situ Hold Time - MP10 at 17' BGS

The last study conducted was designed to assess the effect of the air sparging system on tracer behavior. Ports MP3-12' and MP4-15' were selected as the locations for this experiment based on dissolved oxygen readings as discussed previously. Dissolved oxygen levels at MP3-12' and MP4-15' were <1 mg/L and 6.97 mg/L, respectively. The in situ holding time was 1-h in both ports. The data are listed in Tables 4.4 and 4.5. The tracer behavior in each port is shown in Figures 4.6 and 4.7.

The bromide recoveries in the deoxygenated and oxygenated ports were 100.8% and 93.6%, respectively. The raw data for acetate show recoveries of 84.6% and 79.1%, respectively, in these wells. In order to provide a better basis for comparison, the acetate

and SF_6 recoveries were adjusted to reflect their behavior relative to the conservative tracer (bromide) recovery.

The adjusted acetate recoveries in ports MP-3-12 and MP-4-15 were 83.9% and 84.5%, respectively. These recoveries are interpreted to be equivalent. Results of controlled experiments at ASU showed that acetate degradation was minimal (<7%) after 1 hour in the deoxygenated tank water. It was anticipated that the increased dissolved

SAMPLE	Tot. Vol. Ext. (L)	SF_6 Recovery (%)	Ac Recovery (%)	Br Recovery (%)	SF_6 adj (%)	Ac adj (%)
MP3-12-init						
MP3-12-1	0.800	39.8	74.1	80.8		
MP3-12-2	1.695	47.9	84.6	96.0		
MP3-12-3	2.585	49.8	84.6	98.9		
MP3-12-4	2.990	50.2	84.6	100.0		
MP3-12-5	3.420	50.8	84.6	100.8	50.3	83.9

Table 4.4: Tracer Recovery Data for a Location Unaffected by IAS System - MP3 at 12' BGS

SAMPLE	Tot. Vol. Ext. (L)	SF6 Recovery (%)	Ac Recovery (%)	Br Recovery (%)	SF6 adj (%)	Ac adj (%)
MP4-15-init						
MP4-15-1	0.740	17.3	63.2	70.4		
MP4-15-2	1.500	22.2	79.1	86.9		
MP4-15-3	2.335	25.5	79.1	90.2		
MP4-15-4	2.775	27.1	79.1	91.3		
MP4-15-5	3.240	28.2	79.1	92.3		
MP4-15-6	3.590	29.1	79.1	92.9		
MP4-15-7	4.020	30.0	79.1	93.6	32.1	84.5

Table 4.5: Tracer Recovery Data for a Location Affected by IAS System - MP4 at 15' BGS

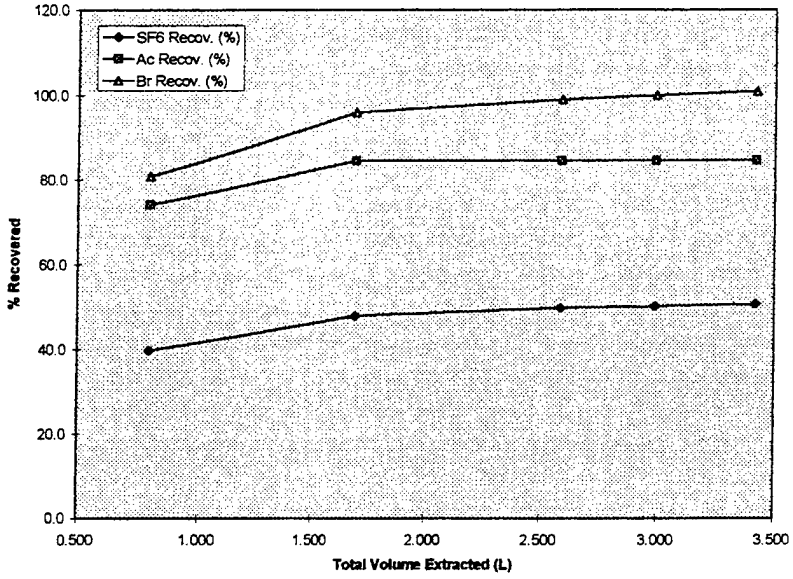

Figure 4.6: % Tracer Recovered vs. Volume Extracted for a Location Unaffected by the IAS System - MP3 at 12' BGS

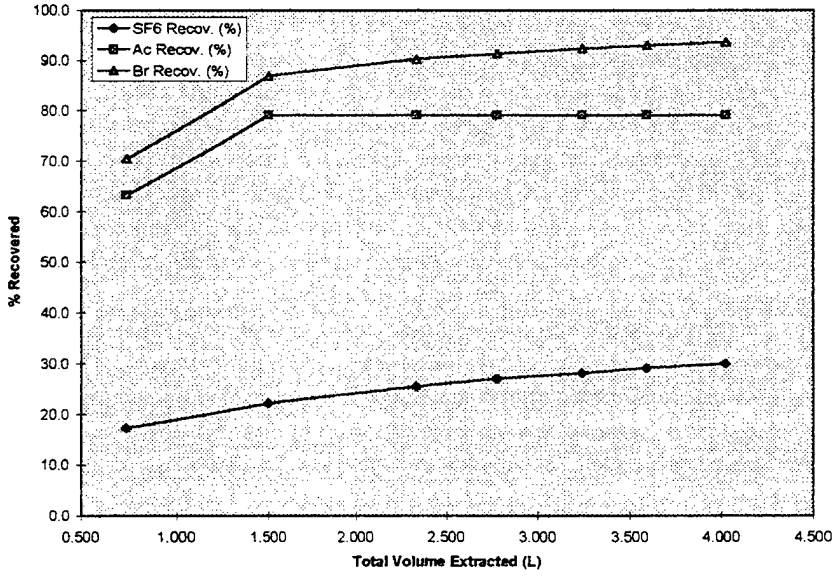

Figure 4.7: % Tracer Recovered vs. Volume Extracted for a Location Affected by the IAS System - MP4 at 15' BGS

oxygen would accelerate the compound's degradation enough that the difference in recovery between deoxygenated and oxygenated conditions would be evident. This was not the case as shown by these data. This could be due to a much lower ground water temperature (22°C) at the field site than in the tank. It is also possible that the two points were not as different in terms of the sparge system's influence as anticipated.

An extended in situ holding time was determined to be necessary for future field work based on these data. The SF_6 behaved as expected with a lower recovery in the oxygenated water than the deoxygenated water, indicating a greater amount of trapped air at the point which appears to be influenced by the sparging system.

5.0 Multi-Tracer Field Experiments

Full field implementation of the multi-tracer solution was conducted over the course of three months during the summer and early fall of 1997. Field tests were again conducted at Port Hueneme Naval Base. Push-pull field tests were conducted June 28-July 5, August 30-September 1, and September 19-September 23, 1997. The June test was conducted with the full tracer solution while the subsequent tests were conducted with bromide and acetate only. Push-pull tests were conducted at the following locations:

Field Test Date	Monitoring Points Included	Depths Included
June 28-July 5, 1997	1, 2, 4, 5, 7, 9, 11	11' BGS
August 30-September 1, 1997	1, 2, 4, 5, 9, 11	11' BGS
September 19-20, 1997	1, 2, 4, 5, 7, 9, 10, 11	11' BGS
September 21-22, 1997	1, 5, 8, 10	13' BGS
September 21-22, 1997	1, 4, 7, 9	15' BGS

5.1 Procedures:

Several modifications to the method used in the experimental tank were necessary for field implementation, although the general procedure remained unchanged. 50 g/L acetate and bromide stock solutions were again prepared prior to going to the field as described in section 4.1. The acetate solution was stored in four separate 40 mL volatile organic analysis (VOA) glass vials with septa. A new vial was used for each solution preparation in the field. The bromide was stored in a 250 mL Nalgene bottle.

Due to the volume of tracer solution required for each test, a Nalgene carboy marked in 5 L increments with attached spigot was used for the field preparation of the

tracer solution. The bottle was fitted with a venting/filling cap and flexible tubing that served the purpose of the stainless steel tubing in the smaller experimental setup. The spigot was equipped with an adapter which reduced the spigot opening from ¾" to ¼" - 3/8". A piece of 3/8" inner diameter flexible tubing was attached at the adapter to be used for solution injection. In order to ensure that the actual headspace in the bottle was known at all liquid volumes, the bottle was marked off in 1 L increments as measured with a 1 L graduated cylinder marked in 10 mL increments. The total volume of the carboy was 11.675 L. A short piece of flexible tubing attached to the inside of the vent-fill cap remained in the headspace of the carboy. A longer piece of tubing with an air stone attached extended to the bottom of the bottle for sparging the solution with N_2 or SF_6.

5.1a June 1997 Field Test

The full tracer solution was prepared for this field test. A 10mL disposable syringe was used to add 9 mL of the bromide and acetate stocks to the carboy. The solutions were diluted with distilled water to the desired total volume of 9 L. Five drops of fluorescein dye were added per liter of solution prepared to allow visual interpretation of tracer recovery during extraction. The solution was sparged with nitrogen until its D.O. concentration was less than 1 mg/L. SF_6 was incorporated into the solution via the vent-fill cap. A peristaltic pump was used to circulate the headspace gas through the solution. A Swagelok "T" fitting with septum placed in the tubing line was used to introduce 2.7 mL of 10 ppthv SF_6 in nitrogen into the carboy, yielding a 10.09 ppmv SF_6 (calculated) headspace. The SF_6 was allowed to circulate through the solution for

approximately 4 hours to ensure incorporation into the solution. An initial mass sample was collected in a N_2 rinsed 1 L Tedlar bag with a 100 mL N_2 headspace via the carboy spigot before each injection. Samples were allowed to equilibrate for at least 30 minutes before analysis. After analyzing the initial mass sample for SF_6, the bag was emptied into a 1 L graduated cylinder to determine the sample volume and a subsample was transferred to a 40 mL VOA vial for at ASU.

During each injection it was important to maintain an oxygen free headspace in the carboy while injecting the tracer solution. A nitrogen-filled 10 L Tedlar bag with twist-lock fitting was attached to one of the vent ports on the carboy cap and opened during injection. The other vent ports on the cap were sealed to prevent any introduction of oxygen. SF_6 circulation was ceased during injection to avoid accidentally introducing the 10 ppmv SF_6 headspace into the ground. The bottom spigot on the carboy was used for injection with the assistance of a second peristaltic pump. The injected volume was monitored using the calibrated 1 L marks on the carboy. After each injection, the spigot and twist-lock fitting were closed to seal the carboy. An additional 1 mL of 10 ppthv SF_6 was added to the carboy to reestablish the 10 ppmv headspace concentration and circulation was started again. Injections were made at approximately 2 hour intervals in order to facilitate the timing of extractions.

After a 25 hr in-situ hold time, an excess volume of ground water was extracted from each well at discrete increments. Extracted samples were collected in 10 L Tedlar bags with a 1 L N_2 headspace. All bags were triple-rinsed with N_2 and checked for leaks before being used for sample collection. A small volume of water was collected in a plastic beaker for a D.O. measurement before attaching the bag. This volume was

measured and added to the extracted volume for each sample. Approximately 1 L of water was pumped into each bag through the twist-lock fitting. The bag was then closed and allowed to equilibrate for at least 30 minutes before headspace analysis. SF_6 concentrations were determined in the field using a Lagus Applied Technologies Autotrac tracer gas analyzer equipped with an ECD. After SF_6 analysis, the bag was opened and drained into the 1 L graduated cylinder to measure the sample volume. A subsample was collected in a 40 mL VOA vial for acetate and bromide analysis. VOA vials were placed in a cooler filled with ice immediately to preserve the samples until analysis. In general, a minimum of 8 L of water were extracted from each point unless the selected point ceased to yield water.

5.1b August and September 1997 Field Tests

The procedures followed during the August and September tests were the same as those from the June test other than the parts of the method attributed to SF_6 incorporation and collection. The decision to exclude SF_6 from these tests was made for two reasons. First, SF_6 had been used in other tracer studies during the summer and background concentrations at some points were well above the aqueous concentrations typically seen in the diagnostic tools test. Second, the subsequent tests were focused on acetate recovery and behavior under field conditions. Since SF_6 was not a required part of these tests and the SF_6 method is more complicated, it was eliminated from the August and September activities.

The August test required 7 L of acetate and bromide tracer solution. Results from the June test indicated that the tracer concentration in solution does not vary significantly

during the injection period. Initial mass samples, therefore, were collected every few liters during this test. Initial solution samples were collected in the 1 L graduated cylinder, measured for volume, and stored in 40 mL VOA vials on ice. The in-situ hold time for this test was also 25 hrs. Extracted volumes were collected in 1 L glass bottles with Teflon lined caps. Dissolved oxygen was measured in the bottles as samples were being collected using a YSI dissolved oxygen probe. Subsamples of each liter were collected in 40 mL VOA vials and placed on ice until analysis.

Two rounds of push-pull tests were conducted during the September field activities. The first round was conducted in 8 monitoring points at a depth of 11' BGS. The second round included 4 points at 13' and 4 points at 15' BGS. The hold time for the September tests was shortened to 12 hrs based on the results of the August test and subsequent discussions. All other procedures followed in September were identical to those in the August test.

5.1c Data Evaluation

Once the raw data were produced some manipulation was necessary to quantify mass transfer rates at individual points. Since bromide is included in the solution as the conservative tracer, SF_6 and acetate recoveries were adjusted for the bromide recovery. That is, acetate and SF_6 recoveries reported as "adjusted" in the results section are the recoveries that would be seen if bromide recovery is exactly 100%. For this reason, adjusted acetate and SF_6 recoveries sometimes appear high in comparison to the bromide recovery. The adjustment, however, gives a common basis for comparing acetate and SF_6 data from different points and field tests.

One of the goals of the diagnostic tools project is to quantify mass transfer rates for air sparging systems. An oxygen "transfer" rate can be calculated from the acetate data. The initial mass of acetate injected at a given point can be calculated from the injection volume and acetate concentration in solution. Similarly, the mass of acetate retrieved from the same point can be calculated as $M = \Sigma(C_i V_i)$ where M is the total mass of acetate recovered (mg) and C_i and V_i are the concentration of acetate (mg/L) and volume extracted (L) for sample i. Subtracting the recovered mass from the injected mass gives the mass of acetate lost during the in-situ hold time, presumably to microbial degradation.

In order to calculated this mass transfer rate, a reference point must be chosen to quantify the amount of the initial acetate mass injected which was in the absence of air sparging. The criteria for designating a reference will depend on the site being assessed and the available data. During this research, selection was based on a combination of dissolved oxygen data, high acetate recovery compared to that other at points, and complementary air distribution data (ERT, neutron probe). Monitoring points 5 and 7 have exhibited background behavior, although this behavior varies with depth and may also change from test to test.

Once a reference point has been chosen, the mass of acetate lost due to air sparging, presumably as a result of aerobic degradation, can be calculated for all other points as follows:

$$(\Delta M)_{aerobic} = (\Delta M)_{total} - (\Delta M)_{reference} \qquad (2.17)$$

$(\Delta M)_{aerobic}$ = mass of acetate lost due to air sparging (presumably aerobic)

$(\Delta M)_{total}$ = total mass of acetate lost

$(\Delta M)_{reference}$ = mass of acetate lost at reference point (presumably biodegradation)

It is then necessary to convert $(\Delta M)_{aerobic}$ to an equivalent mass of oxygen consumed in the process. The conversion can be made directly from the stoichiometry, assuming aerobic metabolism (McKee and McKee, 1996):

Based on the electron balance, 1 mole of acetate produces enough electrons to cause 2 moles of O_2 to be reduced to water via the citric acid cycle and electron transport chain. Conversion from a molar basis to a mass basis yields to relationship that 1.08 grams of oxygen are consumed per gram of acetate oxidized, allowing a direct relation between $(\Delta M)_{aerobic}$ and oxygen consumption. Oxygen loss was normalized to a 1 L solution basis for simplicity. Dividing ΔM_{O_2} by the in situ hold time yields an oxygen consumption rate with units of g/L-d. Since acetate concentrations in the push-pull test were at the mg/L level, oxygen consumption rates have been reported as mg-O_2/L-d.

5.2 Results:

The data for the June 1997 field test are summarized in Tables 5.1 and 5.2. Dissolved oxygen was elevated at points MP4 (4.5 mg/L) and MP9 (6.1 mg/L) only. Measurements of extracted water at these points indicated that D.O. dropped to 3.7 mg/L and <2 mg/L, respectively. Bromide recovery ranged from modest recoveries in MP2, MP4, and MP5 to full recovery in MP9. SF_6 recovery was surprisingly high in all points except MP1 and MP9. The raw SF_6 recoveries in MP2 and MP4 are low as well. Bromide recoveries at these points are the lowest among all points tested, however, so the adjusted SF_6 recoveries are high (94.6% and 114.3%, respectively) at these points. It

Table 5.1: Tracer Recovery Data for June 1997 Push-Pull Tests

Monitoring Point	Depth (ft)	Location	Bromide Recovery (%)	Acetate Recovery (%)	SF_6 Recovery (%)	Adj. Acetate Recovery (%)	Adj. SF_6 Recovery (%)	Acetate/SF_6 Recovery (%)
MP1	11	Downgradient	79.4	65.6	61.4	82.6	77.3	106.8
MP2	11	Upgradient	51.7	0.0	48.9	0.0	94.6	0.0
MP4	11	Upgradient	51.7	36.2	59.0	70.1	114.3	61.4
MP5	11	Downgradient	67.7	61.6	81.3	90.9	120.0	75.7
MP7	11	Downgradient	84.5	49.3	85.7	58.4	101.4	57.5
MP9	11	Crossgradient	103.6	44.5	54.5	42.9	52.6	81.7
MP11	11	Downgradient	81.3	66.2	89.2	81.4	109.7	74.2

Table 5.2: Dissolved Oxygen and Oxygen Consumption Rates for June 1997 Push-Pull Tests

Monitoring Point	Depth (ft)	Location	Dissolved O_2 (pretest) (mg/L)	Dissolved O_2 (test) (mg/L)	O_2 Consumption Rate (mg/L/d)
MP1	11	Downgradient	<2	2.0	8.4
MP2	11	Upgradient	<2	2.1	27.6
MP4	11	Upgradient	4.5	3.7	10.1
MP5	11	Downgradient	<2	<2	0.0
MP7	11	Downgradient	<2	2.1	5.1
MP9	11	Crossgradient	6.1	<2	9.9
MP11	11	Downgradient	<2	<2	2.5

should be noted that previous SF_6 studies conducted at Site 1 have left background concentrations of SF_6 very high. The background SF_6 concentration was subtracted from all samples. Acetate recovery varied greatly across the site from 90% recovery in MP5 to 0% recovery in MP2. The ratio of acetate recovered to SF_6 recovered indicates that % losses due to degradation exceed losses due to volatilization at all points except MP1. The oxygen consumption data show an interesting relationship between D.O. and O_2 consumption. Despite a D.O. level of <2 mg/L, MP2 shows the greatest O_2 consumption rate. The rate at MP2 is almost 3 times the rates at MP4 and MP9 where the D.O. is elevated prior to the tracer solution injection.

Tables 5.3 and 5.4 summarize the data from August 1997. All points showed low D.O. prior to injection with the exception of MP9; extraction from MP9 was extremely slow and only 5 L of water could be pumped from the point before it ceased yielding water. Bromide recovery was good at MP1 and MP5.

As in July, recovery at MP2 was extremely low (26.34%). The solution seems to move from this point very quickly at this location and recovery is difficult after 25 hours. The fluorescein dye allows visual observation of the unique behavior at MP2. At the other points tested, the first two liters recovered are a bright fluorescent green, and subsequent liters appear essentially clear. At MP2, the bright green is not seen. Instead, all extracted liters are a pale green. Although the exact cause of this behavior is unknown, its proximity to the sparge well suggests that the influence of the IAS system is substantial at this point. The usefulness of the adjusted acetate recovery at this location, therefore, is questionable due to the poor bromide recovery.

Table 5.3: Tracer Recovery Data for August 1997 Push-Pull Tests

Monitoring Point	Depth (ft)	Location	Bromide Recovery (%)	Acetate Recovery (%)	Adj. Acetate Recovery (%)
MP1	11	Downgradient	102.1	14.5	14.2
MP2	11	Upgradient	26.3	15.6	59.1
MP4	11	Upgradient	68.2	9.8	14.3
MP5	11	Downgradient	106.3	56.6	53.2
MP9	11	Crossgradient	70.3	30.3	43.1
MP11	11	Downgradient	87.3	20.3	23.2

Table 5.4: Dissolved Oxygen and Oxygen Consumption Rates for August 1997 Push-Pull Tests

Monitoring Point	Depth (ft)	Location	Dissolved O_2 (pretest) (mg/L)	Dissolved O_2 (test) (mg/L)	O_2 Consumption Rate (mg/L/d)
MP1	11	Downgradient	<2	3.5	29.3
MP2	11	Upgradient	<1	<2	34.2
MP4	11	Upgradient	<1	<2	31.3
MP5	11	Downgradient	<1	<2	0.0
MP9	11	Crossgradient	no sample	7.4	19.0
MP11	11	Downgradient	1.3	<2	26.1

Adjusted acetate recoveries for MP11 dropped to 23% in August from 81% in June. Oxygen consumption rates rose in all points except MP5 in the August test. MP2 again exhibited the highest rate despite a very low D.O. level.

The September 1997 field test data are shown in Tables 5.5 and 5.6. Due to the poor bromide recovery at MP2 in August, the September test was shortened to a 12 hr holding time. Two rounds of tests were conducted in September. The first round involved injections into 8 monitoring points at 11' BGS. It should be noted that the dissolved oxygen readings at MP1 through MP6 could not be taken until after the tracer tests were completed due to equipment problems. The most noteworthy change in D.O. from July-August occurred at MP2-11' BGS. This point was freely squirting water and air. The measured D.O. concentration was 7.9 mg/L. Bromide recoveries were improved at all points with the shorter in-situ hold time. MP2, however, required a total of 15 L of water to be extracted to achieve a good bromide recovery (see Table B.16). Bromide recovery at MP10-11' BGS appeared to be 149.64%. Since this port has not been used for tracer injection since October 1996 and the 11' port was pumped for aqueous SF_6 samples prior to tracer injection, there is no obvious explanation for the excessive recovery. Adjusted acetate recovery again fell to 0% at MP2. MP7 demonstrated the highest acetate recovery at 91%. All other points were scattered around 60% acetate recovery. The narrow range of recoveries about 60% translates to oxygen consumption rates for those points ranging from 21 mg-O_2/L-d to 39 mg-O_2/L-d. The value of 26.4 mg-O_2/L-d at MP11 indicates increased activity at this point. The oxygen consumption rate at MP2 rose sharply in September to 94.6 mg-O_2/L-d.

Table 5.5: Tracer Recovery Data for September 1997 Push-Pull Tests

Monitoring Point	Depth (ft)	Location	Bromide Recovery (%)	Acetate Recovery (%)	Adj. Acetate Recovery (%)
MP1	11	Downgradient	106.2	60.9	57.3
MP2	11	Upgradient	94.6	0.0	0.0
MP4	11	Upgradient	86.7	51.0	58.8
MP5	11	Downgradient	111.6	79.5	71.2
MP7	11	Downgradient	118.4	108.0	91.2
MP9	11	Crossgradient	100.9	60.7	60.1
MP10	11	Upgradient	149.6	84.0	56.1
MP11	11	Downgradient	108.3	62.4	57.6
MP1	13	Downgradient	97.2	71.6	73.7
MP5	13	Downgradient	111.3	69.1	62.1
MP8	13	Upgradient	4.4	0.0	0.0
MP10	13	Upgradient	111.9	91.8	82.1
MP1	15	Downgradient	59.5	6.1	10.3
MP4	15	Upgradient	60.4	16.9	28.0
MP7	15	Downgradient	100.7	87.5	86.9
MP9	15	Crossgradient	97.7	88.3	90.4

Table 5.6: Dissolved Oxygen and Oxygen Consumption Rates for September 1997 Push-Pull Tests

Monitoring Point	Depth (ft)	Location	Dissolved O_2 (pretest) (mg/L)	Dissolved O_2 (test) (mg/L)	O_2 Consumption Rate (mg/L/d)
MP1	11	Downgradient	<2	<2	20.6
MP2	11	Upgradient	7.9*	<2	94.6
MP4	11	Upgradient	<1	4.7	38.9
MP5	11	Downgradient	<1	<2	7.7
MP7	11	Downgradient	<2	<2	0.0
MP9	11	Crossgradient	6.5	7.1	28.3
MP10	11	Upgradient	<2	<2	0.8
MP11	11	Downgradient	<2	<2	26.4
MP1	13	Downgradient	<2	<2	17.3
MP5	13	Downgradient	7.0	6.1	21.6
MP8	13	Upgradient	<2	<2	102.7
MP10	13	Upgradient	<2	<2	0.0
MP1	15	Downgradient	6.2	3.8	95.5
MP4	15	Upgradient	6.6	5.5	82.8
MP7	15	Downgradient	<2	<2	0.0
MP9	15	Crossgradient	<2	<2	0.0
* Indicates monitoring point was squirting air at this depth during D.O. sampling					

The second round of tests in September involved four injections at 13' BGS and four at 15' BGS. At 13' BGS D.O. in MP5 is significantly higher than that at the 11' port prior to tracer injection. Both MP1 and MP4 show elevated D.O. at 15' BGS. Bromide recovery was good for all points at 13' with the exception of MP8. Thus, the reliability of the data at MP8 is questionable given the extremely low recovery of bromide at this point. Bromide recoveries at 15' BGS were good in MP7 and MP9 and mediocre at MP1 and MP4. Bromide recoveries were coincidentally lower at points with elevated D.O. The highest acetate recovery at 13' was at MP10. Although the recovery at this point is lower than at other points considered "background" locations, the mass of acetate lost to degradation indicated that its behavior is consistent with that of the other background points. At 15' BGS acetate recoveries follow along D.O. lines. MP7 and MP9, both with D.O. <2 mg/L, show high adjusted acetate recovery. The oxygenated points have low acetate recoveries. Oxygen consumption rates at 13' BGS are among the lowest of points which are considered to be affected by the IAS system. Oxygen consumption rates are extremely high at MP1-15' and MP4-15'. The rate at MP1-15' actually exceeds that at MP2-11' although acetate is still recovered at the former. MP7-15' and MP9-15' are both considered to be background points. Although the 15' D.O. and consumption rate data correlate well, data collected at other points indicate that this is not always the case.

Several trends are evident in Figures 5.1 through 5.7. In general, bromide recovery was improved by shortening the in-situ hold time. Addition of the fluorescein dye is considered a useful tool for assessing whether or not the tracer solution has been

recovered. Having a visual indication that the tracer solution has been recovered is especially important at points such as MP2 and MP4 where the tracer seems to disperse very quickly.

Dissolved oxygen has increased significantly in MP2 since June. A slight increase can also be seen in MP9. The opposite behavior is seen in MP4 which has shown a significant drop in dissolved oxygen level since June. Dissolved oxygen has remained steady in the other points tested.

The percentage of acetate recovered during the August test dropped in all points except MP2, where acetate recovery is always low. There was a corresponding increase in calculated oxygen consumption rate at all points, but the rates do not appear to increase by the same magnitude. This discrepancy is likely due to the fact that acetate recovery is based on the amount recovered compared to the amount injected. Oxygen consumption, however, is determined by subtracting out the acetate loss at a reference point. Therefore, the acetate recoveries and O_2 consumption rates across the site may not be linearly related. Acetate recovery rose again in September in all points except MP2. Since tracer recovery was poor in MP2, the significance of the increase in acetate recovery in the August test is questionable.

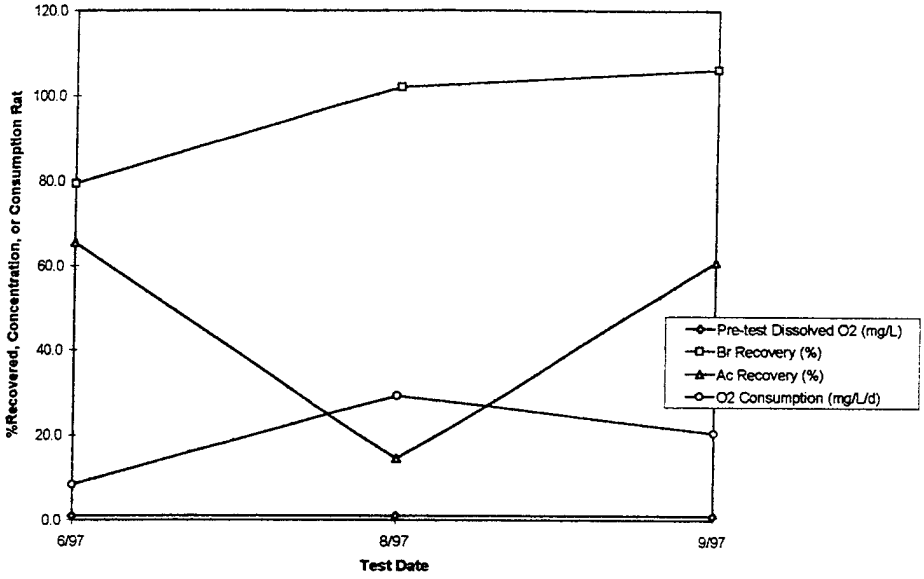

Figure 5.1: Temporal Trends in Tracer Behavior at MP1, 11' BGS

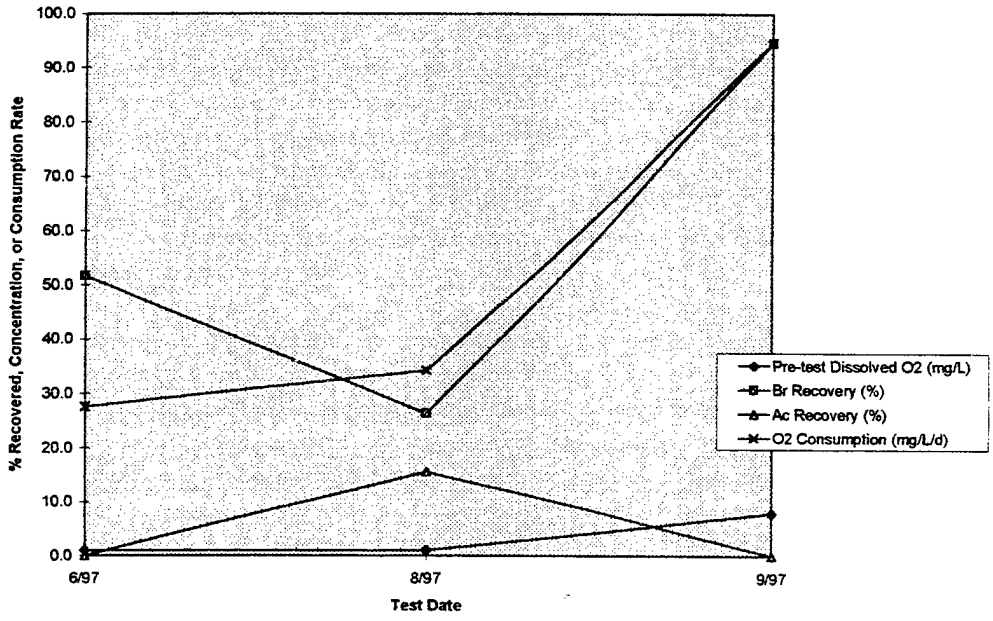

Figure 5.2: Temporal Trends in Tracer Behavior at MP2, 11' BGS

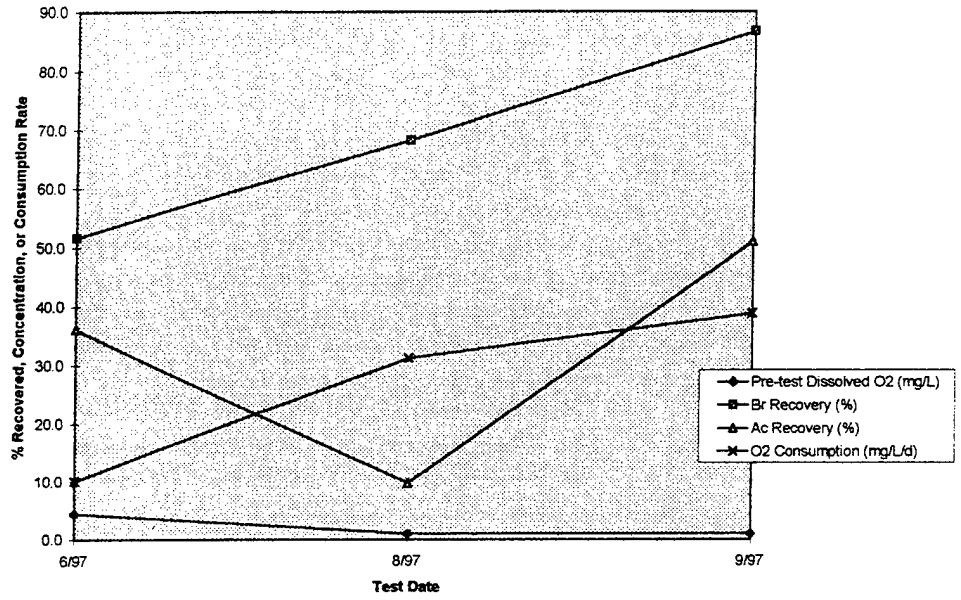

Figure 5.3: Temporal Trends in Tracer Behavior at MP4, 11' BGS

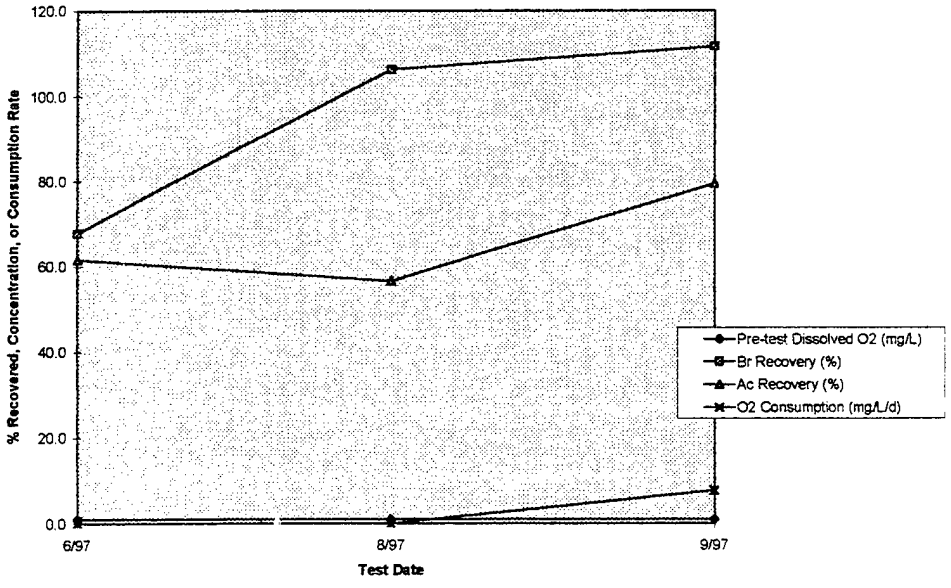

Figure 5.4: Temporal Trends in Tracer Behavior at MP5, 11' BGS

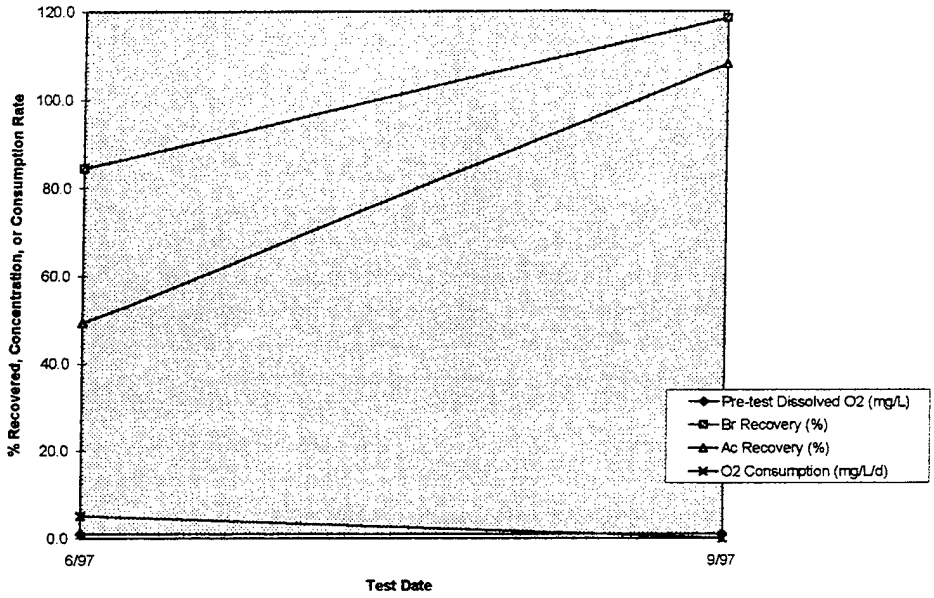

Figure 5.5: Temporal Trends in Tracer Behavior at MP7, 11' BGS

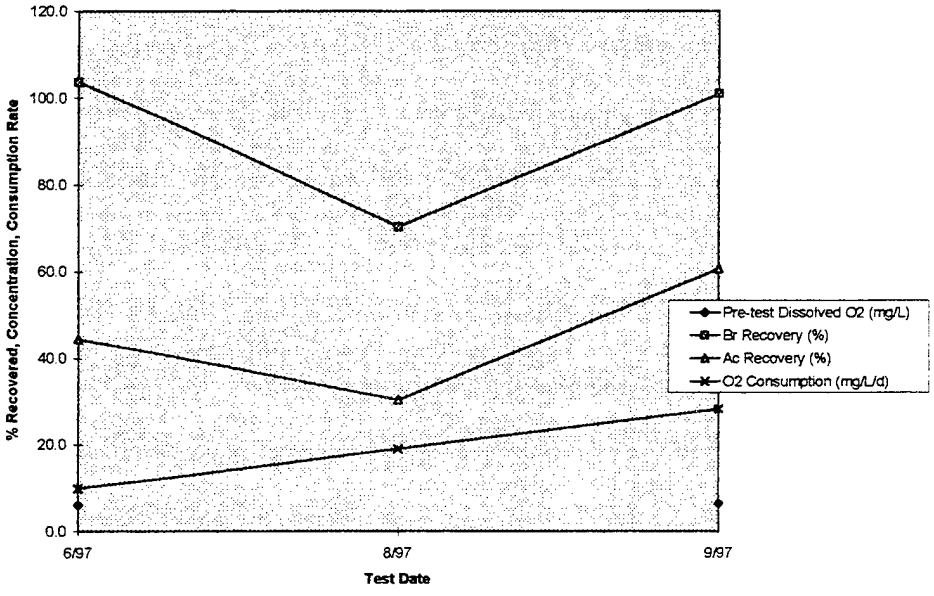

Figure 5.6: Temporal Trends in Tracer Behavior at MP9, 11' BGS

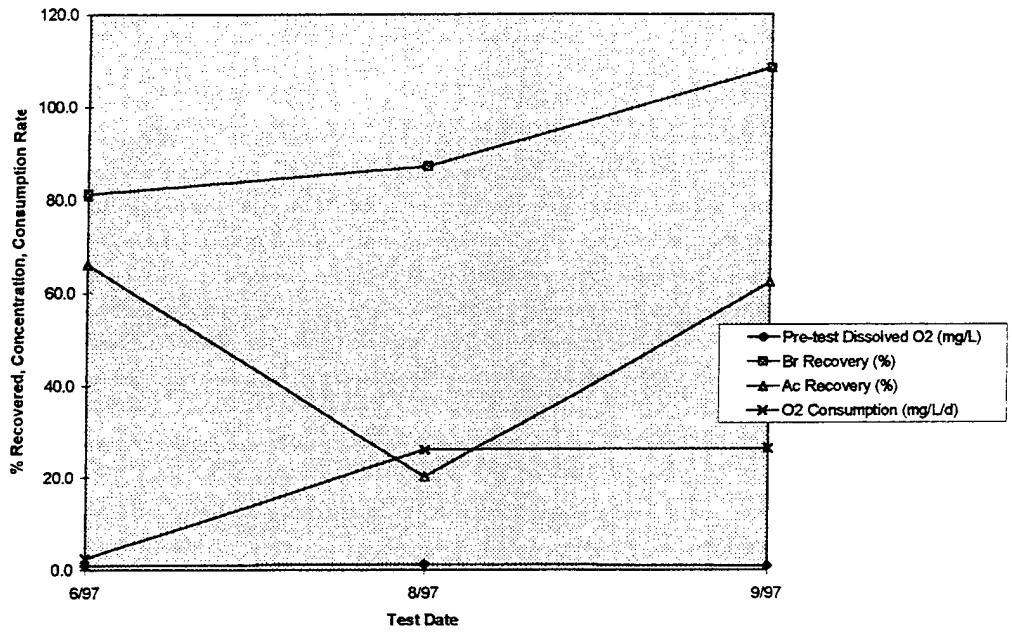

Figure 5.7: Temporal Trends in Tracer Behavior at MP11, 11' BGS

Figures 5.8 through 5.11 present the field data in a slightly different format. The changes in dissolved oxygen concentrations at MP2 and MP4 over time are particularly obvious in Figure 5.8. Figure 5.10 shows that adjusted acetate recovery is not consistently low or high at any given monitoring point. Unadjusted acetate data in Tables 5.1, 5.3, and 5.5 appear to have the same inconsistencies. Figure 5.11 shows, however, that the calculated oxygen consumption rate has a definite upward trend. This may seem contradictory at first. Recall, however, that the acetate recovery is a ratio of mass recovered to mass injected. MP5 and MP11, both of which were thought to be unaffected by the IAS system in June, are showing increasing activity. An unexpected correlation

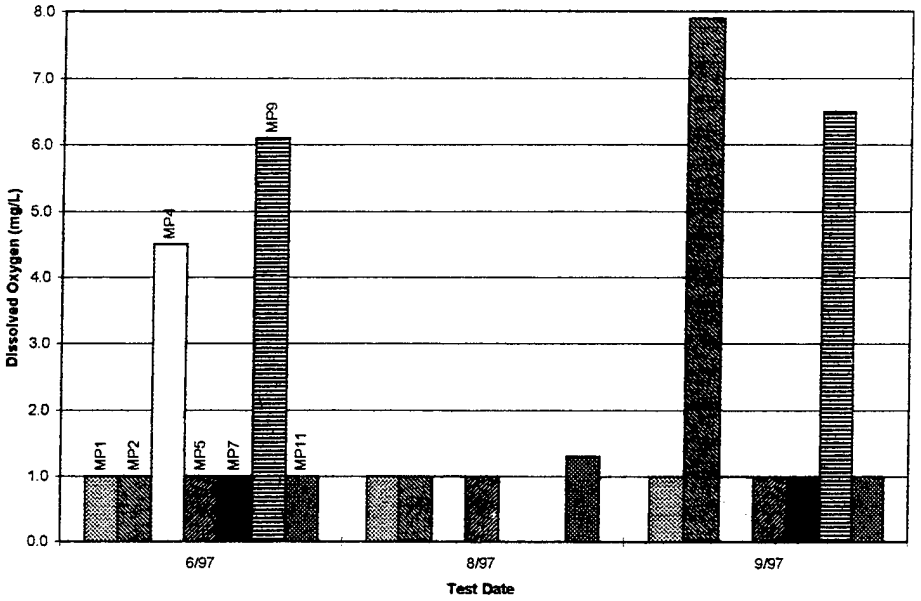

Figure 5.8: Dissolved Oxygen Trends at 11' BGS by Point and Test Date

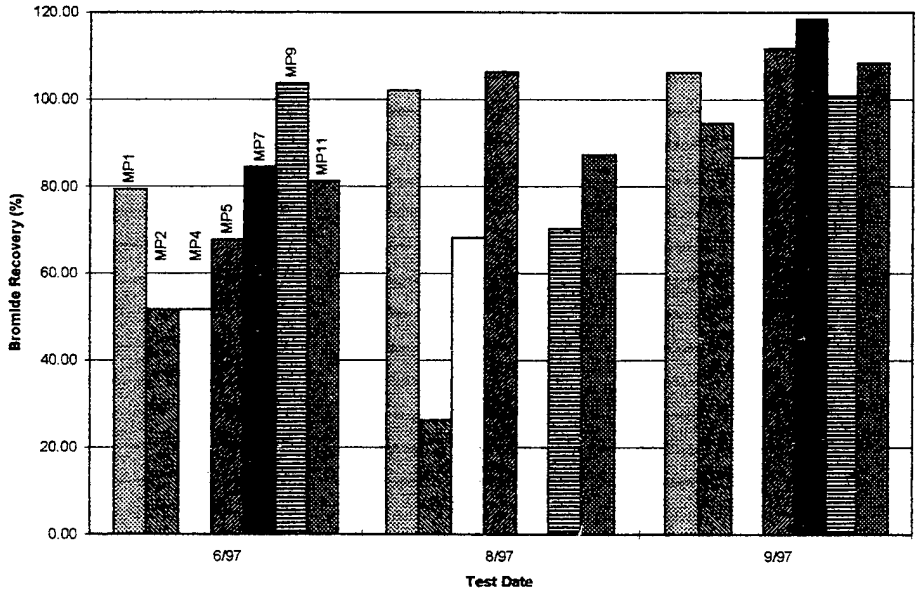

Figure 5.9: Bromide Recovery Trends at 11' BGS by Point and Test Date

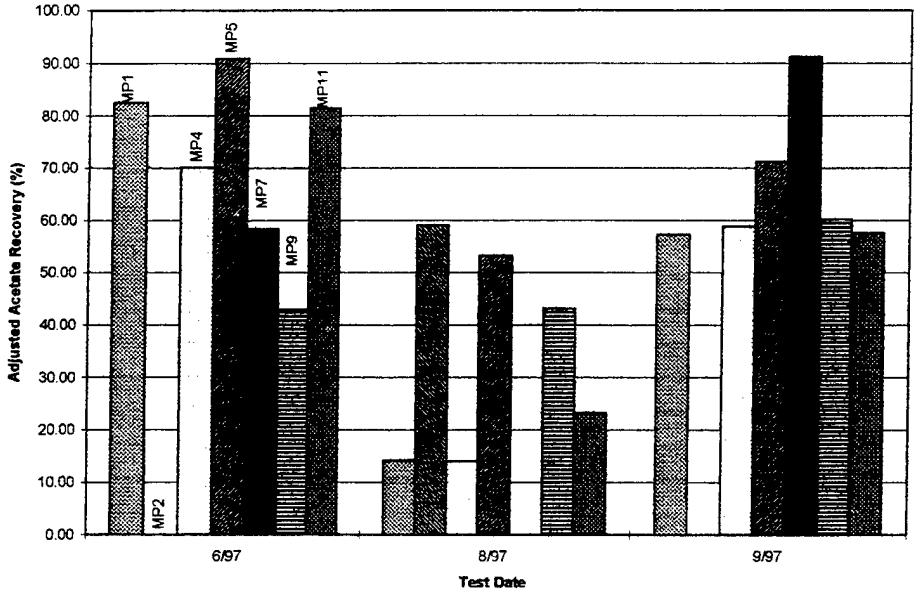

Figure 5.10: Adjusted Acetate Trends at 11' BGS by Point and Test Date

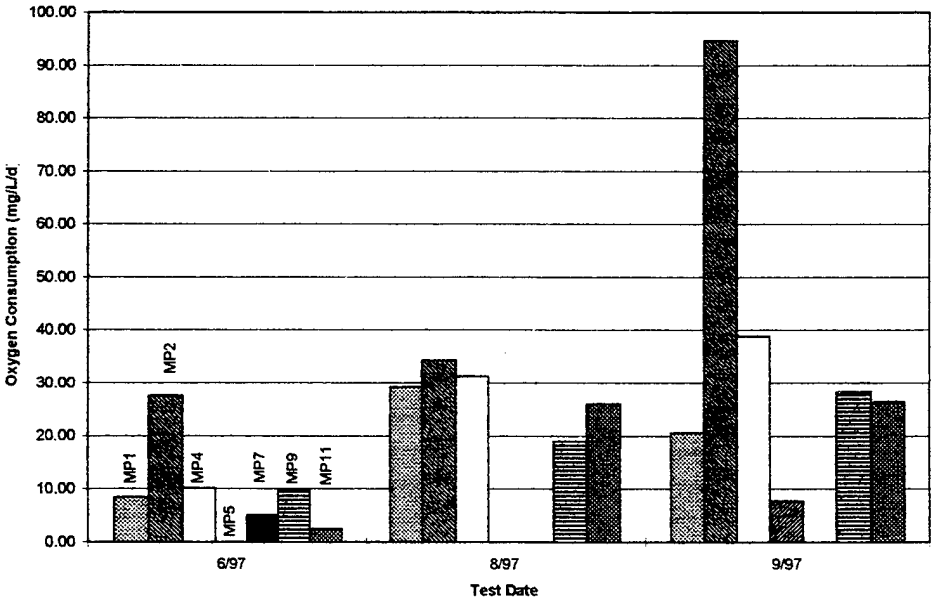

Figure 5.11: Oxygen Consumption Trends at 11' BGS by Point and Test Date

between O_2 consumption rate and position relative to the sparge well was observed in the data. MP2 and MP4, two upgradient wells located 5 and 10 feet from the sparge well, respectively, show the two highest oxygen consumption rates in the September data. The crossgradient well, MP9, has the next highest rate. The downgradient wells have the lowest rates, although MP1, MP5, and MP11 show increasing rates with time.

Figures 5.12 through 5.16 show the results superimposed on a plan view of the field test site. As discussed above, the upgradient wells have the highest oxygen consumption rates at 11' BGS. At 13' BGS influence of the sparge well can be seen downgradient in MP5. The calculated oxygen consumption rate in MP5 at 13' BGS is almost 3 times the rate at 11' BGS. Because tracer recovery at MP8 was so poor, it is not considered reliable but has been included for completeness of the data set. At 15' BGS oxygen consumption rates are significantly different than those at 11' BGS and 13' BGS. MP1 and MP4 both show rates well above those at shallower levels. MP9, which showed notable activity at 11' BGS is showing little impact of sparging at 15' BGS. MP7 appears to be unaffected by the IAS system at both depths tested. At the lower depths, proximity to the sparge well appears to be critical to high O_2 consumption rates. This behavior is not seen to the same degree at the 11' foot level.

