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100-D Area In Situ Redox Treatability Test for Chromate-Contaminated Groundwater

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Summary

A treatability test was conducted for the In Situ Redox Manipulation (ISRM) technology at the 100 D Area of the U. S. Department of Energy's Hanford Site in southeastern Washington State. The target contaminant was dissolved chromate [Cr(VI)] in groundwater. The ISRM technology involves creating a permeable subsurface treatment zone to reduce mobile chromate in groundwater to an insoluble form. The ISRM permeable treatment zone is created by reducing ferric iron [Fe(III)] to ferrous iron [Fe(II)] within the aquifer sediments, which is accomplished by injecting aqueous sodium dithionite into the aquifer and then withdrawing the reaction products.

The goal of the treatability test was to create an ISRM barrier by injecting sodium dithionite into five wells. Well installation and site characterization activities began in the spring of 1997; the first dithionite injection took place in September 1997. The results of this first injection were monitored through the spring of 1998. The remaining four dithionite injections were carried out in May through July of 1998.

These five injections created a reduced zone in the Hanford unconfined aquifer approximately 150 feet in length (perpendicular to groundwater flow) and 50 feet wide. The reduced zone extended over the thickness of the unconfined zone, which is approximately 15 feet. Analysis of post-emplacement groundwater samples showed that the concentrations of chromate, Cr(VI), in groundwater in the reduced zone decreased from approximately 1.0 mg/L before the injection tests to below analytical detection limits (<0.007 mg/L). Chromate concentrations also declined in downgradient monitoring wells to as low as 0.020 mg/L. Laboratory analysis of sediment core samples collected from post-emplacement boreholes showed a high degree of iron reduction, which confirmed the effectiveness of the barrier emplacement. These data, in addition to results from pre-test reducible iron characterization, indicate that the barrier should remain effective for approximately 23 years.

The 100-D Area ISRM barrier is being expanded to a length of up to 2,300 ft to capture a larger portion of the chromate plume. The barrier expansion is funded through a joint EM-50 and EM-40 program, Accelerated Site Technology Deployment Initiative (ASTD). This action required modifications to the existing interim Record of Decision (ROD) for the 100-HR-3 Operable Unit, resulting in a new proposed plan in FY 2000, "*Proposed Plan for an Amendment of the Interim Remedial Action at the 100-HR-3 Operable Unit.*"

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Contents

Figures

Tables

1.0 Introduction

This report describes the results of the site characterization, emplacement, and groundwater monitoring activities conducted for the In Situ Redox Manipulation (ISRM) treatability test for chromate contamination in the aquifer on the west side of 100-D Area (100-HR-3 Operable Unit) of the Hanford Site (see Figures 1.1 and 1.2). This final report is an updated version of earlier project milestone reports (Williams et al. 1999a). Fruchter et al. (1997) contains the Treatability Test Plan that describes the test, data quality objectives, permitting requirements, cultural and biological survey results, data gathering activities, and sampling/analysis plan. The objective of the 100-D Area ISRM treatability test was to develop performance and cost data at a pilot-scale for an assessment of this technology for treating chromate-contaminated groundwater at the Hanford Site. A smaller-scale proof-of-principle test for this technology was conducted at the 100-H Area during 1995 and described in Fruchter et al. (1996; 2000).

1.1 Background

The Hanford Site in southeastern Washington (Figure 1.1) was established in 1943 to produce plutonium for nuclear weapons using reactors and chemical processing plants. The 100 Area of the Hanford Site is situated along the Columbia River and includes nine deactivated U.S. Department of Energy (DOE) nuclear reactors used for plutonium production between 1943 and 1987. Operations at the Hanford Site are now focused on environmental restoration and waste management. In November 1989, the U.S. Environmental Protection Agency (EPA) designated the 100 Area of the Hanford Site a Superfund site and placed it on the National Priorities List because of soil and groundwater contamination from past operations at the nuclear facilities. To organize cleanup efforts under Superfund, contaminated areas at the nine deactivated reactors were subdivided into operable units.

The 100-HR-3 Operable Unit is in the north-central part of the Hanford Site along a section of the Columbia River known as the "Hanford Reach." This operable unit includes the groundwater underlying the 100-D/DR and 100-H reactor areas and the 600 Area between them. The 100-D/DR Area is the site of two deactivated reactors: the D Reactor, which operated from 1944 to 1967, and the DR Reactor, which operated from 1950 to 1965. The H Reactor operated from 1949 to 1965.

During reactor operations, hexavalent chromium, or chromate, in the form of sodium dichromate ($Na_2Cr_2O_7$) was used as an anticorrosion agent in the reactor cooling water. Large volumes of reactor cooling water containing sodium dichromate and short-lived radionuclides were discharged to retention basins for ultimate disposal in the Columbia River through outfall pipelines. Liquid wastes from other reactor operations (decontamination, water treatment, etc.) also contained significant quantities of hexavalent chromium. These wastes were discharged to the soil column at cribs, trenches, and french drains or leaked from storage facilities. Contaminant plumes in groundwater have resulted from these former waste disposal practices. Groundwater beneath the D/DR and H Reactor areas is contaminated with hexavalent chromium and is flowing toward and entering the Columbia River.

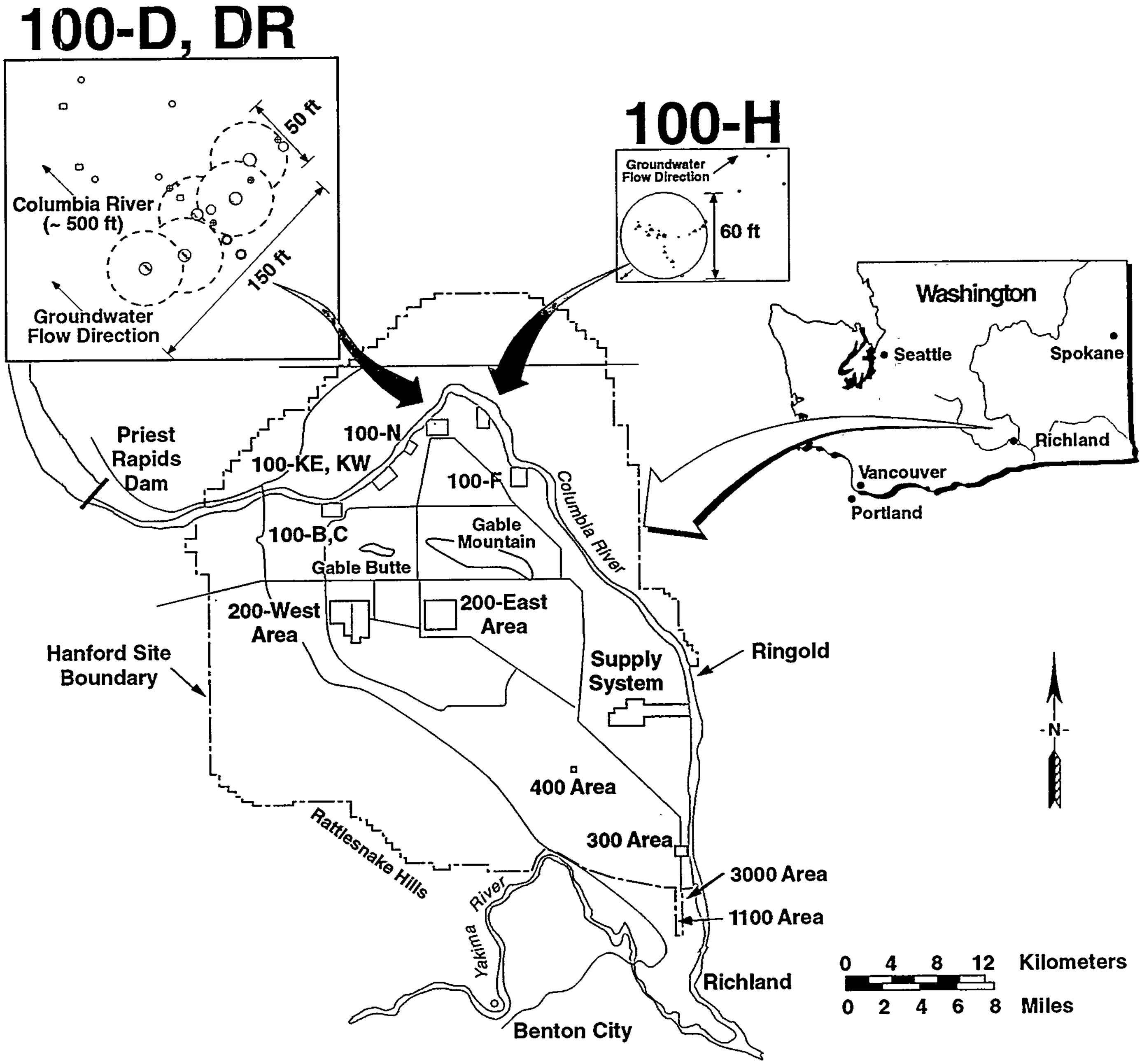

Figure 1.1. Location of the In Situ Redox Manipulation 100-H Area Proof-of-Principle Test Site and 100-D Area Treatability Test Site

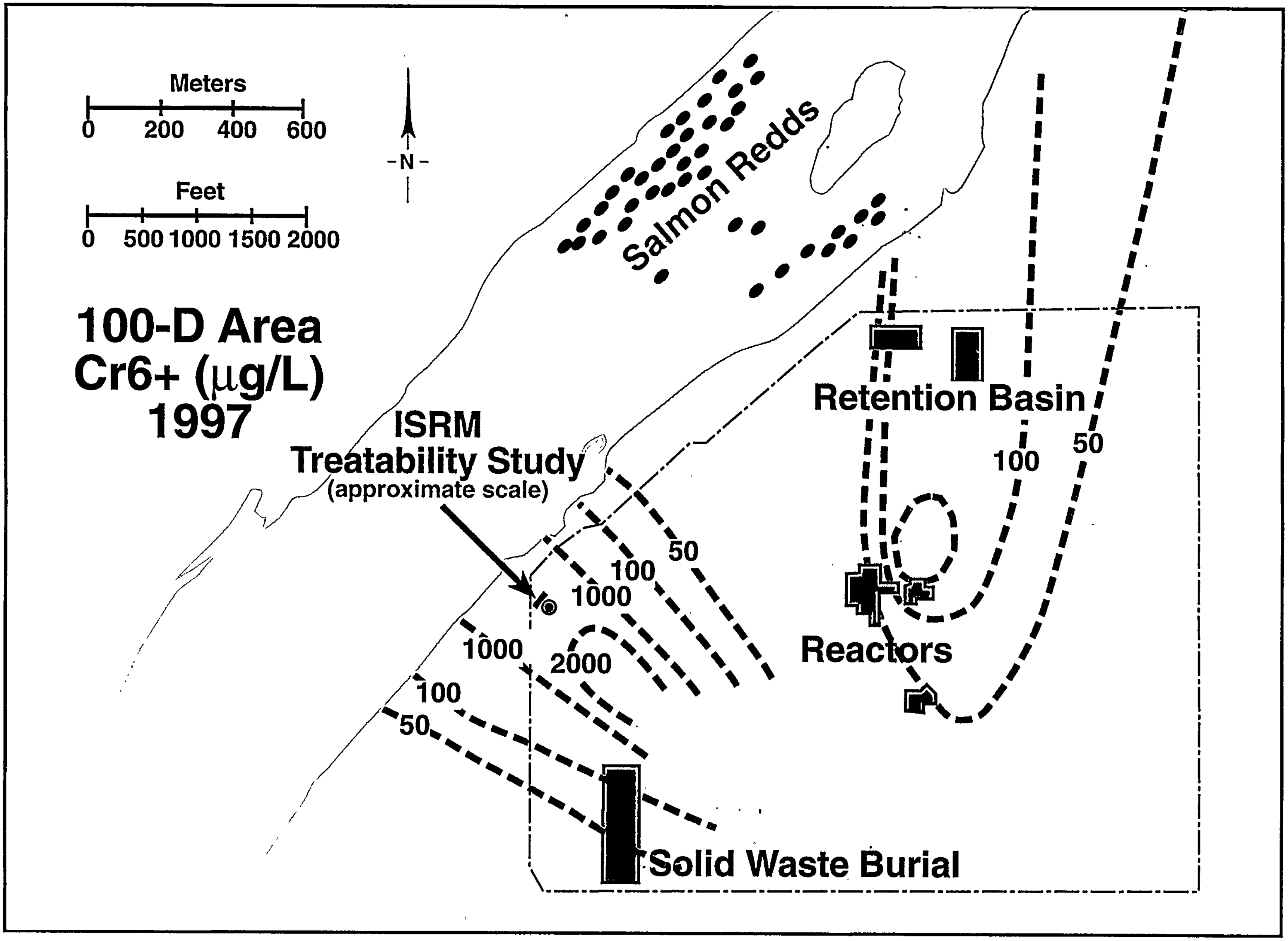

Figure 1.2. 100-D Area Cr^{6+} Groundwater Concentrations (μg/L) for 1997

In addition to the reactor areas, high concentrations (~ 1,000 μg/L) of hexavalent chromium were detected in the groundwater in the 100-HR-3 Operable Unit along the western edge of the 100-D/DR Area at well 199-D4-1, which was drilled in the fall of 1996 (see Figures 1.2 and 1.3). This is the location of the ISRM treatability test described in this report (see Figure 1.2). Well 199-D4-1 was drilled following a characterization program that detected hexavalent chromium concentrations in excess of 600 μg/L in the pore waters of the Columbia River substrate along the 100-D/DR Area (Peterson et al. 1998; Hope and Peterson 1996; Connelly 1997a). The elevated hexavalent chromium concentrations detected in the pore waters of the river substrate pose a potential risk to aquatic organisms in the Columbia River. The 199-D4-1 well (which was drilled approximately 152 m (500 ft) inland from the highest concentrations measured in the river substrate pore water) helped identify groundwater as the source of the hexavalent chromium in the Columbia River substrate pore water (Connelly 1997a). Additional characterization activities, including four new wells installed during the summer of 1997 (Weeks 1997; Connelly 1997b) and 12 new wells installed in 1999 (Lee 1999), have continued to help define the areal extent and the source of this groundwater plume.

The *Proposed Plan for Interim Remedial Measure at the 100-HR-3 Operable Unit* (DOE 1995) identified the preferred alternative for an interim remedial measure at the 100-HR-3 Operable Unit. The preferred alternative is to pump contaminated groundwater from the 100-HR-3 Operable Unit, treat it by ion exchange, and then dispose of it using upgradient injection wells to return it to the aquifer. The 100-D Area chromate "Hot Spot" near well D4-1 had not been identified at the time the interim remedial measure for the 100-HR-3 operable unit was prepared and was therefore not considered. The proposed plan also considered the possibility that alternative technologies could immobilize hexavalent chromium in the aquifer without pumping and treating. One of those technologies, ISRM, would immobilize hexavalent chromium by changing the soil and water chemistry in the aquifer and reducing the chromium to the less toxic and less mobile trivalent form. The ISRM technology promises to 1) prevent movement of hexavalent chromium to sensitive ecological receptors without creating the secondary waste associated with surface treatment technologies and 2) reduce the need for long-term operation and maintenance required of pump-and-treat technologies. Thus ISRM could result in substantial cost savings over the pump-and-treat methods of groundwater plume remediation.

Based on the results of this ISRM treatability study and a cost analysis, a proposal was submitted and funded by the Accelerated Site Technology Deployment Initiative (ASTD) to expand the length of the 100-D Area ISRM barrier to treat a larger portion of the plume (Tortoso et al. 1998). This joint EM-40 and EM-50 project will expand the length of the 100-D Area ISRM barrier up to 2,300 ft parallel to the Columbia River. This action required modifications to the existing Record of Decision (ROD) (DOE 1995), resulting in a new plan, "*Proposed Plan for an Amendment of the Interim Remedial Action at the 100-HR-3 Operable Unit*" (DOE 1999; EPA 1999). A report describing the objectives, design, and sampling and analysis plan for this expansion was also prepared (DOE 2000).

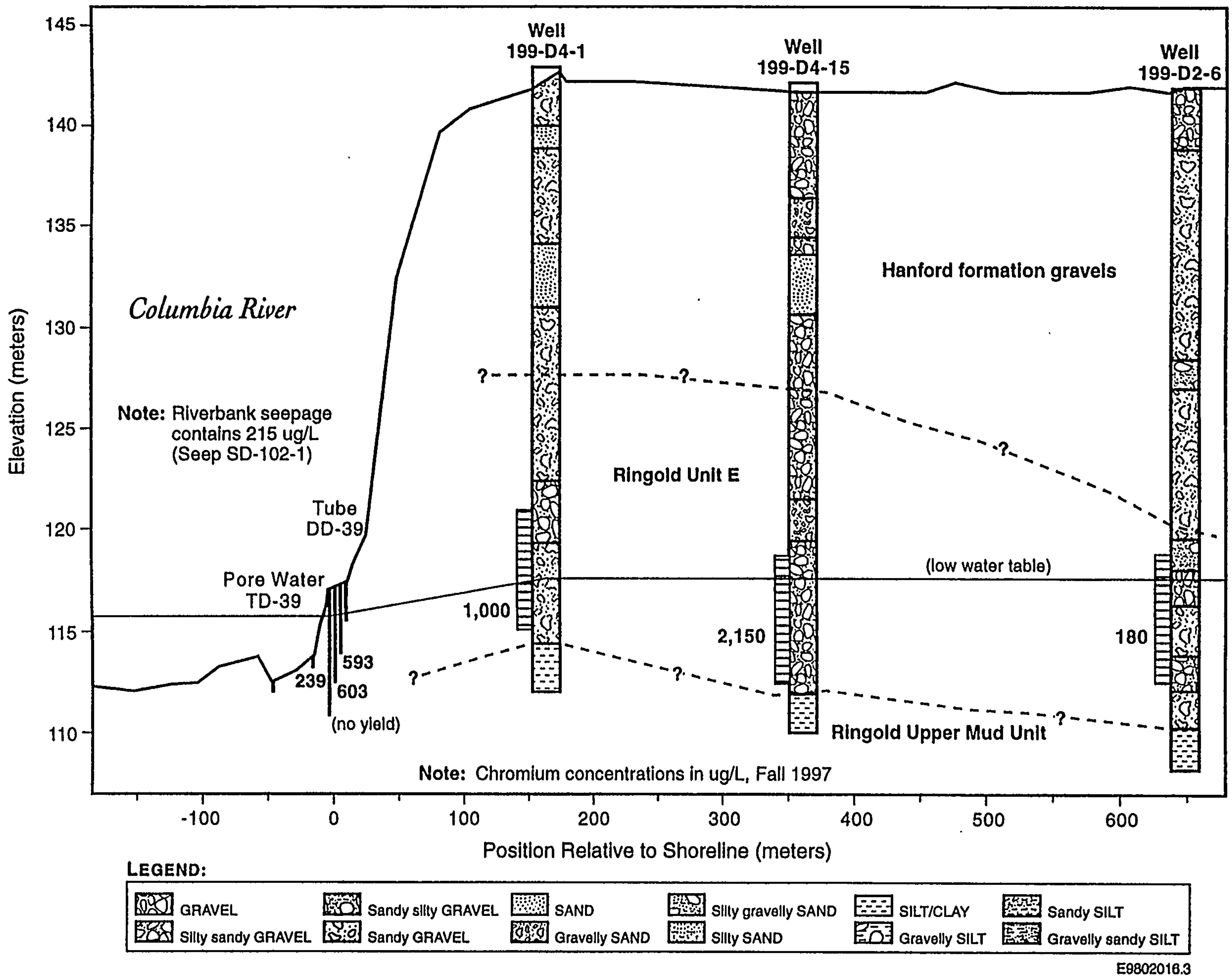

Figure 1.3. Geologic Cross-Section and Hexavalent Chromium Concentrations on the West Side of 100-D Area (Peterson et al. 1998). The ISRM Treatability Test Site is at Well 199-D4-1.

1.2 Technology Description

The In Situ Redox Manipulation (ISRM) technology involves creating a permeable subsurface treatment zone to reduce mobile chromate in groundwater to an insoluble form. An unconfined aquifer is usually an oxidizing environment; therefore, most of the contaminants that are mobile in the aquifer are mobile under oxidizing conditions. If the redox potential of the aquifer can be made reducing, a variety of contaminants could be treated (Figure 1.4a). Redox-sensitive contaminants migrating through this treatment zone would be destroyed (organic solvents) or immobilized (metals). A successful ISRM proof-of principle experiment conducted in the 100-H Area in 1995 (Fruchter et al. 1996, 2000) demonstrated the ability to alter the redox potential of the unconfined aquifer at the Hanford Site and to remove chromate from the groundwater.

The ISRM permeable treatment zone is created by reducing the ferric iron, Fe(III), to ferrous iron, Fe(II), within the aquifer sediments (see Figure 1.4b). This is accomplished by injecting sodium dithionite ($Na_2S_2O_4$) into the aquifer and withdrawing unreacted reagent and reaction products. The sodium dithionite serves as a reducing agent for iron, changing ferric iron to ferrous iron within unconfined aquifer sediments. Using standard wells to create the treatment zone allows treatment of contaminants too deep for conventional trench-and-fill technologies. Sodium dithionite is a strong reducing agent that has a number of desirable characteristics for this type of application, including instability in the natural environment (~days), with reaction and degradation products that ultimately oxidize to sulfate. Potassium carbonate/bicarbonate is added to the injection solution as a pH buffer to enhance the stability of dithionite during the reduction of available iron. Unreacted reagent and reaction products are pumped out of the aquifer through the same well used for injection, starting about two days after injection.

Chromate (CrO_4^{2-}), which is anionic in nature and soluble in groundwater, contains hexavalent chromium, Cr(VI). The altered subsurface environment containing the reduced iron, Fe(II), will act upon the Cr(VI) species, reducing it to Cr(III), which will then precipitate from the groundwater as $Cr(OH)_3$, which is immobile. Thus, hexavalent chromium is reduced to a less toxic form, trivalent chromium, and immobilized (see Figure 1.4b).

An ISRM permeable treatment zone is emplaced perpendicular to the groundwater flow to intercept the contaminant plume, as shown in Figure 1.5. This geometry is created by a series of overlapping injection/withdrawal wells. The design of the injection/ withdrawal wells for this treatability test is shown in Figure 1.6. The width of the permeable treatment zone (in the direction of groundwater flow) and groundwater velocity at the site determines the longevity of the zone, based on the treatment capacity of the sediment. The treatment capacity is a function of the amount of reducible iron in the sediment, the efficiency of the reduction by the field emplacement (dithionite concentrations and time), and the oxidizing potential of the groundwater (e.g., dissolved oxygen and chromate concentrations). The width of the permeable treatment zone multiplied by the pore volumes of treatment capacity of the reduced zone determines the upgradient distance of contaminated groundwater that can be treated. Other dimensions of the permeable treatment zone (i.e., length and depth) are determined by the extent of contamination requiring treatment.

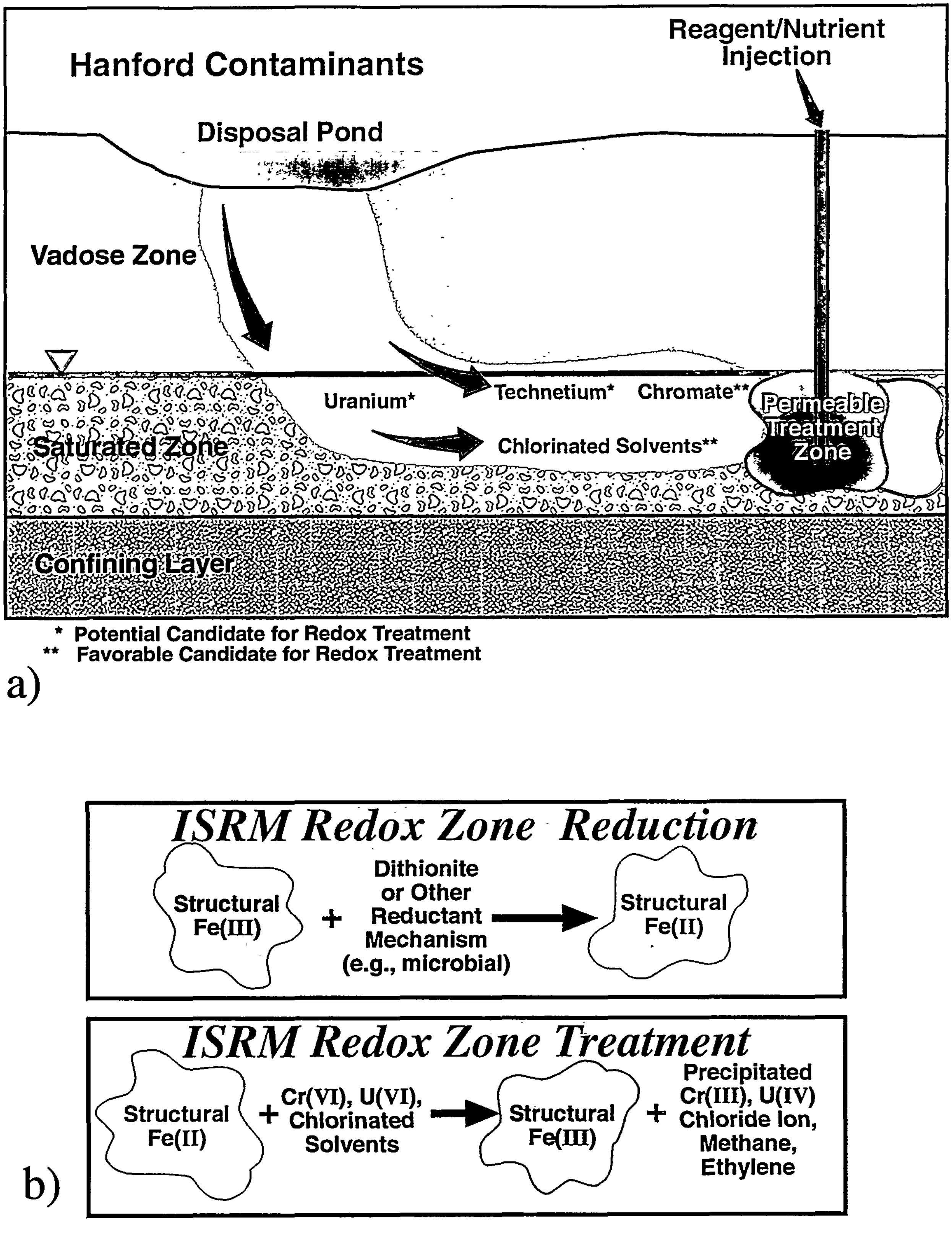

Figure 1.4. In Situ Redox Manipulation Concept

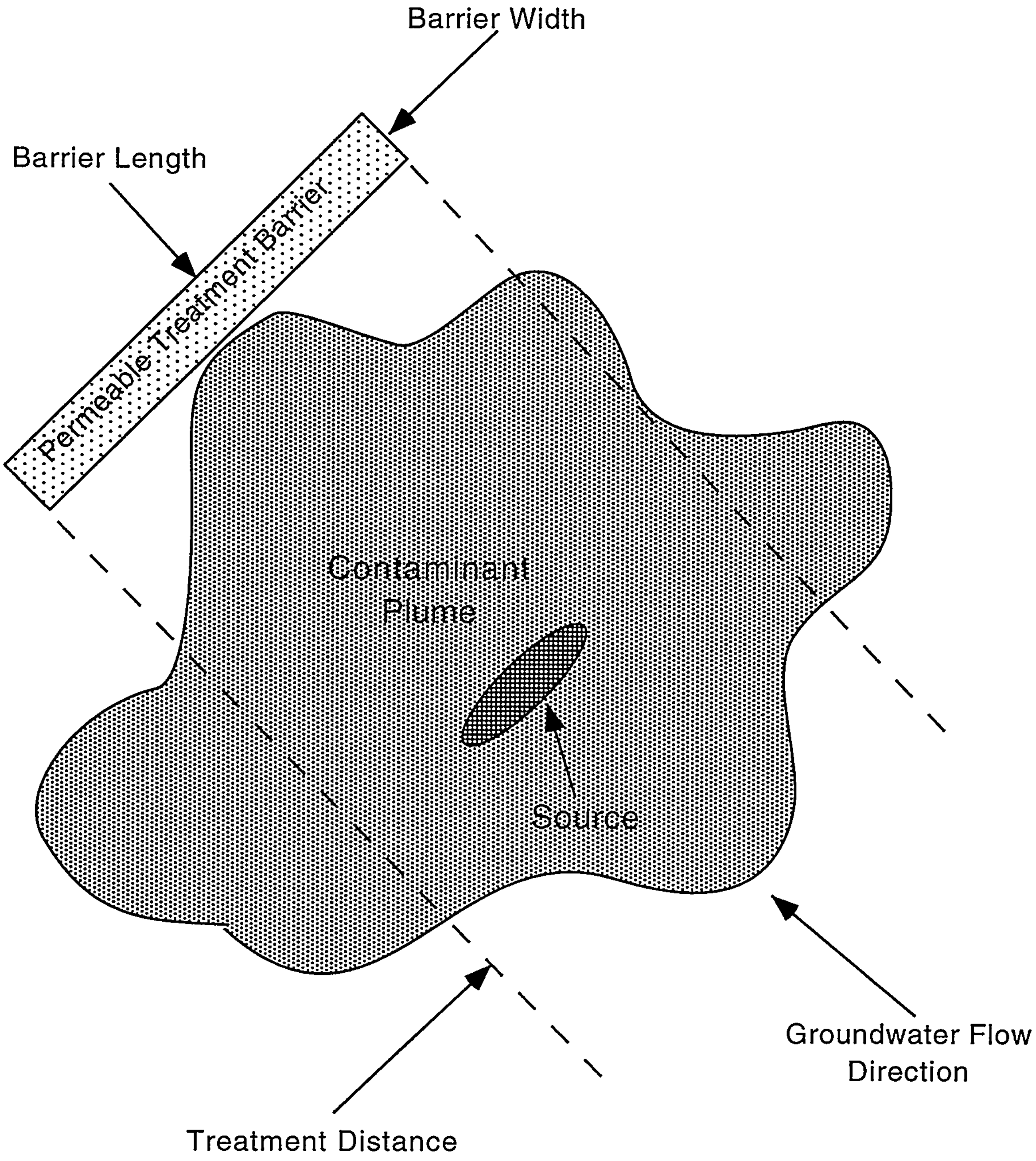

Figure 1.5. Conceptual Diagram of In Situ Redox Manipulation Permeable Treatment Barrier

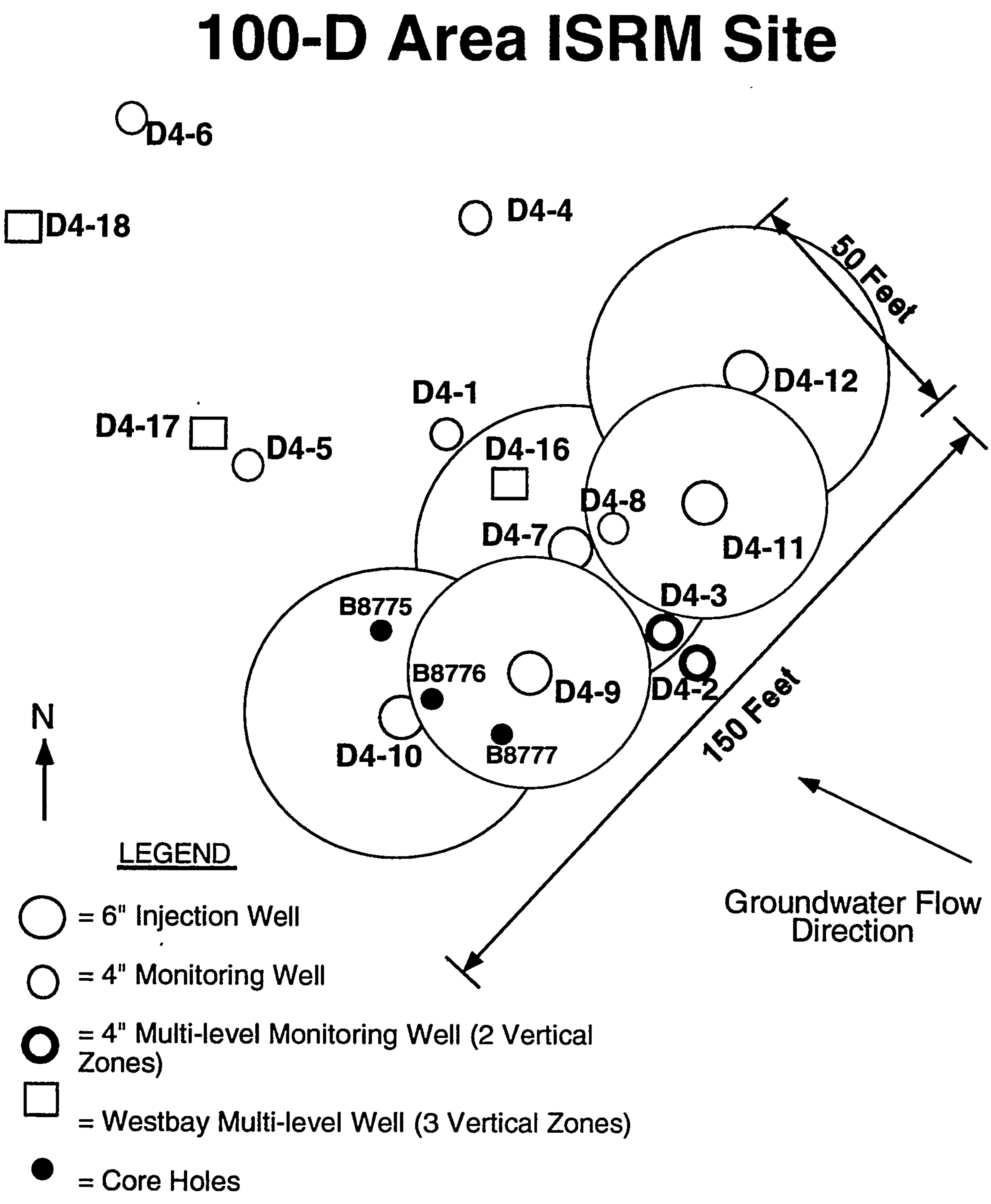

Figure 1.6. Emplacement Strategy and Well Diagram for the 100-D Area In Situ Redox Manipulation Treatability Test

An independent cost analysis was conducted to compare a hypothetical small-scale ISRM system with a pump-and-treat operation over 10 years of operation (Cummings 1997). This study concluded that the ISRM system resulted in an overall cost savings of 62% for this period. A longer-term remediation would result in further savings for the ISRM system over pump and treat because, once installed, operation and maintenance costs for the ISRM system would be reduced to costs associated with compliance monitoring and reporting.

Additional studies and reports as part of this treatability test, in response to comments from the ASME Peer Review conducted in February, 1997, are as follows:

- *Evaluation of Fall Chinook Salmon Spawning Adjacent to the In-Situ Redox Manipulation Treatability Test Site, Hanford Site, Washington* (Mueller and Geist 1998)
- *Uranium Mobility During In Situ Redox Manipulation of the 100 Areas of the Hanford Site* (Szecsody et al. 1998)
- *Anoxic Plume Attenuation in a Fluctuating Water Table System: Impact of 100-D Area In Situ Redox Manipulation on Downgradient Dissolved Oxygen Concentrations* (Williams et al. 1999b; Williams and Oostrom 2000).

1.3 Organization of the Report

A description of the 100-D Area ISRM Treatability Test site setup and site characterization results are presented in Sections 2 and 3. Details on the ISRM geochemistry and the results of bench-scale testing on sediments collected from the site during initial well installation are provided in Section 4. Section 5 describes the emplacement process used for the installation of the ISRM permeable treatment zone, and results and an assessment of the performance of the treatability test are discussed in Section 6. A summary of the treatability test is provided in Section 7, and references cited in the text are listed in Section 8. Supporting documentation can be found in the appendixes.

2.0 Site Setup

The location of the 100-D Area ISRM treatability test site is shown in Figure 2.1. This figure also shows the wells and Columbia River substrate pore water sampling tubes (northwest of the site along the river shoreline) used for emplacement and performance monitoring of the test. An expanded view of the wells at the site, based on survey data, is shown in Figure 2.2. Figure 2.3 shows a composite photograph of the ISRM site with the wells, field trailers, mixing and storage tanks, and analytical equipment. The setup, facilities, and equipment for the test are described in the sections that follow.

2.1 Wells

As shown in Figure 1.6, four types of wells were installed at the 100-D Area ISRM site as part of the treatability test: injection/withdrawal wells, monitoring wells, multilevel monitoring wells, and Westbay monitoring wells. All of these wells were installed using the reverse air rotary method (ODEX). Completion summaries for these wells are listed in Appendix A. A description of the different types of wells used in the treatability study is provided below.

The five injection/withdrawal wells installed at the site (D4-7, D4-9, D4-10, D4-11, and D4-12) were used for the ISRM permeable barrier emplacement and groundwater monitoring. The injection/ withdrawal wells consist of 6-in.-diameter schedule 40 PVC with 20-slot continuous wire wrap screens. These wells are screened across the average saturated thickness of the aquifer (15 ft). They are spaced 28 ft apart with a primary row of three injection/withdrawal wells (D4-10, D4-7, and D4-12) spaced 50 ft apart and a row of two overlapping injection/withdrawal wells (D4-9 and D4-11) to fill the interstices. The overlapping wells were also used for monitoring during the injection/withdrawal operations in the primary wells.

The four standard monitoring wells (D4-4, D4-5, D4-6, and D4-8) installed at the site were used for baseline and performance monitoring of the permeable treatment zone. One well, D4-8, was also used to help determine dithionite concentrations at various distances during emplacement. Monitoring wells were constructed of 4-in.-diameter schedule 40 PVC with 20-slot continuous wire wrap screens. Screen lengths of 20 ft were used for these wells to match the sampling interval of surrounding monitoring wells used for the Hanford Sitewide Groundwater Monitoring Program. Except for D4-8, these wells are located downgradient from the permeable treatment zone to determine the extent of the treatment zone's effectiveness and to assess effects of the technology on groundwater quality (e.g., chromate, dissolved oxygen, and trace metals).

In addition to the standard monitoring wells, two multilevel monitoring wells (D4-2 and D4-3) were installed on the upgradient side of the permeable treatment zone. Each of these wells has two 4.5-ft screen intervals at the top and bottom of the aquifer separated by a 5-ft section of casing and an inflatable packer. The purpose of these wells was to identify vertical differences in chromate concentrations at the site, determine vertical hydraulic conductivity and anisotropy, and monitor tracer/dithionite concentrations during injection/withdrawal tests to determine arrival times between the upper and lower portions of the aquifer.

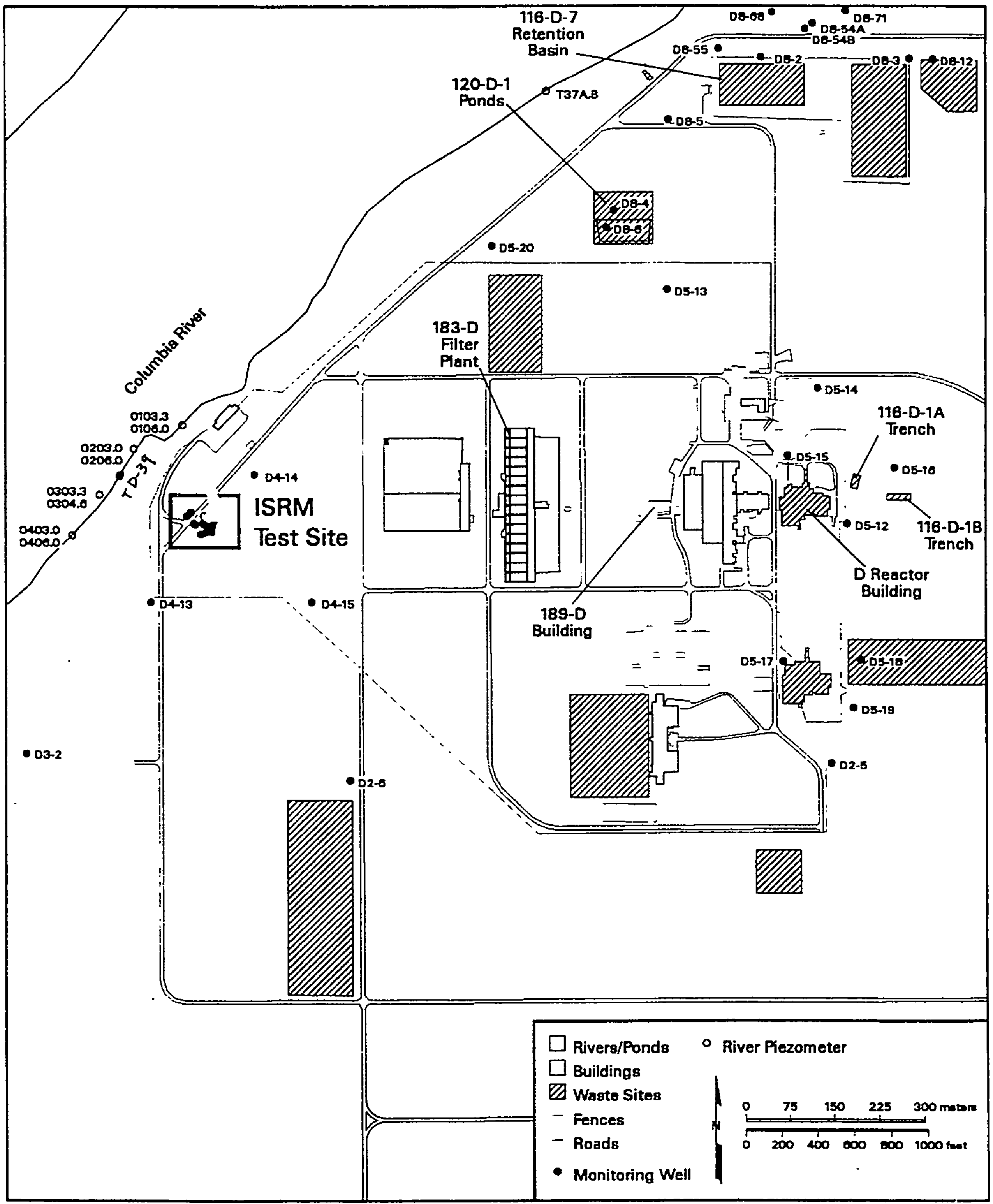

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Figure 2.1. 100-D Area Wells and ISRM Site. The Columbia River Substrate Porewater Sampling Tubes are NW of the Site (0103.3 to 0403.0)

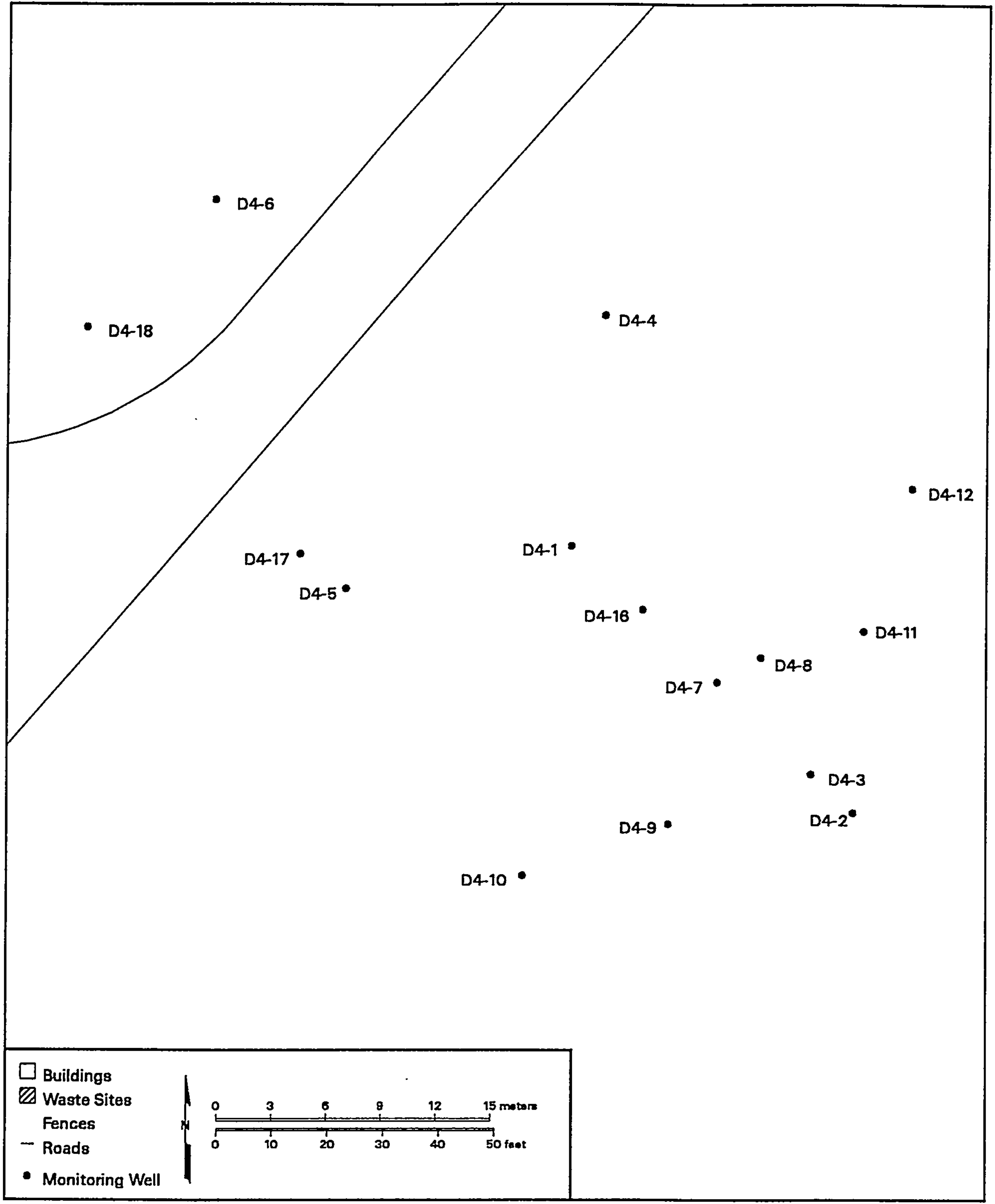

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Figure 2.2. 100-D Area ISRM Wells from Survey Locations

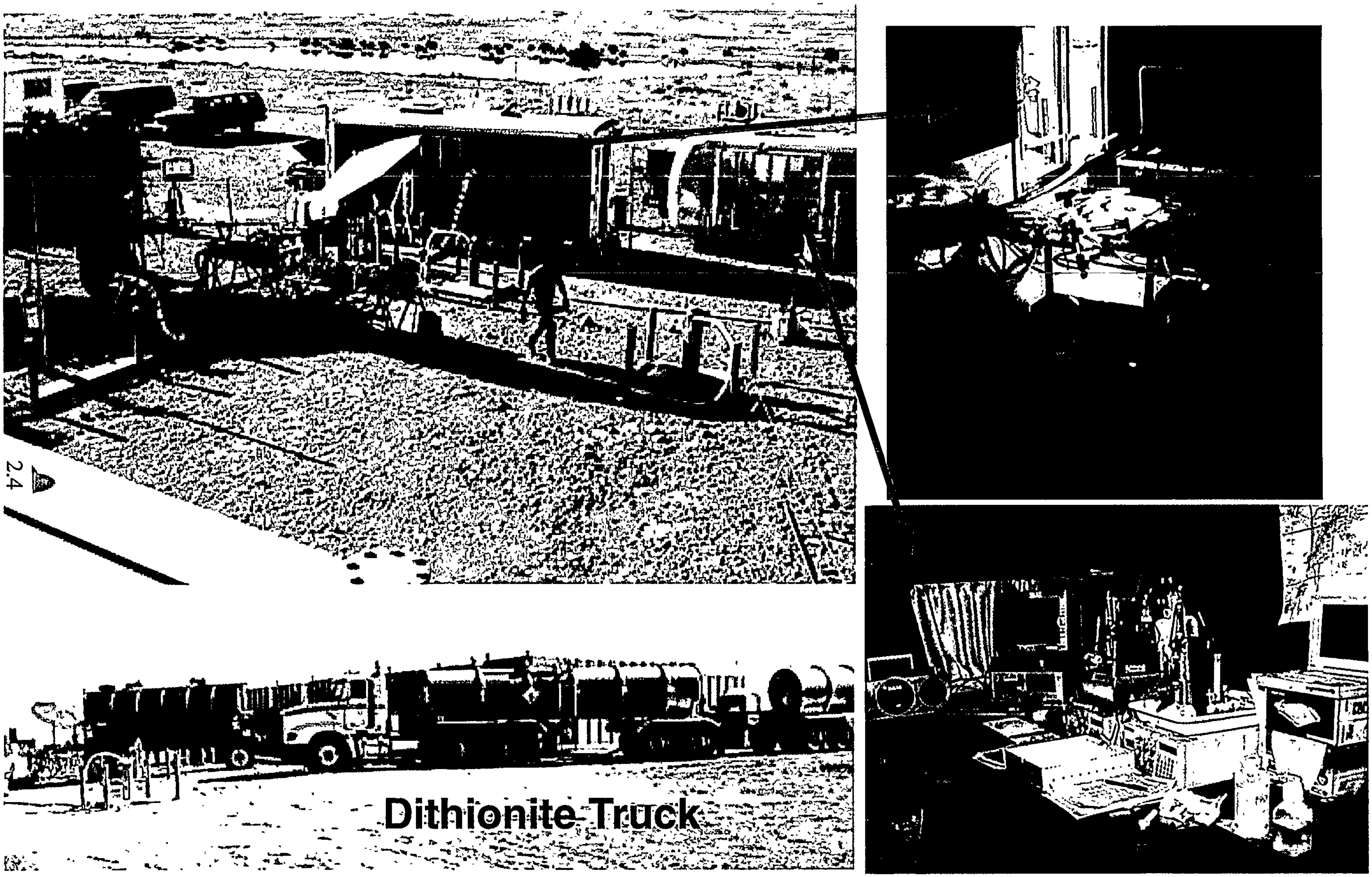


Figure 2.3. Photographs of Site Setup and Equipment at the 100-D Area In Situ Redox Treatability Test Site

The fourth type of wells installed at the site were Westbay multilevel monitoring wells (D4-16, D4-17, and D4-18). The Westbay wells provided for three discrete vertical sampling intervals. One of these wells (D4-16) is located within the treatment zone and was used for monitoring dithionite concentrations during injection/withdrawal tests. The remaining two Westbay wells are located on the downgradient side of the treatment zone to help identify vertical differences in chromate concentration and dissolved oxygen.

2.2 Columbia River Substrate Pore Water Sampling Tubes

A series of sampling tubes was installed in the substrate of the Columbia River (see Figure 2.1) to monitor the groundwater entering the river and determine any impact from the test on the water quality. Four pairs of sampling tubes were installed about 300 ft apart in the river. Each pair includes a shallow (~3-ft depth) and a deep (~6-ft depth) monitoring interval. In addition to the sampling tubes installed for the ISRM test, an existing set of multilevel sampling tubes (TD-39—located between 0203.0 and 0303.3) was monitored as part of this test. Details on the installation of these sampling tubes are described in Peterson et al. (1998).

A portable peristaltic pump was used to collect water samples from these sampling tubes. Electrical conductivity, pH, and dissolved oxygen were measured in the field using electrodes during purging of the tubes. Water samples were collected for chromate and anion analysis once the electrode values had stabilized and were recorded (purge time varied from five to 15 minutes based on length of sampler tubing).

2.3 Tanks

Ten 21,000-gallon onsite storage tanks were used to hold groundwater for dilution of concentrated tracer solutions for tracer tests and reagent for the treatment zone emplacement. The groundwater in these tanks was also used for a "fresh-water push" at the end of the injection stages for the tracer and dithionite injection/withdrawal tests (for details, see Section 3). These tanks were also used to store withdrawal water from the dithionite injection/withdrawal tests prior to disposal.

In the first dithionite injection/withdrawal test, all the withdrawn water was stored in the onsite storage tanks. Following analysis, the withdrawn water was trucked to the 200-Area Effluent Treatment Facility (ETF) for disposal. On subsequent dithionite injection/withdrawals, the first injection volume withdrawn (~40,000 gal) was stored in the onsite storage tanks and disposed of in the 200-Area purge-water modutanks. The remaining withdrawal volume from these tests (up to 160,000 gal) was purged to the ground through a 500-ft-long drip irrigation system (2-gph emitters spaced 1 ft apart) to the west of the ISRM site, upgradient of Well D4-13 (see Figure 2.1 for well location). The irrigation system was designed for a 15-gpm application rate.

A 4,000-gallon mixing tank was also used at the site for preparing the bromide tracer solution for the tracer test and for storing the concentrated dithionite solution prior to injection during the first two injection/withdrawal tests. On subsequent injection/ withdrawal tests, the dithionite injection pump was connected directly to the tanker truck, which stayed at the site for the duration of the injection (~10 hours).

2.4 Injection and Withdrawal Pumps

Two pumps were used for the bromide tracer and dithionite injection/withdrawal tests. A 0.75-hp stainless steel Grundfos centrifugal pump was used to inject the concentrated solution, and a 3-hp Monarch centrifugal pump (standard irrigation pump) was used to pump groundwater stored in the onsite storage tanks for dilution. Mixing and dilution occurred within the injection line. Iomega turbine flow meters were installed to measure flow from each pump. These flow meters were continually logged with a Campbell Scientific CR10 datalogger that also permitted real-time monitoring for adjusting flow rates during the injections to obtain the desired concentrations. This mixing strategy also permitted time-varying concentrations during the dithionite injection that were used in later tests.

For the withdrawal, a 1.5-hp Grundfos submersible pump was used in the injection/withdrawal well. The manifold for the outflow from the withdrawal pump also was connected to 50-micron filters prior to discharging the water to the storage tanks or to the irrigation system for purging to the ground.

2.5 Water Levels

Water levels were measured using a high-accuracy, National Institute of Standards and Technology (NIST) traceable, non-stretch, metal-taped water-level meter marked in 0.01-ft gradations. Pressure transducers (10 and 20 psi, 0.1% of full-scale accuracy) were installed in most of the wells to monitor pressure response during hydraulic and dithionite/tracer injection tests and for measuring the response of the water table to changes in the Columbia River stage. Transducer readings were logged continuously and validated periodically with water level measurements during all phases of testing to check for transducer drift.

Water level measurements for gradient determination were collected over as short a time period as possible. Initial measurements were rechecked throughout the measurement period to quantify any water level changes due to external stress (e.g., river stage fluctuation, barometric pressure change).

2.6 Groundwater Sampling and Analysis

Dedicated Grundfos Rediflo2 sampling pumps were installed in most of the wells at the site (the exceptions were D4-6, which is across a road from the site, and the Westbay wells). The sample tubing from these pumps were connected directly to a sampling manifold located inside the mobile laboratory. Individual pumps could be selected and sampled from within the field trailer.

The main method for groundwater sample collection and measurement of the field parameters (pH, temperature, electrical conductivity, and dissolved oxygen) was through the sampling manifold in the mobile laboratory. A series of flow-through probes was connected to the discharge line of the sampling manifold. Purge times were determined by calculating well bore volumes and when the readings from the flow-through probes stabilized. Flowrates were approximately 2 gpm during sampling, with sample times varying from three to five minutes. In addition to field measurements, archive samples are collected for analysis of hexavalent chromium anions, major anions, trace metals, and dithionite. Groundwater samples were collected for trace metal analysis, filtered (0.45 micron), and 12 mL of the filtered sample dispensed into an acid-washed vial and preserved with 2 mL of ultrapure nitric acid.

Water samples were also collected for duplicate field parameter analysis on a separate verification station. This verification station was the only method used for the samples collected from the Westbay wells due to the limited sample volume (500 mL). Initially, the probes used for the verification station were the same as those in the flow-through manifold. This was changed in May 1998, when the probes in the verification station were changed to micro-flow-through probes using a syringe pump. This permitted the sample to be collected and run directly in a 10-mL disposable syringe, eliminating contact between the sample and atmospheric oxygen.

Hexavalent chromium concentrations were measured in the mobile field laboratory at the site using a Hach DR-2000 spectrophotometer and Accuvac Chromaver 3 ampules. The detection limit of this method is 0.007 mg/L, and the method is EPA approved. Samples were filtered using a 0.45-micron filter prior to hexavalent chromium analysis.

Dithionite measurements were also made in the field trailer during the dithionite injection/withdrawal tests. Due to the instability of dithionite and its reactivity with oxygen, these analyses must be conducted immediately following sample collection. An automated system was developed using syringe pumps for sample dilution and a high-performance liquid chromatograph (HPLC). The dilution water was sparged with ultrahigh-purity nitrogen gas to be completely free of dissolved oxygen, which could consume significant amounts of dithionite because of the high dilution factors required for this method (500 to 700 times) due to its sensitivity.