Ground water contaminant data were collected at this site in June, July, and September and are summarized in Tables 5.7 through 5.9. Samples were analyzed for methyl tert butyl ether (MTBE) and benzene, toluene, ethylbenzene, and xylenes (BTEX).The data were collected at all depths in MP2, MP4, and MP9. Data for MP1, MP5, MP7, MP10, and MP11 were collected only at 10', 15', and 19' BGS and,

therefore, do not match exactly with tracer data. Some comparisons may still be drawn, however. Contaminant levels have reached zero or near zero levels in MP2 as of July 1997. September data indicate that they have remained low. The reduction in contaminant concentration may correspond to the increase in oxygen consumption rate and dissolved oxygen concentration. This is supported by the fact that the dissolved oxygen concentration at MP2 dropped to <2 mg/L during the push-pull test when acetate was present but then recovered to 7.9 mg/L two days after the test was conducted. Comparison of the data sets at MP7 shows that contaminant concentrations have remained high over the test period. The push-pull test results indicated that this point is not affected by the IAS system at 11' with low activity. This compares favorably with the groundwater monitoring data.

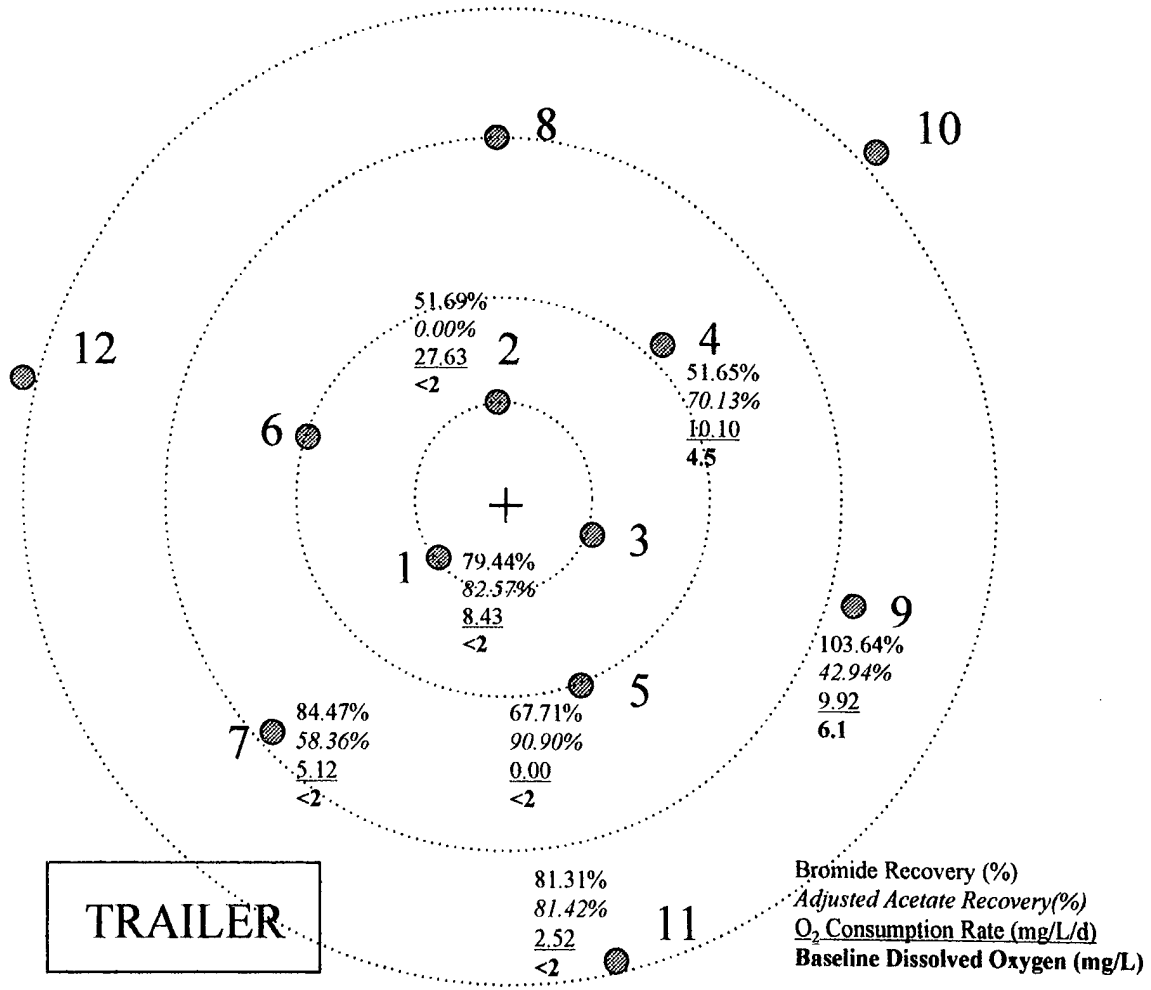

Figure 5.12: Plan View of June 1997 Data Trends - 11' BGS

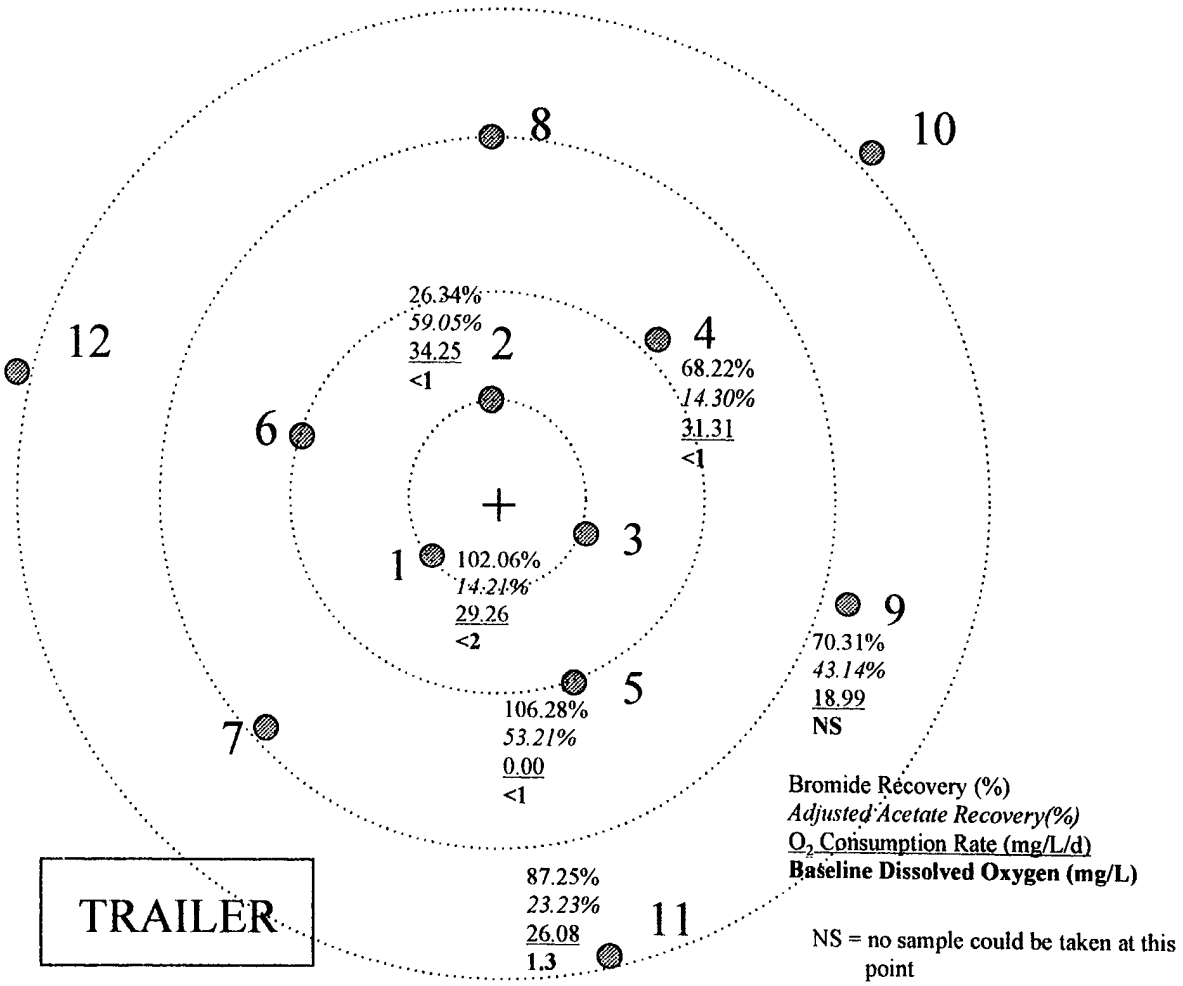

Figure 5.13: Plan View of August 1997 Data Trends - 11' BGS

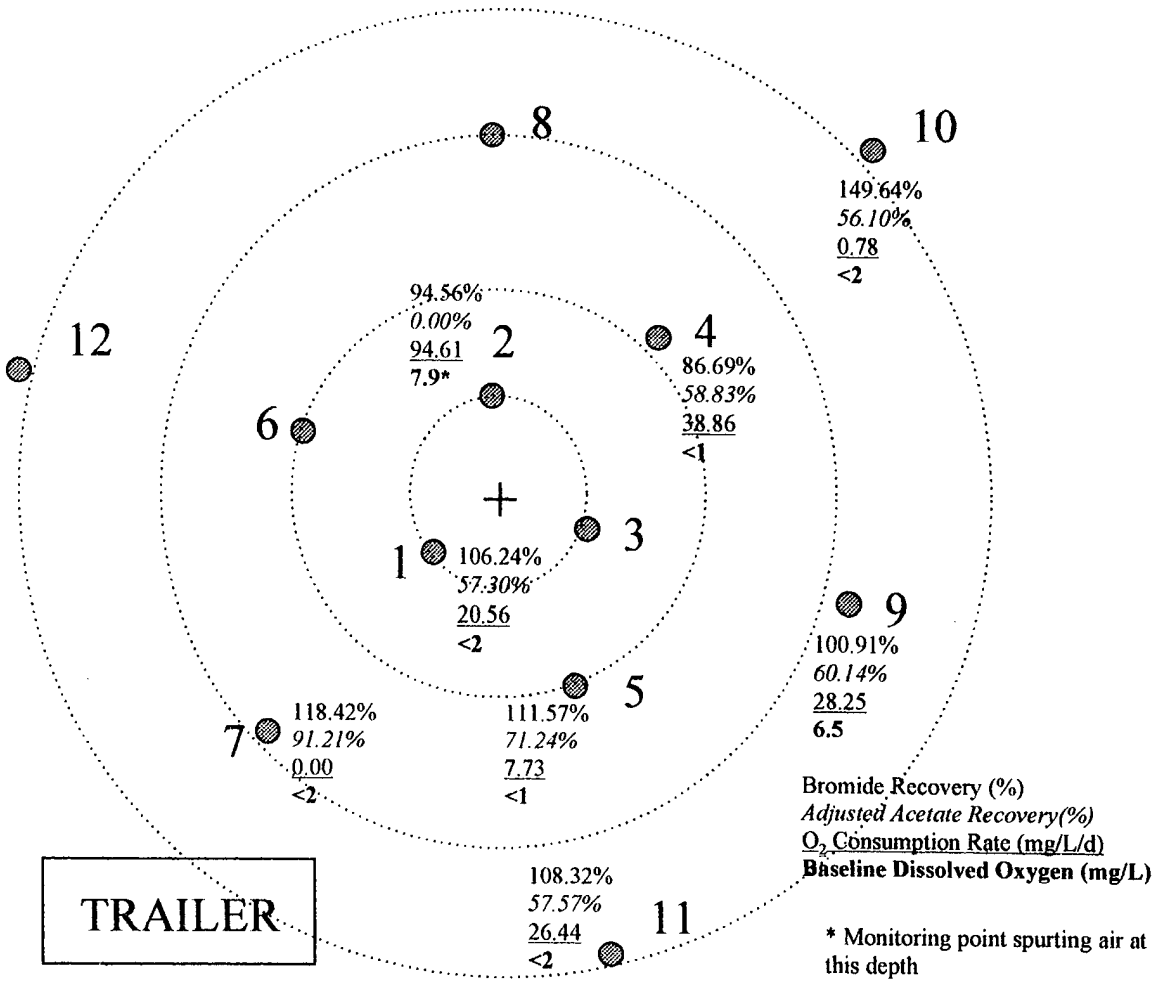

Figure 5.14: Plan View of September 1997 Data Trends - 11' BGS

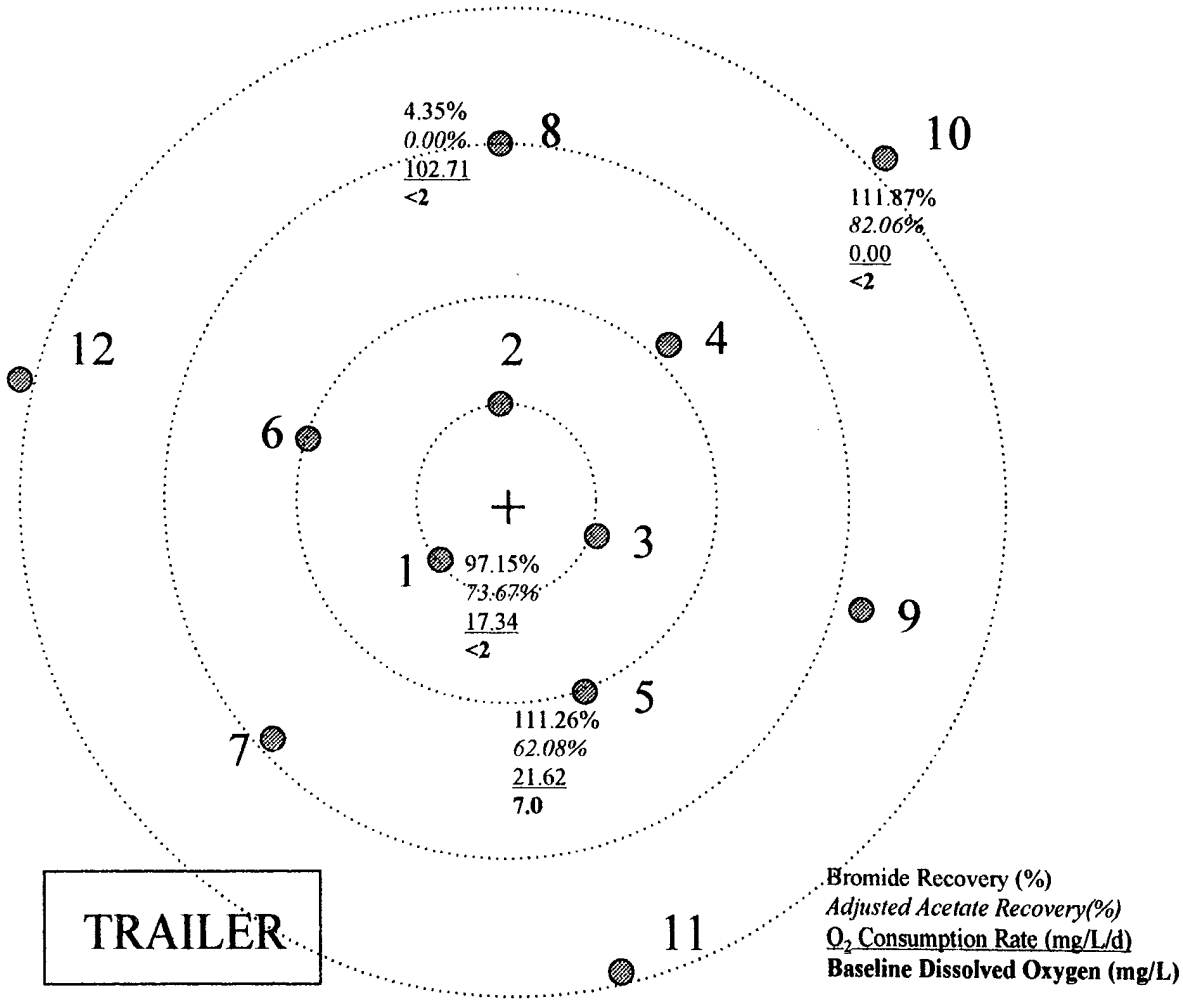

Figure 5.15: Plan View of September 1997 Data Trends - 13' BGS

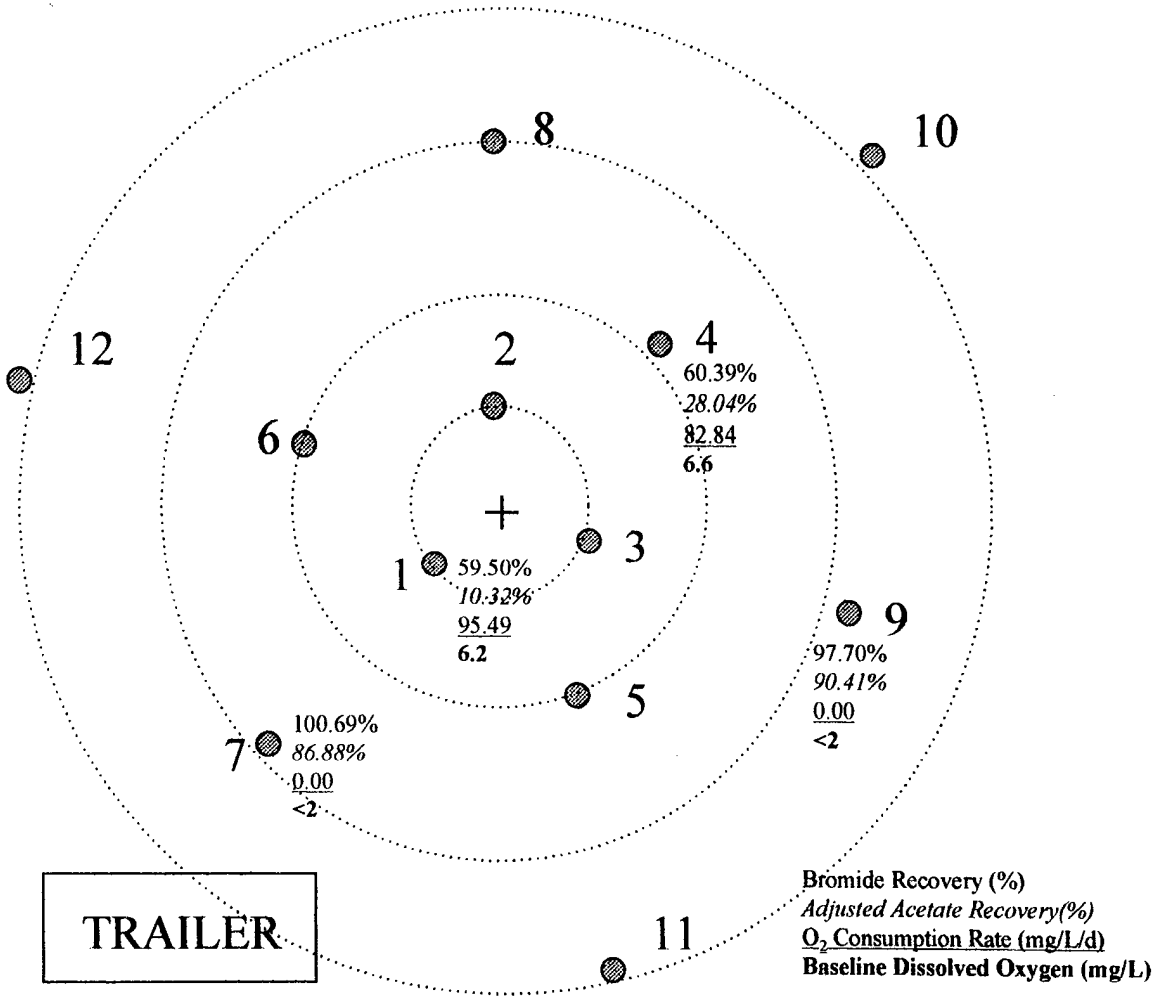

Figure 5.16: Plan View of September 1997 Data Trends - 15' BGS

Table 5.7: June 1997 MTBE and BTEX Data for Utilized Monitoring Points

Monitoring Point	Depth (ft)	MTBE (µg/L)	Benzene (µg/L)	Toluene (µg/L)	Ethylbenzene (µg/L)	m&p-Xylenes (µg/L)	o-Xylene (µg/L)
MP1	10	0	289	2259	600	1544	1083
MP2	10	Data Not Available					
MP4	10	386	0	46	0	0	0
MP5	10	9306	0	1214	1810	3520	1344
MP7	10	5710	1662	3909	639	2278	1240
MP9	10	Data Not Available					
MP11	10	Data Not Available					

Table 5.8: July 1997 MTBE and BTEX Data for Utilized Monitoring Points

Monitoring Point	Depth (ft)	MTBE (µg/L)	Benzene (µg/L)	Toluene (µg/L)	Ethylbenzene (µg/L)	m&p-Xylenes (µg/L)	o-Xylene (µg/L)
MP1	10	178	0	26	0	0	48
MP2	11	0	0	6	0	0	0
MP4	11	0	0	85	0	0	0
MP5	10	1689	59	207	644	1228	160
MP7	10	29867	4210	9742	1428	5131	2733
MP9	11	0	0	0	0	0	0
MP11	10	37267	121	4	348	0	29

Table 5.9: September 1997 MTBE and BTEX Data for Utilized Monitoring Points

Monitoring Point	Depth (ft)	MTBE (µg/L)	Benzene (µg/L)	Toluene (µg/L)	Ethylbenzene (µg/L)	m&p-Xylenes (µg/L)	o-Xylene (µg/L)
MP1	10	880	75	18	0	2	104
MP2	11	0	0	0	2	0	5
MP4	11	118	0	326	0	1	3
MP5	10	5314	41	619	1521	1022	1026
MP7	10	33164	3381	7433	1772	2533	3517
MP9	11	0	1	11	1	2	3
MP10	10	254	32	71	45	0	4
MP11	10	68672	2757	17845	3186	4367	5901
MP1	15	0	0	3	0	0	0
MP4	15	0	1	5	5	5	6
MP7	15	0	0	8	0	0	0
MP9	15	15	2	58	4	9	7

6. Continuous Pumping SF_6 Tracer Tests

A second type of tracer test was conducted at Port Hueneme to assess oxygen transfer from the air sparging system. This continuous ground water pumping SF_6 recovery tracer test was conducted in July and August 1997 at Port Hueneme. The test involves injecting pure SF_6 with the sparge air at ppmv levels while simultaneously withdrawing ground water from monitoring points at the site. A process schematic is shown in Figure 6.1. This test provides data that can be used to assess oxygen delivery rates to various points across the site. In general, it is hypothesized that if dissolved SF_6 is detected at a given point, then dissolved oxygen is delivered to the same location. The oxygen delivery rate could then be calculated by determining the SF_6 delivery rate and then correcting for differences in injection concentration and diffusion coefficients.

The oxygen delivery rate from the SF_6 tests is complementary to the consumption rate derived from the multi-tracer push-pull tests but is expected to be different. During the multi-tracer test oxygen is consumed during acetate degradation. Thus, the multi-tracer test measures oxygen delivery based on degradation of acetate. During the SF_6 test, the tracer is inert and is transported to the monitoring points by diffusion, dispersion, and advection. Therefore, the oxygen delivery rate calculated from the SF_6 recovery rate data is a measure of oxygen transfer to the ground water in the absence of degradation. Therefore, it is a lower bound estimate of the actual oxygen delivery rate.

6.1 Procedures

6.1a Tracer Test Procedure

Before the SF_6 test could be conducted, an assessment of potential pump rates had to be made. To this end, peristaltic pumps were set to maximum speed at all sampling ports within the smear zone (10' to 13' BGS) and the maximum flow rates were measured. Four points which yielded water at rates exceeding 75 mL/min were selected for the continuous pumping tests. These points were MP1 at 11', MP6 at 13', MP9 at 13', and MP11 at 13'. During the August test, MP4 at 11' was substituted for MP6 at 13'. Pumping speeds were reduced to yield flow rates of approximately 50 mL/min. The capture zone will increase with pumping rate. Pumps were operated continuously to ensure that background ground water samples were representative of actual ground water conditions. Since other SF_6 tracer tests have been conducted previously at the site, three background samples were collected prior these tests.

Once background samples were collected, SF_6 injection into the air injection stream was started. SF_6 was incorporated into the sparge air through plastic tubing connecting the SF_6 cylinder to the air supply pipe. The connection to the pipe was sealed with a Swagelok compression fitting. A Dwyer flow meter was placed in line to regulate the flow of SF_6 to the sparge line. The SF_6 injection concentration was approximately 100 ppmv for the July test. The flow rate in August test ranged from 2-3 mL/min as measured on a Dwyer water flowmeter. Once the SF_6 injection was started, ground water samples were collected from each of the four continuously

pumped points as frequently as was feasible to monitor aqueous SF_6 concentrations. Dissolved oxygen measurements were taken prior to SF_6 sample collection at these points. Typically, concentrations would increase until some asymptotic level was reached at each point. Once the asymptotic level was reached, aqueous samples were collected from all points at the site. Samples were collected from every depth of every monitoring point in the July test except for those locations where water could not be extracted. Ground water sampling in August was more limited in scope and included only the 10', 11', and 13' depths of all points.

During the August test, the effects of pumping rate and SF_6 introduction rate were evaluated. SF_6 was originally introduced at 2 mL/min after background samples were collected. Pumping rates at the four points ranged from 50-60 mL/min. Five ground water samples were collected at this pumping rate. After approximately 18 hours the pumping rate was lowered to 25 mL/min to see if the pumping rate had any effect on the delivery rate. At this point MP4 at 11' was substituted for MP6 at 13'. Four samples were collected from each point at the 25 mL/min pumping rate. The flow rate was then increased to 75 mL/min at each point. Only two samples were collected at this pumping rate. Following the variation in pumping rates, all pumps were reset to a rate of 50 mL/min. At that time, the SF_6 introduction rate was raised to 3 mL/min as measured on a Dwyer water flowmeter. Again, aqueous SF_6 concentrations were monitored. The pumping rates and SF_6 introduction rate were allowed to remain at these conditions for approximately 5 hours, after which ground water samples were collected from all points. As mentioned previously, only three

depths were sampled at each location in August. These depths correspond to the smear zone at this site.

6.1b Sample Collection and Analysis Procedures

Aqueous SF_6 samples from the monitoring points were collected in clean 40 mL Volatile Organic Analysis (VOA) vials with septa. Because SF_6 is extremely volatile, caution was taken to ensure that no headspace was left in the vials. Because the Lagus Tracer Gas Analyzer that was used for analysis will not accommodate liquid samples, a procedure was developed to obtain representative gas samples. 1 mL of the aqueous sample was extracted from the original VOA vial and transferred to a second 40 mL vial, also with a septum. Vials used for the 1 mL subsamples were rinsed with distilled water and purged with nitrogen to remove any SF_6 from previous samples. In addition, the vials were pressurized with nitrogen to prevent any ambient SF_6 from contaminating them. Pressure was relieved using a gas tight syringe immediately before transferring the 1 mL subsample. The 1 mL sample was then allowed to equilibrate with the headspace for 10 minutes, after which the vial headspace was analyzed on the Lagus detector.

Since the maximum concentration (C_{max}) of SF_6 entering the subsurface needed to be quantified for data analysis, samples of the injection air were collected several times during each test event. C_{max} samples were collected in 1 L Tedlar bags from a sampling port immediately before the sparge well. The inlet concentration of SF_6 exceeded the analytical range of the Lagus detector and, therefore, had to be diluted.

Two dilution methods were used for each sample. The first method involved injecting 1 mL of the C_{max} sample into a clean Tedlar bag filled with 1 L of nitrogen, thus making a 1/1000 dilution. The diluted sample was allowed to sit for several minutes and was then analyzed on the Lagus.

A second approach was done after the dilution for the first method was made. This approach yields a maximum concentration in water in equilibrium with the injected SF_6 concentration. A syringe was used to introduce 50 mL of distilled water into the 1 L C_{max} sample and allowed to sit for approximately 1 hour. At that time, 40 mL of water were drained into a clean, nitrogen purged VOA vial with no headspace. From this point the sample was treated in the same manner as the ground water samples.

6.1c Data Evaluation

SF_6 concentrations are reported in ppbvv or pptvv by the analytical equipment. For the purposes of this research, however, an oxygen delivery rate is desired. This section describes the assumptions and methods used to convert the SF_6 concentrations into the desired oxygen delivery rates.

Since a delivery rate in units of mg-O_2/L/d was sought, a volume sampled or capture zone around each point had to be determined. This volume was based on the pumping rate and aquifer characteristics such as porosity and maximum ground water velocity. Figure 6.1 should be referred to for this discussion. L is the farthest distance that ground water could

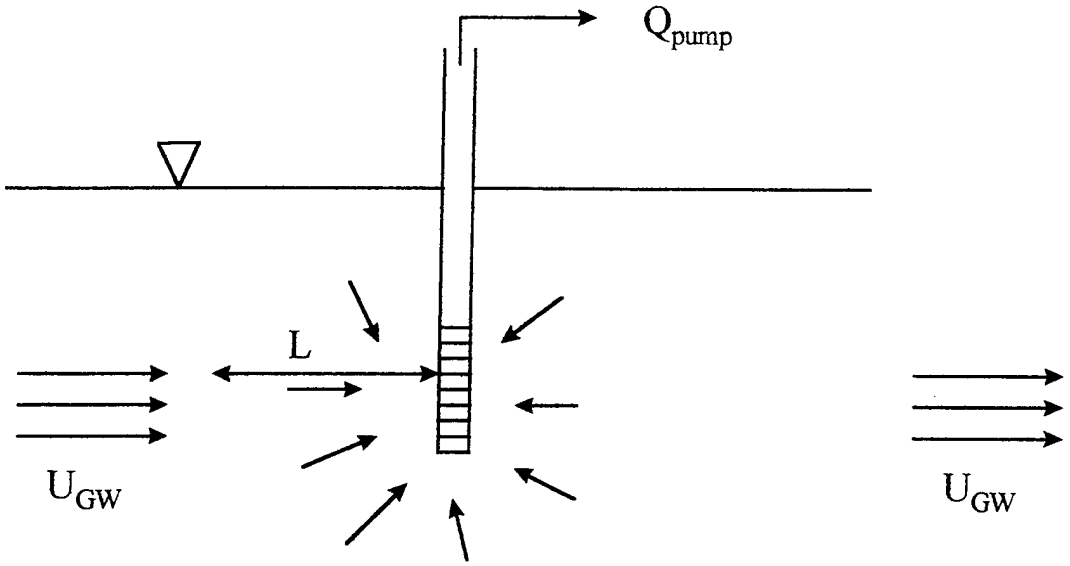

Figure 6.1: Schematic of Data Evaluation Parameters

have been recovered from during the test and is determined as follows:

$$L = U_{GW} * \Delta t \qquad (6.1)$$

L = distance from monitoring point (L)

U_{GW} = ground water velocity (L/T) = 1 ft/day

Δt = duration of test (T) = 1 day

The distance affected by the test, therefore, is 1 ft or 30.5 cm. The radius of influence of the test was calculated from the ground water velocity and pumping rate as follows:

$$U_{GW} \text{ (due to pumping)} \sim \frac{Q}{4/3\,\pi r^3} \qquad (6.2)$$

where r is the radius at which U_{GW} (due to pumping) = U_{GW} (natural). The cross sectional area through which ground water is pumped, A_c, can then be determined from:

$$Ac = \pi r^2 \qquad (6.3)$$

At a pumping rate of 60 cm^3/min, it is found that the radius of influence is 30 cm. Therefore, the oxygen delivery rate ultimately calculated will be based on influenced volume not exceeding 30.5 cm in length and 30 cm in radius. Since both the maximum anticipated ground water flow rate and the maximum pumping rate were used for this calculation, these numbers are thought to be upper end of possible values. Using the length and radius calculated above, the total mass transfer volume at each point is 86,400 cm^3. Given a porosity, assumed saturated, of 0.35 the mass transfer volume of ground water is 30,240 cm^3 or 30.24 L.

In order to calculate an O_2 mass transfer rate, a correction must be made for differences in SF_6 and O_2 injection concentrations and differences in diffusion coefficients in water. First the volume/volume SF_6 concentration, C, is converted to a mass/volume-air concentration using the ideal gas law and the molecular weight of SF_6.

$$\frac{1x10^{-9} atm(C\ ppbv)SF_6}{\left(0.0821\frac{L-atm}{mol-°K}\right)(293°K)} \text{ x (MW } SF_6\text{, g/mol) x (1000 mg/g)}$$

$$= (\text{mg } SF_6\text{/L-air}) \qquad (6.4)$$

In equation 6.4 and subsequent equations, air concentrations refer to those in the headspace of the VOA vials into which 1 mL of ground water sample and 39 mL of nitrogen have been placed. This value can then be converted to a mg/L-water concentration using the ratio of water to air in the vial (6.5).

$$\frac{mg\,SF_6}{L-air} * \frac{39\,mL-air}{1\,mL-H_2O} * \frac{1\,L-air}{1000\,mL-air} * \frac{1000\,mL-H_2O}{1\,L-H_2O} = \frac{mg\,SF_6}{L-H_2O} \quad (6.5)$$

This is only applicable when H>>1 as is the case for SF_6. The pumping rate can then be used to obtain the mass of SF_6 transferred to a given point per day.

(mg-SF_6/L-water) x Q (L-water/min) x 60 min/hr x 24 hrs/day

= mg-SF_6/day (6.6)

In order to convert mg-SF_6/day to mg-O_2/day, the ratio of the maximum concentrations of each compound in water are taken. For SF_6 this number is obtained from the C_{max} sample of distilled water in equilibrium with the inlet air SF_6 concentration. A value of 9 mg-O_2/L-water is assumed to be the C_{max} for O_2 in water. A reasonable approximation of the ratio of diffusion coefficients can be made by taking the ratio of $\frac{\sqrt{MW\,SF6}}{\sqrt{MW\,O_2}}$ which gives a ratio of 2.14. The full conversion is as follows:

$$\text{mg-}SF_6\text{ /day x}\frac{C_{max}\,O_2}{C_{max}\,SF_6}\text{ x 2.14 = mg-}O_2\text{/day} \quad (6.7)$$

Dividing by the volume of 30.24 L calculated previously, an oxygen delivery rate in units of mg-O_2/L-day is obtained. For a given sample, the background SF_6 concentration in ground water was subtracted from the concentration measured during the test. The oxygen delivery rate was then calculated from the resulting SF_6 concentration. The full calculation is shown in equation 6.8.

$$\frac{1x10^{-9}\,atm(C\,ppbv)SF_6}{\left(0.0821\frac{L-atm}{mol-°K}\right)(293°K)} * (\text{MW } SF_6, \text{ g/mol}) * (1000 \text{ mg/g}) *$$

$$\frac{mg\,SF_6}{L-air} * \frac{39\,mL-air}{1\,mL-H_2O} * \frac{1\,L-air}{1000\,mL-air} * \frac{1000\,mL-H_2O}{1\,L-H_2O} *$$

(mg-SF_6/L-water) * Q (L-water/min) * 60 min/hr * 24 hrs/day *

$$\frac{C_{max}\,O_2}{C_{max}\,SF_6} * 2.14 * 1/30.24 \text{ L} = \text{mg-}O_2\text{/L-day} \qquad (6.8)$$

6.2 Results

Calculated oxygen delivery rates for the July and August continuous pumping SF_6 tests are presented in Tables 6.1 and 6.2, respectively. The full spreadsheet showing the calculation for each monitoring point and depth sampled is included as Appendix C. Shaded areas reflect points where dissolved oxygen was elevated above 4 mg/L. Dissolved oxygen was monitored at all points and depths prior to starting this test.

There are several notable implications in these data. First, the calculated delivery rates reported for July and August differ by two to four orders of magnitude at several locations. For example, calculated delivery rate for MP2 at 11' BGS was 126.58 mg-O_2/L-day in July but dropped to 5.70 mg-O_2/L-day in August. The opposite behavior was seen at MP4 at 13' BGS. In July the calculated oxygen delivery rate was 0.03 mg-O_2/L-day at this point. In August, however, an O_2 delivery rate of 20.40 mg-O_2/L-day was calculated from the SF_6 data. One possible cause was changes in operating conditions. There were several occasions in August where the sparge system was not

operating. While attempts were made to bring the system back on line as quickly as possible, several hours of down time usually occurred in each instance. In addition, the system was operated under pulsed conditions for a period between the two tests. It is not known whether or not the pulsed operation contributed to the change in observed delivery rates. Such a notable effect on the oxygen delivery data was not expected as a result of pulsed conditions.

Second, it is evident from the tables that oxygen delivery is occurring to areas that have low dissolved oxygen. Furthermore, there are locations that have elevated D.O. levels and no oxygen delivery is evident. Since dissolved oxygen is a commonly measured parameter for determining the zone of influence for sparge wells, the fact that D.O. readings and oxygen delivery rates do not correlate at all points is significant. D.O. levels are commonly used to assess short term system performance during pilot tests (Johnson et al, 1997). These data, along with the data from the multi-tracer study, indicate that D.O. measurements may be misleading for IAS applications.

The third noteworthy outcome of these tests is that the oxygen delivery rates reported for this test are significantly lower than the oxygen consumption rates obtained from the multi-tracer test. At first glance, this appears to be a disturbing discrepancy. It can be explained, however, by examining the different tracer methods.

Table 6.1: Oxygen Delivery Rates for July 1997

Depth	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8	MP-9	MP-10	MP-11	MP-12
10.00	1.68	41.28	[illegible]	0.34	0.02	[illegible]	0.00	[illegible]	[illegible]	0.10	0.14	0.86
11.00	2.62	126.58	[illegible]	0.78	0.04	[illegible]	0.00	[illegible]	[illegible]	0.25	0.09	0.59
12.00	0.5	[illegible]	14.06	[illegible]	0.00	[illegible]	[illegible]	0.33	[illegible]	[illegible]	0.00	9.11
13.00	0.79	[illegible]	1.38	[illegible]	[illegible]	[illegible]	0.00	[illegible]	[illegible]	1.57	0.13	1.47
14.00	7.44	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.00	0.27	1.31	0.63	0.06	0.04
15.00	2.02	NS	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.29	0.11	0.11	0.00	0.08
16.00	0.93	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.00	[illegible]	0.10	0.25	0.08	NS
17.00	27.8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.85	0.01	0.00	0.00	0.05
18.00	0.44	0.04	0.39	0.00	0.58	[illegible]	0.00	0.34	0.00	0.59	0.12	0.00
19.00	1.09	0.08	0.07	0.00	0.06	[illegible]	0.00	0.14	0.00	0.05	0.11	0.07

Values in mg-O2/L-d

[illegible] Indicates dissolved oxygen exceeds 4.0 mg/L at this point.

Table 6.2 Oxygen Delivery Rates for August 1997

Depth	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8	MP-9	MP-10	MP-11	MP-12
10.00	0.48	[illegible]	9.80	0.80	0.49	[illegible]	0.00	0.93	0.12	0.00	[illegible]	0.00
11.00	9.36	5.70	0.87	14.70	2.63	[illegible]	0.00	0.00	[illegible]	0.00	0.00	0.00
13.00	[illegible]	[illegible]	0.42	[illegible]	[illegible]	[illegible]	0.00	0.00	[illegible]	0.00	0.00	5.01

Values in mg-O2/L-d

[illegible] Indicates dissolved oxygen exceeds 4.0 mg/L at this point.

In the multi-tracer test, acetate was injected in solution and oxygen consumption rates could be quantified from stoichiometry. In this test several assumptions were made to obtain an oxygen delivery. One of these assumptions was that SF_6 delivery is constant. In reality, it may be a first order process with time. SF_6 delivery, therefore, at any point in time is given by

$$\alpha(C_{max} - C_{GW}) \qquad (6.9)$$

α = first order rate constant

C_{max} = maximum aqueous SF_6 concentration

C_{GW} = aqueous SF_6 concentration at a given point

The underestimation of O_2 delivery caused by assuming constant SF_6 delivery may be assessed by expressing the aqueous SF_6 concentrations from the tracer tests as the percentage of C_{max}. The closer the percentage is to 100%, the greater the underestimation. Tables 6.3 and 6.4 show results of this analysis. Values are reported as 0.00 if the aqueous SF_6 concentration measured was at or below the background concentration of SF_6. The data suggest that oxygen delivery rates are underestimated by this method at several points where high oxygen consumption rates were observed in the multi-tracer test. In addition, underestimation appears to be a big factor at the points with the highest calculated oxygen delivery rates.

Table 6.3: Aqueous SF_6 Concentrations Expressed as % C_{max} for July 1997

Depth	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8	MP-9	MP-10	MP-11	MP-12
10.00	3.65	90.01	[illegible]	0.74	0.05	[illegible]	0.00	[illegible]	[illegible]	0.22	0.30	1.87
11.00	5.71	276.04	[illegible]	1.70	0.08	[illegible]	0.00	[illegible]	[illegible]	0.55	0.20	1.29
12.00	1.08	[illegible]	30.67	[illegible]	0.00	[illegible]	[illegible]	0.71	[illegible]	[illegible]	0.00	19.86
13.00	1.72	[illegible]	3.02	[illegible]	[illegible]	[illegible]	0.00	[illegible]	[illegible]	3.42	0.28	3.20
14.00	16.22	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.00	0.59	2.87	1.36	0.13	0.08
15.00	4.41	NS	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.63	0.23	0.23	0.00	0.16
16.00	2.02	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.00	[illegible]	0.22	0.54	0.18	NS
17.00	60.64	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.84	0.02	0.00	0.00	0.11
18.00	0.95	0.09	0.84	0.00	1.26	[illegible]	0.00	0.74	0.00	1.28	0.27	0.00
19.00	2.39	0.17	0.14	0.00	0.14	[illegible]	0.00	0.31	0.00	0.11	0.25	0.15

Values given as % Cmax

[illegible] Indicates dissolved oxygen exceeds 4.0 mg/L at this point.

Table 6.4: Aqueous SF_6 Concentrations Expressed as % C_{max} for August 1997

Depth	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8	MP-9	MP-10	MP-11	MP-12
10.00	1.04	[illegible]	21.38	1.74	1.07	[illegible]	0.00	2.02	0.26	0.00	[illegible]	0.00
11.00	20.40	12.43	1.90	32.11	5.74	[illegible]	0.00	0.00	[illegible]	0.00	0.00	0.00
13.00	[illegible]	[illegible]	0.92	[illegible]	[illegible]	[illegible]	0.00	0.00	[illegible]	0.00	0.00	21.86

Values given as %Cmax

[illegible] Indicates dissolved oxygen exceeds 4.0 mg/L at this point.

7. Conclusions

The following conclusions can be drawn from this research.

- The experimental method for the multi-tracer push-pull tests, including incorporation, sampling, analytical, and preservation procedures, appears to appropriate for assessing oxygen consumption rates.
- The tank and field experiments indicate that bromide is acting conservatively and that the recovery of the volatile and degradable tracers is different for sparging and nonsparging conditions. This result is key because it confirms the use of a simple tracer solution for monitoring air sparging performance. It also indicates that degradation can be monitored using this tracer solution.
- SF_6 does not yield concrete data from the push-pull tests that can indicate sparging effects in one area versus another. SF_6 is likely too volatile to be used as a quantitative assessment of mass transfer. It does, however, seem to yield qualitative information about subsurface conditions from point to point.
- Oxygen consumption rates based on the push-pull tests and oxygen delivery rates based on the continuous ground water pumping and SF_6 injection tests are of different orders of magnitude but both convey important information about oxygen transfer from IAS systems.

- Dissolved oxygen measurements may give misleading information regarding the zone of influence and effectiveness of IAS systems. Oxygen transfer appears to occur at points that do not show elevated D.O.

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APPENDIX A

PRELIMINARY LABORATORY EXPERIMENTS AND RESULTS

A1. SF_6 Initial Mass Measurement:

An experiment was conducted to test the SF_6 incorporation and initial mass measurement procedures. The Lagus SF_6 detector is limited to gas samples only. The multi-tracer solution, however, contains dissolved SF_6. Therefore, the initial mass measurement method needed to accurately represent the aqueous phase SF_6 concentration via a gas phase sample.

Because SF_6 has a Henry's law constant of 150.6 (dimensionless) at 20°C, it seems reasonable to assume that if a sample containing dissolved SF_6 is collected in a container with any headspace, the SF_6 will rapidly partition into the gas phase with a negligible amount left in solution.

SF_6 was incorporated into solution using the apparatus shown in Figure 3.2. A 1 L graduated cylinder was used to measure 900 mL of tap water. The water was placed in the 1 L glass bottle and sealed with the stopper assembly, leaving an approximate 100 mL headspace. A peristaltic pump was used to circulate the headspace through the water. A 100 μL gas tight syringe was used to inject 0.1 mL of 100 ppmv SF_6 through the T connection. The resulting headspace concentration was approximately 100 ppbv SF_6. The headspace was allowed to circulate for approximately 30 minutes following SF_6 introduction.

The initial mass sample was collected after 30 minutes of circulation. The pump was stopped and the tubing disconnected. The pump was operated in reverse until water began to flow from the tubing. The tubing was then connected to a 10 L Tedlar bag with 1 L medical air headspace. Approximately 500 mL of water was

pumped into the bag. The bag was then sealed and allowed to sit for approximately 20 minutes. Immediately before the headspace sample was taken, the bag was shaken briefly. A headspace sample was removed from the bag with a 5 mL gas tight syringe and analyzed on the Lagus.

Since the total mass of solution was assumed to partition into the headspace, the inital mass in solution is readily calculated. As follows:

Measured conc. (pptv) * $1x10^{-12}$*$V_{headspace}$*SF_6 vapor density = $M_{dissolved}$

$V_{headspace}$ = headspace volume = 1 L

SF_6 vapor density = 5.915 g/L

$M_{dissolved}$ = initial dissolved mass of SF_6

The SF_6 incorporation and initial mass measurement procedures were repeated three times. The results are presented below in Table A.1.

Run #	SF_6 Concentration (pptv)	Headspace (L)	SF_6 Vapor Density (g/L)	$M_{dissolved}$ (g)
1	138	1	5.915	8.16E-10
2	145	1	5.915	8.58E-10
3	151	1	5.915	8.93E-10
			Average	8.56E-10
			Std. Dev.	3.85E-11

Table A.1: Results of Initial Mass Measurements

A2. Maximum SF_6 Recovery

Maximum SF_6 recovery tests were conducted to determine the amount of SF_6 that could be recovered using the incorporation, initial mass collection, and sample collection methods without actually injecting the solution into the tank. SF_6 was incorporated into 900 mL of distilled, deionized water using the same procedure outlined in section **3.2** for the multi-tracer solution. A 100 mL initial mass sample was collected in a 1 L Tedlar bag with a 100mL or 500 mL medical air headspace. The initial mass sample was allowed to equilibrate for 30 minutes before the headspace sample was collected and analyzed.

Immediately after the initial mass sample was collected, the tubing was connected to a 10 L Tedlar bag with 1 L medical air headspace. The remainder of the water was pumped from the bottle into the 10 L bag. Approximately 750 mL of water was recovered in the 10 L bag. Care was taken to avoid introducing any of the high concentration bottle headspace into the Tedlar bag. The bag was then allowed to sit for approximately 30 minutes before a headspace sample was collected and analyzed.

The initial mass in solution and the mass of SF_6 in the maximum recovery sample were calculated using the method outlined above. Since the aqueous concentration in the initial mass sample applies to the full volume that would be injected, the aqueous concentration of the initial mass sample was multiplied by the full volume of the water to obtain the mass of SF_6 "injected". The maximum recovery test was repeated six times. The results are tabulated in Table A.2.

Sample	Volume (L)	SF_6 Concentration (ppbv)	Headspace Volume (L)	Mass SF_6 (g)	SF_6 Recovered (%)
Init. Sol'n 1	0.745	2.68	0.5	4.22E-08	
Sample 1	0.745	4.15	1	2.45E-08	58.2
Init. Sol'n 2	0.750	17.8	0.1	6.58E-08	
Sample 2	0.750	10.6	1	6.27E-08	95.3
Init. Sol'n 3	0.740	6.58	0.1	2.30E-08	
Sample 3	0.740	4.59	1	2.71E-08	117.8
Init. Sol'n 4	0.730	5.59	0.1	1.72E-08	
Sample 4	0.730	3.46	1	2.05E-08	118.7
Init. Sol'n 5	0.750	16.4	0.1	6.06E-08	
Sample 5	0.750	4.50	1	2.66E-08	43.9
Init. Sol'n 6	0.740	19.4	0.1	6.53E-08	
Sample 6	0.740	4.03	1	2.38E-08	36.5

Table A.2: SF_6 Maximum Recovery Test Results

The maximum recovery results vary widely from test to test. Two factors in particular affect this procedure. First, the high Henry's law constant for SF_6 indicates that any accidental exposure of the solution to air would result in SF_6 losses. Thus, a low SF_6 recovery would be observed. Second, the high concentration bottle headspace may be introduced to the sample bag, resulting in a high sample concentration and a recovery exceeding 100%. Both factors may affect SF_6 recoveries in the tank and field tests as well.

A3. Acetate Degradation Study

A small scale degradation study was conducted to verify that acetate degradation is accelerated by the presence of oxygen. Unwashed fill identical to that in the 3-dimensional tank was used for these experiments. A 1 L volume of 50 mg/L acetate and bromide solution was prepared using water extracted from the tank. An initial mass sample was collected in a 40 mL VOA vial and placed in the refrigerator until it could be analyzed. The solution was deoxygenated with nitrogen before being used in the experiment.

Four 200 mL flasks were set up for the acetate degradation study. Three of the flasks were filled with 125 grams of soil. The fourth flask was filled with solution only. Approximately 150 mL of solution were added to each flask. The flasks are identified as follows:

Flask 1 - control: unsparged, no headspace

Flask 2 - air sparged

Flask 3 - oxygen sparged

Flask 4 - air sparged, no soil

All four flasks were sealed with Parafilm and wrapped in aluminum foil to prevent exposure to light during the test period.

Flask 1 was filled with solution and sparged with nitrogen to ensure that dissolved oxygen was minimal. The initial D.O. for this flask was <2 mg/L. The flask was sealed with Parafilm and placed on a shaker table until the conclusion of the

experiment 28 hours later. At that time the dissolved oxygen was measured and a sample was collected for analysis.

Flasks 2 and 3 were sparged with air and oxygen, respectively. The initial D.O. in the flasks was 3.2 mg/L in Flask 2 and 3.3 mg/L in Flask 3. Both flasks were sparged for 10 hours. At that time sparging was discontinued to prevent the oxygen cylinder from being unattended. The air sparging was discontinued to match the oxygen flask scenario. Dissolved oxygen measurements were made every 5 hours. Samples were collected from both flasks at those times as well. All samples were placed in the refrigerator until analysis.

Flask 4 was filled with solution only and sparged with air. This was done to see if any acetate degradation was observed in the absence of soil. Dissolved oxygen measurements were taken and samples collected at 5 hour intervals as with Flasks 2 and 3. Again, the flask was sparged for 10 hours before air injection was discontinued.

The results of the acetate degradation study are shown in Figures A.1 through A.4. The figures indicate that acetate degradation is indeed accelerated in the presence of oxygen. The air sparged flask actually showed greater degradation than the oxygen sparged flask. This may have been due to toxicity effects of the high (18 mg/L) D.O. concentration. It is also shown that the presence of the soil was required for degradation to occur. The steady bromide concentrations indicate that the composition of the solution was not significantly altered by evaporation over the course of the test.

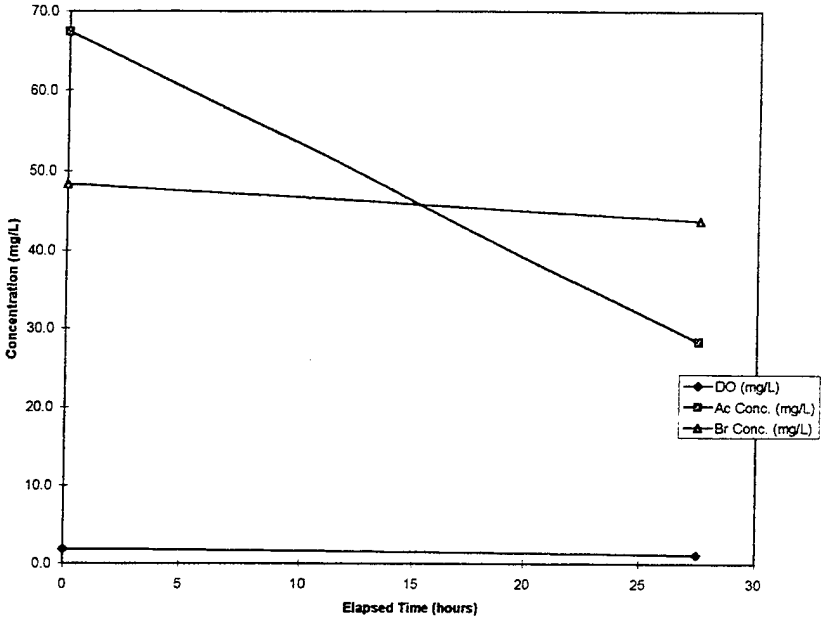


Figure A.1: Acetate Degradation in Control Flask

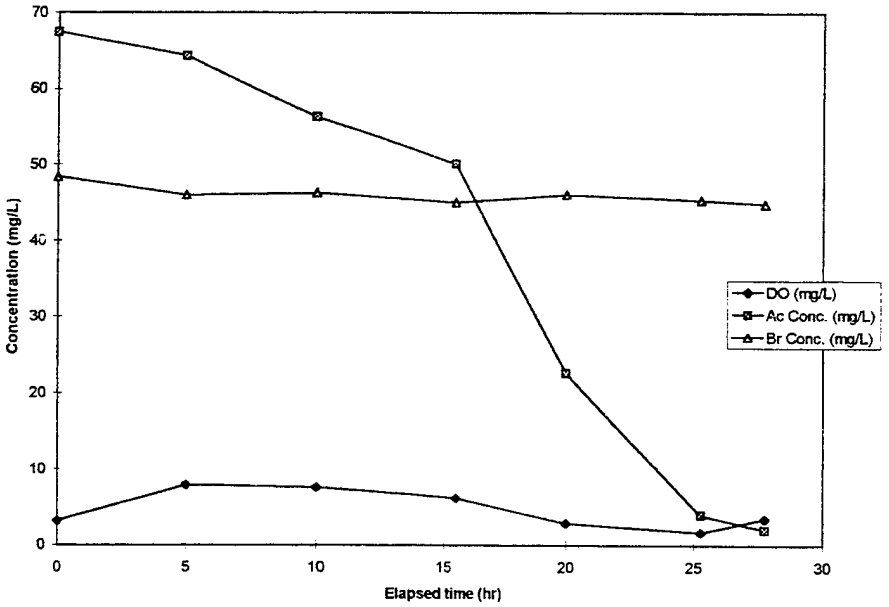


Figure A.2: Acetate Degradation in Air Sparged Flask

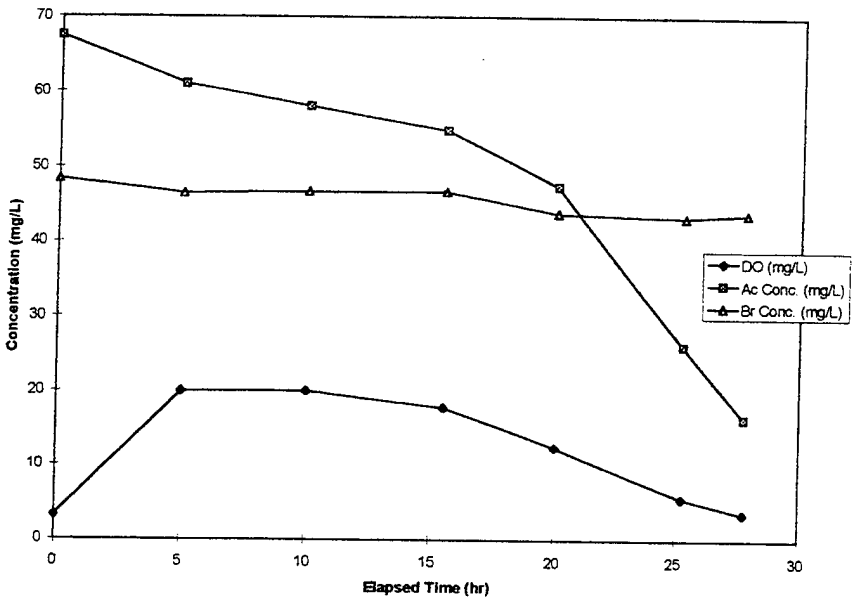


Figure A.3: Acetate Degradation In Oxygen Sparged Flask

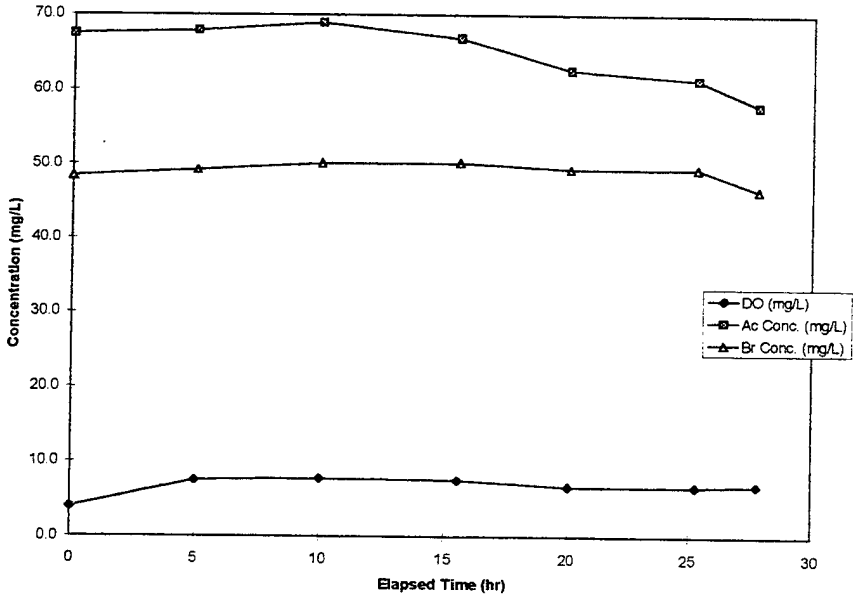


Figure A.4: Acetate Degradation in Air Sparged Flask Without Soil

A4. Acetate Preservation Methods

Potential acetate preservation methods to be used during field implementation were evaluated in a laboratory scale experiment. A 500 mL volume of a 50 mg/L acetate and bromide solution was prepared and injected into the experimental tank. The solution was left in situ for 4 hours. A 1 L volume of water was extracted from the tank. The extracted water was placed in four 40 mL VOA vials. The vials were preserved as follows:

Vial 1 - room temperature, not acidified

Vial 2 - refrigerated, not acidified

Vial 3 - room temperature, acidified

Vial 4 - refrigerated, acidified.

Sulfuric acid was used to acidify vials 3 and 4 until a pH of 2 was reached. This was well below pH 3.6, the pK_a of acetic acid. At this pH the concentration of the acetate anion is negligible.

Since these samples were to be analyzed on the IC, its ability to accurately quantify the concentration of acetate in an acified sample was checked. A 50 mg/L acetate solution was prepared and placed in two VOA vials. Sulfuric acid was added to one vial to reduce the solution to pH 2. A sample from each vial was analyzed on the IC. The results from the two vials differed by approximately 2 mg/L. This difference is within the experimental error usually seen with the equipment.

An initial concentration sample was collected from all four flasks. The IC was not responding properly on the first day of the test and the initial samples could not be analyzed. Samples were collected one day later and were analyzed. The "initial" concentrations, therefore, are indicated by the day 1 samples. Samples from each flask were analyzed again after 6 days and 14 days. The concentration of acetate remaining in each flask over time is shown in Table A.3.

Elapsed Time (days)	Flask 1 Concentration (mg/L)	Flask 2 Concentration (mg/L)	Flask 3 Concentration (mg/L)	Flask 4 Concentration (mg/L)
1	27.4	26.8	26.8	27.4
6	1.3	26.3	24.8	26.3
14	not detected	27.0	not detected	14.1

Table A.3: Results of the Acetate Preservation Study

The results of the study indicated that keeping samples cold was the best method of preservation. Acidification did not prevent degradation and is suspected to promote an acid catalyzed degradation reaction .

APPENDIX B

CONCENTRATION AND RECOVERY PROFILES FOR SUMMER 1997 FIELD WORK

Table B.1
Tracer Concentration and Recovery with Volume Extracted at MP1-11', June 1997

SAMPLE	Vol. Ext.	Tot. Vol. Ext.	Headspace SF_6 Conc.	Adj. Aq. SF_6 Conc.	Ac^- Conc.	Br^- Conc.	D.O. Conc.	Cum. SF_6	Cum. Ac	Cum. Br	SF_6 Recov.	Ac Recov.	Br Recov.
	(L)	(L)	(ppbv)	(mg/L x 10^5)	(mg/L)	(mg/L)	(mg/L)	(mg x 10^5)	(mg)	(mg)	(%)	(%)	(%)
init mass	0.890	0.890	33.8	18.2	51.21	46.69	<2						
1	1.170	1.170	12.2	4.33	16.10	15.35	2.2	5.47	18.84	17.96	33.84%	41.34%	43.22%
2	0.805	1.975	4.55	1.70	5.62	5.28	1.9	6.96	23.36	22.21	43.02%	51.26%	53.45%
3	0.910	2.885	4.10	1.07	2.16	3.23	2.1	8.02	25.33	25.15	49.58%	55.57%	60.53%
4	0.795	3.680	3.14	0.958	3.38	2.41	2.1	8.78	28.02	27.06	54.29%	61.47%	65.13%
5	0.900	4.580	3.04	0.620	0.00	1.86	2.1	9.34	28.02	28.73	57.74%	61.47%	69.15%
6	0.995	5.575	2.87	0.187	0.00	1.52	2.2	9.54	28.02	30.25	58.99%	61.47%	72.79%
7	1.140	6.715	3.31	0.340	1.33	1.45	2.2	9.93	29.53	31.90	61.39%	64.80%	76.78%
8	0.775	7.490	1.94	0.00	0.47	1.42	2.1	9.93	29.89	33.01	61.39%	65.59%	79.44%
										Adj. SF_6	77.28%		
										Adj. Ac	82.57%		

Table B.2
Tracer Concentration and Recovery with Volume Extracted at MP2-11', June 1997

SAMPLE	Vol. Ext.	Tot. Vol. Ext.	Headspace SF_6 Conc.	Adj. Aq. SF_6 Conc.	Ac^- Conc.	Br^- Conc.	D.O. Conc.	Cum. SF_6	Cum. Ac	Cum. Br	SF_6 Recov.	Ac Recov.	Br Recov.
	(L)	(L)	(ppbv)	(mg/L x 10^5)	(mg/L)	(mg/L)	(mg/L)	(mg x 10^5)	(mg)	(mg)	(%)	(%)	(%)
init mass	0.900	0.900	29.8	17.7	51.68	45.73	<2						
1	0.985	0.985	7.05	3.55	0.00	4.21	1.9	3.81	0.00	4.15	24.04%	0.00%	10.07%
2	0.975	1.960	3.54	1.68	0.00	2.85	1.9	5.56	0.00	6.93	35.06%	0.00%	16.83%
3	1.120	3.080	2.36	0.831	0.00	2.66	2.2	6.56	0.00	9.9	41.34%	0.00%	24.06%
4	0.700	3.780	1.1	0.502	0.00	2.5	2.4	6.95	0.00	11.66	43.81%	0.00%	28.32%
5	0.935	4.715	1.19	0.368	0.00	2.35	2.4	7.32	0.00	13.85	46.14%	0.00%	33.65%
6	0.950	5.665	0.949	0.208	0.00	2.29	2.4	7.54	0.00	16.02	47.50%	0.00%	38.93%
7	1.022	6.687	0.739	0.065	0.00	2.14	2.5	7.61	0.00	18.21	47.95%	0.00%	44.24%
8	0.630	7.317	0.623	0.187	0.00	2.08	2.7	7.74	0.00	19.52	48.79%	0.00%	47.43%
9	0.915	8.232	0.548	0.022	0.00	1.91	2.7	7.76	0.00	21.27	48.91%	0.00%	51.69%
										Adj. SF_6	94.62%		
										Adj. Ac	0.00%		

Table B.3
Tracer Concentration and Recovery with Volume Extracted at MP4-11' , June 1997

SAMPLE	Vol. Ext.	Tot. Vol. Ext.	Headspace SF_6 Conc.	Adj. Aq. SF_6 Conc.	Ac^- Conc.	Br^- Conc.	D.O. Conc.	Cum. SF_6	Cum. Ac	Cum. Br	SF_6 Recov.	Ac Recov.	Br Recov.
	(L)	(L)	(ppbv)	(mg/L x 10^5)	(mg/L)	(mg/L)	(mg/L)	(mg x 10^5)	(mg)	(mg)	(%)	(%)	(%)
init mass	0.885	0.885	36.5	18.8	51.82	44.24	<2						
1	0.760	0.760	7.22	5.45	8.24	9.76	3.7	4.14	6.26	7.42	24.92%	13.66%	18.94%
2	1.085	1.845	4.34	2.19	3.32	3.49	3.9	6.52	9.87	11.2	39.24%	21.52%	28.61%
3	0.850	2.695	1.80	1.08	2.62	2.13	3.5	7.44	12.09	13.01	44.77%	26.37%	33.23%
4	1.330	4.025	2.00	0.717	2.03	1.40	3.7	8.39	14.79	14.86	50.51%	32.24%	37.97%
5	0.800	4.825	0.810	0.427	1.81	1.06	3.9	8.73	16.24	15.71	52.56%	35.41%	40.14%
6	1.220	6.045	1.09	0.356	0.00	0.85	3.9	9.17	16.24	16.75	55.18%	35.41%	42.78%
7	1.205	7.250	0.835	0.238	0.00	0.71	4.0	9.45	16.24	17.60	56.90%	35.41%	44.96%
8	0.920	8.170	0.579	0.200	0.00	0.61	3.6	9.64	16.24	18.16	58.01%	35.41%	46.40%
9	0.715	8.885	0.339	0.108	0.00	0.51	3.2	9.72	16.24	18.53	58.48%	35.41%	47.33%
10	0.935	9.820	0.381	0.069	0.11	0.46	3.8	9.78	16.34	18.95	58.86%	35.64%	48.42%
11	1.090	10.910	0.340	0.012	0.00	0.37	3.8	9.79	16.34	19.36	58.94%	35.64%	49.46%
12	0.860	11.770	0.278	0.019	0.00	0.33	3.2	9.81	16.34	16.65	59.04%	35.64%	50.19%
13	1.16	12.930	0.298	0.00	0.10	0.26	3.7	9.81	16.46	19.95	59.04%	35.89%	50.95%
14	1.215	14.145	0.287	0.00	0.13	0.23	3.8	9.81	16.61	20.22	59.04%	36.22%	51.65%
										Adj. SF_6	114.31%		
										Adj. Ac.	70.13%		

Table B.4
Tracer Concentration and Recovery with Volume Extracted at MP5-11', June 1997

SAMPLE	Vol. Ext.	Tot. Vol. Ext.	Headspace SF_6 Conc.	Adj. Aq. SF_6 Conc.	Ac^- Conc.	Br^- Conc.	D.O. Conc.	Cum. SF_6	Cum. Ac	Cum. Br	SF_6 Recov.	Ac Recov.	Br Recov.
	(L)	(L)	(ppbv)	(mg/L x 10^5)	(mg/L)	(mg/L)	(mg/L)	(mg x 10^5)	(mg)	(mg)	(%)	(%)	(%)
init mass	0.890	0.890	35.1	18.9	51.95	44.08	<2						
1	1.110	1.110	13.5	5.37	9.27	10.93	2.2	5.96	10.29	12.13	35.46%	22.26%	30.92%
2	1.370	2.480	10.1	2.53	5.69	5.70	1.9	9.43	18.09	19.94	56.11%	39.13%	50.81%
3	1.495	3.975	8.11	1.38	2.56	2.63	1.9	11.5	21.92	23.87	68.40%	47.42%	60.83%
4	0.790	4.765	3.43	0.740	1.64	1.36	1.9	12.1	23.22	24.94	71.88%	50.22%	63.57%
5	0.625	5.390	2.40	0.443	1.58	0.88	2.3	12.4	24.21	25.49	73.53%	52.36%	64.97%
6	1.080	6.470	4.42	0.593	1.97	0.53	1.9	13.0	26.33	26.06	77.34%	56.95%	66.43%
7	0.920	7.390	3.60	0.486	0.00	0.29	1.9	13.4	26.33	26.33	80.00%	56.95%	67.10%
8	1.035	8.425	3.56	0.206	0.78	0.14	1.9	13.7	27.14	26.47	81.28%	58.70%	67.47%
9	1.105	9.530	3.18	0.00	0.00	0.05	1.9	13.7	27.14	26.53	81.28%	58.70%	67.62%
10	0.900	10.430	2.78	0.00	0.22	0.04	1.9	13.7	27.33	26.56	81.28%	59.13%	67.71%
11	1.100	11.530	2.93	0.00	1.02	0.00	1.9	13.7	28.45	26.56	81.28%	61.55%	67.71%
12	0.600	12.130	1.73	0.00	0.00	0.00	1.9	13.7	28.45	26.56	81.28%	61.55%	67.71%
										Adj. SF_6	120.04%		
										Adj. Ac	90.90%		

Table B.5
Tracer Concentration and Recovery at MP7-11', June 1997

SAMPLE	Vol. Ext.	Tot. Vol. Ext.	Headspace SF_6 Conc.	Adj. Aq. SF_6 Conc.	Ac^- Conc.	Br^- Conc.	D.O. Conc.	Cum. SF_6	Cum. Ac	Cum. Br	SF_6 Recov.	Ac Recov.	Br Recov.
	(L)	(L)	(ppbv)	(mg/L x 10^5)	(mg/L)	(mg/L)	(mg/L)	(mg x 10^5)	(mg)	(mg)	(%)	(%)	(%)
init mass	0.855	0.855	31.1	12.6	52.18	47.15	<2						
1	0.730	0.730	11.2	5.08	17.26	22.19	2.2	4.16	12.60	16.2	38.38%	28.25%	40.19%
2	0.940	1.670	8.56	1.96	7.64	7.00	2.1	6.16	19.78	22.78	56.82%	44.34%	56.51%
3	0.665	2.335	4.61	1.10	0.00	3.73	2.1	6.89	19.78	25.27	63.55%	44.34%	62.67%
4	1.013	3.348	7.95	1.30	0.00	2.72	2.0	8.31	19.78	28.02	76.64%	44.34%	69.50%
5	0.550	3.898	3.52	0.783	4.03	2.35	2.0	8.74	22.00	29.31	80.61%	49.30%	72.70%
6	0.620	4.518	3.54	0.375	0.00	2.18	2.0	8.98	22.00	30.66	82.76%	49.30%	76.06%
7	0.865	5.383	5.38	0.295	0.00	2.03	2.0	9.26	22.00	32.42	85.38%	49.30%	80.42%
8	0.870	6.253	4.88	0.036	0.00	1.88	2.0	9.30	22.00	34.05	85.69%	49.30%	84.47%
										Adj. SF_6	101.44%		
										Adj. Ac	58.36%		

Table B.6
Tracer Concentration and Recovery with Volume Extracted at MP9-11', June 1997

SAMPLE	Vol. Ext.	Tot. Vol. Ext.	Headspace SF_6 Conc.	Adj. Aq. SF_6 Conc.	Ac^- Conc.	Br^- Conc.	D.O. Conc.	Cum. SF_6	Cum. Ac	Cum. Br	SF_6 Recov.	Ac Recov.	Br Recov.
	(L)	(L)	(ppbv)	(mg/L x 10^5)	(mg/L)	(mg/L)	(mg/L)	(mg x 10^5)	(mg)	(mg)	(%)	(%)	(%)
init mass	0.895	0.895	35.4	19.9	54.95	46.95	<2						
1	0.720	0.720	9.21	6.47	18.59	23.97	1.9	5.18	13.38	17.26	29.02%	27.21%	41.07%
2	0.835	1.555	4.38	2.50	7.59	11.51	1.9	7.46	19.72	26.87	41.82%	40.10%	63.94%
3	0.950	2.505	2.33	1.00	0.00	5.01	2.0	8.50	19.72	31.63	47.61%	40.10%	75.27%
4	1.035	3.540	1.42	0.412	0.00	2.81	2.1	8.96	19.72	34.54	50.20%	40.10%	82.20%
5	1.130	4.670	1.40	0.344	0.00	1.96	1.9	9.38	19.72	36.76	52.55%	40.10%	87.47%
6	1.570	6.240	1.31	0.132	0.12	1.54	1.9	9.60	19.91	39.18	53.77%	40.49%	93.23%
7	1.110	7.350	0.889	0.107	0.73	1.29	1.9	9.72	20.72	40.61	54.49%	42.14%	96.65%
8	1.080	8.430	0.364	0.00	0.00	1.32	1.9	9.72	20.72	42.04	54.49%	42.14%	100.04%
9	1.245	9.675	0.698	0.00	0.93	1.22	1.9	9.72	21.88	43.55	54.49%	44.50%	103.64%
										Adj. SF_6	52.58%		
										Adj. Ac	42.94%		

Table B.7
Tracer Concentration and Recovery with Volume Extracted at MP11-11', June 1997

SAMPLE	Vol. Ext.	Tot. Vol. Ext.	Headspace SF_6 Conc.	Adj. Aq. SF_6 Conc.	Ac^- Conc.	Br^- Conc.	D.O. Conc.	Cum. SF_6	Cum. Ac	Cum. Br	SF_6 Recov.	Ac Recov.	Br Recov.
	(L)	(L)	(ppbv)	(mg/L x 10^5)	(mg/L)	(mg/L)	(mg/L)	(mg x 10^5)	(mg)	(mg)	(%)	(%)	(%)
init mass	1.000	1.000	46.3	17.7	50.56	44.38	<2						
1	0.845	0.845	9.46	4.1	26.68	24.29	2.1	3.5	22.54	20.53	19.55%	44.59%	46.25%
2	0.980	1.825	10.3	3.7	5.80	7.79	2	7.1	28.23	28.16	39.97%	55.83%	63.45%
3	1.200	3.025	8.12	1.5	0.47	2.88	1.9	8.8	28.80	31.61	49.93%	56.95%	71.23%
4	1.085	4.110	6.55	1.0	0.24	1.48	1.9	9.9	29.05	33.22	56.29%	57.46%	74.86%
5	1.130	5.240	5.58	0.4	0.00	0.94	1.9	10.4	29.05	34.29	58.76%	57.46%	77.25%
6	1.160	6.400	6.66	0.9	0.00	0.60	1.9	11.4	29.05	34.98	64.41%	57.46%	78.82%
7	1.310	7.710	5.84	0.1	0.00	0.37	2.0	11.5	29.05	35.47	65.16%	57.46%	79.92%
8	1.055	8.765	9.51	2.8	0.00	0.24	2.1	14.5	29.05	35.72	81.86%	57.46%	80.49%
9	0.975	9.740	3.90	0.0	0.93	0.14	2.2	14.5	29.96	35.86	81.86%	59.25%	80.80%
10	0.950	10.690	4.44	0.2	0.31	0.09	1.9	14.7	30.26	35.95	83.10%	59.84%	81.00%
11	0.810	11.500	3.53	0.0	0.34	0.08	2.1	14.7	30.53	36.01	83.29%	60.39%	81.14%
12	1.150	12.650	6.70	0.9	2.55	0.06	1.9	15.8	33.47	36.08	89.22%	66.20%	81.31%
										Adj. SF_6	109.73%		
										Adj. Ac.	81.42%		

Figure B.1
Tracer Concentration Profile with Volume Extracted at MP1-11', June 1997

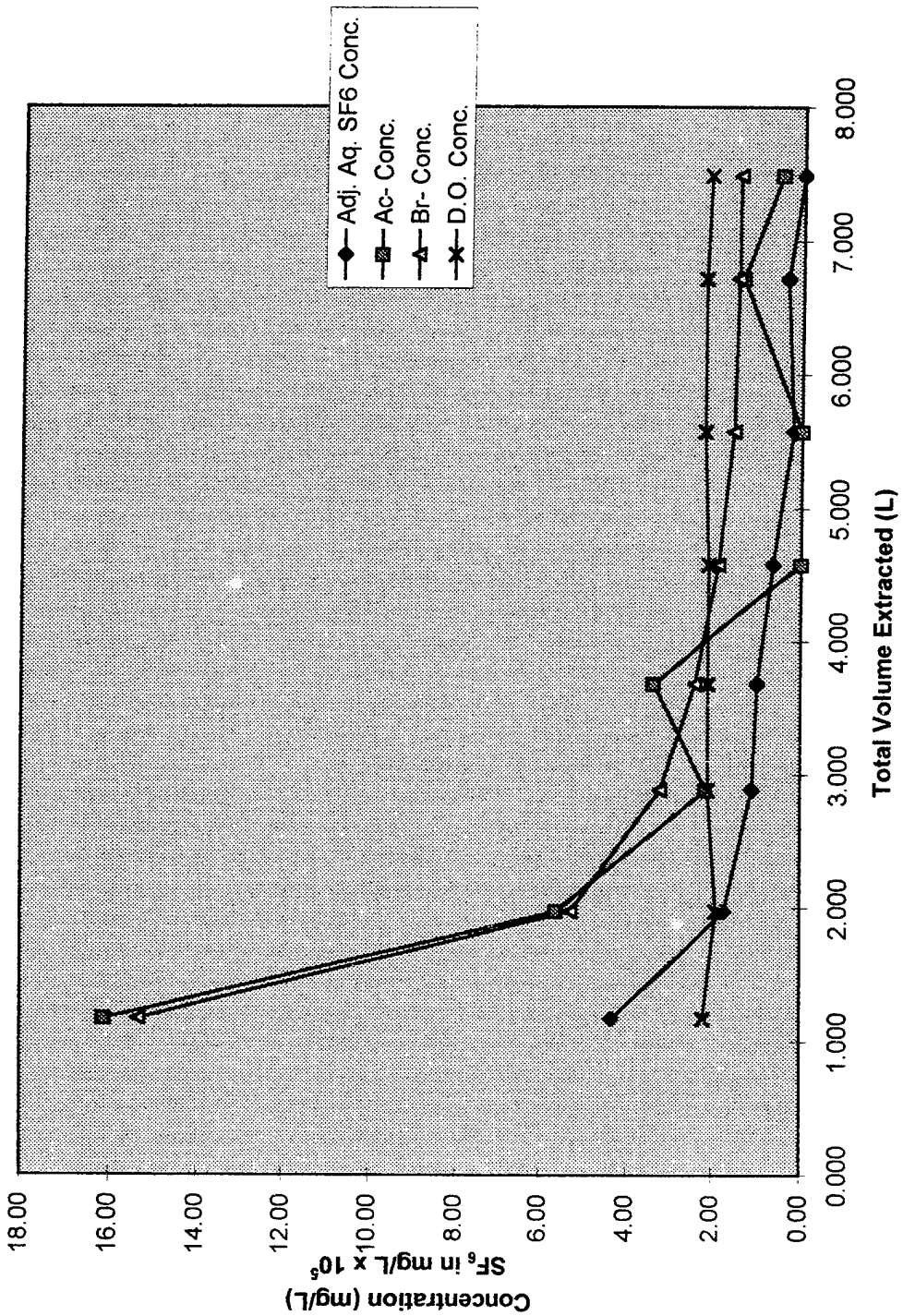


Figure B.2
Tracer Recovery Profile with Volume Extracted at MP1-11', June 1997

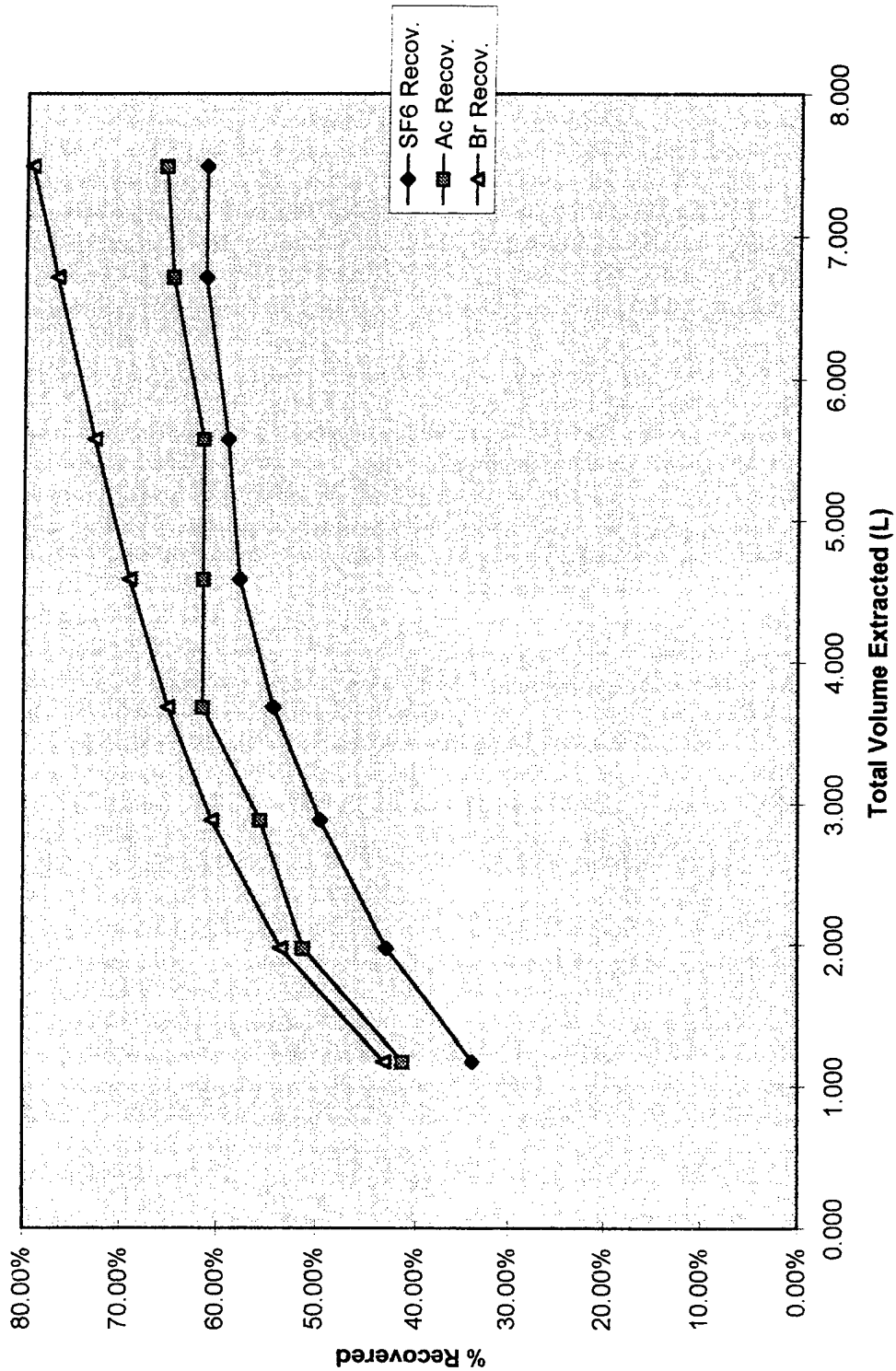


Figure B.3
Tracer Concentration Profile with Volume Extracted at MP2-11', June 1997

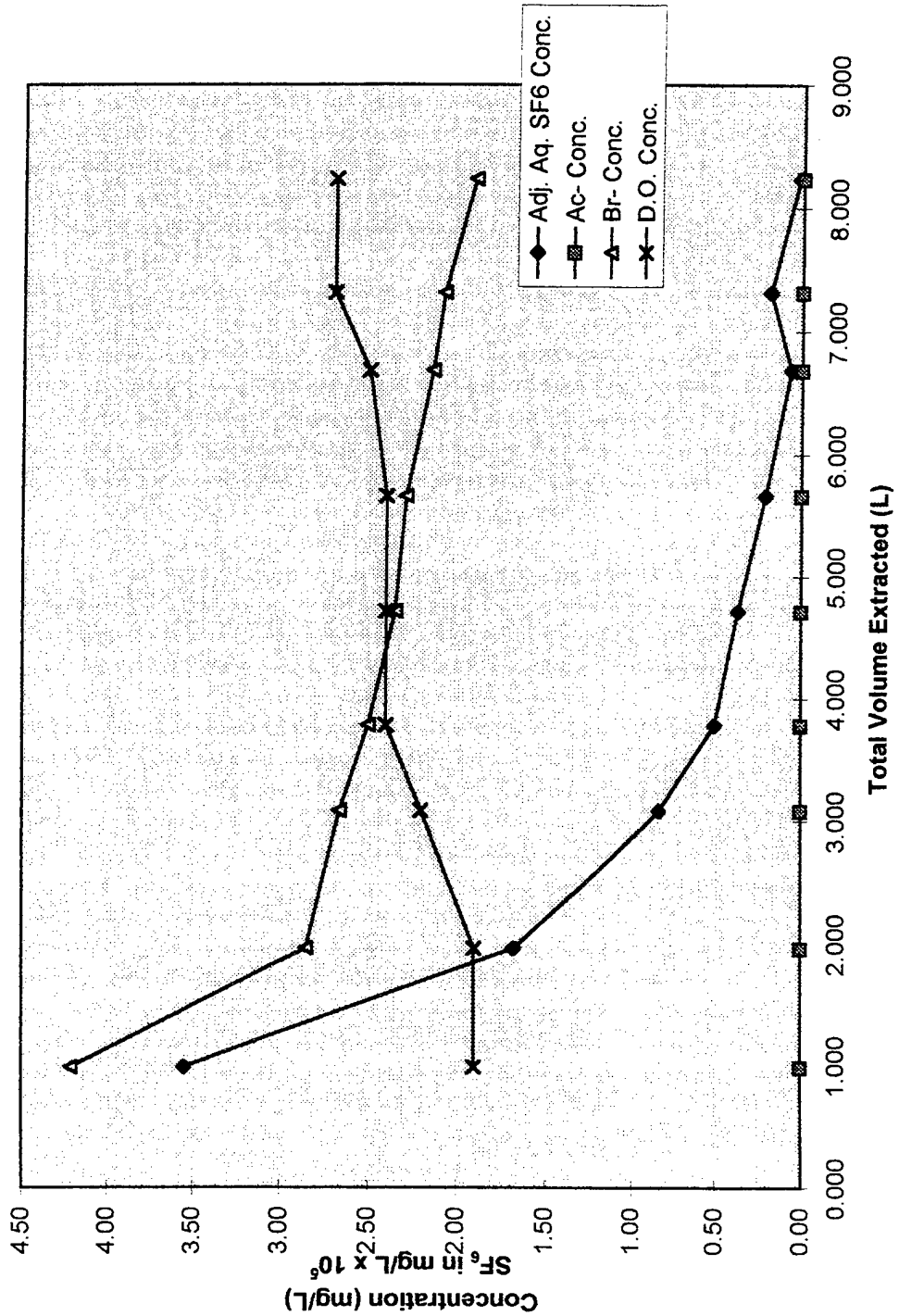


Figure B.4
Tracer Recovery Profile with Volume Extracted at MP2-11', June 1997

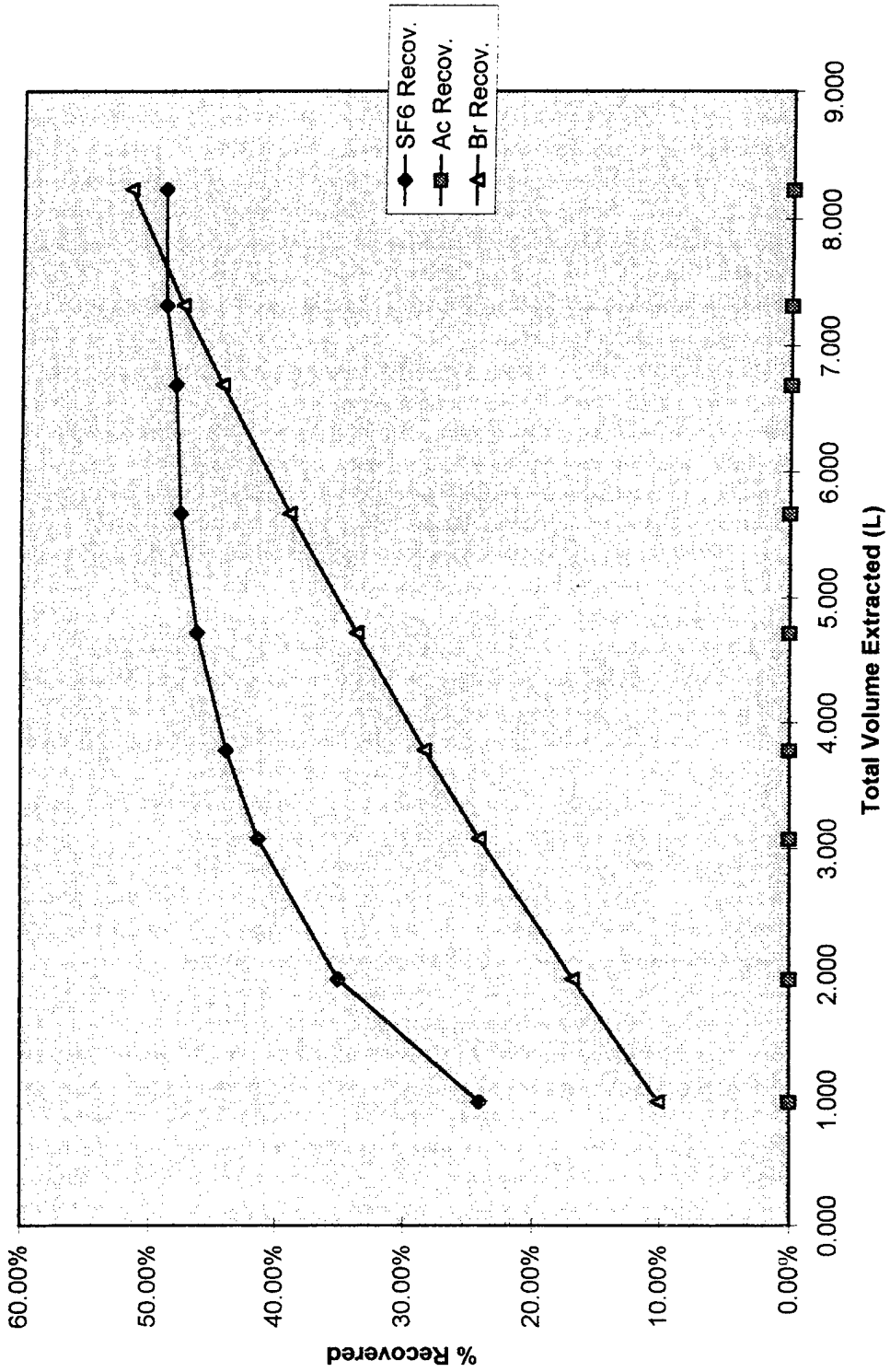


Figure B.5
Tracer Concentration Profile with Volume Extracted at MP4-11', June 1997

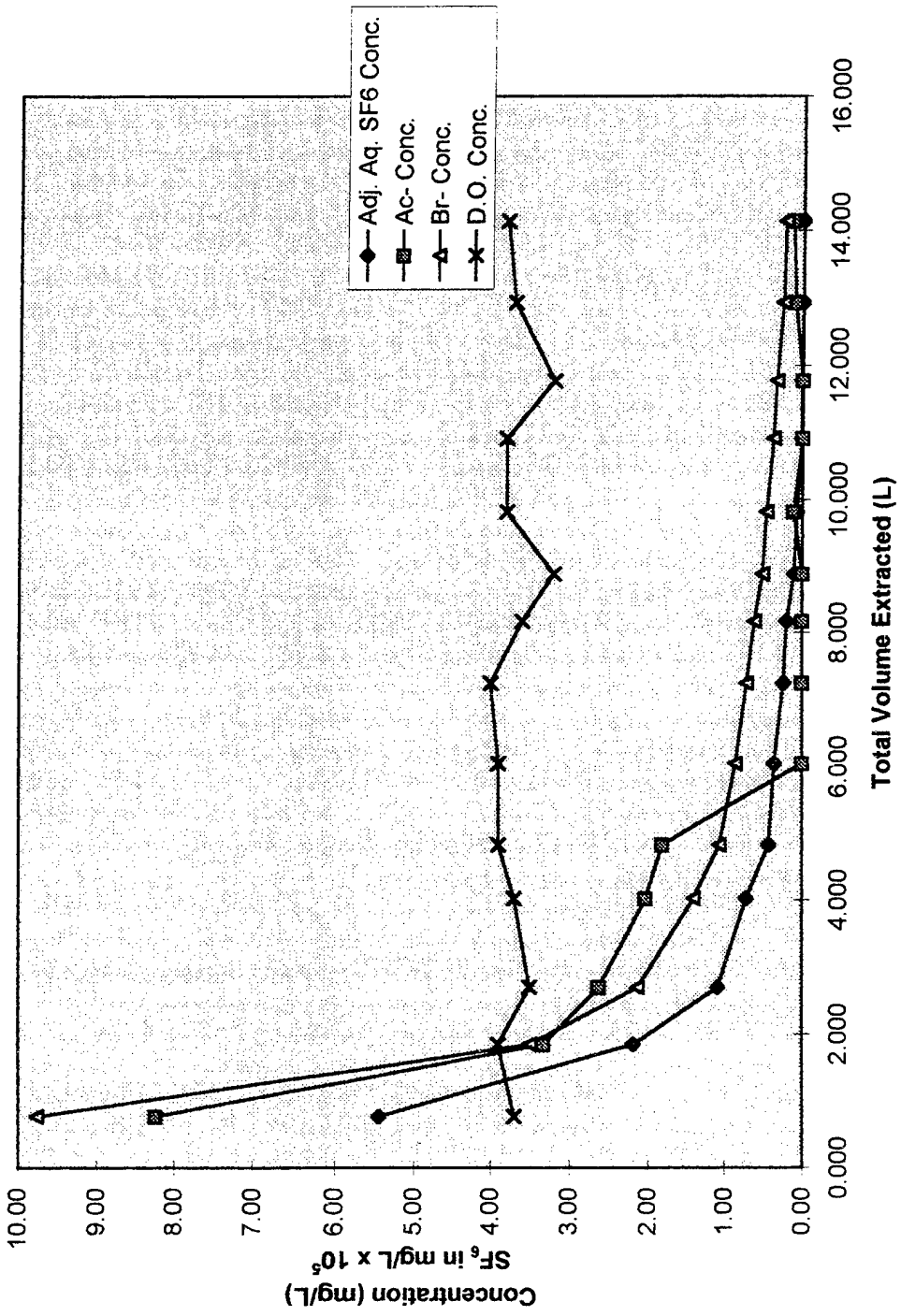


Figure B.6
Tracer Recovery Profile with Volume Extracted at MP4-11', June 1997

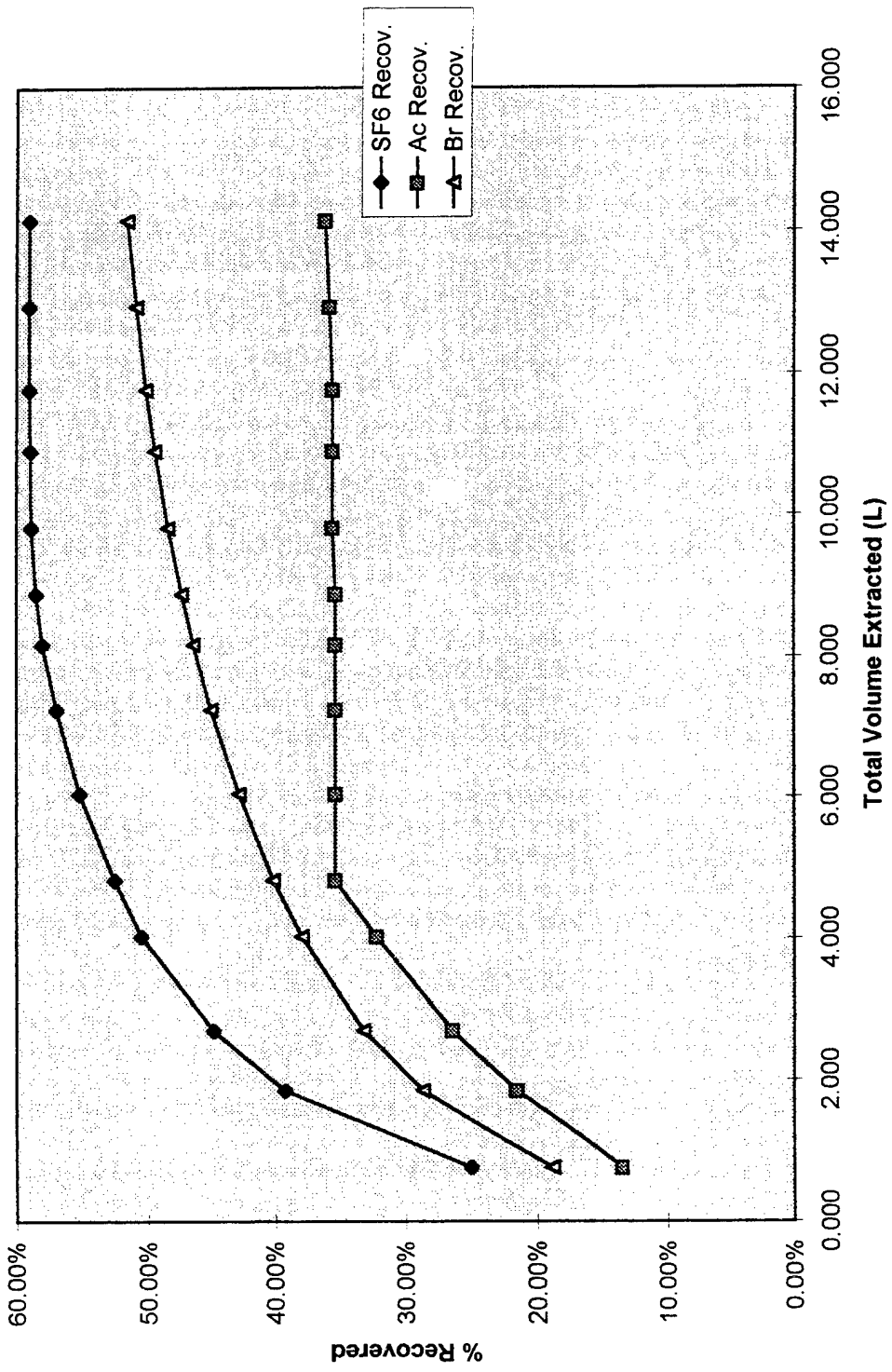


Figure B.7
Tracer Concentration Profile with Volume Extracted at MP5-11', June 1997