3.0 Site Characterization Results

3.1 Hydrogeologic Setting

The general hydrogeologic setting of the 100-HR-3 Operable Unit (encompassing the 100-D and 100-H Areas) is described in Lindsey and Jaeger (1993). Characterization activities of the uppermost unconfined aquifer performed while drilling the wells at the ISRM site conform to the generalized setting for the 100-D Areas and were similar to the cross-section shown in Figure 1.3. Specifically, the unconfined aquifer at the ISRM test site is within a gravel unit of the Ringold Formation. The bottom of the unconfined aquifer is composed of a Ringold mud unit (overbank deposits and paleosols). Deviations in the elevation of the confining unit bounding the bottom of the unconfined aquifer were less than two feet during the drilling of the 15 wells at the site. The unconfined aquifer thickness at the test site is 15 ft during normal stage of the Columbia River. The groundwater flow direction is roughly toward the Columbia River (NW or WNW) during normal river stage.

The ISRM site is approximately 500 ft from the Columbia River. The water table elevation and groundwater flow direction/magnitude at the site are strongly influenced by the large fluctuations in river stage. Hourly water level elevation measurements in the unconfined aquifer at the site (via automated datalogging of pressure transducers installed in the wells) respond to daily, weekly, and seasonal fluctuations in the river stage (although the amplitude is dampened). Numerical modeling of these effects were shown for the 100-D Area ISRM site in Williams et al. (1999b) and Connelly et al. (1997a) for the 100-N area (upriver from 100-D Area). In addition, the aquifer response from record flooding during the winter of 1997 increased the aquifer thickness from 15 ft to about 20 ft. Early water table measurements made at the site show the groundwater flow reversed direction by 180 degrees, flowing away from the river. Water table elevations decreased throughout the summer of 1997, dropping 5 ft by the fall. The uppermost zone of the Westbay wells (with three vertical sampling intervals, as described in Section 2.1 and Appendix A) installed at the site have dried up occasionally during daily low river stage.

3.1.1 Geology

The geology of the site, determined from well-site geologist logs, was relatively consistent across the site and similar to that shown for well D4-1 in Figure 1.3. The depth to the water table was approximately 80 ft during the initial stage of well drilling. Above the water table were sand, sandy gravel, and gravelly sand units. The Hanford/Ringold formation contact ranged from 50 to 57 ft bgs (below ground surface). The unconfined aquifer was in the Ringold Formation and is predominantly sandy gravel and silty sandy gravel. A sandy layer was also detected in most of the wells slightly above the water table. The bottom of the unconfined aquifer was bounded by a Ringold silt/clay layer 96 to 98 ft bgs. The thickness of this silt/clay unit was not determined because drilling did not extend beyond approximately 5 ft of penetration into this unit.

3.1.2 Physical Properties of Sediment Samples

Physical property analysis (porosity, bulk density, and particle size distribution by sieve analysis) was conducted on 15 split tube samples collected during drilling. Particle size ranged from 65 to 85 percent gravel, 14 to 31 percent sand, and less than 6 percent fines (silt/clay). Porosity ranged from 5 to 23 percent with a mean of 14 percent. Bulk density ranged from 2.1 to 2.4 with a mean of 2.3 g/cm^3. Analysis of the sediment samples also showed a layer of cemented mud ripup clasts in three of the wells (D4-3, D4-4, and D4-5) at a depth interval of 84 to 85 ft. Well-site geologists did not observe the ripup clast zone during drilling.

3.2 Hydraulic Testing

Pre- and post- dithionite injection hydraulic tests were conducted to obtain the baseline hydraulic properties required to design the ISRM treatability test and to determine whether the technology caused any significant changes in the formation's hydraulic properties that could alter the groundwater flow direction (e.g., a decrease in hydraulic conductivity associated with formation plugging within the treatment zone). Two constant-rate discharge tests were conducted at the ISRM treatability test site, one prior to the dithionite injections to characterize baseline conditions and one following the dithionite injection in D4-7 to assess impacts of the technology on aquifer hydraulic properties within the treatment zone; the assessment incorporated the analysis of test response data from the injection well and seven surrounding observation wells. A discussion of test results and analysis plots is contained in Appendix B.

Analysis of stress and observation well response data from the pre-injection constant-rate discharge test (baseline conditions) indicates, on average, a hydraulic conductivity of 54 ft/day, vertical anisotropy of 0.01, and storativity of 0.004. Composite analysis suggests that horizontal anisotropic conditions likely exist in the aquifer, and analysis of multilevel observation well response data indicates the presence of a vertically heterogeneous or multilayered system. Both of these findings are consistent with tracer arrival data from the tracer injection test that indicates preferential flow paths between some of the monitoring wells and significantly larger groundwater velocities in the upper part of the aquifer than in the lower part.

A comparison of pre- and post-injection hydraulic test data did indicate a near-well decrease in permeability at the injection/withdrawal well following the injection. This small zone of reduced permeability (i.e., skin effect) may be attributed to entrapment of suspended or colloidal material (or mineralization associated with the carbonate buffer) in the well screen or sandpack zone immediately outside the well screen during the withdrawal phase. The extent and severity of this skin effect cannot be determined uniquely by comparing pre- and post-injection test responses, but it is most likely limited to the region of the screen/sandpack/formation interface. This near-well reduction in permeability caused no adverse effects during the injection or withdrawal phases of the treatability test and is not expected to result in any significant degradation in the overall hydraulic performance of the treatment zone.

3.3 Groundwater Flow Direction

Since field activities at the ISRM treatability test site were initiated in the fall of 1997, water levels in site monitoring wells have been monitored routinely to determine the hydraulic gradient, groundwater flow direction, and the variability in these parameters over the time scale of the treatability test. Water level measurements, along with horizontal and vertical survey data for each well site location, were used to estimate the local gradient and flow direction.

The estimated groundwater flow velocities shown in Figure 3.1 are based on measured hydraulic gradients, an average hydraulic conductivity of 54 ft/day obtained from hydraulic tests using site monitoring wells, and an average sediment porosity of 0.14 obtained by analyzing sediment core samples collected during installation of monitoring wells. As indicated, groundwater typically flows to the west-northwest at approximately 1 ft/day. The deviation from this typical flow direction during the first two monitoring events (8/21/97 and 9/8/97) is most likely associated with recovery from historically high Columbia River flows during the spring and summer of 1997. Water levels in the wells dropped approximately 5 ft from the time of well installation (spring/summer of 1997) to the fall of 1997, resulting in a change of aquifer thickness from 20 to 15 ft.

3.4 Chinook Salmon Survey

Previous salmon surveys based on air-photo analysis indicated there were no fall Chinook salmon redds in the river in a downgradient direction (NW or WNW) of the ISRM site (Hope and Peterson 1996; Luttrell et al. 1995). Hope and Peterson (1996) concluded, based on river substrate characterization conducted along the 100-D and 100-H sections of the Columbia River by divers, that the stretch of river downgradient from the site (upstream of D Island in the vicinity of the "100-D/DR hot spot") was unsuitable for salmon spawning or egg incubation because of the substrate embeddedness.

A more detailed salmon survey was conducted as part of the treatability test of the section of river downgradient from the ISRM site (Mueller and Geist 1998). No fall Chinook salmon redds were discovered in the area during the aerial or underwater video surveys. The study also concluded that "less than 1% of the study area adjacent to the ISRM experiment would be considered suitable for fall Chinook salmon spawning" (Mueller and Geist 1998, p. 9) based on detailed measurements along 11 transects of dominant and subdominant substrate, depth, and velocity.

3.5 Baseline Aqueous Geochemistry

Groundwater samples were collected and analyzed from all the wells at the ISRM site prior to the D4-7 dithionite injection/withdrawal test (September 29, 1997) to establish the baseline aqueous geochemistry of the site. Field parameters (pH, DO, electrical conductivity, hexavalent chromium) were measured on all samples, and a complete set of analyses was run on two sampling rounds (major anions and trace metals). Baseline aqueous geochemistry results for the last

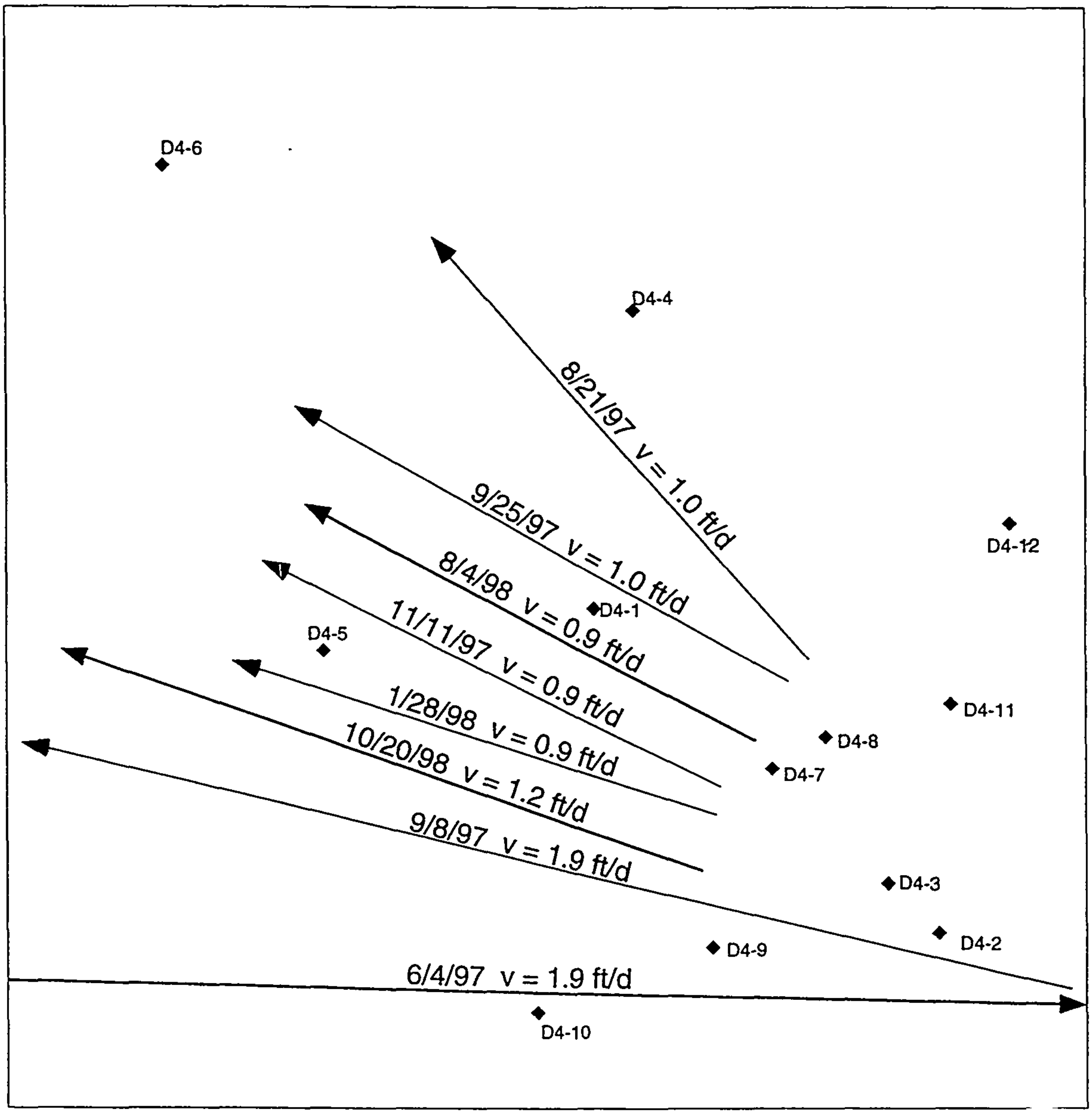


Figure 3.1. Groundwater Flow Directions and Magnitudes Measured at the 100-D Area ISRM Site

sampling (prior to the tracer test discussed in Section 3.7) are listed in Tables 3.1 and 3.2. A complete list of the results from groundwater monitoring at the site is provided in Appendixes F and G. The values for Westbay wells D4-17 and D4-18 were not included because these wells were not completed in time for the baseline sampling. Table 3.3 lists the range and average field parameters measured at the site from the latest baseline analysis. Plan view and cross-section diagrams of this baseline hexavalent chromium data are shown in Figures 3.2 and 3.3. Figure 3.4 shows a plan view diagram for baseline sampling of measured dissolved oxygen concentrations.

Table 3.1. Field Parameters and Major Anions from 9/29/97 Monitoring of ISRM Site. Sampling was conducted before the D4-7 Dithionite Injection.

	FIELD	Sampled and Analysed 9/29/97				(9/24/97)	IC					
Well-ID	**Cond**	**Cond**	**DO**	**DO**	**pH**	**Cr6+**	**F**	**Cl**	**NO3**	**PO4**	**SO4**	**Br-**
	µS/cm	Temp.	mg/L	Temp.		mg/l	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
D4-2 up	455	19.1	10.41	19.0	7.71	1.11	0.5	23.8	72.0	6.1	112.1	u
D4-2 low	534	17.7	10.77	17.7	7.82	1.15	0.6	22.0	45.4	1.9	84.9	u
D4-3 up	646	17.5	10.84	17.4	7.82	1.08						
D4-3 low	526	17.5	11.54	17.2	8.22	1.04	u	18.1	62.8	u	124.9	u
D4-7	637	18.0	11.01	18.1	7.64	1.14	u	21.9	80.4	u	141.5	u
D4-8	633	17.9	11.09	18.1	7.68	1.09	u	21.1	79.2	0.8	139.7	u
D4-9	637	17.8	10.85	17.8	7.71	1.12	u	20.1	81.6	u	139.4	u
D4-11	641	17.6	9.51	17.6	7.60	1.08	u	19.3	78.1	u	141.4	u
D4-16 (1)	704	19.1	5.18	19.1	7.44	0.59	0.7	24.8	55.1	2.1	105.3	5.4
D4-16 (2)	641	19.0	5.59	19.0	7.53	1.01	0.24	23.6	65.2	1.5	105.9	12.4
D4-16 (3)	636	18.9	2.22	18.9	7.60	0.89	0.23	24.5	40	0.7	101.4	11.7
D4-1	442	18.9	9.60	18.3	7.69	1.01	0.02	20.9	58.5	2.5	96.7	u
D4-12	592	17.8	11.01	17.8	7.69	1.12	0.7	18.3	70.2	u	133.4	u
D4-10	665	18.2	10.32	18.2	7.65	0.96	u	20.6	83.0	u	132.6	u
D4-4	622	18.3	10.03	18.4	7.59	0.74	u	17.4	73.7	u	144.1	u
D4-5	637	18.2	9.51	18.2	7.71	0.82*	0.85	24.8	65.8	0.7	96.8	8.4
D4-6	594	18.2	10.71	18.0	7.68	0.92	u	17.2	70.1	u	124.2	u
D4-17 (1)												
D4-17 (2)												
D4-17 (3)												
D4-18 (1)												
D4-18 (2)												
D4-18 (3)												

Notes: Cr6+ Data from 9/24/97 except for D4-5 which was from 9/17/97

Table 3.2. Trace Metal Analysis from 9/29/97 Monitoring of ISRM Site. Sampling was conducted prior to the D4-7 Dithionite Injection.

Well-ID	ICP/MS *Na µg/ml	*Mg µg/ml	K µg/ml	*Ca µg/ml	Al ng/ml	Cr ng/ml	Mn ng/ml	Fe ng/ml	Ni ng/ml	Cu ng/ml	Zn ng/ml	As ng/ml	Se ng/ml	Mo ng/ml	Ag ng/ml	Cd ng/ml	Sn ng/ml	Sb ng/ml	Ba ng/ml	Pb ng/ml	U ng/ml
D4-2 up	12.2	17.9	4.33	80.7	12.9	1060	0.6	261	22.1	5.9	30.0	1.2±0.4	<2	1.3±0.2	<0.4	<0.4	<0.4	<0.4	107.0	0.7	2.2
D4-2 low	7.9	14.9	3.50	69.2	22.4	1146	0.8±0.1	91±20	13±3	4.3	35.7	1.3456	<2	1.4±0.5	<0.4	<0.4	<0.4	<0.4	76.9	0.6±0.1	1.4
D4-3 up	12.4	18.2	4.78	80.3	16.8	1090	1.3±0.2	200±20	18.4	5.9	32±5	1.57569	<2	1.3±0.2	<0.4	<0.4	<0.4	<0.4	104.0	0.7±0.1	2.0
D4-3 low	9.6	13.0	3.65	66.0	19.1	1040	4.3	110±20	13.8	5.0	43.6	1.4±0.2	<2	1.6±0.2	<0.4	<0.4	<0.4	<0.4	71.5	0.6	1.3
D4-7	10.5	17.4	5.41	76.6	18.9	1060	1.2	160±20	18.1	5.8±0.6	34.0	2.17167	<2	1.8±0.2	<0.4	<0.4	0.6±0.1	<0.4	95.9	0.9	2.2±0.3
D4-8	9.4	16.7	5.99	77.6	16±3	1030	1.0	130±50	16.6	5.7	28.7	1.90073	<2	1.5±0.5	<0.4	<0.4	<0.4	<0.4	107.3	0.6	1.8
D4-9	9.8	17.5	4.74	79.7	16±3	1070	0.6	130±40	16.6	4.7	30.2	1.2±0.2	<2	1.2±0.6	<0.4	<0.4	<0.4	<0.4	101.0	0.5±0.1	1.8
D4-11	9.6	17.2	3.92	80.1	19.0	979	7.2	130±20	17±3	4.8±0.7	28.5	1.6±0.5	<2	1.3±0.2	<0.4	<0.4	0.5	<0.4	98.5	0.5±0.1	2.4
D4-16 (1)	10.3	18.1	5.60	88.0	14±3	600	36.2	141	20.6	4.8	30.5	1.2±0.6	<2	4.1±1.0	<0.4	<0.4	<0.4	<0.4	115.0	0.5±0.1	2.0
D4-16 (2)	9.7	17.2	5.80	79.0	11.9	966	2.2	98	13.4	4.8±0.6	29.1	1.2±0.5	<2	1.3±0.4	<0.4	<0.4	<0.4	<0.4	114.0	0.5±0.1	1.8
D4-16 (3)	10.7	16.9	4.93	80.9	13.8	383	263.0	100±20	15.3	5.0	36.1	1.2±0.2	<2	1.6±0.2	<0.4	<0.4	<4	<4	107.0	0.5±0.1	1.7
D4-1	8.6	16.9	4.05	78.6	12.9	997	<0.4	82	14.5	4.8	27.4	1.2±0.2	<2	1.5±0.6	<0.4	<0.4	<0.4	<0.4	97.1	0.7±0.1	1.8
D4-12	8.0	16.2	3.74	76.2	15.8	1110	4.8	120±20	16.4	4.8±0.7	28±4	2.3±0.5	3.8	1.5±0.2	<0.4	<0.4	<0.4	<0.4	71.6	0.9	1.7±0.2
D4-10	9.1	17.1	3.69	82.4	16.6	915	1.5	120±20	15.4	4.3	41.5	1.6±0.6	<2	1.3±0.4	<0.4	<0.4	<0.4	<0.4	86.9	0.7±0.2	1.8
D4-4	13.6	16.3	3.30	80.9	15.9	745	3.8	120±20	22.3	5.1	31.4	2.8±0.5	2.4±1.0	2.4±0.8	<0.4	<0.4	<0.4	<0.4	90.0	0.9±0.4	1.9
D4-5	9.9	19.0	3.82	79.8	16.8	906	3.4	230±50	21.9	6.6	40.7	1.51087	<2	1.5±0.4	<0.4	<0.4	<0.4	<0.4	104.0	0.9	1.4
D4-6	9.2	15.6	3.27	75.4	17±3	832	2.9	150±20	16.7	6.2±0.7	35.7	1.3±0.2	<2	1.5±0.5	<0.4	<0.4	1.2±0.2	<0.4	93.3	0.8	1.6
D4-17 (1)																					
D4-17 (2)																					
D4-17 (3)																					
D4-18 (1)																					
D4-18 (2)																					
D4-18 (3)																					

Table 3.3. Average Baseline Measurements at the 100-D Area ISRM Site (9-29-97)

Parameter	Units	Range	Mean
pH		7.44–8.22	7.69
Electrical Conductivity	μS/cm	442–704	602
Dissolved Oxygen	mg/L	2.22–11.54	9.42
Sulfate	mg/L	84.9–144.1	120
Hexavalent Chromium	mg/L	0.588–1.15	1.00

3.6 Baseline Columbia River Substrate Pore Water Chemistry

The Columbia River substrate pore water sampling tubes were not installed until November and December 1997 (see Figure 2.1), which was after the D4-7 dithionite injection/withdrawal test. Therefore, none of the monitoring results for these pore water samplers can be considered baseline values. Pore water monitoring data are discussed in Section 6, and a complete listing of monitoring data is contained in Appendix C.

3.7 Bromide Tracer Test

The bromide tracer test conducted on August 27, 1997 at the 100-D Area had four objectives:

- Determine volumes and rates required for the dithionite injection/withdrawal tests.
- Establish breakthrough curves and arrival times for wells at different radial distances and orientations to assess the effect of horizontal and vertical heterogeneities at the site on groundwater flow.
- Test dual-injection pump setup and operation for metering/diluting concentrated solutions.
- Test sampling equipment and establish sampling interval requirements for dithionite tests.

The tracer test consisted of the injection of 40,000 gallons of 100 mg/L Br^- (from KBr salts) into well D4-7 at 60 gallons per minute (gpm). After the tracer solution had been injected, 20,000 gallons of groundwater were injected at the same injection rate to increase the tracer's radius of influence. This groundwater injection (i.e., fresh-water push) also provided additional information on arrival times by adding a descending limb to the breakthrough curves. Approximately 30,000 gallons of groundwater were withdrawn from the aquifer one month after the test to provide dilution water for the D4-7 dithionite injection/withdrawal test.

The results of this test showed that volumes lower than the preliminary estimates could be used for the dithionite injection/withdrawal tests. The total volume of 60,000 gallons used for the tracer test was reduced to 38,000 gallons for the first dithionite injection/withdrawal test in well D4-7 (see discussion in Section 5).

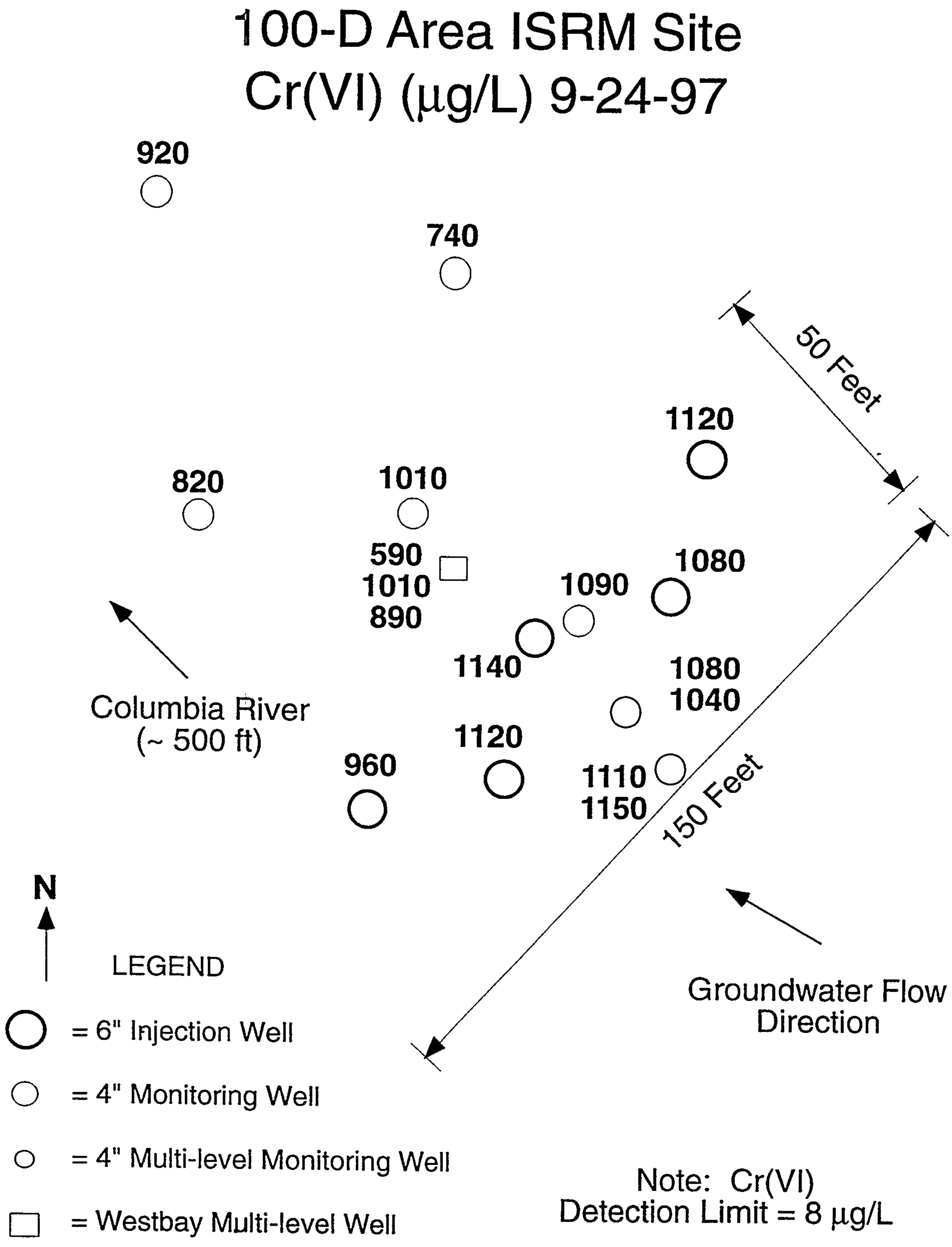


Figure 3.2. Baseline Hexavalent Chromium Concentrations at the 100-D Area ISRM Site

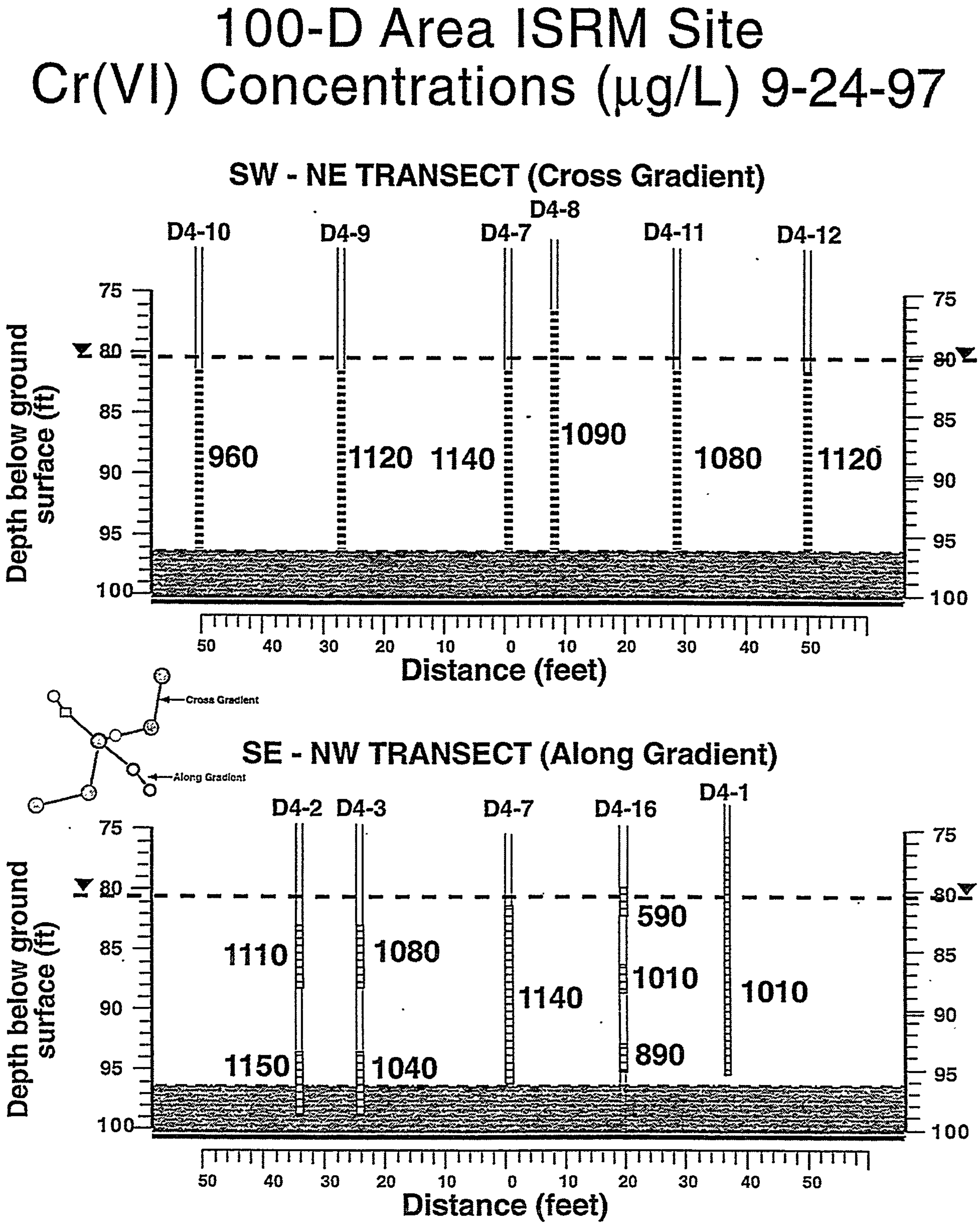


Figure 3.3. Cross-Section of Baseline Hexavalent Chromium at the 100-D Area ISRM Site

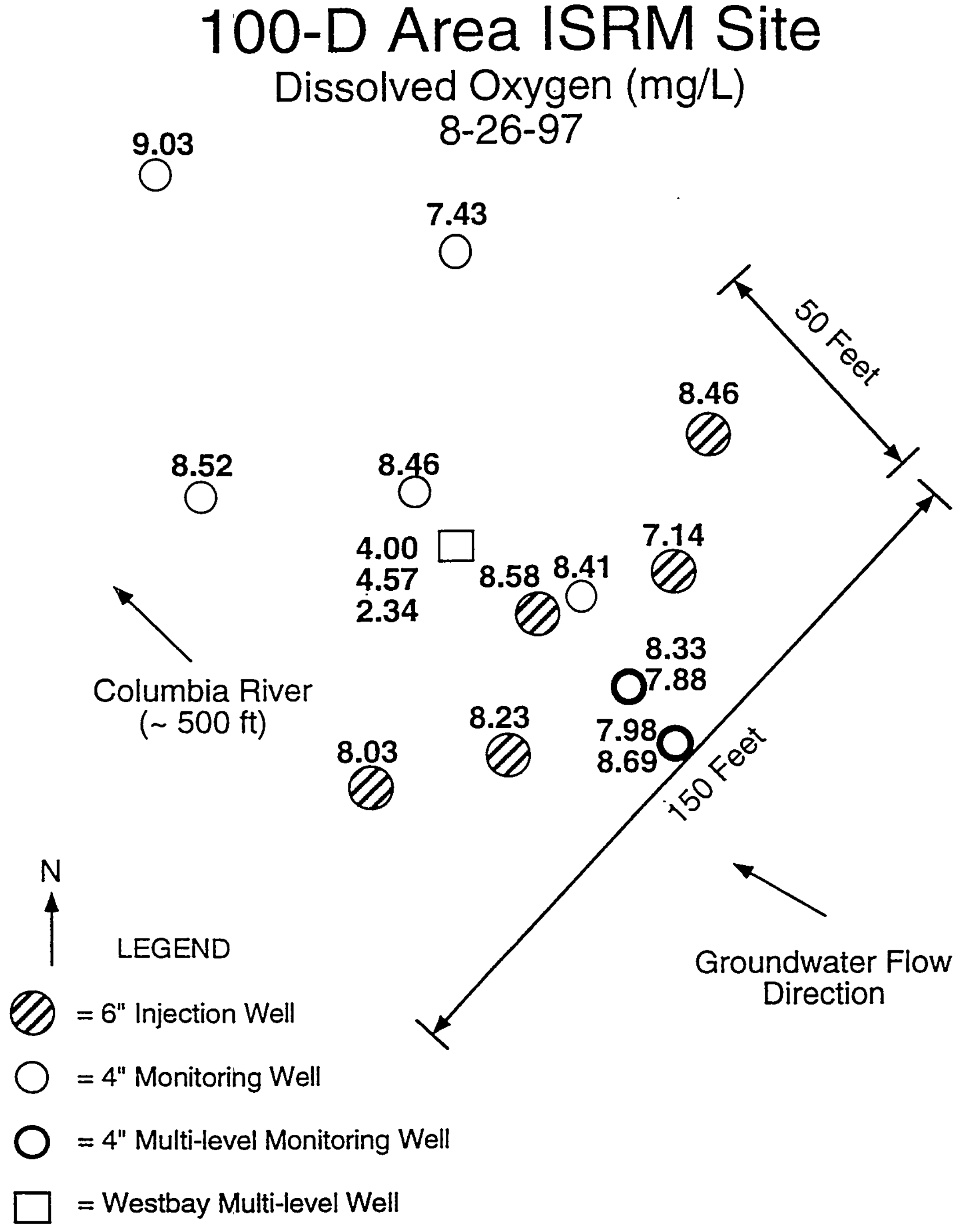


Figure 3.4. Baseline Dissolved Oxygen Concentrations at the 100-D Area ISRM Site

The tracer test showed significant differences in arrival times between the upper and lower portions of the aquifer (see summary in Table 3.4). The tracer breakthrough curves are shown in Appendix D. Arrival times in the upper portion of the aquifer, as measured in wells D4-2 upper, D4-3 upper, and D4-16 zone 1, were significantly faster than those in the lower screens of these wells. The differences are due to greater permeability and/or lower porosity of the upper portion of the aquifer. The wells that responded rapidly to the initial arrival of bromide solution also had similar drops in concentration when the injection solution was switched from the tracer solution to groundwater. The breakthrough curves for the injection/withdrawal wells adjacent to D4-7 (D4-9 and D4-11) were different, even though these wells are the same radial distance from D4-7 and are screened similarly. These data provide additional evidence of hydrogeologic heterogeneities at the site.

Table 3.4. Bromide Tracer Test: Br^- Arrival Time Summary

Well	**Screen** (ft bgs)	**Radial Distance** (ft)	**Arrival Time**		**Maximum Conc.** (%)
			50% (min)	**100%** (min)	
D4-7	81 – 96	0	0	0	100
D4-8	75.6 – 95.6	9.1	92	216	100
D4-16 (1)	80 – 82.5	20	160	414	100
D4-16 (2)	86.5 - 89	20	475	-	91
D4-16 (3)	93 – 95.5	20	435	-	91
D4-3 (u)	83.5 - 88.5	24	47	300	100
D4-3 (l)	93.5 - 98.5	24	916	-	50
D4-2 (u)	83.6 - 88.6	34.3	62	452	100
D4- 2 (l)	93.6 - 99	34.3	-	-	27
D4-9	82 - 97	28.5	86	424	100
D4-11	91.2 - 96.2	28.5	164	592	100
D4-1	74.6 - 94.7	36.3	-	-	45

4.0 Bench-Scale Studies

Bench-scale studies were conducted to characterize the aquifer sediments at the site and to quantify geochemical redox reactions that occur when dithionite is injected into these sediments. Results of these experiments were used to aid in the design of the 100-D dithionite injection/withdrawal experiments and for predicting long-term performance. The main objectives of the bench-scale laboratory studies were to determine the mass of reducible iron in the 100-D ISRM site sediments and the rate of this reduction and subsequent sediment oxidation. The sediment reduction rate controls the amount of time required for the dithionite solution to fully react with sediments, so it affects the reductant injection rate and residence time (i.e., additional time allowed for reductant to react with sediments before it is extracted from the aquifer). Column experiments were conducted in which reduced sediment was oxidized with oxygen-saturated water to provide an additional measure of 1) the mass of reduced iron and 2) the oxidation rate of the sediment. Laboratory experiments that were used to meet these objectives included 1) sediment reduction in batch (static) systems, 2) sediment reduction in 1-D columns, and 3) sediment oxidation in 1-D columns. Multiple reaction modeling of the static systems and reactive transport modeling of the dynamic systems was conducted to quantify the reactant masses and reaction rates.

A secondary objective of the bench-scale studies was to develop an understanding of the changes that occur in iron phases during reduction and oxidation. This information is used to predict how efficiently the sediment can be re-reduced and whether the mobility of iron or other metals becomes an important issue during the redox life cycle. Experimental techniques used to meet these objectives included chemical analysis of iron mineral and amorphous phases in untreated, reduced, and reduced/oxidized sediment and chemical analysis of liquid effluent for metals during reduction and oxidation column experiments.

4.1 Iron Geochemistry During Reduction and Oxidation

The ISRM remediation technology used in this study introduces a reductant (sodium dithionite buffered at high pH) into the contaminated sediment for a short time (typically 24 to 60 hours) to reduce Fe(III) oxides to aqueous or surface-bound Fe(II). The reduced Fe(II) appears to be present in several different phases: adsorbed Fe(II) (dominant phase), structural Fe(II), and Fe(II)-carbonate (siderite). The reaction that theoretically describes a single phase of iron that is reduced by sodium dithionite,

$$S_2O_4^{-2} \ + \ 2\equiv Fe^{3+} \ + \ 2H_2O <==> 2\equiv Fe^{2+} + 2(SO_3^{-2}) + 4H^+ \qquad (1)$$

indicates that the forward rate is a function of the dithionite concentration and the square of the reducible iron concentration. Experimental evidence indicates that: a) more than one type of site can fit the batch and column experimental data better than a single kinetic step, and b) a small fraction of the reducible iron sites were also affected by diffusion (i.e., slow physical access to surface sites). Because adsorbed Fe(II) is the dominant form of reduced iron, it is likely more easily reduced and oxidized. A small fraction of surface sites are reduced and oxidized more slowly and may be siderite or structurally reduced iron in oxides or clays, as described by

$$S_2O_4^{-2} + 2 \equiv Fe^{3+} + 2H_2O \Longleftrightarrow 2 \equiv Fe^{2+} + 2(SO_3^{-2}) + 4H^+ \qquad (2)$$

where the total number of oxidized or reduced iron sites is the sum of sites in reactions 1 and 2. In cases where the mass of iron is far in excess of the dithionite, this can be reduced to a first-order reaction that assumes that Fe^{3+} remains constant:

$$S_2O_4^{-2} \Longleftrightarrow 2Fe^{2+} + SO_3^{-2} \qquad (3)$$

Another reaction occurs in the system that describes the disproportionation of dithionite in contact with sediment:

$$2S_2O_4^{-2} + H_2O \Longleftrightarrow S_2O_3^{-2} + 2(HSO_3^-) \qquad (4)$$

that accounts for the mass loss of dithionite that cannot be used for iron reduction. Other studies have shown that this reaction has a half-life of ~27 h (basaltic sediments). The consequence of this reaction is to limit how slowly dithionite can be reacted with (i.e., injected into) sediment in the field. If dithionite is injected too slowly, a significant amount of its mass is lost to disproportionation.

The oxidation of the adsorbed and structural Fe(II) in the sediments of the permeable redox barrier occurs naturally by the inflow of dissolved oxygen through the barrier but can also be oxidized by contaminants that may be present, such as chromate. The theoretical oxidation of reduced iron in pure mineral phases is relatively well described with the following reactions. Fe(II) species that are known to exist in the dithionite-reduced Hanford 100-D sediments include adsorbed Fe(II) and siderite [$Fe(II)CO_3$]. Theoretically, a single mole of electrons is consumed as a mole of these species is oxidized:

$$Fe^{2+} \Longleftrightarrow Fe^{3+} + e^- \qquad Eh = -0.77\ v \qquad (5)$$

$$Fe^{2+} + 3H_2O \Longleftrightarrow Fe(OH)_3(s) + 3H^+ + e^- \qquad Eh = -0.56\ v \qquad (6)$$

$$FeCO_3(s) + 3H_2O \Longleftrightarrow Fe(OH)_3(s) + 2H^+ + HCO_3^- + e^- \qquad (7)$$

The use of dissolved oxygen as an oxidant is generally divided into two electron sequences, which, combined as

$$O_2 + 4H^+ + 4e^- \Longleftrightarrow H_2O \qquad Eh = 1.23\ v \qquad (8)$$

indicate 4 moles of electrons are available per mole of O_2 consumed. The rate of this reaction (8) has generally been observed to be first order. Experimental evidence indicates that the oxygenation of Fe(II) in solutions (pH >5) is generally found to be first order with respect to Fe(II) and O_2 concentration and second order with respect to OH^-. Therefore, approximately four moles of Fe(II) are oxidized per mole of O_2 consumed (reactions 8–10), and the rate increases 10-fold for a unit increase in pH. At oxygen-saturated conditions (8.4 mg L^{-1} O_2, 1 atm, 25°C), 1.05 mmol L^{-1} Fe(II) is consumed.

The oxidation of reduced iron in the natural sediment appears to be more complex than a single oxidation reaction and is likely controlled by both chemical and physical processes. The combination of reactions 5 and 8 yields

$$4Fe^{2+} + O_2 + 4H^+ \Leftrightarrow 4\,Fe^{3+} + 2H_2O \qquad Eh = -1.85\text{ v} \tag{9}$$

which describes the oxidation of the main reduced iron species that appears to be present in the reduced sediments [adsorbed Fe(II)]. The rate of oxidation of Fe^{II} in solution by oxygen at pH 8 is a few minutes (Eary and Rai 1988; Buerge and Hug 1997). In contrast, the oxidation rate (as a half-life) observed in natural sediments [surface Fe(II) thought to be adsorbed Fe(II) and $Fe(II)CO_3$] was found to be 0.3 to 1.1 hours. Because experiments indicate that a second type of reduced iron species is present (likely siderite) in minor concentrations, a second oxidation reaction,

$$4FeCO_3(s) + O_2 + 4H^+ \Leftrightarrow 4Fe^{3+} + 2\,H_2O + 4\,CO_3^{2-} \tag{10}$$

was considered in reaction models used. Both of these reactions (9 and 10) show that four moles of Fe(II) is consumed per mole of oxygen consumed..

When chromate contamination is present in the groundwater, Cr(VI) is reduced to Cr(III) by Fe(II) oxidation. In general, contaminants such as chromate and TCE are present in such low concentrations that iron oxidation (i.e., remediation barrier destruction) is dominated by dissolved oxygen in water. However, if chromate or TCE are present at high concentrations, their impact on iron oxidation needs to be considered. For chromate:

$$HCrO_4^- + 7H^+ + 3e^- \Longleftrightarrow Cr^{3+} + 4H_2O \tag{11}$$

Three moles of electrons are consumed per mole of chromate reduced. The reduction of one mole of chromate oxidizes three moles of Fe(II) [reactions 5 and 11], or 41 mg L^{-1} chromate is needed to oxidize the equivalent mass of Fe(II) as water saturated with dissolved oxygen [1.05 mmol L^{-1} Fe(II)]. Because the highest chromate concentration found at the Hanford 100-D Area unconfined aquifer is 2 mg/L, its influence on iron oxidation is not significant.

4.2 Batch and Column Experimental Methods

A series of batch and column experiments was conducted to determine the mass and rate of reduction of iron in sediment by the reduction solution (sodium dithionite pH-buffered to 11.0). Batch sediment reduction experiments consisted of a series of septa-top vials in which 6.0 g of sediment was mixed with 10 mL of dithionite solution for a specified time (minutes to tens of hours), then the solution filtered and analyzed for dithionite remaining in solution. The dithionite solution contained 0.06 mol L^{-1} sodium dithionite ($Na_2S_2O_4$), 0.24 mol L^{-1} K_2CO_3, and 0.024 mol L^{-1} $KHCO_3$. These batch experiments were conducted in an anaerobic chamber to prevent the dithionite from reacting with oxygen. The dithionite concentration was measured by UV absorption at 315 nm. Two reactions were studied, the reduction of iron in the sediment, which has a half-life of about five hours, and a disproportionation reaction, which has a half-life of 27 hours. Based on the rate of these reactions, batch reduction experiments were completed within 60 hours. Column reduction experiments consisted of injecting the dithionite solution at a steady rate into a sediment column and measuring the concentration of dithionite over time in the effluent for 48 to 120 hours. The flux rate was chosen to achieve specific residence times of the dithionite solution in the column (2 to 14 hours) relative to the reaction rates. The dithionite concentration in the effluent was measured once per hour using an automated fluid system and data logging equipment.

Sediment oxidation studies were also conducted in 1-D columns to determine the rate at which the dithionite-reduced sediments are oxidized and to provide an additional measure of the mass of reduced iron. This method was considered the most accurate measurement of the reduced iron mass in the dithionite-treated field sediment. These experiments consisted of injecting oxygen-saturated (8.4 mg L^{-1} or 256 μmol L^{-1}) synthetic groundwater at a steady rate into a reduced sediment column and measuring the concentration of dissolved oxygen over time in the effluent for 100 to 400 hours. The flux rate was chosen to achieve specific residence times of the dissolved oxygen in the column relative to the oxidation rate(s) of the sediment.

4.3 Sediment Reduction Results

The mass of reducible iron was calculated from measurements of dithionite breakthrough in column experiments using eight different sediments from four wells in the 100-D area (column experiments D6-D17, Table 4.1). In each experiment, the mass of dithionite needed to reduce iron was calculated from the total dithionite mass loss in the experiment minus the loss due to disproportionation (reaction 4). Sediments used in experiments showed an average of 31.8 ± 5.6 μmol/g for the sediments tested, which were all the <4 mm sieved fraction of the entire field sediment. With the assumption that the >4 mm fraction of the sediment has no reactive surfaces, the 100-D sediments averaged 11.0 ± 3.0 μmol/g of reducible iron. Column experiments in which sediment was subsequently oxidized with dissolved oxygen in water (column experiments D18–D31, Table 4.1) indicated that 47 to 81% of the reduced iron was oxidized.

The rate of iron reduction by the dithionite solution was determined from batch and column experimental data and subsequent modeling. The reduction rate of surface iron by sodium dithionite in batch systems (Figure 4.1a) has shown that the third-order reaction (reaction 1) for the reduction of iron is needed to describe the data. The dynamic nature of the reduction was not fully described using the first-order approach (reaction 3). The rate of iron reduction in this batch experiment was 4.5 hours.

Reduction of iron in sediment during transport is shown by a 1-D column experiment (Figure 4.1b), in which the initial fast breakthrough of dithionite is followed by a slow approach to equilibrium. Reactions (1) and (4) were needed to fit these data (a simpler approach, reactions 3 and 4, could not fit the data). In addition to the two chemical reactions, a slow physical approach to equilibrium was needed. In a column experiment of the breakthrough of dissolved oxygen in

Table 4.1. Reaction Mass and Rates from Column Experiments

experimental parameters							reduction by dithionite					oxidation by dissolved O_2		
exp #	well #	well <4mm	res. time (h/pv)	duration (pv)	dith. (mol/L)	buffer (mol/L)	dith loss[1] (μmol)	disp. loss[1] (μmol)	Fe red.[3] (μmol/g)	half-life[4] (h)	sediment Fe (μmol/g)	btc loss[1] (μmol)	fraction[5] oxidized	half-life[4] (h)
D6	D4-2, 94'	0.323	1.58	11	0.017	0.16	196.	18.	31.0	3.48	10.0	--	--	--
D8	D4-5, 94'	0.426	1.83	11	0.052	0.24	306.	73.	40.5	4.71	17.3	--	--	--
D9	D4-3, 88'	0.351	2.33	9	0.056	0.24	216.	58.	27.5	5.22	9.7	--	--	--
D10	D4-3, 85'	0.314	1.37	16	0.054	0.24	230.	66.	28.5	5.38	8.9	--	--	--
D11	D4-2, 87'	0.357	1.6	13	0.037	0.24	183.	52.	22.8	4.93	8.1	--	--	--
D12	D4-5, 90'	0.273	1.23	21	0.034	0.24	248.	62.	32.3	5.86	8.8	--	--	--
D15	D4-2, 93'	0.335	1.52	15	0.049	0.24	286.	75.	36.7	6.12	12.3	--	--	--
D17	D4-4, 94'	0.362	2.31	19	0.115	0.36	740.	705.	35.0	6.54	12.7	--	--	--
D18	D4-4, 94'	0.362	0.77	95	--	--	--	--		--		66.	0.47	0.75
D20	D4-4, 94'	0.362	2.12	22	0.071	0.36	360.	329.	31.0	5.12	11.2	--	--	--
D21	D4-4, 94'	0.362	0.71	170	--	--	--	--	--	--		82.	0.66	--
D22	D4-4, 94'	0.362	2.15	41	0.012	0.04	148.	121.	27.0	4.00	9.8	--	--	--
D23	D4-4, 94'	0.362	0.72	140	--	--	--	--	--	--		69.	0.64	--
D25	D4-4, 94'		0.74	200	0.0064	0.02	--	--	--	--		64.	--	--
D26	D4-4, 94'	0.362	2.21	20	0.127	0.18	430.	401.	29.0	3.94	10.5	--	--	--
D27	D4-4, 94'	0.362	0.74	190	--	--	--	--	--	--		94.	0.81	--
D28	D4-4, 94'	0.362	2.12	24	0.102	0.09	715.	676.	39.0	6.66	14.1	--	--	--
D29	D4-4, 94'	0.362	0.69	240	--	--	--	--	--	--		109.	0.70	--
D30	D4-4, 94'	0.362	2.71	30	0.111	0.36	640.	610.	30.0	5.96	10.9	--	--	--
D31	D4-4, 94'	0.362	0.91	220	--	--	--	--	--	--		93.	0.77	1.34

[1] mass injected - breakthrough mass

[2] loss of injection mass by disproportionation assumes a 27 h half-life (rxn 2)

[3] (dithionite breakthrough mass loss - disportionation)x 2moles iron reduced/mole dithionite consumed / 11.5 g

[3] based on slope change for dithionite or constant concentration for dissolved oxygen

[3] 0.25*mass loss of dissolved oxygen/mass reduced, based on stoichiometry of rxn 13.

*column capacity 0.59 μmol oxygen-free water, remaining 0.45 μmol assumed trapped air (0.5% of pore volume)

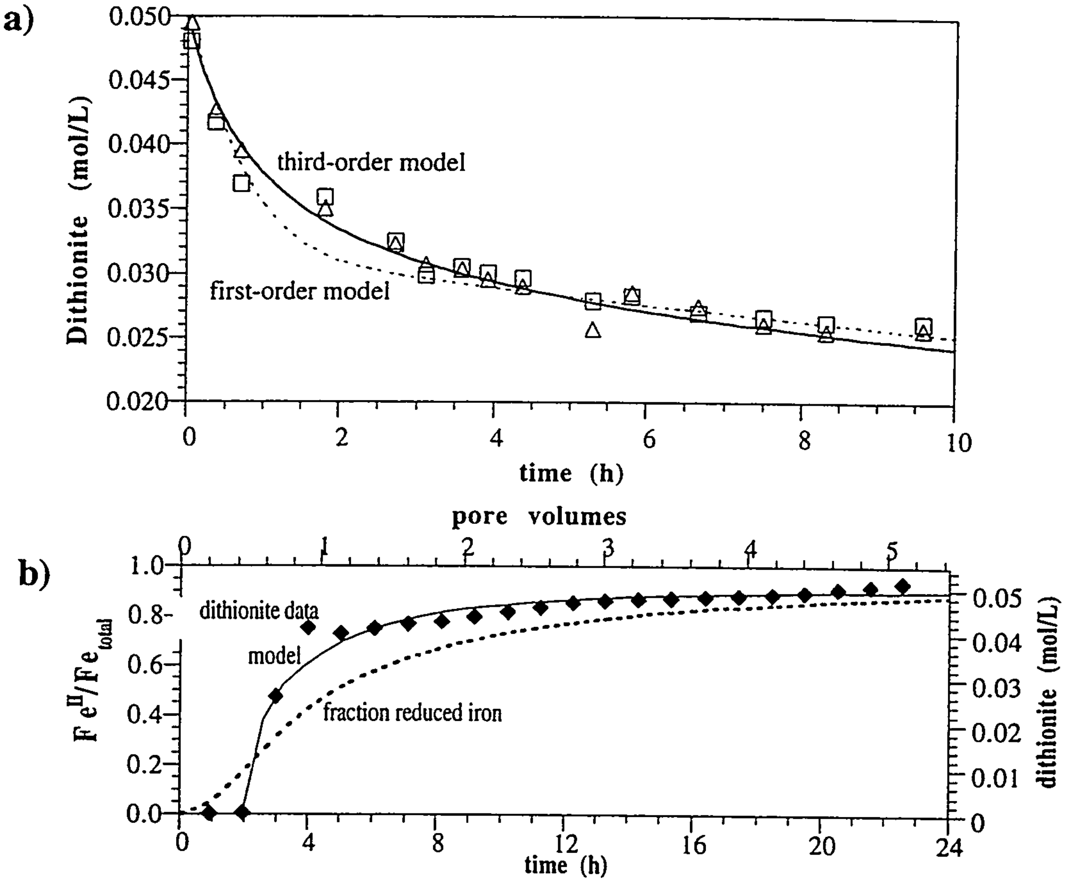


Figure 4.1. Reduction of 100-D Sediment by a Sodium Dithionite Treatment in **a**) batch systems where model fits with reaction 1 (solid line) and model 3 (dashed line); both fits included the disproportionation reaction 4; **b**) 1-D columns with a model fit using reaction 1 (iron reduction) and reaction 4

a nonreduced sediment (not shown), the slow approach to equilibrium (relative to a tracer) indicated that a fraction of the sites were slower to be accessed. Based on this, a diffusion step was added for a fraction of the iron sites (reaction 2) where the total number of oxidized or reduced iron sites is the sum of sites in reactions 1 and 2. The reduction rate for the major fraction of the reducible iron sites averaged 5.5 hr in column experiments (Table 4.1).

Sediment samples from well D4-4 were studied extensively in experiments in which the dithionite concentration and pH buffer concentration were varied. Experiments using various dithionite concentrations showed that considerably more time is required to reduce sediment using low concentrations, so high dithionite concentrations (0.03 to 0.1 mol/L) were recommended for the field injections. In other column experiments, the pH buffer concentration was mended for the field injections. In other column experiments, the pH buffer concentration was varied from one to four times the dithionite concentration. Theoretically, two moles of H^+ ions are released per mole of iron reduced (reaction 1), so pH can be maintained with a pH buffer concentration twice the dithionite concentration. Earlier laboratory and field experiments showed the importance of maintaining a high pH in the injection solution because the disproportionation of dithionite (reaction 3) is considerably faster at low pH. Column experiments with a pH buffer concentration four times the dithionite concentration showed less than a 0.3 pH unit decrease during dithionite injection. With the pH buffer at twice the dithionite concentration, a 1.5 pH unit decrease was observed, and when the pH buffer concentration was the same as the dithionite concentration, the pH dropped from 11.0 to 3.8. These results indicated that the field-scale dithionite injection would reduce the sediment most efficiently when the pH buffer was four times the dithionite concentration.

4.4 Sediment Oxidation Results

Oxidation column experiments were used to determine sediment oxidation rates and predict the longevity of the redox barrier in the field. These experiments showed that a large fraction of reduced sites are oxidized within 100 to 250 pore volumes (of dissolved oxygen), but a small fraction of sites were oxidized more slowly. This concept is illustrated by three oxidation column experiments at differing pore water velocities (Figures 4.2a–c) in which the slowest velocity (Figure 4.2a) shows dissolved oxygen remaining low for 370 pore volumes, after which oxygen saturation is quickly achieved. This equilibrium breakthrough curve shape is caused by the oxidation reaction rate being considerably faster than the residence time in the column (60 hr); therefore, dissolved oxygen had time to react fully with reduced iron. At a velocity in which dissolved oxygen only partially reacts with reduced iron (Figure 4.2b, residence time 1.9 hours), dissolved oxygen breakthrough rises after 100 pore volumes, then slowly approaches oxygen saturation. At a higher velocity (Figure 4.2c, residence time 0.2 hour), partial oxygen breakthrough occurs almost immediately followed by the slow approach to oxygen saturation over hundreds of pore volumes. A rough approximation of the sediment oxidation rate half-life is 0.25 hour, based on the dissolved oxygen plateau in Figure 4.2c (10–60 pore volumes).

The oxidation of reduced iron in the natural sediment appears to be more complex than a single oxidation reaction, and is likely controlled by both chemical and physical processes. A reactive transport model used to simulate the oxidation of the sediment with reaction (1) could not fit the dissolved oxygen breakthrough data shown in Figure 4.2c, which contains multiple slope changes. However, with the addition of a second type of reduced iron (reaction 2), the dynamic breakthrough curve shape can generally be fit using both reactions (line shown in Figure 4.2c). This simulation had 20 percent of the reduced iron modeled with reaction 2 with a considerably slower rate. The breakthrough curve shape is not well fit initially (0 to 20 pore volumes), and a more complex approach is needed for reaction 1. Breakthrough curve tailing in a column experiment of purely dissolved oxygen in nonreduced sediment (not shown) for 5–6 pore volumes indicates diffusional limitations accessing a fraction of the pore volume. This physical tailing for dissolved oxygen could explain the tailing observed for dissolved oxygen for the fast oxidation reaction (Figure 4.2c, 10–40 pore volumes). Measurement of the column effluent Eh (Figure 4.2d, same experiment as Figure 4.2b) also provides an indication of the complexity of the oxidation of the sediment.