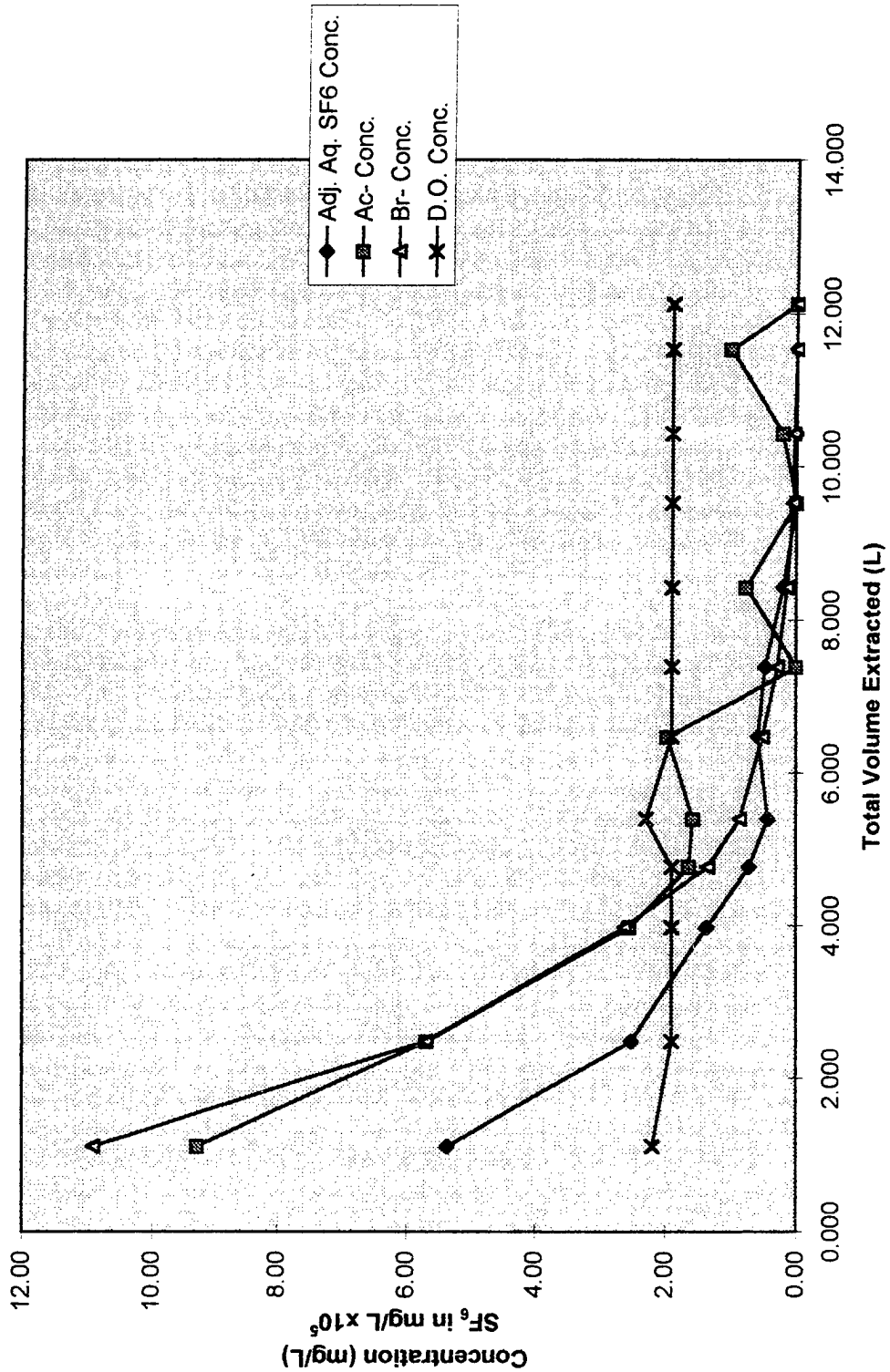


Figure B.8
Tracer Recovery Profile with Volume Extracted at MP5-11', June 1997

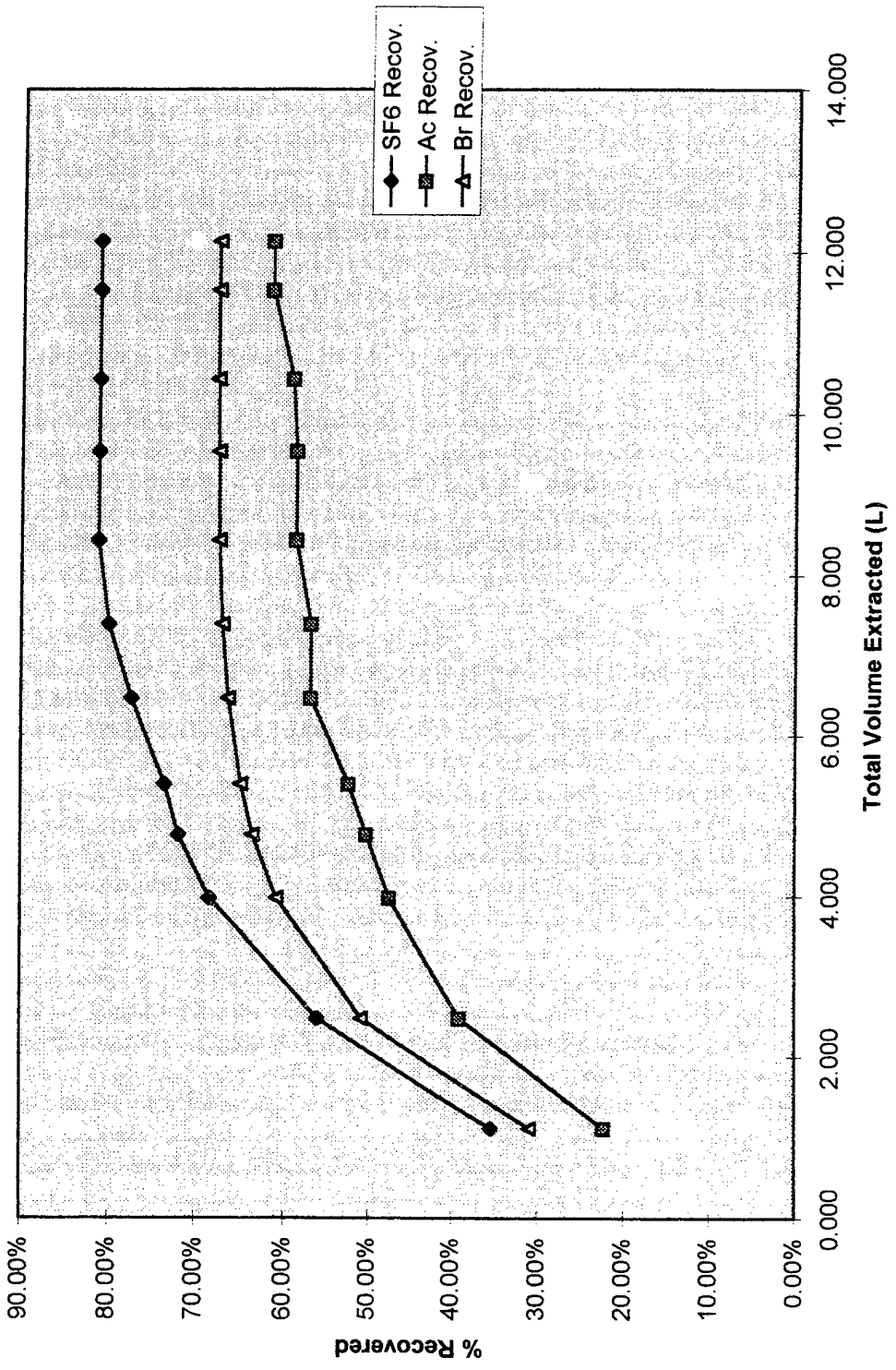


Figure B.9
Tracer Concentration Profile with Volume Extracted at MP7-11', June 1997

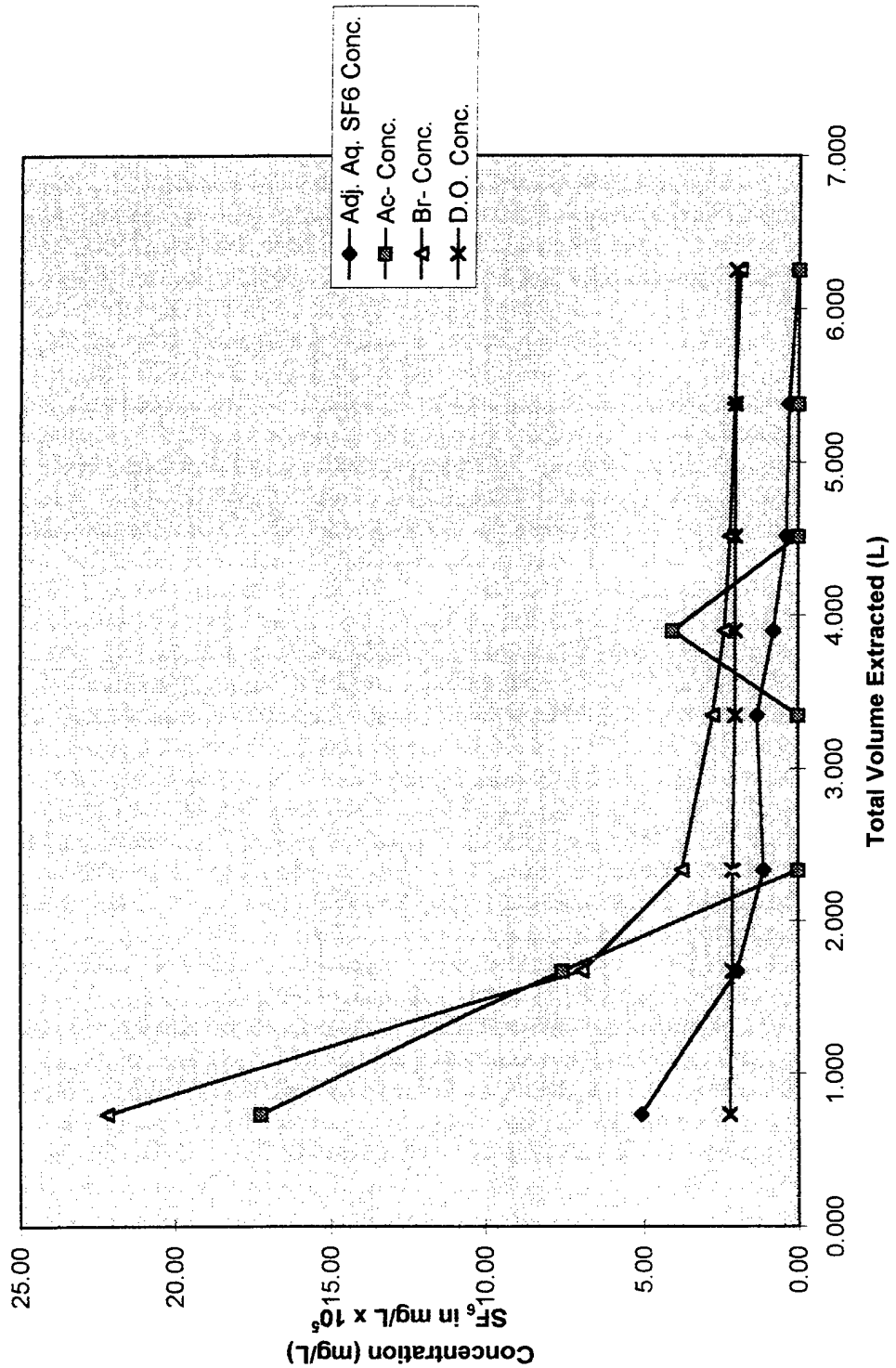


Figure B.10
Tracer Recovery Profile with Volume Extracted at MP7-11', June 1997

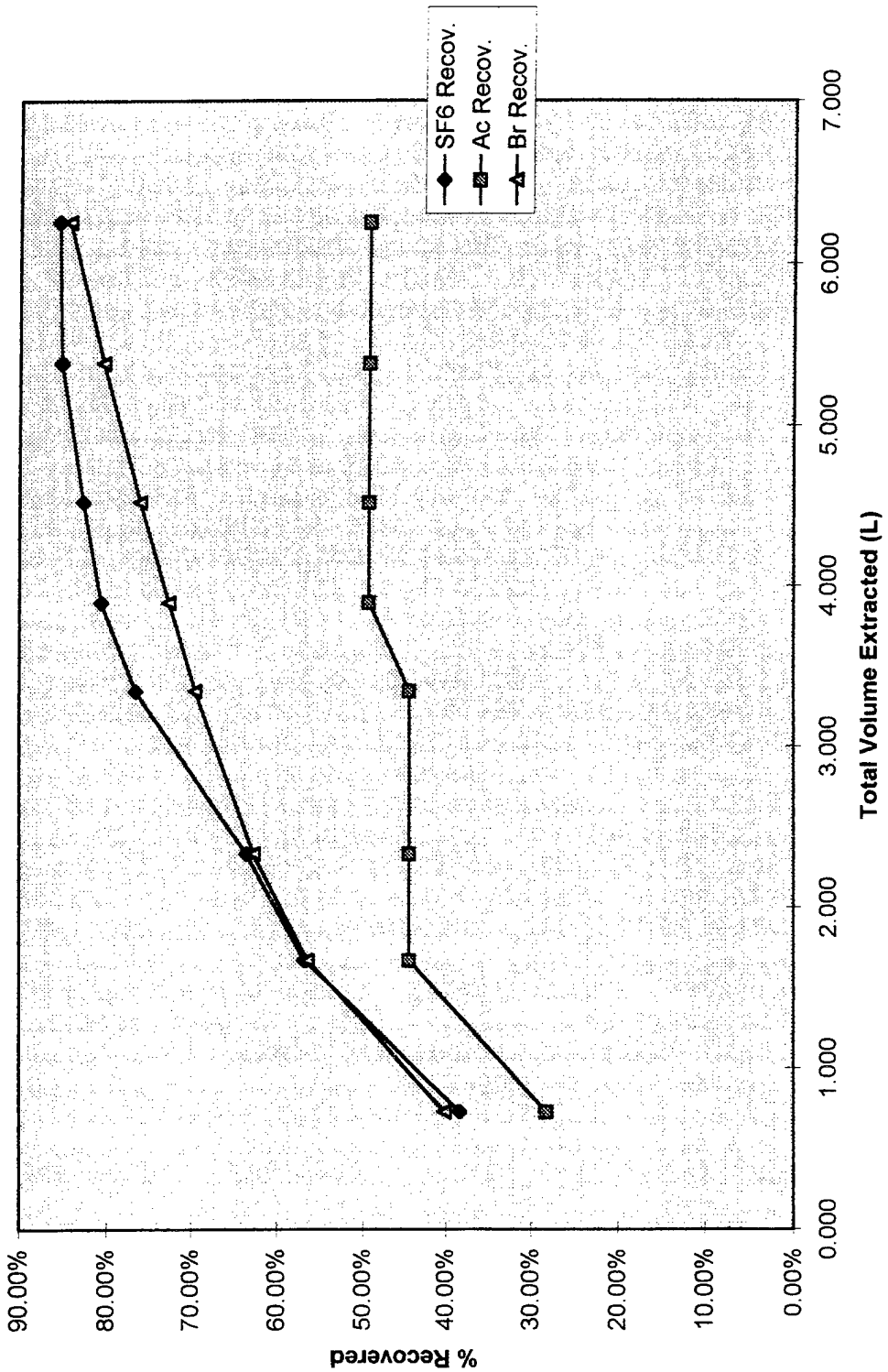


Figure B.11
Tracer Concentration Profile with Volume Extracted at MP9-11', June 1997

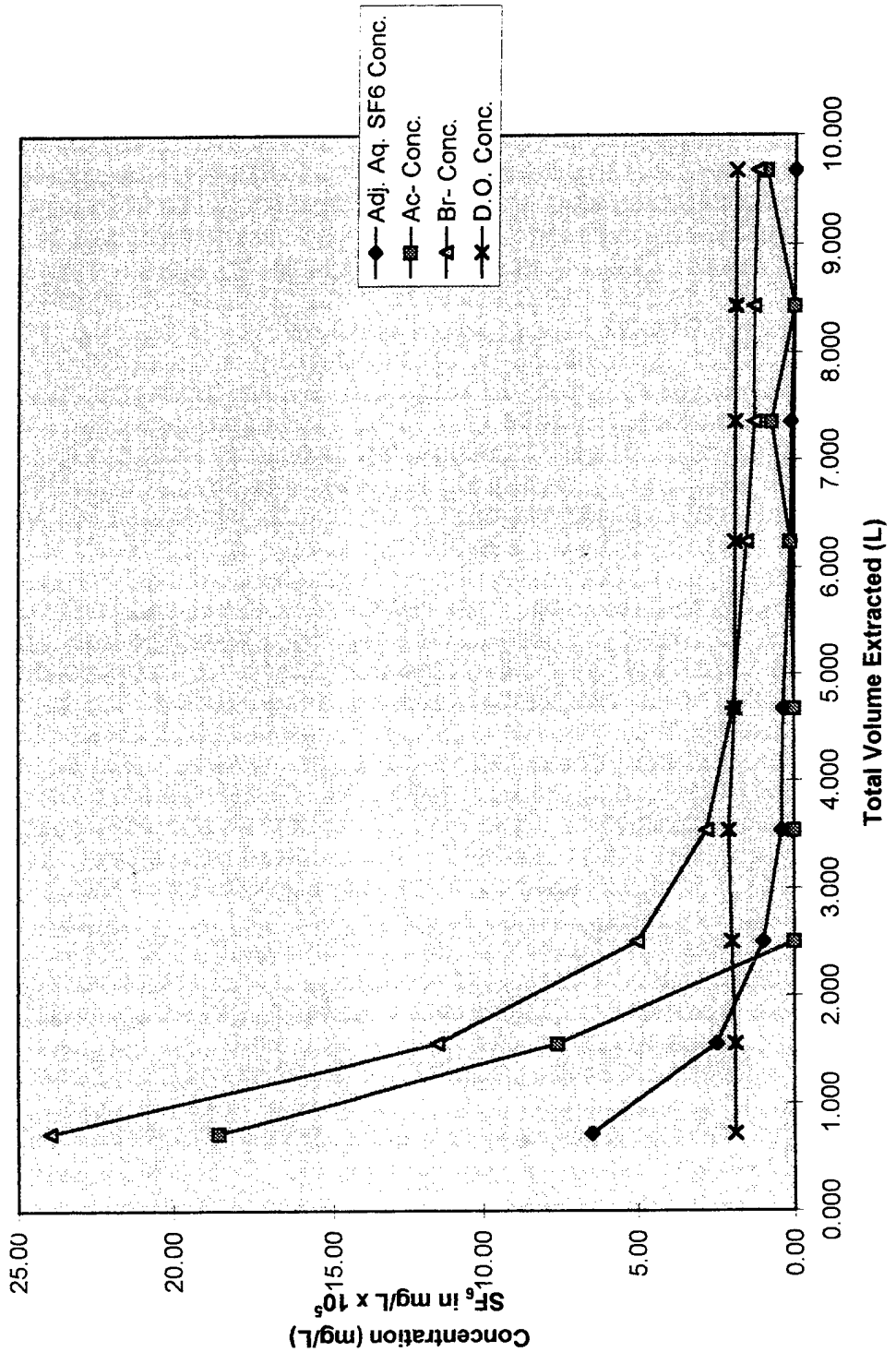


Figure B.12
Tracer Recovery Profile with Volume Extracted at MP9-11', June 1997

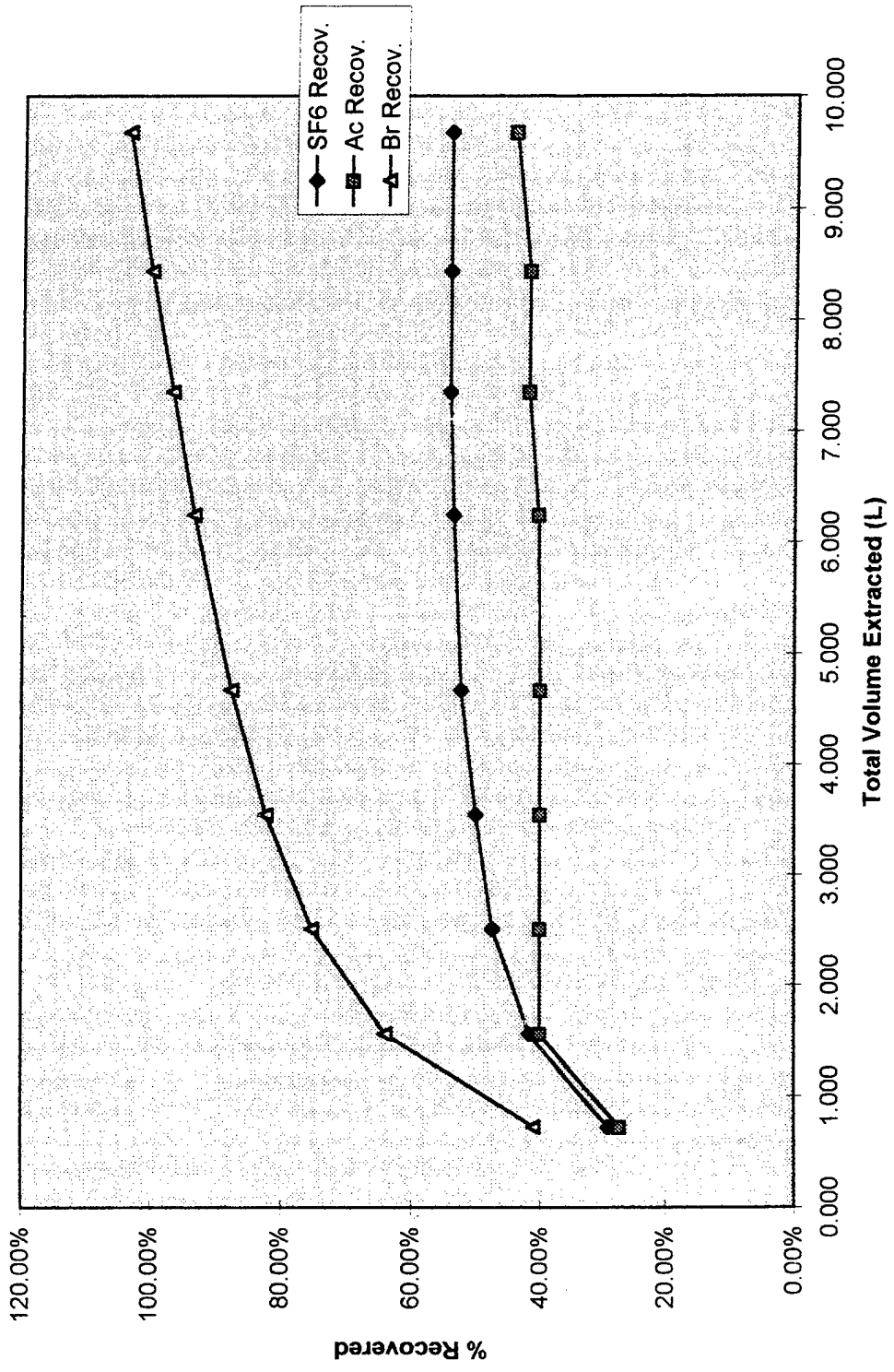


Figure B.13
Tracer Concentration Profile with Volume Extracted at MP11-11', June 1997

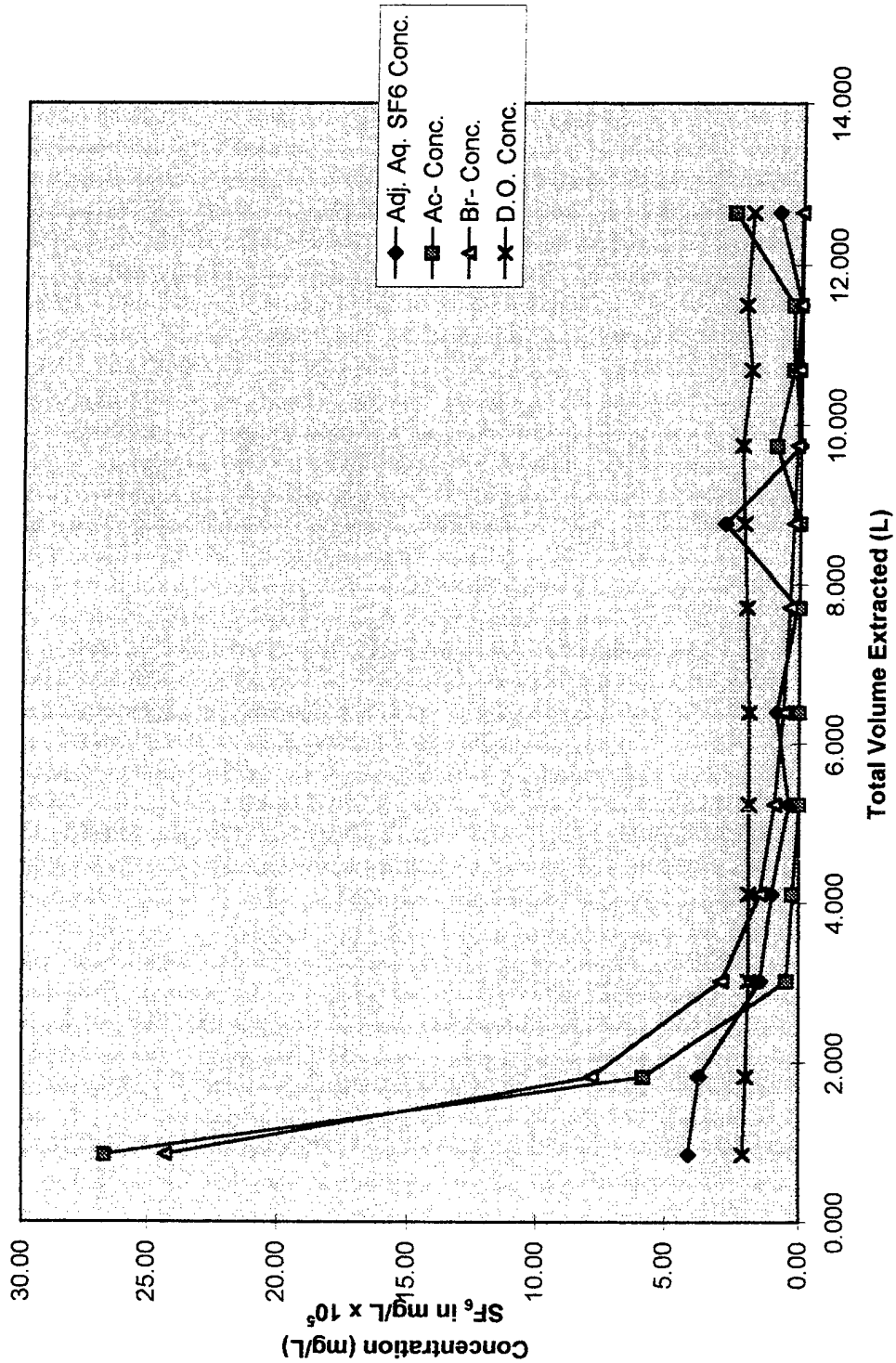


Figure B.14
Tracer Recovery Profile with Volume Extracted at MP11-11', June 1997

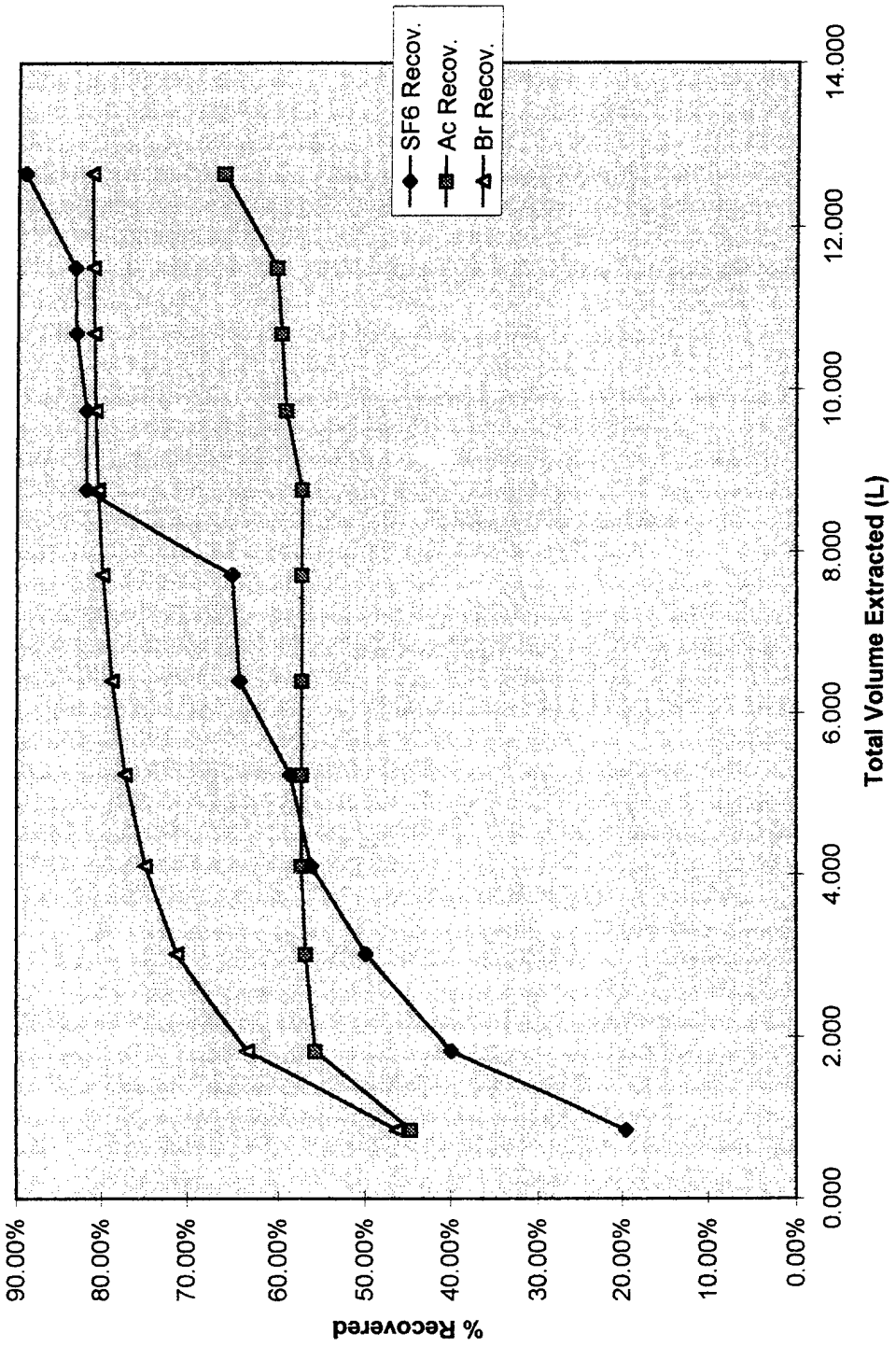


Table B.8
Tracer Concentration and Recovery with Volume Extracted at MP1-11', August 1997

SAMPLE	Vol. Ext. (L)	Tot. Vol. Ext. (L)	Ac^- Conc. (mg/L)	Br^- Conc. (mg/L)	D.O. Conc. (mg/L)	Mass Ac^- (mg)	Mass Br^- (mg)	Cum. Ac (mg)	Cum Br (mg)	Ac Recov. (%)	Br Recov. (%)
init mass	1.000	1.000	51.34	45.34	<2	51.34	45.34				
1	0.990	0.990	4.50	22.33	3.1	4.46	22.11	4.46	22.11	8.68%	48.76%
2	0.990	1.980	1.13	7.52	3.0	1.12	7.45	5.58	29.56	10.87%	65.18%
3	1.000	2.980	0.00	3.99	3.3	0.00	3.99	5.58	33.54	10.87%	73.97%
4	0.995	3.975	0.00	2.76	3.8	0.00	2.75	5.58	36.29	10.87%	80.04%
5	0.990	4.965	0.00	2.18	4.0	0.00	2.16	5.58	38.45	10.87%	84.80%
6	0.995	5.960	0.00	1.89	3.8	0.00	1.88	5.58	40.33	10.87%	88.95%
7	0.985	6.945	0.00	1.70	3.9	0.00	1.68	5.58	42.01	10.87%	92.65%
8	0.995	7.940	0.55	1.56	3.4	0.55	1.55	6.13	43.56	11.94%	96.07%
9	0.980	8.920	0.80	1.45	3.3	0.78	1.42	6.91	44.98	13.46%	99.20%
10	0.945	9.865	0.57	1.37	3.6	0.54	1.30	7.45	46.28	14.50%	102.06%
									Adj. Ac (%)	14.21%	

Table B.9
Tracer Concentration and Recovery with Volume Extracted at MP2-11', August 1997

SAMPLE	Vol. Ext. (L)	Tot. Vol. Ext. (L)	Ac^- Conc. (mg/L)	Br^- Conc. (mg/L)	D.O. Conc. (mg/L)	Mass Ac^- (mg)	Mass Br^- (mg)	Cum. Ac (mg)	Cum Br (mg)	Ac Recov. (%)	Br Recov. (%)
init mass	1.000	1.000	51.34	45.34	<2	51.34	45.34				
1	0.990	0.990	0.00	2.32	1.9	0.00	2.30	0.00	2.30	0.00%	5.07%
2	0.990	1.980	0.78	1.22	1.9	0.77	1.21	0.77	3.51	1.50%	7.73%
3	0.995	2.975	0.00	1.13	1.9	0.00	1.13	0.77	4.63	1.50%	10.22%
4	0.985	3.960	0.00	1.13	1.9	0.00	1.12	0.77	5.75	1.50%	12.68%
5	0.990	4.950	1.56	1.10	1.9	1.55	1.09	2.32	6.84	4.52%	15.08%
6	1.000	5.950	0.00	1.07	1.9	0.00	1.07	2.32	7.91	4.52%	17.44%
7	1.000	6.950	1.75	1.07	1.9	1.75	1.07	4.07	8.98	7.93%	19.80%
8	0.995	7.945	0.00	1.05	1.9	0.00	1.04	4.07	10.02	7.93%	22.10%
9	0.995	8.940	1.98	1.03	1.9	1.97	1.02	6.04	11.05	11.76%	24.36%
10	0.900	9.840	2.16	0.99	1.9	1.95	0.90	7.99	11.94	15.55%	26.34%
									Adj. Ac (%)	59.05%	

Table B.10
Tracer Concentration and Recovery with Volume Extraced at MP4-11', August 1997

SAMPLE	Vol. Ext. (L)	Tot. Vol. Ext. (L)	Ac^- Conc. (mg/L)	Br^- Conc. (mg/L)	D.O. Conc. (mg/L)	Mass Ac^- (mg)	Mass Br^- (mg)	Cum. Ac (mg)	Cum Br (mg)	Ac Recov. (%)	Br Recov. (%)
init mass	1.000	1.000	51.34	45.34	<2	51.34	45.34				
1	0.985	0.985	3.66	11.34	1.9	3.61	11.17	3.61	11.17	7.02%	24.63%
2	0.980	1.965	0.00	4.46	1.9	0.00	4.37	3.61	15.54	7.02%	34.28%
3	1.000	2.965	0.00	3.13	1.9	0.00	3.13	3.61	18.68	7.02%	41.19%
4	0.985	3.950	0.00	2.48	1.9	0.00	2.44	3.61	21.12	7.02%	46.57%
5	0.980	4.930	0.13	2.13	1.9	0.13	2.09	3.74	23.21	7.28%	51.18%
6	0.990	5.920	0.18	1.89	1.9	0.18	1.87	3.92	25.08	7.63%	55.31%
7	0.995	6.915	0.23	1.69	1.9	0.23	1.69	4.15	26.77	8.08%	59.03%
8	0.980	7.895	0.41	1.60	1.9	0.40	1.57	4.55	28.33	8.86%	62.48%
9	0.985	8.880	0.17	1.48	1.9	0.17	1.46	4.72	29.79	9.19%	65.70%
10	0.820	9.700	0.36	1.40	1.9	0.29	1.15	5.01	30.94	9.76%	68.22%
									Adj. Ac (%)	14.30%	

Table B.11
Tracer Concentration and Recovery with Volume Extracted at MP5-11', August 1997

SAMPLE	Vol. Ext. (L)	Tot. Vol. Ext. (L)	Ac^- Conc. (mg/L)	Br^- Conc. (mg/L)	D.O. Conc. (mg/L)	Mass Ac^- (mg)	Mass Br^- (mg)	Cum. Ac (mg)	Cum Br (mg)	Ac Recov. (%)	Br Recov. (%)
init mass	0.750	0.750	51.34	45.34	<2	38.51	34.01				
1	0.955	0.955	8.41	11.72	1.9	8.03	11.19	8.03	11.19	20.85%	32.92%
2	0.980	1.935	6.51	7.73	1.9	6.38	7.57	14.41	18.77	37.42%	55.19%
3	0.990	2.925	3.49	5.15	1.9	3.45	5.09	17.86	23.86	46.39%	70.17%
4	0.985	3.910	2.09	3.57	1.9	2.06	3.52	19.92	27.38	51.74%	80.52%
5	0.980	4.890	1.01	2.63	1.9	0.99	2.57	20.92	29.96	54.32%	88.09%
6	0.900	5.790	0.76	2.06	1.9	0.68	1.86	21.60	31.82	56.10%	93.55%
7	0.990	6.780	0.00	1.66	1.9	0.00	1.64	21.60	33.45	56.10%	98.37%
8	0.995	7.775	0.18	1.44	1.9	0.18	1.43	21.78	34.88	56.55%	102.57%
9	0.995	8.770	0.00	1.27	1.9	0.00	1.26	21.78	36.14	56.55%	106.28%
									Adj. Ac (%)	53.21%	

Table B.12
Tracer Concentration and Recovery with Volume Extracted at MP9-11', August 1997

SAMPLE	Vol. Ext. (L)	Tot. Vol. Ext. (L)	Ac^- Conc. (mg/L)	Br^- Conc. (mg/L)	D.O. Conc. (mg/L)	Mass Ac^- (mg)	Mass Br^- (mg)	Cum. Ac (mg)	Cum Br (mg)	Ac Recov. (%)	Br Recov. (%)
init mass	1.000	1.000	51.34	45.34	<2	51.34	45.34				
1	0.420	0.420	25.52	31.58	6.8	10.72	13.27	10.72	13.27	20.88%	29.25%
2	0.455	0.875	10.43	15.17	7.2	4.74	6.90	15.46	20.17	30.12%	44.47%
3	0.980	1.855	0.00	5.52	7.3	0.00	5.41	15.46	25.58	30.12%	56.41%
4	0.800	2.655	0.00	2.86	7.6	0.00	2.29	15.46	27.87	30.12%	61.46%
5	0.615	3.270	0.09	2.13	7.4	0.06	1.31	15.52	29.18	30.23%	64.35%
6	0.560	3.830	0.00	1.78	7.6	0.00	1.00	15.52	30.17	30.23%	66.55%
7	0.700	4.530	0.00	1.51	7.7	0.00	1.06	15.52	31.23	30.23%	68.87%
9	0.530	5.060	0.10	1.23	8.0	0.05	0.65	15.57	31.88	30.33%	70.31%
									Adj. Ac (%)	43.14%	

Table B.13
Tracer Concentration and Recovery with Volume Extracted at MP11-11', August 1997

SAMPLE	Vol. Ext. (L)	Tot. Vol. Ext. (L)	Ac^- Conc. (mg/L)	Br^- Conc. (mg/L)	D.O. Conc. (mg/L)	Mass Ac^- (mg)	Mass Br^- (mg)	Cum. Ac (mg)	Cum Br (mg)	Ac Recov. (%)	Br Recov. (%)
init mass	1.000	1.000	51.34	45.34	<2	51.34	45.34				
1	0.970	0.970	3.49	16.38	1.9	3.39	15.89	3.39	15.89	6.60%	35.04%
2	0.985	1.955	0.00	5.22	1.9	0.00	5.15	3.39	21.03	6.60%	46.39%
3	0.985	2.940	1.46	3.44	1.9	1.44	3.39	4.82	24.42	9.39%	53.86%
4	0.980	3.920	1.83	2.95	1.9	1.79	2.89	6.61	27.31	12.88%	60.23%
5	0.980	4.900	2.07	2.68	1.9	2.03	2.63	8.64	29.94	16.83%	66.02%
6	0.995	5.895	0.31	2.45	1.9	0.31	2.44	8.95	32.37	17.43%	71.39%
7	0.990	6.885	0.52	2.23	1.9	0.51	2.21	9.46	34.58	18.43%	76.27%
8	0.990	7.875	0.63	2.10	1.9	0.62	2.08	10.08	36.66	19.64%	80.85%
9	0.980	8.855	0.33	1.97	1.9	0.32	1.93	10.41	38.59	20.27%	85.10%
10	0.535	9.390	0.00	1.82	1.9	0.00	0.97	10.41	39.56	20.27%	87.25%
									Adj. Ac (%)	23.23%	

Figure B.15
Tracer Concentration Profile with Volume Extracted at MP1-11', August 1997

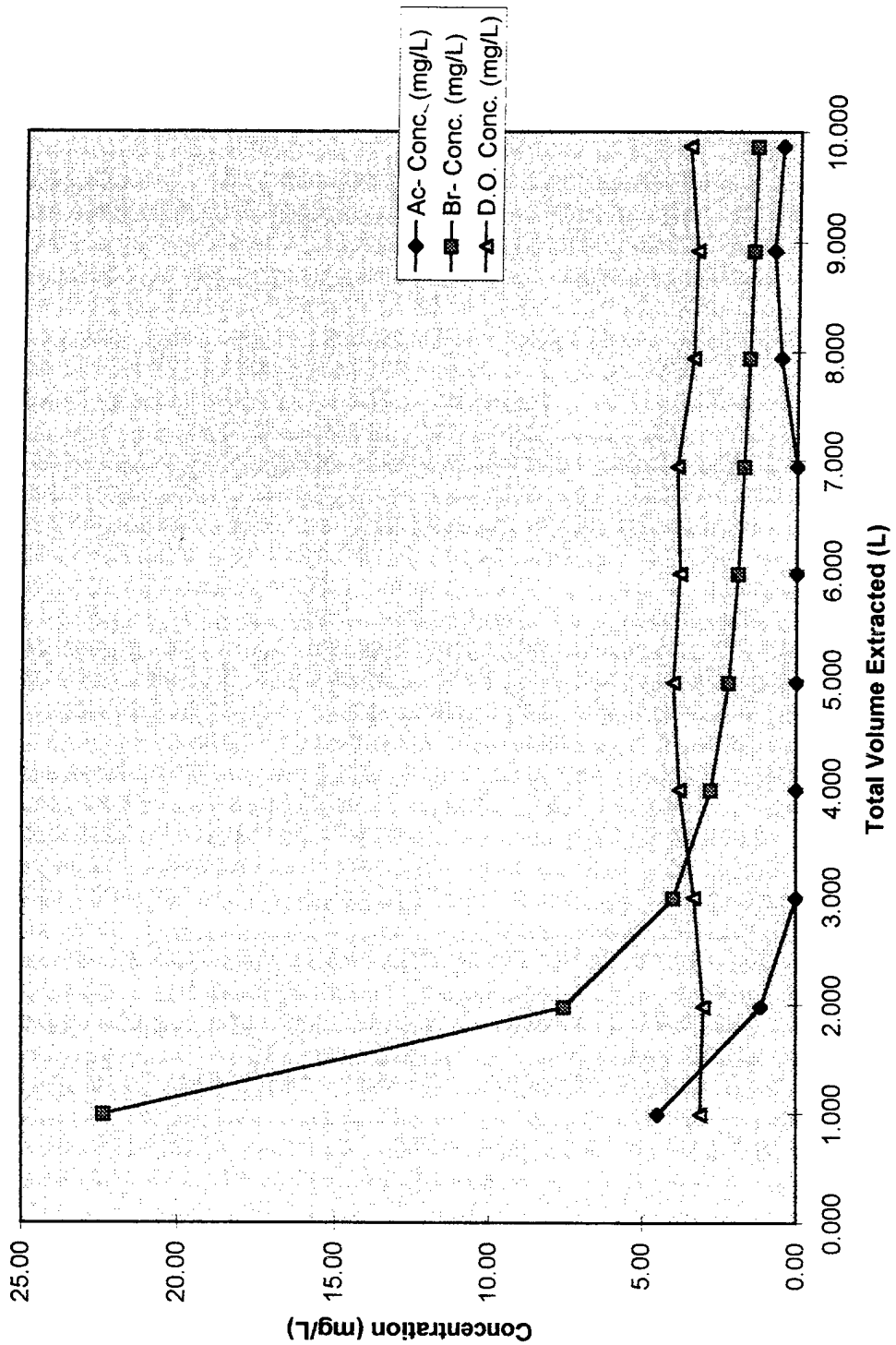


Figure B.16
Tracer Recovery Profile with Volume Extracted at MP1-11', August 1997

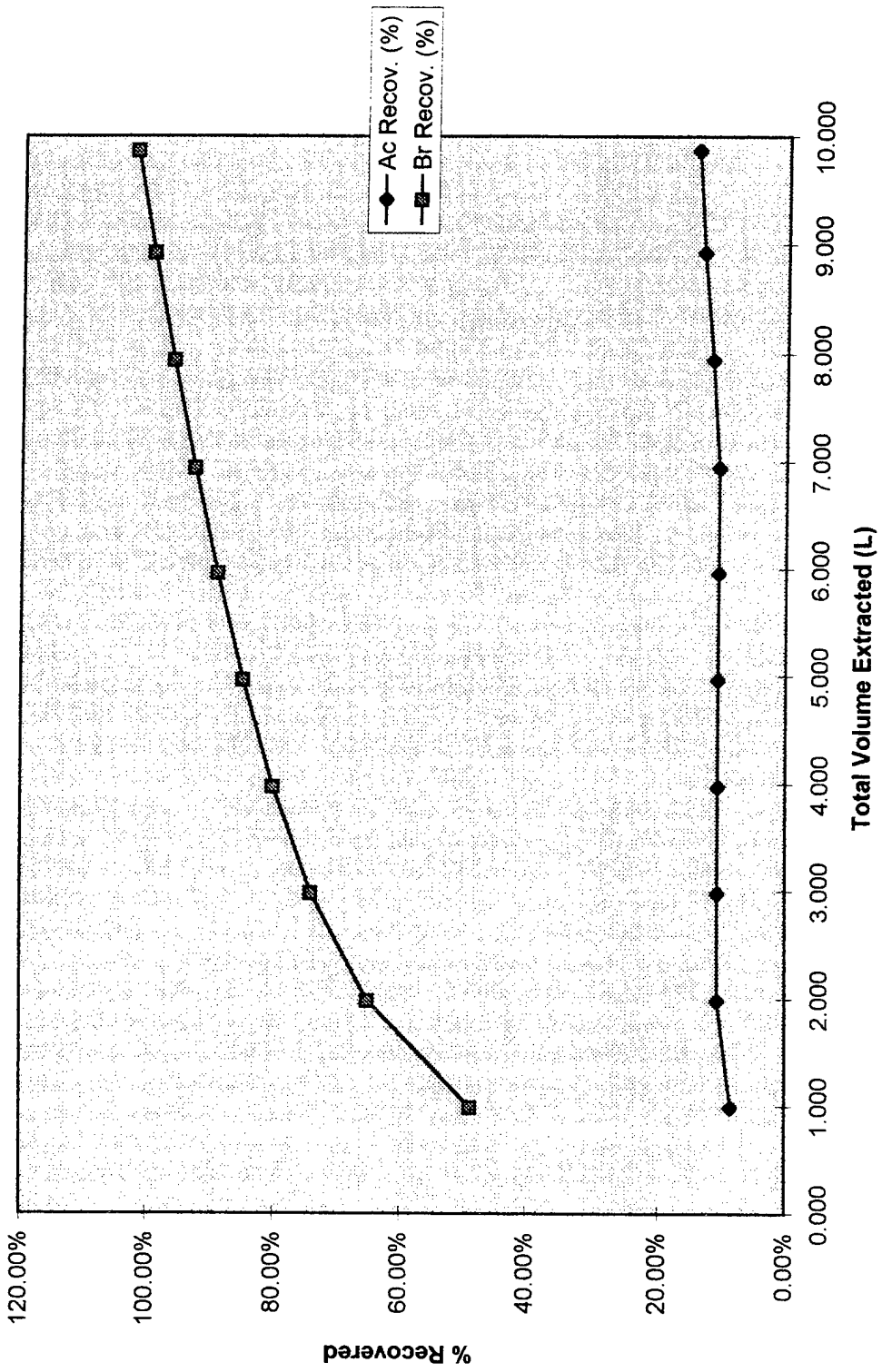


Figure B.17
Tracer Concentration Profile with Volume Extracted at MP2-11', August 1997

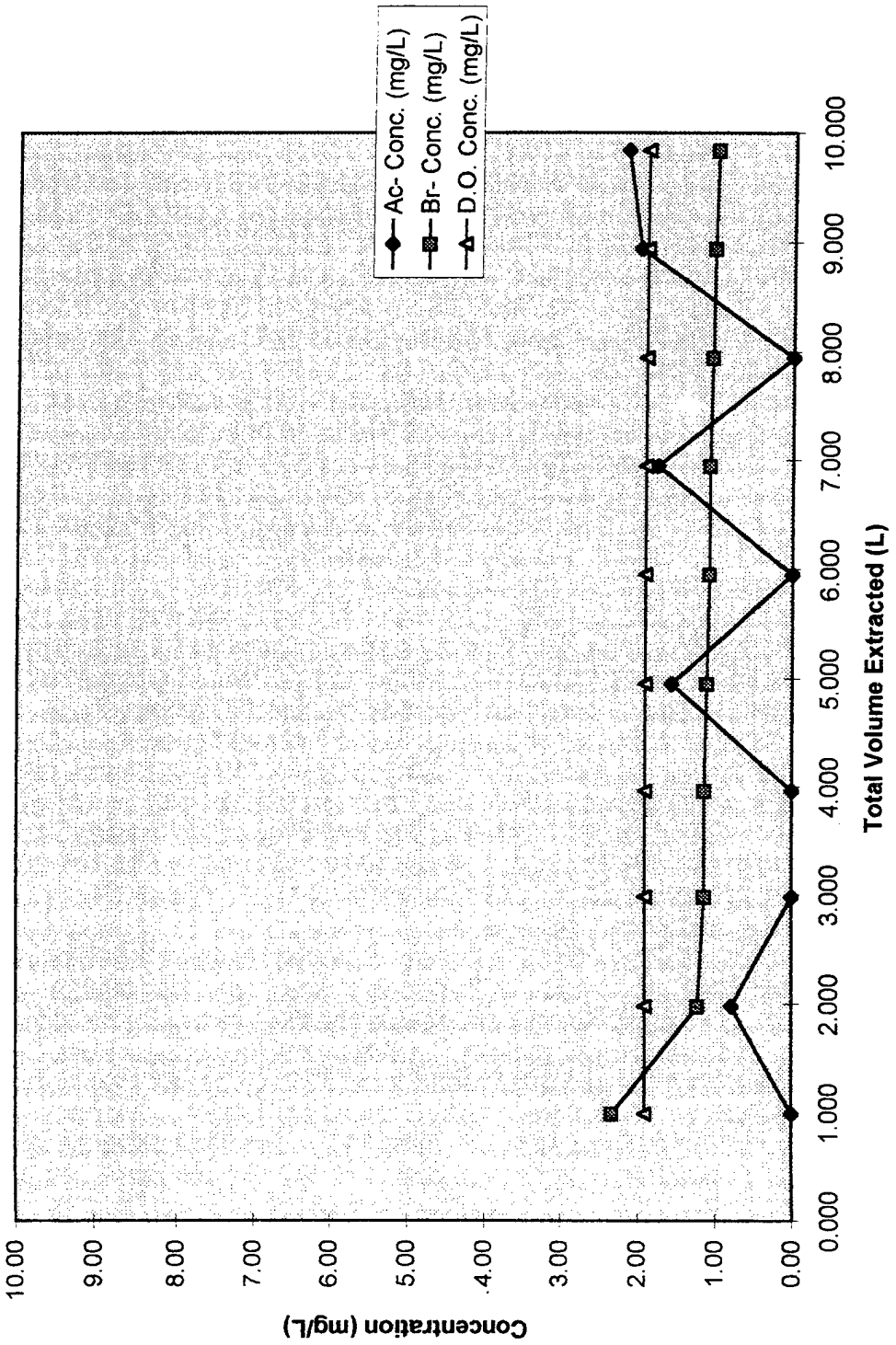


Figure B.18
Tracer Recovery Profile with Volume Extracted at MP2-11', August 1997

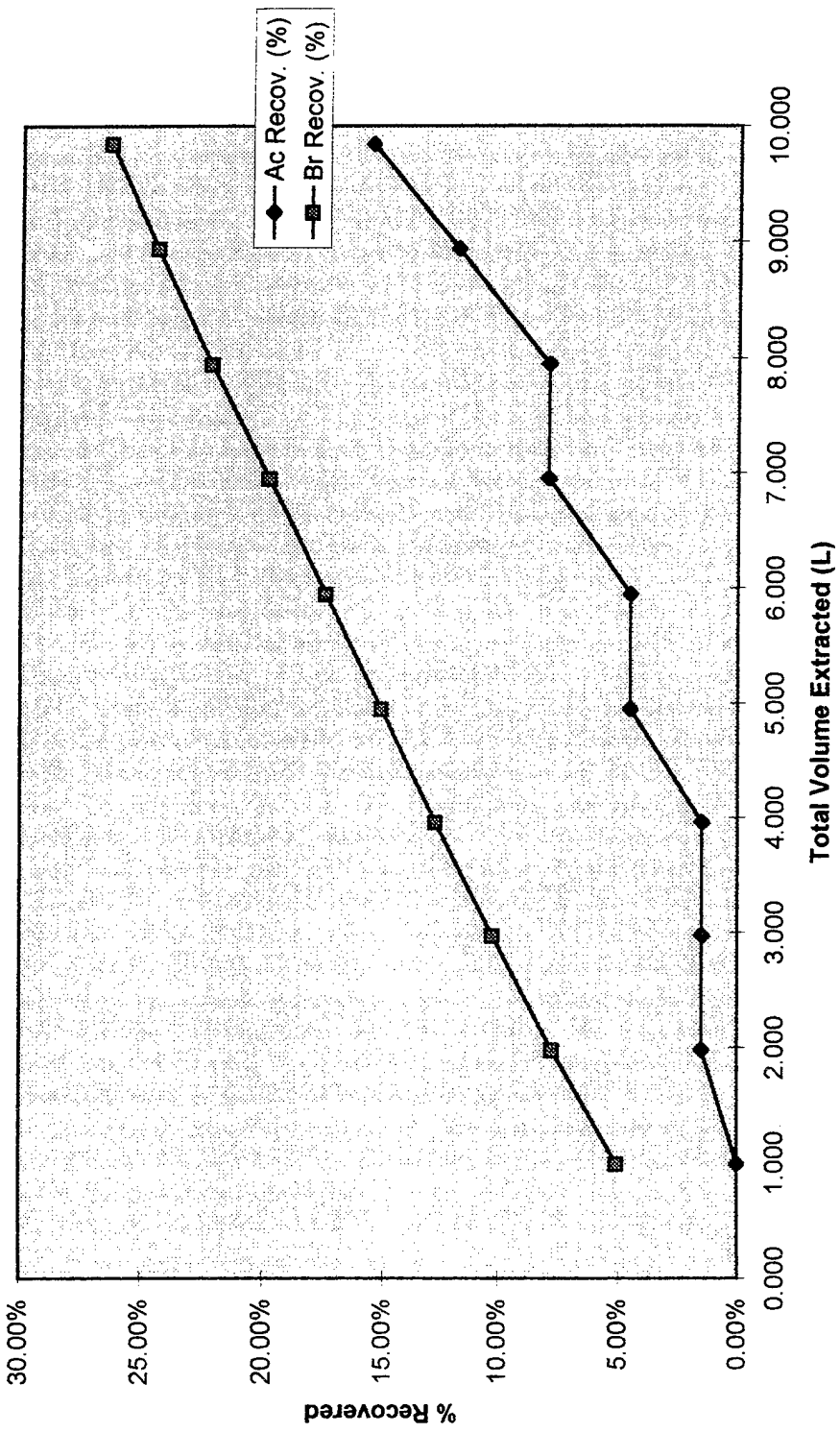


Figure B.19
Tracer Concentration Profile with Volume Extracted at MP4-11', August 1997

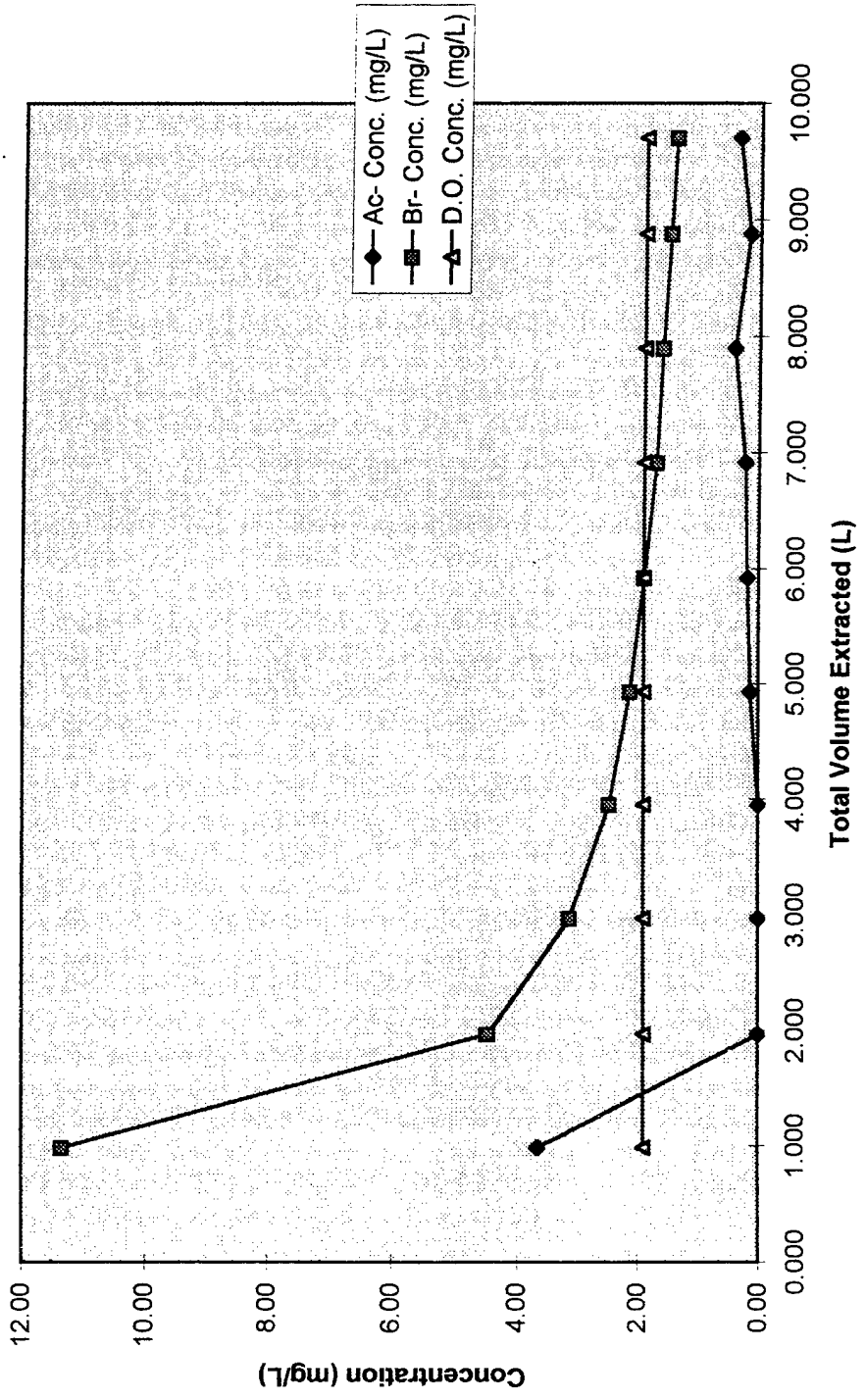


Figure B.20
Tracer Recovery Profile with Volume Extraction at MP4-11', August 1997

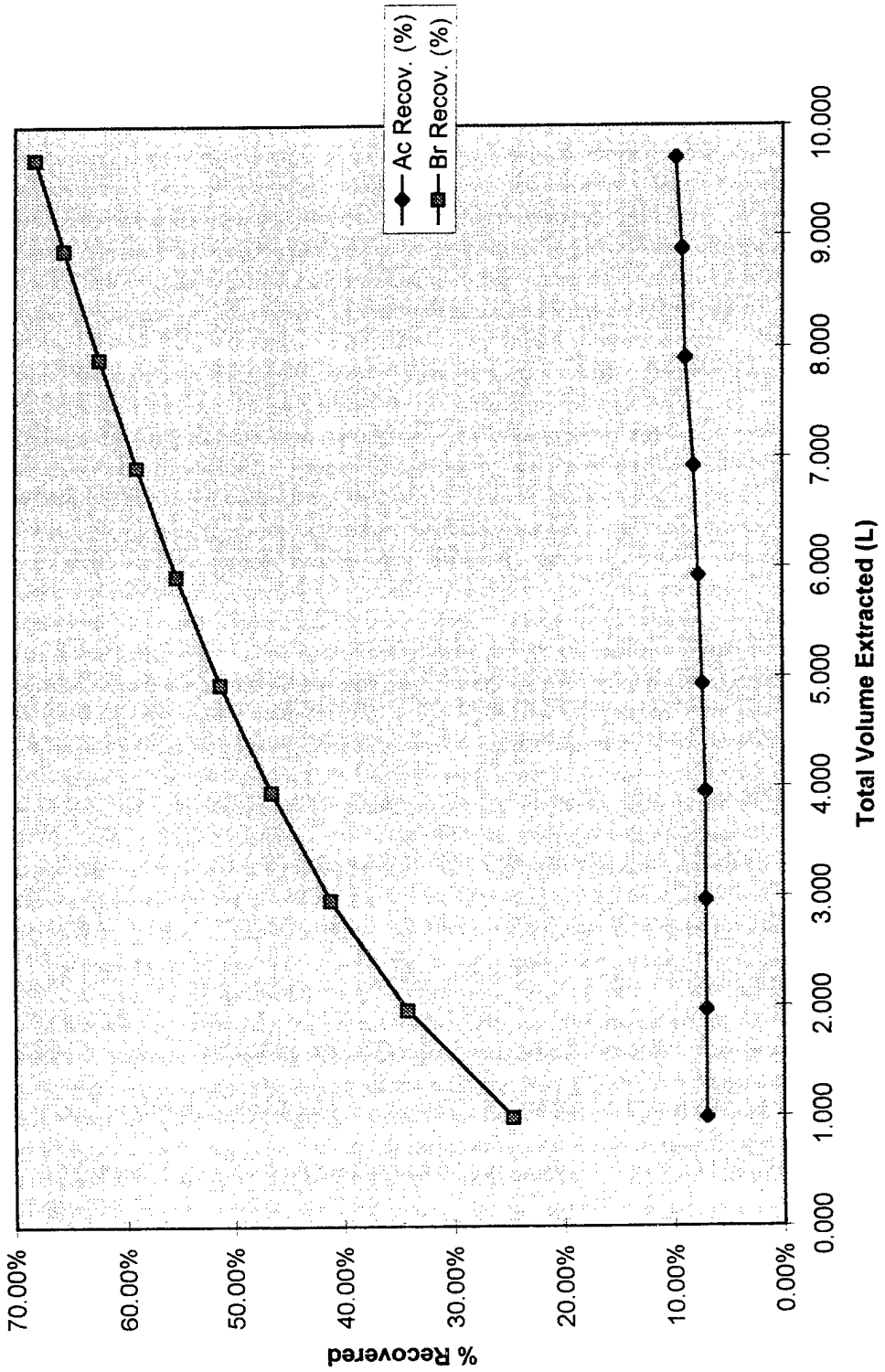


Figure B.21
Tracer Concentration Profile with Volume Extracted at MP5-11', August 1997

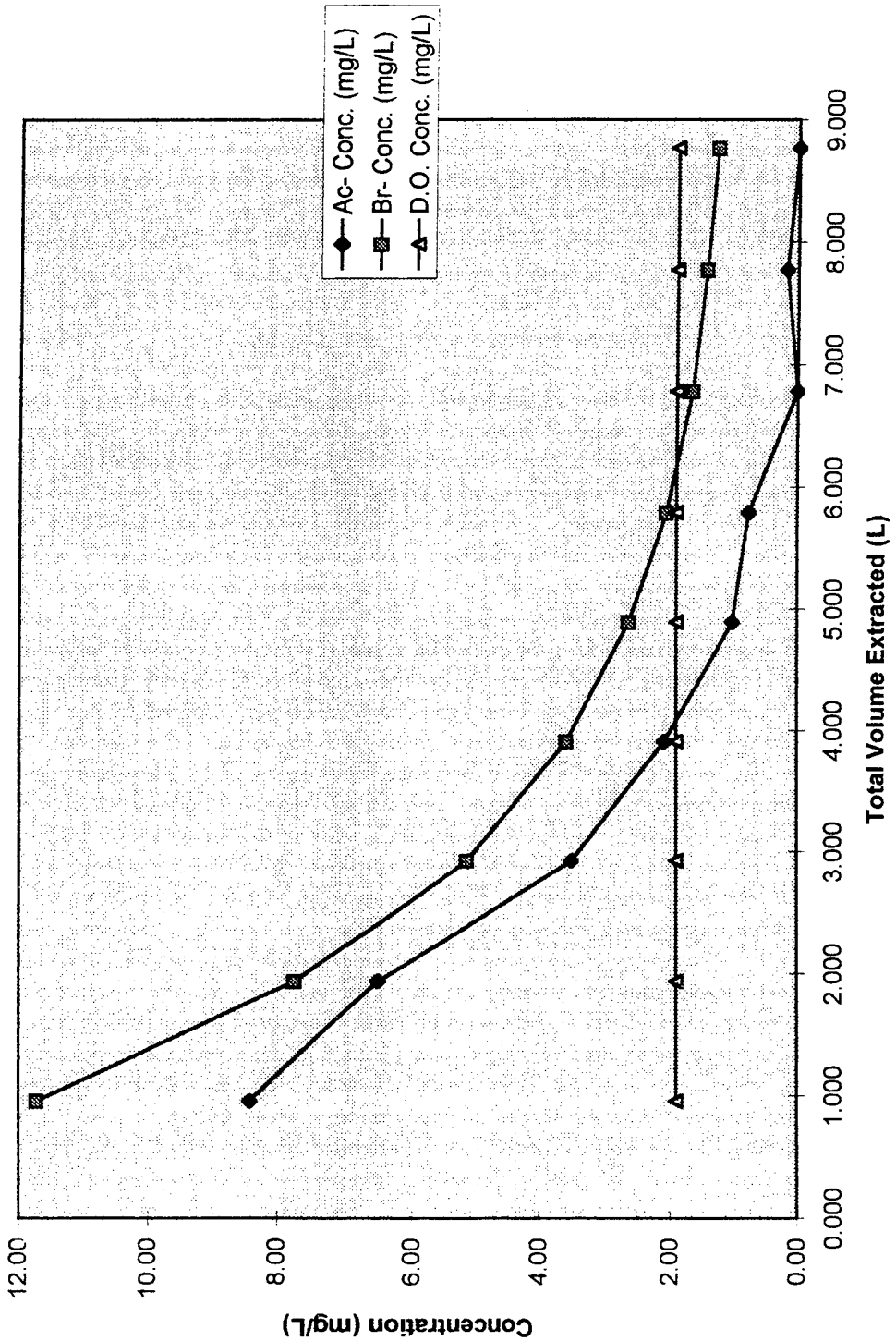


Figure B.22
Tracer Recovery Profile with Volume Extracted at MP5-11', August 1997

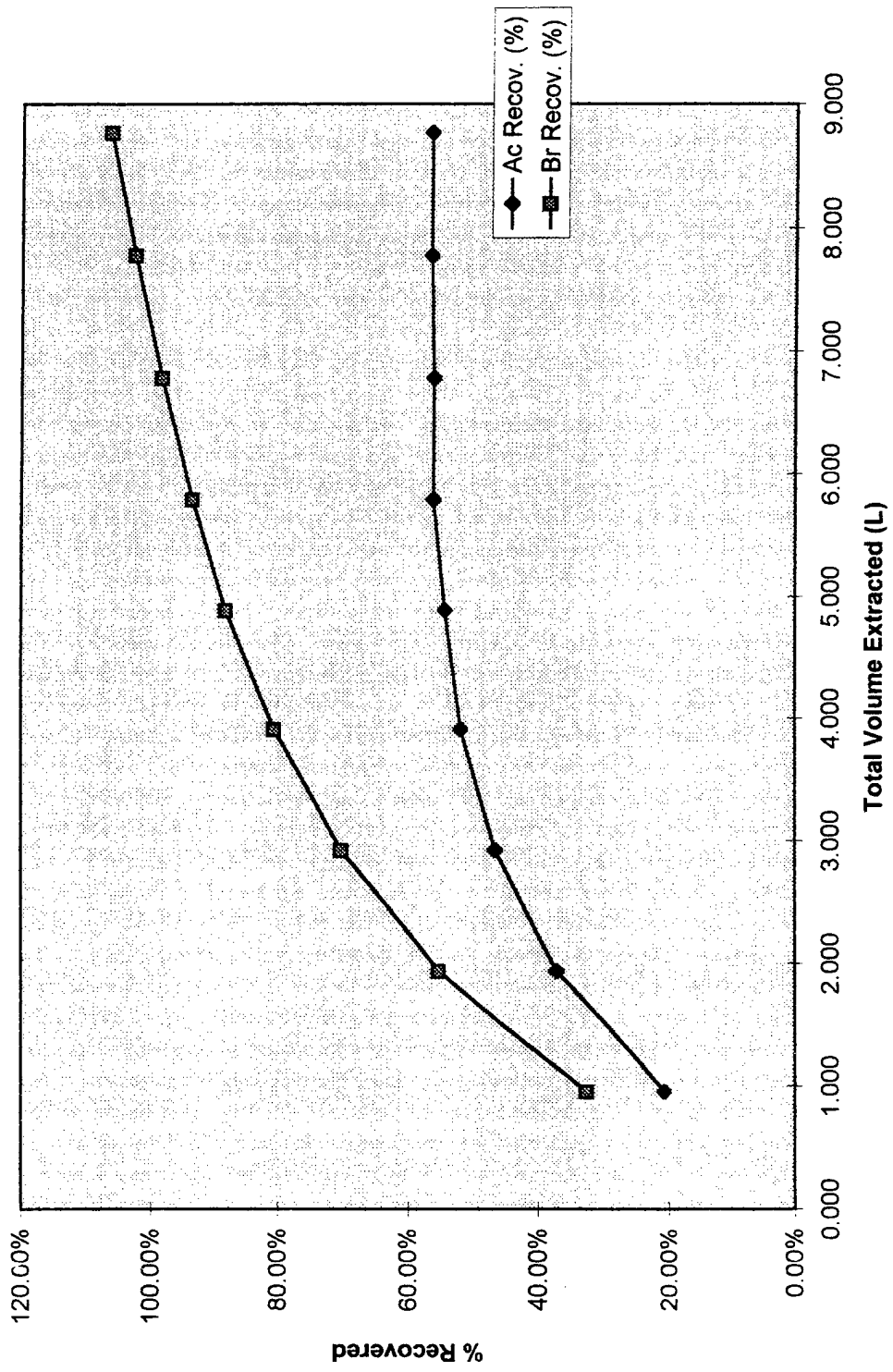


Figure B.23
Tracer Concentration Profile with Volume Extracted at MP9-11', August 1997

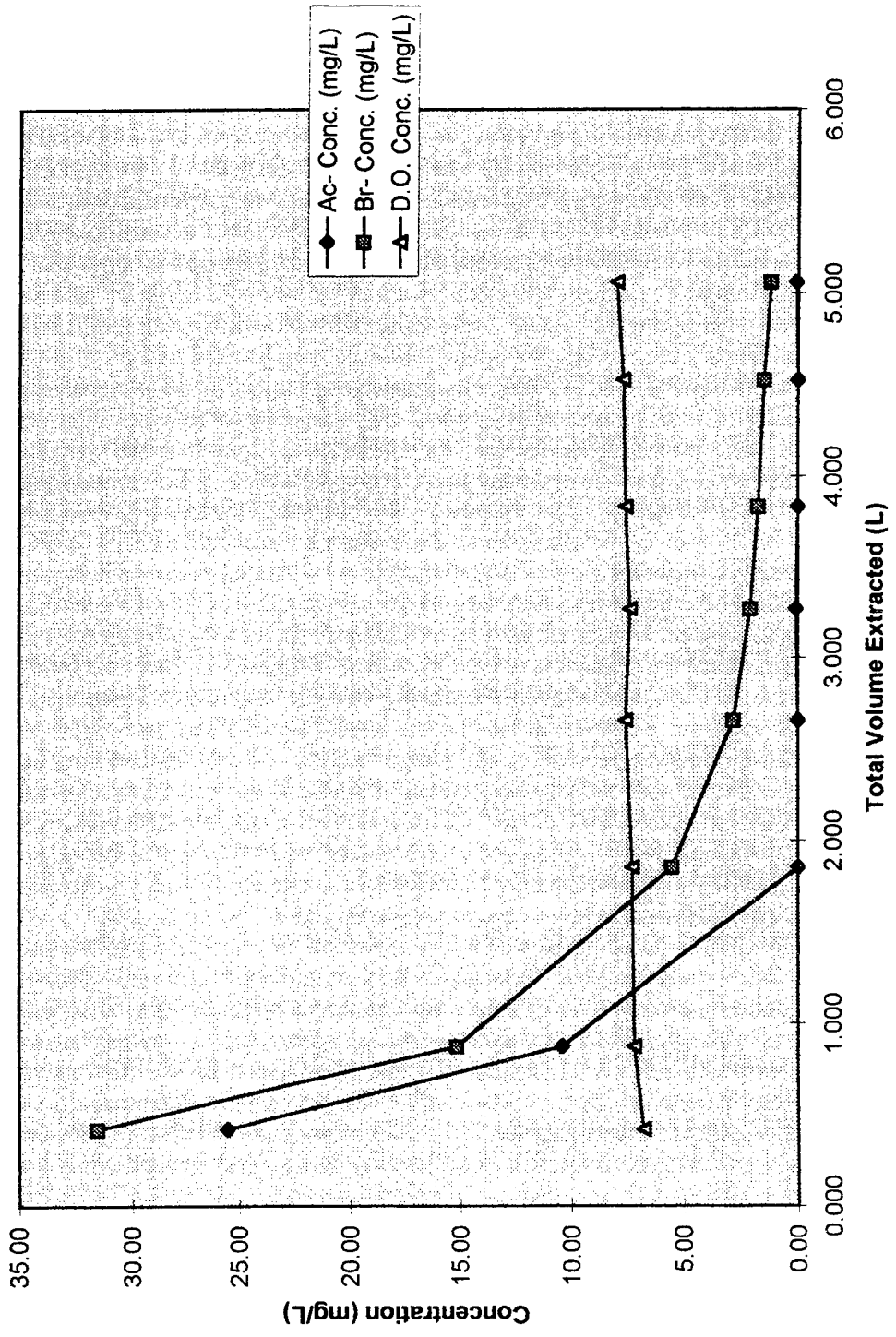


Figure B.24
Tracer Recovery Profile with Volume Extracted at MP9-11', August 1997

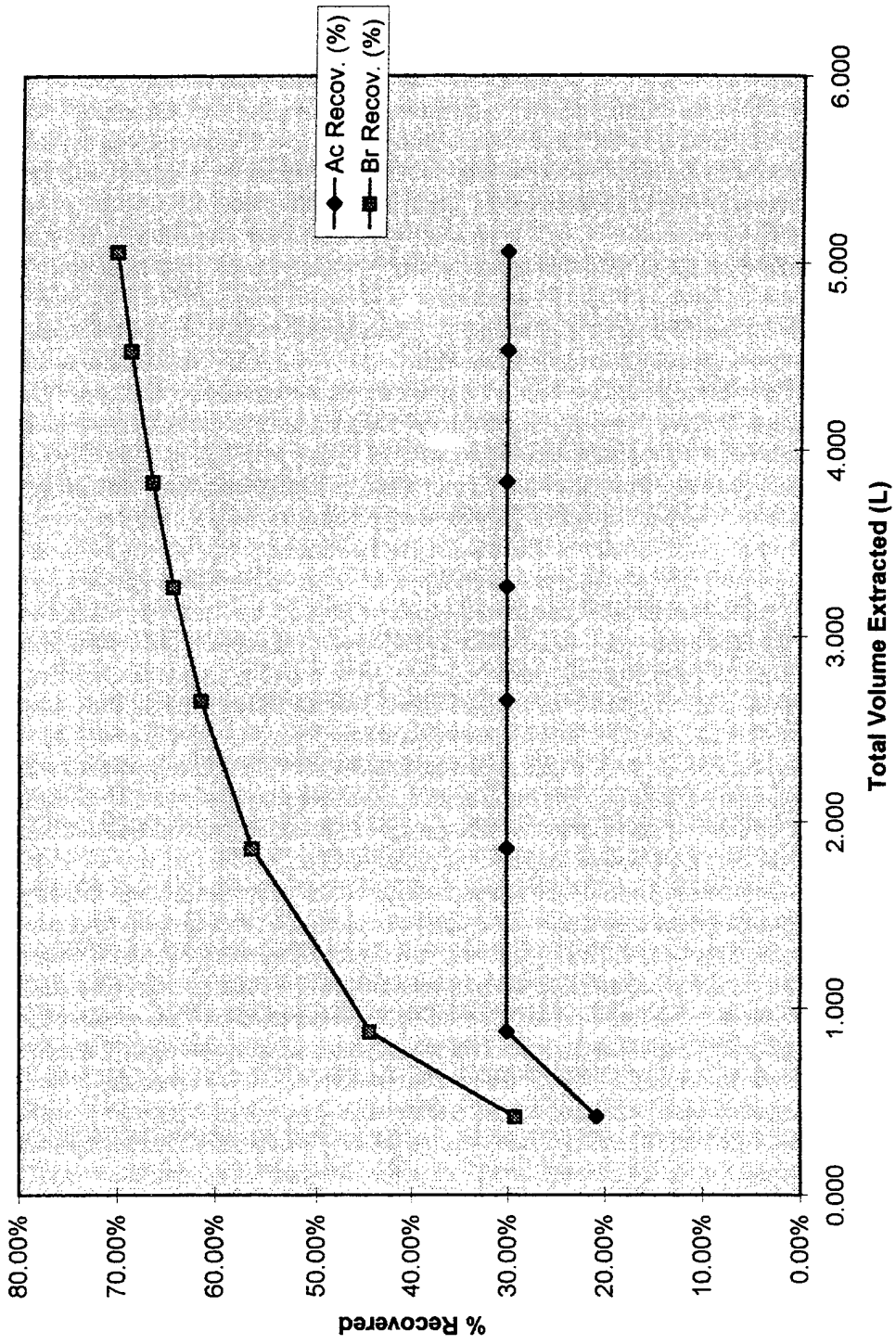


Figure B.25
Tracer Concentration Profile with Volume Extracted at MP11-11', August 1997

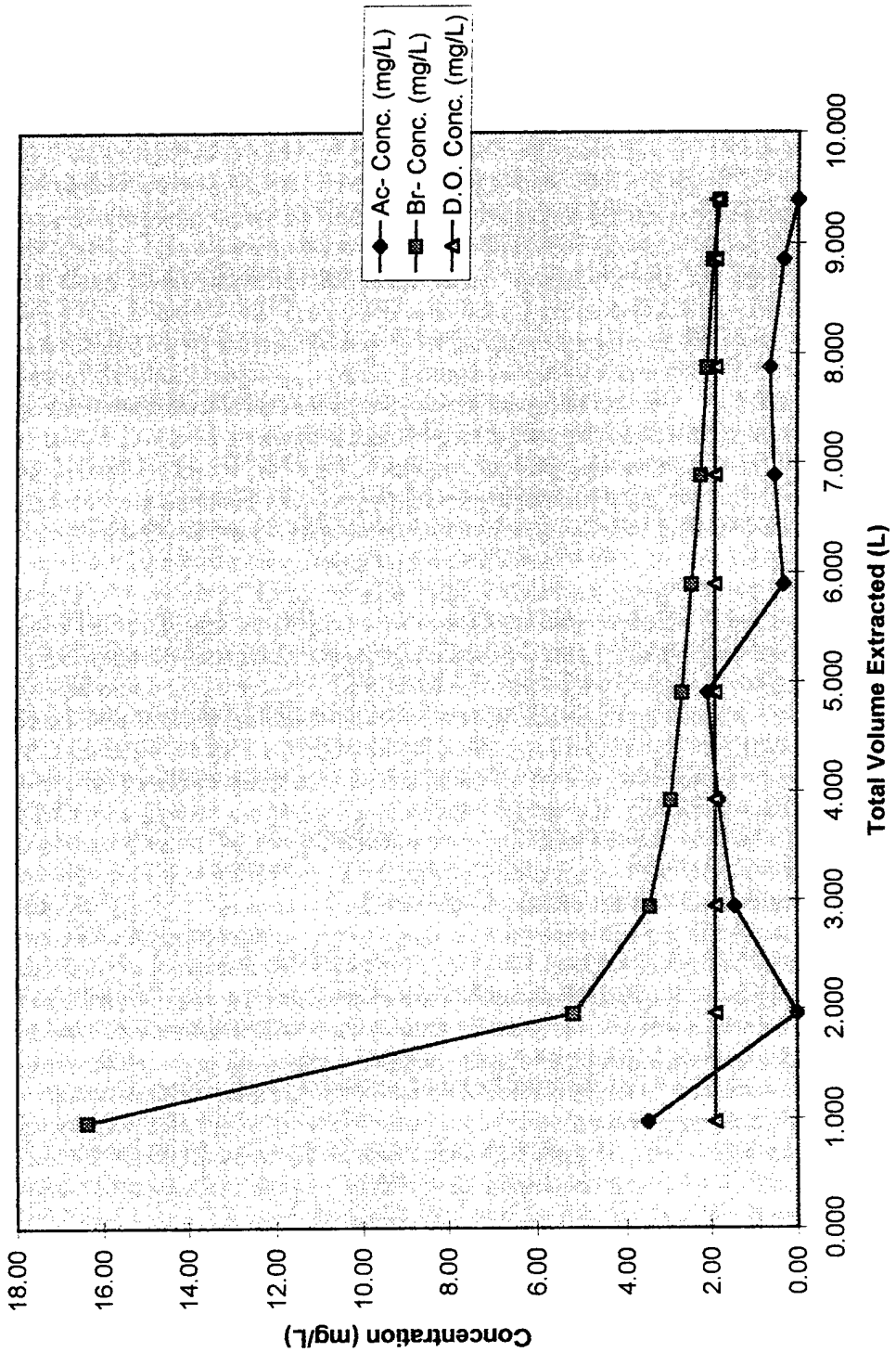


Figure B.26
Tracer Recovery Profile with Volume Extracted at MP11-11', August 1997

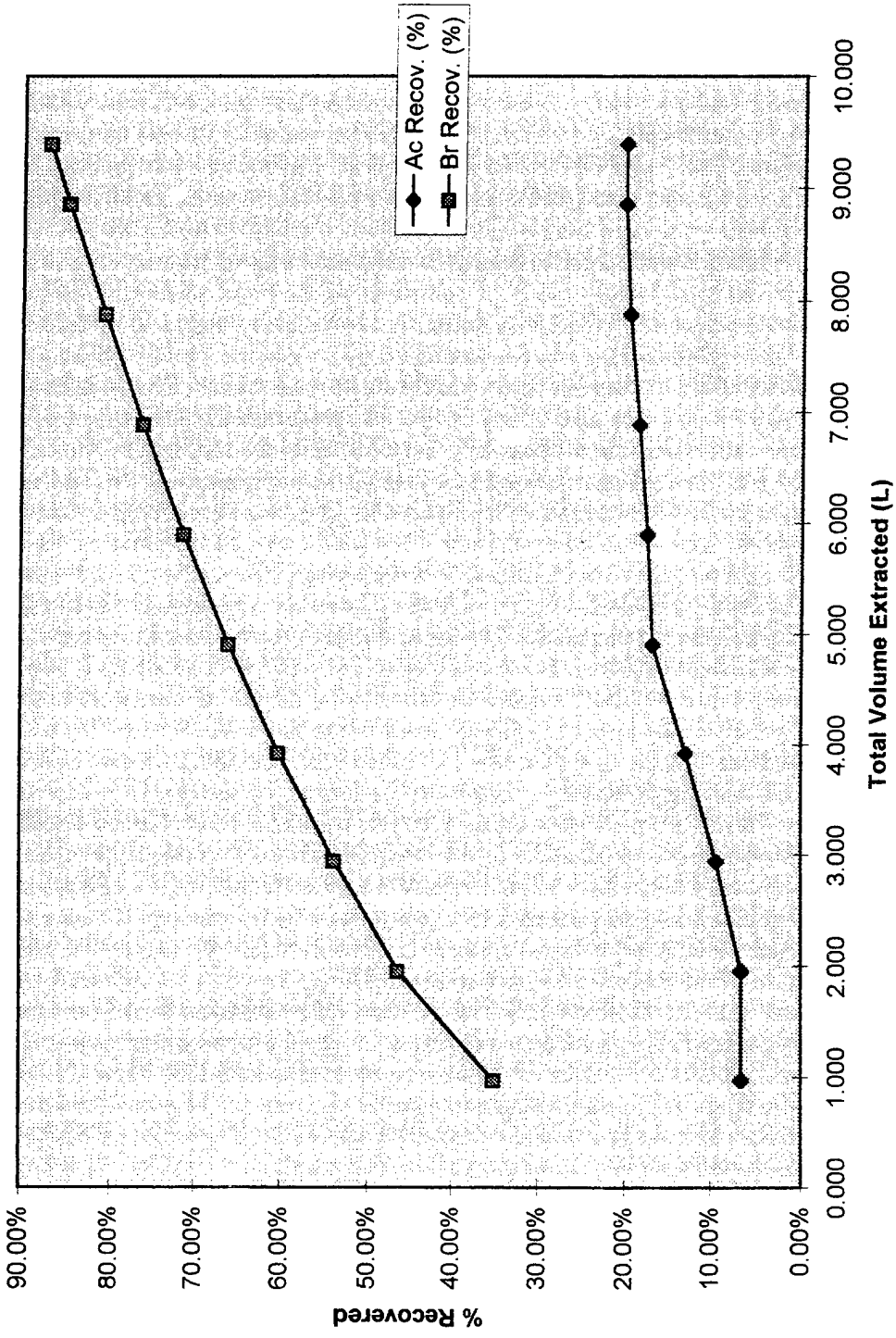


Table B.14
Tracer Concentration and Recovery with Volume Extracted at MP1-11', September 1997

SAMPLE	Vol. Ext. (L)	Tot. Vol. Ext. (L)	Ac^- Conc. (mg/L)	Br^- Conc. (mg/L)	D.O. Conc. (mg/L)	Mass Ac^- (mg)	Mass Br^- (mg)	Cum. Ac (mg)	Cum Br (mg)	Ac Recov. (%)	Br Recov. (%)
init mass	0.825	0.825	50.61	43.07	<2	41.75	35.53				
1	0.990	0.990	21.88	20.63	1.9	21.66	20.42	21.66	20.42	51.88%	57.48%
2	0.990	1.980	3.79	5.15	1.9	3.75	5.10	25.42	25.53	60.88%	71.84%
3	0.995	2.975	0.00	2.86	1.9	0.00	2.84	25.42	28.37	60.88%	79.84%
4	0.990	3.965	0.00	1.81	1.9	0.00	1.79	25.42	30.16	60.88%	84.89%
5	0.995	4.960	0.00	1.51	1.9	0.00	1.50	25.42	31.66	60.88%	89.11%
6	0.995	5.955	0.00	1.39	1.9	0.00	1.38	25.42	33.04	60.88%	93.00%
7	1.000	6.955	0.00	1.25	1.9	0.00	1.25	25.42	34.29	60.88%	96.51%
8	0.995	7.950	0.00	1.19	1.9	0.00	1.19	25.42	35.48	60.88%	99.85%
9	1.000	8.950	0.00	1.16	1.9	0.00	1.16	25.42	36.64	60.88%	103.11%
10	0.995	9.945	0.00	1.12	1.9	0.00	1.11	25.42	37.75	60.88%	106.24%
									Adj. Ac (%)	57.30%	

Table B.15
Tracer Concentration and Recovery with Volume Extracted at MP2-11', September 1997

SAMPLE	Vol. Ext. (L)	Tot. Vol. Ext. (L)	Ac^- Conc. (mg/L)	Br^- Conc. (mg/L)	D.O. Conc. (mg/L)	Mass Ac^- (mg)	Mass Br^- (mg)	Cum. Ac (mg)	Cum Br (mg)	Ac Recov. (%)	Br Recov. (%)
init mass	1.000	1.000	50.61	43.07	<2	50.61	43.07				
1	0.990	0.990	0.00	6.91	1.9	0.00	6.84	0.00	6.84	0.00%	15.88%
2	0.995	1.985	0.00	4.16	1.9	0.00	4.14	0.00	10.98	0.00%	25.49%
3	0.995	2.980	0.00	4.06	1.9	0.00	4.04	0.00	15.02	0.00%	34.88%
4	0.990	3.970	0.00	3.69	1.9	0.00	3.65	0.00	18.67	0.00%	43.36%
5	0.990	4.960	0.00	3.27	1.9	0.00	3.24	0.00	21.91	0.00%	50.88%
6	1.000	5.960	0.00	2.93	1.9	0.00	2.93	0.00	24.85	0.00%	57.69%
7	0.995	6.955	0.00	2.64	1.9	0.00	2.62	0.00	27.47	0.00%	63.78%
8	0.995	7.950	0.00	2.36	1.9	0.00	2.35	0.00	29.82	0.00%	69.23%
9	1.000	8.950	0.00	2.09	1.9	0.00	2.09	0.00	31.90	0.00%	74.07%
10	0.995	9.945	0.00	1.88	1.9	0.00	1.87	0.00	33.77	0.00%	78.42%
11	0.995	10.940	0.00	1.65	1.9	0.00	1.64	0.00	35.41	0.00%	82.23%
12	0.985	11.925	0.00	1.53	2.2	0.00	1.50	0.00	36.92	0.00%	85.72%
13	0.995	12.920	0.00	1.38	2.2	0.00	1.37	0.00	38.29	0.00%	88.89%
14	0.995	13.915	0.00	1.26	2.2	0.00	1.25	0.00	39.54	0.00%	91.80%
15	0.990	14.905	0.00	1.20	2.2	0.00	1.19	0.00	40.73	0.00%	94.56%
									Adj. Ac (%)	0.00%	

Table B.16
Tracer Concentration and Recovery with Volume Extracted at MP4-11', September 1997

SAMPLE	Vol. Ext. (L)	Tot. Vol. Ext. (L)	Ac^- Conc. (mg/L)	Br^- Conc. (mg/L)	D.O. Conc. (mg/L)	Mass Ac^- (mg)	Mass Br^- (mg)	Cum. Ac (mg)	Cum Br (mg)	Ac Recov. (%)	Br Recov. (%)
init mass	1.000	1.000	50.61	43.07	<2	50.61	43.07				
1	0.995	0.995	21.80	18.43	3.8	21.69	18.34	21.69	18.34	42.86%	42.57%
2	0.980	1.975	4.20	5.49	4.9	4.12	5.38	25.81	23.71	51.00%	55.06%
3	1.000	2.975	0.00	3.22	5.0	0.00	3.22	25.81	26.93	51.00%	62.53%
4	0.980	3.955	0.00	2.28	4.5	0.00	2.23	25.81	29.16	51.00%	67.71%
5	0.995	4.950	0.00	1.77	5.1	0.00	1.76	25.81	30.93	51.00%	71.81%
6	1.000	5.950	0.00	1.52	5.0	0.00	1.52	25.81	32.45	51.00%	75.34%
7	0.995	6.945	0.00	1.38	4.5	0.00	1.37	25.81	33.82	51.00%	78.53%
8	0.895	7.840	0.00	1.29	5.0	0.00	1.15	25.81	34.97	51.00%	81.20%
9	0.995	8.835	0.00	1.21	4.6	0.00	1.21	25.81	36.18	51.00%	84.00%
10	0.990	9.825	0.00	1.17	4.7	0.00	1.16	25.81	37.34	51.00%	86.69%
									Adj. Ac (%)	58.83%	

Table B.17
Tracer Concentration and Recovery with Volume Extracted at MP5-11', September 1997

SAMPLE	Vol. Ext. (L)	Tot. Vol. Ext. (L)	Ac^- Conc. (mg/L)	Br^- Conc. (mg/L)	D.O. Conc. (mg/L)	Mass Ac^- (mg)	Mass Br^- (mg)	Cum. Ac (mg)	Cum Br (mg)	Ac Recov. (%)	Br Recov. (%)
init mass	1.000	1.000	50.61	43.07	<2	50.61	43.07				
1	0.990	0.990	23.92	23.12	1.9	23.68	22.89	23.68	22.89	46.80%	53.15%
2	0.990	1.980	16.70	9.63	1.9	16.54	9.54	40.22	32.43	79.48%	75.30%
3	0.990	2.970	0.00	5.07	1.9	0.00	5.02	40.22	37.45	79.48%	86.95%
4	0.990	3.960	0.00	2.80	1.9	0.00	2.77	40.22	40.22	79.48%	93.38%
5	0.990	4.950	0.00	1.83	1.9	0.00	1.81	40.22	42.03	79.48%	97.58%
6	1.000	5.950	0.00	1.42	1.9	0.00	1.42	40.22	43.45	79.48%	100.89%
7	0.995	6.945	0.00	1.23	1.9	0.00	1.22	40.22	44.67	79.48%	103.72%
8	0.995	7.940	0.00	1.16	1.9	0.00	1.15	40.22	45.82	79.48%	106.39%
9	0.995	8.935	0.00	1.18	1.9	0.00	1.17	40.22	47.00	79.48%	109.12%
10	0.990	9.925	0.00	1.07	1.9	0.00	1.06	40.22	48.05	79.48%	111.57%
									Adj. Ac (%)	71.24%	

Figure B.18
Tracer Concentration and Recovery with Volume Extracted at MP7-11', September 1997

SAMPLE	Vol. Ext. (L)	Tot. Vol. Ext. (L)	Ac^- Conc. (mg/L)	Br^- Conc. (mg/L)	D.O. Conc. (mg/L)	Mass Ac^- (mg)	Mass Br^- (mg)	Cum. Ac (mg)	Cum Br (mg)	Ac Recov. (%)	Br Recov. (%)
init mass	1.000	1.000	50.61	43.07	<2	50.61	43.07				
1	0.990	0.990	26.94	25.83	1.9	26.67	25.58	26.67	25.58	52.70%	59.38%
2	0.985	1.975	21.89	8.52	1.9	21.56	8.39	48.23	33.97	95.31%	78.87%
3	1.000	2.975	6.43	3.96	1.9	6.43	3.96	54.66	37.93	108.01%	88.07%
4	0.990	3.965	0.00	2.81	1.9	0.00	2.78	54.66	40.71	108.01%	94.53%
5	0.995	4.960	0.00	2.27	1.9	0.00	2.26	54.66	42.97	108.01%	99.78%
6	1.000	5.960	0.00	2.04	1.9	0.00	2.04	54.66	45.02	108.01%	104.52%
7	0.960	6.920	0.00	1.84	1.9	0.00	1.77	54.66	46.79	108.01%	108.63%
8	0.985	7.905	0.00	1.77	1.9	0.00	1.75	54.66	48.53	108.01%	112.68%
9	0.760	8.665	0.00	1.69	1.9	0.00	1.29	54.66	49.82	108.01%	115.67%
10	0.730	9.395	0.00	1.63	1.9	0.00	1.19	54.66	51.00	108.01%	118.42%
									Adj. Ac (%)	91.21%	

Figure B.19
Tracer Concentration and Recovery with Volume Extracted at MP9-11', September 1997

SAMPLE	Vol. Ext. (L)	Tot. Vol. Ext. (L)	Ac^- Conc. (mg/L)	Br^- Conc. (mg/L)	D.O. Conc. (mg/L)	Mass Ac^- (mg)	Mass Br^- (mg)	Cum. Ac (mg)	Cum Br (mg)	Ac Recov. (%)	Br Recov. (%)
Init mass	1.000	1.000	50.61	43.07	<2	50.61	43.07				
1	0.900	0.900	27.65	31.76	7.1	24.88	28.59	24.88	28.59	49.17%	66.38%
2	1.000	1.900	5.83	8.73	7.0	5.83	8.73	30.72	37.32	60.69%	86.65%
3	0.635	2.535	0.00	4.09	7.1	0.00	2.60	30.72	39.92	60.69%	92.68%
4	0.735	3.270	0.00	2.93	7.1	0.00	2.15	30.72	42.07	60.69%	97.68%
5	0.590	3.860	0.00	2.36	7.1	0.00	1.39	30.72	43.46	60.69%	100.91%
									Adj. Ac (%)	60.14%	

Table B.20
Tracer Concentration and Recovery with Volume Extracted at MP10-11', September 1997

SAMPLE	Vol. Ext. (L)	Tot. Vol. Ext. (L)	Ac^- Conc. (mg/L)	Br^- Conc. (mg/L)	D.O. Conc. (mg/L)	Mass Ac^- (mg)	Mass Br^- (mg)	Cum. Ac (mg)	Cum Br (mg)	Ac Recov. (%)	Br Recov. (%)
init mass	0.875	0.875	50.61	43.07	<2	44.28	37.69				
1	0.970	0.970	34.39	32.88	1.9	33.36	31.89	33.36	31.89	75.34%	84.62%
2	0.990	1.960	3.85	8.60	1.9	3.81	8.52	37.18	40.41	83.95%	107.22%
3	1.000	2.960	0.00	3.20	1.9	0.00	3.20	37.18	43.61	83.95%	115.72%
4	1.000	3.960	0.00	2.11	1.9	0.00	2.11	37.18	45.72	83.95%	121.31%
5	1.000	4.960	0.00	1.74	1.9	0.00	1.74	37.18	47.46	83.95%	125.93%
6	1.000	5.960	0.00	1.46	1.9	0.00	1.46	37.18	48.92	83.95%	129.82%
7	0.995	6.955	0.00	1.41	1.9	0.00	1.40	37.18	50.32	83.95%	133.53%
8	0.990	7.945	0.00	1.40	1.9	0.00	1.39	37.18	51.71	83.95%	137.22%
9	1.000	8.945	0.00	3.20	1.9	0.00	3.20	37.18	54.91	83.95%	145.70%
10	0.995	9.940	0.00	1.49	1.9	0.00	1.48	37.18	56.39	83.95%	149.64%
									Adj. Ac (%)	56.10%	

Table B.21
Tracer Concentration and Recovery with Volume Extracted at MP11-11', September 1997

SAMPLE	Vol. Ext. (L)	Tot. Vol. Ext. (L)	Ac^- Conc. (mg/L)	Br^- Conc. (mg/L)	D.O. Conc. (mg/L)	Mass Ac^- (mg)	Mass Br^- (mg)	Cum. Ac (mg)	Cum Br (mg)	Ac Recov. (%)	Br Recov. (%)
init mass	1.000	1.000	50.61	43.07	<2	50.61	43.07				
1	0.990	0.990	23.13	23.61	1.9	22.90	23.37	22.90	23.37	45.25%	54.26%
2	0.990	1.980	3.38	7.22	1.9	3.34	7.15	26.24	30.52	51.86%	70.86%
3	0.995	2.975	2.36	4.01	1.9	2.34	3.99	28.59	34.51	56.49%	80.12%
4	0.995	3.970	2.99	2.83	1.9	2.98	2.82	31.56	37.32	62.37%	86.66%
5	0.990	4.960	0.00	2.24	1.9	0.00	2.22	31.56	39.54	62.37%	91.81%
6	1.000	5.960	0.00	1.86	1.9	0.00	1.86	31.56	41.41	62.37%	96.14%
7	0.995	6.955	0.00	1.54	1.9	0.00	1.53	31.56	42.94	62.37%	99.70%
8	0.990	7.945	0.00	1.35	1.9	0.00	1.33	31.56	44.27	62.37%	102.79%
9	0.995	8.940	0.00	1.29	1.9	0.00	1.28	31.56	45.55	62.37%	105.77%
10	0.980	9.920	0.00	1.12	1.9	0.00	1.10	31.56	46.65	62.37%	108.32%
									Adj. Ac (%)	57.57%	

Figure B.27
Tracer Concentration Profile with Volume Extracted at MP1-11', September 1997