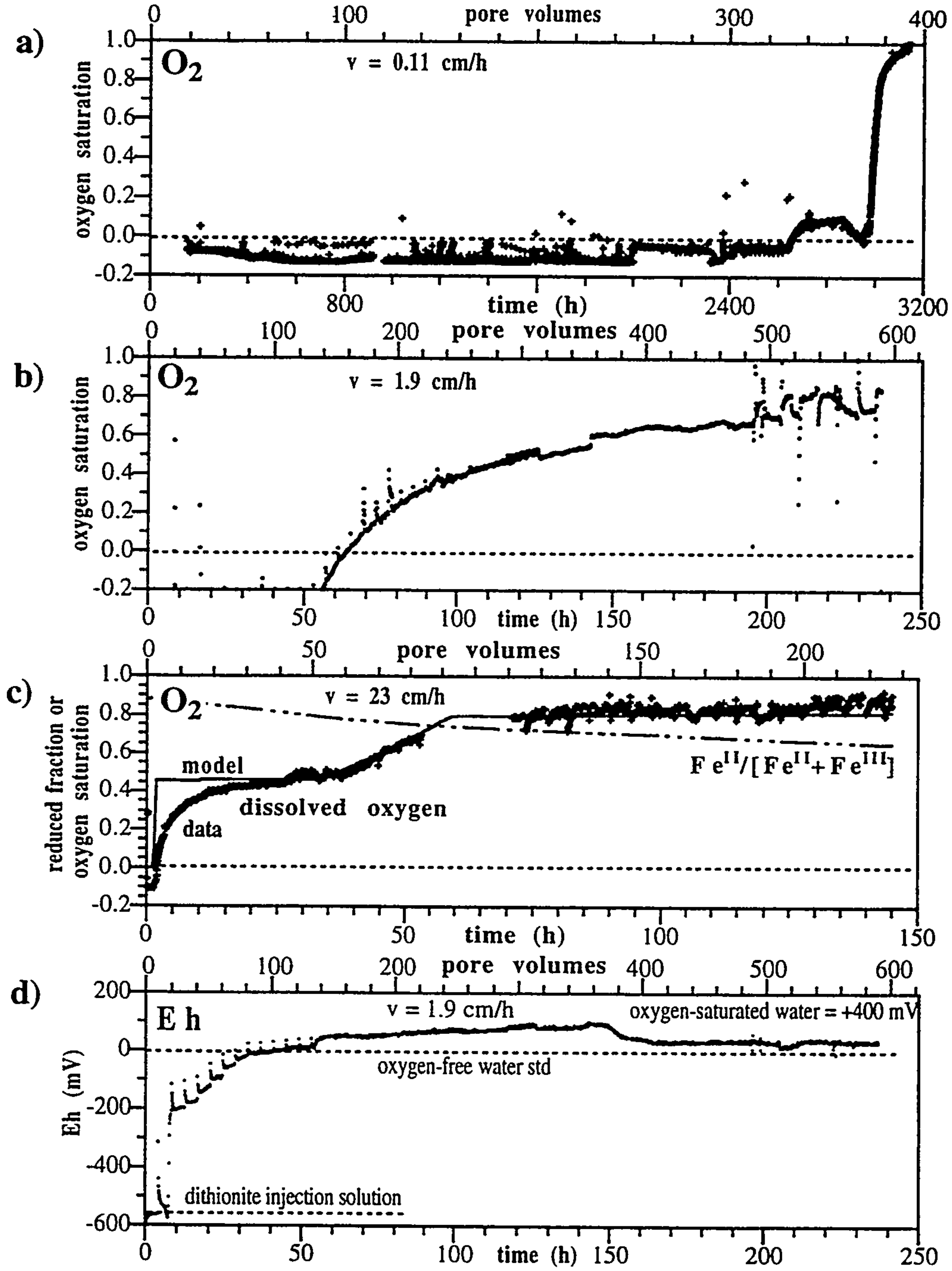


Figure 4.2. Oxidation of Dithionite-Reduced Sediment by Dissolved Oxygen in Water (8.2 mg/L) in Three 1-D Column Experiments with Different Velocities Resulting in Different Contact Times of Dissolved Oxygen with Adsorbed Fe(II): **a**) 60-hr, **b**) 1.9-hr, and **c**) 0.2-hr residence. Sediment oxidation was simulated with a model that considers fast and slow oxidation by dissolved oxygen (reactions 19 and 20) as shown in (c) for dissolved oxygen and fraction of reduced iron. The Eh of the effluent solution during sediment oxidation (**d**, same experiment as b) also illustrates partial oxidation of a fraction of surface sites.

4.5 Mineralogical Changes During Dithionite Treatment

Iron extractions were conducted on unreduced, reduced, and reduced/oxidized sediments to specifically determine the changes in iron phases that occur during reduction and subsequent oxidation of the sediment. The total extractable Fe(II) and Fe(III) in the <4 mm fraction of Hanford 100-D sediments was 76 ± 25 µmol/g, of which 70 to 80 percent was Fe(III) oxides. The amorphous Fe(III) phases ranged from 30 to 60 percent of the total Fe(III) oxides. Extractions conducted on reduced sediments showed a measurable decrease in the amorphous Fe(III) phases, a large increase in the adsorbed Fe(II), and a small increase in $Fe(II)CO_3$. inductively coupled plasma mass spectrometry (ICP-MS) analysis of the redox reactive fraction of sediment showed that iron species accounted for 97 percent of the reactivity and Mn species the remaining 3 percent. Oxidation of the sediment in a column (600 pore volumes of oxygen-saturated water) resulted in a loss of all the adsorbed Fe(II), little change in $Fe(II)CO_3$, and an increase in both amorphous and crystalline Fe(III) oxides. Therefore, the dithionite treatment appears to mainly dissolve amorphous Fe(III) oxides and create adsorbed Fe(II). The dithionite treatment appears to reduce only a fraction of the available Fe(III) oxides. The Fe(II) is highly adsorbed; less than 0.1 percent was measured in the effluent from several column experiments after 300 pore volumes. Iron extractions indicated a loss of up to 10 percent in total iron in the sediment after 600 pore volumes of water were injected through the sediment. These results indicate that a reduced sediment barrier can be re-reduced with only a small loss in iron capacity. Sediment from the 100-H area was, in fact, reduced/oxidized twice and had a 6 percent loss in reduced iron in the second reduction.

4.6 Immobilization of Chromate

An oxidation column experiment was conducted to test the immobility of chromate because the emplacement of the redox barrier in the 100-D area of the Hanford Site is to prevent chromate in the shallow aquifer from reaching the Columbia River. Chromium is a redox-sensitive contaminant that will be immobilized at the redox barrier as a result of precipitation reactions when Cr(VI) is reduced to the less soluble Cr(III). Although the reduction of chromate oxidizes Fe(II), because most chromate contamination is <5 mg/L, dissolved oxygen is mainly responsible for oxidizing the Fe(II). Chromate would need to be present at a concentration of 120 mg/L to have an equivalent ability to oxidize the redox barrier as dissolved oxygen. Therefore, while chromate oxidation of the reduced sediment and the subsequent effect on uranium transport was not considered likely, because chromate is a stronger oxidant than dissolved oxygen, it may have some impact on the barrier oxidation rate even if present at a low concentration. Chromate transport behavior was also studied because of the relative difference in mobility compared with uranium species. Cr(III) is not readily oxidized to Cr(VI) when the redox barrier is ultimately oxidized. To test this difference in behavior, a long-term column experiment was conducted in which Cr(VI) was injected through reduced sediment and the remobilization behavior monitored once the sediment was oxidized.

The column experiment was conducted by injecting water that was nearly oxygen-saturated (average of 6 mg L^{-1}) and 2.3 mg L^{-1} Cr (as chromate) into a reduced Hanford 100-H sediment until the sediment is oxidized. This 4,000-hour (six-month) experiment was conducted with

Hanford formation sediment that was treated with the reductant in a method similar to that used at the field scale (sodium dithionite injected for 12 hours, then a 48-hour no-flow interval). This experiment confirmed the expected behavior of Cr(III) species. Chromate was generally immobilized in the reduced sediment until the sediment was oxidized (at ~800 pore volumes), after which the chromate effluent was equivalent to the influent concentration. The mass of injected chromate (CrO_4^{2-}) (42.7 mg) was not recovered even after 4,000 hours or 1500 pore volumes of oxic water was flushed through the sediment (effluent was 20.7 mg or 48%) (Figure 4.3). This was expected due to the slow dissolution rate for solid $Cr(OH)_3$ in oxic water.

4.7 Trace Metals Mobilization

Trace metal mobilization studies were conducted using fluvial sands and gravels from the Fort Lewis ISRM site in Tacoma, Washington (Szecsody et al. 2000). During these laboratory-scale column experiments, effluent samples taken during Fort Lewis sediment reduction (about 10 pore volumes) and oxidation (550 pore volumes) were assessed for potential migration of trace metals (22 metals including Ni, Cu, As, Cd, Sn, Sb, Ba, Cr). Some metals are elevated in aqueous concentration during sediment reduction because of increased solubility in the reducing environment, but all trace metals dropped to pre-injection levels within five pore volumes of injection of oxygen-saturated water; this is the basis of the withdrawal of three to five pore volumes of the amount of water injected during a dithionite injection in field-scale injections. The concentrations of the major metals injected (K^+ from the >0.2 mol/L K_2CO_3 and Na^+ from the sodium dithionite) took a considerably greater number of pore volumes to approach pre-injection levels asymptotically.

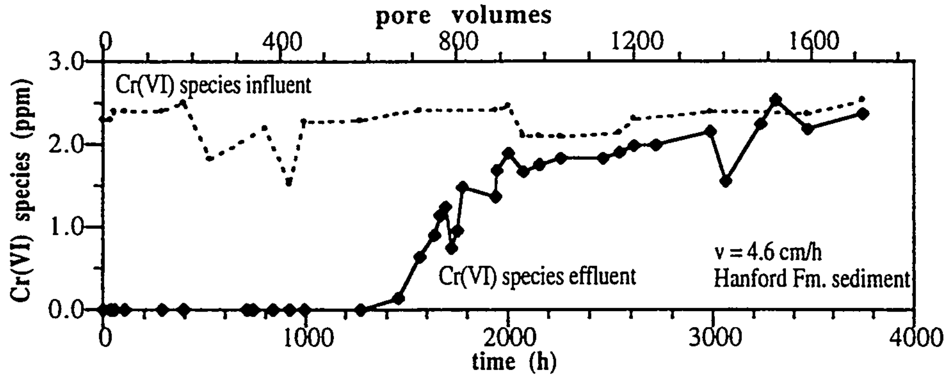


Figure 4.3. 1-D Column Experiment Results Showing the Reduction and Immobilization of Cr(VI) Species when Hanford Sediment Is Reduced (first 800 pore volumes), and Lack of Dissolution of the Immobilized Cr(III) Species in Oxic Sediments for a Subsequent 1000 Pore Volumes

5.0 Emplacement Process

5.1 Emplacement Strategy

The ISRM emplacement process uses an injection/withdrawal or "push/pull" method to create the permeable treatment zone. The emplacement process is conducted in three stages, injection, reaction, and withdrawal. In the injection stage, the reagent (sodium dithionite with a potassium carbonate/bicarbonate pH buffer to enhance dithionite stability) is injected into the injection/withdrawal well. Dithionite concentrations and other parameters are measured on the injection stream and in the monitoring wells located at various radial distances. The injection stage lasts about 10 hours. When injection is complete, a reaction stage follows, providing time for the dithionite and iron reactions. The length of the reaction stage is about one to two days. In the final stage (withdrawal), unreacted reagent and reaction products are extracted from the aquifer by pumping water from the same well used for the injection. The length of the withdrawal stage is about one week. Pumping rates used in the withdrawal stage are less than the injection rate (15–20 gpm for withdrawal; ~60 gpm for injection) because of excessive drawdown in the well. The withdrawal stage is also longer because up to five "injection volumes" are withdrawn to recover a majority of the reaction products (i.e., minimize residual chemicals in the aquifer). Dithionite concentrations and other water quality parameters are monitored in the nearby wells and in the extraction stream during both the reaction and withdrawal stages.

This push-pull emplacement process creates a roughly cylindrical zone of reduced iron (Fe^{2+}) centered on the injection/withdrawal well. The actual shape depends on the spatial distribution of hydraulic properties (permeability and porosity) within the aquifer (heterogeneities). The exact shape is not fully characterized due to the limited number of monitoring wells installed. To create a linear barrier to intercept a contaminated groundwater plume, a series of overlapping injection wells is used to coalesce these cylindrical zones of reduced iron (see Figures 1.5 and 1.6).

For the 100-D Area ISRM treatability test, five injection/withdrawal wells were used to create a treatment zone approximately 150 ft long, 50 ft wide, and 15 ft thick (the entire thickness of the unconfined aquifer). The three main injection/withdrawal wells (D4-10, D4-7, and D4-12) are spaced 50 ft apart. The two overlapping injection/withdrawal wells (D4-9 and D4-11) are offset from the line of main injection/withdrawal wells and are spaced 28 ft radially from the adjacent main injection/withdrawal wells.

This overlapping well design serves two main purposes. It reduces the risk of gaps in the permeable treatment zone and provides for monitoring the extent of dithionite concentrations during dithionite injection in the main injection/withdrawal wells. The 50-ft radial spacing of the main dithionite injection/withdrawal wells is too large to monitor dithionite concentrations in adjacent wells adequately for establishing the extent of the reduced zone around an injection/withdrawal well during an injection. Practical limitations of the push-pull method based on the volumes required, length of time, and the instability/decay of dithionite limit the radial influence around a single injection/withdrawal well. In addition, increasing the radius of influence for a dithionite injection increases not only the well spacing but also the barrier width, which may result in significant overdesign and waste for a given application. The other benefits of the push-pull approach are that it provides the maximum percentage of recovery of injected solute, enhanced reagent penetration of low permeability zones due to changing hydraulic gradients during the injection/reaction/withdrawal stages, and ease of operation. Alternative emplacement approaches that do not have these radial geometry limitations are horizontal wells or simultaneous operation of injection/ withdrawal wells (e.g., dipoles).

5.2 Emplacement Description

A concentrated sodium dithionite, potassium carbonate, and potassium bicarbonate solution was delivered to the ISRM site in a 4,000- to 7,000-gallon tanker truck (see Figure 2.3). The solution was chilled and blanketed with nitrogen or argon gas in the headspace of the tank to minimize contact with atmospheric oxygen. The dry chemicals were dissolved in chilled water and loaded into the tanker truck at a chemical plant in Kalama, Washington. Once loaded, the reagent was trucked directly to the 100-D Area ISRM site for injection. Two onsite storage tanks (21,000 gallons each) at the site were prefilled with groundwater pumped from wells at the site for diluting the concentrated reagent to the concentration required for injection. Two injection pumps and two flow meters were used for in-line mixing of the concentrated reagent with groundwater during the injection. As mentioned, a 4,000-gallon tank was used in the first two dithionite injection/withdrawal tests to offload the concentrated mixture from the tanker truck prior to injection. The remaining injections were conducted with an injection pump connected directly to the tanker truck.

A summary of the dithionite injection/withdrawal tests is given in Table 5.1. The results of the first test (D4-7) were used to refine the design for subsequent tests. For this purpose, the D4-7 test contained the greatest number of monitoring wells at sufficient radial distances for monitoring the emplacement. Two-hundred groundwater samples were collected during the D4-7 injection, and 500 were collected over the entire injection/reaction/withdrawal stages of the D4-7 test. These groundwater samples were measured for electrical conductivity, pH, temperature, dissolved oxygen, and dithionite in the mobile laboratories at the site. Archive samples were also collected for all these samples for later analysis of anions and/or trace metals, if needed.

The D4-7 dithionite injection/withdrawal is described in the following section. Details on the modifications of subsequent tests based on these results are also described.

5.3 D4-7 Dithionite Injection/Withdrawal Test

5.3.1 Injection Stage

The injection stage of the D4-7 dithionite injection/withdrawal test was started on September 29, 1997. The chemical reagent was injected into the aquifer at a rate of 60 gpm for 10.4 hours, yielding a total injection volume of 37,300 gallons. Concentrations were maintained at a constant level during the injection stage: 0.09 M sodium dithionite, 0.36 M potassium carbonate, and 0.036 M potassium bicarbonate.

Table 5.1. Dithionite Injection/Withdrawal Summary

Injection Well	Dates	Volume Injected (gal)	Dithionite Concentration[a] (m)	Volume Withdrawn (gallons)
D4-7	9/29/97 to 10/8/97	37,300 reagent	0.09 m for 10.4 hr	154,500 (4.1 injection volumes). Disposed at ETF.
D4-12	5/4/98 to 5/13/98	29,500 reagent 6,500 groundwater	0.1 m for 1.1 hr 0.07 m for 6.5 hr	182,000 (5 injection volumes). 36,000 gallons to purge water modutanks, remainder purged to ground.
D4-10	5/19/98 to 6/5/98	29,500 reagent 8,400 groundwater	0.1 m for 1.5 hr 0.065 m for 6.5 hr	192,500 (5.1 injection volumes). 38,000 gallons to purge water modutanks, remainder purged to ground. Note: pump failure during withdrawal.
D4-11	7/13/98 to 7/23/98	20,000 reagent	0.06 m for 5 hr	100,000 (5 injection volumes). 20,000 gallons to purge water modutanks,.remainder purged to ground.
D4-9	7/13/98 to 7/23/98	20,000 reagent	0.06 m for 5 hr	100,000 (5 injection volumes). 20,000 gallons to Purge water modutanks, remainder purged to ground.

(a) Potassium carbonate concentrations were four times the sodium dithionite concentrations; potassium bicarbonate concentrations were 0.4 times sodium dithionite concentrations.

Breakthrough curves at the monitoring wells for dithionite concentrations and electrical conductivity (whose behavior was similar to the conservative bromide tracer) are provided in Appendix E. Arrival times in the monitoring wells during injection were similar to the results measured in the bromide tracer test with wells screened in the upper portion of the aquifer having significantly earlier breakthrough and much higher concentrations relative to wells screened in the lower portion of the aquifer.

In response to the 60-gpm injection rate, a significant injection mound formed in the unconfined aquifer where the water table elevation is raised above its pre-injection level, as shown in Figure 5.1. The extent of the injection mound is a function of the hydraulic properties of the aquifer, the injection rate, and the injection duration.

5.3.2 Reaction Stage

The reaction stage lasted 35 hours, from the end of the injection stage to the start of the withdrawal stage. Dithionite concentrations were monitored during the reaction stage to indicate the presence of reducible Fe(III) in the sediment. Because the rate of the dithionite/ Fe(III) redox reaction is relatively fast (~5-hr half-life), high concentrations of dithionite that are still detected in wells after a significant number of half-lives have elapsed indicate that all the available Fe(III) up to the radial distance of the well has been reduced to Fe(II). The duration of the reaction

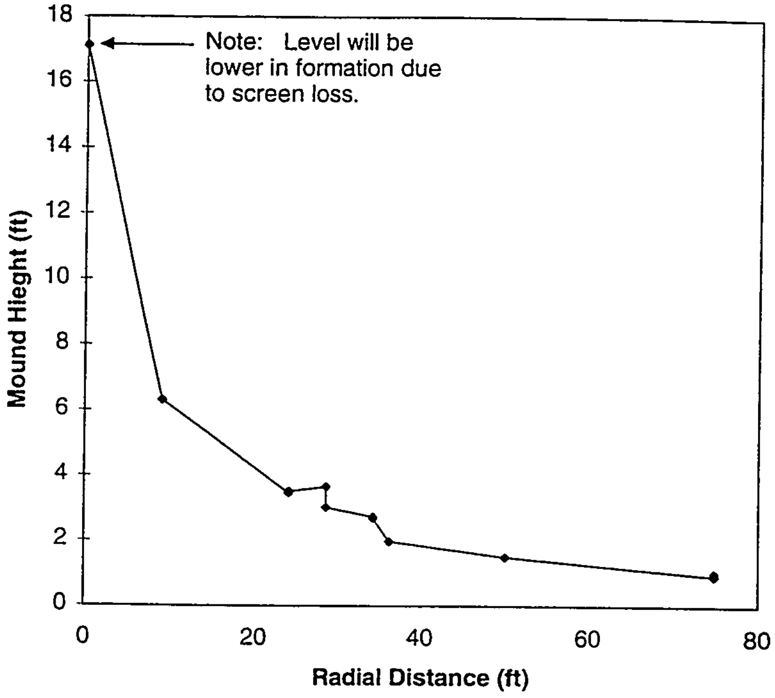


Figure 5.1. Extent of Injection Mound Formed During D4-7 Dithionite Injection

stage was approximately seven reduction half-lives; therefore, injection/withdrawal dithionite concentrations would be lowered to less than 1 percent of the concentrations at the beginning of the reaction stage if reducible Fe(III) were still present.

The higher concentrations injected into the upper portion of the aquifer, along with the density of the sodium dithionite solution (~1.06 g/mL), caused the reagent plume to sink during the reaction stage. This was evident in the measurements from the multilevel monitoring wells (see D4-2 and D4-3 results in Appendix E). When the injection pump was turned off at the end of the injection stage, fluid density gradients caused the higher-concentration solutions in the upper portion of the aquifer to sink rapidly. This effect helped to increase the amount of dithionite reaching the lower portion of the aquifer and create a more uniform treatment zone.

5.3.3 Withdrawal Stage

The withdrawal stage of the D4-7 dithionite test lasted eight days at an extraction rate of 20 gpm. The total volume of water withdrawn was 154,500 gallons, representing 4.1 injection volumes. The water was stored in onsite storage tanks. Samples were collected from the tanks and analyzed to ensure suitability for disposal at the ETF. Results are shown in Table 5.2. The water was approved for the ETF and trucked to the facility for treatment and disposal.

Table 5.2. ISRM Groundwater Sample Analyses

Sample ID	pH	Density (g/ml)	TDS (g/L)	TSS (mg/L)	Total C (mg/L)	TOC (mg/L)	F^{1} (mg/L)	Cl^{-1} (mg/L)	NO$_2^{-1}$ (mg/L)	NO$_3^{-1}$ (mg/L)	PO$_4^{-3}$ (mg/L)	SO$_4^{-2}$ (mg/L)	Br^{-1} (mg/L)	SO$_3^{2-}$ (mg/L)	S2O$_3^{2-}$ (mg/L)
DT-1	9.45	1.0137	10.1	4	829	21	1.05	32	<2	61	<3	870	5.7	1780	9.8
DT-2	9.45	1.0159	14.9	<2	1300	30	1.4	23	<2	60	<3	1470	6.9	2530	13
DT-3	9.13	1.0167	2.5	(3)	202	3.5	0.53	26	<2	63	<3	40	4.4	330	1.9
DT-4	9.45	1.0130	9.5	(3)	800	24	1.06	25	<2	63	<3	850	5.7	1680	9.5
DT-5	9.45	1.0130	9.6	6	793	19	1.06	24	<2	62	<3	840	5.8	1650	9.4
DT-6	9.44	1.0130	9.4	5	788	21	1.04	24	<2	62	<3	1010	5.8	1610	8.9
DT-7	9.42	1.0135	9.1	<3	756	20	1.03	24	<2	61	<3	1070	6.0	1580	6.8
DT-8	9.45	1.0131	9.5	<3	774	20	1.00	25	<2	63	<3	890	6.0	1690	8.9
VWA*	9.40	1.0139	8.96	<4	746	19.14	1.00	26	<2	62	<3	841	5.7	1546	8.2

Sample ID	As (mg/L)	Ba (mg/L)	Ca (mg/L)	Cd (mg/L)	Cr (mg/L)	Cu (mg/L)	Fe (mg/L)	K (mg/L)	Mg (mg/L)	Mn (mg/L)	Na (mg/L)	Ni (mg/L)	P (mg/L)	Pb (mg/L)	S$^{(a)}$ (mg/L)	S$^{(b)}$ (mg/L)	Se (mg/L)	Si (mg/L)	Zn (mg/L)
DT-1	<0.3	0.16	18	<0.1	0.11	<0.2	3.3	3200	38	0.12	840	0.07	0.7	<.3	960	1030	<.3	3.4	<.03
DT-2	<0.3	0.57	16	<0.1	0.16	<0.2	3.9	4700	51	0.11	1200	0.08	1.2	<.3	1400		<.3	3.4	<.03
DT-3	<0.3	0.08	19	<0.1	0.04	<0.05	0.11	1780	20	0.12	220	0.05	1.3	<.06	280		<.06	3.7	<.006
DT-4	<0.3	0.17	18	<0.1	<0.1	<0.2	2.5	3200	38	0.11	780	0.07	0.9	<.3	900		<.3	3.4	<.03
DT-5	<0.3	0.19	18	<0.1	<0.1	<0.2	2.5	2700	38	0.11	660	0.07	1	<.3	930	960	<.3	3.3	<.03
DT-6	<0.3	0.18	18	<0.1	<0.1	<0.2	2.4	2700	39	0.11	670	0.06	0.9	<.3	980		<.3	3.1	<.03
DT-7	<0.3	0.18	19	<0.1	<0.1	<0.2	2.2	2900	40	0.11	770	0.06	0.8	<.3	910		<.3	3.1	<.03
DT-8	<0.3	0.19	19	<0.1	<0.1	<0.2	2.5	3200	40	0.11	770	0.06	0.8	<.3	950		<.3	3.1	<.03
VWA*	<0.3	0.19	18.26	<0.1	0.10	<0.18	2.3	2939	37.15	0.11	708	0.06	0.9	<.0.27	882	995	<0.27	3.3	<0.03

* Volume Weighted Average

[a] S analysis was performed on unpreserved samples treated with $NH_4OH + H_2O_2$

[b] S analysis was performed on glycerine preserved samples treated with $NH_4OH + H_2O_2$

A mass balance was calculated for the injection/withdrawal test to estimate the percent recovery of the injected chemicals from the withdrawal stage. The estimate was based on the total mass of sulfur species (sulfate, sulfite, and thiosulfate) measured in both the injection and withdrawal stages from samples collected periodically throughout those stages. The mass balance calculations resulted in an estimate from 62 to 65 percent, which was significantly less than the 89 percent recovery obtained from the 100-H Area ISRM test in 1995 (Fruchter et al. 1997). Although the recovery from the D4-7 test was less than that from the 100-H Area test, the residual chemicals in the aquifer at the end of the tests were similar. Potential factors influencing the lower recovery at the 100-D Area ISRM site are

- greater extent of the injection mound due to the lower hydraulic conductivity of the aquifer, causing reagent to be trapped in the vadose zone and difficult to recover
- lower groundwater velocities in the lower portion of the aquifer inhibit the recovery of the reagent that sunk into the lower portion of the aquifer during the reaction stage due to density effects.

The design of the subsequent dithionite injection/withdrawal tests was modified to help improve the reagent recovery during the withdrawal stage (as discussed in the following section).

5.4 Additional Dithionite Injection/Withdrawal Tests

The modifications to the remaining four dithionite injection/withdrawal tests that completed the emplacement of the permeable treatment zone for the treatability study involved using a smaller mass of chemicals, decreasing reagent concentrations during injection, and disposing of withdrawal water. These modifications are described below.

Analysis of the D4-7 test results, based on the concentrations of dithionite measured in the monitoring wells during the test and the amount of reducible Fe(III) in the aquifer sediments, indicated that lower concentrations of dithionite could be used. The mass of chemicals used for the remaining two main dithionite/injection withdrawal tests (D4-12 and D4-10) were each 50 percent of the mass used in the D4-7 test. Lower dithionite concentrations and volumes were also used for the two overlapping injection/withdrawal wells due to the smaller radius of influence required for these wells. The mass of chemicals used for each of these overlapping wells was 60 percent of the mass used for the D4-12 and D4-10 tests (or 30 percent of the D4-7 test). The reductions in concentrations resulted in reduced chemical costs, waste generation, and residual chemicals left in the aquifer

Dithionite concentrations were decreased in a stepwise fashion during the injection for the D4-12 and D4-10 tests because the highest concentrations are needed at the front of the plume where dispersion effects, reaction time, and amount of Fe(III) along the pathline are greatest. Table 5.1 shows the stepped concentrations used for these tests. Toward the end of the injection stage of these tests the reagent injection was ended, and groundwater containing no reagent was injected into the aquifer. This fresh-water push was used to help flush out reagent in the injection mound and enhance recovery during the withdrawal stage because most of the available Fe(III) surrounding the injection/withdrawal well was reduced during the earlier portion of the injection stage (and no additional reagent would be required). The estimated recovery during the withdrawal stage of the D4-12 injection was 72 ± 10 percent.

The final modification to the injection/withdrawal tests involved disposing of the withdrawal water from the tests. For the remaining four dithionite injection/withdrawal tests, only the first injection volume of withdrawn water was contained and subsequently shipped to a wastewater treatment facility for disposal. After the initial injection/withdrawal test in D4-7, the purge water modutanks were used for disposing of this water instead of the ETF. The remaining portion of the withdrawal water was purged to the ground to the west of the site, upgradient from well D4-13, through a 500-ft-long drip irrigation system. Vadose zone modeling and analysis of the irrigation system showed that the sulfate concentrations in the aquifer below the surface discharge would be below 250 mg/L. The groundwater sampling frequency for well D4-13 by the Hanford Groundwater Monitoring Project was increased to a quarterly interval to assess and verify the impacts of the purge water on the water quality. Sulfate analysis results for well D4-13 are shown in Figure 5.2. This trend shows an increase in the sulfate concentrations shortly after the first withdrawal water disposal in May 1998. However, these data show the sulfate levels remained below the target limit of 250 mg/L sulfate during the peak and appear to be declining back toward predisposal levels. Additional ISRM withdrawal water disposal also took place at this location in September 1999 during emplacement activities for expansion of the ISRM treatability test barrier (see Section 7 for details).

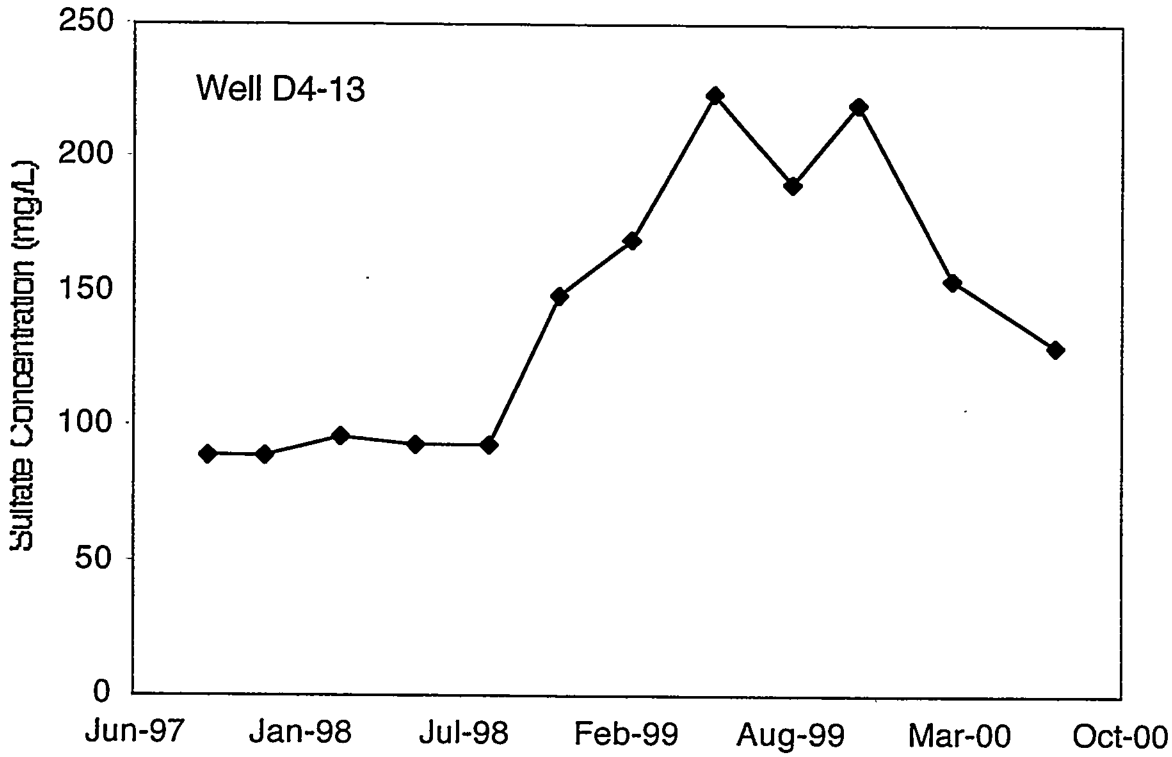


Figure 5.2. Sulfate Concentrations Measured in Well D4-13, Downgradient of Location Used for Purge Water Disposal

6.0 Performance Results

The performance of the 100-D Area ISRM treatability test was assessed by comparing post-emplacement groundwater quality with baseline groundwater quality at the site, assessing water quality in the downgradient monitoring wells following emplacement, analyzing sediment samples collected from core holes in the treatment zone to estimate longevity, and evaluating potential secondary effects of this technology (i.e., dissolved oxygen depletion, trace metal mobilization, and aquifer plugging). The results of these analyses are discussed below.

6.1 Groundwater Quality

Post-emplacement groundwater monitoring was conducted at the site as part of the treatability study on a monthly to bimonthly basis during FY 1998 and roughly quarterly during FY 1999. After FY 1999, quarterly groundwater monitoring and reporting of a subset of wells from the 100-D Area ISRM site were transferred to the Hanford Site Groundwater Monitoring Project (see Hartman et al. 2000). Analytes consisted of field parameters (EC, pH, and dissolved oxygen), chromate, anions (see Appendix F), and trace metals (see Appendix G). Results from the last complete sampling event from this study (April 6, 1999) are shown in Tables 6.1 and 6.2. Average values and ranges of selected parameters for this sampling event are given for wells within the treatment zone in Table 6.1 and for the downgradient wells in Table 6.2. Hexavalent chromium results are shown in plan and cross-section views in Figures 6.1 and 6.2. The ISRM site wells were also sampled in July 1999 but without anion and trace metal analysis. The chromate measurements from this sampling event are shown in Figure 6.3. Dissolved oxygen concentrations are shown in Figure 6.4. These analyses are discussed below and compared with the baseline groundwater quality data collected prior to any dithionite injection/withdrawal tests (see Section 3.5).

Concentrations of Cr(VI) measured in the wells significantly influenced by dithionite during the emplacement process were all below the detection limits of the field analysis equipment (Hach DR-2000) of 0.007 mg/L (see Figures 6.1, 6.2, and 6.3). Average baseline Cr(VI) concentrations measured for all the wells in the last baseline round of sampling (September 1997) were 1.0 mg/L (compare Tables 6.1 and 3.3).

Although concentrations of chromate and dissolved oxygen have decreased significantly from baseline values in the downgradient wells (decreased to as low as 0.02 mg/L from baseline values of 1.0 mg/L), the full impact downgradient from the treatment zone cannot be determined from this treatability test due to the limited duration of the test. While the Cr(VI) concentrations in the downgradient wells showed a continuous decline from the emplacement through April 1999, sufficient time had not elapsed since the last emplacement (mid-July 1998) for the groundwater migrating through the treatment zone to fully influence the aquifer downgradient. An increase in the Columbia River stage in the spring and summer of 1999 from the freshet generally reversed the hydraulic gradient direction (i.e., away from the river), causing the downgradient Cr(VI) concentrations to increase by the July 1999 sampling event (compare Figures 6.1 and 6.3). This flow reversal from the spring and summer high river stage can also be

Table 6.1. Groundwater Measurement Summary Within the Treatment Zone (4/6/99)

Parameter	Units	Range	Mean
pH		7.71 to 8.78	8.38
Electrical Conductivity	µS/cm	792 to 1891	1206
Dissolved Oxygen*	mg/L	0	0
Sulfate	mg/L	197 to 886	455
Hexavalent Chromium	mg/L	0	0
*Note: Westbay Well D4-16 DO measurements were not included.			

Table 6.2. Groundwater Measurement Summary Downgradient of the Treatment Zone (4/6/99)

Parameter	Units	Range	Mean
pH		7.50 to 7.82	7.61
Electrical Conductivity	µS/cm	728 to 1180	956
Dissolved Oxygen	mg/L	0.00 to 4.45	2.66
Sulfate	mg/L	249 to 535	403
Hexavalent Chromium	mg/L	0.02 to 0.21	0.075

seen by the decrease in Cr(VI) concentrations from the April to July 1999 sampling events in the upgradient well (D4-2). In addition, based on groundwater flow directions from water table measurements (Figure 3.1), well D4-4 is on the eastern downgradient edge (or outside) of the treatment zone at least some of the time and may not be useful for assessing the downgradient effects of the treatment zone at its current length.

Differences between the post-emplacement and baseline groundwater parameters within the treatment zone, in addition to the hexavalent chromium concentrations discussed above, include dissolved oxygen, pH, electrical conductivity, sulfate, iron, and manganese. Dissolved oxygen reacts with the Fe(II) within the treatment zone. The oxidizing capacity of dissolved oxygen is greater than the hexavalent chromium concentrations at the site and mainly determines the longevity of the treatment zone. Like the observed Cr(VI) concentrations, water within the treatment zone is anoxic (see Figure 6.4) and the downgradient concentrations of dissolved oxygen have been generally decreasing since the barrier emplacement. A study was conducted on the fate of the anoxic plume downgradient from the ISRM site at 100-D Area (see Williams et al. 1999b; Williams and Oostrom 2000). Numerical modeling as part of this study predicted that dissolved oxygen concentrations increased 75 to 95 percent of saturation by the time the groundwater discharges to the Columbia River. The most important reoxygenation mechanism found in this study was from air entrapment during water table fluctuations induced by changes in the Columbia River stage. Additional details on dissolved oxygen monitoring at the 100-D Area ISRM site are also included in Williams et al. (1999b).

The pH within the treatment zone is above baseline values, as shown in Tables 3.3 and 6.1. The pH is elevated within the treatment zone from residual potassium carbonate/ potassium bicarbonate pH buffer added to the reagent to enhance dithionite stability. The electrical conductivity is

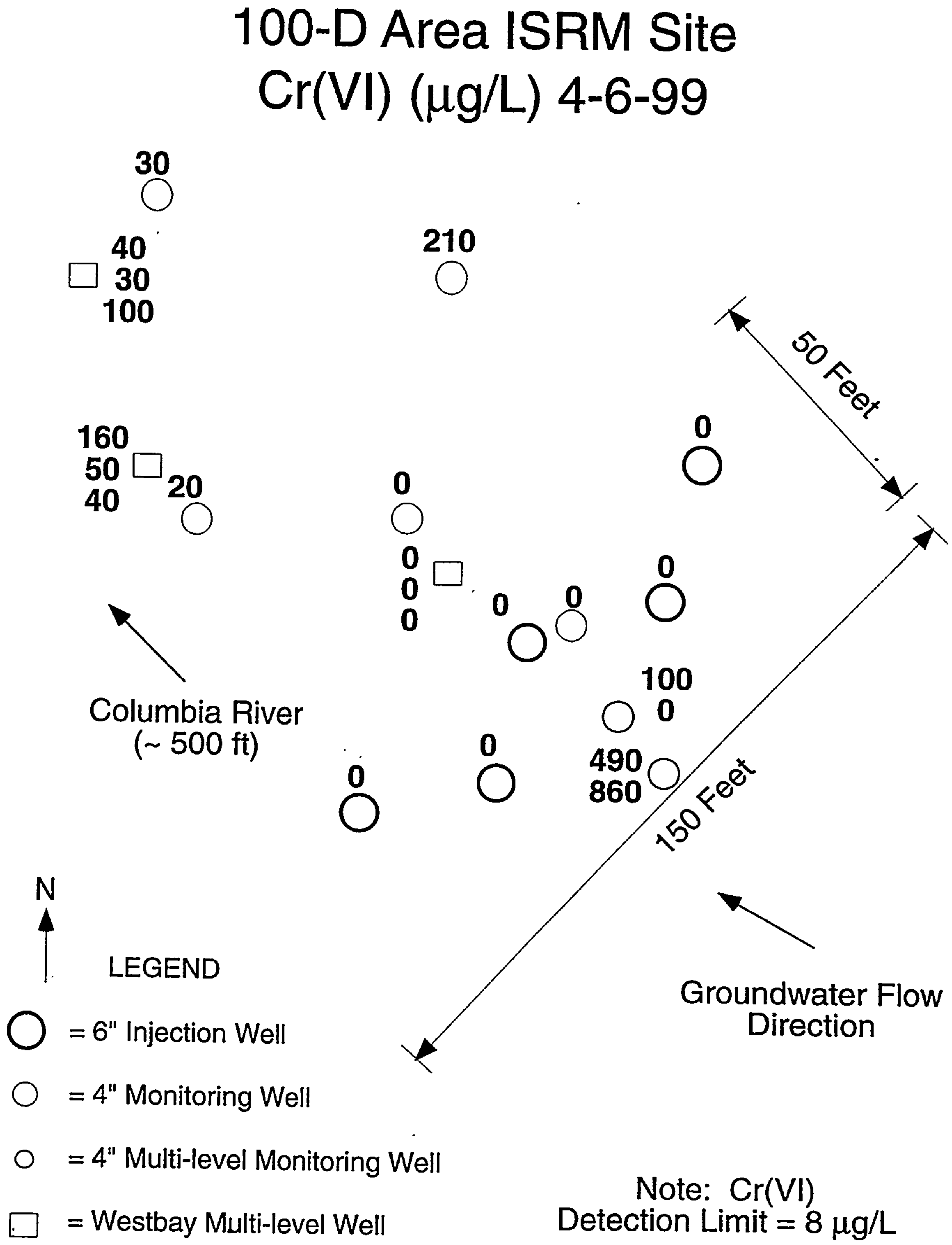


Figure 6.1. Post-Emplacement Hexavalent Chromium Concentrations at the 100-D Area ISRM Site

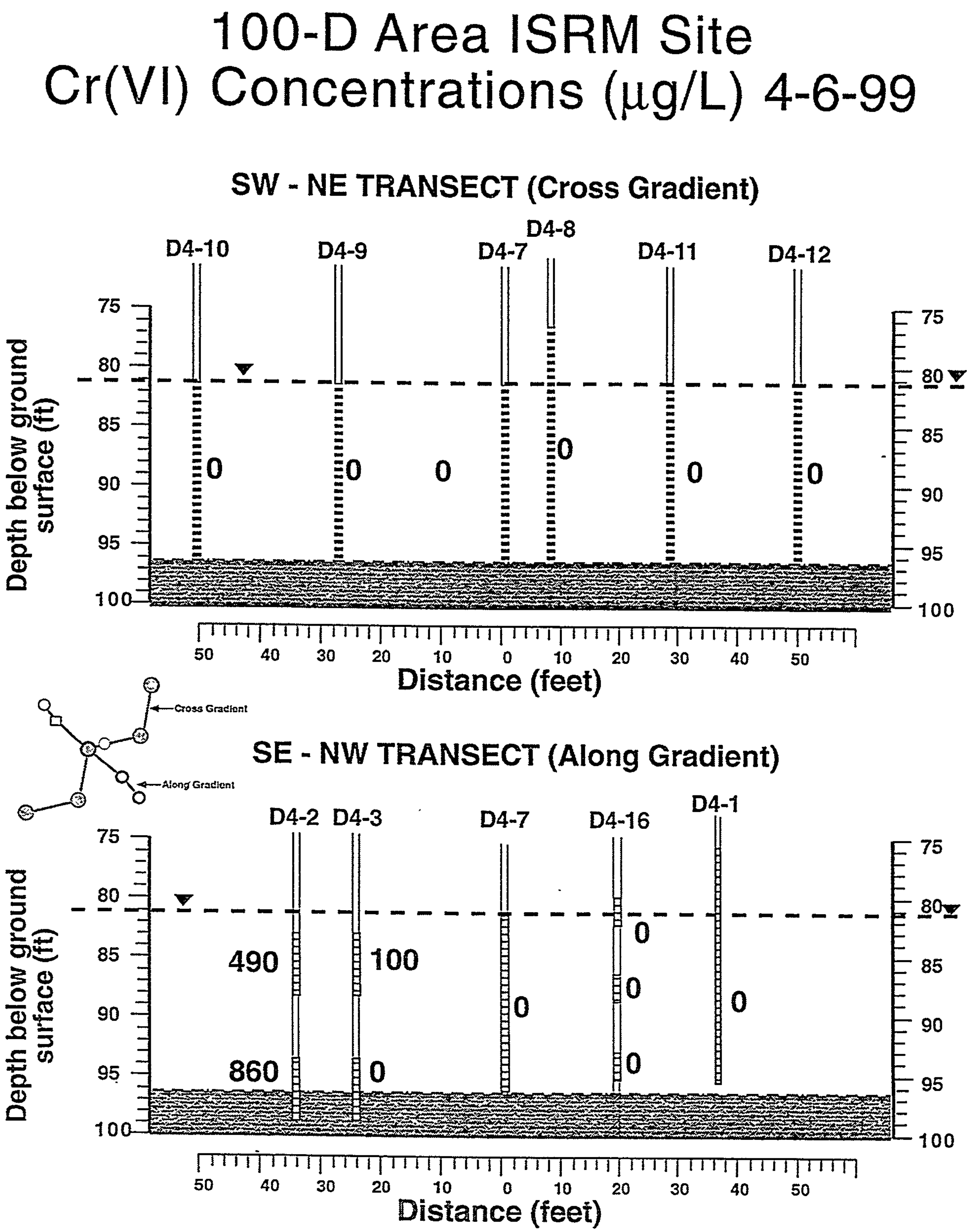


Figure 6.2. Cross-Section of Post-Emplacement Hexavalent Chromium at the 100-D Area ISRM Site

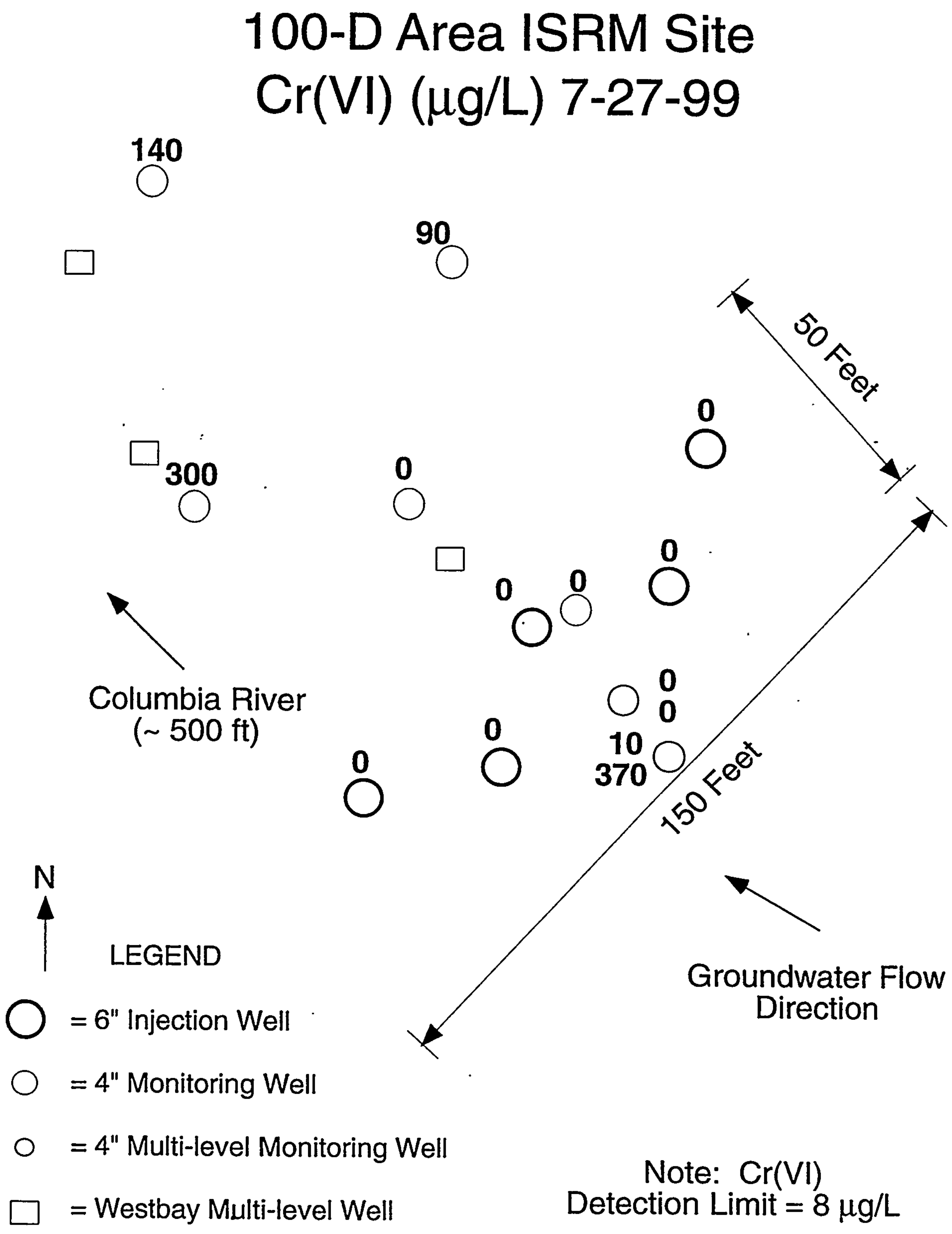
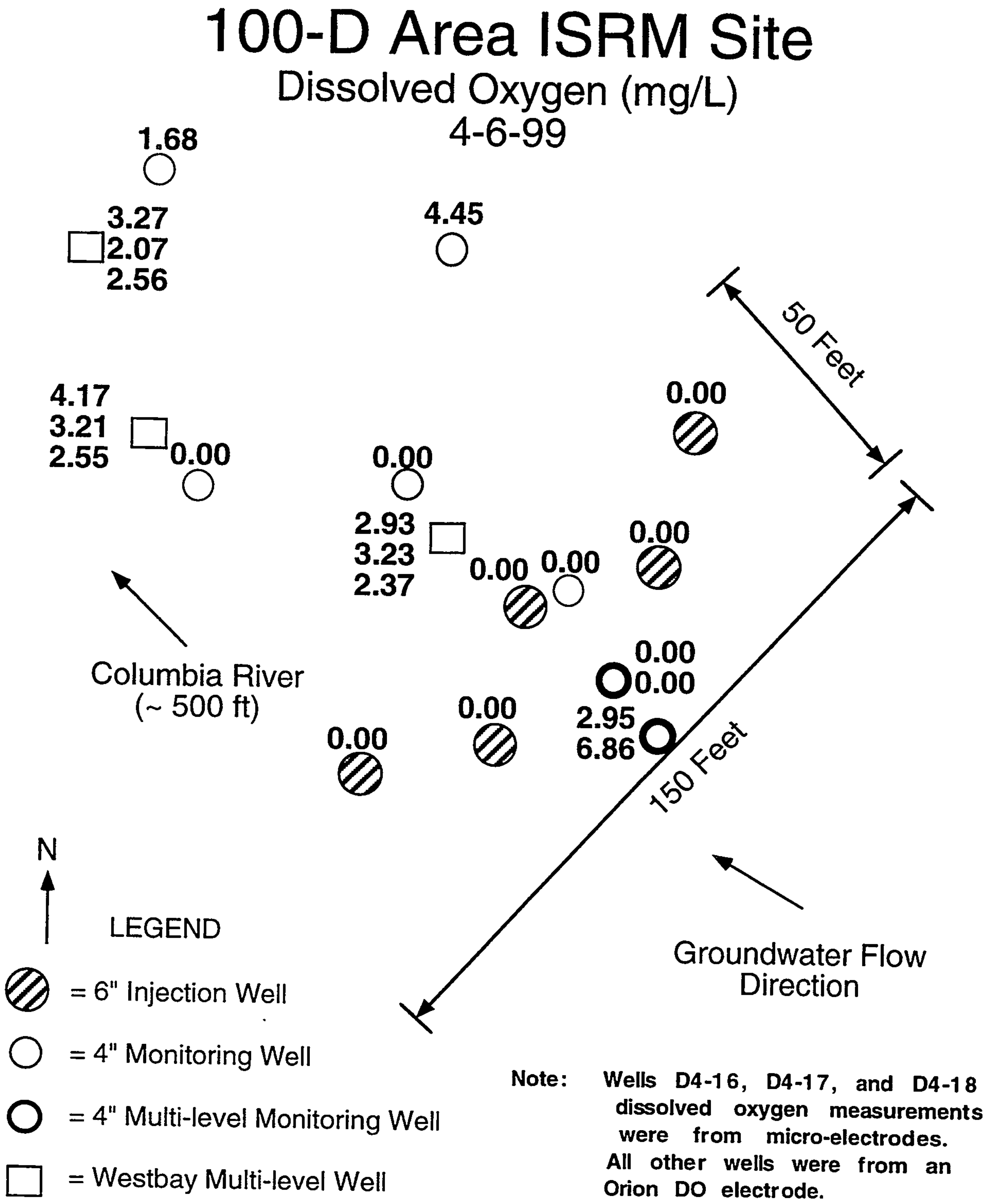


Figure 6.3. Post-Emplacement Hexavalent Chromium Concentrations at the 100-D Area ISRM Site (July 1999)



Note: Wells D4-16, D4-17, and D4-18 dissolved oxygen measurements were from micro-electrodes. All other wells were from an Orion DO electrode.

Figure 6.4. Post-Emplacement Dissolved Oxygen Concentrations at the 100-D Area ISRM Site

elevated in the reduced zone above baseline values due to the residual chemicals left in the aquifer from unrecovered reaction products associated with the injected reagents (sodium, potassium, carbonate/ bicarbonate, and sulfate).

Electrical conductivity and sulfate analysis indicate that the vadose zone is the source of the elevated levels due to reagent trapped in the injection mound during the emplacement. The highest concentrations were seen in the uppermost Westbay well (D4-16 zone 1) and Well D4-1 on the downgradient edge of the treatment zone following the injection. Higher concentrations on the downgradient side of the treatment zone and in the upper portions of the aquifer suggest concentrations increasing along the flow path through the treatment zone from vadose zone recharge. Concentrations of the residuals (e.g., sulfate) are not expected to persist for extended periods of time following emplacement.

Since the ISRM treatment zone was emplaced, nitrate concentrations at the site have decreased from baseline levels of 40 to 80 mg/L to concentrations of less than 30 mg/L within and downgradient of the treatment zone by the April 1999 sampling event (see Appendix F). Many wells have nitrate concentrations less than 10 mg/L. Variations in the measured nitrate concentrations in the injection and downgradient wells indicate that the nitrate degradation is nonuniform and has a relatively slow degradation rate. The potential nitrate degradation seen in these monitoring data at the 100-D Area ISRM site has not been confirmed in laboratory experiments with dithionite-treated sediment and the actual mechanism (chemical or microbial under reducing conditions) and the reaction pathways and products have not been identified.

Within the treatment zone, iron and manganese concentrations were elevated above baseline conditions due to dissolution of oxide minerals from the dithionite solution and the enhanced solubility of naturally occurring iron and manganese oxides within the sediments under reducing conditions. Elevated manganese and iron concentrations were also detected in the D4-5 downgradient monitoring well in the April 1999 sampling event (see Appendix G). Although these concentrations are elevated within and near the treatment zone, they should not be mobile for a substantial distance beyond the treatment zone because of its high retardation factor and reprecipitation once it contacts oxidizing sediments downgradient.

The manganous ion (Mn^{2+}) is the predominant reduced form of manganese in acidic and near neutral aqueous solutions ($pH < 7.5$). At a pH of 7.5 to 10.5 in reducing conditions $MnCO_3$ precipitates, and at higher pH $Mn(OH)_2$ precipitates, so Mn(II) mobility at high pH is limited (Stumm and Morgan 1996). Decreasing equilibrium concentration of Mn^{2+} exists under reducing conditions ($Eh < 0.0$) as the pH increases >7.5. Higher Mn^{2+} concentrations than should exist assuming geochemical equilibrium may be caused by the slow formation of $MnCO_3$.

The manganous ion is moderately strongly adsorbed to soils, especially organic poor soils and sediments, in the pH range 5–9. The average distribution coefficient for loam sand is 10 (Shuman 1977). At pH higher than 9, formation of bicarbonate ($Mn(HCO_3)^+$) and hydroxide complexes ($Mn(OH)^+$) can lower adsorption significantly. It is possible that the presence of these complexes formed in the reduced zone, combined with competition for adsorption sites from potassium ions from the buffer solution, may cause the migration of manganese a short distance downgradient of the reduced zone.

Once oxidizing conditions are established downgradient, manganese transport is also inhibited by oxidation to largely insoluble phases such as MnO_2 and other Mn (III) and Mn(IV) solids (MnOOH). However, oxidation of Mn^{2+} is autocatalyzed by pre-existing MnO_2 in the aquifer solids (Coughlin and Matsui 1976). If MnO_2 solids are not present in the aquifer in any significant quantities the oxidation may be slow, allowing some additional short-range migration of manganese.

6.2 Columbia River Pore Water Sampling Tubes

A series of sampling tubes was installed in the substrate of the Columbia River (see Figure 2.1) to monitor the groundwater entering the river and to determine any impact from the test on the water quality. Four pairs of sampling tubes were installed about 300 ft apart in the river. Each pair includes a shallow (~1-m [3-ft] depth) and a deep (~2-m [6-ft] depth) monitoring interval. In addition to the sampling tubes installed for the ISRM test, an existing set of multilevel sampling tubes (TD-39, located between 0203.0 and 0303.3) was monitored as part of this test. Details on the installation of sampling tubes are described in Peterson et al. (1998).

A portable peristaltic pump was used to collect water samples from the sampling tubes. Electrical conductivity, pH, and dissolved oxygen are measured in the field using electrodes. Water samples were collected for chromate and anion analysis after the electrode values were stabilized and recorded. Purge times varied from five to 15 minutes based on the length of the tubing.

The electrical conductivity, Cr(VI), and dissolved oxygen measurements from the 100-D Area ISRM Columbia River pore water sampling tubes are plotted in Figure 6.5 (see Figure 2.1 for locations). ISRM pore water sampling tubes (Redox-0103.3, 0106.0, 0203.0, 0206.0, 0303.3, 0304.6, 0403.0, and 0406.0) were installed in November and December 1997, after the D4-7 dithionite injection/withdrawal test. Four pairs of sampling tubes were installed at four locations along the river downgradient from the ISRM site with two sampling depths each (the last two digits of the ID are the sampling depths in feet). The TD-39 sampling tubes were installed prior to the ISRM emplacement (Peterson et al. 1998).

Water samples collected from the sampling tubes are a mixture of river water and groundwater. The contribution of each source to the sample is related to the river stage and aquifer pressures at the time of sampling. Samples collected at high river stage are dominated by river water. Because the river water and groundwater have distinct ranges of electrical conductivity (river water ~150 microS/cm and groundwater ~600 microS/cm), the electrical conductivity can be used to distinguish the relative contribution of each (see mixing curves in Peterson et al. 1998; Hope and Peterson 1996). It is important to consider the electrical conductivity measurements of the samples to establish the relative river water dilution when interpreting the hexavalent chromium measurements. Concentrations of Cr(VI) in the aquifer in this area (prior to the ISRM test) were 1.0 mg/L. Cr(VI) has not been detected in the water samples collected from the Columbia River at the 100-D Area. The field analysis method used for Cr(VI) has a detection limit of 0.007 mg/L.

Considering both the Cr(VI) and electrical conductivity, most of the variability in the measurements shown in Figure 6.5 can be explained by river water mixing (e.g., when electrical

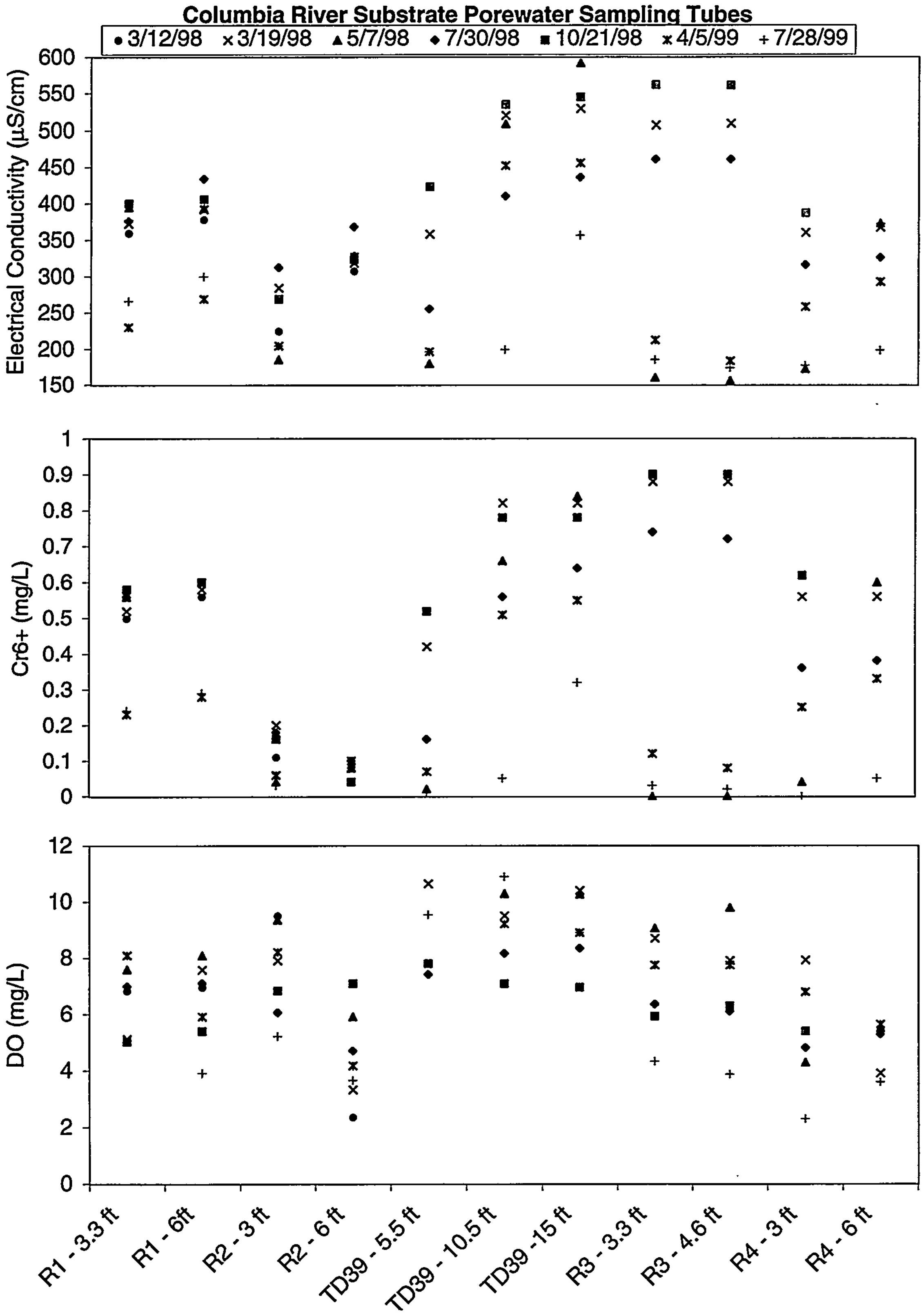


Figure 6.5. Columbia River Substrate Pore Water Sampling Tubes Downgradient from the 100 D Area ISRM Site. Locations are shown in Figure 2.1.

conductivity is low, Cr(VI) is also low). This relationship is also shown in Figure 6.6. No clear trend can be determined from the dissolved oxygen data (i.e., DO concentration versus EC) in Figure 6.5. Based on the data shown in Figures 6.5 and 6.6, mixing and dilution of river water within the substrate pore water can result in concentrations ranging from 0 to 90 percent of the baseline (i.e., pre-ISRM test) aquifer concentrations measured at the ISRM treatability test site.

Hexavalent chromium, electrical conductivity, dissolved oxygen, and pH results from all the sampling events of the ISRM Columbia River pore water sampling tubes are provided in Appendix C. Major anion analysis was also conducted for the some of the sampling event and these results are also included in Appendix C.

One tube, Redox02 at a 6-ft depth, appears to be consistently low in Cr(VI) while maintaining relatively high electrical conductivity. The dissolved oxygen at Redox02-6 ft is also lower (on average) than other tubes, but the recent values are within the ranges of dissolved oxygen measured in the other tubes at other times. The trend of increasing dissolved oxygen concentration seems to suggest that the water quality in this tube may be influenced from its installation (e.g., negative Eh from crushing minerals) as seen in monitoring wells after installation prior to sufficient development. Although Cr(VI) concentrations in the Redox02-6 ft tube are lower than baseline aquifer concentrations (even when accounting for river water dilution), it cannot be concluded that this reduction in chromate is a downgradient effect of the ISRM treatability study. In addition, the groundwater velocities required to move this distance (160 m) before the first sampling event of this tube in December 1997 (these data are not shown on Figure 2.5 because the samples measured for electrical conductivity were collected at a different times than those for Cr(VI) measurements) is outside the range of current estimates of the travel time to the river—1.5 to 2.5 years.

6.3 Estimated Reductive Capacity and Barrier Longevity

Indirect evidence of the reduction of aquifer sediments was obtained by collecting and analyzing aqueous samples from the site (e.g., dissolved oxygen and total chromium/hexavalent chromium concentrations). Direct measurement of reductive capacity, which is required to predict long-term barrier performance (i.e., barrier longevity), was achieved by analyzing sediment samples collected from core holes drilled after emplacement of the treatment zone. The mass of reducible iron was calculated from measurements of dithionite breakthrough and oxygen breakthrough in 13 laboratory experiments with sediments from three depths in each of the three core holes (see Figure 1.6 for core hole locations and Table 6.1 for laboratory results) to determine the efficiency and lateral extent of dithionite-treatment of sediment at the field scale.

Three boreholes (B8775, B8776, B8777, shown in Figure 6.1) were drilled and sampled in the 100-D Area between June 7 and 11, 1999 using the resonant-sonic drill method. Core samples were obtained by applying a resonating harmonic vibration to a core barrel or split-spoon sampler ahead of the sonically advanced casing. Between core runs, the casing was advanced and cleaned out with a vibrating core barrel. The targeted interval for sediment sampling included only the capillary fringe zone and the upper 15 ft of the saturated zone. All samples

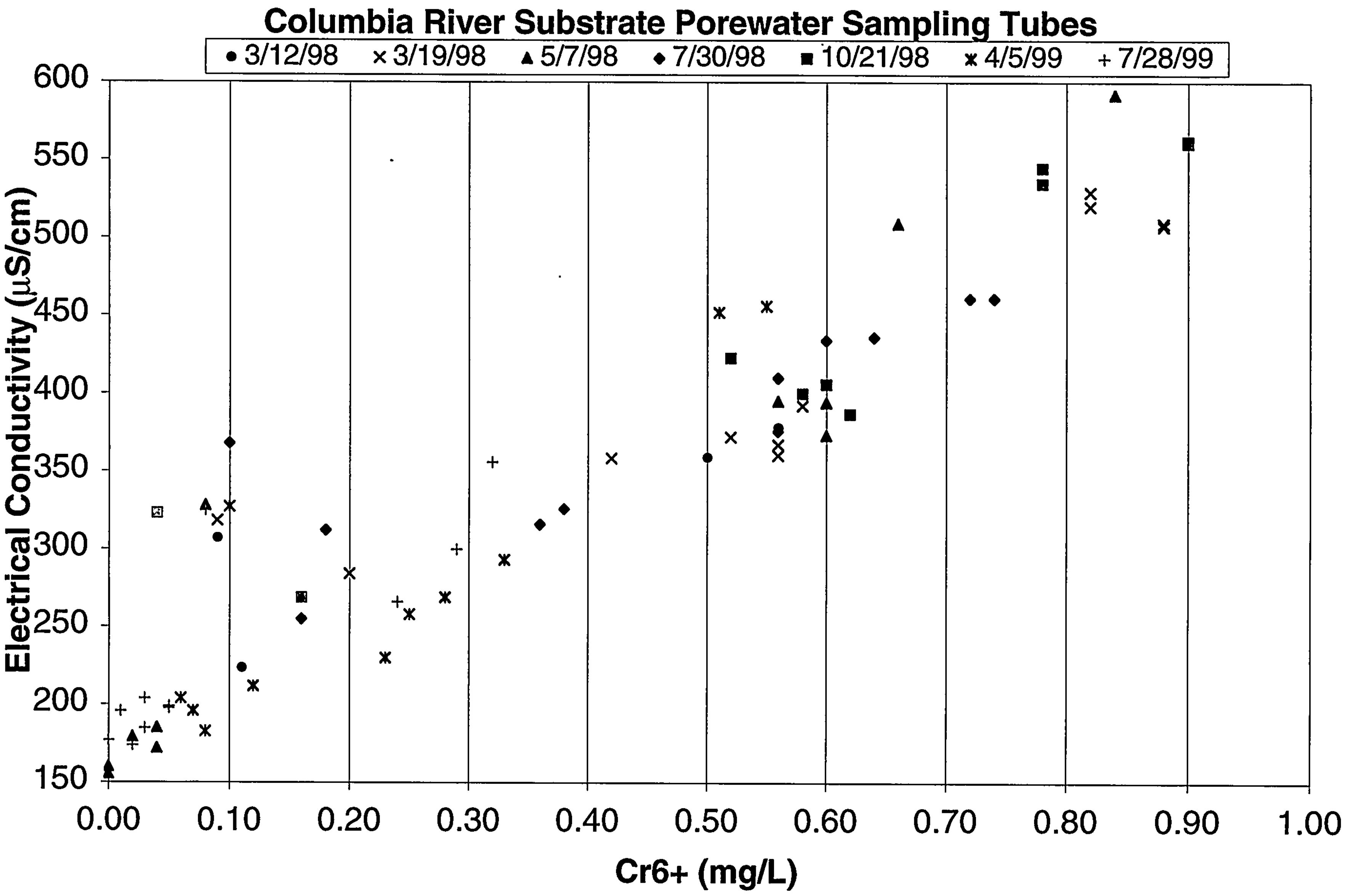


Figure 6.6. Groundwater and River Water Mixing Trends from Columbia River Substrate Pore Water Sampling Tubes

collected for laboratory analysis came from Unit E gravels of the Miocene-Pliocene-age Ringold Formation. All three boreholes were abandoned when drilling and sampling activities were complete.

Cores for laboratory analysis from each hole were obtained using a 5-ft long, 4-in.-diameter split-spoon sampler lined with plastic lexan. Clean lexan liners, precut to 0.5 ft, were used to line the inside of the split spoon. Once the casing was advanced and the hole cleaned out, the split-spoon sampler was driven (i.e., vibrated) 5 ft into the underlying undisturbed material. Upon bringing the split-spoon assembly to the surface, the head, shoe, and top half of the split spoon were removed. The lower half of the split spoon, containing the sediment-filled 0.5 ft lexan liners, was immediately placed inside an argon-filled glovebox located onsite. Within the glovebox, the outsides of the individual liners were cleaned off and labeled with borehole number, depth interval, and an "up" arrow. Next, the samples for reductive capacity analysis were identified; normally, every other 0.5 ft segment was selected. Preference was given to those cores that were from the interior portion of the 5-ft core or appeared to be more reduced, avoiding the ends, which have a higher probability of containing disturbed sloughed material, or partially empty liners. Normally, five core segments were selected for potential reductive capacity analysis from each split-spoon. Prior to removal from the glovebox, the reductive-capacity core segments were capped with plastic endcaps and secured with duct tape. After the glovebox was opened these samples were immediately transferred to argon-filled Zip-Loc bags and placed into a cooler on ice. At the end of each day's sampling all cores for reductive capacity analysis were transported to an anoxic glovebox, specifically designated for the 100-D Area cores at PNNL in Richland.

The sediment oxidation studies of the reduced cores collected from the treatment zone were conducted in 1-D columns to determine the rate at which the dithionite-reduced sediments are oxidized and to provide an additional measure of the mass of reduced iron (see Section 4.2). This method was considered the most accurate measurement of the reduced iron mass in the field dithionite-treated sediment. These experiments consisted of injecting oxygen-saturated (8.4 mg L^{-1} or 256 μmol L^{-1}) synthetic groundwater at a steady rate into a reduced sediment column and measuring the concentration of dissolved oxygen over time in the effluent for 100 to 400 hours. The flux rate was chosen to achieve specific residence times of the dissolved oxygen in the column relative to the oxidation rate(s) of the sediment.

The field-reduced sediment samples averaged 11.2 ± 7.4 μmol Fe(II) per gram of sediment (whole sediment), with a range of 2.5 to 20.3 μmol/g (Table 6.3 and Appendix H). In one of the core samples the fraction of reducible iron mass in the sample was calculated from additional experiments in which the field-reduced sediment, after being oxidized to determine the mass of field-reduced iron, was re-reduced in the laboratory and oxidized a second time. The results of this analysis for core hole B8775 at 82.8 ft indicated that 75 percent of the potential reducible Fe(III) of the sample was reduced in the field (16.5 μmole Fe/g field-reduced versus 22 μmol Fe/g lab-reduced).

The average potential reducible iron capacity of the sediments at the site was 11.0 ± 3.0 μmol Fe(III) per gram of soil (as determined by bench-scale reduction and oxidation experiments of sediment cores collected prior to ISRM barrier emplacement, as discussed in Section 4). The average reductive capacity of the field-reduced sediment (11.2 ± 7.4 μmol/g) was similar to the average potential reductive capacity determined for the site sediments (11.0 ± 3.0 4 μmol/g), indicating the dithionite injection strategy was effective at reducing the targeted aquifer sediments for creation of the ISRM treatment zone.

The variability in the field-reduced sediment illustrates the heterogeneity in the unconfined aquifer at 100-D Area (see Table 6.3). In core holes B8776 and B8777, the deeper portions of the aquifer had a greater treatment capacity than the upper portions of the aquifer. Alternatively, in core hole B8775, the samples from the center to upper portion of the aquifer had a greater treatment capacity than the deepest sample. No clear trend was evident in the field reductive capacity measurements based on the locations of the core holes relative to the injection/withdrawal wells in these data either (see Figure 1.6 for locations). The spatial distribution of reductive capacity is a function of heterogeneities in both the reducible Fe(III) content of the sediment and in hydraulic properties, which impact the dithionite concentrations and contact times that the sediment is exposed to during injection. With a homogeneous site, a higher percentage of reduction would be expected for samples from locations close to the injection/withdrawal well (e.g., core hole B8776) than the more distal locations, given the greater concentrations and contact time these proximal sediments were exposed to during injection/withdrawal operations. A clear trend in decreasing percent reduction with increasing radial distance was demonstrated by the post-emplacement reductive capacity measurements at the 100-H Area ISRM site (Fruchter et al. 1996; 2000), but only after the reductive capacity measurements were normalized to the maximum reductive capacity of the sample, which accounts for the spatial variability in reducible iron content. Because most of the field-treated core samples in this study were not subjected to the additional analysis required to normalize the reductive capacity to the maximum achievable capacity of the sample, it could not be determined whether this same trend of decreasing capacity with distance was established at the 100-D Area treatability test site.

The barrier longevity was estimated from the mass of reducible iron determined in the field-reduced sediments. Given the 11.2 ± 7.4 μmol/g of reducible iron (whole sediment), the barrier should reduce chromate for an estimated 174 pore volumes (using 14 percent porosity, 2.3 g/cm^3 dry bulk density, and groundwater concentrations of 8 mg/L dissolved oxygen and 1 mg/L hexavalent chromium). Assuming this average reductive capacity was attained for a 50-ft width at the 100-D Area site, the predicted longevity of the 100-D Area ISRM permeable treatment zone is 23 years (using a 1 ft/day groundwater velocity).

6.4 Natural Gradient Tracer Test

A natural gradient tracer test was conducted at the ISRM treatability test site on May 15, 1999. The test was designed to provide additional information on the hydraulic performance of the emplaced treatment zone. As discussed in Section 3.2, comparison of pre- and post-injection pressure response data indicated that injection of the sodium dithionite reagent resulted in no significant degradation in the overall hydraulic performance of the treatment zone. To verify these results, a natural gradient tracer test was conducted which consisted of injecting a tracer solution on the upgradient side of the treatment zone and monitoring tracer concentration as it migrated into and through the treatment zone.

Table 6.3. Summary of Reductive Capacity Measurements on Sediment Samples from the 100-D Area ISRM Treatment Zone (see Figure 1.6 for core hole locations)

Core Hole ID	**Depth** (ft)	**< 4 mm Fe(II) Lab Oxidized** (μmol/g)	**Whole Sediment Fe(II) Reduced** (μmol/g)
B8776	90.0	14.7	6.42
	94.8	46.0	17.6
B8777	85.0	9.95	3.72
	90.0	16.3	5.81
	95.0	40.2	17.5
B8775	82.8	35.7	16.5
	88.0	45.9	20.3
	93.0	5.13	2.23
Lab Reduced B8775	82.8	47.5	22.0
Lab Reduced B8776	84.5	38.4	14.0

The natural gradient tracer test consisted of injecting 3600 gallons of potassium bromide solution with a bromide ion concentration of approximately 110 mg/L into a well upgradient of the treatment zone (199-D4-2, see Figure 1.6). The tracer was injected at a rate of 20 gpm, which resulted in an injection duration of three hours. The tracer was then allowed to drift under natural gradient conditions through the treatment zone and toward a downgradient monitoring well (199-D4-5). During the tracer injection and subsequent drift period, tracer was measured continuously in the injection well, treatment zone wells (D4-3, D4-7, and D4-9) and downgradient wells using an in situ ion selective electrode (TEMPHION™, Instrumentation Northwest Inc.) Throughout the test, verification samples were also collected using dedicated submersible pumps for analysis using bench-top ion selective electrodes (Cole Parmer, Br^-) and ion chromatography.

Tracer concentration data for wells monitored during the natural gradient tracer test are shown in Figure 6.7. For clarity of presentation, only the in situ ion selective electrode data are displayed for most wells. These data provide the only continuous record of bromide concentration in the monitored wells and the general shape of these curves is supported by the bench-top ion selective electrode and ion chromatography verification data. By day 13 of the test, water samples collected from well D4-5 on the downgradient side of the barrier indicated the arrival of tracer. Therefore, an in situ ion selective electrode was removed from well D4-2 and installed in D4-5. Bromide data for well D4-5 shown in Figure 6.7 prior to day 13 are from water samples collected from the well and measured in the field laboratory with a bench-top ion selective electrode.

Due to formation heterogeneity at the site, tracer breakthrough was observed at all of the treatment zone monitoring wells during the injection phase of the tracer experiment. Monitoring well D4-3 reached injection concentration, and D4-9 and D4-7 saw concentrations of approximately 50 and 20 percent of the injection concentration, respectively. Concentrations in RM-7 continued to increase over the first seven days of the drift phase, indicating that tracer was moving into the treatment zone. By day 14, samples collected from the downgradient well

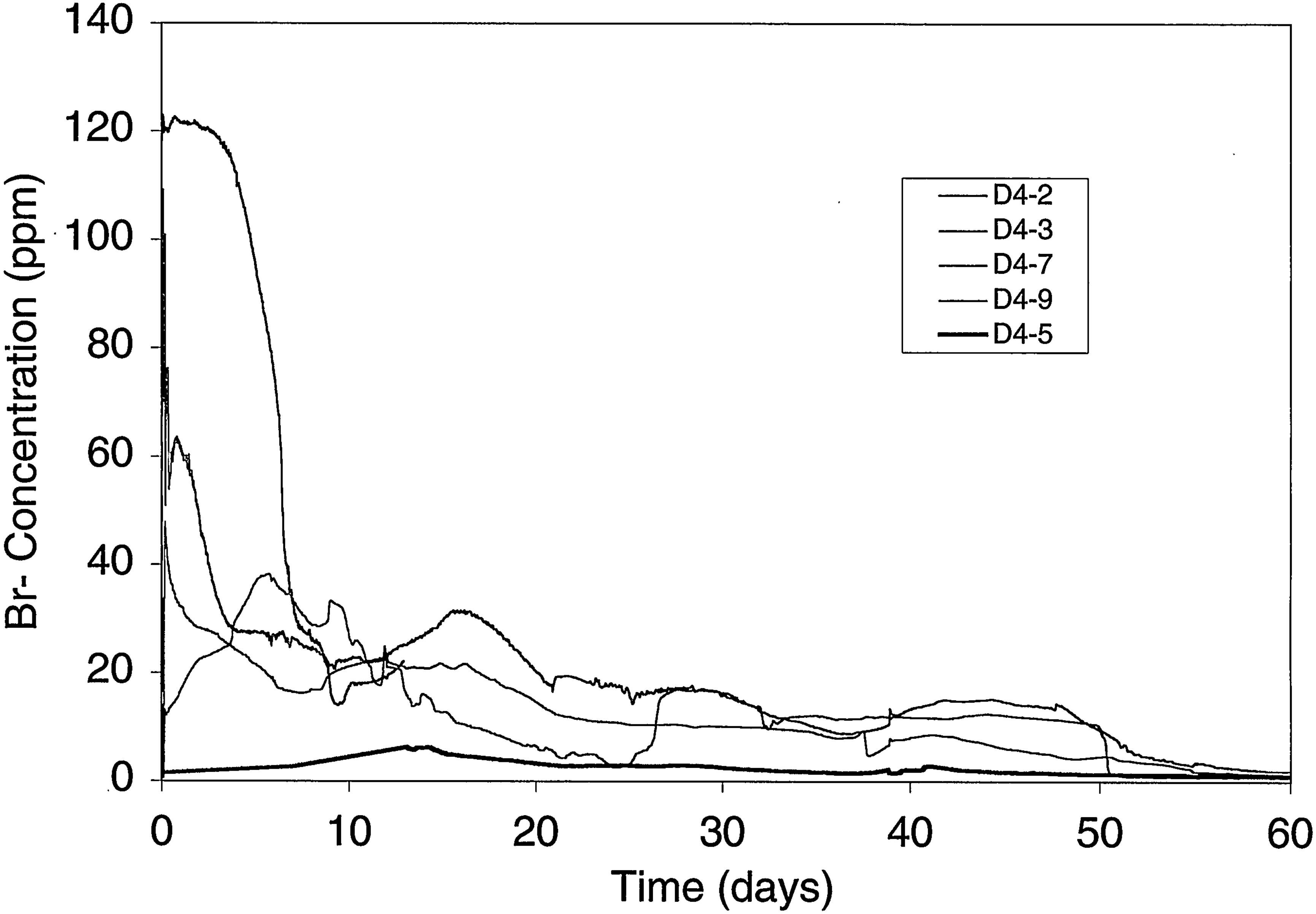


Figure 6.7. Bromide Concentration Data for the Injection Well (D4-2), Treatment Zone Wells (D4-3, D4-7, and D4-9), and Downgradient Monitoring Well (D4-5)

(D4-5) showed a measurable increase in bromide concentration, indicating that tracer had been transported through the treatment zone and migrated downgradient under natural conditions.

Bromide concentration data from wells within the treatment zone indicate that some time between day 7 and day 14 there may have been a significant change in groundwater flow direction that complicated interpretation of the results. This is consistent with groundwater flow direction and magnitude calculation results from water-level measurements made on monitoring wells during the tracer test (Figure 6.8). Pre-test conditions (May 14, 1999) indicate that groundwater was flowing in the prevailing direction at 0.5 ft/day, approximately one-half the previously measured average groundwater velocity (see Figure 3.1); water-level measurements collected on day six of the tracer test indicated similar conditions. However, water-level measurements collected on days 12 and 21 indicated a significant deviation from the prevailing groundwater flow direction. This variability in groundwater flow direction is associated with high Columbia River stage conditions. A comparison of groundwater flow data presented in Figures 3.1 and 6.8 provides a measure of the temporal variability in groundwater flow direction and magnitude at the site.

Due to other activities at the field site, the natural gradient tracer test could not be conducted until early spring, 1999. Although spring is not the ideal time to conduct this type of test, the plan was to start it early enough that the test objectives would be met prior to Columbia River high water stage, and subsequent groundwater flow reversal, associated with spring runoff. If additional natural gradient tracer tests are required at this site, they should be planned for the fall or winter months.

Because of the formation heterogeneities at the site and temporal variability in the groundwater flow direction, this test did not provide a quantitative estimate of effective porosity or groundwater velocity beneath the ISRM treatability test site. However, the data obtained were sufficient to meet the primary objective of the test; arrival of tracer in wells within the treatment zone and in the downgradient monitoring well, along with comparisons of pre- and post-injection hydraulic test data, indicates that emplacement of the ISRM treatment zone resulted in no significant degradation in the overall hydraulic performance of the aquifer.

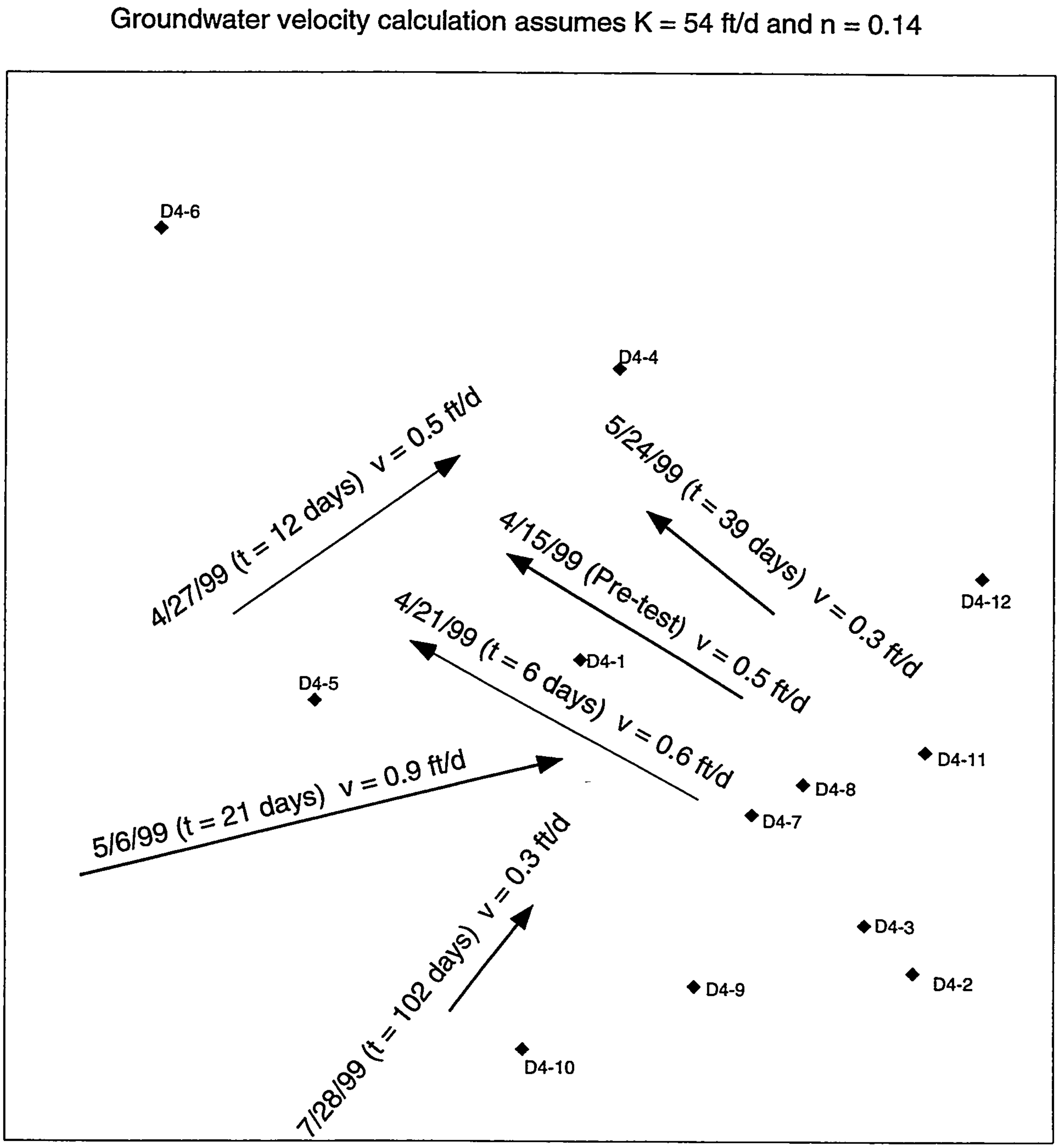


Figure 6.8. Groundwater Flow Directions and Magnitudes Measured During the Natural Gradient Tracer Test at the 100-D Area ISRM Site

7.0 Treatability Test Summary

Five dithionite injection/withdrawal operations (as shown in Figure 1.6) were designed to create a reduced zone in the aquifer approximately 150 ft long (perpendicular to groundwater flow), 50 ft wide, and 15 ft thick, extending over the thickness of the unconfined aquifer. Well installation for the 100-D Area ISRM treatability test started in the spring of 1997. Well installation and site characterization activities continued through the summer and were completed in November 1997. Characterization activities included sediment core sample collection, hydraulic testing, establishing baseline aqueous geochemistry, and conducting a tracer injection test. The first dithionite injection/withdrawal operation took place during September and October of 1997; ground water monitoring was conducted from the fall of 1997 to the spring of 1998. The remaining four dithionite injection/withdrawal tests were conducted from May to July 1998.

Analysis of the post-emplacement groundwater sampling at the site showed Cr(VI) concentrations below detection limits (0.007 mg/L) within the treatment zone. Average baseline concentrations were 1.0 mg/L. Cr(VI) concentrations have also declined in the downgradient wells to as low as 0.02 mg/L over the duration of this study. Dissolved oxygen concentrations are also significantly lower within the treatment zone and downgradient wells from the baseline values. Predictions from numerical modeling resulted in dissolved oxygen concentrations from 75 to 95 percent of saturation by the time the groundwater discharges to the Columbia River (Williams et al. 1999b). Sulfate, sodium, and potassium concentrations are elevated at the site from the dithionite residuals. Major trace metals involved in the redox process (iron, manganese) are elevated above baseline values in the reduced zone due to dissolution of iron and manganese oxides by the dithionite solution and the enhanced solubility of these naturally occurring oxides in the aquifer sediments under reducing conditions. Although these metals are elevated in the treatment zone, they are probably not mobilized a substantial distance downgradient from the reduced zone due to their high retardation factors and re-precipitation once they contact oxidizing sediments outside the zone.

Laboratory analysis of sediment collected from the aquifer during the initial site characterization activities measured the average potential average reductive capacity of the sediment was 11.0 ± 3.0 μmol Fe(III) per gram of sediment. Following treatment zone creation, sediment samples were collected from core holes within the reduced zone to measure the reductive capacity of the sediment that was achieved by the treatability test dithionite injection/withdrawal operations. The average reductive capacity of the field-reduced sediment (11.2 ± 7.4 μmol/g) was similar to the average potential reductive capacity determined for the site sediments, indicating the dithionite injection strategy was effective at reducing the targeted aquifer sediments for creation of the ISRM treatment zone. The range in the results of these analyses, and as measured in breakthrough curves during field tracer and dithionite injection tests, are a function of the physical and chemical heterogeneities at the site.

Barrier longevity was estimated from the reductive capacity of the field-reduced sediments. Using 11.2 μmol Fe(II) per gram of sediment, the treatment zone should reduce chromate for an estimated 174 pore volumes (using 14 percent porosity, 2.3 g/cm^3 dry bulk density, and groundwater concentrations of 8 mg/L dissolved oxygen and 1 mg/L Cr(VI)). Assuming this average reductive capacity was attained for a 50-ft width at the 100-D Area site, the predicted longevity of the 100-D Area ISRM permeable treatment zone is 23 years (using a 1 ft/day groundwater velocity).

Groundwater monitoring at the site continued on a quarterly basis through FY 1999 as part of this treatability test. After that time, monitoring of a selected set of wells from the ISRM site was transferred to the Hanford Sitewide Groundwater Monitoring Program and will be reported in the annual groundwater monitoring reports (e.g., see Figure 2.5-9 in Hartman et al. 2000). Additional upgradient and downgradient wells were installed at the 100-D Area ISRM site in the summer of 1999 at distances greater than the existing well network.

Based on the successful results of this ISRM treatability study and a cost analysis, a proposal was submitted and funded by the Accelerated Site Technology Deployment Initiative (ASTD) to expand the length of the 100-D Area ISRM barrier to treat a larger portion of the plume (Tortoso et al. 1998). This joint EM-40 and EM-50 project will expand the length of the 100-D Area ISRM barrier up to 2,300 ft parallel to the Columbia River. This action required modifications to the existing Record of Decision (ROD) (DOE 1995), resulting in a new plan, "*Proposed Plan for an Amendment of the Interim Remedial Action at the 100-HR-3 Operable Unit*" (DOE 1999; EPA 1999). A report describing the objectives, design, and sampling and analysis plan for this expansion was also prepared (DOE 2000).

8.0 References

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Appendix A

Well Summary Diagrams

Pacific Northwest National Laboratory

WELL COMPLETION SUMMARY

Page 1 of 1

Project In-Situ Redox Manipulation
Location Hanford Site, 100-D Area
Drilling Co. Layne Christenson
Driller(s) Willie Franklin, Randy Smith, Dean Walton
Other (companies)
Geologist(s) SS Teel

Well No. 199-D4-2 Temp. Well No. B8058
Coordinates E: 1,879,253.025 ft N: 497,215.743 ft
Elevation: Casing 474.259 ft Survey Marker 471.647 ft
Coordinate System: Washington State Plane Coordinates (South Zone)

DRILLING METHOD

Drilling Method(s) ODEX air rotary w/downhole hammer
Drilling Fluid Air
Other

COMPLETION DATA

Drilled Depth (ft) 100
Completed Depth (ft) 99
Date Started 5/6/97
Date Completed 5/22/97
Static Water Level (ft) 79.81 Date 5/9/97

OTHER (check if performed)

	Well Abandonment		Manhole Cover
X	Well Development		Pad w/Manhole Cover
X	Aquifer Testing	X	Pad (05/22/97)
	Geophysical Log(s)	X	Guardposts
X	Lock and Cap	X	Protective Casing

SCREEN

0.15 ft blank: bottom of screen to bottom joint.
0.35 ft blank: top of screen to top joint.

Type	Cap (ft)	Outer Dia. (in.)	Length (ft)	Slot Size	Interval (ft) Joint-to-Joint	Interval (ft) Slot-to-Slot
Continuous wire wrap PVC (Johnson brand)	0.37	4	4.98	20	93.65 - 99.00	94.0 - 98.5
Continuous wire wrap PVC (Johnson brand)		4	4.98	20	83.65 - 88.63	84.0 - 88.5

TEMPORARY CASING

Type	Nominal Dia. (in.)	Max. Outer Dia. (in.)	Interval (ft)
Threaded Carbon Steel	8		0 - 100
			-

PERMANENT CASING

Type	Nominal Dia. (in.)	Max. Outer Diameter	Interval (ft)
Sch. 40 PVC	4		88.63 - 93.65
Sch. 40 PVC	4		+1.54 - 83.65
Steel Protective Casing	6		+3 -

ANNULAR SEAL/FILL

Type	Interval (ft)	Quantity	Volume (ft^3)
10-20 Colorado Silica Sand	92.5 - 100	2.6 Bags (100#)	2.78
Slough	91.8 92.5	Not Measured	-----
1/4-in Bentonite Pellets	88.75 - 91.8	3/4 Bucket (50#)	0.5
10-20 Colorado Silica Sand	81.3 - 88.75	3.4 Bags	3.64
1/4-in Bentonite Pellets	77.9 - 81.3	5.75 Buckets	57
Cement grout	0 - 77.9	~270 Gal.	~36
Concrete pad (6" thick, w/survey marker)	-		

PUMP

Type None Depth to Inlet Date Set

ACCEPTANCE

Completed Well: Accept Conditionally Accept
Reject

COMMENTS

Well depth (bls, measured 08/21/97) = 100.54' (casing string) + 1.46' (distance from TOC-4" to TOC-6") - 3' (6" casing stick-up) = 99'

Reviewed by Date *Depths are below land surface unless noted.*

Pacific Northwest National Laboratory

WELL COMPLETION SUMMARY

Page 1 of 1

Project In-Situ Redox Manipulation
Location Hanford Site, 100-D Area
Drilling Co. Layne Christenson
Driller(s) Willie Franklin, Randy Smith
Other (companies)
Geologist(s) SS Teel

Well No. 199-D4-3 Temp. Well No. B8059
Coordinates E: 1,879,245.492 ft N: 497,222.820 ft
Elevation: Casing 474.042 ft Survey Marker 471.365 ft
Coordinate System: Washington State Plane Coordinates (South Zone)

DRILLING METHOD

Drilling Method(s) ODEX air rotary w/downhole hammer
Drilling Fluid Air
Other Water added during completion to equalize potentiometric surface.

COMPLETION DATA

Drilled Depth (ft) 102
Completed Depth (ft) 99.06
Date Started 5/9/97
Date Completed 5/17/97
Static Water Level (ft) 79.15 Date 5/13/97

OTHER (check if performed)

	Well Abandonment		Manhole Cover
X	Well Development		Pad w/Manhole Cover
X	Aquifer Testing	X	Pad
	Geophysical Log(s)	X	Guardposts
X	Lock and Cap	X	Protective Casing

SCREEN

0.15 ft blank: bottom of screen to bottom joint.
0.35 ft blank: top of screen to top joint.

Type	Cap (ft)	Outer Dia. (in.)	Length (ft)	Slot Size	Interval (ft) Joint-to-Joint	Interval (ft) Slot-to-Slot
Continuous wire wrap PVC (Johnson brand)	0.37	4	4.98	20	93.71 - 99.06	94.1 - 98.5
Continuous wire wrap PVC (Johnson brand)		4	4.98	20	83.71 - 88.69	84.1 - 88.5

TEMPORARY CASING

Type	Nominal Dia. (in.)	Max. Outer Dia. (in.)	Interval (ft)
Threaded Carbon Steel	8	(0.72 ft)	0 - 102
			-

PERMANENT CASING

Type	Nominal Dia. (in.)	Max. Outer Diameter	Interval (ft)
Sch. 40 PVC	4		88.69 - 93.71
Sch. 40 PVC	4		+2.6 - 83.71
Threaded Steel Protective Casing	6		+3.1 - 5.8

ANNULAR SEAL/FILL

Type	Interval (ft)	Quantity	Volume (ft^3)
10-20 Colorado Silica Sand	92.6 - 102	3.25 Bags	3.48
1/4-in Bentonite Pellets	88.5 - 92.6	0.5 Bucket	0.31
10-20 Colorado Silica Sand	81.4 - 88.5	2.25 Bags	2.41
1/4-in Bentonite Pellets	78.0 - 81.4	4.5 Buckets	2.79
Cement Grout	6 - 78.0	36 Bags	~325 Gal.
Backfill and Concrete (outside 6-in casing)	0 - 6	12 Bags (Sackcrete)	Not Measured
Cement Grout (within annulus of 4-in and 6-in casing)	0 - 5.8	Not Measured	Not Measured
Concrete Pad (6" thick, w/survey marker)	-		

PUMP

Type None Depth to Inlet Date Set

ACCEPTANCE

Completed Well: Accept Conditionally Accept
Reject

COMMENTS

Well depth (bls, measured 05/27/97) = 101.66' (casing string) + 0.5' (distance from TOC-4" to TOC-6") - 3.1' (6" casing stick-up) = 99.06'

Reviewed by Date *Depths are below land surface unless noted.*

Pacific Northwest National Laboratory

WELL COMPLETION SUMMARY

Page 1 of 1

Project In-Situ Redox Manipulation
Location Hanford Site, 100-D Area
Drilling Co. Layne Christenson
Driller(s) Willie Franklin, Randy Smith
Other (companies)
Geologist(s) SS Teel

Well No. 199-D4-4 Temp. Well No. B8060
Coordinates E: 1,879,207.882 ft N: 497,306.449 ft
Elevation: Casing 473.517 ft Survey Marker 470.574 ft
Coordinate System: Washington State Plane Coordinates (South Zone)

DRILLING METHOD

Drilling Method(s) ODEX air rotary
Drilling Fluid Air
Other

COMPLETION DATA

Drilled Depth (ft) 102
Completed Depth (ft) 98.22
Date Started 5/13/97
Date Completed 5/22/97
Static Water Level (ft) 77.84 Date 5/19/97

OTHER (check if performed)

___ Well Abandonment
___ Well Development
___ Aquifer Testing
___ Geophysical Log(s)
X Lock and Cap
___ Manhole Cover
___ Pad w/Manhole Cover
X Pad
X Guardposts
X Protective Casing

SCREEN

0.16 ft blank: bottom of screen to bottom joint.
0.37 ft blank: top of screen to top joint.

Type	Cap (ft)	Outer Dia. (in.)	Length (ft)	Slot Size	Interval (ft) Joint-to-Joint	Interval (ft) Slot-to-Slot
Continuous wire wrap PVC (Johnson brand)	0.35	4	9.99	20	87.88 - 98.22	88.3 - 97.7
Continuous wire wrap PVC (Johnson brand)		4	10.00	20	77.88 - 87.88	78.3 - 87.7

TEMPORARY CASING

Type	Nominal Dia. (in.)	Max. Outer Dia. (in.)	Interval (ft)
Threaded Steel	8		0 - 101.9
			-

PERMANENT CASING

Type	Nominal Dia. (in.)	Max. Outer Diameter	Interval (ft)
Sch. 40 PVC	4		+2.2 - 77.88
Protective Casing	6		+3.3 - 2.48
			-

ANNULAR SEAL/FILL

Type	Interval (ft)	Quantity	Volume (ft^3)
10-20 Colorado Silica Sand	73.7 - 102	11 Bags	11.77
1/4-in and 1/2-in Bentonite Pellets	68.0 - 73.7	2.5 Buckets	1.5
Cement Grout	0.0 - 68.0	27 Bags	~243 Gal
Concrete Pad (6" thick, w/survey marker)	-		
	-		
	-		
	-		
	-		

PUMP

Type None Depth to Inlet Date Set

ACCEPTANCE

Completed Well: Accept Conditionally Accept
Reject

COMMENTS

Well depth (bls, measured 05/19/97) = 100.42' (casing string) + 1.1' (distance from TOC-4" to TOC-6") - 3.3' (6" casing stick-up) = 98.22'

Reviewed by Date *Depths are below land surface unless noted.*

Pacific Northwest National Laboratory

WELL COMPLETION SUMMARY

Page 1 of 1

Project In-Situ Redox Manipulation
Location Hanford Site, 100-D Area
Drilling Co. Layne Christenson
Driller(s) Willie Franklin, Randy Smith
Other (companies)
Geologist(s) SS Teel

Well No. 199-D4-5 Temp. Well No. B8061
Coordinates E: 1,879,161.722 ft N: 497,256.877 ft
Elevation: Casing 472.966 ft Survey Marker 470.197 ft
Coordinate System: Washington State Plane Coordinates (South Zone)

DRILLING METHOD

Drilling Method(s) ODEX air rotary w/downhole hammer
Drilling Fluid Air
Other

COMPLETION DATA

Drilled Depth (ft) 100.2
Completed Depth (ft) 98.2
Date Started 5/17/97
Date Completed 5/22/97
Static Water Level (ft) 76.44 Date 5/27/97

OTHER (check if performed)

	Well Abandonment		Manhole Cover
	Well Development		Pad w/Manhole Cover
	Aquifer Testing	X	Pad
	Geophysical Log(s)	X	Guardposts
X	Lock and Cap	X	Protective Casing

SCREEN

0.15 ft blank: bottom of screen to bottom joint.
0.35 ft blank: top of screen to top joint.

Type	Cap (ft)	Outer Dia. (in.)	Length (ft)	Slot Size	Interval (ft) Joint-to-Joint	Interval (ft) Slot-to-Slot
Continuous wire wrap PVC (Johnson brand)	0.37	4	9.99	20	87.84 - 98.20	88.2 - 97.7
Continuous wire wrap PVC (Johnson brand)		4	9.99	20	77.85 - 87.84	78.2 - 87.7

TEMPORARY CASING

Type	Nominal Dia. (in.)	Max. Outer Dia. (in.)	Interval (ft)
Threaded Steel	8		0 - 99.5

PERMANENT CASING

Type	Nominal Dia. (in.)	Max. Outer Diameter	Interval (ft)
Sch. 40 PVC	4		+2.5 - 77.85
Threaded Steel (Protective Casing)	6		+3 - 5.0

ANNULAR SEAL/FILL

Type	Interval (ft)	Quantity	Volume (ft^3)
10-20 Colorado Silica Sand	72.5 - 100.2	14 Bags	14.9
1/2-in Bentonite Pellets	68.0 - 72.5	2.5 Buckets	1.5
Cement Grout	5 - 68.0	25 Bags	~30 (~225 Gal.)
Backfill (around 6-in casing)	0 - 5	-----	-----
Concrete (within annulus of 4-in and 6-in casing)	0 - 5	Not Measured	Not Measured
Concrete Pad (~3" thick, w/survey marker)	-		

PUMP

Type None Depth to Inlet Date Set

ACCEPTANCE

Completed Well: Accept Conditionally Accept
Reject

COMMENTS

Well depth (bls, measured 05/16/97) = 100.7' (casing string) + 0.5' (distance from TOC-4" to TOC-6") - 3' (6" casing stick-up) = 98.2'

Reviewed by Date *Depths are below land surface unless noted.*

Pacific Northwest National Laboratory

WELL COMPLETION SUMMARY

Page 1 of 1

Project In-Situ Redox Manipulation
Location Hanford Site, 100-D Area
Drilling Co. Layne Christenson
Driller(s) Willie Franklin, Randy Smith
Other (companies)
Geologist(s) SS Teel

Well No. 199-D4-6 Temp. Well No. B8064
Coordinates E: 1,879,138.089 ft N: 497,327.152 ft
Elevation: Casing 472.539 ft Survey Marker 470.102 ft
Coordinate System: Washington State Plane Coordinates (South Zone)

DRILLING METHOD

Drilling Method(s) ODEX air rotary
Drilling Fluid Air
Other

COMPLETION DATA

Drilled Depth (ft) 99.5
Completed Depth (ft) 96.25
Date Started 6/9/97
Date Completed 6/12/97
Static Water Level (ft) 74.3 Date 6/13/97

OTHER (check if performed)

	Well Abandonment		Manhole Cover
	Well Development		Pad w/Manhole Cover
	Aquifer Testing	X	Pad
	Geophysical Log(s)	X	Guardposts
X	Lock and Cap	X	Protective Casing

SCREEN

0.15 ft blank: bottom of screen to bottom joint.
0.35 ft blank: top of screen to top joint.

Type	Cap (ft)	Outer Dia. (in.)	Length (ft)	Slot Size	Interval (ft) Joint-to-Joint	Interval (ft) Slot-to-Slot
Continuous wire wrap PVC (Johnson brand)	0.37	4	9.99	20	85.89 - 96.25	86.2 - 95.7
Continuous wire wrap PVC (Johnson brand)		4	9.99	20	75.90 - 85.89	76.3 - 85.7

TEMPORARY CASING

Type	Nominal Dia. (in.)	Max. Outer Dia. (in.)	Interval (ft)
Threaded Steel Drill Casing	8		0 - 99.5
			-

PERMANENT CASING

Type	Nominal Dia. (in.)	Max. Outer Diameter	Interval (ft)
Sch. 40 PVC	4		+2.6 - 75.90
Carbon Steel (Protective Casing)	8		+3.0 - 2.8 (?)
			-

ANNULAR SEAL/FILL

Type	Interval (ft)	Quantity	Volume (ft^3)
10-20 Colorado Silica Sand	71.6 - 99.5	10.25 Bags (100#)	11.0
1/4-in Bentonite Pellets	66.2 - 71.6	2 Buckets	1.2
Cement Grout	2.5 - 66.2	22 Bags	16.6
Sackrete	~0.5 2.5	Not Measured	-----
Concrete w/Survey Marker	~+0.5 - ~0.5	Not Measured	-----
	-		
	-		
	-		

PUMP

Type None Depth to Inlet Date Set

ACCEPTANCE

Completed Well: Accept Conditionally Accept
Reject

COMMENTS

Well depth (bls, measured 06/13/97) = 98.85' (casing string) + 0.4' (distance from TOC-4" to TOC-8") - 3.0' (8" casing stick-up) = 96.25'

Reviewed by Date *Depths are below land surface unless noted.*

Pacific Northwest National Laboratory

WELL COMPLETION SUMMARY

Page 1 of 1

Project: In-Situ Redox Manipulation
Location: Hanford Site, 100-D Area
Drilling Co.: Layne Christenson
Driller(s): Willie Franklin, Randy Smith
Other (companies):
Geologist(s): SS Teel

Well No. 199-D4-7 Temp. Well No. B8065
Coordinates E: 1,879,228.401 ft N: 497,239.664 ft
Elevation: Casing 473.274 ft Survey Marker 470.364 ft
Coordinate System: Washington State Plane Coordinates (South Zone)

DRILLING METHOD

Drilling Method(s): ODEX air rotary
Drilling Fluid: Air w/Water Assist
Other: Total water added during drilling = ~300 Gal.

COMPLETION DATA

Drilled Depth (ft): 96
Completed Depth (ft): 95.57
Date Started: 6/14/97
Date Completed: 6/17/97
Static Water Level (ft): 74.25 Date 6/20/97

OTHER (check if performed)

___	Well Abandonment	___	Manhole Cover
___	Well Development	___	Pad w/Manhole Cover
___	Aquifer Testing	X	Pad
___	Geophysical Log(s)	X	Guardposts
X	Lock and Cap	X	Protective Casing

SCREEN

0.18 ft blank: bottom of screen to bottom joint.
0.40 ft blank: top of screen to top joint.

Type	Cap (ft)	Outer Dia. (in.)	Length (ft)	Slot Size	Interval (ft) Joint-to-Joint	Interval (ft) Slot-to-Slot
Continuous wire wrap PVC (Johnson brand)	0.45	6	4.98	20	90.14 - 95.57	90.5 - 94.9
Continuous wire wrap PVC (Johnson brand)		6	9.99	20	80.15 - 90.14	80.6 - 90.0

TEMPORARY CASING

Type	Nominal Dia. (in.)	Max. Outer Dia. (in.)	Interval (ft)
Threaded Steel Drill Casing	10	(0.9 ft)	0 - 96.4
			-

PERMANENT CASING

Type	Nominal Dia. (in.)	Max. Outer Diameter	Interval (ft)
Sch. 40 PVC	6		+2.93 - 80.15
Carbon Steel (Protective Casing)	10		+3.4 - 2.6 (?)
			-

ANNULAR SEAL/FILL

Type	Interval (ft)	Quantity	Volume (ft^3)
Slough	95.3 - 96	-----	-----
10-20 Colorado Silica Sand	76.25 - 95.3	8 Bags (100#)	8.6
Slough	74.6 - 76.25	-----	-----
1/4-in Bentonite Pellets	69.7 - 74.6	13.25 Buckets	8.24
Cement Grout	2.5 (?) - 69.7	35 Bags	30.5 (~228 Gal)
Concrete w/Survey Marker	0 - 2.5 (?)	Not Measured	-----
	-		
	-		

PUMP

Type: None Depth to Inlet: ______ Date Set: ______

ACCEPTANCE

Completed Well: Accept ______ Conditionally Accept ______
Reject ______

COMMENTS

Well depth (bls, measured 06/20/97) = 98.50' (casing string) + 0.47' (distance from TOC-6" to TOC-10") - 3.4' (10" casing stick-up) = 95.57'

Reviewed by ______ Date ______ ***Depths are below land surface unless noted.***

Pacific Northwest National Laboratory

WELL COMPLETION SUMMARY

Page 1 of 1

Project In-Situ Redox Manipulation
Location Hanford Site, 100-D Area
Drilling Co. Layne Christenson
Driller(s) Willie Franklin, Randy Smith
Other (companies)
Geologist(s) SS Teel

Well No. 199-D4-8 Temp. Well No. B8066
Coordinates E: 1,879,236.381 ft N: 497,244.235 ft
Elevation: Casing 473.081 ft Survey Marker 470.302 ft
Coordinate System: Washington State Plane Coordinates (South Zone)

DRILLING METHOD

Drilling Method(s) ODEX air rotary
Drilling Fluid Air
Other

COMPLETION DATA

Drilled Depth (ft) 99
Completed Depth (ft) 95.99
Date Started 6/12/97
Date Completed 6/13/97
Static Water Level (ft) 75.25 Date 6/14/97

OTHER (check if performed)

☐	Well Abandonment	☐	Manhole Cover
☐	Well Development	☐	Pad w/Manhole Cover
☐	Aquifer Testing	X	Pad
☐	Geophysical Log(s)	X	Guardposts
X	Lock and Cap	X	Protective Casing

SCREEN

0.15 ft blank: bottom of screen to bottom joint.
0.35 ft blank: top of screen to top joint.