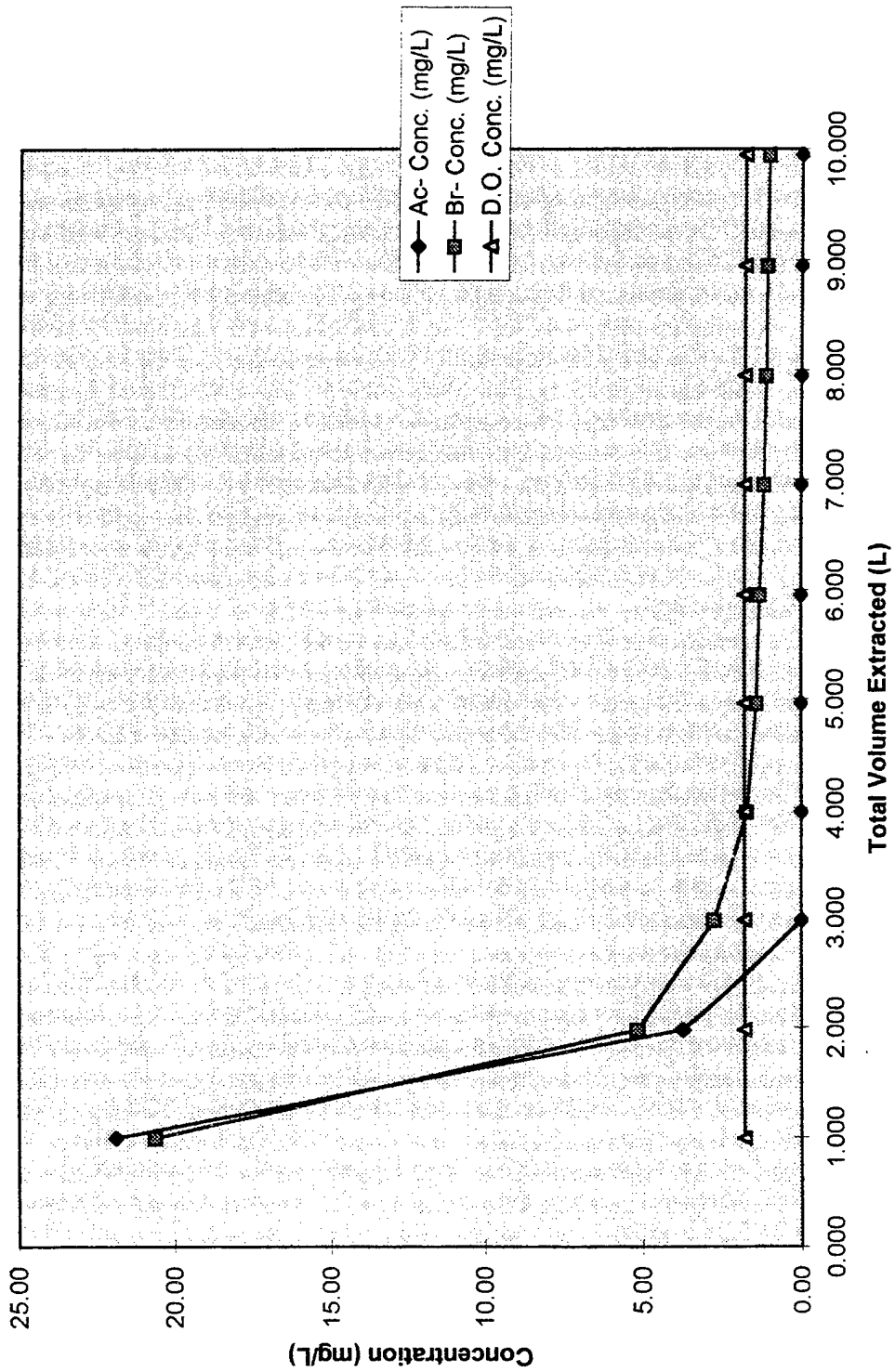


Figure B.28
Tracer Recovery Profile with Volume Extracted at MP1-11', September 1997

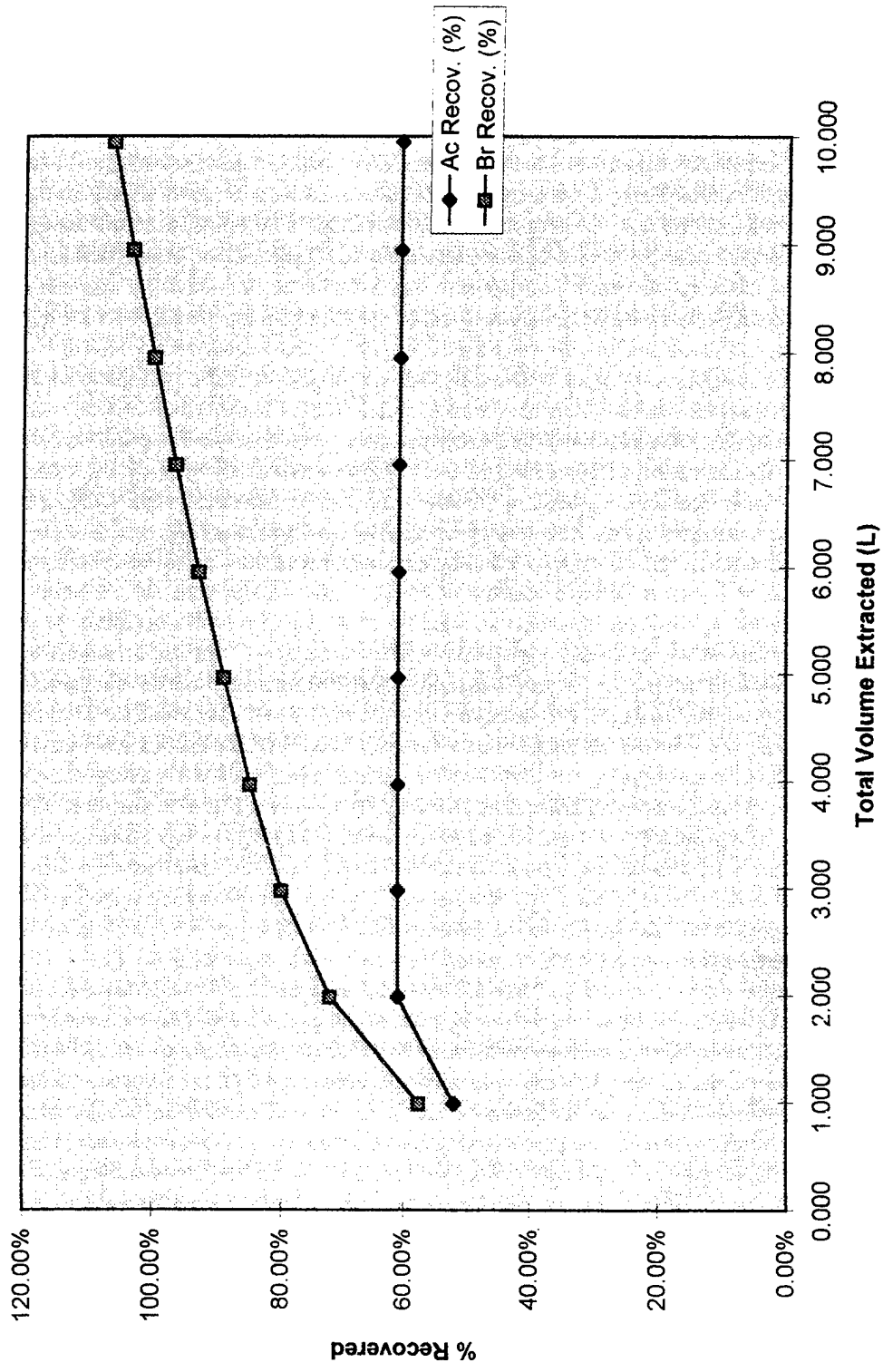


Figure B.29
Tracer Concentration Profile with Volume Extracted at MP2-11', September 1997

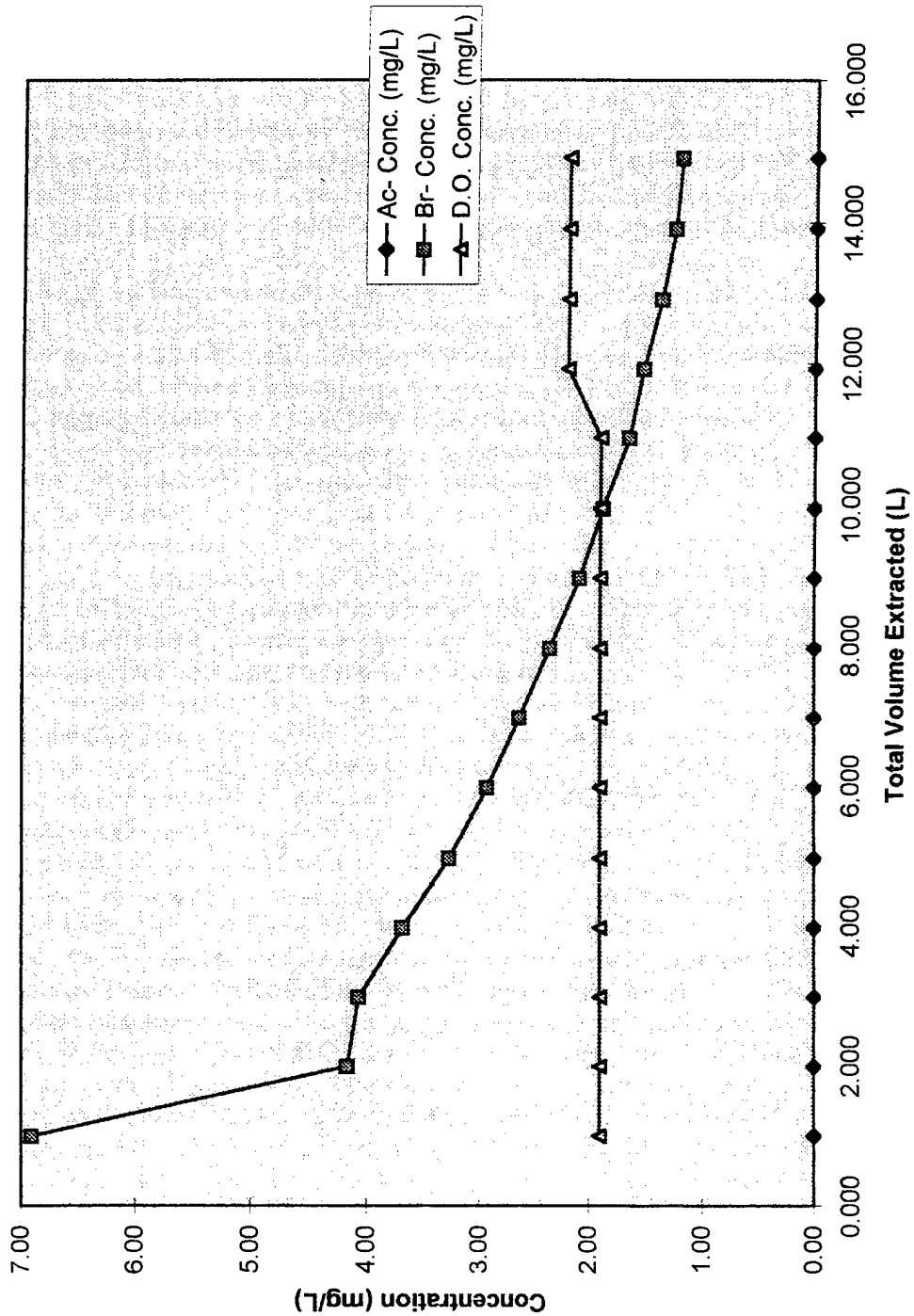


Figure B.30
Tracer Recovery Profile with Extracted Volume at MP2-11', September 1997

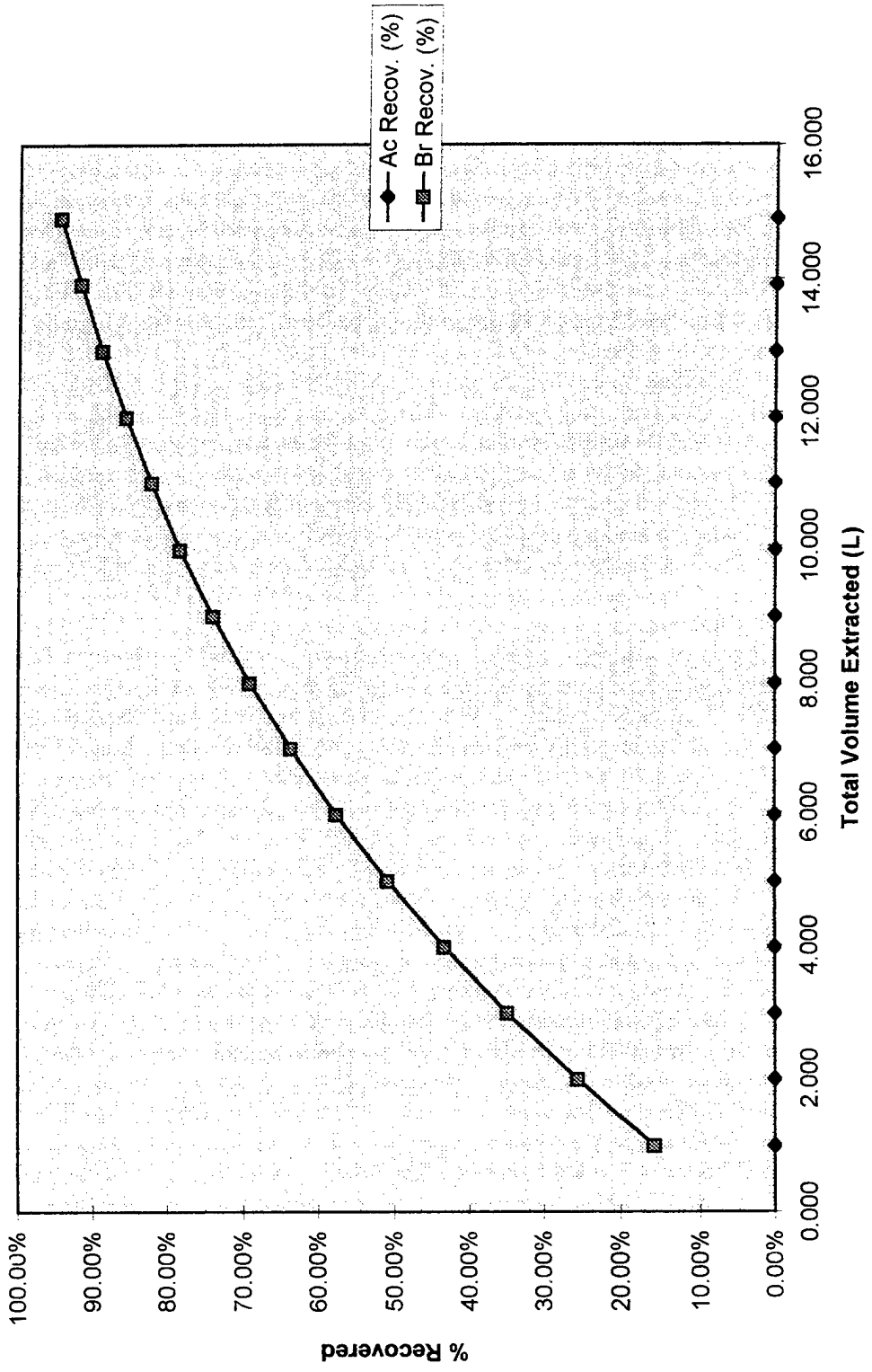


Figure B. 31
Tracer Concentration Profile with Volume Extracted at MP4-11', September 1997

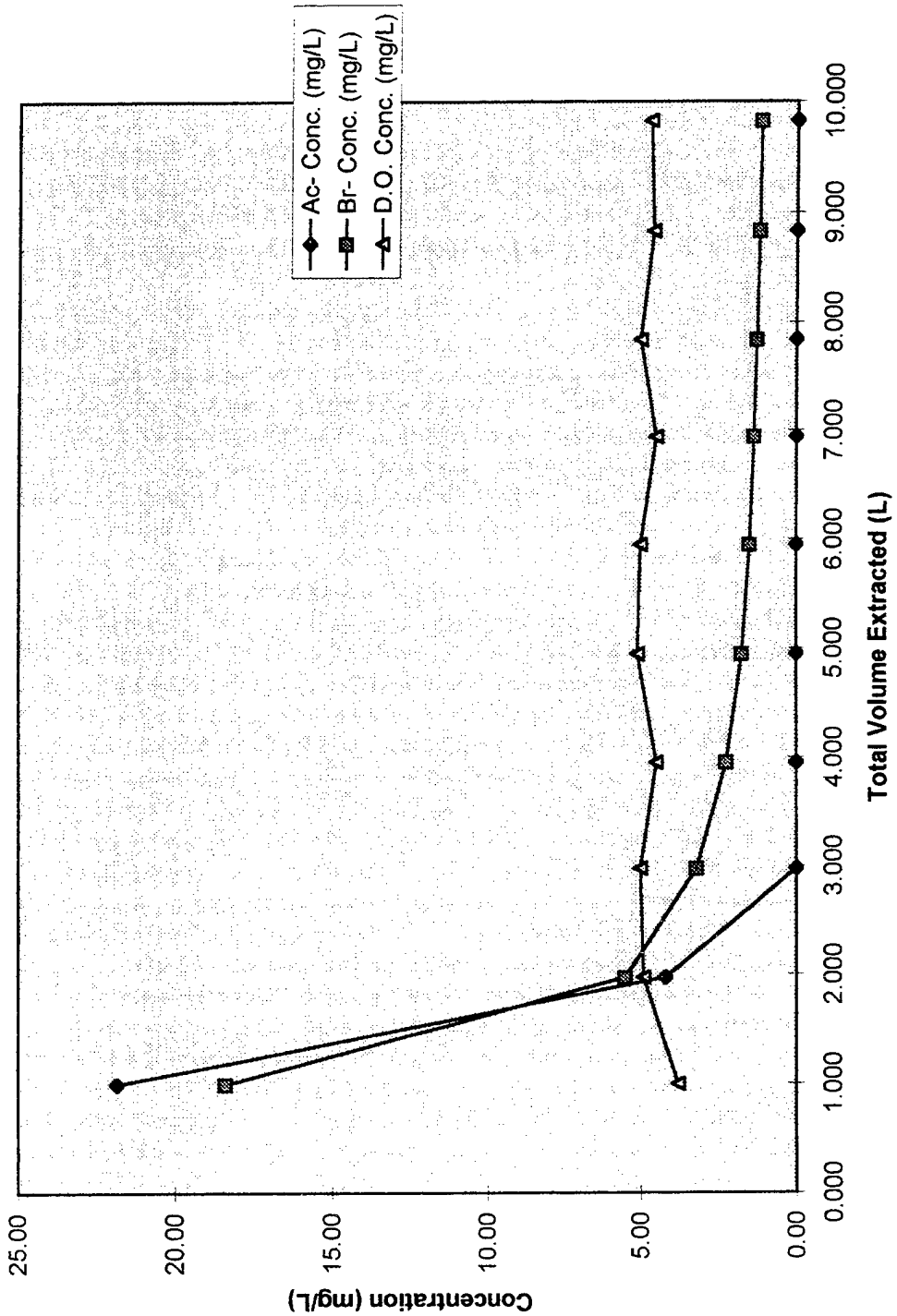


Figure B.32
Tracer Recovery Profile with Volume Extracted at MP4-11', September 1997

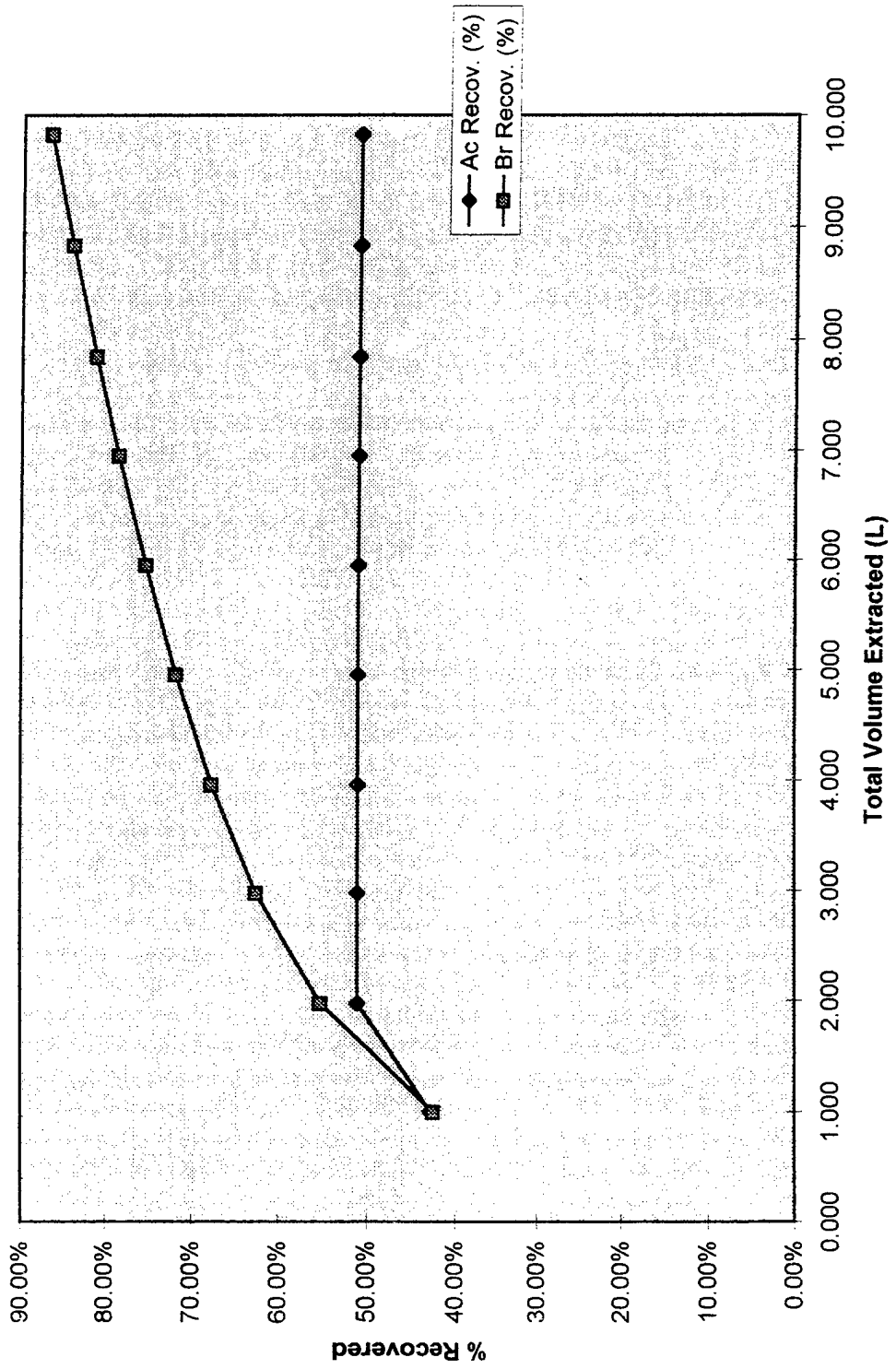


Figure B.33
Tracer Concentration Profile with Volume Extracted at MP5-11', September 1997

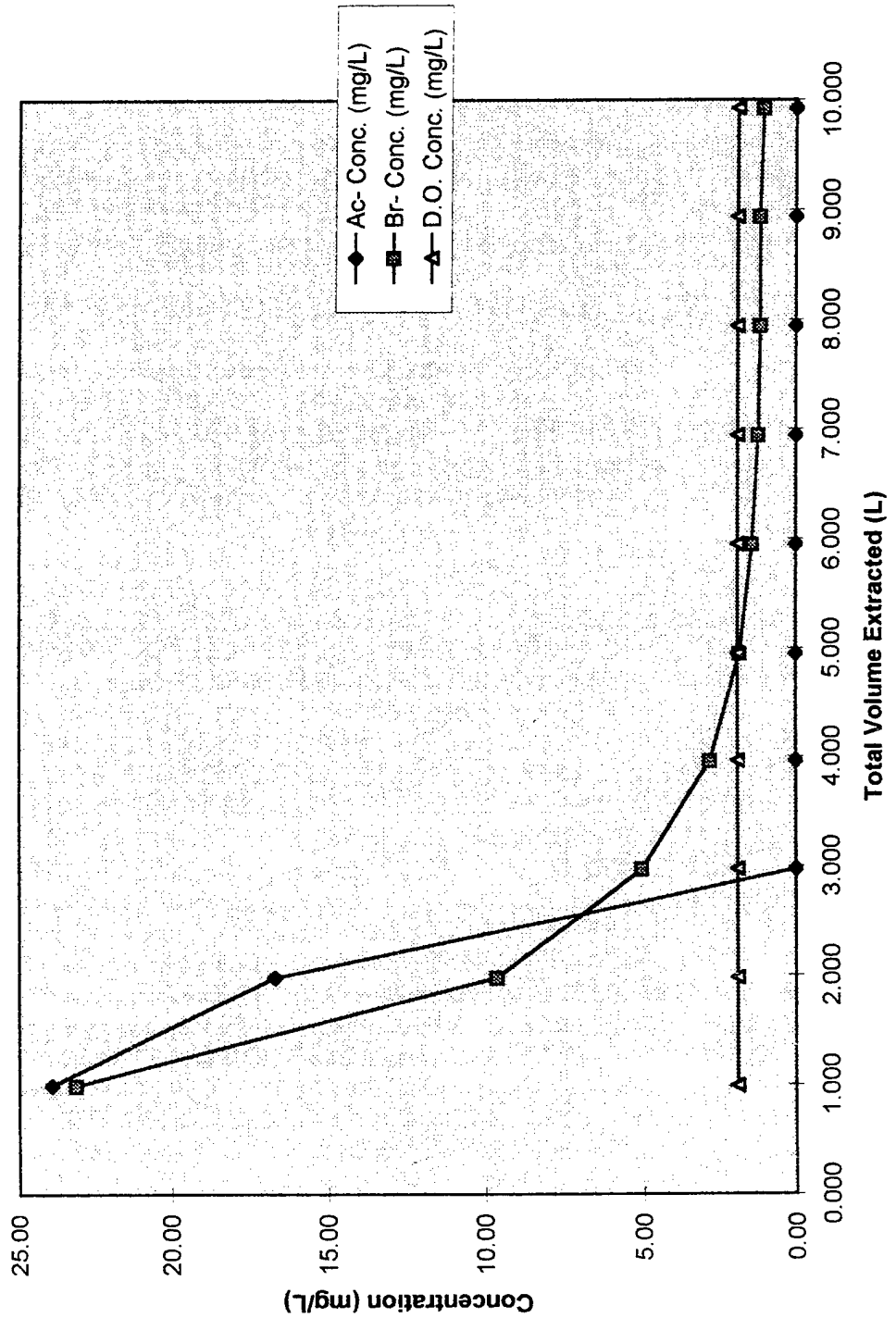


Figure B.34
Tracer Recovery Profile with Extracted Volume at MP5-11', September 1997

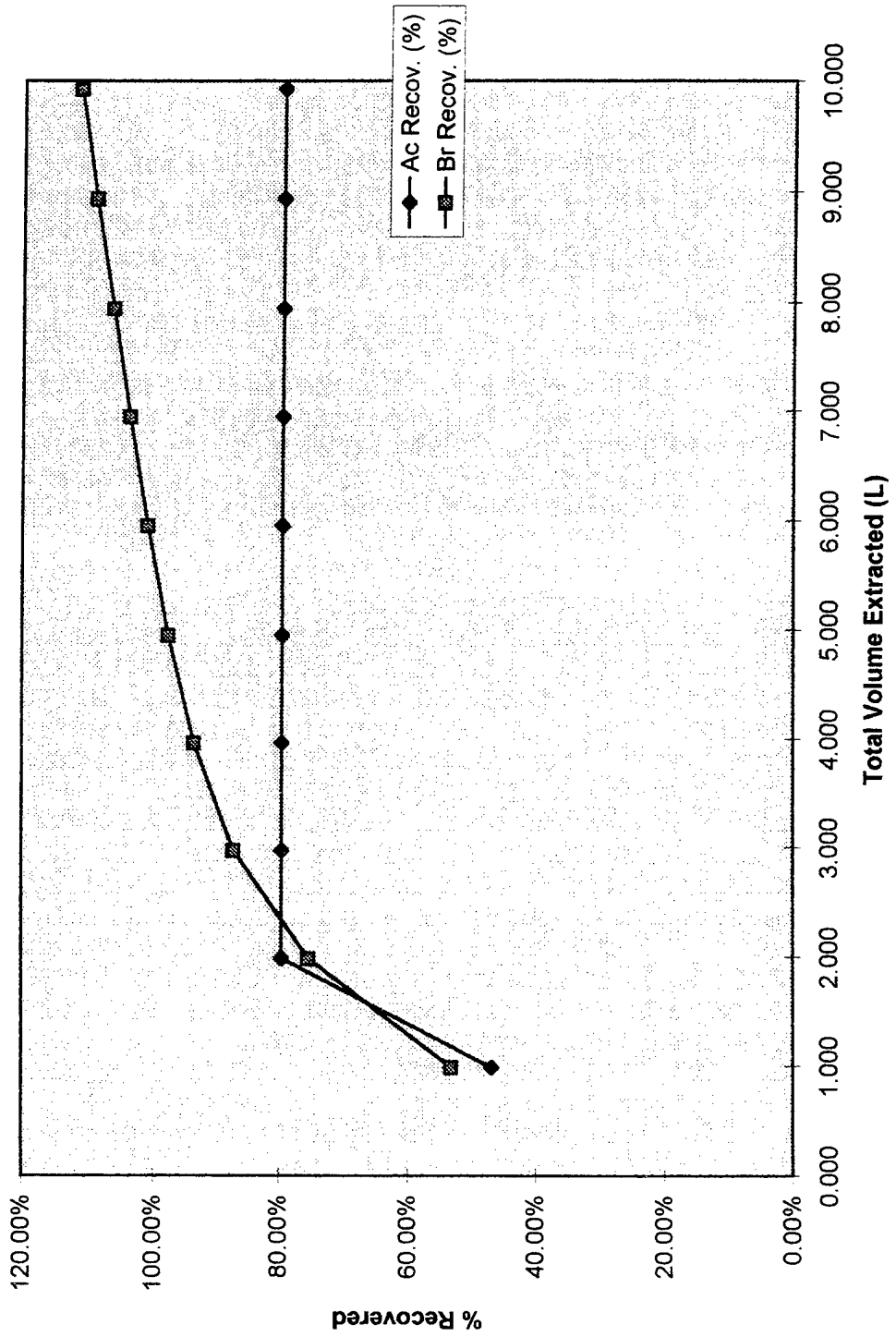


Figure B.35
Tracer Concentration Profile with Volume Extracted at MP7-11', September 1997

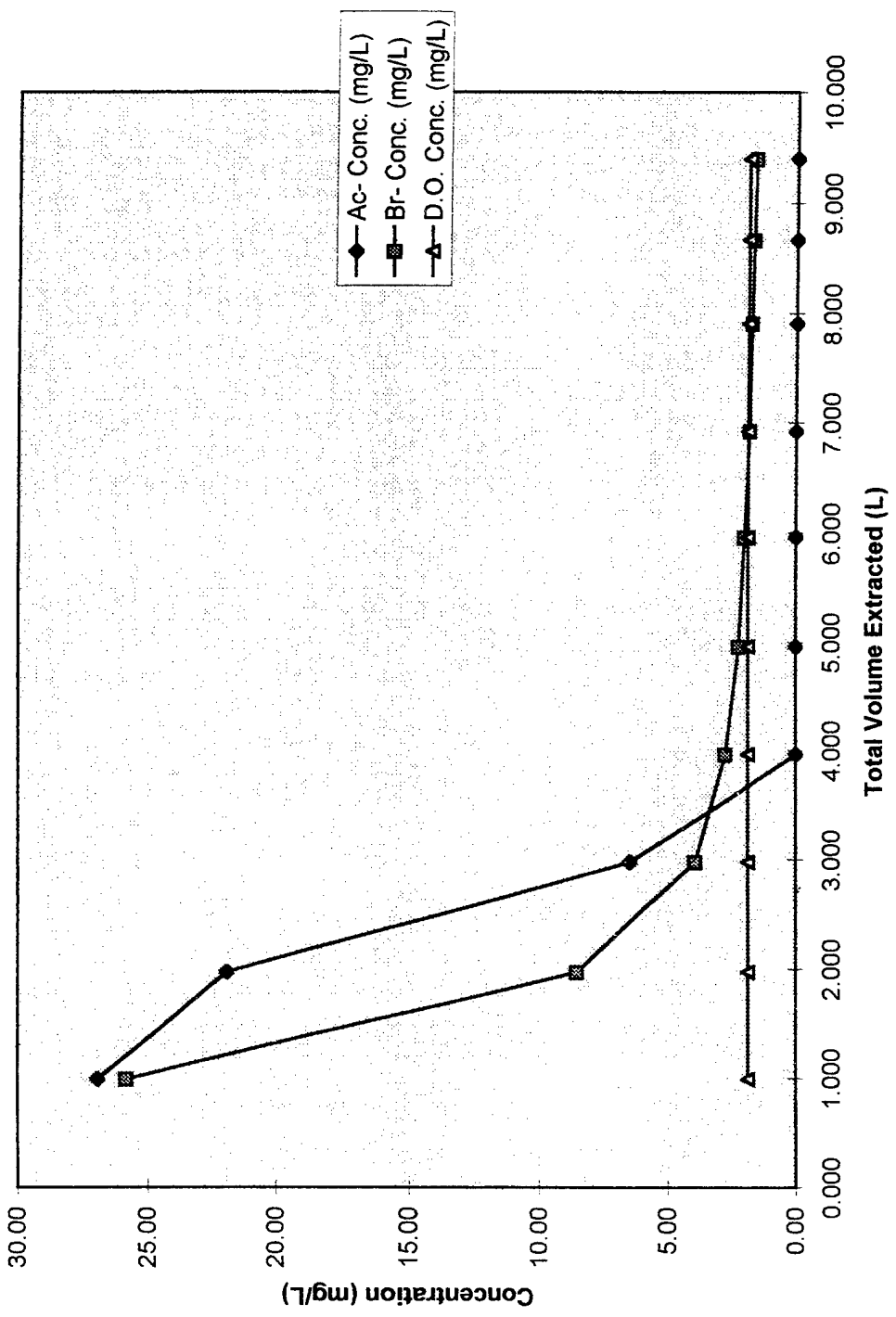


Figure B.36
Tracer Recovery Profile with Volume Extracted at MP7-11', September 1997

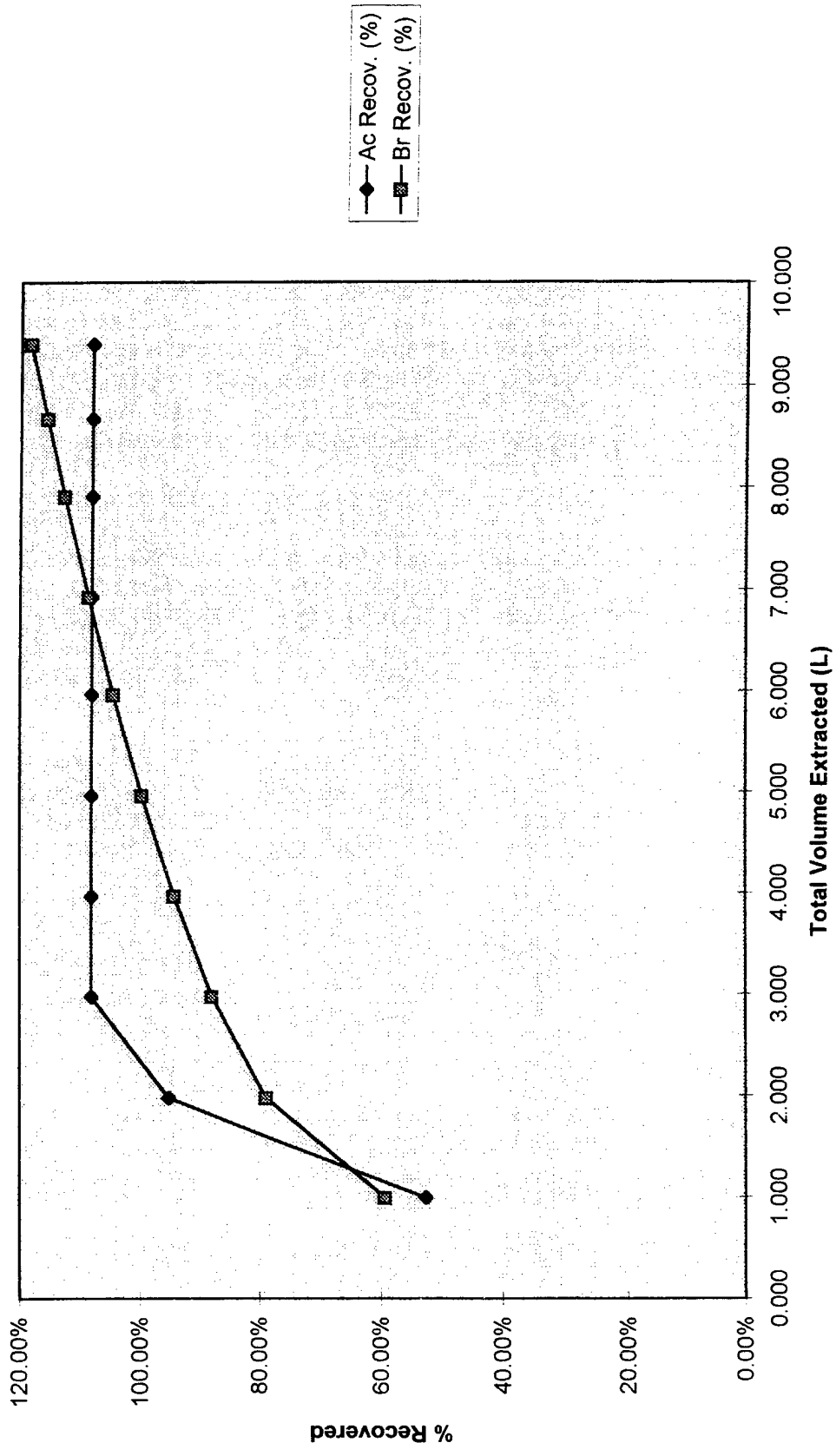


Figure B.37
Tracer Concentration Profile with Volume Extracted at MP9-11', September 1997

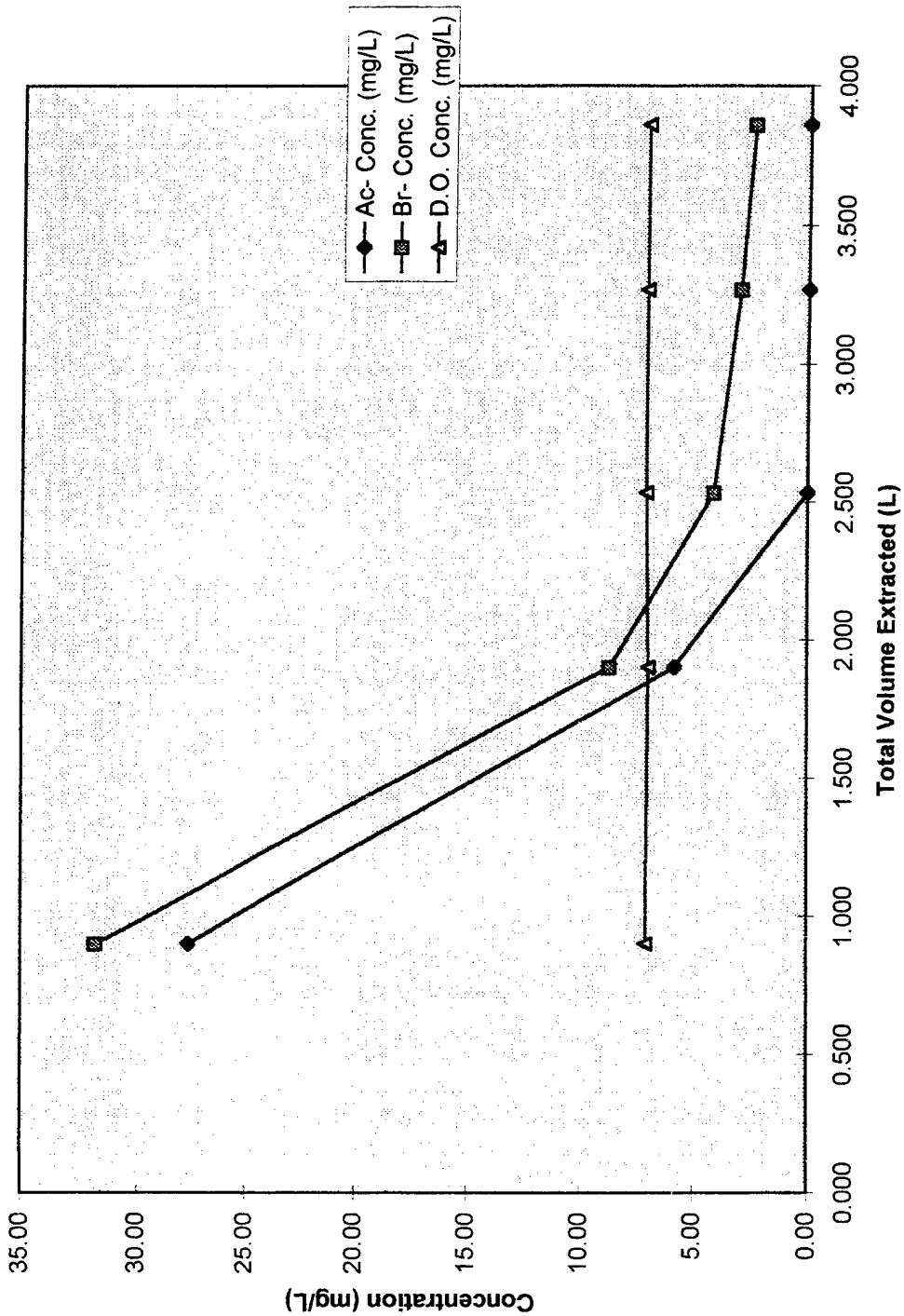


Figure B.38
Tracer Recovery Profile with Volume Extracted at MP9-11', September 1997

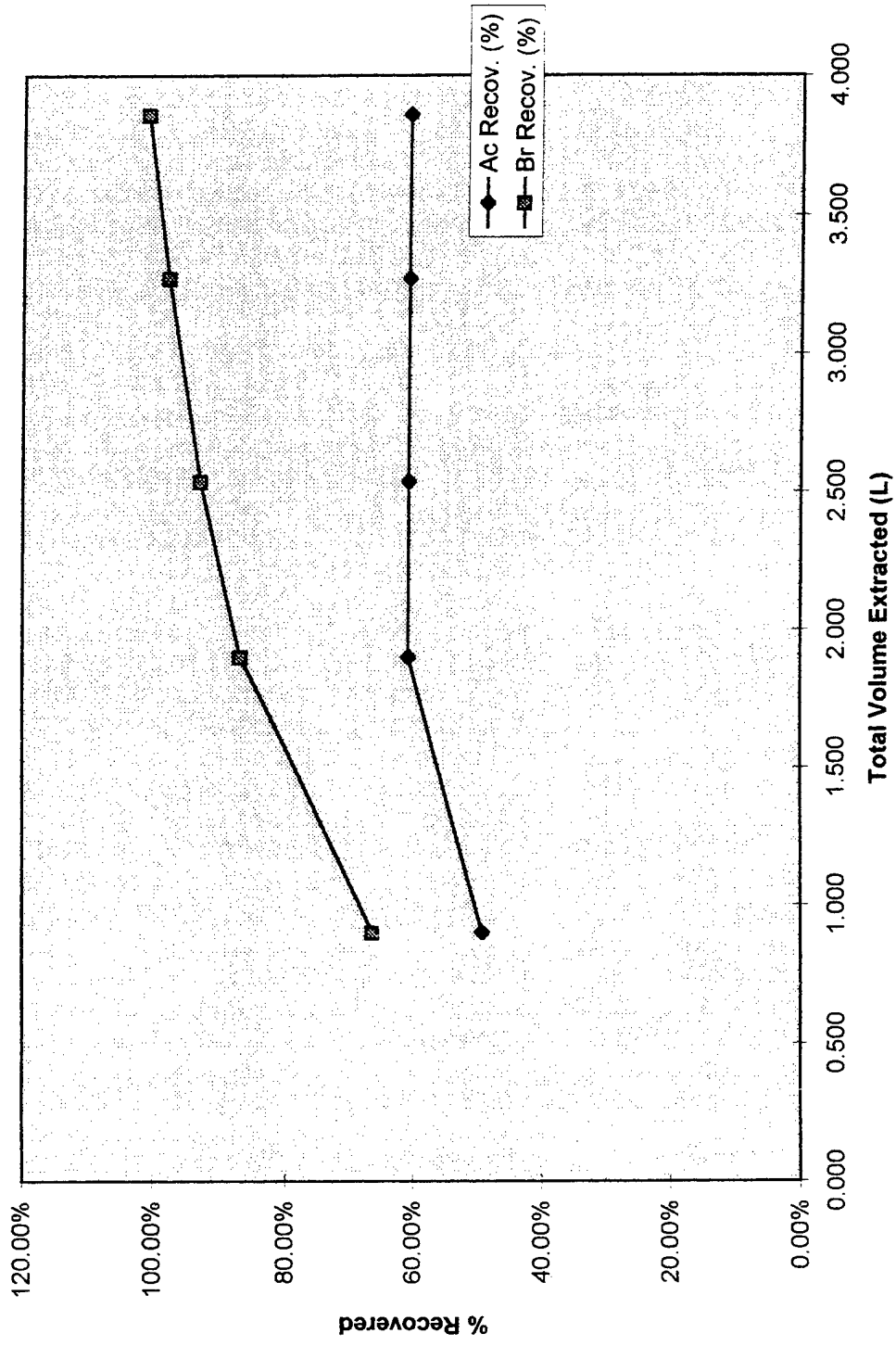


Figure B.39
Tracer Concentration Profile with Volume Extracted at MP10-11', September 1997

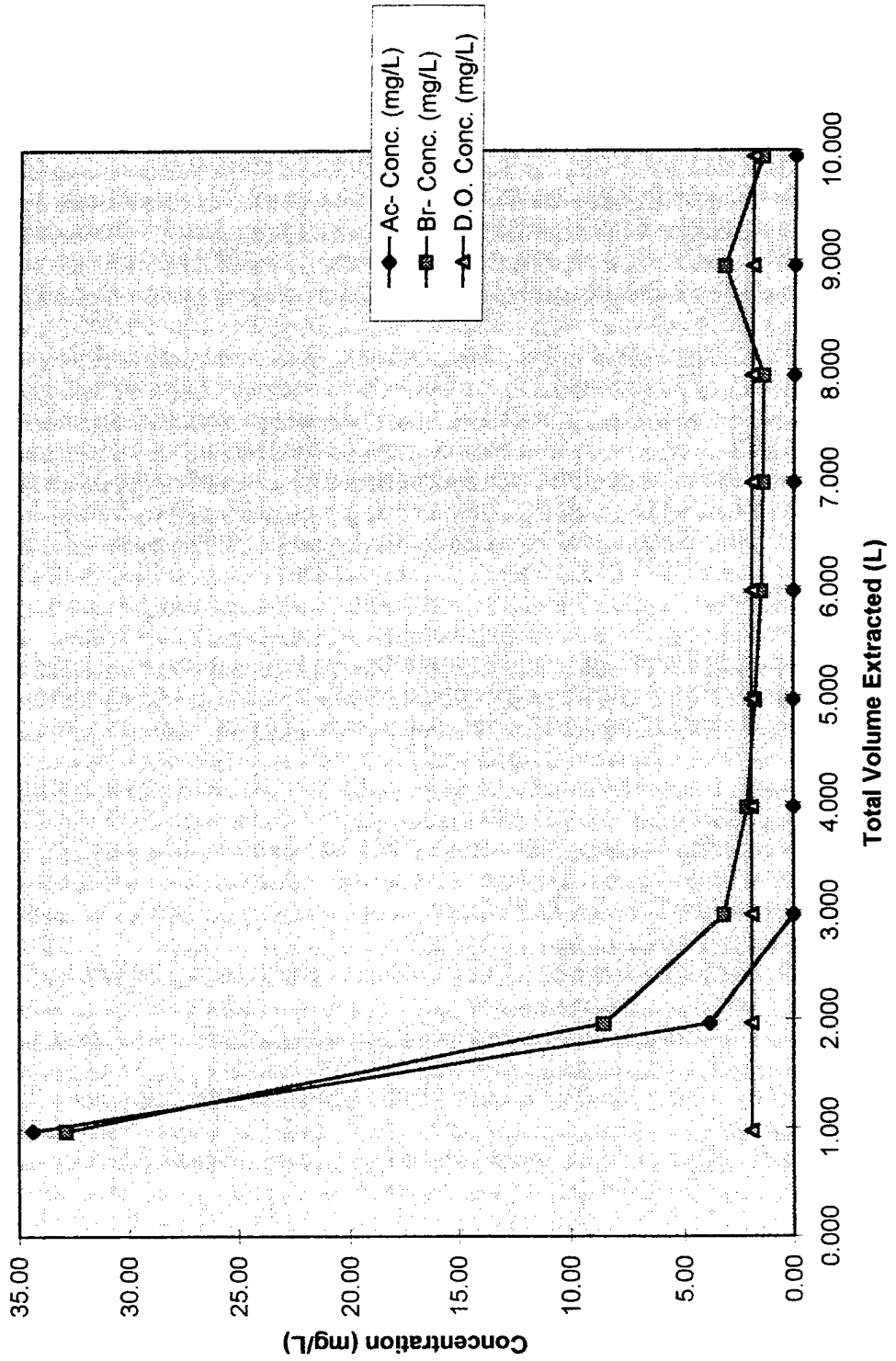


Figure B.40
Tracer Recovery Profile with Volume Extracted at MP10-11', September 1997