Type	Cap (ft)	Outer Dia. (in.)	Length (ft)	Slot Size	Interval (ft) Joint-to-Joint	Interval (ft) Slot-to-Slot
Continuous wire wrap PVC (Johnson brand)	0.37	4	9.80	20	85.82 - 95.99	86.2 - 95.5
Continuous wire wrap PVC (Johnson brand)		4	9.80	20	76.02 - 85.82	76.4 - 85.7

TEMPORARY CASING

Type	Nominal Dia. (in.)	Max. Outer Dia. (in.)	Interval (ft)
Threaded Steel Drill Casing	8		0 - 99
			-

PERMANENT CASING

Type	Nominal Dia. (in.)	Max. Outer Diameter	Interval (ft)
Sch. 40 PVC	4		+2.75 - 76.02
Carbon Steel (Protective Casing)	8		+3.2 - 2.8
			-

ANNULAR SEAL/FILL

Type	Interval (ft)	Quantity	Volume (ft^3)
10-20 Colorado Silica Sand	71.9 - 99	11.5 Bags (100#)	12.3
1/4-in Bentonite Pellets	66.25 - 71.9	3.5 Buckets (50#)	2.2
Cement Grout	2.5 - 66.2	27 Bags (94#)	23.4 (~175 Gal)
Concrete w/Survey Marker	0 - 2.5	Not Measured	-----
	-		
	-		
	-		
	-		

PUMP

Type None Depth to Inlet N/A Date Set N/A

ACCEPTANCE

Completed Well: Accept Conditionally Accept
Reject

COMMENTS

Well depth (bls, measured 06/14/97) = 98.74' (casing string) + 0.45' (distance from TOC-4" to TOC-8") - 3.2' (8" casing stick-up) = 95.99'

Reviewed by Date

Depths are below land surface unless noted.

Pacific Northwest National Laboratory

WELL COMPLETION SUMMARY

Page 1 of 1

Project: In-Situ Redox Manipulation
Location: Hanford Site, 100-D Area
Drilling Co.: Layne Christenson
Driller(s): Willie Franklin, Randy Smith
Other (companies):
Geologist(s): VR Vermeul
SS Teel

Well No. 199-D4-9 Temp. Well No. B8067
Coordinates E: 1,879,219.667 ft N: 497,213.620 ft
Elevation: Casing 473.980 ft Survey Marker 471.142 ft
Coordinate System: Washington State Plane Coordinates (South Zone)

DRILLING METHOD

Drilling Method(s): ODEX air rotary
Drilling Fluid: Air w/Water Assist
Other: Total water added during drilling = ~800 Gal.

COMPLETION DATA

Drilled Depth (ft): 97.5
Completed Depth (ft): 96.66
Date Started: 6/18/97
Date Completed: 6/20/97
Static Water Level (ft): 75.5 Date 6/20/97

OTHER (check if performed)

	Well Abandonment		Manhole Cover
	Well Development		Pad w/Manhole Cover
	Aquifer Testing	X	Pad
	Geophysical Log(s)	X	Guardposts
X	Lock and Cap	X	Protective Casing

SCREEN

0.18 ft blank: bottom of screen to bottom joint.
0.40 ft blank: top of screen to top joint.

Type	Cap (ft)	Outer Dia. (in.)	Length (ft)	Slot Size	Interval (ft) Joint-to-Joint	Interval (ft) Slot-to-Slot
Continuous wire wrap PVC (Johnson brand)	0.44	6	4.98	20	91.24 - 96.66	91.6 - 96.0
Continuous wire wrap PVC (Johnson brand)		6	9.97	20	80.27 - 90.24	80.7 - 90.1

TEMPORARY CASING

Type	Nominal Dia. (in.)	Max. Outer Dia. (in.)	Interval (ft)
Threaded Steel Drill Casing	10	(0.9 ft)	0 - 97.5
			-

PERMANENT CASING

Type	Nominal Dia. (in.)	Max. Outer Diameter	Interval (ft)
Sch. 40 PVC	6		+2.9 - 80.27
Carbon Steel (Protective Casing)	10		+3.3 - 2.7 (?)
			-

ANNULAR SEAL/FILL

Type	Interval (ft)	Quantity	Volume (ft^3)
Slough	97.0 - 97.5	Not Measured	-----
10-20 Colorado Silica Sand	77.1 - 97.0	8.75 Bags (100#)	9.4
Slough	74.9 - 77.1	Not Measured	-----
1/4-in Bentonite Pellets	69.0 - 74.9	17 Buckets	10.5
Cement Grout	1 - 69.0	36 Bags	31.7 (~234 Gal)
Concrete w/Survey Marker	0 - 1	Not Measured	-----
	-		
	-		
	-		

PUMP

Type: None Depth to Inlet: Date Set:

ACCEPTANCE

Completed Well: Accept ______ Conditionally Accept ______
Reject ______

COMMENTS

Well depth (bls, measured 06/20/97) = 99.56' (casing string) + 0.4' (distance from TOC-6" to TOC-10") - 3.3' (10" casing stick-up) = 99.66'

Reviewed by ______ Date ______ ***Depths are below land surface unless noted.***

Pacific Northwest National Laboratory

WELL COMPLETION SUMMARY

Page 1 of 1

Project In-Situ Redox Manipulation
Location Hanford Site, 100-D Area
Drilling Co. Layne Christenson
Driller(s) Willie Franklin, Randy Smith
Other (companies)
Geologist(s) BN Bjornstad
TL Liikala
VR Vermeul

Well No. 199-D4-10 Temp. Well No. B8068
Coordinates E: 1,879,193.560 ft N: 497,204.187 ft
Elevation: Casing 473.304 ft Survey Marker 470.623 ft
Coordinate System: Washington State Plane Coordinates (South Zone)

DRILLING METHOD

Drilling Method(s) ODEX air rotary
Drilling Fluid Air
Other

COMPLETION DATA

Drilled Depth (ft) 98.9
Completed Depth (ft) 96.7
Date Started 6/30/97
Date Completed 7/1/97
Static Water Level (ft) 75.9 Date 7/1/97

OTHER (check if performed)

	Well Abandonment		Manhole Cover
	Well Development		Pad w/Manhole Cover
	Aquifer Testing	X	Pad
	Geophysical Log(s)	X	Guardposts
X	Lock and Cap	X	Protective Casing

SCREEN

0.18 ft blank: bottom of screen to bottom joint.
0.40 ft blank: top of screen to top joint.

Type	Cap (ft)	Outer Dia. (in.)	Length (ft)	Slot Size	Interval (ft) Joint-to-Joint	Interval (ft) Slot-to-Slot
Continuous wire wrap PVC (Johnson brand)	0.45	6	4.98	20	91.27 - 96.7	91.7 - 96.1
Continuous wire wrap PVC (Johnson brand)		6	9.98	20	81.29 - 91.27	81.7 - 91.1

TEMPORARY CASING

Type	Nominal Dia. (in.)	Max. Outer Dia. (in.)	Interval (ft)
Threaded Steel Drill Casing	10	(0.9 ft)	0 - 97.5
			-

PERMANENT CASING

Type	Nominal Dia. (in.)	Max. Outer Diameter	Interval (ft)
Sch. 40 PVC	6		+2.7 - 81.29
Carbon Steel (Protective Casing)	10		+3.1 - 2.9
			-

ANNULAR SEAL/FILL

Type	Interval (ft)	Quantity	Volume (ft^3)
10-20 Colorado Silica Sand	76.4 - 97.9	9 Bags (100#)	9.6
1/4-in Bentonite Pellets	70.2 - 76.4	17 Buckets	10.5
Cement Grout	1 - 69.0	36 Bags	31.3
Concrete w/Survey Marker	0 - 1	Not Measured	-----
	-		
	-		
	-		
	-		
	-		

PUMP

Type None Depth to Inlet Date Set

ACCEPTANCE

Completed Well: Accept Conditionally Accept
Reject

COMMENTS

Well depth (bls, measured 09/03/97) = 99.40' (casing string) - 2.7' (6" casing stick-up) = 96.7

Reviewed by Date

Depths are below land surface unless noted.

Pacific Northwest National Laboratory

WELL COMPLETION SUMMARY

Page 1 of 1

Project: In-Situ Redox Manipulation
Location: Hanford Site, 100-D Area
Drilling Co.: Layne Christenson
Driller(s): Willie Franklin, Randy Smith
Other (companies):
Geologist(s): SS Teel

Well No. 199-D4-11 Temp. Well No. B8069
Coordinates E: 1,879,254.892 ft N: 497,216.320 ft
Elevation: Casing 473.425 ft Survey Marker 470.420 ft
Coordinate System: Washington State Plane Coordinates (South Zone)

DRILLING METHOD

Drilling Method(s): ODEX air rotary
Drilling Fluid: Air
Other:

COMPLETION DATA

Drilled Depth (ft): 97.8
Completed Depth (ft): 95.84
Date Started: 6/21/97
Date Completed: 6/25/97
Static Water Level (ft): 74.9 Date 6/26/97

OTHER (check if performed)

	Well Abandonment		Manhole Cover
	Well Development		Pad w/Manhole Cover
	Aquifer Testing	X	Pad
	Geophysical Log(s)	X	Guardposts
X	Lock and Cap	X	Protective Casing

SCREEN

0.17 ft blank: bottom of screen to bottom joint.
0.41 ft blank: top of screen to top joint.

Type	Cap (ft)	Outer Dia. (in.)	Length (ft)	Slot Size	Interval (ft) Joint-to-Joint	Interval (ft) Slot-to-Slot
Continuous wire wrap PVC (Johnson brand)	0.45	6	5.00	20	90.39 - 95.84	90.8 - 95.2
Continuous wire wrap PVC (Johnson brand)		6	9.99	20	80.40 - 90.39	80.8 - 90.2

TEMPORARY CASING

Type	Nominal Dia. (in.)	Max. Outer Dia. (in.)	Interval (ft)
Threaded Steel Drill Casing	10	(0.9 ft)	0 - 97.8

PERMANENT CASING

Type	Nominal Dia. (in.)	Max. Outer Diameter	Interval (ft)
Sch. 40 PVC	6		+3.05 - 80.4
Carbon Steel (Protective Casing)	10		+3.45 - 2.6 (?)

ANNULAR SEAL/FILL

Type	Interval (ft)	Quantity	Volume (ft^3)
Slough	97.1 - 97.8	Not Measured	-----
10-20 Colorado Silica Sand	76.6 - 97.1	10 Bags (100#)	10.7
1/4-in Bentonite Pellets	70.7 - 76.6	17 Buckets	10.54
Cement Grout	2.5 (?) - 70.7	36 Bags	31.3 (~234 Gal)
Concrete w/Survey Marker	0 - 2.5 (?)	Not Measured	-----

PUMP

Type: None Depth to Inlet: Date Set:

ACCEPTANCE

Completed Well: Accept Conditionally Accept
Reject

COMMENTS

Well depth (bls, measured 06/26/97) = 98.89' (casing string) + 0.4' (distance from TOC-6" to TOC-10") - 3.45' (10" casing stick-up) = 95.84'
Approximately 160 gal were bailed to settle the sand pack.

Reviewed by Date

Depths are below land surface unless noted.

Pacific Northwest National Laboratory

WELL COMPLETION SUMMARY

Page 1 of 1

Project In-Situ Redox Manipulation
Location Hanford Site, 100-D Area
Drilling Co. Layne Christenson
Driller(s) Willie Franklin, Randy Smith
Other (companies)
Geologist(s) SS Teel
BN Bjornstad

Well No. 199-D4-12 Temp. Well No. B8070
Coordinates E: 1,879,263.564 ft N: 497,275.198 ft
Elevation: Casing 473.839 ft Survey Marker 470.830 ft
Coordinate System: Washington State Plane Coordinates (South Zone)

DRILLING METHOD

Drilling Method(s) ODEX air rotary
Drilling Fluid Air
Other

COMPLETION DATA

Drilled Depth (ft) 97.8
Completed Depth (ft) 97.13
Date Started 6/26/97
Date Completed 6/27/97
Static Water Level (ft) 75.5 Date 6/27/97

OTHER (check if performed)

	Well Abandonment		Manhole Cover
	Well Development		Pad w/Manhole Cover
	Aquifer Testing	X	Pad
	Geophysical Log(s)	X	Guardposts
X	Lock and Cap	X	Protective Casing

SCREEN

0.18 ft blank: bottom of screen to bottom joint.
0.40 ft blank: top of screen to top joint.

Type	Cap (ft)	Outer Dia. (in.)	Length (ft)	Slot Size	Interval (ft) Joint-to-Joint	Interval (ft) Slot-to-Slot
Continuous wire wrap PVC (Johnson brand)	0.45	6	4.99	20	91.69 - 97.13	92.1 - 96.5
Continuous wire wrap PVC (Johnson brand)		6	9.99	20	81.70 - 91.69	82.1 - 91.5

TEMPORARY CASING

Type	Nominal Dia. (in.)	Max. Outer Dia. (in.)	Interval (ft)
Threaded Steel Drill Casing	10		0 - 97.8

PERMANENT CASING

Type	Nominal Dia. (in.)	Max. Outer Diameter	Interval (ft)
Sch. 40 PVC	6		+3 - 81.7
Carbon Steel (Protective Casing)	10		+3.54 - 2.6 (?)

ANNULAR SEAL/FILL

Type	Interval (ft)	Quantity	Volume (ft^3)
10-20 Colorado Silica Sand	76.5 - 98.7	9.5 Bags (100#)	10.2
1/4-in Bentonite Pellets	71.1 - 76.5	15 Buckets	9.3
Cement Grout	1 - 71.1	32 Bags	
Concrete w/Survey Marker	0 - 1'	Not Measured	-----

PUMP

Type None Depth to Inlet Date Set

ACCEPTANCE

Completed Well: Accept Conditionally Accept
Reject

COMMENTS

Well depth (bls, measured 06/27/97) = 100.13' (casing string) - 3' (6" casing stick-up) = 97.13'

Reviewed by Date *Depths are below land surface unless noted.*

Pacific Northwest National Laboratory

WELL COMPLETION SUMMARY

Page 1 of 1

Project In-Situ Redox Manipulation
Location Hanford Site, 100-D Area
Drilling Co. Layne Christenson
Driller(s) Willie Franklin, Randy Smith
Other (companies)
Geologist(s) BN Bjornstad
TL Liikala

Well No. 199-D4-16 Temp. Well No. B8059
Coordinates E: 1,879,214.871 ft N: 497,253.015 ft
Elevation: Casing 473.389 ft Survey Marker 470.587 ft
Coordinate System: Washington State Plane Coordinates (South Zone)

DRILLING METHOD

Drilling Method(s) ODEX air rotary
Drilling Fluid Air
Other

COMPLETION DATA

Drilled Depth (ft) 101.7
Completed Depth (ft) 100.94
Date Started 7/8/97
Date Completed
Static Water Level (ft) 76.65 Date 7/12/97

OTHER (check if performed)

	Well Abandonment		Manhole Cover
X	Well Development (Pre-)		Pad w/Manhole Cover
	Aquifer Testing	X	Pad
	Geophysical Log(s)	X	Guardposts
X	Lock and Cap	X	Protective Casing

SCREEN

0.20 ft blank: bottom of screen to bottom joint.
0.30 ft blank: top of screen to top joint.

Type	Cap (ft)	Outer Dia. (in.)	Length (ft)	Slot Size	Interval (ft) Joint-to-Joint			Interval (ft) Slot-to-Slot		
Flush-threaded Continuous wire wrap PVC		4	2.48	20	93.08	-	95.56	93.4	-	95.4
Flush-threaded Continuous wire wrap PVC		4	2.47	20	86.61	-	89.08	86.9	-	88.9
Flush-threaded Continuous wire wrap PVC		4	2.45	20	80.15	-	82.60	80.5	-	82.4

TEMPORARY CASING

Type	Nominal Dia. (in.)	Max. Outer Dia. (in.)	Section Length (ft)	Interval (ft)		
Threaded Carbon Steel	8		105.10	+3.6	-	101.5

PERMANENT CASING

Type	Cap (ft)	Nominal Dia. (in.)	Max. Outer Diameter	Section Length (ft)	Interval (ft)		
Flush-threaded Sch. 40 PVC	0.38	4		5.00	95.56	-	100.94
Flush-threaded Sch. 40 PVC		4		4.00	89.08	-	93.08
Flush-threaded Sch. 40 PVC		4		4.01	82.60	-	86.61
Flush-threaded Sch. 40 PVC		4		82.45	+2.30	-	80.15
Threaded Steel Protective Casing		8				-	

ANNULAR SEAL/FILL

* Calculated for 1/4" Pellets

Type	Interval (ft)			Quantity	Volume (ft^3)
10-20 Colorado Silica Sand	92.1	-	101.7	7.25 Sacks (100#)	7.76
3/8-in TR30 Bentonite Pellets	98.9	-	92.1	1.5 Buckets (50#)	0.93*
10-20 Colorado Silica Sand	85.5	-	98.9	3.25 Sacks (100#)	3.48
3/8-in TR30 Bentonite Pellets	83.6	-	85.5	1.5 Buckets (50#)	0.93*
10-20 Colorado Silica Sand	79	-	83.6	3 Sacks (100#)	3.21
Misc. Bentonite Pellets from 100-N	7.1	-	79	94 Buckets (50#)	
Concrete Pad (6" thick, w/survey marker)		-			

PUMP

Type None (A Westbay MP38 Monitoring Port will be installed in each screened interval) Depth to Inlet (ft) N/A Date Set N/A

ACCEPTANCE

Completed Well: Accept Conditionally Accept
Reject

COMMENTS

Well depth (bls, measured 07/12/97) = 103.24' (casing string) - 2.3' (4" casing stick-up) = 100.94'

Reviewed by Date *Depths are below land surface unless noted.*

Pacific Northwest National Laboratory

WELL COMPLETION SUMMARY

Page 1 of 1

Project In-Situ Redox Manipulation
Location Hanford Site, 100-D Area
Drilling Co. Layne Christenson
Driller(s) Willie Franklin, Randy Smith
Other (companies)
Geologist(s) DC Weekes

Well No. 199-D4-17 Temp. Well No. B8459
Coordinates E: 1,879,153.670 ft N: 497,263.219 ft
Elevation: Casing 473.232 ft Survey Marker 470.404 ft
Coordinate System: Washington State Plane Coordinates (South Zone)

DRILLING METHOD

Drilling Method(s) ODEX air rotary w/downhole hammer
Drilling Fluid Air
Other

COMPLETION DATA

Drilled Depth (ft) 102.9
Completed Depth (ft) 101.52
Date Started 9/12/97
Date Completed
Static Water Level (ft) Date

OTHER (check if performed)

☐	Well Abandonment	☐	Manhole Cover
X	Well Development (Pre-)	☐	Pad w/Manhole Cover
☐	Aquifer Testing	X	Pad
☐	Geophysical Log(s)	X	Guardposts
X	Lock and Cap	X	Protective Casing

SCREEN

0.15 ft blank: bottom of screen to bottom joint.
0.35 ft blank: top of screen to top joint.

Type	Cap (ft)	Outer Dia. (in.)	Length (ft)	Slot Size	Interval (ft) Joint-to-Joint	Interval (ft) Slot-to-Slot
Flush-joint threaded continuous wire wrap PVC		4	2.49	20	93.64 - 96.13	94.0 - 96.0
Flush-joint threaded continuous wire wrap PVC		4	2.48	20	87.13 - 89.61	87.5 - 89.5
Flush-joint threaded continuous wire wrap PVC		4	2.48	20	80.61 - 83.09	81.0 - 82.9

TEMPORARY CASING

Type	Nominal Dia. (in.)	Max. Outer Dia. (in.)	Section Length (ft)	Interval (ft)
Flush-joint threaded Carbon Steel	8	8 5/8	106.9	+4.7 - 102.2

PERMANENT CASING

Type	Cap (ft)	Nominal Dia. (in.)	Max. Outer Diameter	Section Length (ft)	Interval (ft)
Flush-joint threaded Sch. 40 PVC	0.37	4		5.02	96.13 - 101.52
Flush-joint threaded Sch. 40 PVC		4		4.03	89.61 - 93.64
Flush-joint threaded Sch. 40 PVC		4		4.04	83.09 - 87.13
Flush-joint threaded Sch. 40 PVC		4		83.63	+3.02 - 80.61
Threaded Steel Protective Casing		8			-

ANNULAR SEAL/FILL

* Calculated for 1/4" Pellets

Type	Interval (ft)	Quantity	Volume (ft^3)
10-20 Colorado Silica Sand	92.6 - 102.7	3.75 Sacks (100#)	4.01
3/8-in TR30 Bentonite Pellets	90.6 - 92.6	0.66 Bucket (50#)	0.4*
10-20 Colorado Silica Sand	85.7 - 90.6	1.2 Sacks (100#)	1.28
3/8-in TR30 Bentonite Pellets	84 - 85.7	0.83 Bucket (50#)	.51*
10-20 Colorado Silica Sand	79.7 - 84	2.3 Sacks (100#)	2.46
1/4-in TR30 Bentonite Pellets	54 - 79.7	11 Buckets (50#)	6.82
Granular Bentonite (#8)	4.9 - 54	16.75 Sacks (50#)	11.89
Quikrete	0 - 4.9	3 Sacks (80#)	
Concrete Pad (6" thick, w/survey marker)	-		

PUMP

Type None (A Westbay MP38 Monitoring Port will be installed in each screened interval) Depth to Inlet (ft) N/A Date Set N/A

ACCEPTANCE

Completed Well: Accept Conditionally Accept

Reject

COMMENTS

Well depth (bls, measured 09/17/97) = 104.54' (casing string) - 3.02' (4" casing stick-up) = 101.52'

Reviewed by Date

Depths are below land surface unless noted.

Pacific Northwest National Laboratory	**WELL COMPLETION SUMMARY**	Page 1 of 1

Project In-Situ Redox Manipulation
Location Hanford Site, 100-D Area
Drilling Co. Layne Christenson
Driller(s) Willie Franklin, Randy Smith
Other (companies)
Geologist(s) TL Liikala

Well No. 199-D4-18 Temp. Well No.
Coordinates E: 1,879,115.108 ft N: 497,304.221 ft
Elevation: Casing 475.341 ft Survey Marker 469.108 ft
Coordinate System: Washington State Plane Coordinates (South Zone)

DRILLING METHOD

Drilling Method(s) ODEX air rotary w/downhole hammer
Drilling Fluid Air
Other

COMPLETION DATA

Drilled Depth (ft)	101		
Completed Depth (ft)	100.50		
Date Started	9/18/97		
Date Completed			
Static Water Level (ft)	86.02	Date	9/19/97

OTHER (check if performed)

	Well Abandonment		Manhole Cover
X	Well Development (Pre-)		Pad w/Manhole Cover
	Aquifer Testing	X	Pad
	Geophysical Log(s)	X	Guardposts
X	Lock and Cap	X	Protective Casing

SCREEN

0.20 ft blank: bottom of screen to bottom joint.
0.30 ft blank: top of screen to top joint.

Type	Cap (ft)	Outer Dia. (in.)	Length (ft)	Slot Size	Interval (ft) Joint-to-Joint	Interval (ft) Slot-to-Slot
Flush-joint threaded continuous wire wrap PVC		4	2.49	20	92.51 - 95.00	92.8 - 94.8
Flush-joint threaded continuous wire wrap PVC		4	2.50	20	85.93 - 88.43	86.2 - 88.2
Flush-joint threaded continuous wire wrap PVC		4	2.47	20	79.38 - 81.85	79.7 - 81.7

TEMPORARY CASING

Type	Nominal Dia. (in.)	Max. Outer Dia. (in.)	Section Length (ft)	Interval (ft)
Flush-joint threaded Carbon Steel	8		105.5	+4.5 - 101

PERMANENT CASING

Type	Cap (ft)	Nominal Dia. (in.)	Max. Outer Diameter	Section Length (ft)	Interval (ft)
Flush-joint threaded Sch. 40 PVC	0.48	4		5.02	95.00 - 100.50
Flush-joint threaded Sch. 40 PVC		4		4.08	88.43 - 92.51
Flush-joint threaded Sch. 40 PVC		4		4.08	81.85 - 85.93
Flush-joint threaded Sch. 40 PVC		4		82.63	+3.25 - 79.38
Threaded Steel Protective Casing		8			-

ANNULAR SEAL/FILL

* Calculated for 1/4" Pellets

Type	Interval (ft)	Quantity	Volume (ft^3)
10-20 Colorado Silica Sand	91.1 - 102.7	3.42 Bags (100#)	3.7
3/8-in TR30 Pel-Plug Bentonite Pellets	89.3 - 91.1	0.67 Bucket (50#)	0.4*
10-20 Colorado Silica Sand	84.8 - 89.3	1.25 Bags (100#)	1.3
3/8-in TR30 Pel-Plug Bentonite Pellets	83.1 - 84.8	0.67 Bucket (50#)	.4*
10-20 Colorado Silica Sand	78.9 - 83.1	2.24 Bags (100#)	2.4
Miscellaneous Bentonite Pellets	75 - 78.9	2.06 Buckets (50#)	1.3*
10-20 Colorado Silica Sand	74 - 75	0.25 Bag (100#)	0.3
Miscellaneous Bentonite Pellets	51.5 - 74	10 Buckets (50#)	6.2*
#8 Wyoming Bentonite	4.9 - 51.5	15.33 Bags (50#)	
Quikrete	0 - 4.9	4 Bags (80#)	
Concrete Pad (6" thick, w/survey marker)	-		

PUMP

Type None (A Westbay MP38 Monitoring Port will be installed in each screened interval) Depth to Inlet (ft) N/A Date Set N/A

ACCEPTANCE

Completed Well: Accept Conditionally Accept
Reject

COMMENTS

Well depth (bls, measured 09/20/97) = 103.75' (casing string) - 3.25' (4" casing stick-up) = 100.5'

SS Soil Gas monitoring point and 0.25" polyethylene tubing strapped to outside of 4" PVC. Pt is 74.5' bls.

Reviewed by Date *Depths are below land surface unless noted.*

Appendix B

Comparison of Pre- and Post-Injection Pumping Results

F. A. Spane Jr.
V. R. Vermeul

May 1998

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DRAFT

Comparison of Pre- and Post-Injection Pumping Test Results for Evaluating Possible Hydrologic Property Changes at the 100-D Test Facility

Prepared by:

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V. R. Vermeul

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May 1998

1.0 Executive Summary

The primary objective of the In Situ REDOX Manipulation field remediation demonstration is to produce a reducing condition within the aquifer by "altering" the redox potential of iron-bearing minerals within the subsurface geologic framework from Fe^{+3} to Fe^{+2}. The manipulated or fixed reduced-iron minerals can then react with redox-sensitive contaminants to precipitate or form less hazardous chemical forms. For this field demonstration, the targeted contaminant to be reduced was the mobile Cr^{+6} phase of chromium (CrO_4^{2-}) within an identified contaminated groundwater plume located in the northern part of the Hanford Site (i.e., in the 100-D Area). A more detailed discussion of the contaminated area and aspects of the redox manipulation field demonstration are provided in Fruchter et al. (1997).

Since this demonstrated remediation technology relies on the continuing flow of contaminated groundwater through the created reactive geochemical wall, it is important to determine whether the applied technology (i.e., injection of the strong reducing agent) causes any significant changes in the subsurface hydrologic properties that could alter subsurface groundwater flow directions (e.g., through induced decreases in hydraulic properties within the reactive wall area). To assist in assessing the applied technology impacts, two constant-rate pumping tests were conducted at the 100-D field demonstration site to provide information that could be used to evaluate possible changes in subsurface hydrologic conditions. The pumping tests were conducted prior to and following injection and withdrawal of the strong geochemical reducing reagent, sodium diothionite. The pre- and post injection pumping test responses for the injection well (well D4-7) and surrounding seven observation wells were analyzed individually and compared to assess changes in the subsurface hydrologic conditions. Pertient findings of the test result comparisons are listed below:

2.0 Pre-Injection Test Results (Homogeneous Model)

1. Analysis of individual well test results indicate the following range and mean values for selected hydrologic properties for the aquifer prior to injection of the sodium diothionite:

	Range	Mean (± 1σ)
Hydraulic Conductivity, K_h:	40.7 - 62.1 ft/d	54.5 ± 6.93 ft/d
Vertical Anisotropy, K_v/K_h:	0.006 - 0.031	0.015 ± 0.010
Storativity, S:	0.0017 - 0.0058	0.0040 ± 0.0017
Specific Yield, S_y:	0.014 - 0.031	0.020 ± 0.0063

2. While certain groupings of observation wells provide a consistent "composite" analysis result, the range in hydraulic conductivity exhibit for all analysis results suggests that horizontal anisotropic conditions likely exist in the aquifer (i.e., K_xK_y).

3. Comparison of test responses for multi-level observation wells (i.e., well D4-2 Upper and Lower Zone, and D4-3 Upper and Lower Zone) suggests a vertical heterogeneous or multi-layered system for the test aquifer.

3.0 Post Injection Test Results (Homogeneous Model)

1. Comparison of pre- and post injection test responses indicate several discernable effects associated with the redox experiment. The recognized effects include:

   a) formation of a significant skin effect or zone of reduced permeability immediately surrounding the injection well (well D4-7)
   b) a slight increase in formation hydraulic conductivity was exhibited for most observation well post injection test responses

2. The observed post injection response is consistent with a conceptual model where permeability of the aquifer is enhanced areally by chemical and dissolution reactions of the injected redox reagent, while a zone of reduced permeability (i.e., well skin) is produced around the injection well during the reagent withdrawal phase.. The skin developed can be visualized as forming around the well due to entrapment of colloidal particulates within the converging pumpback fluids, which were mobilized during the injection phase.

3. The presence of a zone of reduced permeability surrounding the injection well (following injection and withdrawal of the reducing reagent) is supported by significantly greater drawdown observed at the injection well and delayed time response exhibited at most of the observation well locations during the post injection pumping test.

4. The extent and severity of the zone of permeability reduction surrounding the injection well can not be determined uniquely by comparing pre- and post test responses (i.e., different combinations of skin thickness and permeability can produce similar test responses). However if it is assumed that the skin formed and was limited to region of the sand-pack installation surrounding the well screen (a plausible explanation due to convergent flow and to possible changes in sand pack and formation hydraulic properties), then a skin zone with a permeability 1/20th that of the aquifer surrounding the injection well location is indicated (i.e., 2.69 ft/d versus 56.7 ft/d).

5. A comparison of pre- and post injection observation well test results also indicates a slight decrease in recovery response at most observation well locations. This decreased test response suggests a slight increase in inter-well hydraulic conductivity caused by the injection/withdrawal of the reducing reagent. As noted previously, this observation is consistent with a conceptual model associated with dissolution mobilization processes associated with administering and removal of the redox reagent.

4.0 References/Bilbiography

Fruchter, J.S., .E. Amonette, C.R. Cole, Y.A. Gorby, M.D. Humphrey, J.D. Isok, F.A. Spane, J.E. Szecsody, S.S. Teel, V.R. Vermeul, M.D. Williams, and S.B. Yabusaki. 1996. In Situ Redox. Manipulation Field Injection Test Report - Hanford 100-H Area. Pacific Northwest National Laboratory, PNNL-11372, Richland, Washington.

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Vermeul, V.R., S.S. Teel, J.E. Amonette, C.R. Cole, J.S. Fruchter, Y.A. Gorby, F.A. Spane, J.E. Szecsody, M.D. Williams, and S.B. Yabusaki. 1995. Geologic, Geochemical, Microbiologic, and Hydrologic Characterization at the In Situ Redox. Manipulation Test Site. Pacific Northwest Laboratory, PNL-10633, Richland, Washington.

Table 1. Pertinent Well Completion and Distance Aspects for 100-D Wells

Well Site	Distance from D4-7 ft	Azimuth From D4-7 Degrees*	Well Screen Diameter ft	Well Screen Completion top/bottom ft bls	Well Screen Completion in aquifer ft bla**
D4-1	36.3	135	0.250	74.65 94.67	0.0 14.11
D4-2 Upper Zone	34.3	316	0.167	83.65 88.6	3.09 8.04
D4-2 Lower Zone	34.3	316	0.167	93.65 99.0	13.09 15.94
D4-3 Upper Zone	24.0	315	0.167	83.5 88.5	2.94 7.94
D4-3 Lower Zone	24.0	315	0.167	93.5 98.8	12.94 15.94
D4-4	69.9	107	0.167	78.06 98.4	0.0 15.94
D4-7	0	0	0.250	80.2 95.6	0.0 15.04
D4-8	9.2	30	0.167	75.43 95.4	0.0 14.84
D4-9	27.5	252	0.250	81.3 96.7	0.74 15.94
D4-11	28.1	20	0.250	80.26 95.7	0.0 15.14
D4-12	50.0	45	0.250	(-)	(-)

* measure counterclockwise from due East (East = 0 degrees)

** ft below aquifer top (ft bla); aquifer thickness = 15.94 ft

(-) assumed to be fully penetrating

Table 2. Pre-Injection Hydraulic Property Analysis Results Using ISOAQX and WTAQ3 Analytical Models

Well Site	K_h ft/d		K_D		S		S_y	
	Isoaqx	Wtaq3	Isoaqx	Wtaq3	Isoaqx	Wtaq3	Isoaqx	Wtaq3
D4-1	76.2		.009		.0104		.0270	
D4-2 Upper Zone	59.8	59.8	.008	.009	.0055	.0050	.0184	.0184
D4-2 Lower Zone	54.8	54.8	.029	.031	.0061	.0058	.0253	.0253
D4-3 Upper Zone	62.1	62.1	.006	.006	.0056	.0054	.0134	.0139
D4-3 Lower Zone	55.2	55.2	.025	.029	.0053	.0050	.0166	.0165
D4-4	105.3		.011		.0140		.032	
D4-7	47.7	56.7	.047	.01	.0098	.0025	.170	.0306
D4-8	30.8	40.7	.030	.01	.0034	.0017	.081	.0230
D4-9	50.3	51.9	.010	.010	.0027	.0025	.015	.0138
D4-11	40.2		.024		.0080		.057	
D4-12	73.4		.014		.0125		.047	

Table 3. Comparison of Post- to Pre-Experiment Pumping Test Recovery Buildup Responses

Wells	Distance From Well 199-D4-7, ft	Comparison of Post- to Pre-Experiment Test Responses		
		1st Segment	2nd Segment	3rd Segment
199-D4-1	36.3			
-D4-2 Upper Zone	34.3	=	↓	↓
-D4-2 Lower Zone	34.3	→	↓	↓
-D4-3 Upper Zone	24.0	→	↓	↓
-D4-3 Lower Zone	24.0	→	↓	↓
-D4-4	69.9			
-D4-7	0	=	↑	↑
-D4-8	9.2	→	↓	↓
-D4-9	27.5	→	↓	↓
-D4-11	28.1			
-D4-12	50.0			

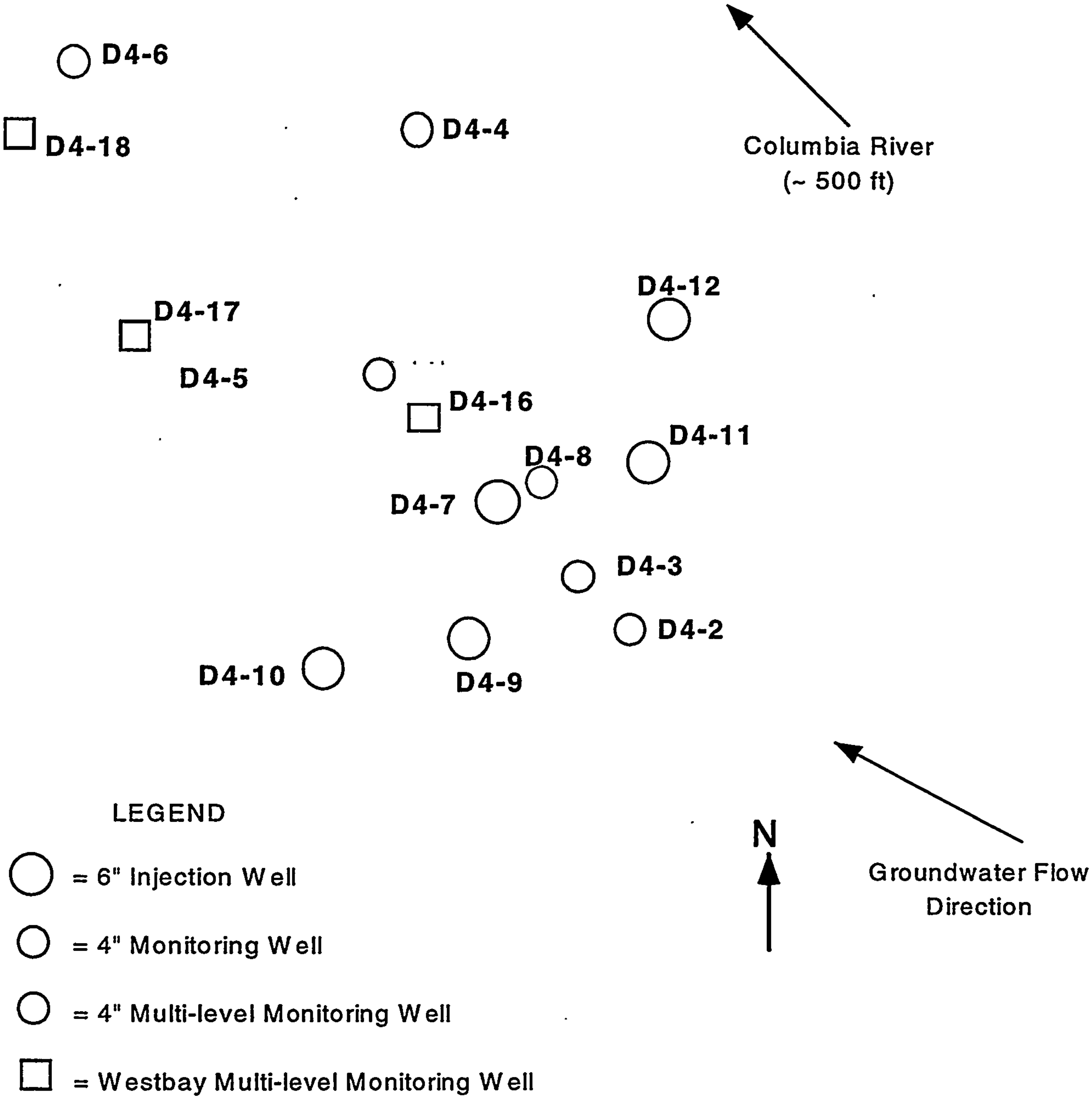
Symbol Definition:

→	Post experiment time response exhibits a delay (i.e., shift to the right)
←	Post experiment time response exhibits an advance (i.e., shift to the left)
↑	Post experiment buildup response exhibits an increase (i.e., shift upward)
↓	Post experiment buildup response exhibits a decrease (i.e., shift downward)
=	Post experiment time/buildup response exhibits no change

Table 4. Pre- and Post-Injection Hydraulic Property Analysis Results Using WTAQ3 Analytical Model

Well Site	K_h (ft/d)		K_D		S		S_y		S_k	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
D4-1									0	
D4-2 Upper Zone	59.8	62.5	.009	.010	.0050	.0047	.0184	.0184	0	0
D4-2 Lower Zone	54.8	54.8	.031	.041	.0058	.0043	.0253	.0187	0	+9.0
D4-3 Upper Zone	62.1	60.3	.006	.011	.0054	.0061	.0139	.0198	0	+6.0
D4-3 Lower Zone	55.2	58.8	.029	.036	.0050	.0046	.0166	.0164	0	+6.0
D4-4									0	
D4-7	56.7	56.7	.010	.010	.0025	.0025	.0306	.0306	0	+9.5
D4-8	40.7	44.4	.010	.009	.0017	.0017	.0235	.0235	0	+6.0
D4-9	51.9	57.8	.010	.010	.0025	.0025	.0141	.0141	0	+3.0
D4-11									0	
D4-12									0	

*Note: test data analyzed had standard Jacob's correction for unconfined aquifer dewatering applied.



Note: Drawing not to scale. Locations are approximate.

Figure 1. Schematic Layout of 100-D Test Well Facility

5.0 Pre-Injection Test Analysis Plots

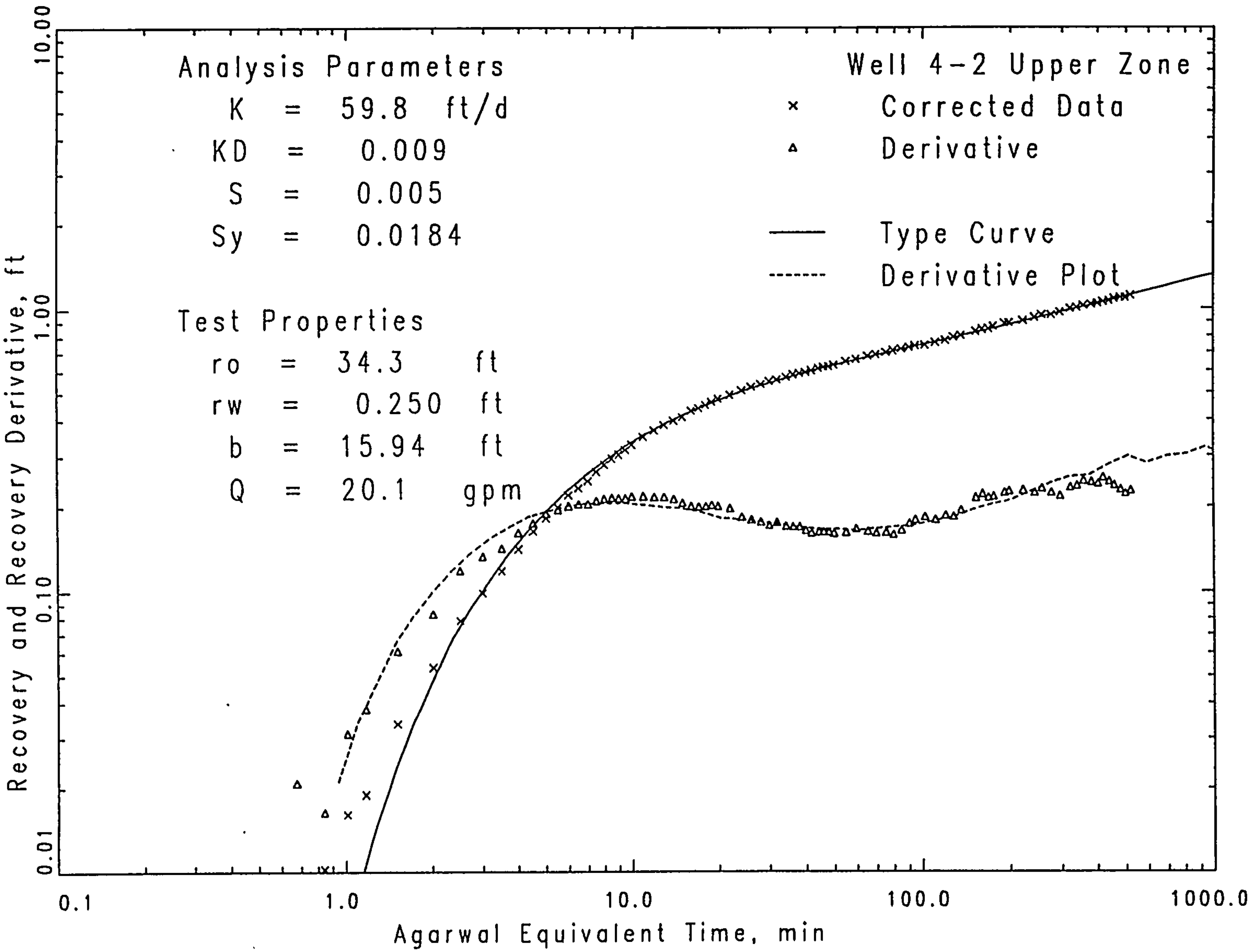


Figure 5.1. Pre-Injection Pumping Test Recovery Analysis Plot for Well D4-2 Upper Zone

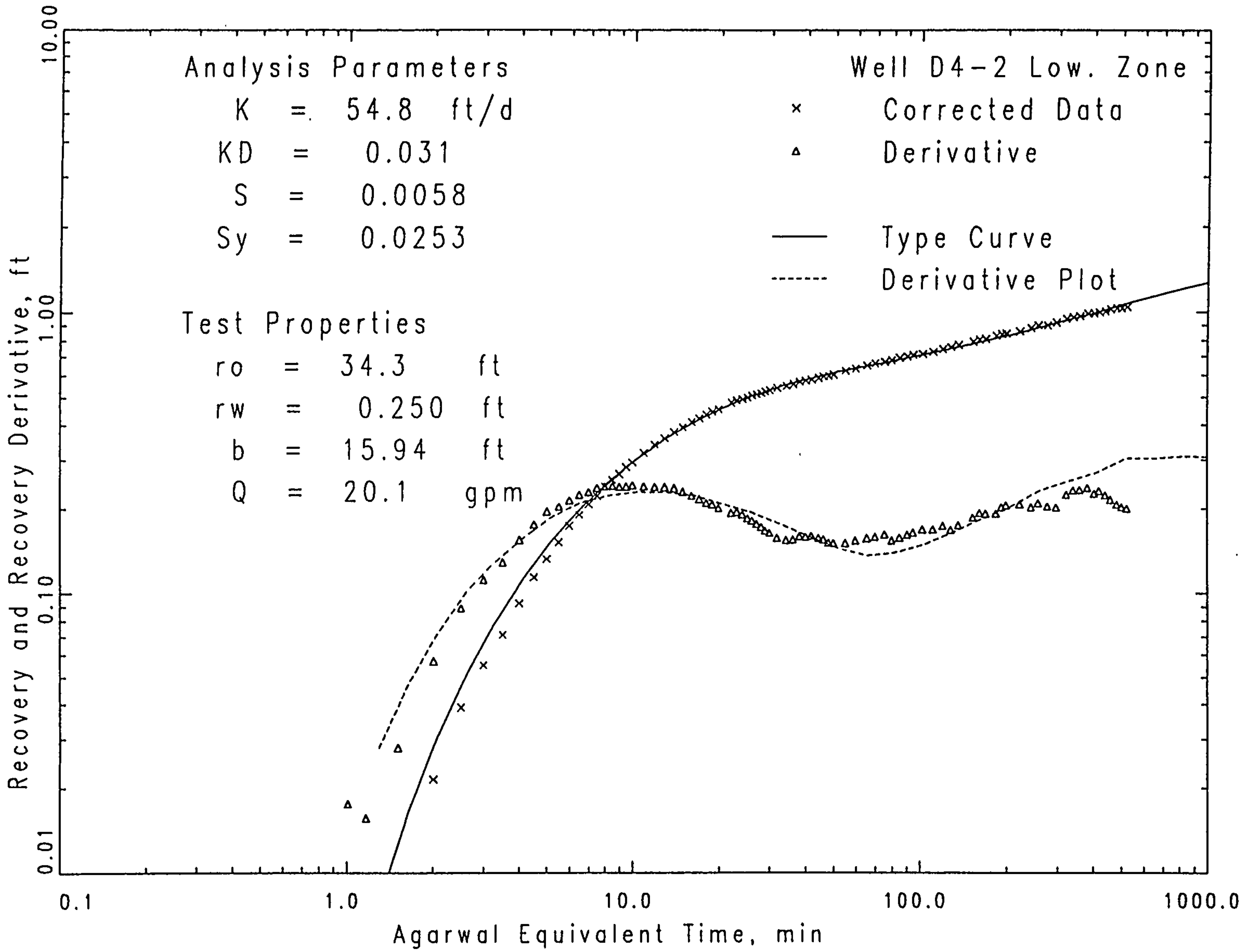


Figure 5.2. Pre-Injection Pumping Test Recovery Analysis Plot for Well D4-2 Lower Zone

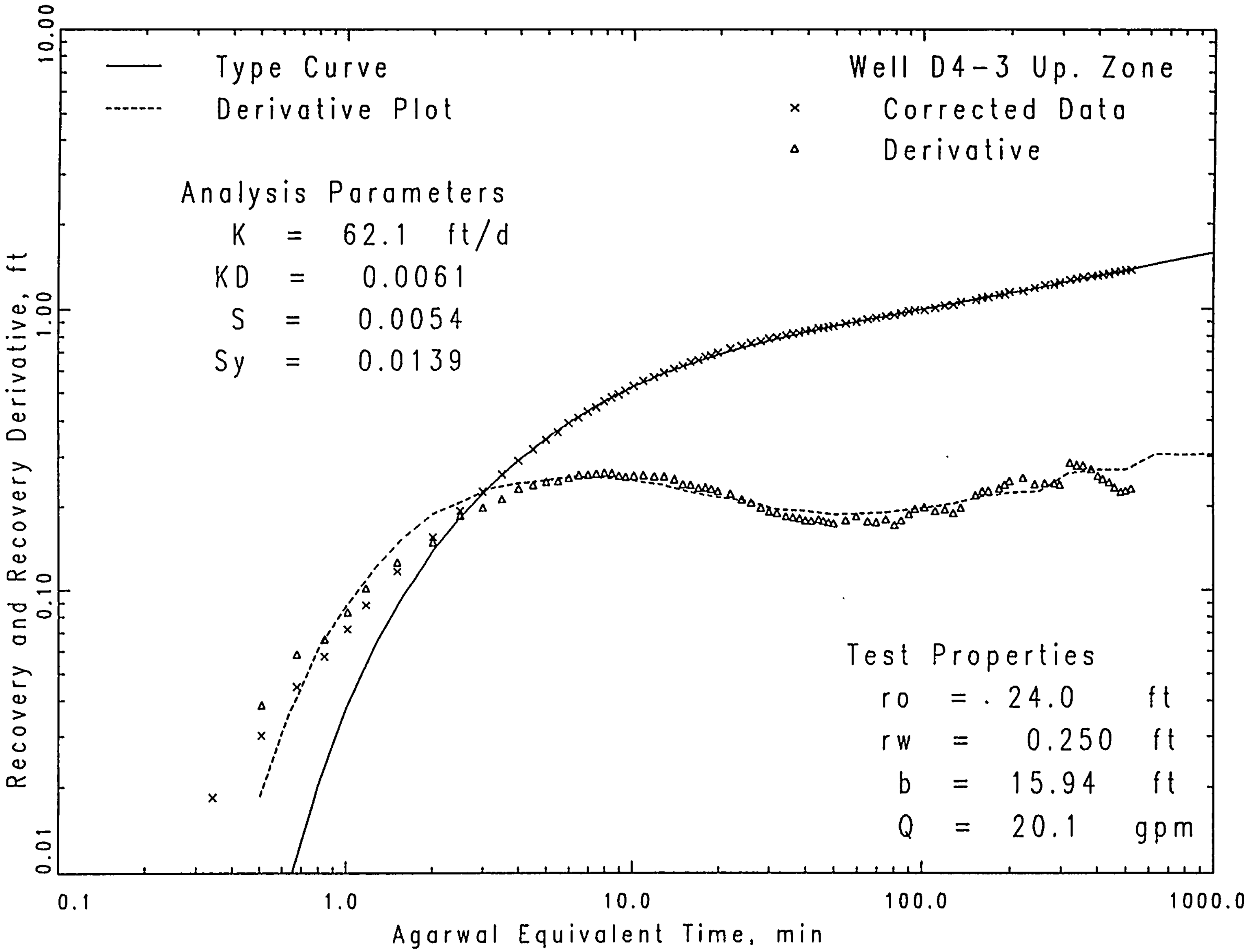


Figure 5.3. Pre-Injection Pumping Test Recovery Analysis Plot for Well D4-3 Upper Zone

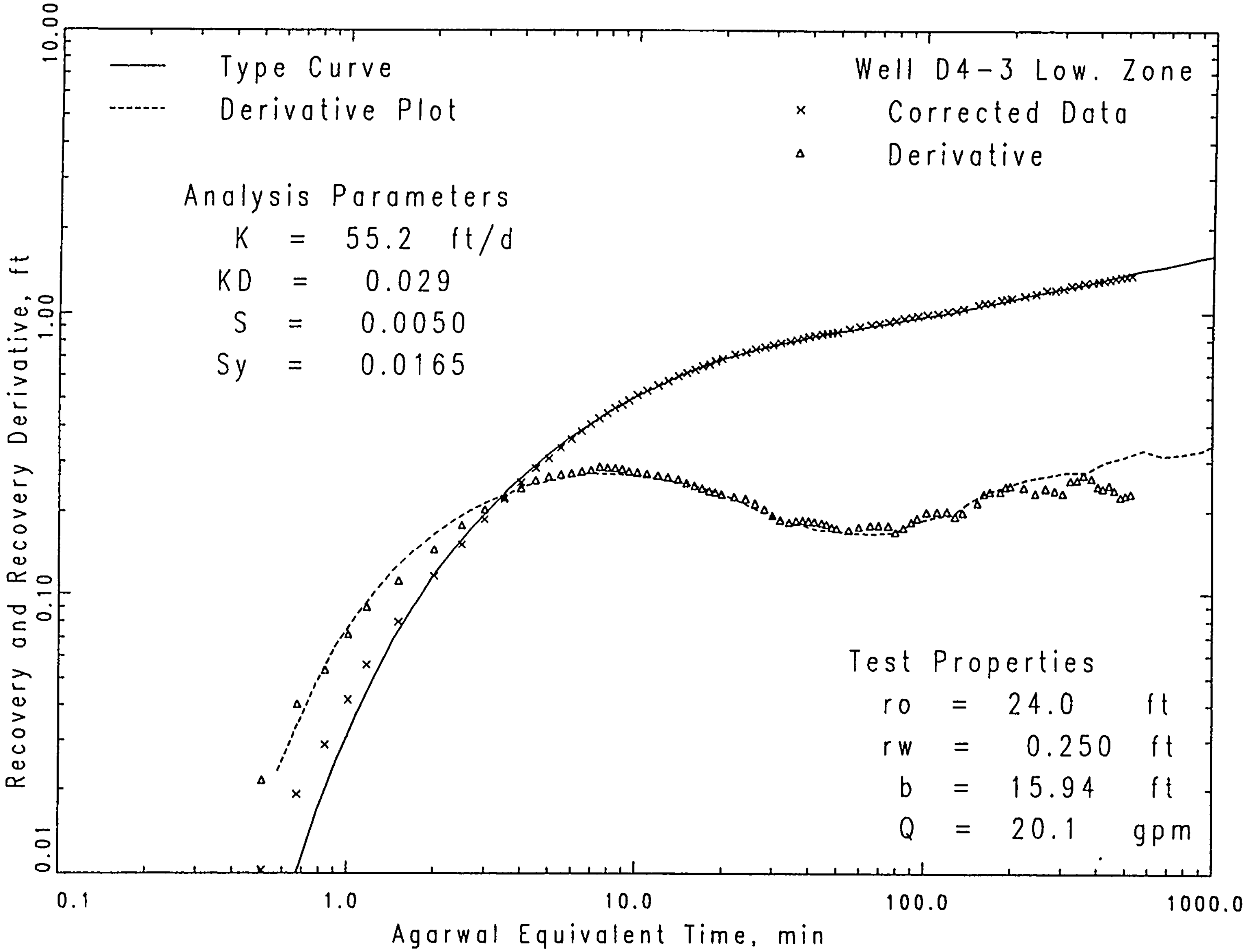


Figure 5.4. Pre-Injection Pumping Test Recovery Analysis Plot for Well D4-3 Lower Zone

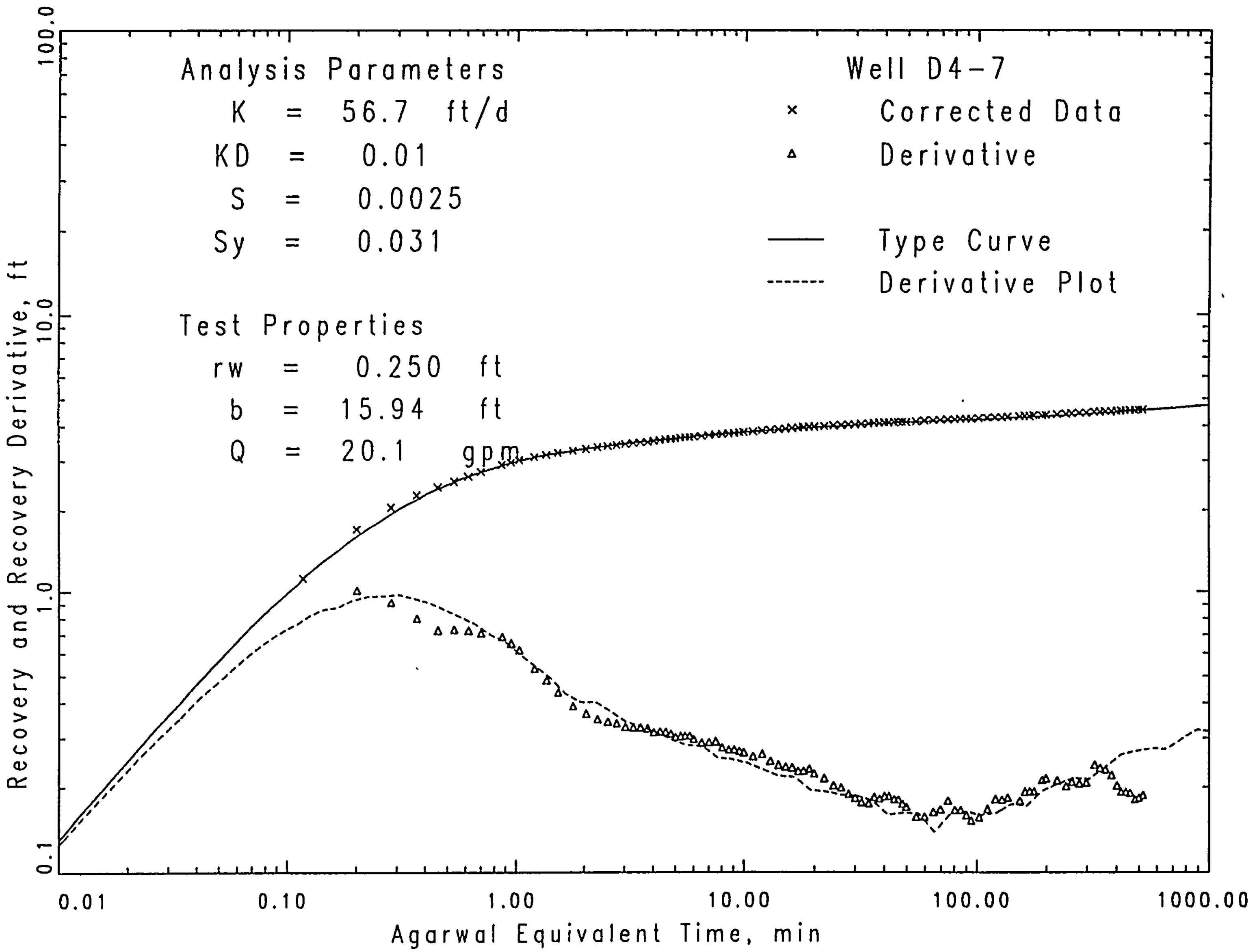


Figure 5.5. Pre-Injection Pumping Test Recovery Analysis Plot for Well D4-7 (Injection Well)

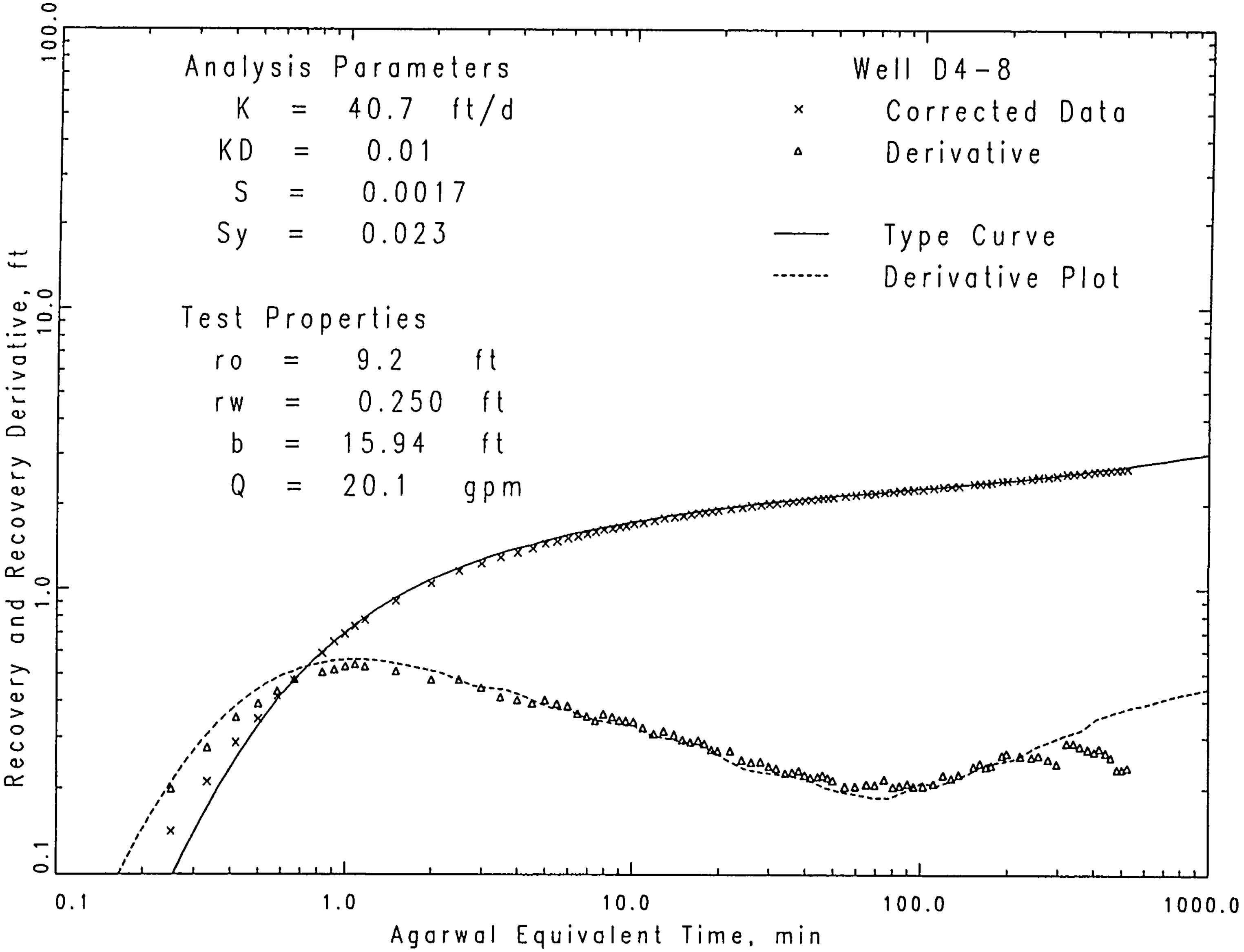


Figure 5.6. Pre-Injection Pumping Test Recovery Analysis Plot for Well D4-8

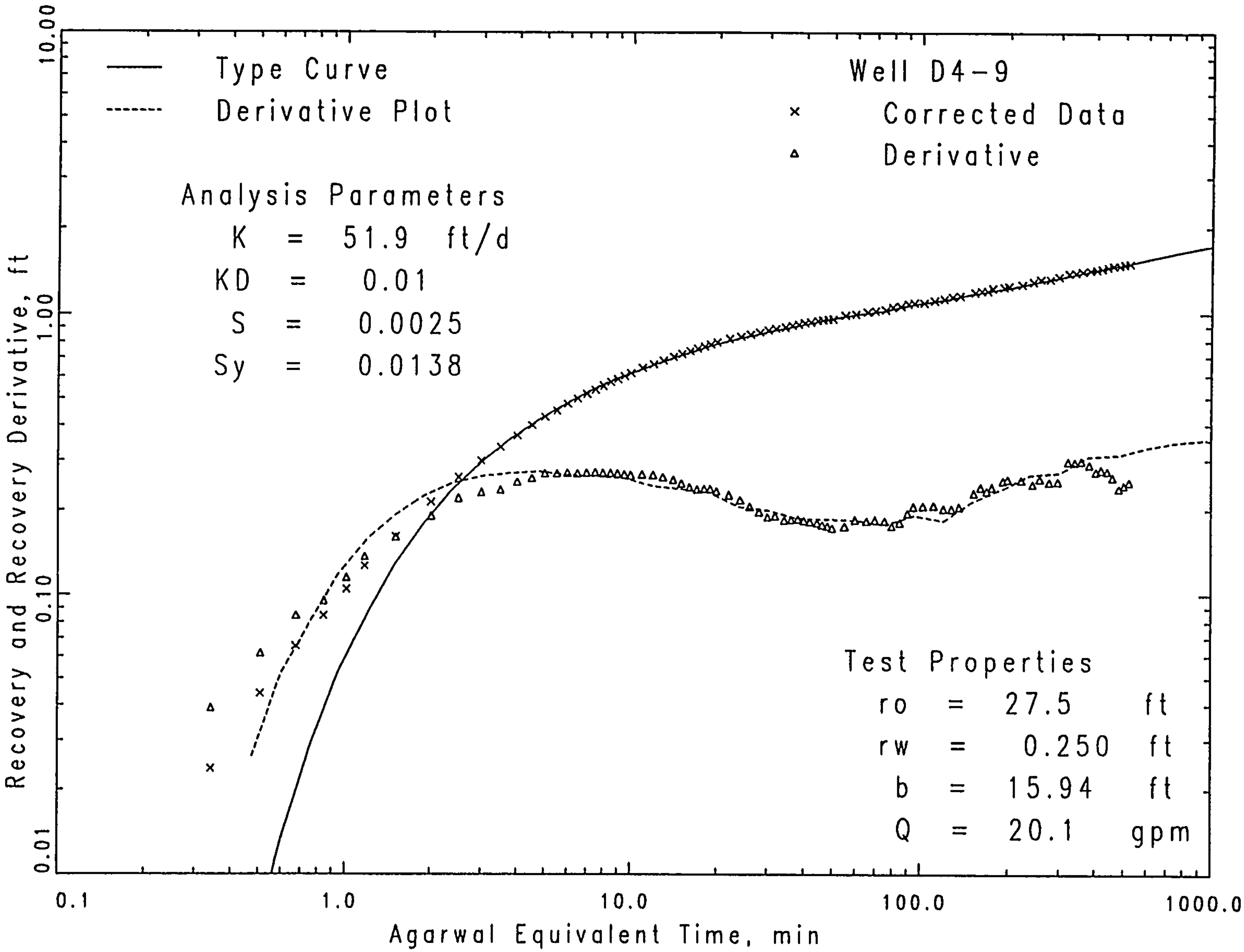


Figure 5.7. Pre-Injection Pumping Test Recovery Analysis Plot for Well D4-9

6.0 Post Injection Test Analysis Plots

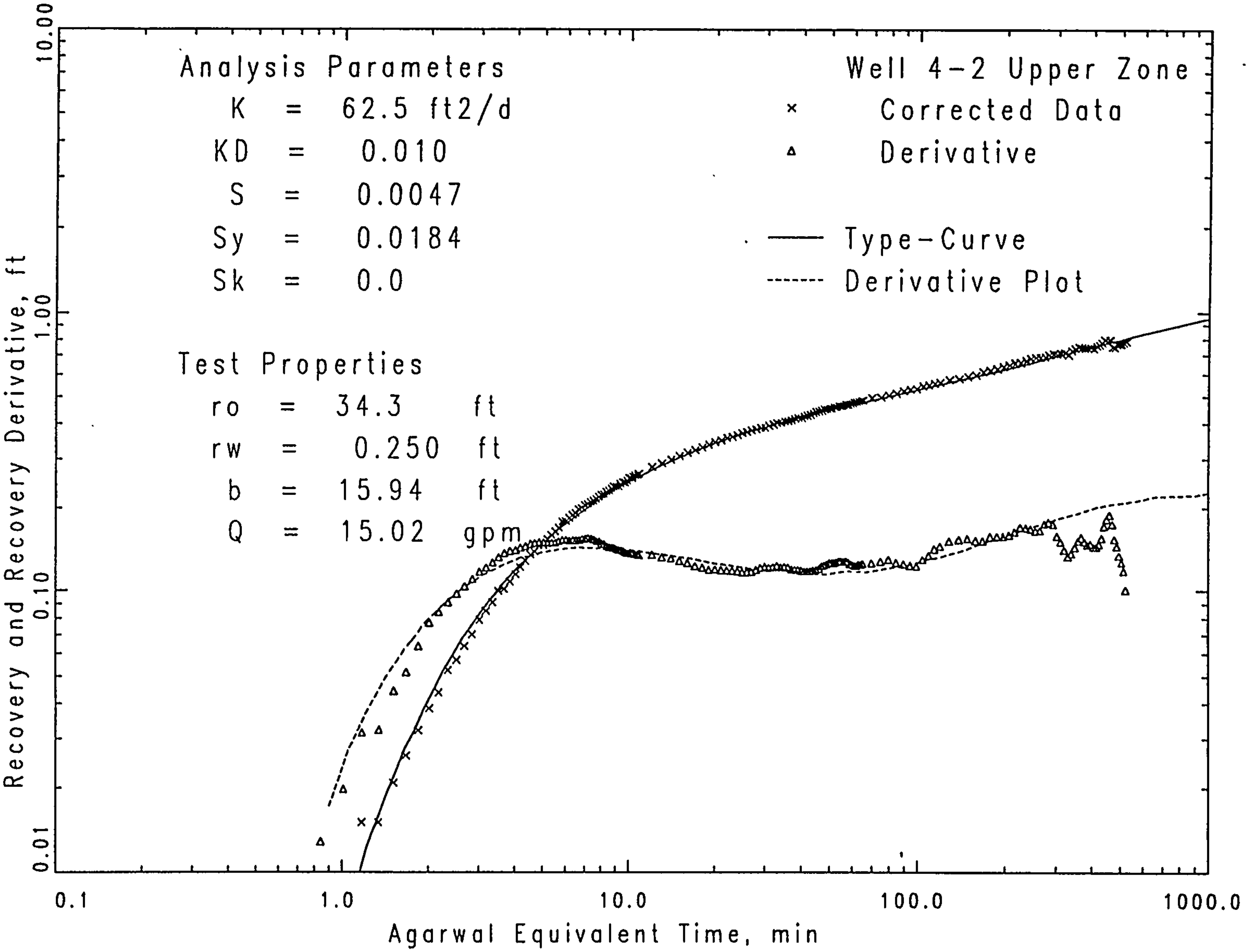


Figure 6.1. Post Injection Pumping Test Recovery Analysis Plot for Well D4-2 Upper Zone

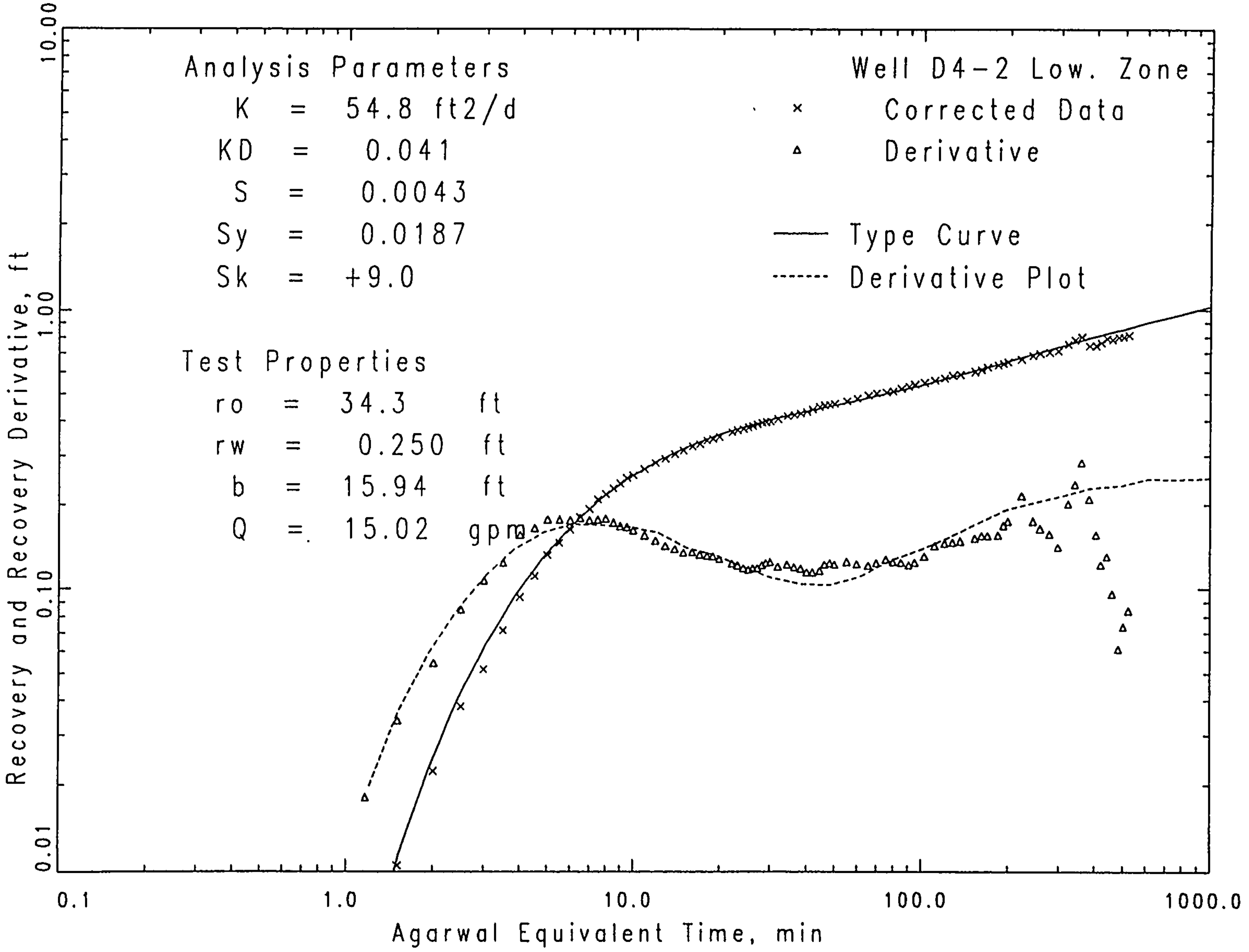


Figure 6.2. Post Injection Pumping Test Recovery Analysis Plot for Well D4-2 Lower Zone

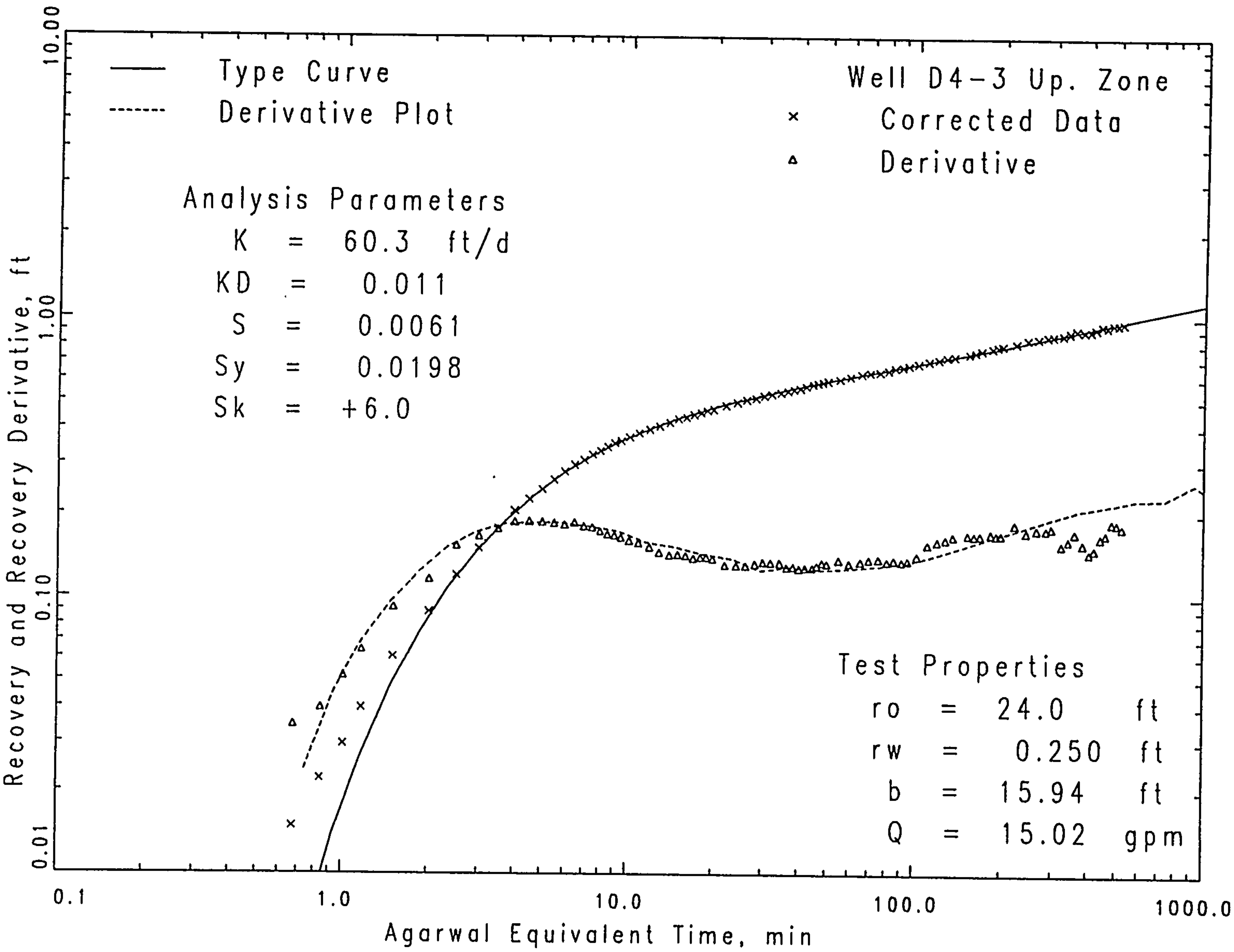


Figure 6.3. Post Injection Pumping Test Recovery Analysis Plot for Well D4-3 Upper Zone

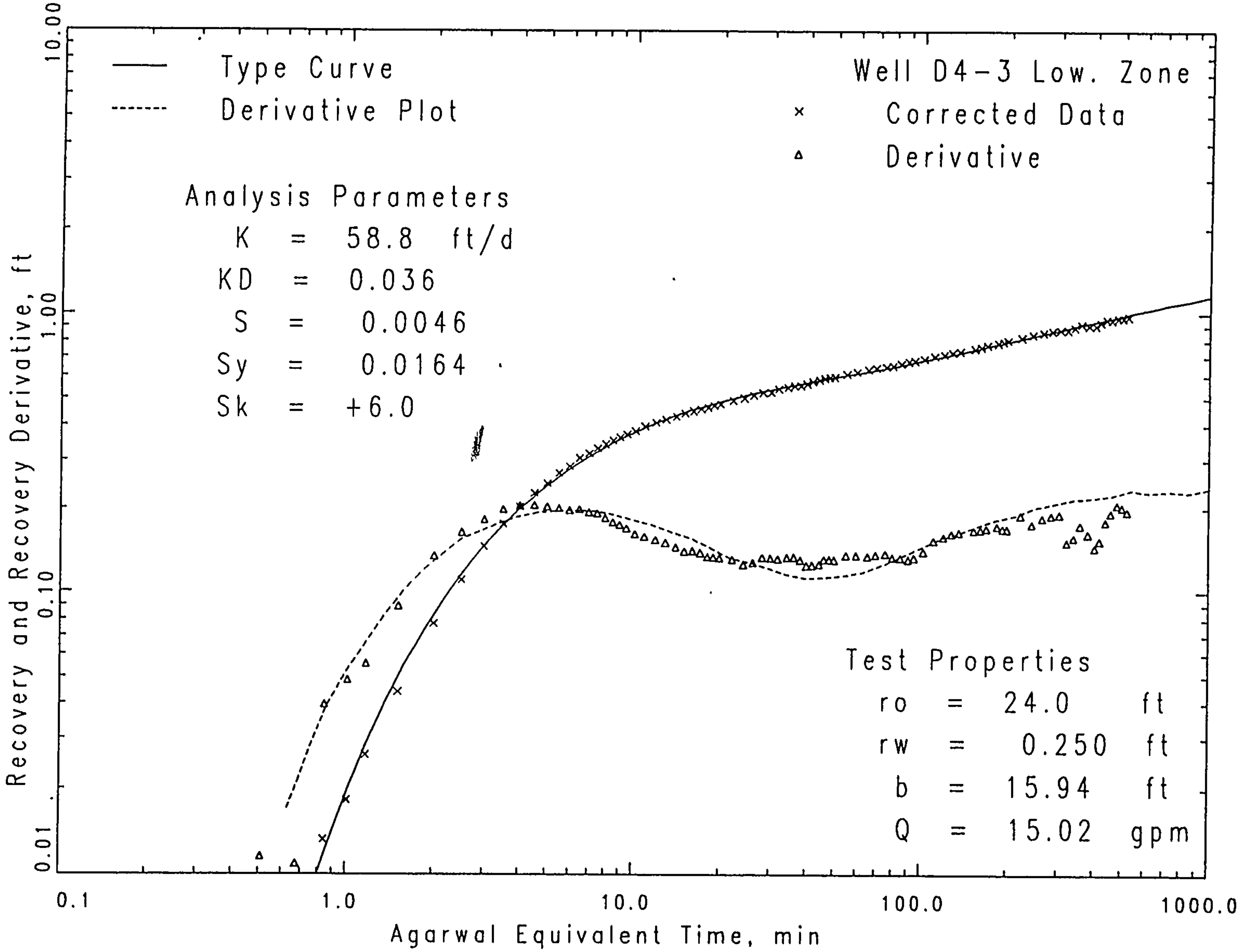


Figure 6.4. Post Injection Pumping Test Recovery Analysis Plot for Well D4-3 Lower Zone

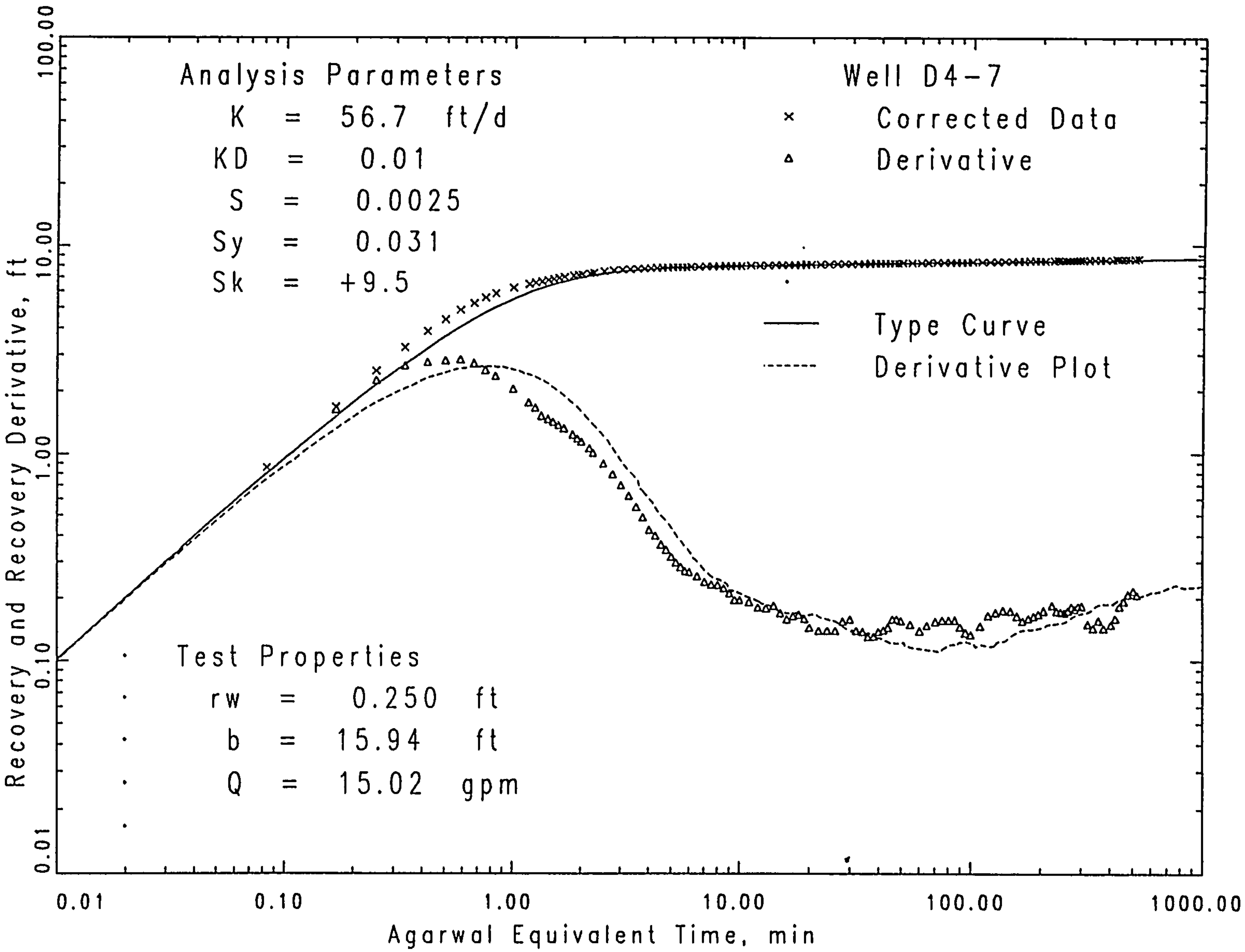


Figure 6.5. Post Injection Pumping Test Recovery Analysis Plot for Well D4-7 (Injection Well)

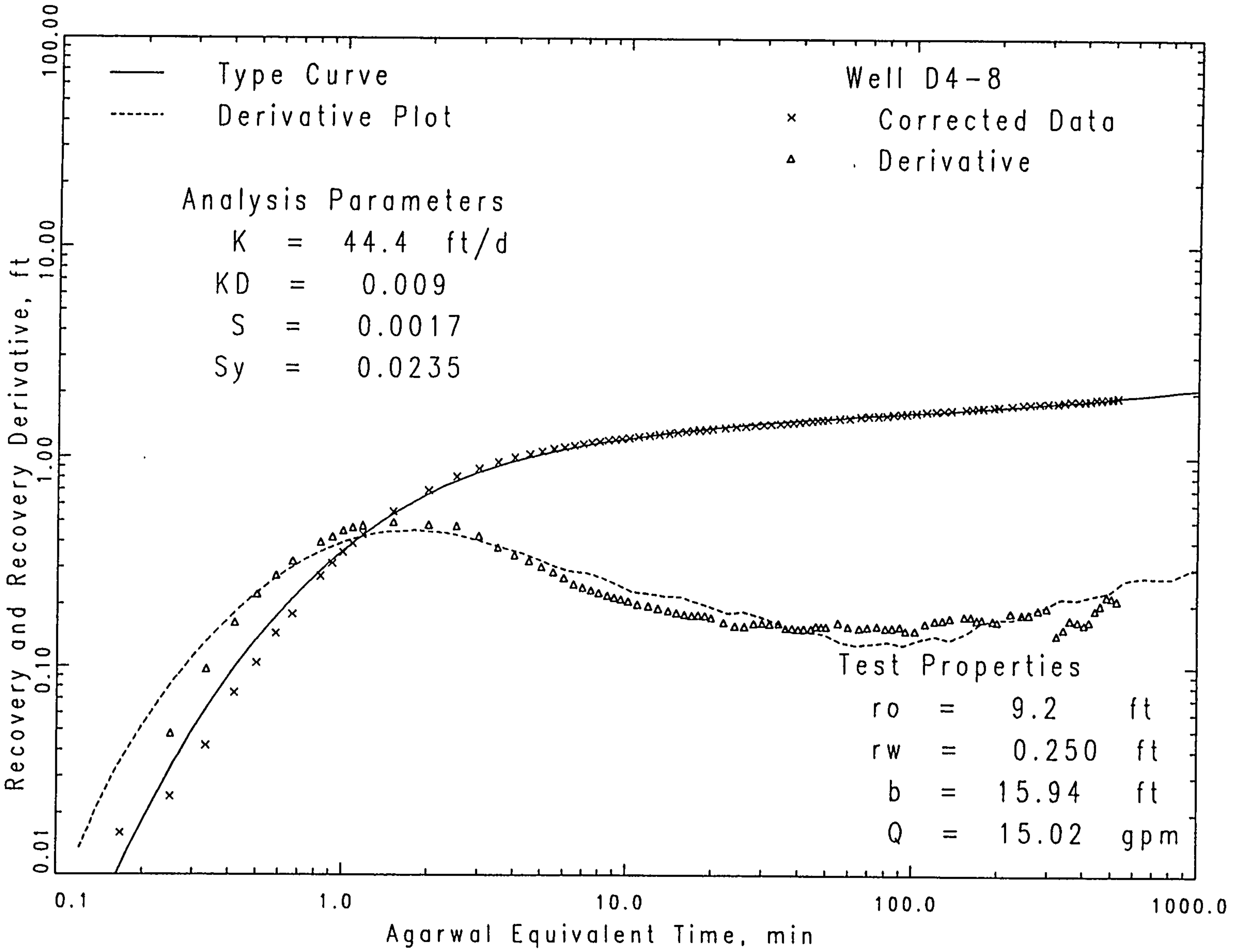


Figure 6.6. Post Injection Pumping Test Recovery Analysis Plot for Well D4-8

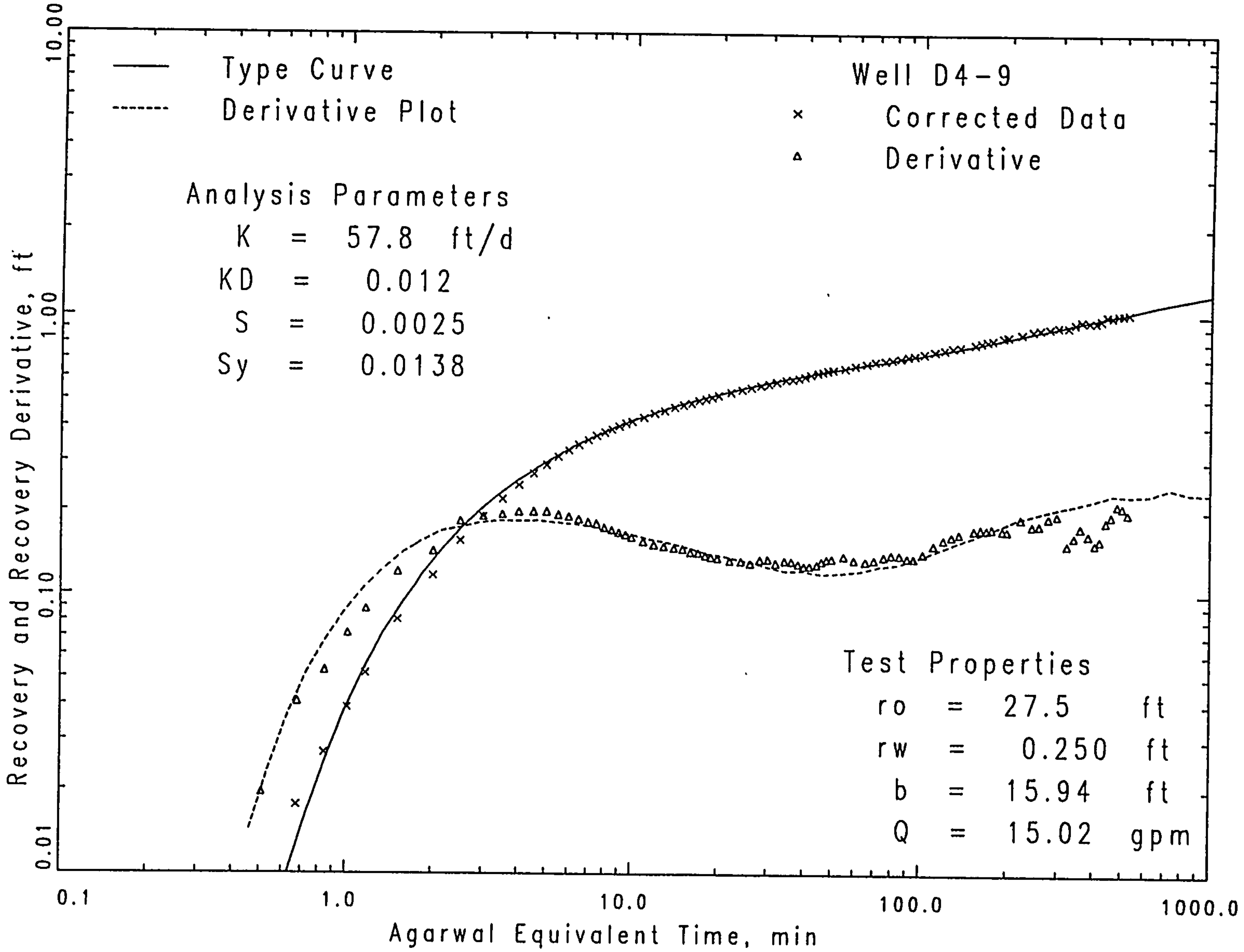


Figure 6.7. Post Injection Pumping Test Recovery Analysis Plot for Well D4-9

Appendix C

Columbia River Substrate Porewater Sampling Tube Results

Cond. (µs/cm)	**Columbia River Porewater Sampler ID**				11-3-97 11-4-97
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	369				340
6	330				350.1
10					
15					

*Note: Redox01 samples taken 11-3-97

*Note: Redox04 samples taken 11-4-97

Cr6+ (mg/L)	**Columbia River Porewater Sampler ID**				11-3-97 11-4-97
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	0.432				0.378
6	0.228				0.411
10					
15					

*Note: Redox01 samples taken 11-3-97

*Note: Redox04 samples taken 11-4-97

Cond. (µs/cm)	**Columbia River Porewater Sampler ID**				12-10-97 12-11-97
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	305.8	161.1		148.8	221.6
6*					
10					
15					

*Note: Cond. Is from 12-10-97, Cr6+ is from 12-11-97

Cr6+ (mg/L)	**Columbia River Porewater Sampler ID**				12-10-97 12-11-97
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	0.356	0.039		0.031	0.148
6					
10					
15					

*Note: Cond. Is from 12-10-97, Cr6+ is from 12-11-97

pH	Columbia River Porewater Sampler ID				3/12/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	7.43	7.64			
6	7.58	7.5			
10					
15					

Cond. (µs/cm)	Columbia River Porewater Sampler ID				3/12/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	359	224			
6	378	307			
10					
15					

DO (mg/L)	Columbia River Porewater Sampler ID				3/12/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	6.82	9.5			
6	6.95	2.35			
10					
15					

Cr6+ (mg/L)	Columbia River Porewater Sampler ID				3/12/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	0.5	0.11			
6	0.56	0.09			
10					
15					

pH	Columbia River Porewater Sampler ID				3/19/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	7.35	7.53		7.78	7.75
6	7.59	7.4	7.68	7.8	8.02
10			7.73		
15			7.73		

Cond. (µs/cm)	Columbia River Porewater Sampler ID				3/19/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	372	284		507	360
6	392	318	358	509	367
10			520		
15			529		

DO (mg/L)	Columbia River Porewater Sampler ID				3/19/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	5.12	7.9		8.7	7.93
6	7.58	3.33	10.64	7.9	3.9
10			9.5		
15			10.4		

Cr6+ (mg/L)	Columbia River Porewater Sampler ID				3/19/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	0.52	0.2		0.88	0.56
6	0.58	0.09	0.42	0.88	0.56
10			0.82		
15			0.82		

pH	Columbia River Porewater Sampler ID				5/7/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	7.31	7.55		7.96	7.9
6*	7.46	7.36	7.65	7.95	7.84
10			7.66		
15			7.63		

*Note: Lower Depth of Redox03 is 4.6 ft.

Cond. (us/cm)	Columbia River Porewater Sampler ID				5/7/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	395	185.4		160.4	172.3
6*	394	328	179.3	155.5	373
10			509		
15			592		

*Note: Lower Depth of Redox03 is 4.6 ft.

DO (mg/L)	Columbia River Porewater Sampler ID				5/7/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	7.6	9.35		9.06	4.3
6*	8.1	5.9	12.8	9.79	5.5
10			10.3		
15			10.27		

*Note: Lower Depth of Redox03 is 4.6 ft.

Cr6+ (mg/L)	Columbia River Porewater Sampler ID				5/7/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	0.56	0.04		0	0.04
6*	0.6	0.08	0.02	0	0.6
10			0.66		
15			0.84		

*Note: Lower Depth of Redox03 is 4.6 ft.

SO_4^{2-} (ppm)	Columbia River Porewater Sampler ID				5/7/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	61.9	17.3		7	11.1
6	61.8	39.9	9.41	8.5	53.6
10			70.3		
15			100		

Cl^- (ppm)	Columbia River Porewater Sampler ID				5/7/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	12.7	2.3		2.87	3.2
6	13.2	8.51	3.1	0.92	13.7
10			13		
15			18.3		

NO_3^- (ppm)	Columbia River Porewater Sampler ID				5/7/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	36.5	0.56		<2	2.6
6	36.6	19	2.35	0.85	30.9
10			40.3		
15			57		

PO_4^{3-} (ppm)	Columbia River Porewater Sampler ID				5/7/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	<2	0.22		<2	<2
6	<2	<2	<2	0.26	<2
10			2.1		
15			<2		

F^- (ppm)	Columbia River Porewater Sampler ID				5/7/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	<2	0.37		2.62	<2
6	2.4	<2	<2	0.45	<2
10			<2		
15			<2		

pH	Columbia River Porewater Sampler ID				7/30/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	7.22	7.36		7.62	7.7
6*	7.45	7.26	7.52	7.63	7.73
10			7.67		
15			7.69		

*Note: Lower Depth of Redox03 is 4.6 ft.

Cond. (us/cm)	Columbia River Porewater Sampler ID				7/30/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	376	312		461	316
6*	434	368	255	461	326
10			410		
15			436		

*Note: Lower Depth of Redox03 is 4.6 ft.

DO (mg/L)	Columbia River Porewater Sampler ID				7/30/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	6.99	6.06		6.35	4.8
6*	7.1	4.7	7.41	6.09	5.29
10			8.16		
15			8.34		

*Note: Lower Depth of Redox03 is 4.6 ft.

Cr6+ (mg/L)	Columbia River Porewater Sampler ID				7/30/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	0.56	0.18		0.74	0.36
6*	0.6	0.1	0.16	0.72	0.38
10			0.56		
15			0.64		

*Note: Lower Depth of Redox03 is 4.6 ft.

SO_4^{2-} (ppm)	Columbia River Porewater Sampler ID				7/30/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	59.1	42.2		72.7	41.7
6	66.1	52.7	28.2	72.2	
10			63		
15			68.2		

Cl^- (ppm)	Columbia River Porewater Sampler ID				7/30/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	11.4	7.68		15.3	9.73
6	15.4	10.3	4.1	14.9	
10			12.3		
15			14.5		

NO_3^- (ppm)	Columbia River Porewater Sampler ID				7/30/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	27	19.2		35.4	19.4
6	36.2	21.9	11.3	34.8	
10			30.7		
15			56.3		

PO_4^{3-} (ppm)	Columbia River Porewater Sampler ID				7/30/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	< 0.2	0.94		0.62	< 0.2
6	1.02	0.36	1.4	1.3	
10			0.46		
15			< 0.2		

F^- (ppm)	Columbia River Porewater Sampler ID				7/30/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	0.34	0.31		0.37	0.31
6	0.4	0.34	0.23	0.35	
10			0.31		
15			0.43		

pH	Columbia River Porewater Sampler ID				10/21/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	7.16	7.38		7.63	7.7
6*	7.32	7.28	7.4	7.62	0
10			7.55		
15			7.56		

*Note: Lower Depth of Redox03 is 4.6 ft.

Cond. (µs/cm)	Columbia River Porewater Sampler ID				10/21/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	400	269		562	387
6*	406	323	423	561	0
10			535		
15			545		

*Note: Lower Depth of Redox03 is 4.6 ft.

DO (mg/L)	Columbia River Porewater Sampler ID				10/21/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	5.03	6.83		5.93	5.4
6*	5.4	7.09	7.79	6.3	0
10			7.08		
15			6.96		

*Note: Lower Depth of Redox03 is 4.6 ft.

Cr6+ (mg/L)	Columbia River Porewater Sampler ID				10/21/98
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	0.58	0.16		0.9	0.62
6*	0.6	0.04	0.52	0.9	0
10			0.78		
15			0.78		

*Note: Lower Depth of Redox03 is 4.6 ft.

pH	Columbia River Porewater Sampler ID				4/5/99
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	7.5	7.67		8	8
6*	7.69	7.49	7.79	8.02	7.92
10			7.85		
15			7.89		

*Note: Lower Depth of Redox03 is 4.6 ft.

Cond. (µs/cm)	Columbia River Porewater Sampler ID				4/5/99
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	230	204		212	258
6*	269	327	196	183	293
10			452		
15			456		

*Note: Lower Depth of Redox03 is 4.6 ft.

DO (mg/L)	Columbia River Porewater Sampler ID				4/5/99
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	8.09	8.21		7.75	6.79
6*	5.9	4.16	12.91	7.74	5.64
10			9.21		
15			8.9		

*Note: Lower Depth of Redox03 is 4.6 ft.

Cr6+ (mg/L)	Columbia River Porewater Sampler ID				4/5/99
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	0.23	0.06		0.12	0.25
6*	0.28	0.1	0.07	0.08	0.33
10			0.51		
15			0.55		

*Note: Lower Depth of Redox03 is 4.6 ft.

pH	Columbia River Porewater Sampler ID				7/28/99
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	7.29	7.33		7.94	7.84
6*	7.4	7.28	7.64	7.9	7.81
10			7.87		
15			7.77		

*Note: Lower Depth of Redox03 is 4.6 ft.

Cond. (μs/cm)	Columbia River Porewater Sampler ID				7/28/99
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	266	204		185	177.3
6*	300	325	195.9	174	198
10			199		
15			356		

*Note: Lower Depth of Redox03 is 4.6 ft.

DO (mg/L)	Columbia River Porewater Sampler ID				7/28/99
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	5.01	5.22		4.33	2.3
6*	3.9	3.65	9.54	3.87	3.6
10			10.9		
15			8.9		

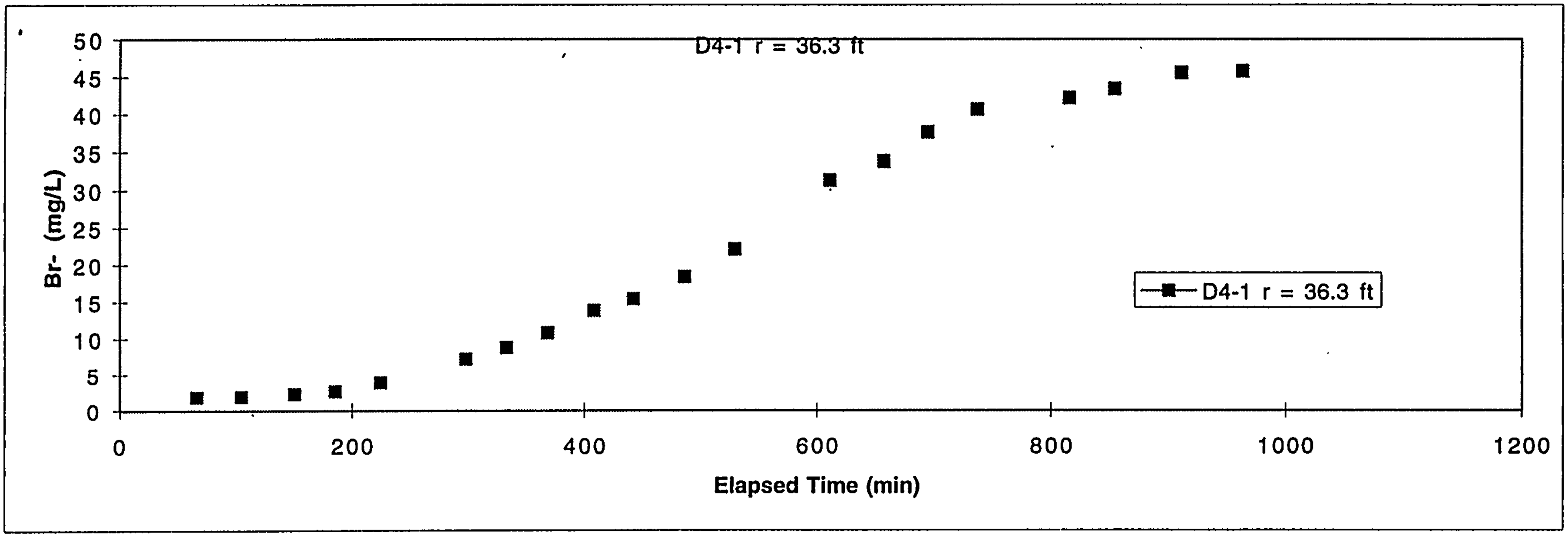
*Note: Lower Depth of Redox03 is 4.6 ft.

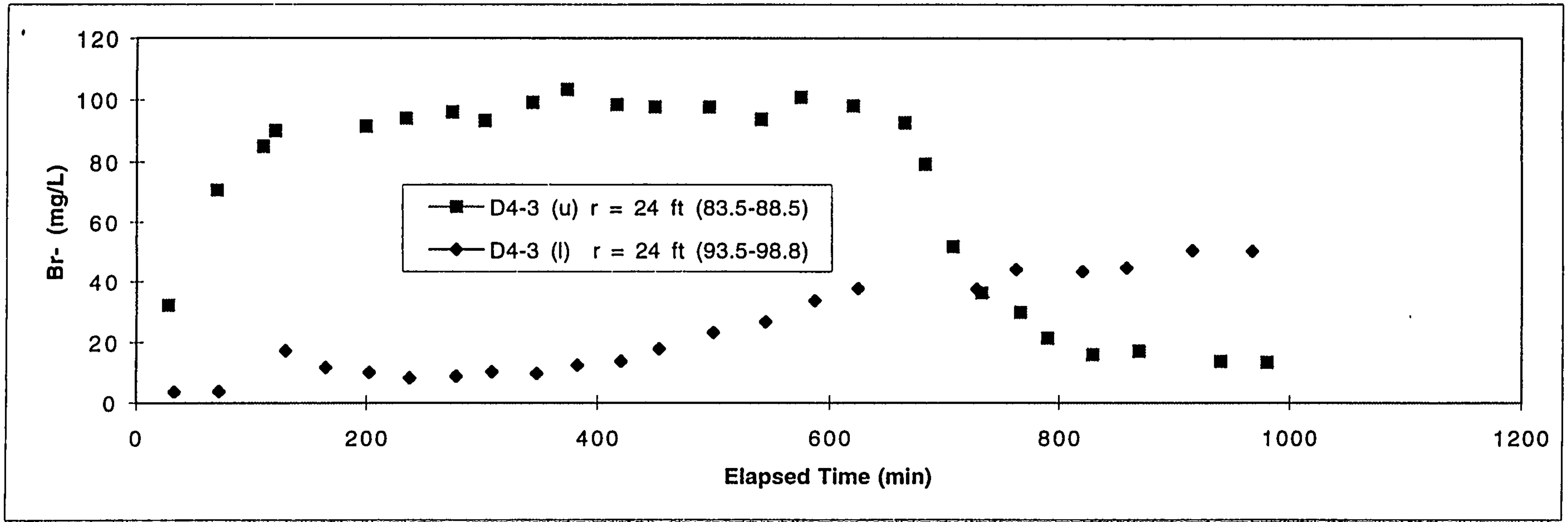
Cr6+ (mg/L)	Columbia River Porewater Sampler ID				7/28/99
Depth (ft)	Redox01	Redox02	TD39	Redox03	Redox04
3	0.24	0.03		0.03	0
6*	0.29	0.08	0.01	0.02	0.05
10			0.05		
15			0.32		

*Note: Lower Depth of Redox03 is 4.6 ft.