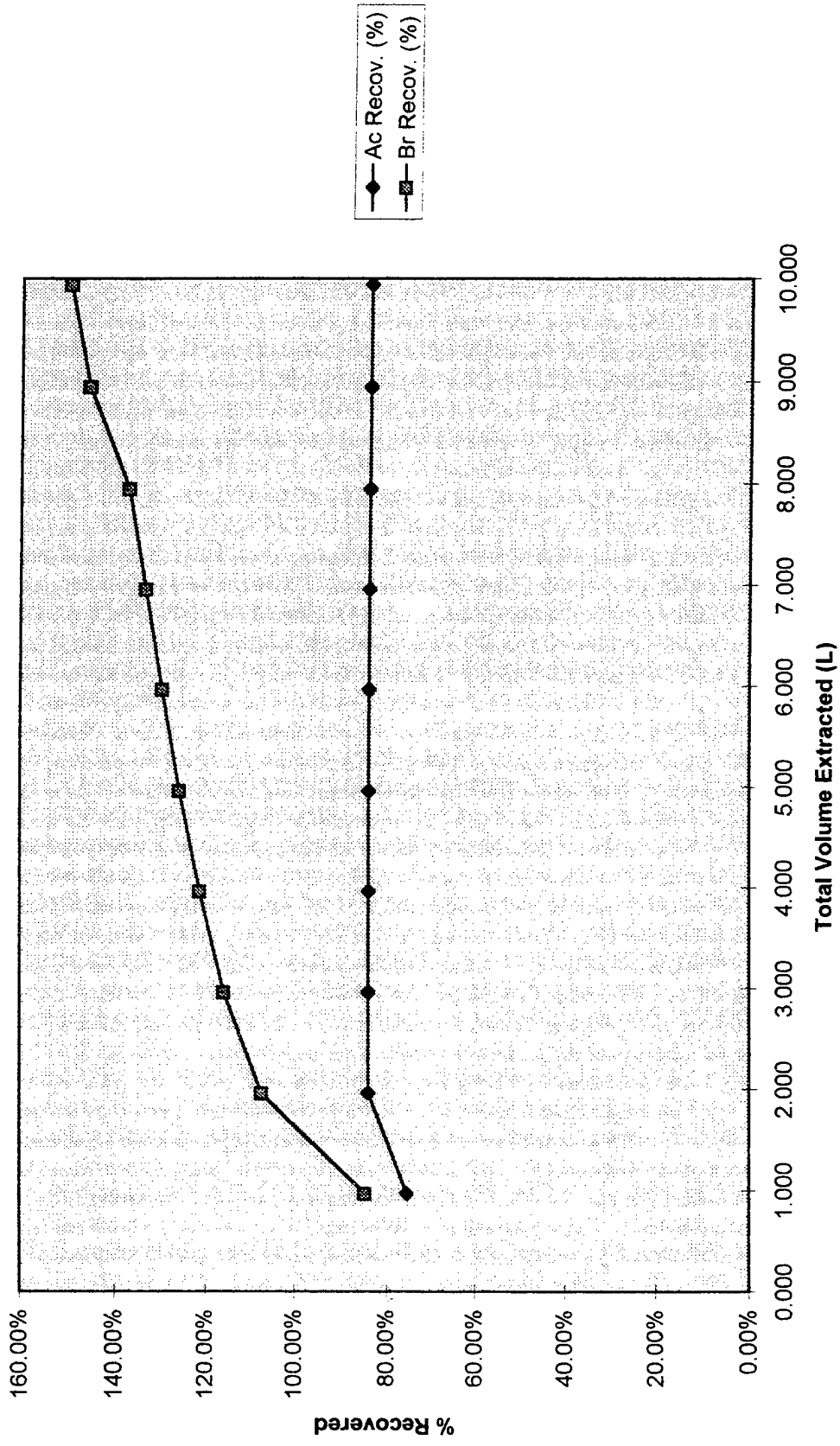


Figure B.41
Tracer Concentration Profile with Volume Extracted at MP11-11', September 1997

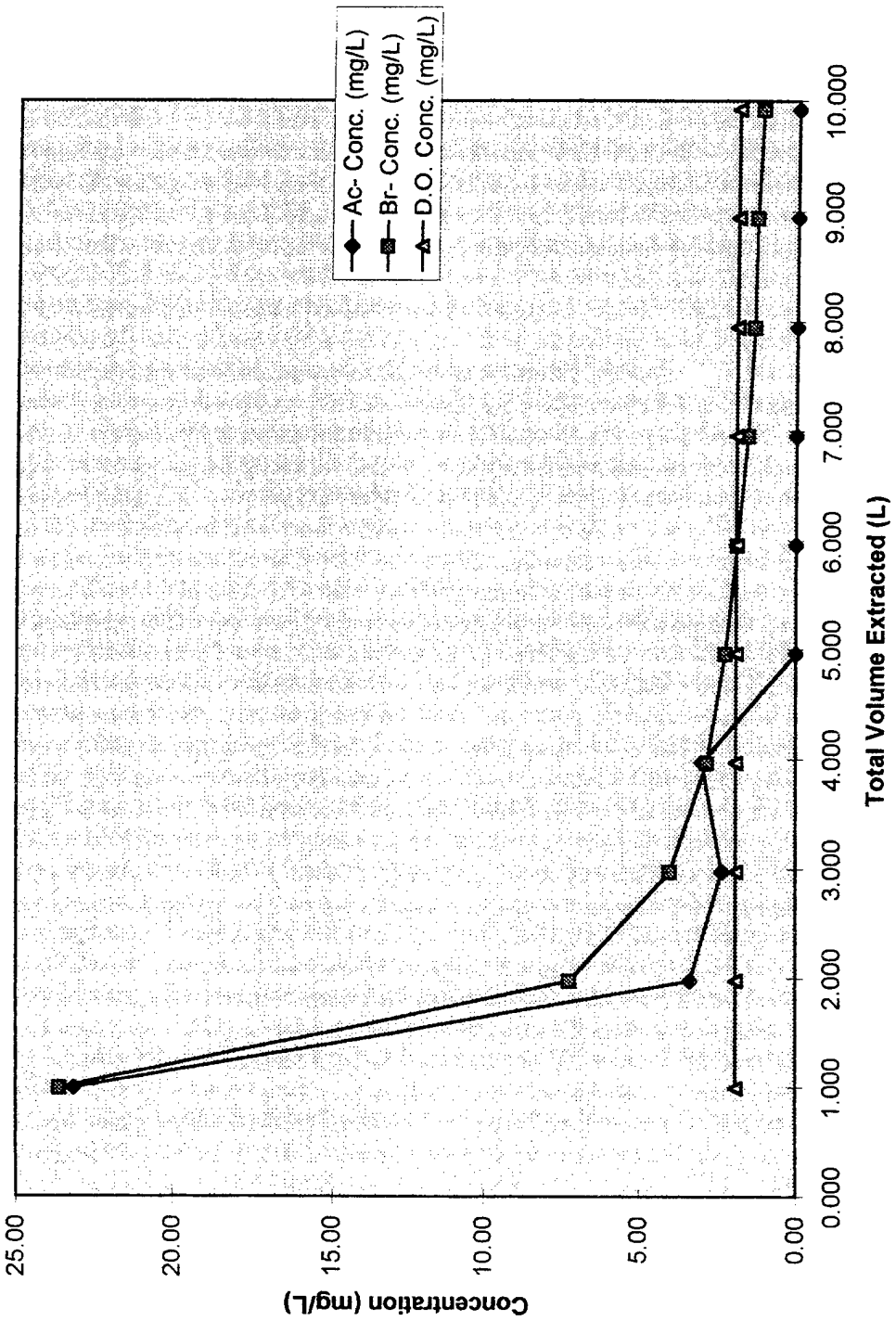


Figure B.42
Tracer Recovery Profile with Volume Extracted at MP11-11', September 1997

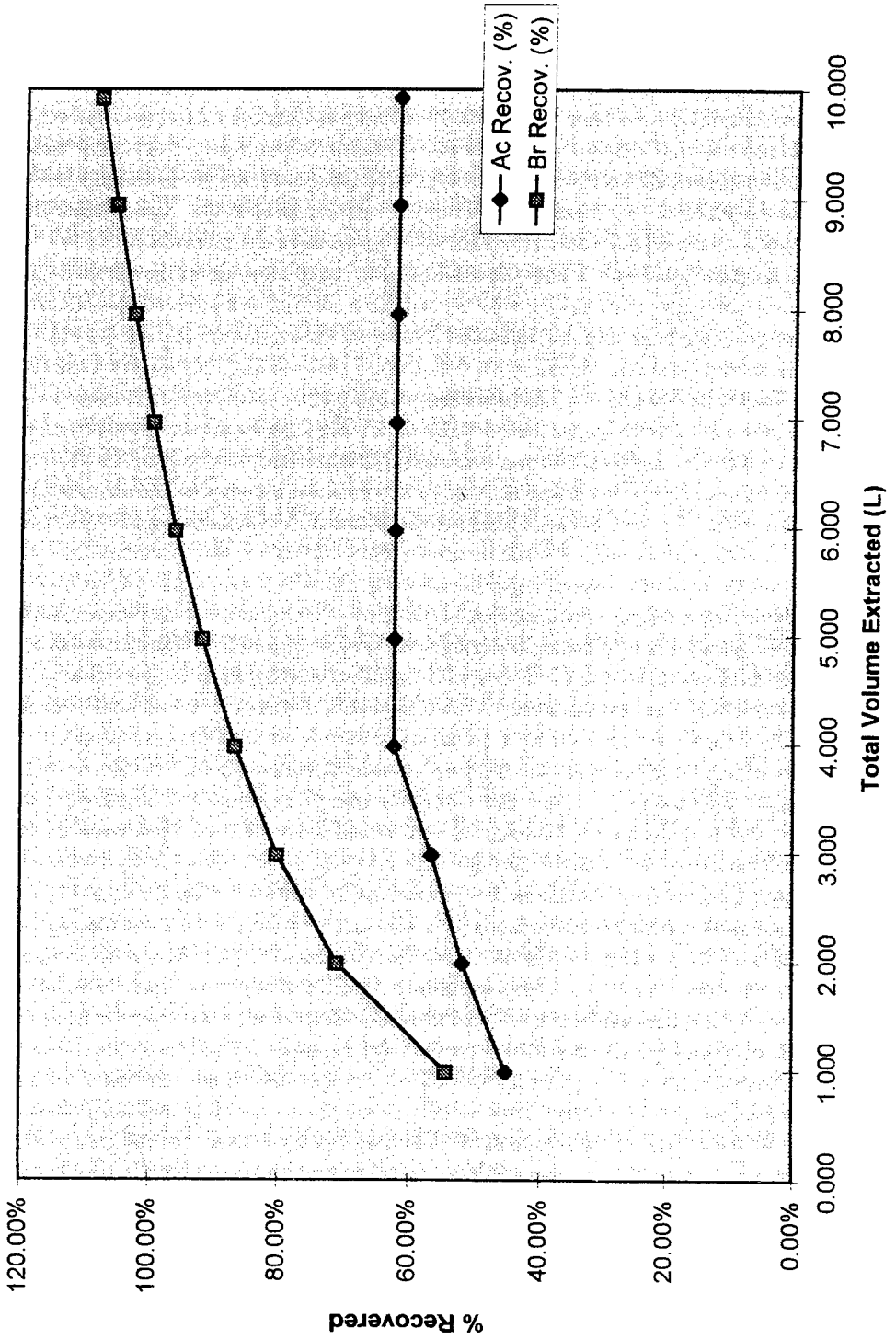


Table B.22
Tracer Concentration and Recovery with Volume Extracted at MP1-13', September 1997

SAMPLE	Vol. Ext. (L)	Tot. Vol. Ext. (L)	Ac^- Conc. (mg/L)	Br^- Conc. (mg/L)	D.O. Conc. (mg/L)	Mass Ac^- (mg)	Mass Br^- (mg)	Cum. Ac (mg)	Cum Br (mg)	Ac Recov. (%)	Br Recov. (%)
init mass	0.960	0.960	54.36	50.30	<2	52.18	48.29				
1	0.990	0.990	32.19	27.69	1.9	31.87	27.41	31.87	27.41	61.07%	56.76%
2	0.990	1.980	4.36	6.65	1.9	4.32	6.58	36.19	33.99	69.35%	70.39%
3	0.995	2.975	1.16	2.99	1.9	1.16	2.98	37.34	36.97	71.57%	76.55%
4	0.990	3.965	0.00	2.09	1.9	0.00	2.07	37.34	39.03	71.57%	80.83%
5	0.985	4.950	0.00	1.78	1.9	0.00	1.75	37.34	40.78	71.57%	84.45%
6	1.000	5.950	0.00	1.54	1.9	0.00	1.54	37.34	42.32	71.57%	87.65%
7	0.995	6.945	0.00	1.43	1.9	0.00	1.42	37.34	43.74	71.57%	90.58%
8	0.990	7.935	0.00	1.18	1.9	0.00	1.17	37.34	44.91	71.57%	93.00%
9	0.995	8.930	0.00	1.06	1.9	0.00	1.05	37.34	45.97	71.57%	95.19%
10	1.000	9.930	0.00	0.95	1.9	0.00	0.95	37.34	46.91	71.57%	97.15%
									Adj. Ac (%)	73.67%	

Table B.23
Tracer Concentration and Recovery with Volume Extracted at MP5-13', September 1997

SAMPLE	Vol. Ext. (L)	Tot. Vol. Ext. (L)	Ac^- Conc. (mg/L)	Br^- Conc. (mg/L)	D.O. Conc. (mg/L)	Mass Ac^- (mg)	Mass Br^- (mg)	Cum. Ac (mg)	Cum Br (mg)	Ac Recov. (%)	Br Recov. (%)
init mass	1.000	1.000	54.36	50.30	<2	54.36	50.30				
1	0.980	0.980	28.07	29.50	6.0	27.51	28.91	27.51	28.91	50.61%	57.48%
2	0.930	1.910	4.74	10.87	6.2	4.41	10.11	31.91	39.02	58.71%	77.58%
3	0.980	2.890	5.74	5.36	6.2	5.63	5.25	37.54	44.28	69.07%	88.02%
4	0.980	3.870	0.00	3.20	6.4	0.00	3.13	37.54	47.41	69.07%	94.25%
5	0.960	4.830	0.00	2.20	6.2	0.00	2.12	37.54	49.52	69.07%	98.45%
6	0.975	5.805	0.00	1.76	6.1	0.00	1.71	37.54	51.24	69.07%	101.86%
7	0.980	6.785	0.00	1.42	6.1	0.00	1.40	37.54	52.63	69.07%	104.63%
8	0.990	7.775	0.00	1.24	6.1	0.00	1.22	37.54	53.86	69.07%	107.06%
9	0.980	8.755	0.00	1.11	6.0	0.00	1.09	37.54	54.95	69.07%	109.23%
10	0.990	9.745	0.00	1.03	6.0	0.00	1.02	37.54	55.97	69.07%	111.26%
									Adj. Ac (%)	62.08%	

Table B.24
Tracer Concentration and Recovery with Volume Extracted at MP8-13', September 1996

SAMPLE	Vol. Ext. (L)	Tot. Vol. Ext. (L)	Ac^- Conc. (mg/L)	Br^- Conc. (mg/L)	D.O. Conc. (mg/L)	Mass Ac^- (mg)	Mass Br^- (mg)	Cum. Ac (mg)	Cum Br (mg)	Ac Recov. (%)	Br Recov. (%)
init mass	1.000	1.000	54.36	50.30	<2	54.36	50.30				
1	0.990	0.990	0.00	0.80	1.9	0.00	0.79	0.00	0.79	0.00%	1.57%
2	0.970	1.960	0.00	0.72	1.9	0.00	0.70	0.00	1.49	0.00%	2.95%
3	0.995	2.955	0.00	0.71	1.9	0.00	0.70	0.00	2.19	0.00%	4.35%
									Adj. Ac (%)	0.00%	

Table B.25
Tracer Concentration and Recovery with Volume Extracted at MP10-13', September 1997

SAMPLE	Vol. Ext. (L)	Tot. Vol. Ext. (L)	Ac^- Conc. (mg/L)	Br^- Conc. (mg/L)	D.O. Conc. (mg/L)	Mass Ac^- (mg)	Mass Br^- (mg)	Cum. Ac (mg)	Cum Br (mg)	Ac Recov. (%)	Br Recov. (%)
init mass	1.000	1.000	54.36	50.30	<2	54.36	50.30				
1	0.995	0.995	36.22	33.88	1.9	36.03	33.71	36.03	33.71	66.29%	67.01%
2	0.985	1.980	14.07	9.67	1.9	13.86	9.53	49.90	43.24	91.80%	85.95%
3	1.000	2.980	0.00	3.67	1.9	0.00	3.67	49.90	46.91	91.80%	93.25%
4	0.995	3.975	0.00	2.09	1.9	0.00	2.08	49.90	48.98	91.80%	97.38%
5	0.995	4.970	0.00	1.54	1.9	0.00	1.53	49.90	50.52	91.80%	100.43%
6	1.000	5.970	0.00	1.29	1.9	0.00	1.29	49.90	51.81	91.80%	103.00%
7	1.040	7.010	0.00	1.15	1.9	0.00	1.19	49.90	53.00	91.80%	105.37%
8	0.990	8.000	0.00	1.09	1.9	0.00	1.08	49.90	54.08	91.80%	107.51%
9	0.995	8.995	0.00	1.17	1.9	0.00	1.17	49.90	55.25	91.80%	109.83%
10	1.000	9.995	0.00	1.02	1.9	0.00	1.02	49.90	56.27	91.80%	111.87%
									Adj. Ac (%)	82.06%	

Figure 43
Tracer Concentration Profile with Volume Extracted at MP1-13', September 1997

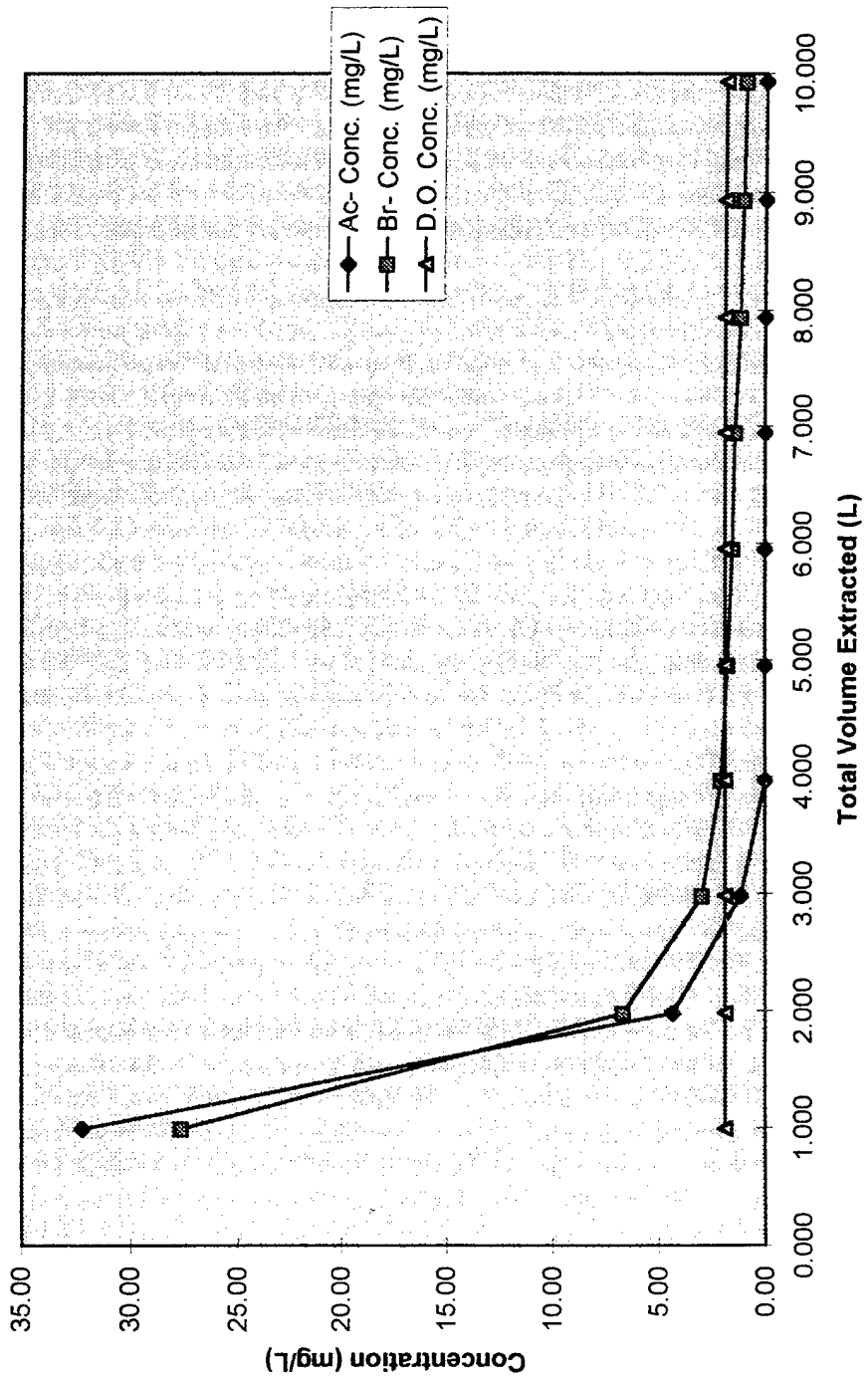


Figure B.44
Tracer Recovery Profile with Volume Extracted at MP1-13', September 1997

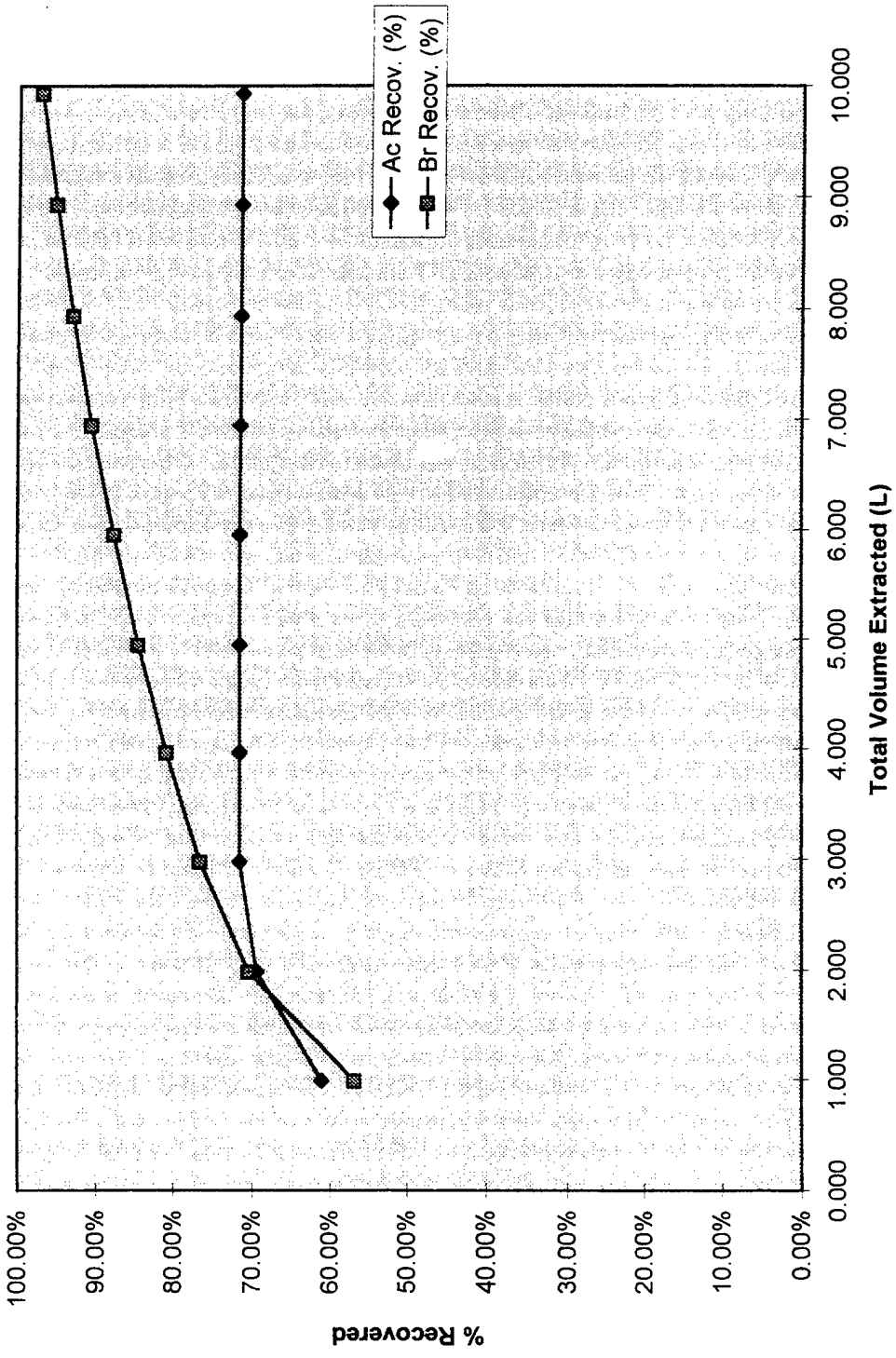


Figure B.45
Tracer Concentration Profile with Volume Extracted at MP5-13', September 1997

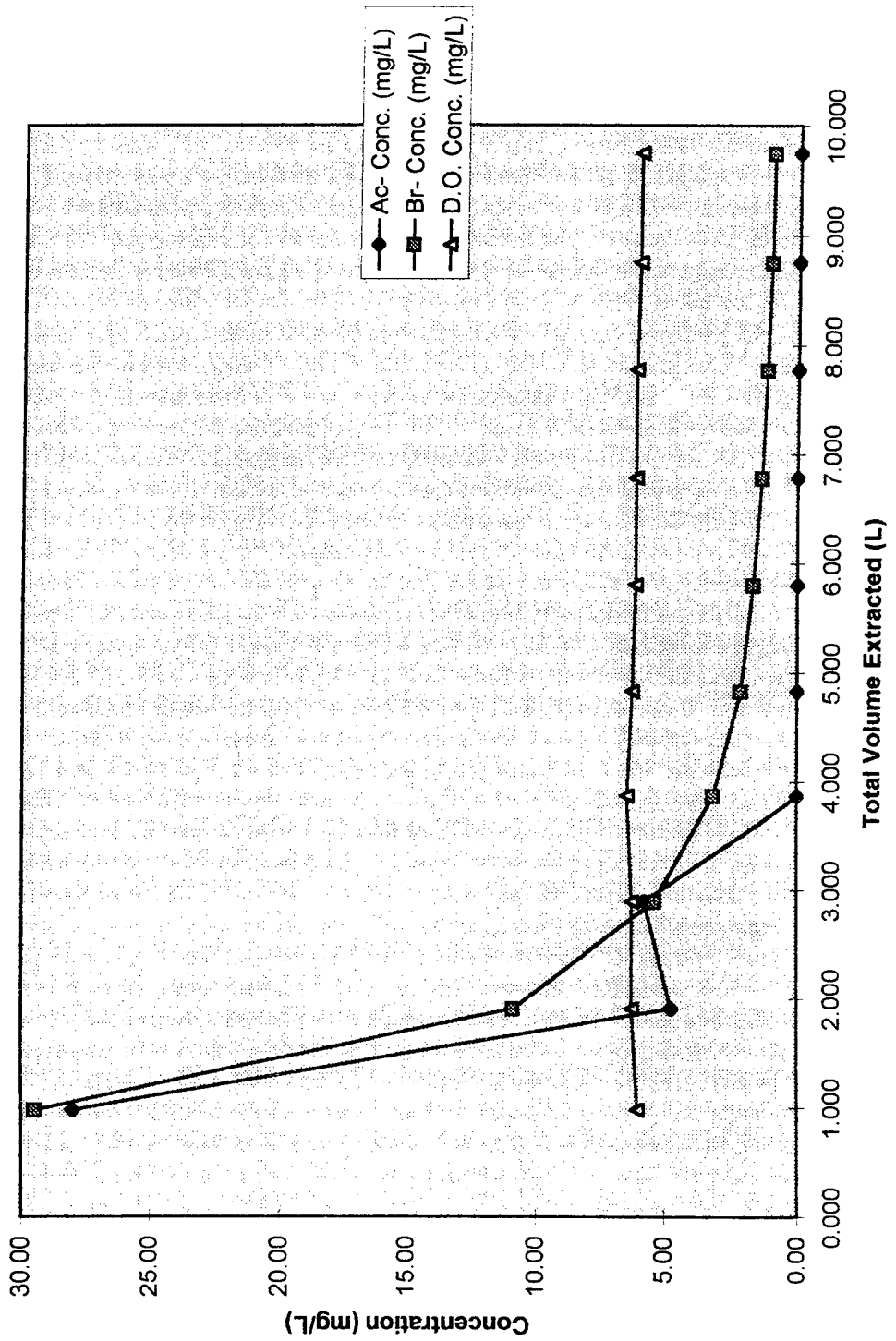


Figure B.46
Tracer Recovery Profile with Volume Extracted at MP5-13', September 1997

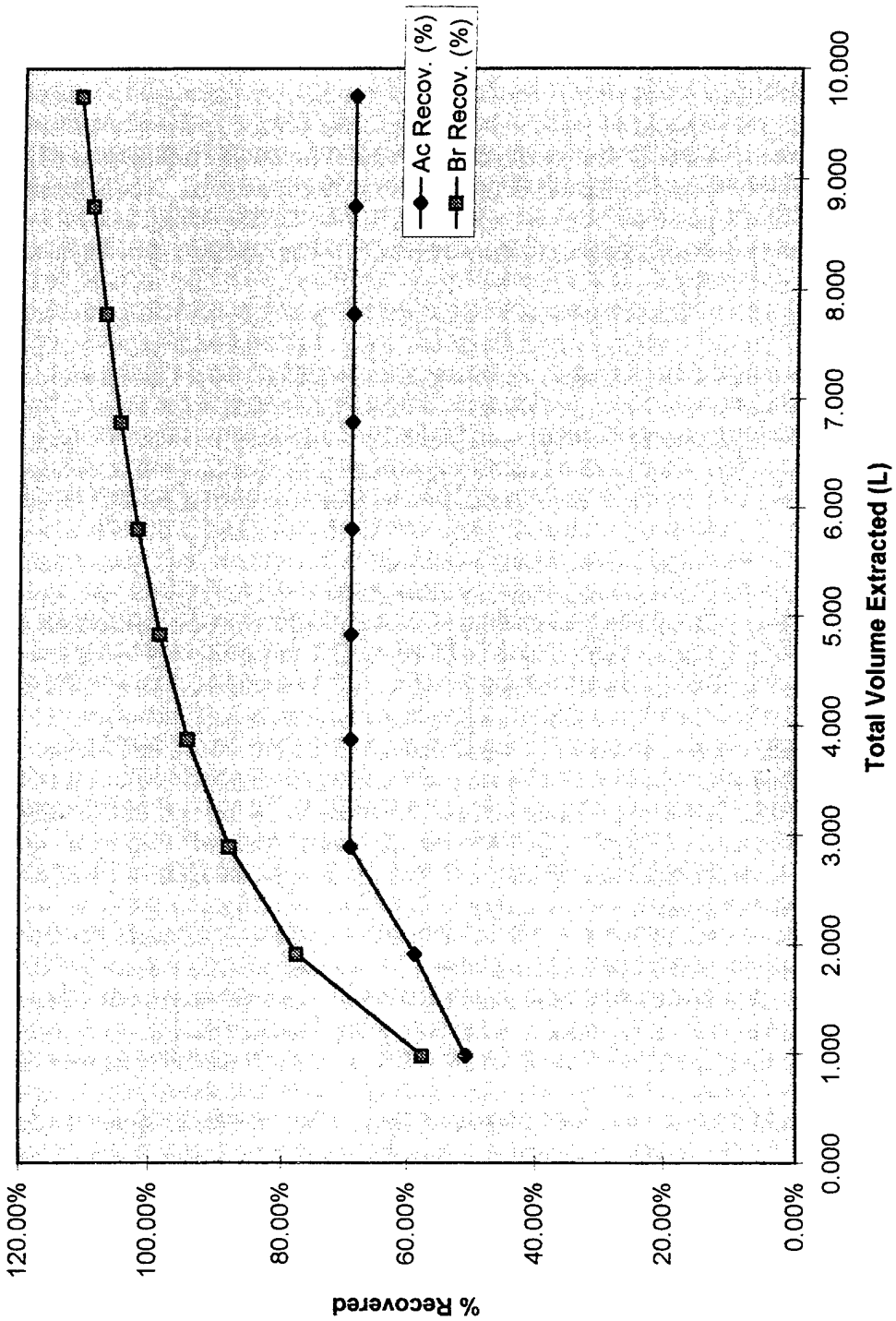


Figure B.47
Tracer Concentration Profile with Volume Extracted at MP10-13', September 1997

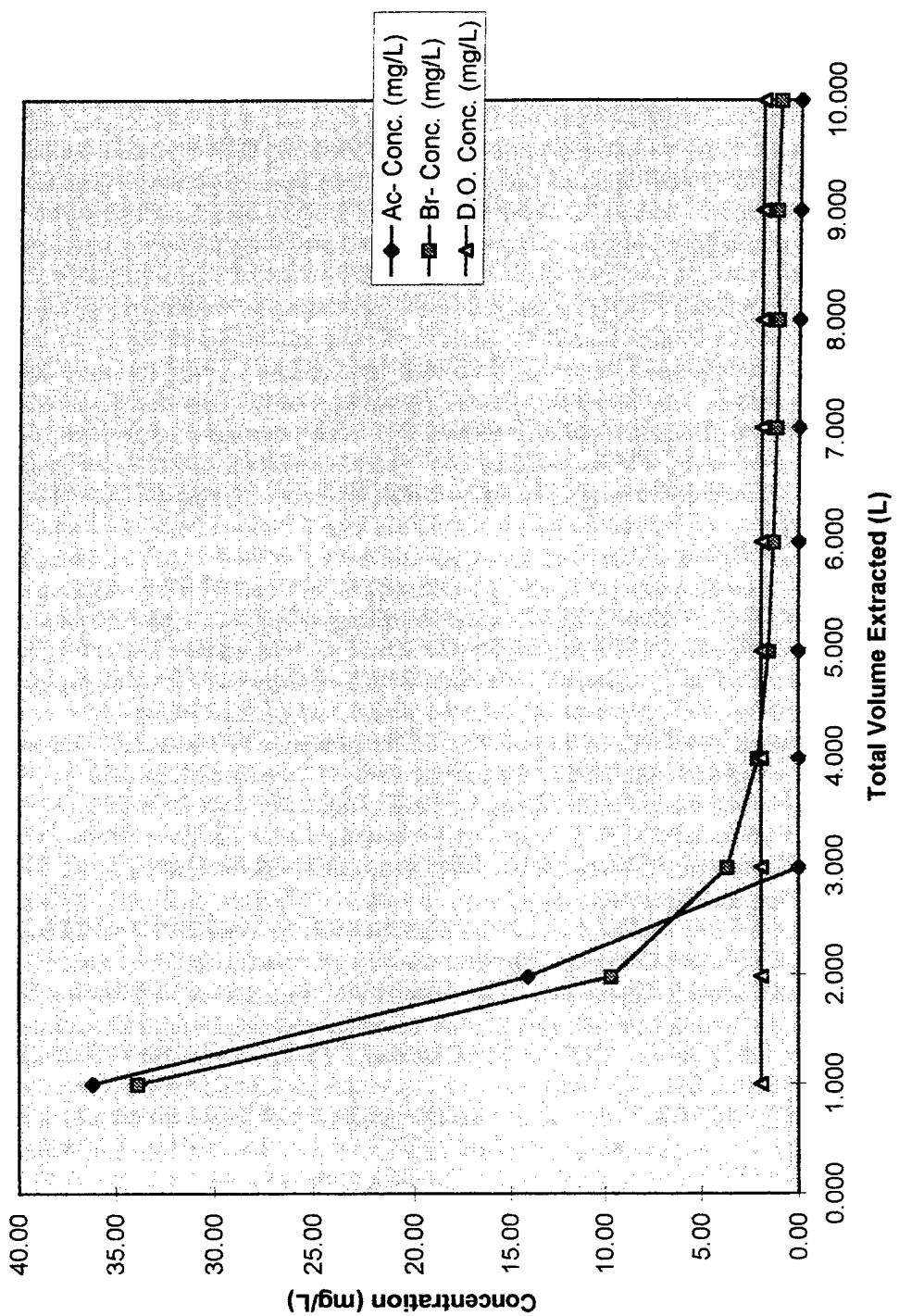


Figure B.48
Tracer Recovery Profile with Volume Extracted at MP10-13', September 1997

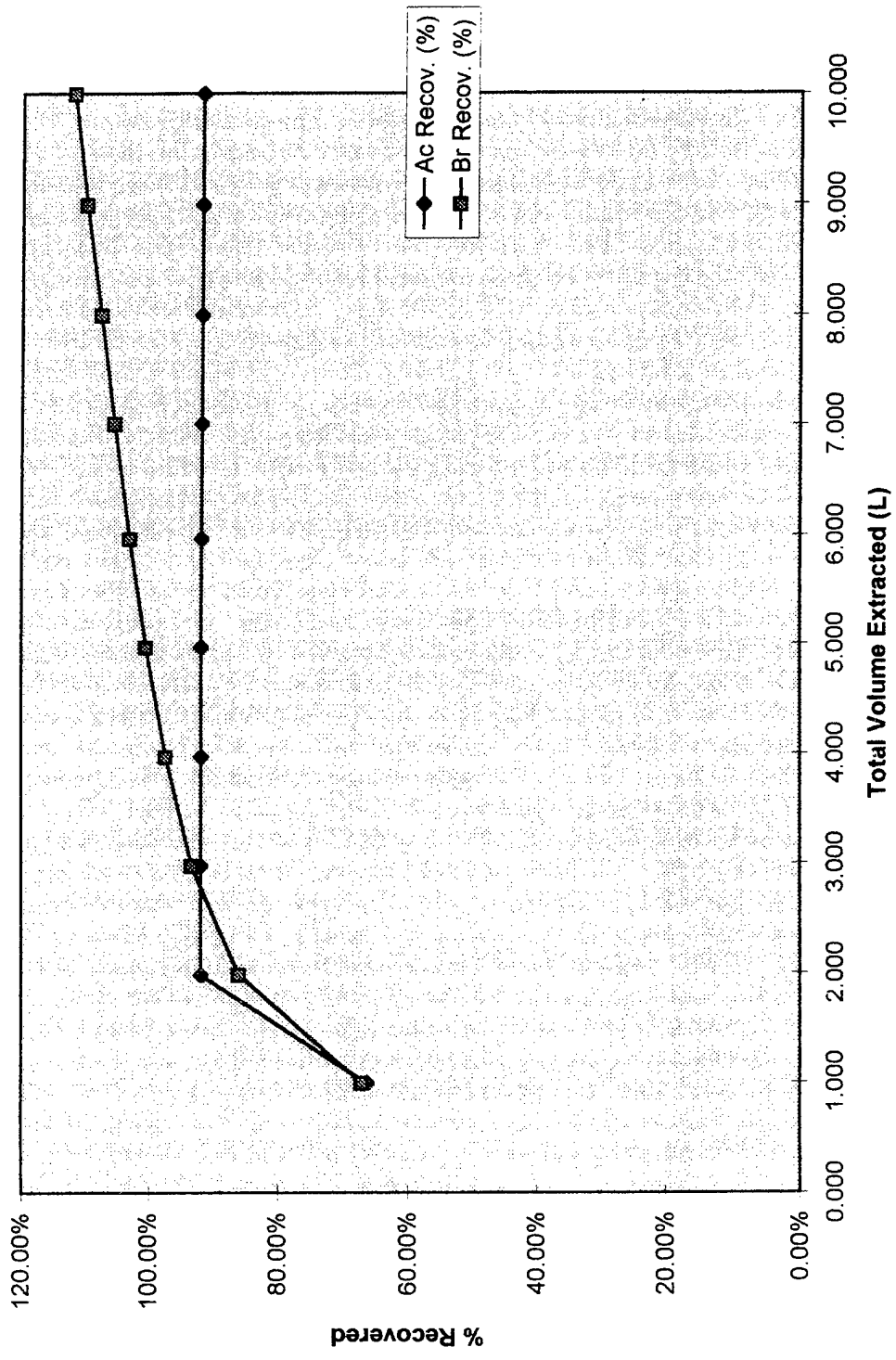


Table B.26
Tracer Concentration and Recovery with Volume Extracted at MP1-15', September 1997

SAMPLE	Vol. Ext. (L)	Tot. Vol. Ext. (L)	Ac^- Conc. (mg/L)	Br^- Conc. (mg/L)	D.O. Conc. (mg/L)	Mass Ac^- (mg)	Mass Br^- (mg)	Cum. Ac (mg)	Cum Br (mg)	Ac Recov. (%)	Br Recov. (%)
init mass	1.000	1.000	54.36	50.30	<2	54.36	50.30				
1	0.995	0.995	3.35	14.12	2.6	3.34	14.05	3.34	14.05	6.14%	27.94%
2	0.995	1.990	0.00	5.09	3.4	0.00	5.07	3.34	19.12	6.14%	38.01%
3	0.995	2.985	0.00	2.47	3.6	0.00	2.45	3.34	21.57	6.14%	42.89%
4	0.990	3.975	0.00	1.68	3.9	0.00	1.66	3.34	23.24	6.14%	46.19%
5	0.995	4.970	0.00	1.56	3.9	0.00	1.56	3.34	24.79	6.14%	49.28%
6	1.000	5.970	0.00	1.20	3.9	0.00	1.20	3.34	25.99	6.14%	51.66%
7	0.980	6.950	0.00	1.06	3.9	0.00	1.04	3.34	27.02	6.14%	53.72%
8	0.995	7.945	0.00	1.01	4.3	0.00	1.00	3.34	28.02	6.14%	55.71%
9	0.990	8.935	0.00	0.98	4.1	0.00	0.97	3.34	28.99	6.14%	57.63%
10	0.990	9.925	0.00	0.95	4.2	0.00	0.94	3.34	29.93	6.14%	59.50%
									Adj. Ac (%)	10.32%	

Table B.27
Tracer Concentration and Recovery with Volume Extracted at MP4-15', September 1997

SAMPLE	Vol. Ext. (L)	Tot. Vol. Ext. (L)	Ac^- Conc. (mg/L)	Br^- Conc. (mg/L)	D.O. Conc. (mg/L)	Mass Ac^- (mg)	Mass Br^- (mg)	Cum. Ac (mg)	Cum Br (mg)	Ac Recov. (%)	Br Recov. (%)
init mass	1.000	1.000	54.36	50.30	<2	54.36	50.30				
1	0.990	0.990	0.00	2.88	5.1	0.00	2.85	0.00	2.85	0.00%	5.66%
2	0.995	1.985	0.53	3.99	5.0	0.53	3.97	0.53	6.82	0.97%	13.56%
3	1.000	2.985	8.07	3.95	5.0	8.07	3.95	8.59	10.77	15.81%	21.40%
4	1.000	3.985	0.61	3.45	5.4	0.61	3.45	9.20	14.21	16.93%	28.25%
5	1.000	4.985	0.00	3.17	5.6	0.00	3.17	9.20	17.38	16.93%	34.55%
6	1.050	6.035	0.00	3.02	5.3	0.00	3.17	9.20	20.55	16.93%	40.85%
7	1.000	7.035	0.00	2.84	5.6	0.00	2.84	9.20	23.39	16.93%	46.50%
8	0.990	8.025	0.00	2.56	5.9	0.00	2.53	9.20	25.92	16.93%	51.53%
9	0.995	9.020	0.00	2.36	5.9	0.00	2.34	9.20	28.26	16.93%	56.19%
10	0.995	10.015	0.00	2.12	5.9	0.00	2.11	9.20	30.38	16.93%	60.39%
									Adj. Ac (%)	28.04%	

Table B.28
Tracer Concentration and Recovery with Volume Extracted at MP7-15', September 1997

SAMPLE	Vol. Ext. (L)	Tot. Vol. Ext. (L)	Ac^- Conc. (mg/L)	Br^- Conc. (mg/L)	D.O. Conc. (mg/L)	Mass Ac^- (mg)	Mass Br^- (mg)	Cum. Ac (mg)	Cum Br (mg)	Ac Recov. (%)	Br Recov. (%)
init mass	1.000	1.000	54.36	50.30	<2	54.36	50.30				
1	1.000	1.000	39.53	31.05	1.9	39.53	31.05	39.53	31.05	72.73%	61.73%
2	0.995	1.995	8.06	8.27	1.9	8.02	8.23	47.55	39.28	87.49%	78.09%
3	1.000	2.995	0.00	3.02	1.9	0.00	3.02	47.55	42.30	87.49%	84.09%
4	1.000	3.995	0.00	1.85	1.9	0.00	1.85	47.55	44.15	87.49%	87.77%
5	1.000	4.995	0.00	1.44	1.9	0.00	1.44	47.55	45.59	87.49%	90.62%
6	0.995	5.990	0.00	1.20	1.9	0.00	1.19	47.55	46.78	87.49%	93.00%
7	0.995	6.985	0.00	1.08	1.9	0.00	1.07	47.55	47.85	87.49%	95.13%
8	0.995	7.980	0.00	0.99	1.9	0.00	0.99	47.55	48.84	87.49%	97.10%
9	1.000	8.980	0.00	0.92	1.9	0.00	0.92	47.55	49.77	87.49%	98.94%
10	1.000	9.980	0.00	0.88	1.9	0.00	0.88	47.55	50.65	87.49%	100.69%
									Adj. Ac (%)	86.88%	

Table B.29
Tracer Concentration and Recovery with Volume Extracted at MP9-15', September 1997

SAMPLE	Vol. Ext. (L)	Tot. Vol. Ext. (L)	Ac^- Conc. (mg/L)	Br^- Conc. (mg/L)	D.O. Conc. (mg/L)	Mass Ac^- (mg)	Mass Br^- (mg)	Cum. Ac (mg)	Cum Br (mg)	Ac Recov. (%)	Br Recov. (%)
init mass	0.960	0.960	54.36	50.30	<2	52.18	48.29				
1	1.090	1.090	23.65	17.78	1.9	25.78	19.38	25.78	19.38	49.41%	40.14%
2	0.995	2.085	15.44	8.20	1.9	15.36	8.16	41.14	27.54	78.85%	57.03%
3	1.000	3.085	1.33	4.03	1.9	1.33	4.03	42.47	31.56	81.40%	65.36%
4	0.990	4.075	3.65	3.11	1.9	3.61	3.08	46.09	34.65	88.32%	71.75%
5	1.000	5.075	0.00	2.62	1.9	0.00	2.62	46.09	37.27	88.32%	77.18%
6	1.000	6.075	0.00	2.83	1.9	0.00	2.83	46.09	40.10	88.32%	83.03%
7	1.000	7.075	0.00	2.06	1.9	0.00	2.06	46.09	42.16	88.32%	87.30%
8	0.995	8.070	0.00	1.80	1.9	0.00	1.79	46.09	43.95	88.32%	91.01%
9	1.000	9.070	0.00	1.78	1.9	0.00	1.78	46.09	45.73	88.32%	94.71%
10	0.995	10.065	0.00	1.45	1.9	0.00	1.44	46.09	47.18	88.32%	97.70%
									Adj. Ac (%)	90.41%	

Figure B.49
Tracer Concentration Profile with Volume Extracted at MP1-15', September 1997

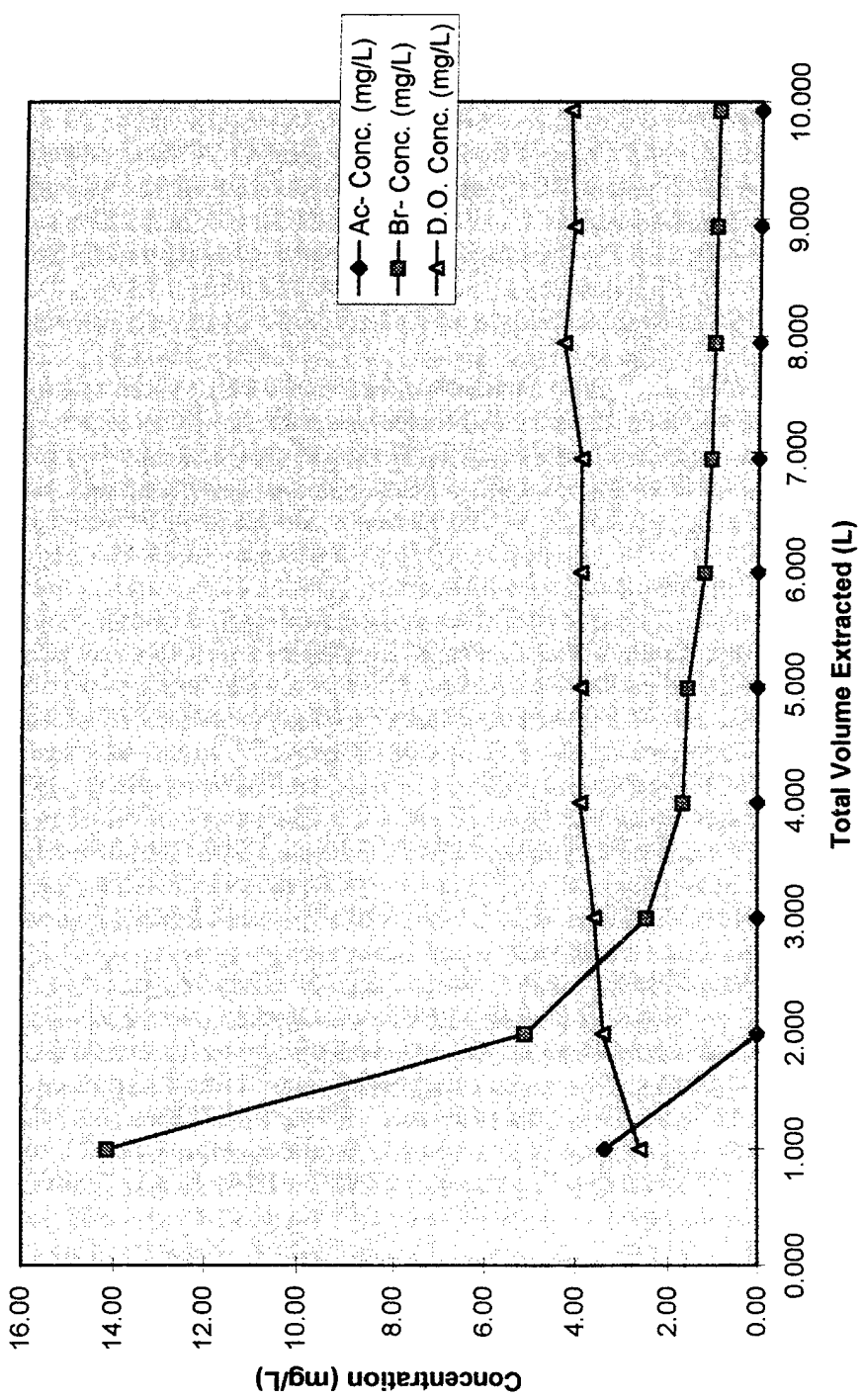


Figure B.50
Tracer Recovery Profile with Volume Extracted at MP1-15', September 1997