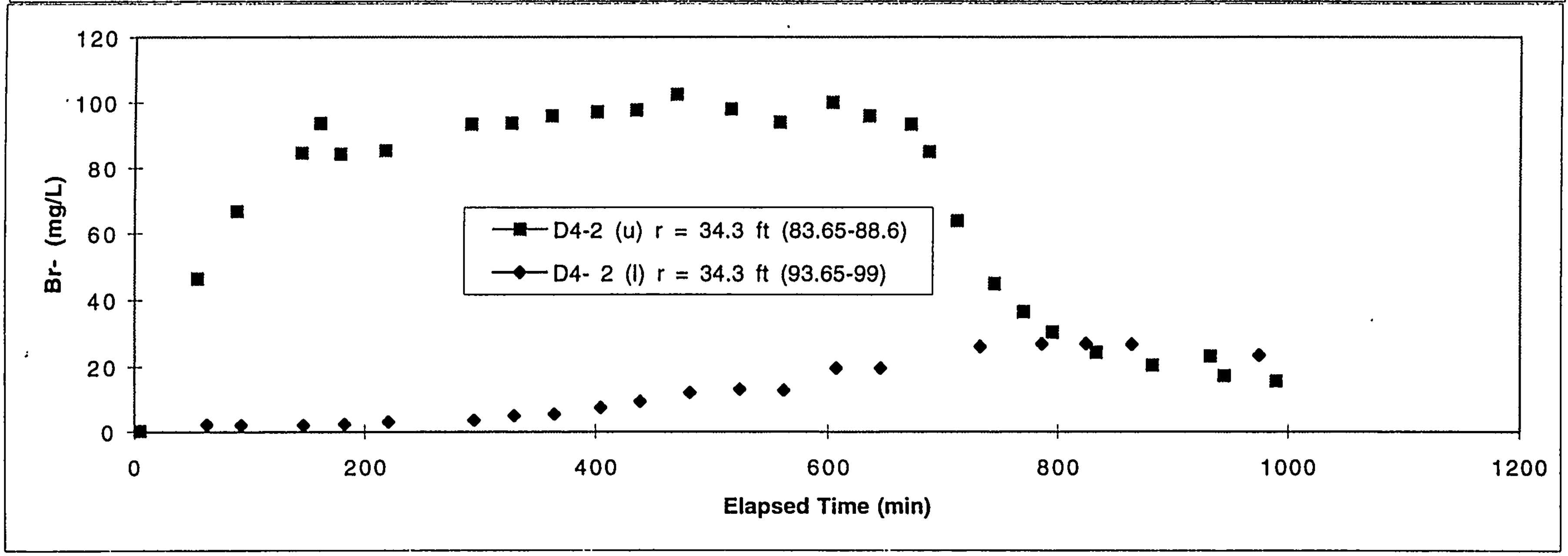
Appendix D

Bromide Tracer Test Breakthrough Curves

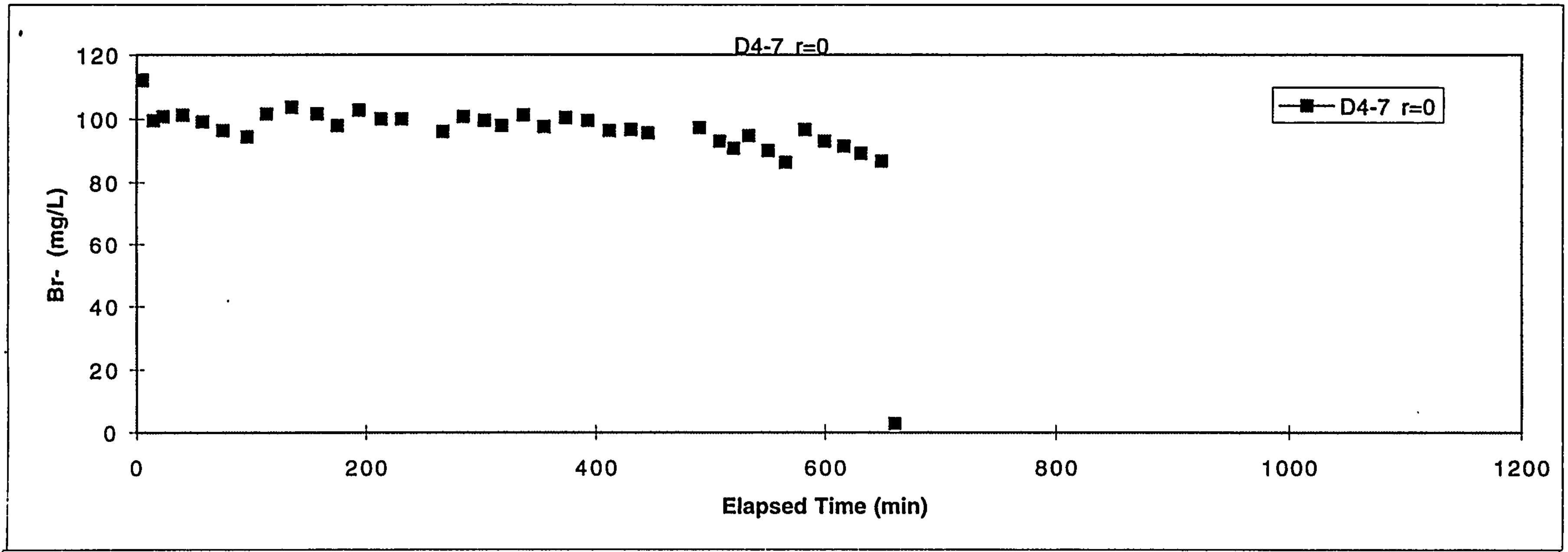

D4-1 r = 36.3 ft
Br- (mg/L)
0
5
10
15
20
25
30
35
40
45
50
0
200
400
600
800
1000
1200
Elapsed Time (min)
D4-1 r = 36.3 ft

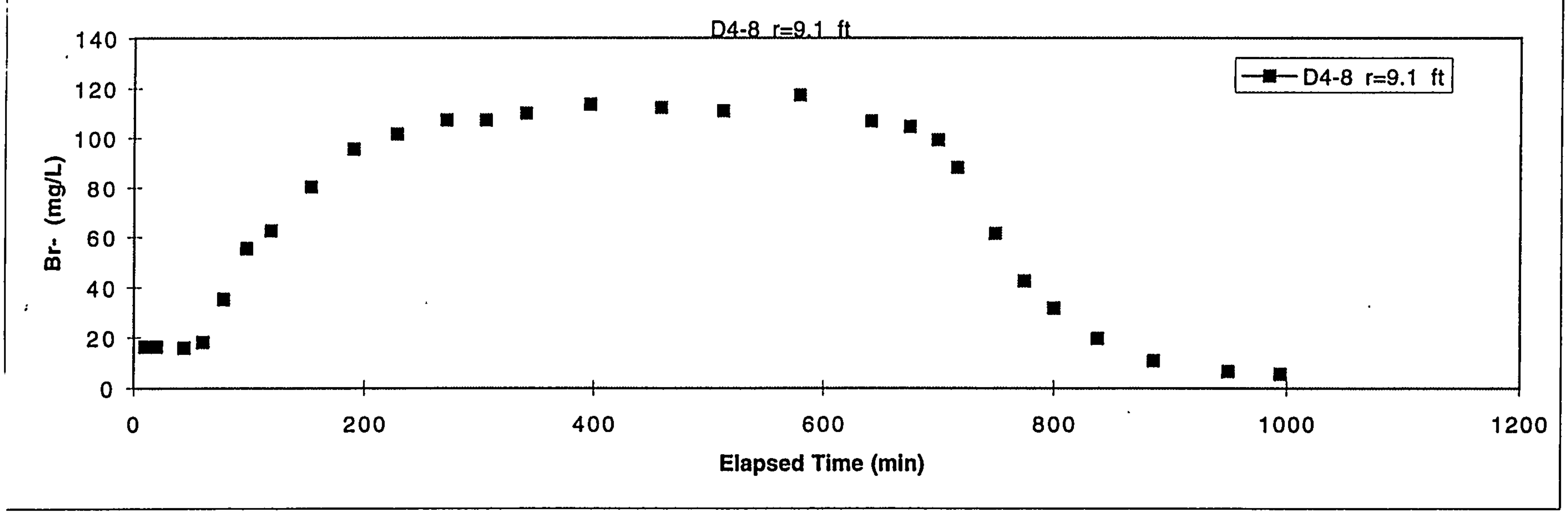


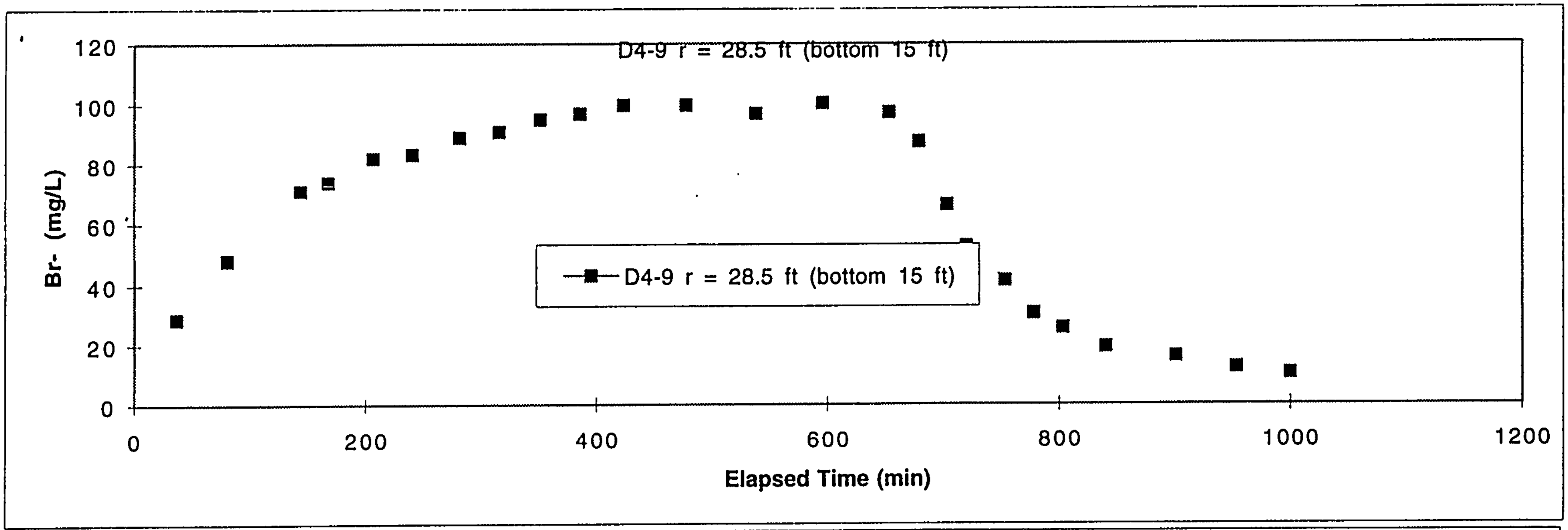
Br- (mg/L)
0
20
40
60
80
100
120
Elapsed Time (min)
0
200
400
600
800
1000
1200
■ D4-3 (u) r = 24 ft (83.5-88.5)
◆ D4-3 (l) r = 24 ft (93.5-98.8)

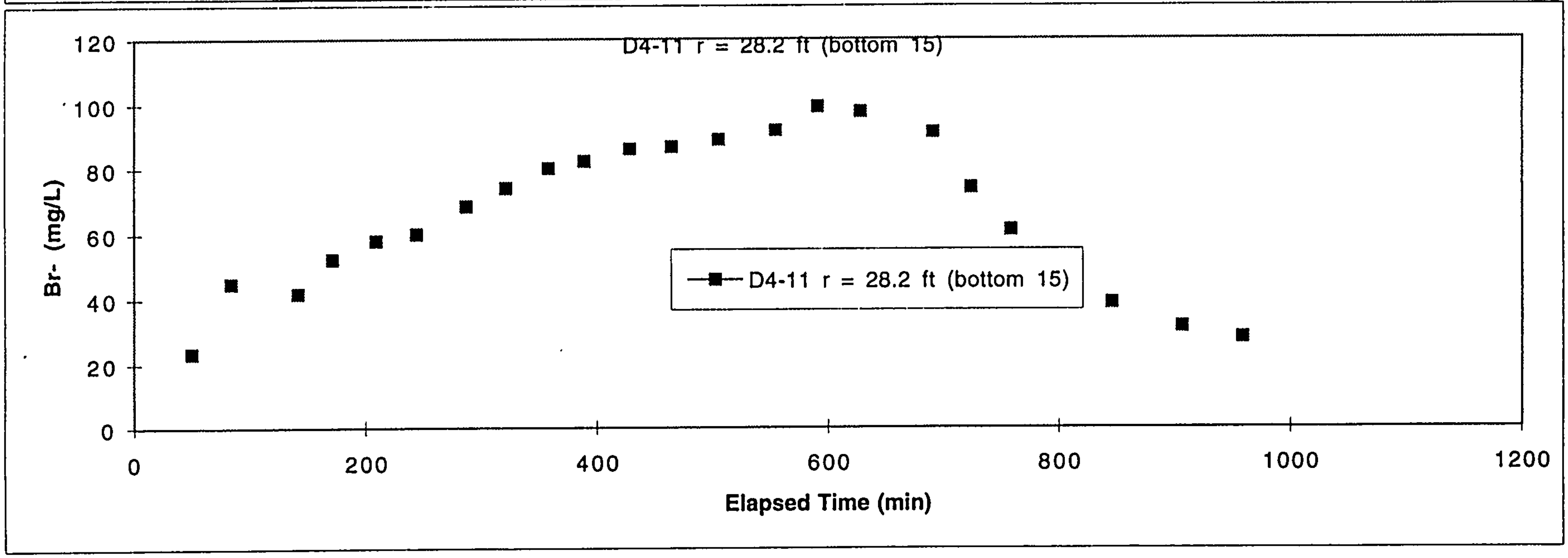


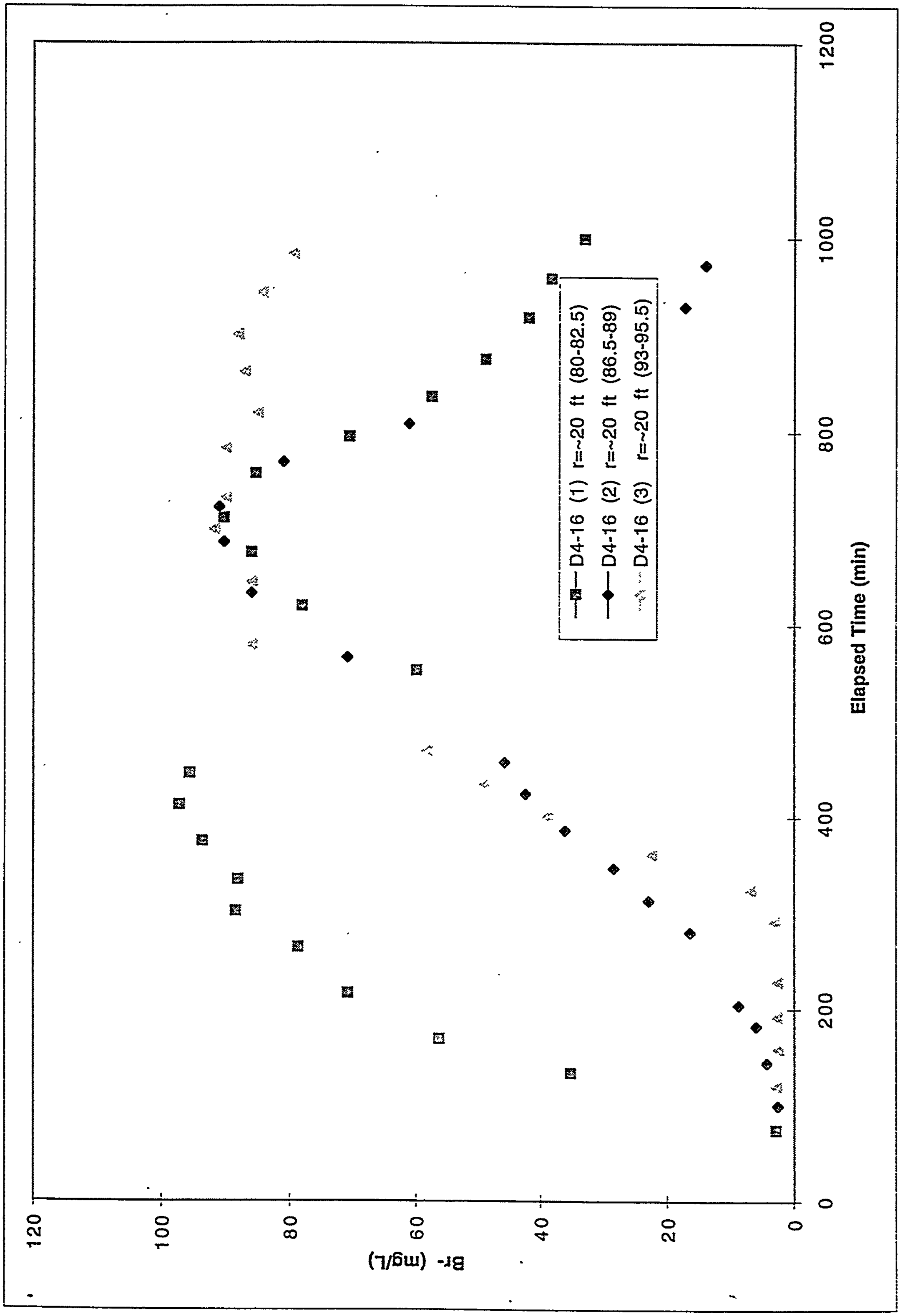
Br- (mg/L)
0
20
40
60
80
100
120
Elapsed Time (min)
0
200
400
600
800
1000
1200
■ D4-2 (u) r = 34.3 ft (83.65-88.6)
◆ D4- 2 (l) r = 34.3 ft (93.65-99)


D4-7 r=0
D4-7 r=0
Br- (mg/L)
120
100
80
60
40
20
0
0
200
400
600
800
1000
1200
Elapsed Time (min)


D4-8 r=9.1 ft
D4-8 r=9.1 ft
Br- (mg/L)
140
120
100
80
60
40
20
0
0
200
400
600
800
1000
1200
Elapsed Time (min)


D4-9 r = 28.5 ft (bottom 15 ft)
Br- (mg/L)
0
20
40
60
80
100
120
0
200
400
600
800
1000
1200
Elapsed Time (min)
D4-9 r = 28.5 ft (bottom 15 ft)

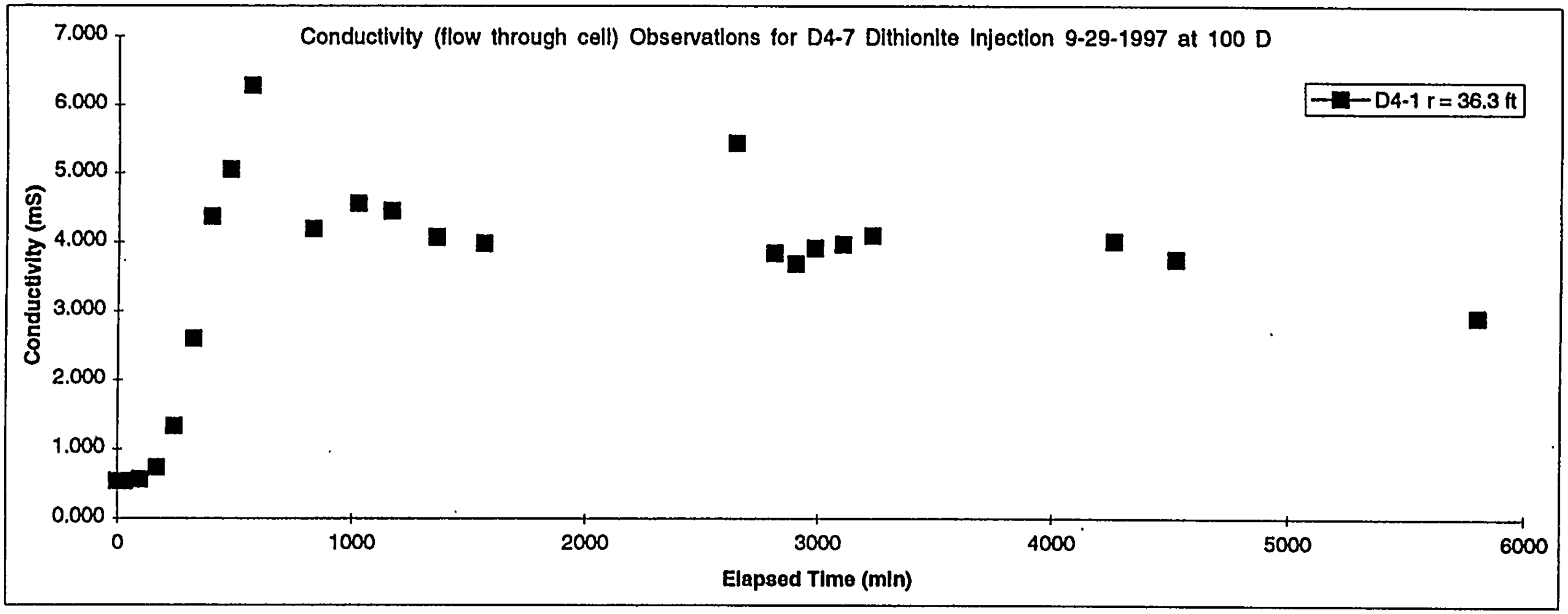

D4-11 r = 28.2 ft (bottom 15)
Br- (mg/L)
0
20
40
60
80
100
120
0
200
400
600
800
1000
1200
Elapsed Time (min)
D4-11 r = 28.2 ft (bottom 15)

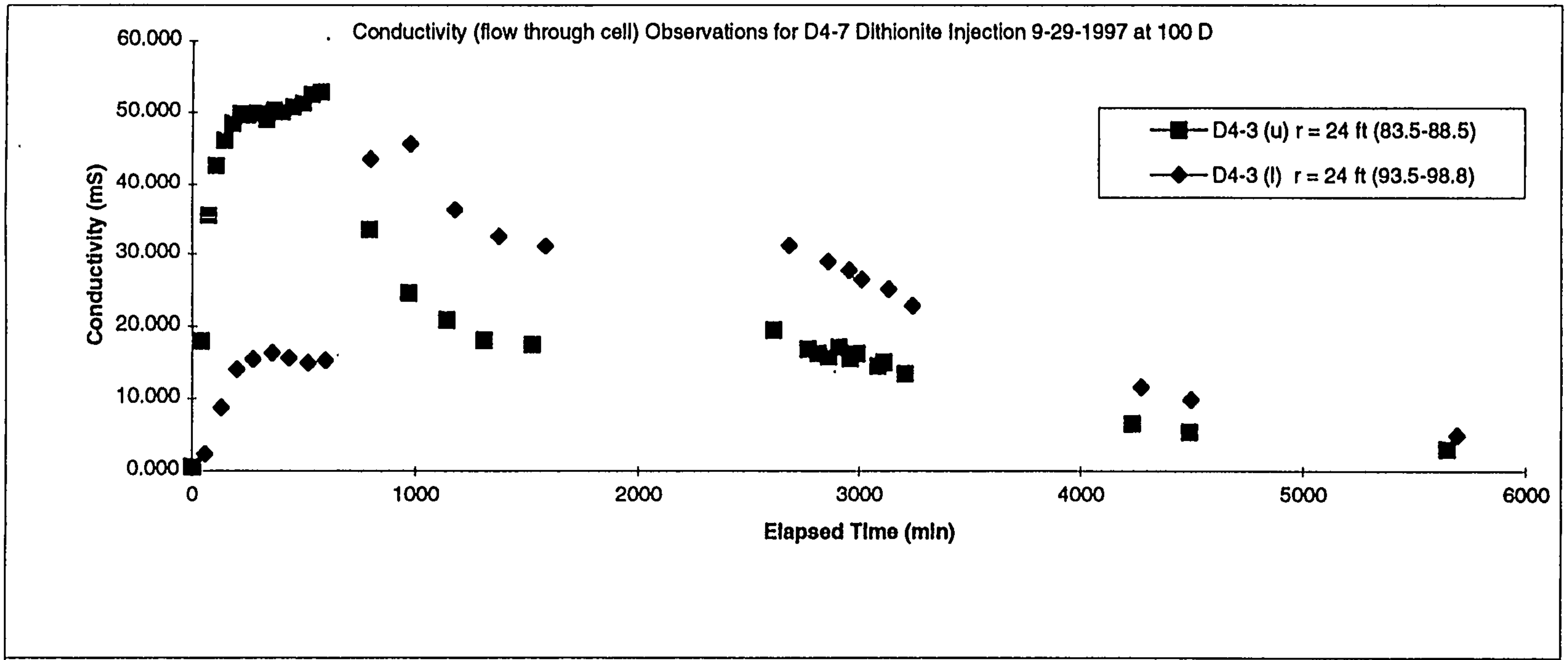


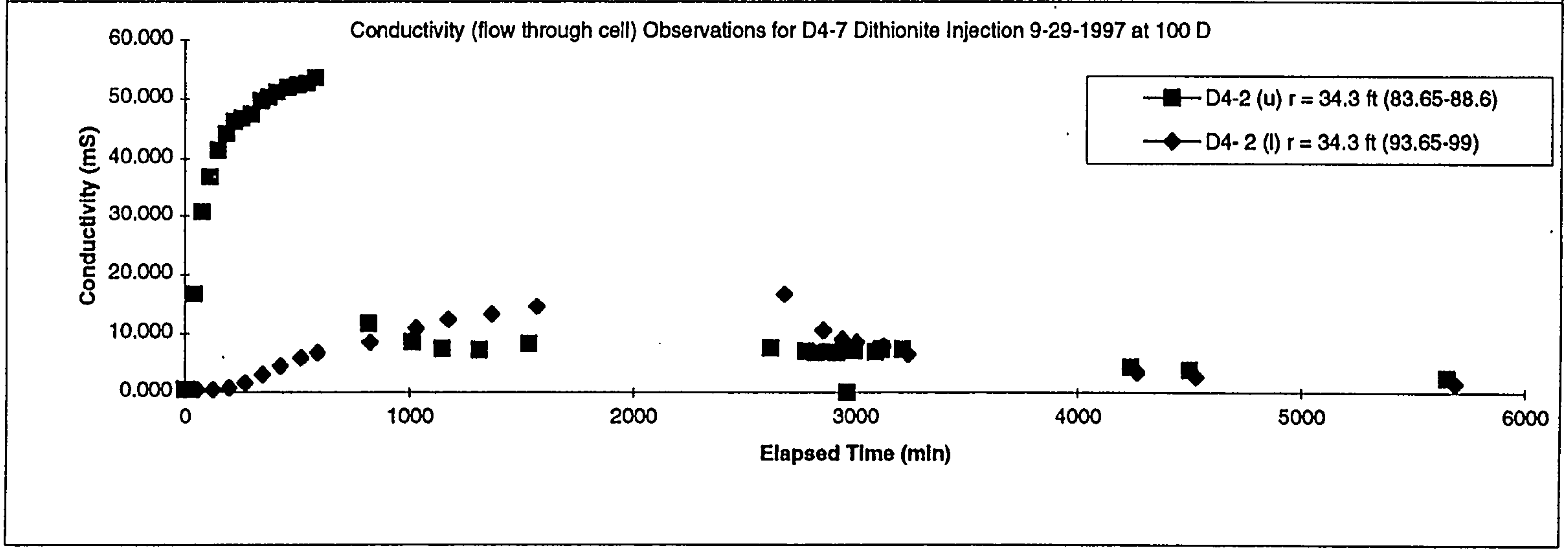
Br- (mg/L)
0
20
40
60
80
100
120
Elapsed Time (min)
0
200
400
600
800
1000
1200
D4-16 (1) r=~20 ft (80-82.5)
D4-16 (2) r=~20 ft (86.5-89)
D4-16 (3) r=~20 ft (93-95.5)

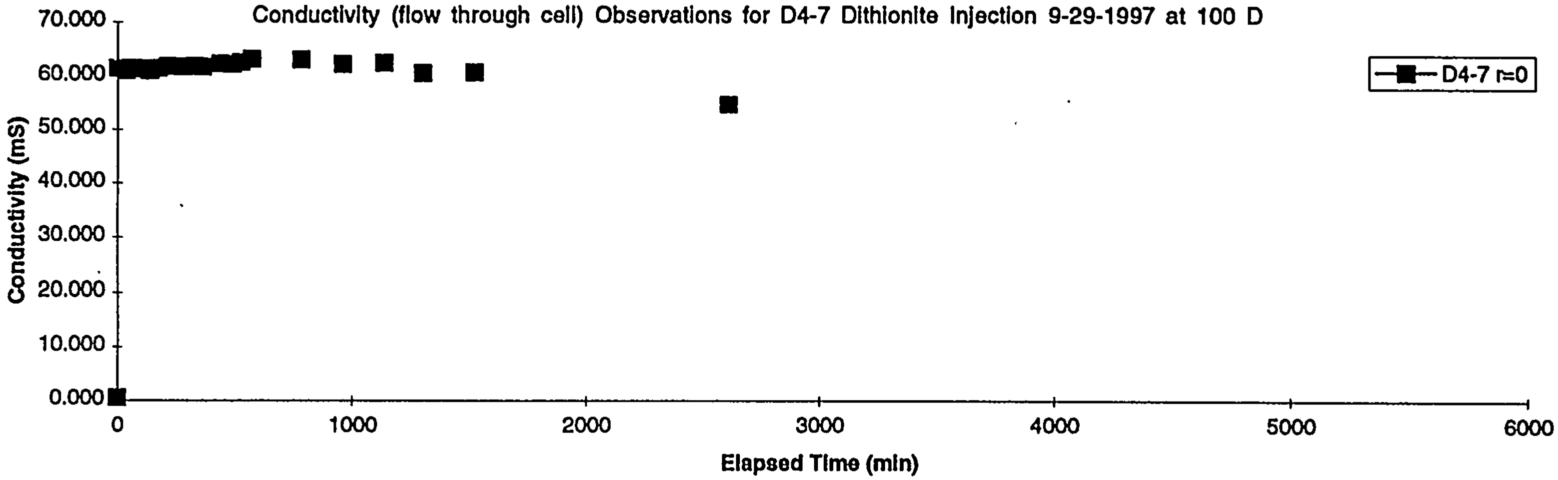
Appendix E

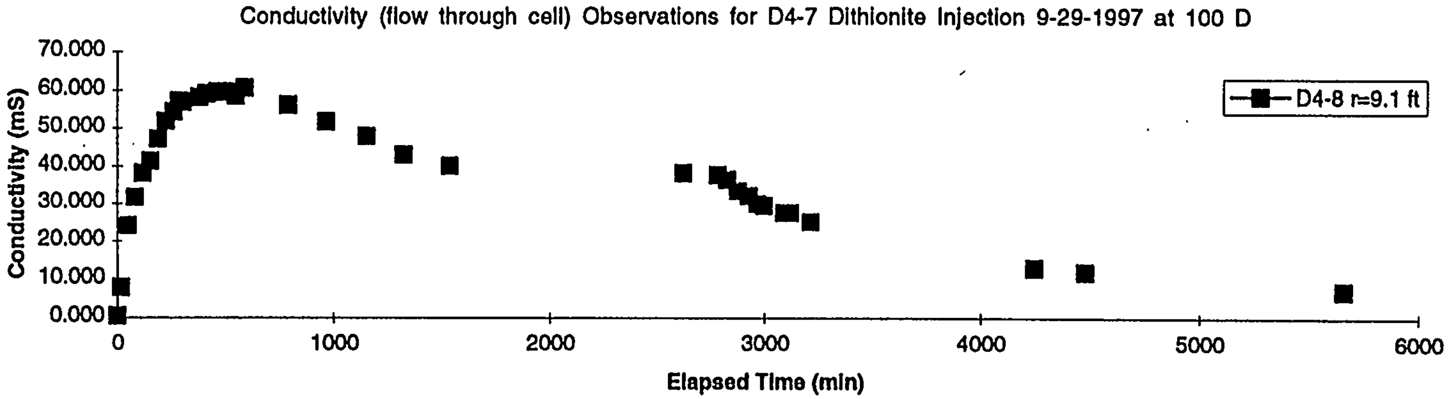
D4-7 Dithionite Injection/Withdrawal Test Breakthrough Curves

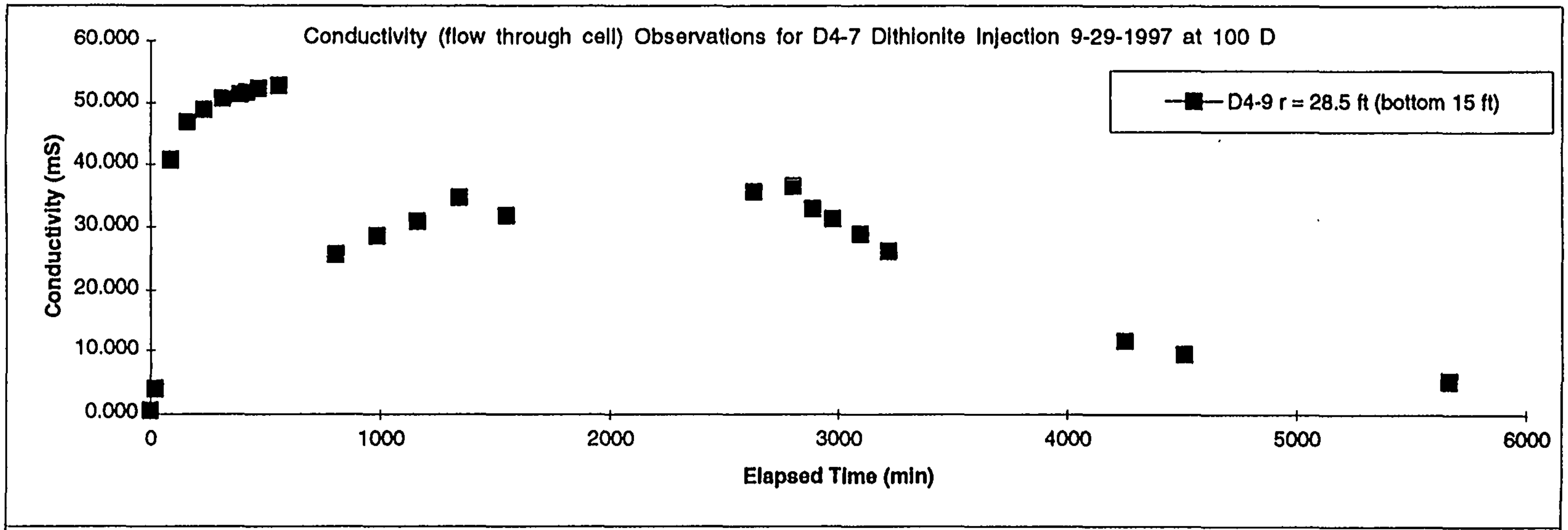

Conductivity (flow through cell) Observations for D4-7 Dithionite Injection 9-29-1997 at 100 D
D4-1 r = 36.3 ft
Conductivity (mS)
7.000
6.000
5.000
4.000
3.000
2.000
1.000
0.000
0
1000
2000
3000
4000
5000
6000
Elapsed Time (min)

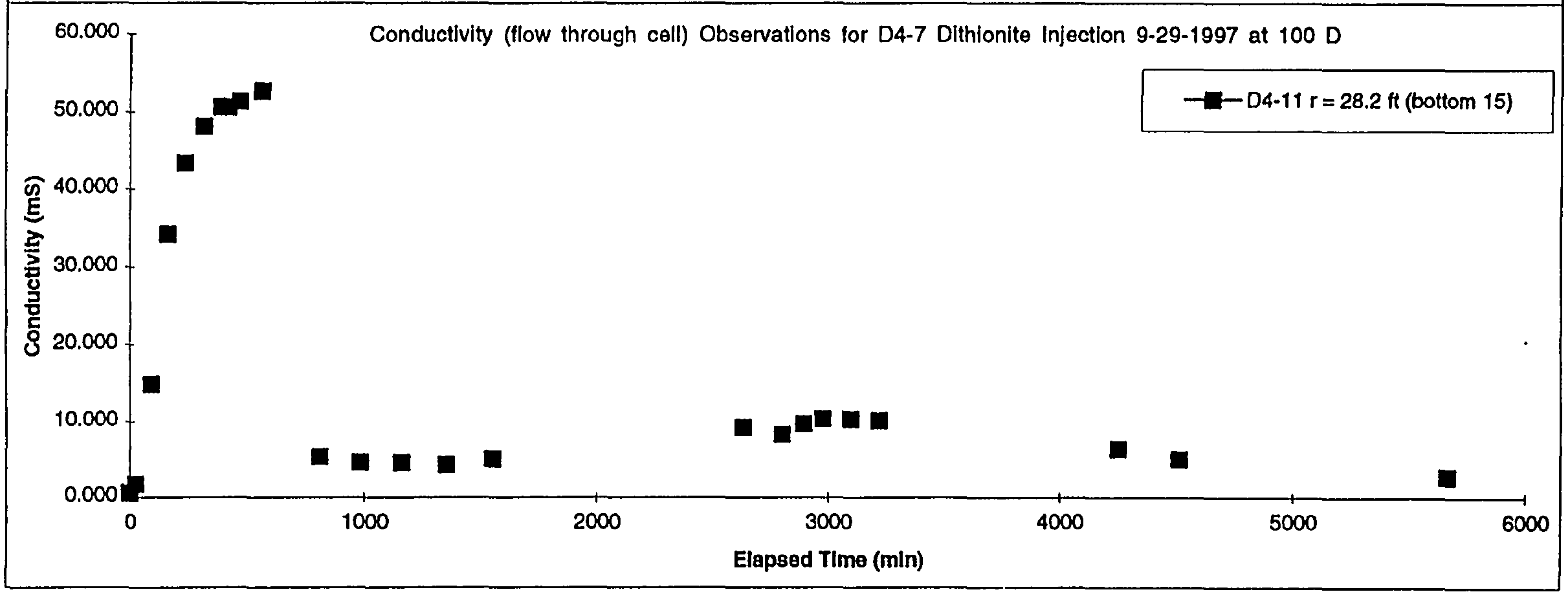

Conductivity (flow through cell) Observations for D4-7 Dithionite Injection 9-29-1997 at 100 D

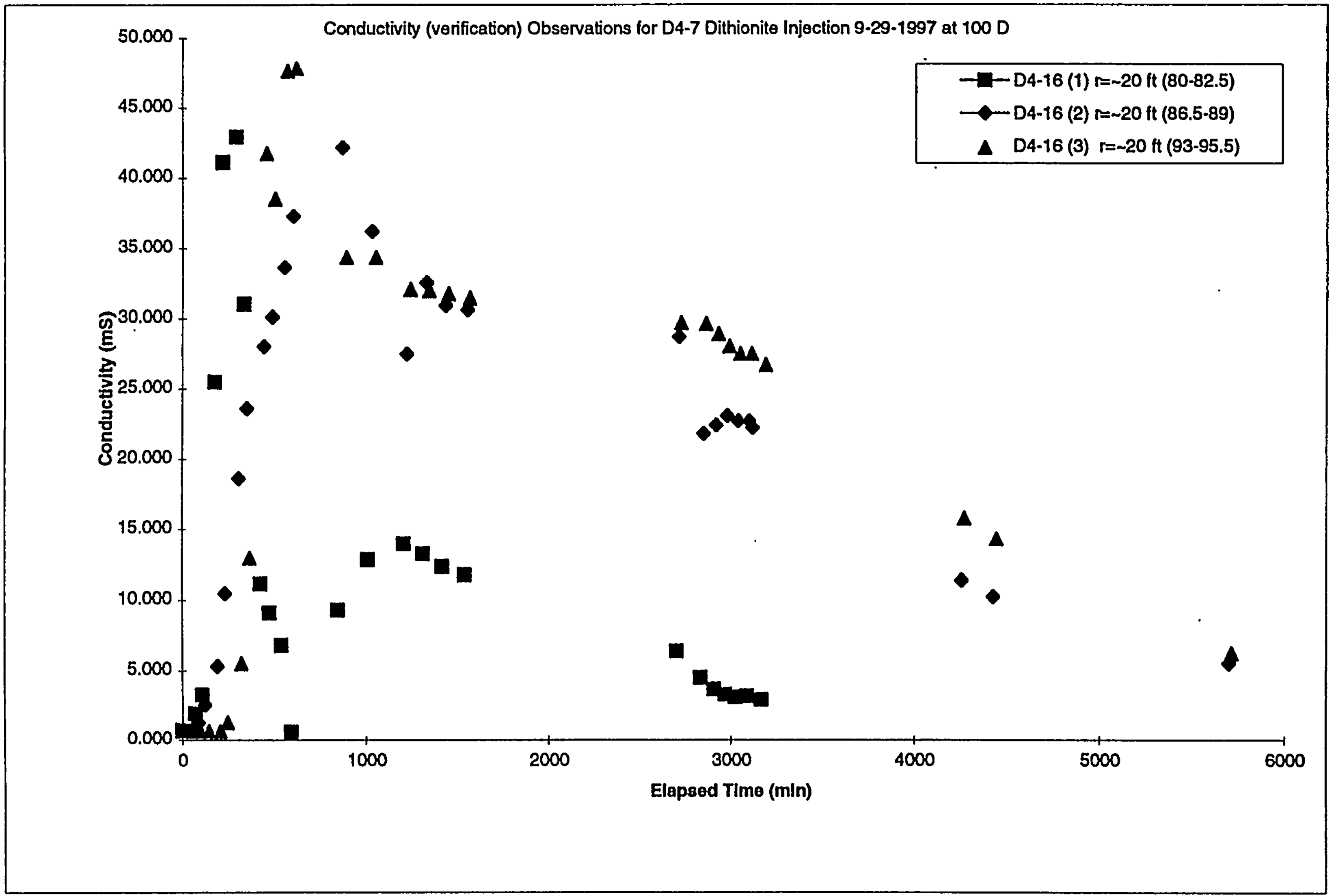

Conductivity (flow through cell) Observations for D4-7 Dithionite Injection 9-29-1997 at 100 D

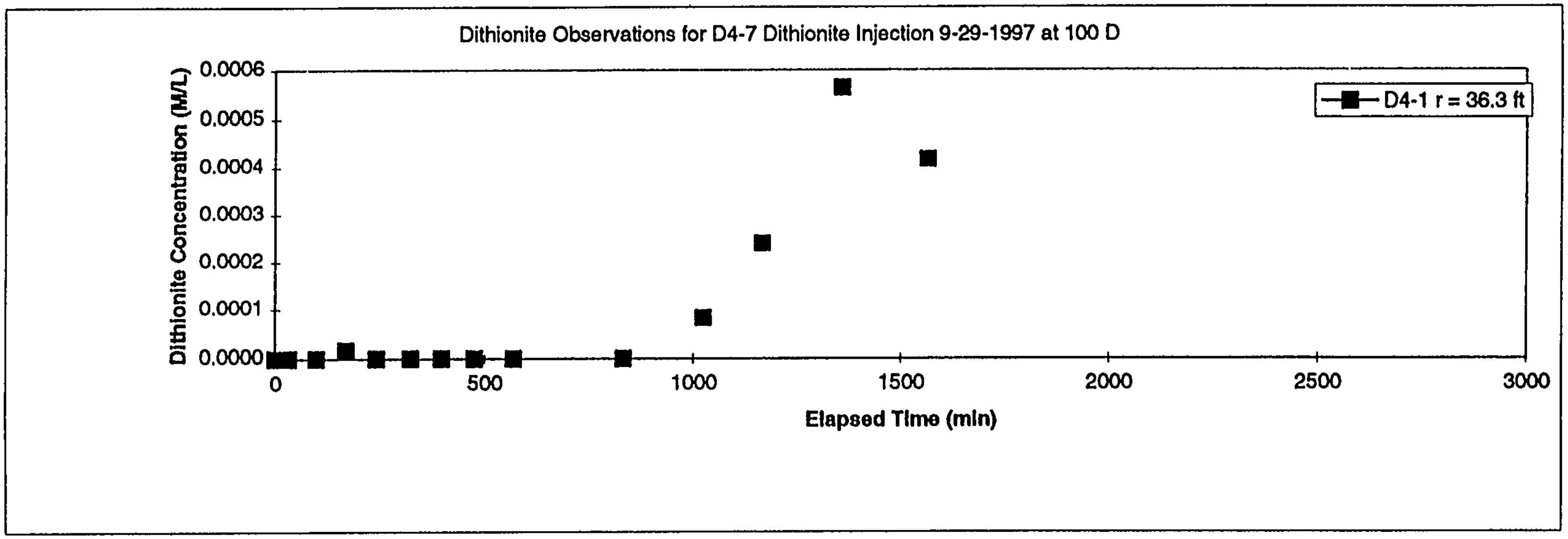

Conductivity (flow through cell) Observations for D4-7 Dithionite Injection 9-29-1997 at 100 D


Conductivity (flow through cell) Observations for D4-7 Dithionite Injection 9-29-1997 at 100 D

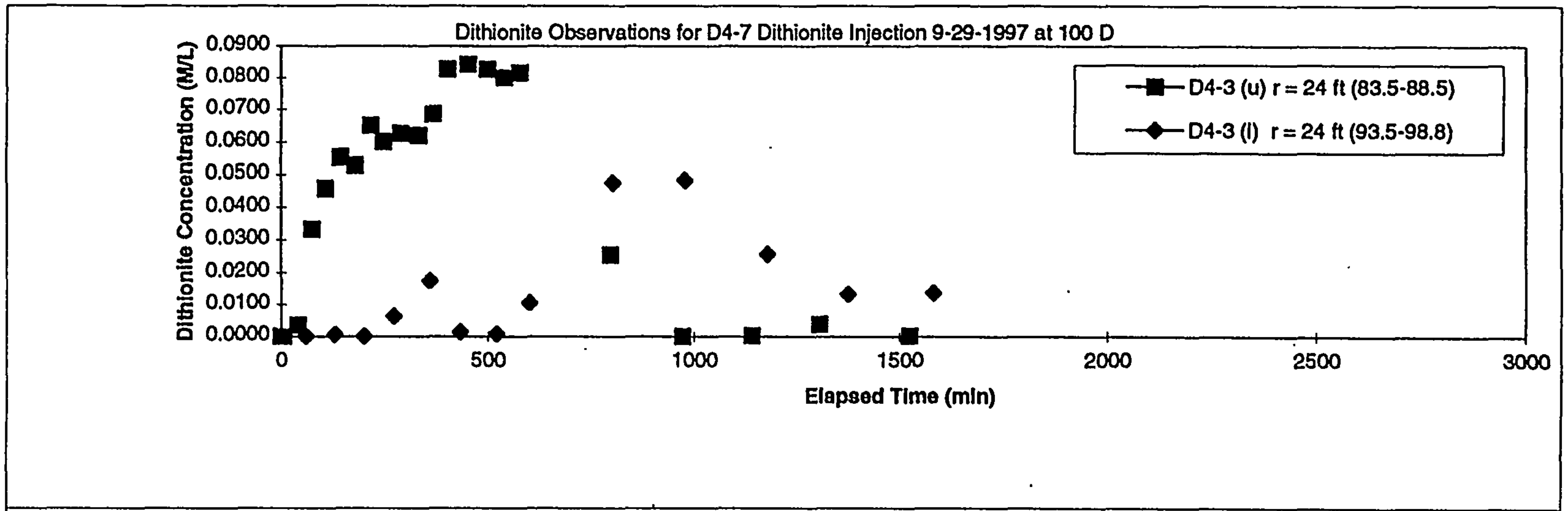

Conductivity (flow through cell) Observations for D4-7 Dithionite Injection 9-29-1997 at 100 D
D4-9 r = 28.5 ft (bottom 15 ft)
Conductivity (mS)
60.000
50.000
40.000
30.000
20.000
10.000
0.000
0
1000
2000
3000
4000
5000
6000
Elapsed Time (min)

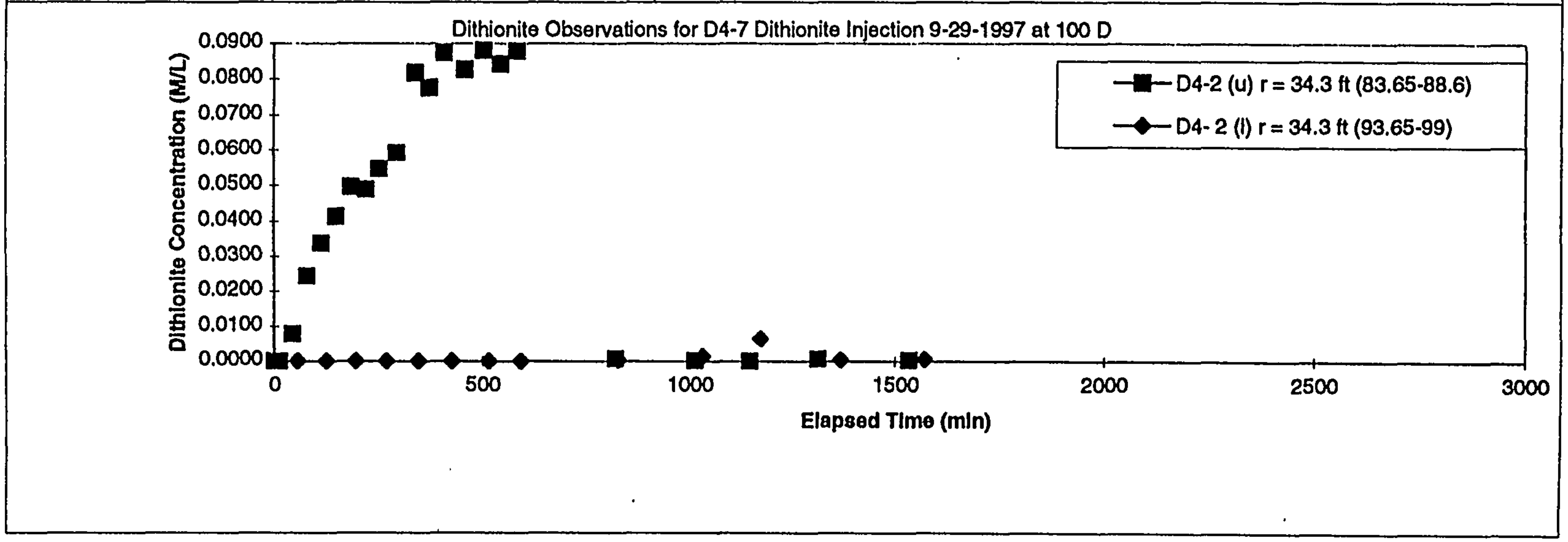

Conductivity (flow through cell) Observations for D4-7 Dithionite Injection 9-29-1997 at 100 D
D4-11 r = 28.2 ft (bottom 15)
Conductivity (mS)
60.000
50.000
40.000
30.000
20.000
10.000
0.000
0
1000
2000
3000
4000
5000
6000
Elapsed Time (min)

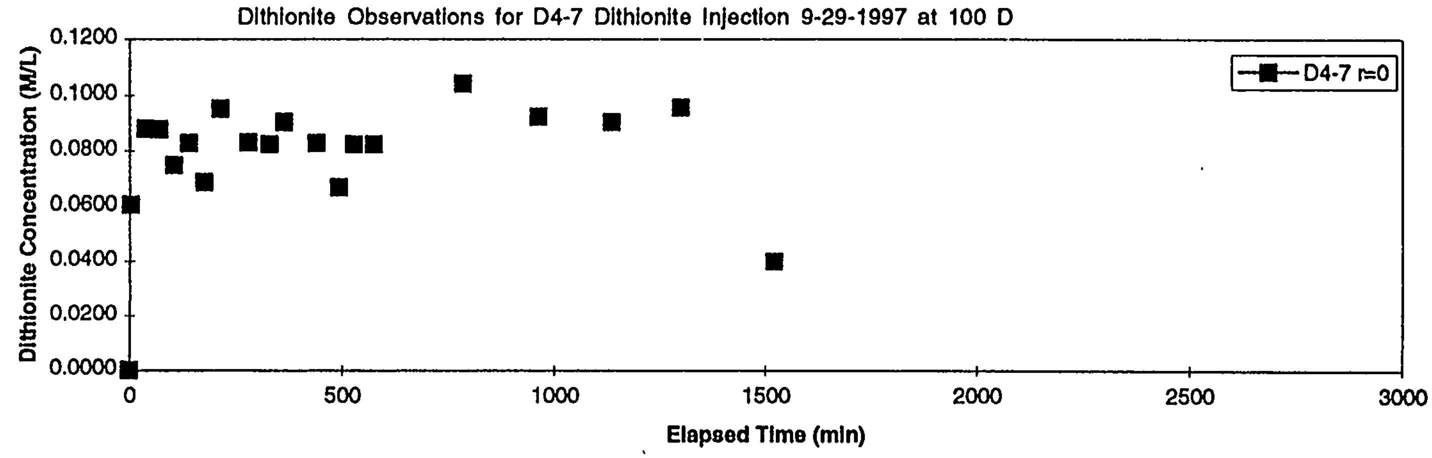

Conductivity (verification) Observations for D4-7 Dithionite Injection 9-29-1997 at 100 D
D4-16 (1) r=~20 ft (80-82.5)
D4-16 (2) r=~20 ft (86.5-89)
D4-16 (3) r=~20 ft (93-95.5)
Conductivity (mS)
50.000
45.000
40.000
35.000
30.000
25.000
20.000
15.000
10.000
5.000
0.000
0
1000
2000
3000
4000
5000
6000
Elapsed Time (min)

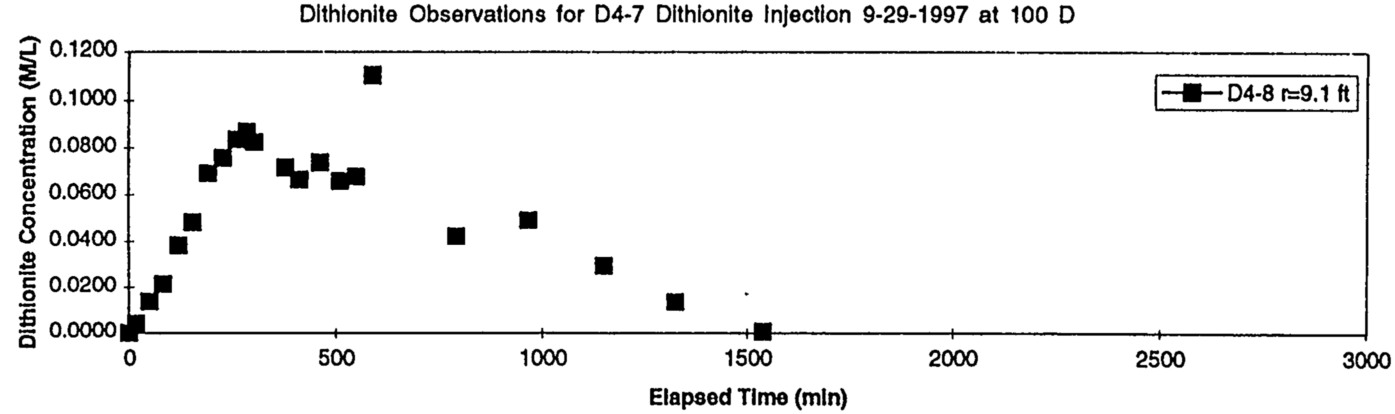


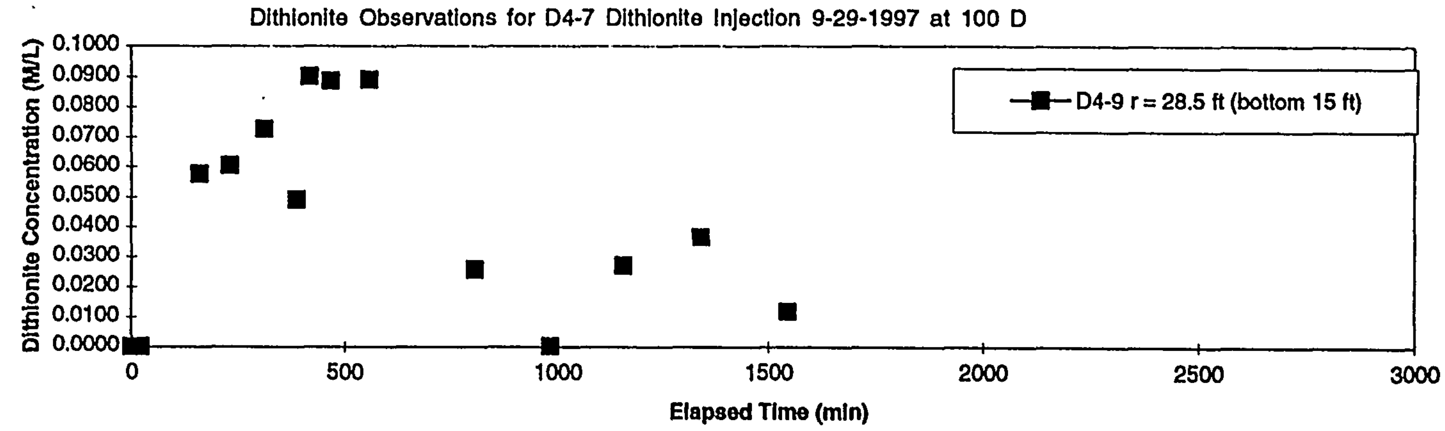
Dithionite Observations for D4-7 Dithionite Injection 9-29-1997 at 100 D

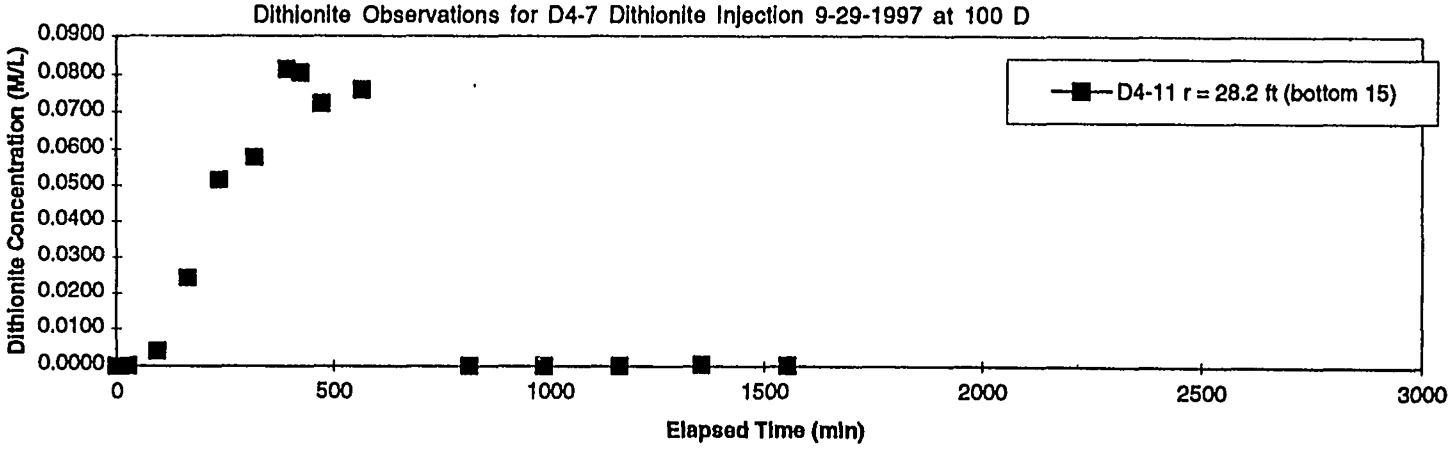

Dithionite Observations for D4-7 Dithionite Injection 9-29-1997 at 100 D

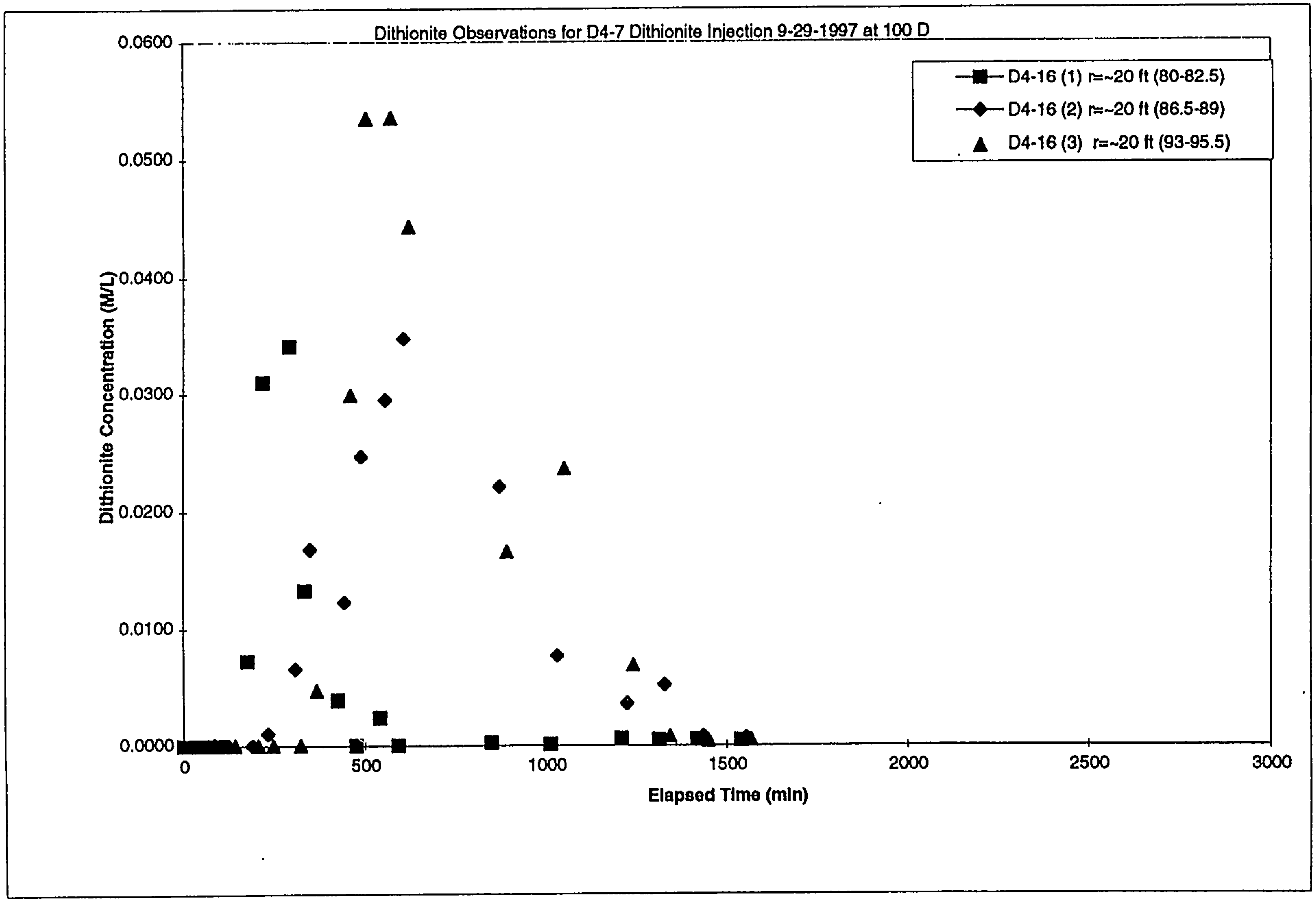

Dithionite Observations for D4-7 Dithionite Injection 9-29-1997 at 100 D


Dithionite Observations for D4-7 Dithionite Injection 9-29-1997 at 100 D


Dithionite Observations for D4-7 Dithionite Injection 9-29-1997 at 100 D


Dithionite Observations for D4-7 Dithionite Injection 9-29-1997 at 100 D


Dithionite Observations for D4-7 Dithionite Injection 9-29-1997 at 100 D


Dithionite Observations for D4-7 Dithionite Injection 9-29-1997 at 100 D
D4-16 (1) r=~20 ft (80-82.5)
D4-16 (2) r=~20 ft (86.5-89)
D4-16 (3) r=~20 ft (93-95.5)
Dithionite Concentration (M/L)
0.0600
0.0500
0.0400
0.0300
0.0200
0.0100
0.0000
0
500
1000
1500
2000
2500
3000
Elapsed Time (min)