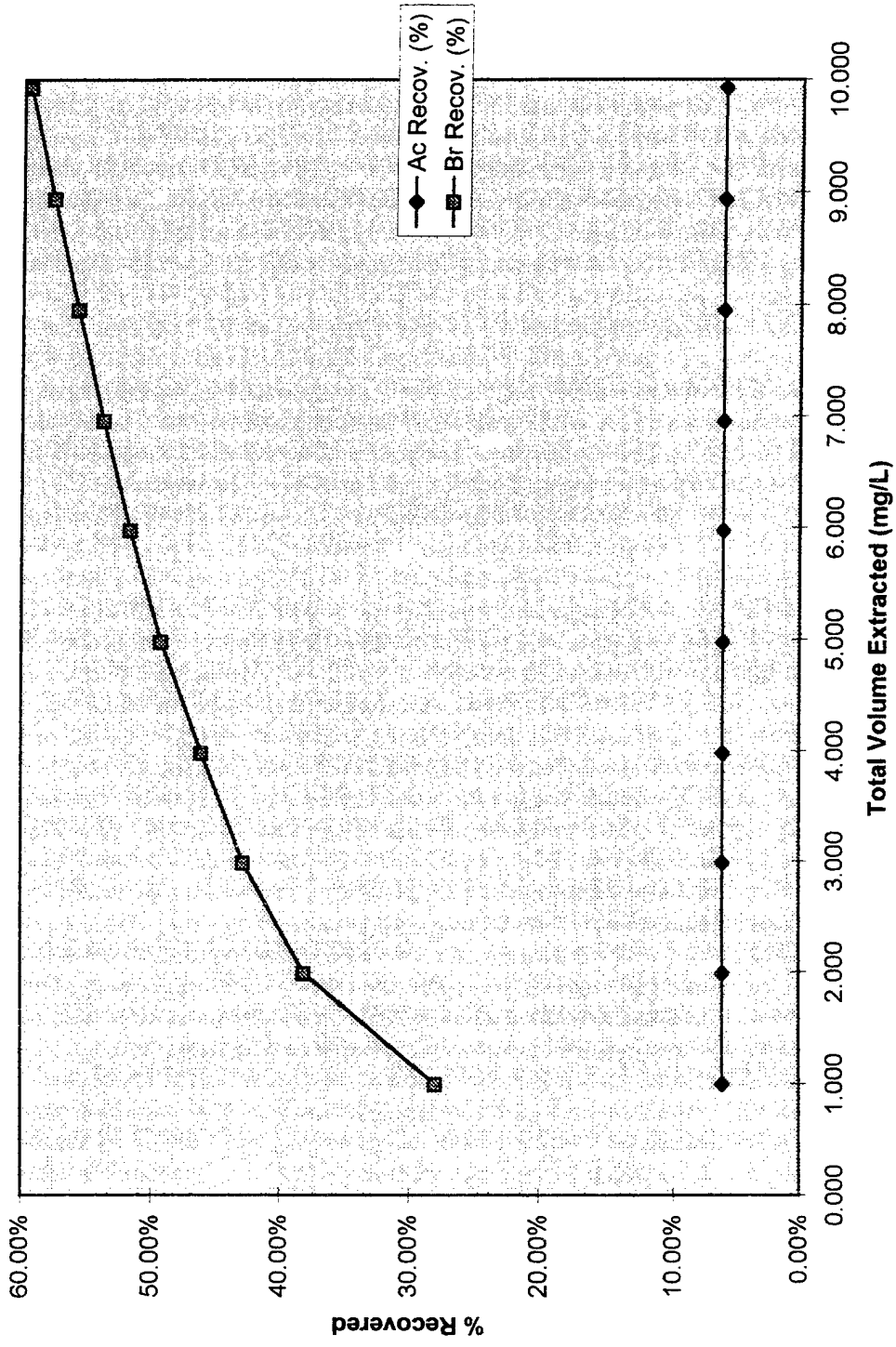


Figure B.51
Tracer Concentration Profile With Volume Extracted at MP4-15', September 1997

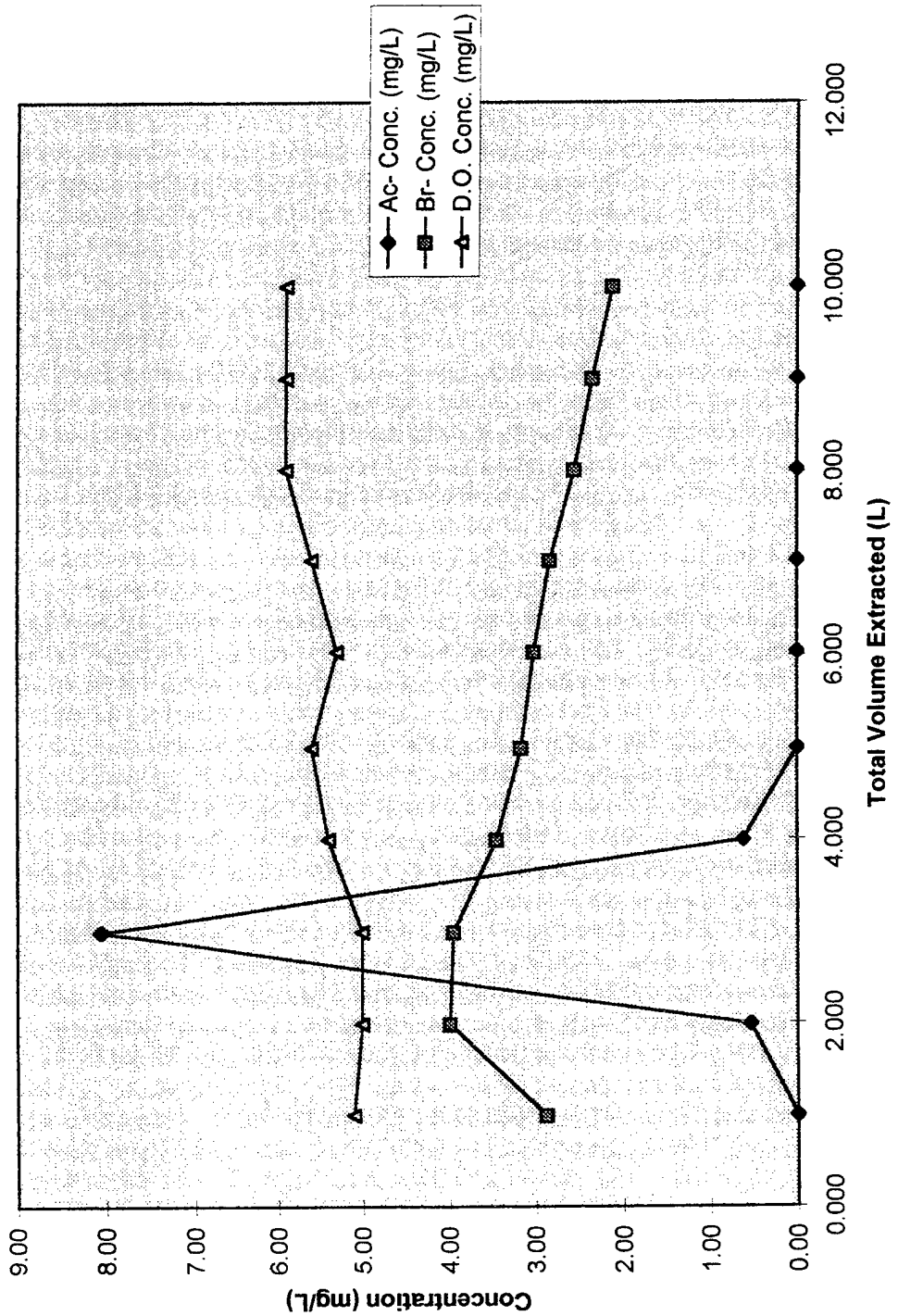


Figure B.52
Tracer Recovery Profile with Volume Extracted at MP4-15', September 1997

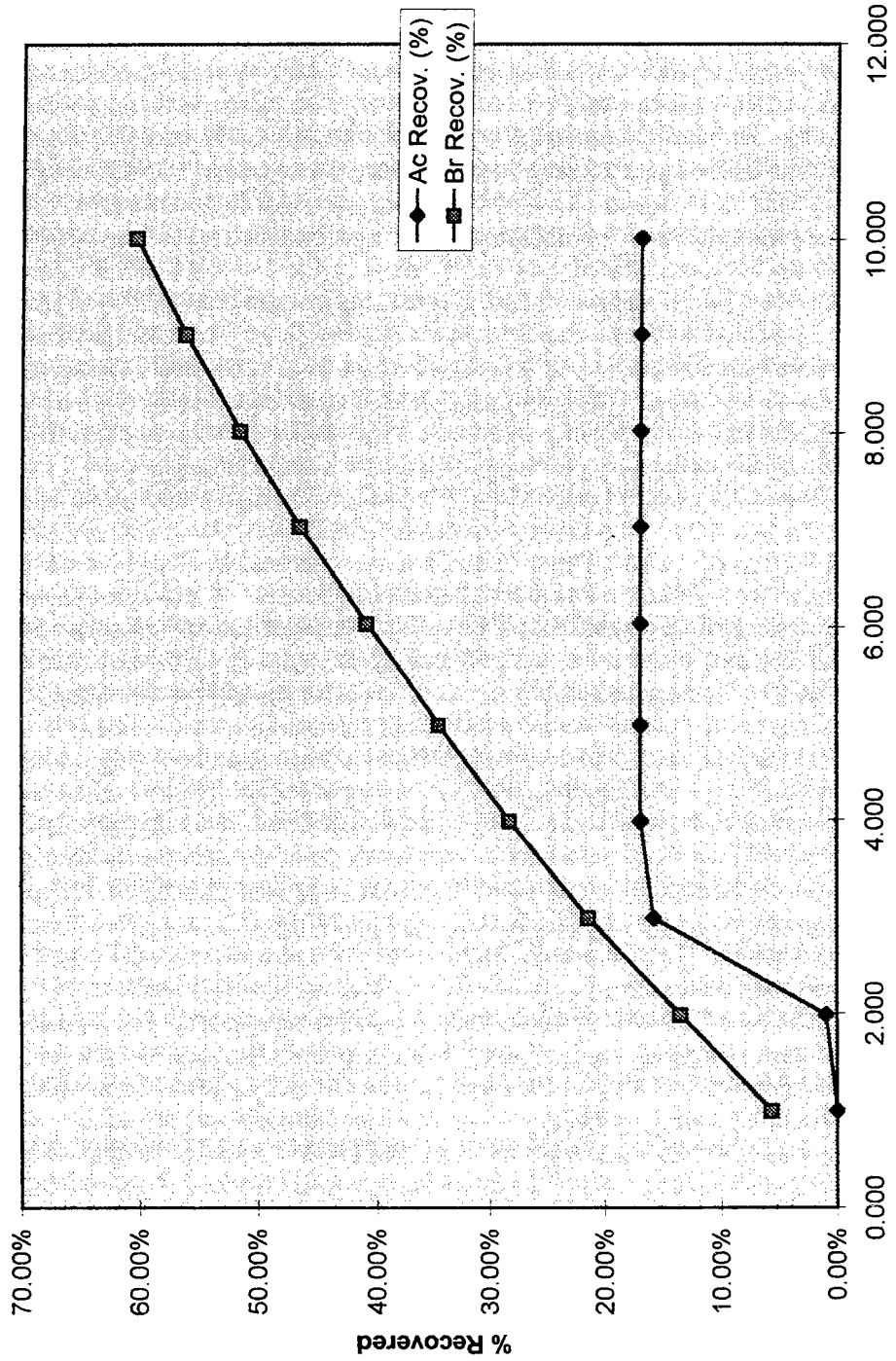


Figure B.53
Tracer Concentration Profile with Volume Extracted at MP7-15', September 1997

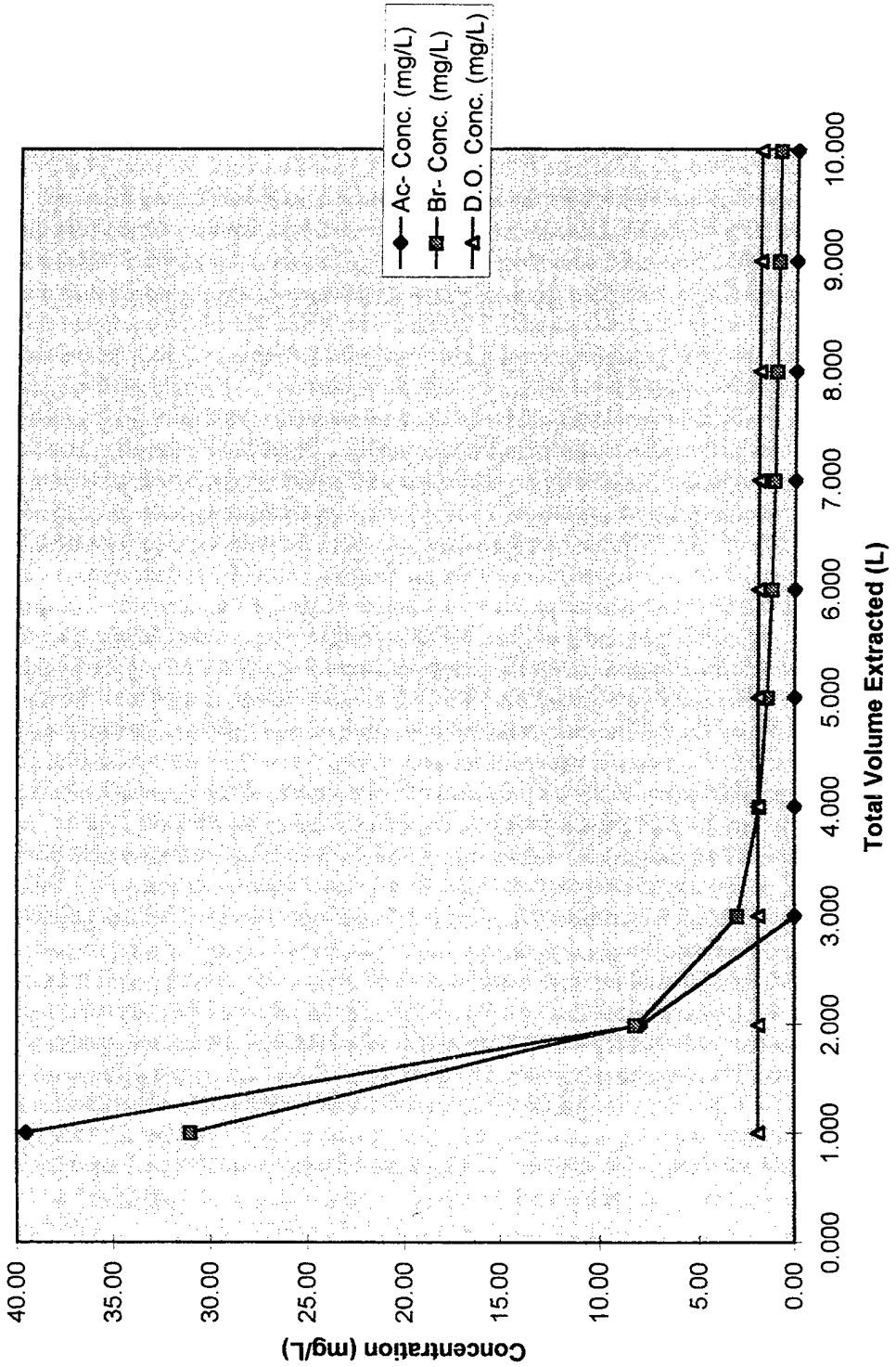


Figure B.54
Tracer Recovery Profile with Volume Extracted at MP7-15', September 1997

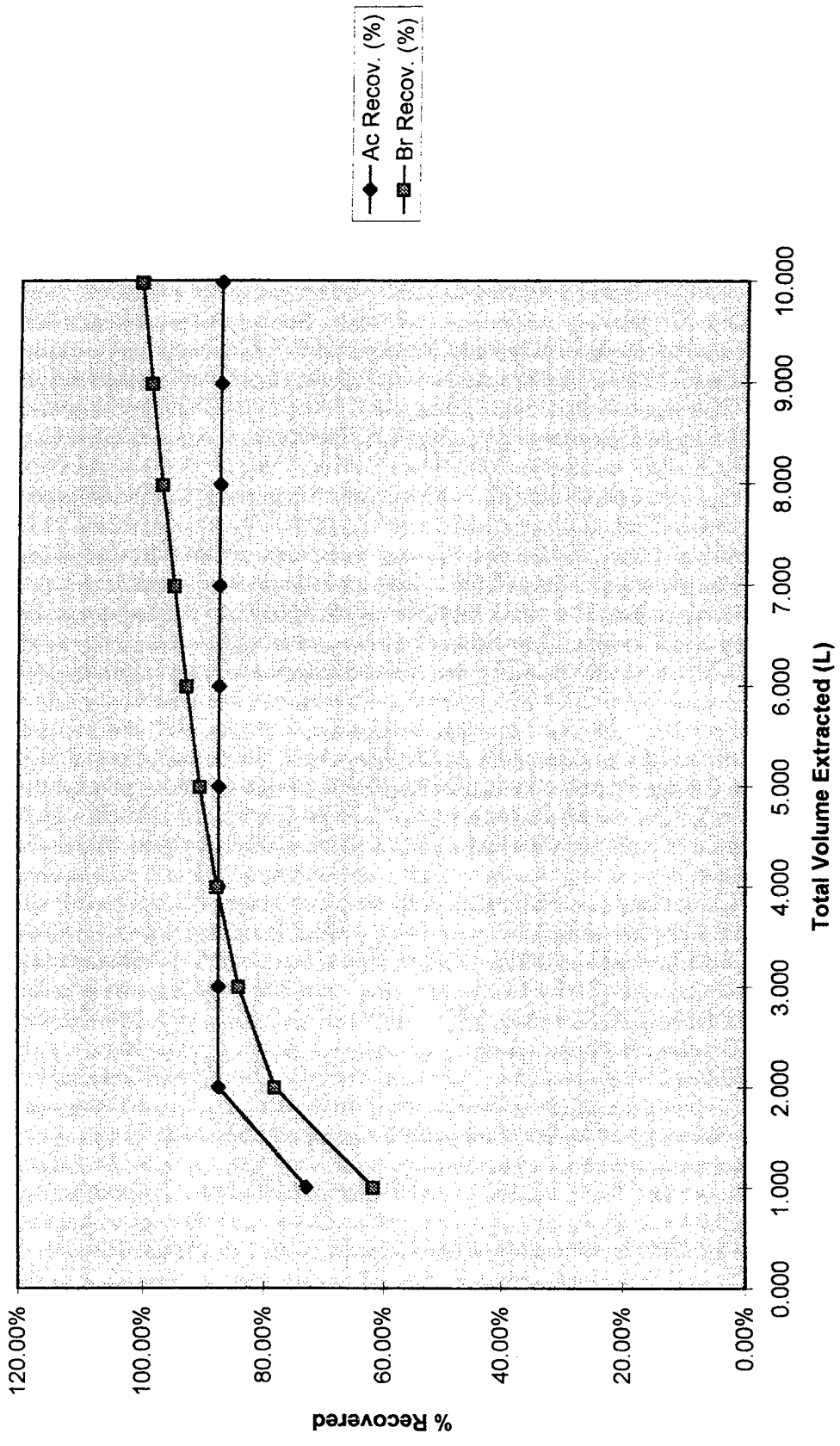


Figure B.55
Tracer Concentration Profile with Volume Extracted at MP9-15', September 1997

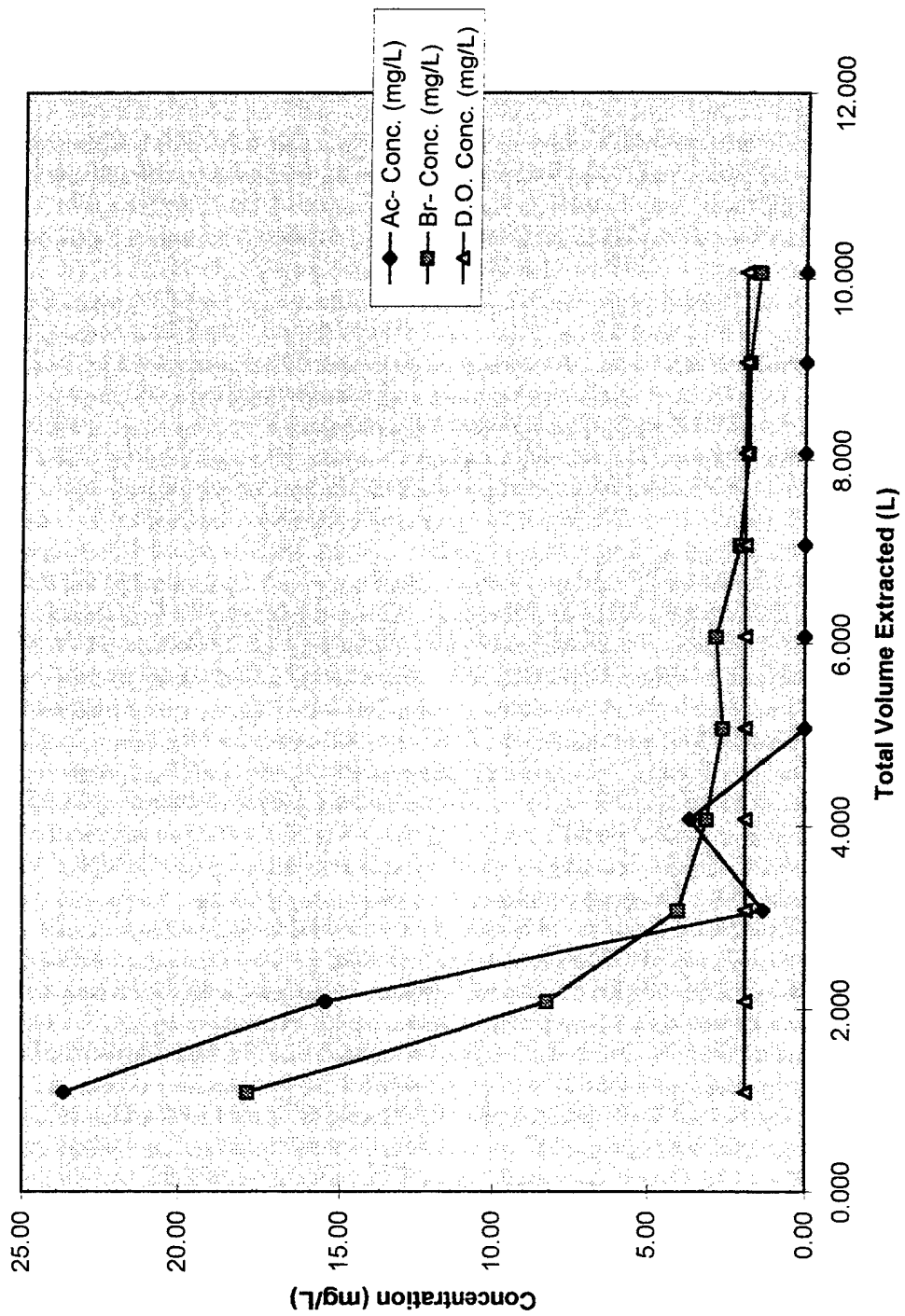
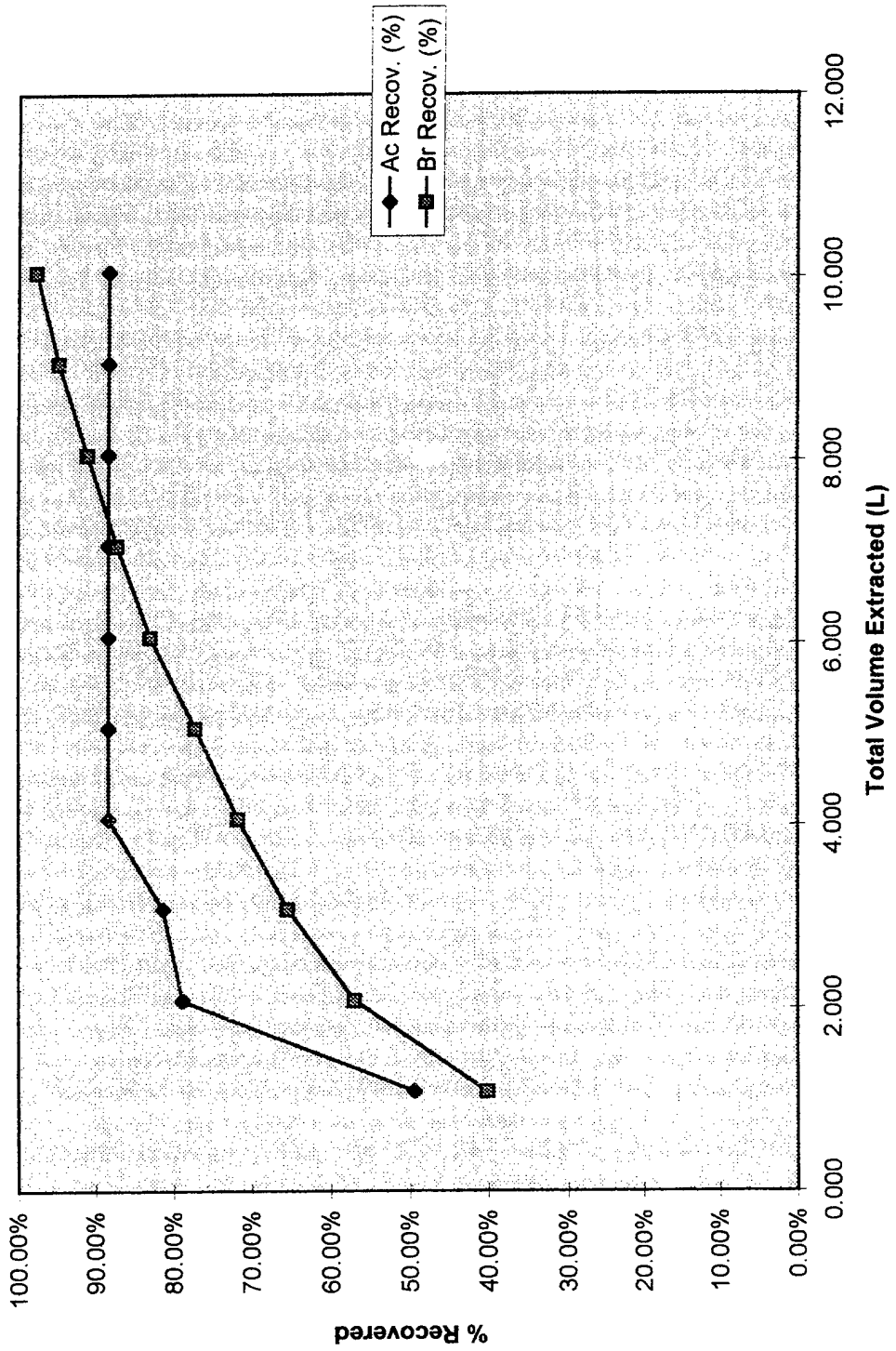


Figure B.56
Tracer Recovery Profile with Volume Extracted at MP9-15', September 1997



APPENDIX C

OXYGEN DELIVERY RATE SPREADSHEETS

Table C.1
Continuous Ground Water Pumping SF6 Tracer Test - Oxygen Delivery Calculations - July 1997

		Vial Vol (mL)	40	SF6 MW	146	O2 MW	32	Assumed radius (cm)	30	Porosity	0.35
		Water Vol (mL)	1	Background SF6	0.1	Max O2 (mg/L)	9	Assumed length (cm)	30.48	Density (kg/L)	1.7
		HS Vol (mL)	39	Max SF6 (ppbv-HS)	85	Max SF6 (mg/L-H2O	0.020145	Assumed vol (L)	30.24		
Location	Depth (ft bgs)	SF6 (ppbv-HS)	Q (mL/min)	ΔSF6 (mg/L-HS)	ΔSF6 (mg/L-H2O)	m* (mg-SF6/d)	Mo2 (mg-O2/d)	(mg-O2/L-d)	(mg-O2/kg-d)	(mg-HC/kg-d)	Csf6 (% Cmax)
MP1	10	3.21	50	1.9E-05	7.4E-04	5.3E-02	5.1E+01	1.68	0.35	0.12	3.65
	11	4.96	50	3.0E-05	1.2E-03	8.3E-02	7.9E+01	2.62	0.54	0.18	5.71
	12	1.02	50	5.6E-06	2.2E-04	1.6E-02	1.5E+01	0.50	0.10	0.03	1.08
	13	1.56	50	8.9E-06	3.5E-04	2.5E-02	2.4E+01	0.79	0.16	0.05	1.72
	14	13.9	50	8.4E-05	3.3E-03	2.4E-01	2.2E+02	7.44	1.53	0.51	16.22
	15	3.85	50	2.3E-05	8.9E-04	6.4E-02	6.1E+01	2.02	0.42	0.14	4.41
	16	1.82	50	1.0E-05	4.1E-04	2.9E-02	2.8E+01	0.93	0.19	0.06	2.02
	17	51.7	50	3.1E-04	1.2E-02	8.8E-01	8.4E+02	27.81	5.72	1.91	60.64
	18	0.91	50	4.9E-06	1.9E-04	1.4E-02	1.3E+01	0.44	0.09	0.03	0.95
	19	2.13	50	1.2E-05	4.8E-04	3.5E-02	3.3E+01	1.09	0.23	0.08	2.39
MP2	10	76.7	50	4.6E-04	1.8E-02	1.3E+00	1.2E+03	41.28	8.50	2.83	90.01
	11	235	50	1.4E-03	5.6E-02	4.0E+00	3.8E+03	126.58	26.06	8.69	276.04
	12	49.1	50	3.0E-04	1.2E-02	8.4E-01	8.0E+02	26.41	5.44	1.81	57.58
	13	82.3	50	5.0E-04	1.9E-02	1.4E+00	1.3E+03	44.30	9.12	3.04	96.60
	14	36.8	50	2.2E-04	8.7E-03	6.3E-01	6.0E+02	19.78	4.07	1.36	43.13
	15		50	-6.1E-07	-2.4E-05	-1.7E-03	-1.6E+00	-0.05	-0.01	0.00	-0.12
	16	30.4	50	1.8E-04	7.2E-03	5.2E-01	4.9E+02	16.33	3.36	1.12	35.61
	17	0.053	50	-2.9E-07	-1.1E-05	-8.0E-04	-7.7E-01	-0.03	-0.01	0.00	-0.06
	18	0.178	50	4.7E-07	1.8E-05	1.3E-03	1.3E+00	0.04	0.01	0.00	0.09
	19	0.243	50	8.7E-07	3.4E-05	2.4E-03	2.3E+00	0.08	0.02	0.01	0.17
MP3	10	0.363	50	1.6E-06	6.2E-05	4.5E-03	4.3E+00	0.14	0.03	0.01	0.31
	11	1.88	50	1.1E-05	4.2E-04	3.0E-02	2.9E+01	0.96	0.20	0.07	2.09
	12	26.2	50	1.6E-04	6.2E-03	4.4E-01	4.3E+02	14.06	2.90	0.97	30.67
	13	2.67	50	1.6E-05	6.1E-04	4.4E-02	4.2E+01	1.38	0.29	0.10	3.02
	14	27.4	50	1.7E-04	6.5E-03	4.7E-01	4.4E+02	14.71	3.03	1.01	32.08
	15	18.8	50	1.1E-04	4.4E-03	3.2E-01	3.0E+02	10.08	2.07	0.69	21.97
	16	13.5	50	8.1E-05	3.2E-03	2.3E-01	2.2E+02	7.22	1.49	0.50	15.75
	17	6.86	50	4.1E-05	1.6E-03	1.2E-01	1.1E+02	3.64	0.75	0.25	7.94
	18	0.819	50	4.4E-06	1.7E-04	1.2E-02	1.2E+01	0.39	0.08	0.03	0.84
	19	0.222	50	7.4E-07	2.9E-05	2.1E-03	2.0E+00	0.07	0.01	0.00	0.14
MP4	10	0.728	50	3.8E-06	1.5E-04	1.1E-02	1.0E+01	0.34	0.07	0.02	0.74
	11	1.55	50	8.8E-06	3.4E-04	2.5E-02	2.4E+01	0.78	0.16	0.05	1.70
	12	5.33	50	3.2E-05	1.2E-03	8.9E-02	8.5E+01	2.82	0.58	0.19	6.15

Table C.1
Continuous Ground Water Pumping SF6 Tracer Test - Oxygen Delivery Calculations - July 1997

Location	Depth (ft bgs)	SF6 (ppbv-HS)	Q (mL/min)	ΔSF6 (mg/L-HS)	ΔSF6 (mg/L-H2O)	m* (mg-SF6/d)	Mo2 (mg-O2/d)	(mg-O2/L-d)	(mg-O2/kg-d)	(mg-HC/kg-d)	Csf6 (% Cmax)
	13	0.16	50	3.6E-07	1.4E-05	1.0E-03	9.8E-01	0.03	0.01	0.00	0.07
	14	0.133	50	2.0E-07	7.8E-06	5.6E-04	5.4E-01	0.02	0.00	0.00	0.04
	15	3.97	50	2.3E-05	9.2E-04	6.6E-02	6.3E+01	2.09	0.43	0.14	4.55
	16	0.207	50	6.5E-07	2.5E-05	1.8E-03	1.7E+00	0.06	0.01	0.00	0.13
	17	0.377	50	1.7E-06	6.6E-05	4.7E-03	4.5E+00	0.15	0.03	0.01	0.33
	18	0.021	50	-4.8E-07	-1.9E-05	-1.3E-03	-1.3E+00	-0.04	-0.01	0.00	-0.09
	19	0.039	50	-3.7E-07	-1.4E-05	-1.0E-03	-9.9E-01	-0.03	-0.01	0.00	-0.07
MP5	10	0.143	50	2.6E-07	1.0E-05	7.3E-04	7.0E-01	0.02	0.00	0.00	0.05
	11	0.166	50	4.0E-07	1.6E-05	1.1E-03	1.1E+00	0.04	0.01	0.00	0.08
	12	0.022	50	-4.7E-07	-1.8E-05	-1.3E-03	-1.3E+00	-0.04	-0.01	0.00	-0.09
	13	0.407	50	1.9E-06	7.3E-05	5.2E-03	5.0E+00	0.17	0.03	0.01	0.36
	14	0.59	50	3.0E-06	1.2E-04	8.4E-03	8.0E+00	0.26	0.05	0.02	0.58
	15	3.43	50	2.0E-05	7.9E-04	5.7E-02	5.4E+01	1.79	0.37	0.12	3.91
	16	0.041	50	-3.6E-07	-1.4E-05	-1.0E-03	-9.6E-01	-0.03	-0.01	0.00	-0.07
	17	0.05	50	-3.0E-07	-1.2E-05	-8.5E-04	-8.1E-01	-0.03	-0.01	0.00	-0.06
	18	1.17	50	6.5E-06	2.5E-04	1.8E-02	1.7E+01	0.58	0.12	0.04	1.26
	19	0.217	50	7.1E-07	2.8E-05	2.0E-03	1.9E+00	0.06	0.01	0.00	0.14
MP6	10	25.9	50	1.6E-04	6.1E-03	4.4E-01	4.2E+02	13.90	2.86	0.95	30.32
	11	45.6	50	2.8E-04	1.1E-02	7.8E-01	7.4E+02	24.52	5.05	1.68	53.47
	12		50	-6.1E-07	-2.4E-05	-1.7E-03	-1.6E+00	-0.05	-0.01	0.00	-0.12
	13	19.3	50	1.2E-04	4.5E-03	3.3E-01	3.1E+02	10.35	2.13	0.71	22.56
	14	39.5	50	2.4E-04	9.3E-03	6.7E-01	6.4E+02	21.23	4.37	1.46	46.30
	15	24.1	50	1.5E-04	5.7E-03	4.1E-01	3.9E+02	12.93	2.66	0.89	28.20
	16	0.289	50	1.1E-06	4.5E-05	3.2E-03	3.1E+00	0.10	0.02	0.01	0.22
	17	0.201	50	6.1E-07	2.4E-05	1.7E-03	1.6E+00	0.05	0.01	0.00	0.12
	18	0.277	50	1.1E-06	4.2E-05	3.0E-03	2.9E+00	0.10	0.02	0.01	0.21
	19	0.596	50	3.0E-06	1.2E-04	8.5E-03	8.1E+00	0.27	0.06	0.02	0.58
MP7	10	0.029	50	-4.3E-07	-1.7E-05	-1.2E-03	-1.2E+00	-0.04	-0.01	0.00	-0.08
	11	0.043	50	-3.5E-07	-1.3E-05	-9.7E-04	-9.3E-01	-0.03	-0.01	0.00	-0.07
	12	0.044	50	-3.4E-07	-1.3E-05	-9.5E-04	-9.1E-01	-0.03	-0.01	0.00	-0.07
	13	0.055	50	-2.7E-07	-1.1E-05	-7.7E-04	-7.3E-01	-0.02	0.00	0.00	-0.05
	14	0.031	50	-4.2E-07	-1.6E-05	-1.2E-03	-1.1E+00	-0.04	-0.01	0.00	-0.08
	15	0.017	50	-5.0E-07	-2.0E-05	-1.4E-03	-1.4E+00	-0.04	-0.01	0.00	-0.10
	16	0.028	50	-4.4E-07	-1.7E-05	-1.2E-03	-1.2E+00	-0.04	-0.01	0.00	-0.08
	17	0.116	50	9.7E-08	3.8E-06	2.7E-04	2.6E-01	0.01	0.00	0.00	0.02
	18	0.053	50	-2.9E-07	-1.1E-05	-8.0E-04	-7.7E-01	-0.03	-0.01	0.00	-0.06
	19	0.067	50	-2.0E-07	-7.8E-06	-5.6E-04	-5.4E-01	-0.02	0.00	0.00	-0.04
MP8	10	0.346	50	1.5E-06	5.8E-05	4.2E-03	4.0E+00	0.13	0.03	0.01	0.29
	11	0.63	50	3.2E-06	1.3E-04	9.0E-03	8.6E+00	0.29	0.06	0.02	0.62

Table C.1
Continuous Ground Water Pumping SF6 Tracer Test - Oxygen Delivery Calculations - July 1997

Location	Depth	SF6	Q	ΔSF6	ΔSF6	m*	Mo2				Csf6
	(ft bgs)	(ppbv-HS)	(mL/min)	(mg/L-HS)	(mg/L-H2O)	(mg-SF6/d)	(mg-O2/d)	(mg-O2/L-d)	(mg-O2/kg-d)	(mg-HC/kg-d)	(% Cmax)
	12	0.708	50	3.7E-06	1.4E-04	1.0E-02	9.9E+00	0.33	0.07	0.02	0.71
	13	0.186	50	5.2E-07	2.0E-05	1.5E-03	1.4E+00	0.05	0.01	0.00	0.10
	14	0.604	50	3.1E-06	1.2E-04	8.6E-03	8.2E+00	0.27	0.06	0.02	0.59
	15	0.634	50	3.2E-06	1.3E-04	9.1E-03	8.7E+00	0.29	0.06	0.02	0.63
	16	1.98	50	1.1E-05	4.5E-04	3.2E-02	3.1E+01	1.01	0.21	0.07	2.21
	17	1.67	50	9.5E-06	3.7E-04	2.7E-02	2.6E+01	0.85	0.17	0.06	1.84
	18	0.727	50	3.8E-06	1.5E-04	1.1E-02	1.0E+01	0.34	0.07	0.02	0.74
	19	0.364	50	1.6E-06	6.2E-05	4.5E-03	4.3E+00	0.14	0.03	0.01	0.31
MP9	10	61.2	50	3.7E-04	1.4E-02	1.0E+00	1.0E+03	32.93	6.78	2.26	71.80
	11	69.4	50	4.2E-04	1.6E-02	1.2E+00	1.1E+03	37.34	7.69	2.56	81.44
	12	3.3	50	1.9E-05	7.6E-04	5.5E-02	5.2E+01	1.72	0.36	0.12	3.76
	13	9.77	50	5.9E-05	2.3E-03	1.6E-01	1.6E+02	5.21	1.07	0.36	11.36
	14	2.54	50	1.5E-05	5.8E-04	4.2E-02	4.0E+01	1.31	0.27	0.09	2.87
	15	0.297	50	1.2E-06	4.7E-05	3.4E-03	3.2E+00	0.11	0.02	0.01	0.23
	16	0.286	50	1.1E-06	4.4E-05	3.2E-03	3.0E+00	0.10	0.02	0.01	0.22
	17	0.121	50	1.3E-07	5.0E-06	3.6E-04	3.4E-01	0.01	0.00	0.00	0.02
	18	0.09	50	-6.1E-08	-2.4E-06	-1.7E-04	-1.6E-01	-0.01	0.00	0.00	-0.01
	19	0.1	50	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.00	0.00	0.00	0.00
MP10	10	0.29	50	1.2E-06	4.5E-05	3.2E-03	3.1E+00	0.10	0.02	0.01	0.22
	11	0.566	50	2.8E-06	1.1E-04	7.9E-03	7.6E+00	0.25	0.05	0.02	0.55
	12	0.404	50	1.8E-06	7.2E-05	5.2E-03	5.0E+00	0.16	0.03	0.01	0.36
	13	3.01	50	1.8E-05	6.9E-04	5.0E-02	4.7E+01	1.57	0.32	0.11	3.42
	14	1.26	50	7.0E-06	2.7E-04	2.0E-02	1.9E+01	0.63	0.13	0.04	1.36
	15	0.299	50	1.2E-06	4.7E-05	3.4E-03	3.2E+00	0.11	0.02	0.01	0.23
	16	0.562	50	2.8E-06	1.1E-04	7.9E-03	7.5E+00	0.25	0.05	0.02	0.54
	17	0.027	50	-4.4E-07	-1.7E-05	-1.2E-03	-1.2E+00	-0.04	-0.01	0.00	-0.09
	18	1.19	50	6.6E-06	2.6E-04	1.9E-02	1.8E+01	0.59	0.12	0.04	1.28
	19	0.197	50	5.9E-07	2.3E-05	1.7E-03	1.6E+00	0.05	0.01	0.00	0.11
MP11	10	0.358	50	1.6E-06	6.1E-05	4.4E-03	4.2E+00	0.14	0.03	0.01	0.30
	11	0.273	50	1.1E-06	4.1E-05	2.9E-03	2.8E+00	0.09	0.02	0.01	0.20
	12	0.102	50	1.2E-08	4.7E-07	3.4E-05	3.3E-02	0.00	0.00	0.00	0.00
	13	0.336	50	1.4E-06	5.6E-05	4.0E-03	3.8E+00	0.13	0.03	0.01	0.28
	14	0.207	50	6.5E-07	2.5E-05	1.8E-03	1.7E+00	0.06	0.01	0.00	0.13
	15	0.089	50	-6.7E-08	-2.6E-06	-1.9E-04	-1.8E-01	-0.01	0.00	0.00	-0.01
	16	0.257	50	9.5E-07	3.7E-05	2.7E-03	2.6E+00	0.08	0.02	0.01	0.18
	17	0.085	50	-9.1E-08	-3.6E-06	-2.6E-04	-2.4E-01	-0.01	0.00	0.00	-0.02
	18	0.33	50	1.4E-06	5.4E-05	3.9E-03	3.7E+00	0.12	0.03	0.01	0.27
	19	0.311	50	1.3E-06	5.0E-05	3.6E-03	3.4E+00	0.11	0.02	0.01	0.25
MP12	10	1.69	50	9.7E-06	3.8E-04	2.7E-02	2.6E+01	0.86	0.18	0.06	1.87

Table C.1
Continuous Ground Water Pumping SF6 Tracer Test - Oxygen Delivery Calculations - July 1997

Location	Depth	SF6	Q	ΔSF6	ΔSF6	m*	Mo2				Csf6
	(ft bgs)	(ppbv-HS)	(mL/min)	(mg/L-HS)	(mg/L-H2O)	(mg-SF6/d)	(mg-O2/d)	(mg-O2/L-d)	(mg-O2/kg-d)	(mg-HC/kg-d)	(% Cmax)
	11	1.2	50	6.7E-06	2.6E-04	1.9E-02	1.8E+01	0.59	0.12	0.04	1.29
	12	17	50	1.0E-04	4.0E-03	2.9E-01	2.8E+02	9.11	1.87	0.62	19.86
	13	2.82	50	1.7E-05	6.4E-04	4.6E-02	4.4E+01	1.47	0.30	0.10	3.20
	14	0.172	50	4.4E-07	1.7E-05	1.2E-03	1.2E+00	0.04	0.01	0.00	0.08
	15	0.24	50	8.5E-07	3.3E-05	2.4E-03	2.3E+00	0.08	0.02	0.01	0.16
	16		50	-6.1E-07	-2.4E-05	-1.7E-03	-1.6E+00	-0.05	-0.01	0.00	-0.12
	17	0.192	50	5.6E-07	2.2E-05	1.6E-03	1.5E+00	0.05	0.01	0.00	0.11
	18	0.088	50	-7.3E-08	-2.8E-06	-2.0E-04	-2.0E-01	-0.01	0.00	0.00	-0.01
	19	0.228	50	7.8E-07	3.0E-05	2.2E-03	2.1E+00	0.07	0.01	0.00	0.15

Table C.2
Continuous Ground Water Pumping SF6 Tracer Tracer Test - Oxygen Delivery Calculations - August 1997

		Vial Vol (mL)	40	SF6 MW	146	O2 MW	32	Assumed radius (cm)	30	Porosity	0.35	
		Water Vol (mL)	1	Background SF6	1.332	Max O2 (mg/L)	9	Assumed length (cm)	30.48	Density (kg/L)	1.7	
		HS Vol (mL)	39	Max SF6 (ppbv-HS)	41.9	Max SF6 (mg/L-H2O	0.00993	Assumed vol (L)	30.24			
Location	Depth	SF6	Q	ΔSF6	ΔSF6	m*	Mo2				DO	Csf6
	(ft bgs)	(ppbv-HS)	(mL/min)	(mg/L-HS)	(mg/L-H2O)	(mg-SF6/d)	(mg-O2/d)	(mg-O2/L-d)	(mg-O2/kg-d)	(mg-HC/kg-d)	(mg/L)	(% Cmax)
MP1	10	1.77	50	2.7E-06	1.0E-04	7.5E-03	1.4E+01	0.48	0.10	0.03	1	1.04
	11	9.89	50	5.2E-05	2.0E-03	1.5E-01	2.8E+02	9.36	1.93	0.64	1	20.40
	13	0.8575	50	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.00	0.00	0.00	6	0.00
MP2	10	23.25	50	1.3E-04	5.2E-03	3.7E-01	7.2E+02	23.96	4.93	1.64	6	52.25
	11	6.545	50	3.2E-05	1.2E-03	8.9E-02	1.7E+02	5.70	1.17	0.39	1	12.43
	13										8	
MP3	10	10.3	50	5.4E-05	2.1E-03	1.5E-01	3.0E+02	9.80	2.02	0.67	1	21.38
	11	2.13	50	4.8E-06	1.9E-04	1.4E-02	2.6E+01	0.87	0.18	0.06	1	1.90
	13	1.72	50	2.4E-06	9.2E-05	6.6E-03	1.3E+01	0.42	0.09	0.03	1	0.92
MP4	10	2.06	50	4.4E-06	1.7E-04	1.2E-02	2.4E+01	0.80	0.16	0.05	1	1.74
	11	14.8	50	8.2E-05	3.2E-03	2.3E-01	4.5E+02	14.72	3.03	1.01	1	32.11
	13	20	50	1.1E-04	4.4E-03	3.2E-01	6.2E+02	20.41	4.20	1.40	7.7	44.50
MP5	10	1.78	50	2.7E-06	1.1E-04	7.6E-03	1.5E+01	0.49	0.10	0.03	3.1	1.07
	11	3.74	50	1.5E-05	5.7E-04	4.1E-02	8.0E+01	2.63	0.54	0.18	1	5.74
	13	9.73	50	5.1E-05	2.0E-03	1.4E-01	2.8E+02	9.18	1.89	0.63	6.1	20.02
MP6	10										8.6	
	11										8.6	
	13										7.7	
MP7	10	0.645	50	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.00	0.00	0.00	1	0.00
	11	0.193	50	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.00	0.00	0.00	1	0.00
	13	0.629	50	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.00	0.00	0.00	1	0.00
MP8	10	2.18	50	5.1E-06	2.0E-04	1.4E-02	2.8E+01	0.93	0.19	0.06	1	2.02
	11	0.841	50	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.00	0.00	0.00	1	0.00
	13	0.444	50	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.00	0.00	0.00	1	0.00
MP9	10	1.44	50	6.6E-07	2.6E-05	1.8E-03	3.6E+00	0.12	0.02	0.01	1	0.26
	11										8	
	13	4.23	25	1.8E-05	6.9E-04	2.5E-02	4.8E+01	1.58	0.33	0.11	6.6	6.91
MP10	10	0.236	25	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.00	0.00	0.00	3.6	0.00
	11	0.13	25	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.00	0.00	0.00	1	0.00
	13	1.02	25	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.00	0.00	0.00	3.2	0.00
MP11	10	0.356	25	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.00	0.00	0.00	5.5	0.00
	11	0.17	25	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.00	0.00	0.00	1	0.00
	13	1.05	25	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.00	0.00	0.00	1	0.00
MP12	10	0.692	25	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.00	0.00	0.00	1	0.00
	11	0.549	25	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.00	0.00	0.00	1	0.00

Table C.2
Continuous Ground Water Pumping SF6 Tracer Tracer Test - Oxygen Delivery Calculations - August 1997

Location	Depth	SF6	Q	ΔSF6	ΔSF6	m*	Mo2				DO	Csf6
	(ft bgs)	(ppbv-HS)	(mL/min)	(mg/L-HS)	(mg/L-H2O)	(mg-SF6/d)	(mg-O2/d)	(mg-O2/L-d)	(mg-O2/kg-d)	(mg-HC/kg-d)	(mg/L)	(% Cmax)
	13	10.5	25	5.6E-05	2.2E-03	7.8E-02	1.5E+02	5.01	1.03	0.34	1	21.86

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