Appendix F

Groundwater Monitoring Result—

Field Parameters and Anions Analysis

Well-ID	FIELD	Sampled and Analysed 8/13/97					IC	Analysed				
	Cond µS/cm	**Cond** Temp.	**DO** mg/L	**DO** Temp.	**pH**	**Cr6+** mg/l	**F** mg/L	**Cl** mg/L	**NO3** mg/L	**PO4** mg/L	**SO4** mg/L	**Br-** mg/L
D4-2 up	599	17.1	12.49	18.6	7.74	0.94	0.282	24.0	66.0	<0.2	117	
D4-2 low	531	16.7	10.30	21.1	7.69	1.04	<0.2	23.3	46.3	<0.2	91.9	
D4-3 up	571	16.4	9.50	23.4	8.30	0.90	<0.2	28.0	61.4	<0.2	109	
D4-3 low	489	16.1	8.01	23.2	8.78	0.88	<0.2	24.4	49.3	<0.2	91	
D4-7	621	17.4	9.08	24.6	7.71	0.88	0.255	32.7	67.4	<0.2	115	
D4-8	641	16.8	9.16	23.6	7.67	0.88	<0.2	38.1	70.3	<0.2	116	
D4-9	653	16.7	8.00	23.2	7.72	0.80	<0.2	38.2	69.9	<0.2	120	
D4-11	670	17.2	7.71	24.3	7.66	0.88	<0.2	42.1	77.3	<0.2	122	
D4-16 (1)												
D4-16 (2)												
D4-16 (3)												
D4-1	594	16.8	9.46	19.2	7.70	0.90	<0.2	26.0	55.4	<0.2	103	
D4-12	643	20.7	8.06	24.1	7.59	0.86	<0.2	29.0	66.3	<0.2	134	
D4-10	654	20.9	8.84	24.5	7.62	0.74	<0.2	41.3	69.0	<0.2	124	
D4-4	636	20.4	8.38	23.3	7.60	0.68	<0.2	26.7	66.4	<0.2	131	
D4-5	688	21.8	10.20	22.4	7.67	0.80	<0.2	41.5	89.9	<0.2	117	
D4-6	546	22.2	11.20	23.0	7.71	0.82	0.549	21.0	55.2	<0.2	98.5	
D4-17 (1)												
D4-17 (2)												
D4-17 (3)												
D4-18 (1)												
D4-18 (2)												
D4-18 (3)												

Figure F.1. Groundwater Monitoring Result for August 13, 1997

Well-ID	FIELD	Sampled and Analysed 8/20/97				
	Cond	**Cond**	**DO**	**DO**	**pH**	**Cr6+**
	µS/cm	Temp.	mg/L	Temp.		mg/l
D4-2 up	590	17.2	0.70	19.3	7.78	0.97
D4-2 low	517	16.6	10.26	19.2	7.78	1.05
D4-3 up	561	17.2	8.24	20.3	8.47	0.90
D4-3 low	475	16.9	7.36	20.1	8.68	0.90
D4-7	580	17.2	8.80	20.3	7.76	0.94
D4-8	629	17.6	7.26	20.6	7.68	0.85
D4-9	650	17.7	6.66	19.6	7.72	0.86
D4-11	696	17.4	6.75	18.7	7.60	0.86
D4-16 (1)						
D4-16 (2)						
D4-16 (3)						
D4-1	583	16.9	8.07	19.3	7.72	0.88
D4-12	611	19.4	7.97	22.0	7.62	0.88
D4-10	637	20.6	8.93	22.7	7.63	0.76
D4-4	624	19.3	7.02	21.6	7.62	0.65
D4-5	660	19.0			7.62	0.82
D4-6	541	18.4	8.52	20.9	7.76	0.83
D4-17 (1)						
D4-17 (2)						
D4-17 (3)						
D4-18 (1)						
D4-18 (2)						
D4-18 (3)						

Figure F.2. Groundwater Monitoring Result for August 20, 1997

Well-ID	FIELD	Sampled and Analysed 8/26/97				
	Cond	**Cond**	**DO**	**DO**	**pH**	**Cr6+**
	µS/cm	Temp.	mg/L	Temp.		mg/l
D4-2 up	577	18.6	7.89	28.3	7.64	1.04
D4-2 low	497	17.5	8.69	26.7	7.71	1.07
D4-3 up	558	18.0	8.33	27.1	8.01	0.88
D4-3 low	485	17.3	7.88	27.5	8.52	0.90
D4-7	562	18.9	8.58	27.4	7.00	0.98
D4-8	596	17.9	8.41	26.6	7.65	0.94
D4-9	579	17.8	8.23	26.8	7.67	0.90
D4-11	591	17.3	7.88	25.6	7.57	0.80
D4-16 (1)	556	28.0	4.00	26.8	7.62	0.25
D4-16 (2)	560	26.8	4.57	25.5	7.51	0.80
D4-16 (3)	526	19.3	2.34	20.2	7.61	0.38
D4-1	541	17.8	8.46	25.6	7.66	0.86
D4-12	537	22.4	8.46	28.5	7.69	0.94
D4-10	596	22.2	7.03	27.1	7.56	0.74
D4-4	569	22.6	7.73	27.4	7.58	0.76
D4-5	583	22.7	8.52	28.4	7.55	0.72
D4-6	516	22.3	9.03	27.2	7.70	0.68
D4-17 (1)						
D4-17 (2)						
D4-17 (3)						
D4-18 (1)						
D4-18 (2)						
D4-18 (3)						

Figure F.3. Groundwater Monitoring Result for August 26, 1997

Well-ID	FIELD	Sampled and Analysed 9/3/97				
	Cond	**Cond**	**DO**	**DO**	**pH**	**Cr6+**
	µS/cm	Temp.	mg/L	Temp.		mg/l
D4-2 up	601	17.0	9.56	18.0	7.50	0.96
D4-2 low	500	15.0	10.29	17.3	7.71	1.06
D4-3 up	590	16.0	9.92	17.7	7.88	1.00
D4-3 low	525	15.0	10.00	17.3	8.40	1.00
D4-7	617	21.0	8.46	22.3	7.57	0.94
D4-8	600	19.0	8.94	20.7	7.60	0.92
D4-9	601	16.0	9.10	18.2	7.66	0.94
D4-11	650	16.0	8.41	17.4	7.54	0.90
D4-16 (1)						0.52
D4-16 (2)						0.80
D4-16 (3)						0.16
D4-1	597	15.0	8.29	17.7	7.61	0.90
D4-12	614	17.0	8.91	18.3	7.54	0.88
D4-10	662	17.0	9.53	18.9	7.52	0.74
D4-4	583	17.0	9.18	18.4	7.55	0.66
D4-5	606	17.0	10.30	18.9	7.61	0.84
D4-6	517	17.0	10.69	18.8	7.66	0.72
D4-17 (1)						
D4-17 (2)						
D4-17 (3)						
D4-18 (1)						
D4-18 (2)						
D4-18 (3)						

Figure F.4. Groundwater Monitoring Result for September 3, 1997

Well-ID	FIELD Cond µS/cm	Sampled and Analysed 9/8/97 Cond Temp.	 DO mg/L	 DO Temp.	 pH	 Cr6+ mg/l
D4-2 up	556	22.1	8.40	24.9	7.6	
D4-2 low	478	16.9	9.46	23.1	7.69	
D4-3 up	581	16.2	10.19	18.4	7.83	
D4-3 low	496	15.6	10.27	17.8	8.32	
D4-7	580	21.0	9.60	23.0	7.6	
D4-8	605	19.2	9.54	20.6	7.6	
D4-9	589	16.6	9.86	18.7	7.65	
D4-11	613	15.8	9.20	18.2		
D4-16 (1)						
D4-16 (2)						
D4-16 (3)						
D4-1	584	17.1	6.99	22.8	7.59	
D4-12	594	19.8	10.04	20.8	7.53	
D4-10	648	20.6	9.47	23.4	7.52	
D4-4	564	20.4	9.88	21.4	7.54	
D4-5	581	19.6	11.13	21.0	7.62	
D4-6	505	21.9	10.95	22.5	7.62	
D4-17 (1)						
D4-17 (2)						
D4-17 (3)						
D4-18 (1)						
D4-18 (2)						
D4-18 (3)						

Figure F.5. Groundwater Monitoring Result for September 8, 1997

Well-ID	FIELD	Sampled and Analysed 9/17/97				
	Cond	**Cond**	**DO**	**DO**	**pH**	**Cr6+**
	µS/cm	Temp.	mg/L	Temp.		mg/l
D4-2 up	560	15.6	10.20	18.7	7.6	1.02
D4-2 low	451	15.7	10.96	18.8	7.69	1.06
D4-3 up	559	15.0	10.03	17.7	7.86	1.00
D4-3 low	444	15.1	10.47	17.9	8.25	1.02
D4-7	540	17.5	10.44	19.4	7.67	1.06
D4-8	554	17.1	10.09	19.2	7.63	0.98
D4-9	545	15.8	9.95	19.4	7.65	1.04
D4-11	551	15.2	9.25	19.0	7.55	1.02
D4-16 (1)	692	18.0	2.98	19.3	7.27	0.48
D4-16 (2)	627	17.0	4.85	19.2	7.38	0.86
D4-16 (3)	612	16.0	2.25	18.7	7.44	0.70
D4-1	557	15.6	8.33	18.0	7.62	0.98
D4-12	537	17.0	10.37	19.2	7.58	1.00
D4-10	582	16.9	10.13	19.2	7.57	0.88
D4-4	528	16.2	9.83	18.7	7.57	0.62
D4-5	509	17.8	10.65	20.3	7.71	0.82
D4-6	494	18.3	10.66	20.3	7.63	0.84
D4-17 (1)						
D4-17 (2)						
D4-17 (3)						
D4-18 (1)						
D4-18 (2)						
D4-18 (3)						

Figure F.6. Groundwater Monitoring Result for September 17, 1997

Well-ID	FIELD	Sampled and Analysed 9/29/97				(9/24/97)	IC					
	Cond	Cond	DO	DO	pH	Cr6+	F	Cl	NO3	PO4	SO4	Br-
	µS/cm	Temp.	mg/L	Temp.		mg/l	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
D4-2 up	455	19.1	10.41	19.0	7.71	1.11	0.5	23.8	72.0	6.1	112.1	u
D4-2 low	534	17.7	10.77	17.7	7.82	1.15	0.6	22.0	45.4	1.9	84.9	u
D4-3 up	646	17.5	10.84	17.4	7.82	1.08						
D4-3 low	526	17.5	11.54	17.2	8.22	1.04	u	18.1	62.8	u	124.9	u
D4-7	637	18.0	11.01	18.1	7.64	1.14	u	21.9	80.4	u	141.5	u
D4-8	633	17.9	11.09	18.1	7.68	1.09	u	21.1	79.2	0.8	139.7	u
D4-9	637	17.8	10.85	17.8	7.71	1.12	u	20.1	81.6	u	139.4	u
D4-11	641	17.6	9.51	17.6	7.60	1.08	u	19.3	78.1	u	141.4	u
D4-16 (1)	704	19.1	5.18	19.1	7.44	0.59	0.7	24.8	55.1	2.1	105.3	5.4
D4-16 (2)	641	19.0	5.59	19.0	7.53	1.01	0.24	23.6	65.2	1.5	105.9	12.4
D4-16 (3)	636	18.9	2.22	18.9	7.60	0.89	0.23	24.5	40	0.7	101.4	11.7
D4-1	442	18.9	9.60	18.3	7.69	1.01	0.02	20.9	58.5	2.5	96.7	u
D4-12	592	17.8	11.01	17.8	7.69	1.12	0.7	18.3	70.2	u	133.4	u
D4-10	665	18.2	10.32	18.2	7.65	0.96	u	20.6	83.0	u	132.6	u
D4-4	622	18.3	10.03	18.4	7.59	0.74	u	17.4	73.7	u	144.1	u
D4-5	637	18.2	9.51	18.2	7.71	0.82*	0.85	24.8	65.8	0.7	96.8	8.4
D4-6	594	18.2	10.71	18.0	7.68	0.92	u	17.2	70.1	u	124.2	u
D4-17 (1)												
D4-17 (2)												
D4-17 (3)												
D4-18 (1)												
D4-18 (2)												
D4-18 (3)												

Notes: Cr6+ Data from 9/24/97 except for D4-5 which was from 9/17/97

Figure F.7. Groundwater Monitoring Result for September 29, 1997

Well-ID	FIELD	Sampled and Analysed 10/29/97				
	Cond	**Cond**	**DO**	**DO**	**pH**	**Cr6+**
	µS/cm	Temp.	mg/L	Temp.		mg/l
D4-2 up	876	16.6	0.00	22.3	8.45	0.00
D4-2 low						
D4-3 up	995	16.2	0.00	18.3	8.54	0.00
D4-3 low	100	16.0	0.00	20.6	9.16	0.00
D4-7	1253	18.0	0.00	19.4	8.98	0.00
D4-8	1599	17.5	0.00	22.7	8.78	0.00
D4-9	1116	17.2	0.00	21.9	8.51	0.00
D4-11	814	16.1	0.00	21.1	8.43	0.00
D4-16 (1)	4.63	17.4	0.90	17.1	7.48	0.00
D4-16 (2)	6.75	17.6	0.00	17.2	8.89	0.00
D4-16 (3)	7.12	17.3	0.00	16.9	8.91	0.00
D4-1	1225	16.6	0.00	18.8	8.07	0.00
D4-12	515	16.1	10.05	18.7	7.76	1.12
D4-10	734	16.4	3.40	18.9	7.66	0.58
D4-4	552	16.7	8.92	18.6	7.62	0.68
D4-5	758	16.8	5.51	19.9	7.67	0.62
D4-6	800.0	16.90	5.18	16.6	7.81	0.32
D4-17 (1)						
D4-17 (2)						
D4-17 (3)						
D4-18 (1)						
D4-18 (2)						
D4-18 (3)						

Figure F.8. Groundwater Monitoring Result for October 29, 1997

Well-ID	FIELD	Sampled and Analysed 11/15/97				
	Cond	**Cond**	**DO**	**DO**	**pH**	**Cr6+**
	µS/cm	Temp.	mg/L	Temp.		mg/l
D4-2 up	849	15.3	0.00	16.7	8.48	0.00
D4-2 low	995	15.0	2.00	16.5	8.43	0.03
D4-3 up	936	16.0	0.00	17.0	8.59	0.00
D4-3 low	998	16.0	0.00	16.8	9.08	0.00
D4-7	1150	16.7	0.00	17.6	8.98	0.00
D4-8	1356	16.6	0.00	17.6	8.79	0.00
D4-9	1093	16.0	0.00	17.1	8.56	0.00
D4-11	785	15.9	0.00	17.1	8.49	0.00
D4-16 (1)	4870	18.9	2.47	18.6	7.61	0.00
D4-16 (2)	5660	18.5	0.00	18.3	8.91	0.00
D4-16 (3)	6240	17.0	0.00	16.8	8.93	0.00
D4-1	1274	16.0	0.00	17.2	8.03	0.00
D4-12	542	15.8	11.20	17.0	7.78	1.10
D4-10	803	15.8	2.90	17.0	7.68	0.50
D4-4	554	116.2	10.60	17.1	7.67	0.78
D4-5	903	15.7	5.10	17.0	7.68	0.53
D4-6	746	17.3	3.10	18.1	7.74	0.34
D4-17 (1)						
D4-17 (2)						
D4-17 (3)						
D4-18 (1)						
D4-18 (2)						
D4-18 (3)						

Figure F.9. Groundwater Monitoring Result for November 15, 1997

Well-ID	FIELD	Sampled and Analysed 11/18/97				
	Cond	**Cond**	**DO**	**DO**	**pH**	**Cr6+**
	µS/cm	Temp.	mg/L	Temp.		mg/l
D4-2 up	767	16.5	0.00	20.1	8.37	0.00
D4-2 low	547	15.8	5.19	19.3	8.15	0.12
D4-3 up	843	16.6	0.00	18.9	8.46	0.00
D4-3 low	875	16.2	0.00	18.9	8.89	0.00
D4-7	960	17.6	0.00	19.4	8.78	0.00
D4-8	1178	17.5	0.00	19.5	8.67	0.00
D4-9	1018	16.9	0.00	19.7	8.47	0.00
D4-11	703	16.8	0.00	20.1	8.37	0.00
D4-16 (1)	5470	17.5	0.00	17.5	8.64	0.00
D4-16 (2)	4150	16.5	0.00	16.4	8.78	0.00
D4-16 (3)	4590	17.0	0.00	16.5	8.89	0.00
D4-1	1324	17.3	0.00	20.3	8.01	0.00
D4-12	524	16.5	10.42	19.4	7.75	1.08
D4-10	760	16.8	3.49	19.9	7.61	0.50
D4-4	574	16.7	9.36	19.8	7.59	0.80
D4-5	1056	16.6	2.57	19.8	7.53	0.33
D4-6	803	15.5	1.30	19.5	7.64	0.21
D4-17 (1)						
D4-17 (2)						
D4-17 (3)						
D4-18 (1)						
D4-18 (2)						
D4-18 (3)						

Figure F.10. Groundwater Monitoring Result for November 18, 1997

Well-ID	FIELD Cond µS/cm	Sampled and Analysed 12/5/97 Cond Temp.	DO mg/L	DO Temp.	pH	Cr6+ mg/l
D4-2 up	688	17.2	0.00	16.9	8.28	0.00
D4-2 low	588	16.9	7.01	17.0	8.20	0.34
D4-3 up	718	17.4	0.00	17.9	8.43	0.00
D4-3 low	763	16.8	0.00	16.4	8.85	0.00
D4-7	841	17.5	0.00	16.8	8.78	0.00
D4-8	1155	16.4	0.10	16.8	8.65	0.00
D4-9	918	17.3	0.00	17.1	8.50	0.00
D4-11	647	17.0	0.06	16.7	8.31	0.00
D4-16 (1)	4110	11.4	0.20	13.9	8.20	0.00
D4-16 (2)	2880	13.2	0.47	15.0	8.59	0.00
D4-16 (3)	3500	14.5	0.91	16.0	8.88	0.00
D4-1	1445	17.7	0.00	17.6	7.93	0.00
D4-12	511	17.0	11.80	16.5	7.81	1.08
D4-10	659	17.4	5.61	17.1	7.71	0.70
D4-4	507	16.8	10.64	17.1	7.63	0.98
D4-5	929	17.2	1.98	16.9	7.52	0.13
D4-6	809	16.0	0.60	15.8	7.63	0.21
D4-17 (1)						
D4-17 (2)						
D4-17 (3)						
D4-18 (1)						
D4-18 (2)						
D4-18 (3)						

Figure F.11. Groundwater Monitoring Result for December 5, 1997

Well-ID	FIELD Cond µS/cm	Sampled and Analysed 1/6/98 Cond Temp.	DO mg/L	DO Temp.	pH	Cr6+ mg/l	IC F mg/L	Analysed Cl mg/L	NO3 mg/L	PO4 mg/L	SO4 mg/L	Br- mg/L
D4-2 up	693	14.9	0.00	16.4	8.24	0.28	<2	26.8	73.8	<2	173	
D4-2 low	554	14.8	8.54	16.3	8.16	0.78	2.3	26.6	54.3	<2	123.8	
D4-3 up	753	15.1	0.00	16.4	8.36	0.00	<2	23.1	56.3	<2	194.6	
D4-3 low	724	14.4	0.00	16.1	8.77	0.00	<2	23.5	45.8	<2	177	
D4-7	842	17.0	0.00	17.5	8.70	0.00	<2	21.8	44.5	<2	236	
D4-8	1100	16.2	0.00	17.0	8.63	0.00	<2	21.9	45.7	<2	340	
D4-9	882	15.0	0.00	16.6	8.33	0.00	<2	25.5	50.9	<2	276	
D4-11	643	15.1	0.00	16.4	8.25	0.03	<2	21.9	60.8	<2	153	
D4-16 (1)	4630	14.6	0.00	14.8	8.23	0.00	4.73	26.2	16.6	<2	1480	
D4-16 (2)	2880	14.8	0.20	15.0	8.67	0.00	3.05	26.7	8.6	<2	786	
D4-16 (3)	2860	15.3	0.20	15.5	8.80	0.00	2.7	23.9	<2	4	803	
D4-1	1276	15.4	0.00	19.8	7.99	0.01	2.7	24.2	22.9	<2	459	
D4-12	527	15.2	11.77	16.5	7.83	1.06	<2	22.2	633.0	<2	109.7	
D4-10	717	15.3	3.90	16.6	7.68	0.60	<2	25.3	73.9	<2	197	
D4-4	554	14.5	10.92	16.3	7.67	0.76	2.4	24.2	73.8	<2	151	
D4-5	1160	15.2	2.21	16.6	17.49	0.18	3.6	27.0	54.0	<2	441	
D4-6	825	14.0	2.04	15.7	7.58	0.41	<2	25.3	61.4	<2	266	
D4-17 (1)	923	14.8	0.90	15.1	7.48	0.01	6.65	29.6	3.1	<2	218	
D4-17 (2)	1080	14.8	3.20	15.0	7.54	0.28	2.1	26.3	53.6	<2	358	
D4-17 (3)	1262	14.8	1.50	15.0	7.55	0.13	<2	29.8	53.6	<2	480	
D4-18 (1)	835	14.3	1.25	14.6	7.78	0.00	<2	26.4	22.8	<2	248.2	
D4-18 (2)	881	14.6	3.20	15.0	7.45	0.08	<2	22.9	52.3	<2	248	
D4-18 (3)	576	14.4	6.40	14.7	7.62	0.72	<2	23.8	56.1	<2	114	

Figure F.12. Groundwater Monitoring Results for January 6, 1998

	FIELD	Sampled and Analysed 3/12/98				
Well-ID	**Cond**	**Cond**	**DO**	**DO**	**pH**	**Cr6+**
	µS/cm	Temp.	mg/L	Temp.		mg/l
D4-2 up	609	17.9	0.97	17.3	8.16	0.14
D4-2 low	504	17.0	8.49	16.8	8.09	1.06
D4-3 up	657	17.4	0.00	17.0	8.31	0.01
D4-3 low	598	17.0	0.25	16.7	8.59	0.01
D4-7	739	18.0	0.00	17.6	8.70	0.00
D4-8	905	17.8	0.00	17.3	8.60	0.00
D4-9	764	17.8	0.00	17.4	8.27	0.00
D4-11	609	17.4	2.51	17.1	8.08	0.38
D4-16 (1)	4060	17.9	0.00	17.6	8.24	0.00
D4-16 (2)	2230	18.0	0.67	17.9	8.72	0.00
D4-16 (3)	2200	18.2	1.25	18.0	8.74	0.00
D4-1	1147	18.2	0.00	17.7	7.91	0.05
D4-12	511	17.6	10.89	17.3	7.81	1.04
D4-10	669	18.0	2.93	17.5	7.68	0.44
D4-4	510	18.0	9.97	17.5	7.62	0.70
D4-5	998	18.5	2.48	17.8	7.53	0.18
D4-6	691	19.5	5.50	18.7	7.51	0.52
D4-17 (1)	1031	18.2	1.54	18.0	7.70	0.00
D4-17 (2)	1089	18.1	13.41	18.0	7.47	0.19
D4-17 (3)	1133	18.4	4.43	18.0	7.50	0.20
D4-18 (1)	756	18.4	1.47	18.2	7.75	0.07
D4-18 (2)	868	18.7	5.93	18.5	7.54	0.08
D4-18 (3)	626	18.4	7.25	18.2	7.65	0.53

Figure F.13. Groundwater Monitoring Results for March 12, 1998

	FIELD	Sampled and Analysed 4/28/98				
Well-ID	**Cond**	**Cond**	**DO**	**DO**	**pH**	**Cr6+**
	µS/cm	Temp.	mg/L	Temp.		mg/l
D4-2 up	574	19.3	1.80	23.0	8.16	0.26
D4-2 low	505	18.7	8.30	23.4	8.06	1.14
D4-3 up	618	18.8	0.00	23.3	8.18	0.08
D4-3 low	566	17.8	0.98	22.0	8.41	0.10
D4-7	647	18.9	0.00	22.1	8.61	0.00
D4-8	728	18.9	0.00	22.0	8.55	0.00
D4-9	651	20.4	0.00	25.2	8.22	0.00
D4-11	549	19.5	2.39	24.9	8.14	0.40
D4-16 (1)						dry
D4-16 (2)	1612	21.9	0.00	21.9	8.38	0.00
D4-16 (3)	1913	18.8	0.00	18.8	8.77	0.00
D4-1	1025	19.9	0.00	23.7	8.01	0.09
D4-12	511	19.8	8.43	24.4	7.78	1.06
D4-10	612	19.8	1.71	23.3	7.82	0.32
D4-4	527	19.9	8.42	24.5	7.63	0.82
D4-5	841	20.7	5.28	24.3	7.55	0.72
D4-6	777	22.0	4.58	24.7	7.46	0.56
D4-17 (1)	837	18.9	2.10	18.7	7.39	0.27
D4-17 (2)	713	18.6	2.60	18.5	7.60	0.76
D4-17 (3)	719	19.0	2.60	19.0	7.59	0.78
D4-18 (1)	758	19.5	2.70	19.2	7.55	0.32
D4-18 (2)	899	19.1	2.39	18.7	7.60	0.40
D4-18 (3)	760	19.4	6.15	19.0	7.63	0.30

Figure F.14. Groundwater Monitoring Results for April 28, 1998

Well-ID	FIELD	Sampled and Analysed 7/30/98				
	Cond	Cond	DO	DO	pH	Cr6+
	µS/cm	Temp.	mg/L	Temp.		mg/l
D4-2 up	832	18.6	0.00	18.4	8.49	0.00
D4-2 low	1030	21.8	4.32	21.9	7.48	0.00
D4-3 up	1005	17.8	0.00	17.8	8.73	0.00
D4-3 low	1900	17.7	0.00	17.5	9.46	0.00
D4-7	1914	18.1	0.00	18.1	9.33	0.00
D4-8	2120	18.0	0.00	18.2	9.08	0.00
D4-9	1677	19.0	0.00	19.3	9.29	0.00
D4-11	2010	18.9	0.00	19.0	9.18	0.00
D4-16 (1)						0.00
D4-16 (2)						0.00
D4-16 (3)						0.00
D4-1	1738	18.6	0.00	18.5	8.21	0.00
D4-12	2550	18.9	0.00	19.0	8.33	0.00
D4-10	1564	18.7	0.00	18.7	8.96	0.00
D4-4	586	18.6	8.58	18.5	7.53	0.64
D4-5	762	18.9	0.65	18.9	7.55	0.23
D4-6	750	21.8	4.32	21.9	7.48	0.35
D4-17 (1)						0.46
D4-17 (2)						0.20
D4-17 (3)						0.33
D4-18 (1)						0.33
D4-18 (2)						0.25
D4-18 (3)						0.29

Figure F.15. Groundwater Monitoring Results for July 30, 1998

Well-ID	FIELD Sampled and Analysed 9/3/98						IC Analysed 9/10/98				
	Cond µS/cm	**Cond** Temp.	**DO** mg/L	**DO** Temp.	**pH**	**Cr6+** mg/L	**F** mg/L	**Cl** mg/L	**NO3** mg/L	**PO4** mg/L	**SO4** mg/L
D4-2 up	641	18.0	0.00	18.0	8.19	0.00	< 2	20.6	49.1	< 2	154
D4-2 low	787	17.5	0.00	17.4	8.78	0.00	< 2	21.3	34.1	< 2	151
D4-3 up	793	18.0	0.00	17.9	8.48	0.00	< 2	22.2	22.9	< 2	232
D4-3 low	1386	17.6	0.00	17.5	9.3	0.00	< 2	21.9	15.0	< 2	307
D4-7	1195	18.0	0.00	18.0	9.1	0.00	1.4	21.6	2.7	< 2	320
D4-8	1744	18.1	0.00	18.2	8.84	0.00	2.26	19.4	0.7	< 2	537
D4-9	1141	18.3	0.00	18.6	9.27	0.00	1.16	21.9	19.2	2	273
D4-11	1144	18.4	0.00	18.4	8.86	0.00	< 2	20.2	2.7	< 2	352
D4-16 (1)	4550		-		7.93	-	< 20	43.9	< 20	< 20	1300
D4-16 (2)	3380		-		8.07	0.00	< 20	42.3	< 20	< 20	902
D4-16 (3)	3004		-		8.2	0.00	< 20	46	< 20	< 20	1060
D4-1	2320	18.4	0.00	18.3	8.11	0.00	-	-	-	-	939
D4-12	1503	18.5	0.00	18.6	8.5	0.00	2.1	18.2	< 2	< 2	463
D4-10	1139	18.5	0.00	18.5	9.11	0.00	< 2	21.6	10.2	< 2	301
D4-4	652	18.5	8.30	18.4	7.47	0.55	< 2	14.3	49.0	2.1	206
D4-5	878	18.7	0.61	18.7	7.47	0.16	< 2	20.5	24.3	< 2	361
D4-6	963	20.5	3.87	20.5	7.45	0.26	< 2	19.2	30.2	< 2	389
D4-17 (1)	632		1.61		7.97	0.00	< 2	22.1	11.7	< 2	218
D4-17 (2)	687		2.25		8.37	0.30	0.75	20.3	33.6	1.51	285
D4-17 (3)	668		2.08		7.79	0.30	< 2	22.4	37.3	2.71	333
D4-18 (1)	520		4.88		8.1	0.40	< 2	27.9	56.1	< 2	142
D4-18 (2)	716		4.88		7.9	0.20	< 2	19.7	28	< 2	370
D4-18 (3)	543		5.77		7.76	0.35	< 2	19.4	39.3	< 2	192

Figure F.16. Groundwater Monitoring Result for September 3, 1998

Well-ID	FIELD	Sampled and Analysed 4/6/99					IC	Analysed 4/29./99			
	Cond	**Cond**	**DO**	**DO**	**pH**	**Cr6+**	**F**	**Cl**	**NO3**	**PO4**	**SO4**
	µS/cm	Temp.	mg/L	Temp.		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
D4-2 up	576	17.5	2.95	18.5	7.93	0.49	0.43	24.1	56.4	<0.2	118
D4-2 low	510	17.3	6.86	18.6	8.04	0.86	0.4	21.8	43.4	<0.2	102
D4-3 up	581	17.3	0.00	18.3	8.1	0.10	0.59	28.1	44.5	<0.2	131
D4-3 low	721	17.1	0.00	17.9	8.88	0.00	0.73	33.9	21.5	<0.2	174
D4-7	911	17.4	0.00	17.6	8.71	0.00	0.93	35.1	13.6	<0.2	270
D4-8	1371	17.6	0.00	18.5	8.69	0.00	1.27	40.2	1.91	<0.2	499
D4-9	870	17.9	0.00	20.1	8.48	0.00	0.77	38.5	29.9	<0.2	252
D4-11	910	17.5	0.00	19.2	8.42	0.00	0.81	32.9	16.7	<0.2	324
D4-16 (1)	1387		2.93		8.08	0.00	1.55	34.2	2.48	<0.2	530
D4-16 (2)	1309		3.23		8.18	0.00	1.42	33.7	<0.2	<0.2	500
D4-16 (3)	1660		2.37		8.23	0.00	1.97	41.7	0.31	<0.2	886
D4-1	1891	17.8	0.00	18.8	7.71	0.00	1.53	36.80	0.83	<0.2	746
D4-12	964	17.8	0.00	19.0	8.54	0.00	1.14	31.2	0.82	<0.2	352
D4-10	792	17.8	0.00	18.8	8.78	0.00	0.78	36.7	18.5	0.46	197
D4-4	757	17.1	4.45	17.3	7.6	0.21	0.87	25.1	20.9	<0.2	297
D4-5	728	17.5	0.00	17.7	7.56	0.02	0.81	29.1	15.8	<0.8	249
D4-6	1180		1.68		7.63	0.03	1.26	33.8	4.83	<0.2	526
D4-17 (1)	905		4.17		7.82	0.16	0.71	26.5	29.1	<0.2	299
D4-17 (2)	860		3.21		7.7	0.05	0.69	25.4	19.7	<0.2	281
D4-17 (3)	1050		2.55		7.61	0.04	0.98	27.6	8.84	<0.2	477
D4-18 (1)	1052		3.27		7.5	0.04	1.03	27.7	5.33	<0.2	509
D4-18 (2)	1081		2.07		7.55	0.03	1	27.7	4.67	<0.2	535
D4-18 (3)	994		2.56		7.56	0.10	0.88	25.5	11.9	<0.2	458

Note:EC,DO, and pH Measurements for D4-6 and Westbay wells are from flow-through micro-electrodes.

Figure F.17. Groundwater Monitoring Results for April 6, 1999

Well-ID	FIELD	Sampled and Analysed 7/27/99				
	Cond	**Cond**	**DO**	**DO**	**pH**	**Cr6+**
	µS/cm	Temp.	mg/L	Temp.		mg/L
D4-2 up	836	18.3	0.00	18.1	8.31	0.01
D4-2 low	663	18.0	1.81	17.7	8.11	0.37
D4-3 up	843	17.6	0.00	17.8	8.39	0.00
D4-3 low	905	17.4	0.00	17.5	8.67	0.00
D4-7	887	17.6	0.00	17.8	8.66	0.00
D4-8	1287	17.8	0.00	18.1	8.7	0.00
D4-9	1377	18.3	0.00	18.5	8.65	0.00
D4-11	4530	18.0	0.05	18.0	8.45	0.00
D4-16 (1)						
D4-16 (2)						
D4-16 (3)						
D4-1	931	18.7	0.00	18.5	8.16	0.00
D4-12	2160	18.4	0.00	18.3	8.19	0.00
D4-10	770	18.6	0.00	18.5	8.85	0.00
D4-4	942	18.9	3.36	18.6	7.55	0.09
D4-5	670	18.6	0.07	18.6	7.82	0.30
D4-6	766	21.2	9.93	21.2	7.72	0.14
D4-17 (1)						
D4-17 (2)						
D4-17 (3)						
D4-18 (1)						
D4-18 (2)						
D4-18 (3)						

Figure F.18. Groundwater Monitoring Results for July 27, 1999

Appendix G

Groundwater Monitoring Result—Trace Metal Analysis

Well-ID	ICP/MS •Na µg/ml	•Mg µg/ml	K µg/ml	•Ca µg/ml	Al ng/ml	Cr ng/ml	Mn ng/ml	Fe ng/ml	Ni ng/ml	Cu ng/ml	Zn ng/ml	As ng/ml	Se ng/ml	Mo ng/ml	Ag ng/ml	Cd ng/ml	Sn ng/ml	Sb ng/ml	Ba ng/ml	Pb ng/ml	U ng/ml
D4-2 up	11.3	14.1	3.56	65.0	21.6	869	1.8	185	16.7	16.1	61.9				<0.5	<0.5	0.5	1.8±0.5	71.7	<0.5	1.5
D4-2 low	9.7	13.5	3.85	58.3	23.1	993	3.5	188	16±2	16.4	73.8				<0.5	<0.5	0.8±0.2	1.0±0.2	74.4	<0.5	1.3
D4-3 up	13.3	13.1	4.80	64.1	22.4	870	1.9	486	33.2	18.4	62.8				<0.5	<0.5	0.5	0.7±0.5	87.3	<0.5	1.2±0.2
D4-3 low	10.6	9.5	3.49	49.9	18±2	698	6.3	346	25.2	16.1	108.8				<0.5	<0.5	<0.5	<0.5	62.6	<0.5	0.8
D4-7	10.4	15.6	4.22	71.9	23±3	851	5.1	480	35.9	17.0	61.9				<0.5	<0.5	0.63	<0.5	84.2	1.1	1.2
D4-8	9.5	15.0	4.24	71.5	20.6	841	4.5	333	26.7	16.6	60.3				<0.5	<0.5	0.5	<0.5	87.1	<0.5	1.3
D4-9	12.3	15.0	4.69	71.6	23.5	742	37.4	558	41.1	17.2	55.2				<0.5	<0.5	0.6	<0.5	89.4	<0.5	1.2
D4-11	10.9	16.6	4.23	83.2	22±3	776	76.0	601	42.8	18.8	65.1				<0.5	<0.5	0.5	<0.5	93.9	<0.5	1.0
D4-16 (1)																					
D4-16 (2)																					
D4-16 (3)																					
D4-1	9.9	15.4	3.84	68.9	22.3	886	2.6	222	19.0	16.8	57.9				<0.5	<0.5	<0.5	1	74.7	<0.5	1.8
D4-12	10.5	15.8	4.57	79.9	24.3	849	15.8	483	38.4	19.5	77.7				<0.5	<0.5	0.62	0.5	55.7	0.6	1.2
D4-10	10.5	17.1	3.73	77.0	18.3	605	10.9	400	32.4	14.9	46.1				<0.5	<0.5	1.17	<0.5	57.6	<0.5	0.9±0.1
D4-4	14.4	13.5	3.30	70.7	20.0	600	12.4	350	29.3	15.7	54.6				<0.5	<0.5	<0.5	<0.5	70.0	<0.5	1.4
D4-5	10.2	16.5	3.62	80.3	30.2	750	13.9	300	26.6	17.8	63.1				<0.5	<0.5	0.5±0.1	0.6±0.1	91.6	<0.5	1.1
D4-6	10.0	14.6	4.11	65.2	26.2	826	16.5	346	28.3	18.1	65.5				<0.5	<0.5	0.6	<0.5	84.4	0.5	1.6
D4-17 (1)																					
D4-17 (2)																					
D4-17 (3)																					
D4-18 (1)																					
D4-18 (2)																					
D4-18 (3)																					

Figure G.1. Trace Metal Analyses, August 13, 1997

Well-ID	ICP/MS																				
	*Na µg/ml	*Mg µg/ml	K µg/ml	*Ca µg/ml	Al ng/ml	Cr ng/ml	Mn ng/ml	Fe ng/ml	Ni ng/ml	Cu ng/ml	Zn ng/ml	As ng/ml	Se ng/ml	Mo ng/ml	Ag ng/ml	Cd ng/ml	Sn ng/ml	Sb ng/ml	Ba ng/ml	Pb ng/ml	U ng/ml
D4-2 up	12.2	17.9	4.33	80.7	12.9	1060	0.6	261	22.1	5.9	30.0	1.2±0.4	<2	1.3±0.2	<0.4	<0.4	<0.4	<0.4	107.0	0.7	2.2
D4-2 low	7.9	14.9	3.50	69.2	22.4	1146	0.8±0.1	91±20	13±3	4.3	35.7	1.3456	<2	1.4±0.5	<0.4	<0.4	<0.4	<0.4	76.9	0.6±0.1	1.4
D4-3 up	12.4	18.2	4.78	80.3	16.8	1090	1.3±0.2	200±20	18.4	5.9	32±5	1.57569	<2	1.3±0.2	<0.4	<0.4	<0.4	<0.4	104.0	0.7±0.1	2.0
D4-3 low	9.6	13.0	3.65	66.0	19.1	1040	4.3	110±20	13.8	5.0	43.6	1.4±0.2	<2	1.6±0.2	<0.4	<0.4	<0.4	<0.4	71.5	0.6	1.3
D4-7	10.5	17.4	5.41	76.6	18.9	1060	1.2	160±20	18.1	5.8±0.6	34.0	2.17167	<2	1.8±0.2	<0.4	<0.4	0.6±0.1	<0.4	95.9	0.9	2.2±0.3
D4-8	9.4	16.7	5.99	77.6	16±3	1030	1.0	130±50	16.6	5.7	28.7	1.90073	<2	1.5±0.5	<0.4	<0.4	<0.4	<0.4	107.3	0.6	1.8
D4-9	9.8	17.5	4.74	79.7	16±3	1070	0.6	130±40	16.6	4.7	30.2	1.2±0.2	<2	1.2±0.6	<0.4	<0.4	<0.4	<0.4	101.0	0.5±0.1	1.8
D4-11	9.6	17.2	3.92	80.1	19.0	979	7.2	130±20	17±3	4.8±0.7	28.5	1.6±0.5	<2	1.3±0.2	<0.4	<0.4	0.5	<0.4	98.5	0.5±0.1	2.4
D4-16 (1)	10.3	18.1	5.60	88.0	14±3	600	36.2	141	20.6	4.8	30.5	1.2±0.6	<2	4.1±1.0	<0.4	<0.4	<0.4	<0.4	115.0	0.5±0.1	2.0
D4-16 (2)	9.7	17.2	5.80	79.0	11.9	966	2.2	98	13.4	4.8±0.6	29.1	1.2±0.5	<2	1.3±0.4	<0.4	<0.4	<0.4	<0.4	114.0	0.5±0.1	1.8
D4-16 (3)	10.7	16.9	4.93	80.9	13.8	383	263.0	100±20	15.3	5.0	36.1	1.2±0.2	<2	1.6±0.2	<0.4	<0.4	<4	<4	107.0	0.5±0.1	1.7
D4-1	8.6	16.9	4.05	78.6	12.9	997	<0.4	82	14.5	4.8	27.4	1.2±0.2	<2	1.5±0.6	<0.4	<0.4	<0.4	<0.4	97.1	0.7±0.1	1.8
D4-12	8.0	16.2	3.74	76.2	15.8	1110	4.8	120±20	16.4	4.8±0.7	28±4	2.3±0.5	3.8	1.5±0.2	<0.4	<0.4	<0.4	<0.4	71.6	0.9	1.7±0.2
D4-10	9.1	17.1	3.69	82.4	16.6	915	1.5	120±20	15.4	4.3	41.5	1.6±0.6	<2	1.3±0.4	<0.4	<0.4	<0.4	<0.4	86.9	0.7±0.2	1.8
D4-4	13.6	16.3	3.30	80.9	15.9	745	3.8	120±20	22.3	5.1	31.4	2.8±0.5	2.4±1.0	2.4±0.8	<0.4	<0.4	<0.4	<0.4	90.0	0.9±0.4	1.9
D4-5	9.9	19.0	3.82	79.8	16.8	906	3.4	230±50	21.9	6.6	40.7	1.51087	<2	1.5±0.4	<0.4	<0.4	<0.4	<0.4	104.0	0.9	1.4
D4-6	9.2	15.6	3.27	75.4	17±3	832	2.9	150±20	16.7	6.2±0.7	35.7	1.3±0.2	<2	1.5±0.5	<0.4	<0.4	1.2±0.2	<0.4	93.3	0.8	1.6
D4-17 (1)																					
D4-17 (2)																					
D4-17 (3)																					
D4-18 (1)																					
D4-18 (2)																					
D4-18 (3)																					

Figure G.2. Trace Metal Analyses, September 29, 1997

Well-ID	ICP/MS *Na µg/ml	*Mg µg/ml	Si µg/ml	K µg/ml	*Ca µg/ml	Al ng/ml	Cr ng/ml	Mn ng/ml	Fe ng/ml	Ni ng/ml	Cu ng/ml	Zn ng/ml	As ng/ml	Se ng/ml	Mo ng/ml	Ag ng/ml	Cd ng/ml	Sn ng/ml	Sb ng/ml	Ba ng/ml	Pb ng/ml	U ng/ml
D4-2 up	19.5	17.3	10.8	103	49.9	55.3	3.9±1.4	119	<40	<2	<2	<5	<2	<20	<2	<2	<2	<2	<2	47.8	<2	<2
D4-2 low	30.2	12.8	11.0	182	33.8	39±5	50.5	24.8	<40	<2	<2	<5	<2	<20	<2	<2	<2	<2	<2	53.9	<2	<2
D4-3 up	32.5	13.3	7.07	178	28.0	40±5	4.4±0.6	22.3	<40	<2	<2	<5	<2	<20	<2	<2	<2	<2	<2	47.7	<2	<2
D4-3 low	88.0	4.19	6.26	342	7.96	70.4	2.4±0.7	7.06	149	7.9±0.9	<2	<5	<2	<20	2.3±1.1	<2	<2	<2	<2	25.0	<2	<2
D4-7	70.7	4.90	3.62	339	7.02	49.7	5.5±1.2	6.85	73±17	8.34	<2	<5	<2	<20	3.8±0.7	<2	<2	<2	<2	44.5	<2	<2
D4-8	159	16.8	3.64	444	10.8	44.5	4.6±0.7	17.0	151	21.5	2.4±0.3	<5	3.6±2.0	<20	10.7	<2	<2	<2	<2	72±8	<2	<2
D4-9	51.0	5.53	4.74	322	7.48	47.0	5.30	5.0±0.8	<40	8.6±3.3	3.2±0.8	<5	3.6±0.9	<20	3.1±1.6	<2	<2	<2	<2	26.7	<2	<2
D4-11	74.0	9.16	5.14	278	14.6	48.2	4.6±1.4	21.2	<40	12.5	<2	<5	<2	<20	5.8±1.1	<2	<2	<2	<2	45.6	<2	<2
D4-16 (1)	<0.5	<0.04	2.27	<0.5	0.56	218	13.4	2.24	256	<2	13±2	5±1	<2	<20	<2	<2	<2	<2	<2	<2	<2	<2
D4-16 (2)	224	41.8	9.82	500	101	43.7	7.29	180	99	76.7	<2	<5	<2	<20	9.1±1.0	<2	<2	<2	<2	80.0	<2	<2
D4-16 (3)	212	52.8	10.4	466	137	40.9	4.9±0.5	240	97	51.0	<2	<5	<2	<20	11±2	<2	<2	<2	<2	64.6	<2	<2
D4-1	180	36.5	9.42	453	98.1	39.5	4.1±1.1	385	199	75.0	<2	<5	<2	<20	11±2	<2	<2	<2	<2	137	<2	<2
D4-12	105	14.6	8.06	313	27.6	49.1	6.0±0.9	104	106	45.4	16.2	7±4	<2	<20	9.3±1.2	<2	<2	<2	<2	133	<2	<2
D4-10	61.6	4.74	5.72	357	11.2	66.1	5.1±1.2	19.8	50.4	3.3±0.9	<2	<5	10±3	<20	4.0±0.8	<2	<2	<2	<2	58.7	<2	<2
D4-4	17.2	22.6	13.6	7±1	119	39.4	535	2.90	<40	7.0±1.5	2.9±0.5	<5	<2	<20	<2	<2	<2	<2	<2	92.6	<2	2.16
D4-5	45.8	29.4	13.6	25.6	141	87.6	176	86.1	<40	37.3	34.7	<5	<2	<20	<2	<2	<2	<2	<2	80±9	<2	2.7±0.8
D4-6	51.1	30.7	12.3	48.4	145	39.0	244	64±8	<40	32.8	6.2±1.1	<5	<2	<20	2.3±0.7	<2	<2	<2	<2	85.9	<2	2.1±0.5
D4-17 (1)	51.8	24.6	13.6	7±1	120	42.2	25.8	313	<40	23.0	<2	<5	<2	<20	<2	<2	<2	<2	<2	80.2	<2	3.0±0.9
D4-17 (2)	32.4	29.5	13.7	14.5	131	47.7	289	4.97	<40	18±2	22.2	8.0	<2	<20	2.8±0.7	<2	<2	<2	<2	91.9	<2	<2
D4-17 (3)	32.7	30.1	12.8	13.7	136	36.6	287	4.6±0.6	122	17.3	10.5	<5	<2	<20	<2	<2	<2	<2	<2	95.8	<2	2.8±0.4
D4-18 (1)	10±1	19.1	11.8	<5	106	40.4	390	5.61	<40	2.6±1.0	5.4±0.6	6±1	<2	<20	<2	<2	<2	4.0±1.3	<2	98.3	<2	<2
D4-18 (2)	21.3	34.2	12.9	8±1	166	35.2	189	3.5±0.8	<40	23.4	10.1	<5	<2	<20	<2	<2	<2	<2	<2	118	<2	3.72
D4-18 (3)	12.0	28.1	14.1	7±1	111	47±17	333	2.3±0.5	<40	10±3	2.6±1.5	10.4	<2	<20	<2	<2	<2	<2	<2	110	<2	3.6±0.4

Figure G.3. Trace Metal Analyses, September 3, 1998

Well-ID	ICP/MS																				
	Na µg/ml	Mg µg/ml	K µg/ml	Ca µg/ml	Al ng/ml	Cr ng/ml	Mn ng/ml	Fe ng/ml	Ni ng/ml	Cu ng/ml	Zn ng/ml	As ng/ml	Se ng/ml	Mo ng/ml	Ag ng/ml	Cd ng/ml	Sn ng/ml	Sb ng/ml	Ba ng/ml	Pb ng/ml	U ng/ml
D4-2 up	16.5	19.4	43.2	71.0	17.5	529	4.2	170	9.35	3±0.4	2±0.6	0.9±0.6	<5	0.8±0.4	<0.5	<0.5	<0.5	0.7	77.7	<0.5	2.28
D4-2 low	14.2	16.2	44.2	61.2	35.5	956	6.8	170	8.65	3±0.4	2±1	1±0.2	<5	1.0	<0.5	<0.5	<0.5	0.9±0.1	58.6	<0.5	1±0.3
D4-3 up	18.1	17.4	72.3	53.4	27.9	109	46.5	320	8.29	2±0.3	2±0.4	0.944	<5	1±0.5	<0.5	<0.5	<0.5	1±0.2	71.1	<0.5	1.2
D4-3 low	27.8	6.00	202	12.9	20.6	5.9	24.3	180	6.21	59.4	30.4	7±1	<5	2±0.5	<0.5	<0.5	<0.5	0.908	33.4	0.8±0.1	<0.5
D4-7	47.3	9.38	248	16.7	18.5	1±0.1	10.6	110	14.1	2±0.3	2±1	5±1	<5	4.19	<0.5	<0.5	0.6	1±0.2	58.3	<0.5	<0.5
D4-8	74.6	11.3	407	18.9	17.3	2.1	22.7	160	36.4	1.3	2±0.4	4.84	<5	5.44	<0.5	<0.5	<0.5	1±0.2	76.3	<0.5	<0.5
D4-9	42.0	14.8	208	24.9	17.4	1.5	19.7	160	23.2	2±0.3	<1	2±0.3	<5	2±0.4	<0.5	<0.5	<0.5	0.9±0.1	55.8	<0.5	0.6+0.1
D4-11	40.6	15.5	208	43.2	19.9	<1	43.3	140	29.5	1.3	2±1	2±1	<5	4±0.4	<0.5	<0.5	<0.5	0.9±0.2	101	0.5±0.1	<0.5
D4-16 (1)	94.4	11.7	371	41.2	16.6	1.2	268	110	42.5	4.53	18.4	2.97	<5	7.54	<0.5	<0.5	<0.5	0.6±0.2	50.5	0.5	1.0
D4-16 (2)	76.5	16.7	295	53.7	18.8	1.2	196	190±20	24.4	1±0.2	2±1	4.18	<5	8.05	<0.5	<0.5	<0.5	0.7±0.2	52.4	<0.5	<0.5
D4-16 (3)	163	31.9	450	75.8	38.2	4.9	360	380	72.1	2±0.3	6±1	4.08	<5	14.8	<0.5	<0.5	<0.5	0.7±0.1	57.0	0.7±0.1	<0.5
D4-1	124	37.5	257	127	25.3	1±0.2	771	270	72.8	2.78	2±0.5	2±0.3	<5	10±1	<0.5	<0.5	<0.5	0.6±0.1	75.4	<0.5	<0.5
D4-12	38.2	12.3	206	29.0	19.9	1.2	60.2	170±20	11.8	2.70	3±1	2.54	<5	5±1	<0.5	<0.5	<0.5	0.9±0.3	113	<0.5	<0.5
D4-10	30.3	7.26	185	17.2	24.7	2±0.3	21.9	150	8.84	1.8	1±0.6	6±1	<5	3±0.4	<0.5	<0.5	<0.5	1±0.2	77.6	<0.5	<0.5
D4-4	21.1	27.7	6.2	141	19.7	194	4±1	180	43.1	10±1	4±1	0.6±0.2	<5	2±0.6	<0.5	<0.5	<0.5	0.8±0.1	83.4	<0.5	2.19
D4-5	40.6	20.8	37.7	92.8	17.9	31.1	176	160±20	25.5	6.53	4±1	1.03	<5	3.53	<0.5	<0.5	<0.5	1.0	58.1	<0.5	1.0
D4-6	72.7	35.5	42.5	166	24.1	35.5	19.2	230	69.2	14.1	6.93	1±0.6	<5	5±1	<0.5	<0.5	<0.5	0.7±0.1	59.1	0.7	2.02
D4-17 (1)	40.2	26.4	6±1	136	18.4	160	6.45	260	37.9	7.79	24.8	0.863	<5	1.9	<0.5	<0.5	<0.5	0.8±0.2	93.8	<0.5	2.21
D4-17 (2)	53.7	24.1	21.5	111	19.9	58.5	1.8	200	32.9	7.50	16±2	0.7±0.2	<5	4.28	<0.5	<0.5	<0.5	0.8±0.1	53.9	<0.5	1.4
D4-17 (3)	71.9	36.5	12.3	166	21.4	45.4	3.8	300	53.9	15.8	21.6	0.9±0.2	<5	4.76	<0.5	<0.5	<0.5	0.7±0.3	54.0	<0.5	2.03
D4-18 (1)	70.5	38.3	4.6	187	19.0	39.3	2.7	260	56.7	12.1	19.2	0.7±0.4	<5	2±0.3	<0.5	<0.5	2.93	0.6±0.2	90.4	1.5	3.12
D4-18 (2)	67.3	39.5	5±1	190	21.8	33.8	1.6	320	63.2	15.7	15±2	0.7±0.2	<5	4±1	<0.5	<0.5	<0.5	0.6±0.1	52.6	<0.5	2.58
D4-18 (3)	28.6	45.3	6.0	174	19.9	107	2±2	300	59.5	14.1	11±2	0.6±0.2	<5	3±0.4	<0.5	<0.5	<0.5	0.6±0.1	96.5	<0.5	3.92

Figure G.4. Trace Metal Analyses, April 6, 1999

Appendix H

Reduction Capacity Measurements on Core Samples from the ISRM Treatment Zone

Appendix H

Reduction Capacity Measurements on Core Samples

Table H.1. Reduction Capacity Measurement Summary of Core Samples from the ISRM Treatment Zone (see Figure 1.6 for core hole locations)

Experimental parameters					Dithionite btc		Oxygen breakthrough			Fe(II) for whole sediment	
sediment	experiment	name	fraction < 4 mm	res. time (h/pv)	Fe reduced (µmol/g)	red.rate half-life (h)	injection mass (mol)	btc mass loss (mol)	Fe(II) oxidized (µmol/g)	Fe(II) lab reduced (µmol/g)	Fe(II) field reduced (µmol/g)
					<4 mm				<4 mm	whole sediment	whole sediment
B8776, 84.5'	oxidation of field red.	MM	0.363	0.89			6.48E-05	2.24E-05	6.82		*
B8776, 90'	oxidation of field red.	MN	0.437	0.50			8.42E-05	3.42E-05	14.7		6.42
B8776, 84.5'	reduction after MM	MT	0.363	5.63	41.5	6.35				15.1	
B8776, 84.5'	oxidation, after MT	MU	0.363	0.56			4.55E-04	2.21E-04	38.4	14.0	
B8775, 88'	oxidation of field red.	MW	0.442	0.86			5.75E-04	2.47E-04	45.9		20.3
B8777, 95'	oxidation of field red.	MX	0.435	1.30			1.85E-04	1.08E-04	40.2		17.5
B8776, 94.8'	oxidation of field red.	MY	0.382	1.30					46.0		17.6
B8775, 82.8'	oxidation of field red.	MZ	0.462	1.20			2.18E-04	7.41E-05	35.7		16.5
B8775, 82.8'	reduction after MZ	MZC	0.462	4.25	40.8	7.26				18.8	
B8775, 82.8'	oxidation after MZC	MZD	0.462	0.48			1.59E-04	9.88E-05	47.5	22.0	
B8775, 93'	oxidation of field red.	MZR	0.435	0.61					5.13		2.23
B8777, 85'	oxidation of field red.	MZS	0.374	0.43					9.95		3.72
B8777, 90'	oxidation of field red.	MZT	0.357	0.45					16.3		5.81
										Average	11.2±7.4

* core showed evidence of oxidation from atmospheric contamination prior to analysis

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Information Release (5)	K1-06