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Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Hanford 100-D Area Biostimulation Treatability Test Results

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September 2009

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Executive Summary

Pacific Northwest National Laboratory conducted a treatability test designed to demonstrate that in situ biostimulation can be applied to help meet cleanup goals in the Hanford Site 100-D Area. In situ biostimulation has been extensively researched and applied for aquifer remediation over the last 20 years for various contaminants. In situ biostimulation, in the context of this project, is the process of amending an aquifer with a substrate that induces growth and/or activity of indigenous bacteria for the purpose of inducing a desired reaction. For application at the 100-D Area, the purpose of biostimulation is to induce reduction of chromate, nitrate, and oxygen to remove these compounds from the groundwater. The in situ biostimulation technology is intended to provide supplemental treatment upgradient of the In Situ Redox Manipulation (ISRM) barrier previously installed in the Hanford 100-D Area and thereby increase the longevity of the ISRM barrier. Substrates for the treatability test were selected to provide information about two general approaches for establishing and maintaining an in situ permeable reactive barrier based on biological reactions, i.e., a biobarrier. These approaches included 1) use of a soluble (miscible) substrate that is relatively easy to distribute over a large areal extent, is inexpensive, and is expected to have moderate longevity; and 2) use of an immiscible substrate that can be distributed over a reasonable areal extent at a moderate cost and is expected to have increased longevity. For the treatability test, molasses was selected to represent a commercially available approach based on a soluble substrate. Emulsified vegetable oil, consisting of the commercially available EOS® 598 product (EOS Remediation, LLC.), was selected as the immiscible substrate.

The following conclusions related to the test objectives for the soluble substrate are supported by the test data. Substrate was successfully distributed to a radius of about 15 m (50 ft) from the injection well. Monitoring data indicate that microbial growth initiated rapidly, and this rapid growth could limit the ability to inject substrate to significantly larger zones from a single injection well. As would be expected, the uniformity of substrate distribution was impacted by subsurface heterogeneity. However, subsequent microbial activity and ability to reduce the targeted species were observed throughout the monitored zone, and low oxygen, nitrate, and chromium concentrations were maintained for the approximately 2-year duration of monitoring. Aquifer permeability reduction within the test zone was moderate and likely due to growth of bacteria. The injected substrate and associated organic degradation products persisted for about 1 year. Over the second year of barrier monitoring, organic substrate concentrations were low; the continued effectiveness of the treatment zone is attributed to recycling of organic compounds associated with the biomass that was produced during the first year.

The following conclusions related to the test objectives for the immiscible substrate are supported by the test data. Substrate was successfully distributed to a radius of about 8 m (25 ft) from the injection well. As would be expected, the uniformity of substrate distribution was impacted by subsurface heterogeneity. However, subsequent microbial activity and ability to reduce the targeted species were observed throughout the monitored zone, and low oxygen, nitrate, and chromium concentrations were maintained for the approximately 10-month duration of monitoring. Aquifer permeability reduction within the test zone was moderate and occurred quickly after substrate injection, likely due to physical effects from the presence of immiscible liquid in the aquifer. The monitoring period for the immiscible test was short compared to the expected longevity of the substrate. Therefore, additional monitoring would be necessary to determine the longevity of the treatment.

Acknowledgments

Funding for this project was provided by the U.S. Department of Energy Office of Environmental Management (EM-22) Columbia River Protection Supplemental Technologies Project. We thank R. Blaine Rowley and Skip Chamberlain (DOE Headquarters, EM-22), K. Mike Thompson (DOE Richland Operations Office), and Jonathan S. Fruchter (PNNL), for overall management of the EM-22 project and support of this project. We also acknowledge and appreciate the BER Environmental Remediation Science Program support to Susan Hubbard for the column experiments conducted in conjunction with the geophysical field monitoring activities.

Acronyms and Abbreviations

bgs	below ground surface
DOE	U.S. Department of Energy
EBF	electromagnetic borehole flow meter
EPA	U.S. Environmental Protection Agency
ft	foot, feet
gal	gallon(s)
gpm	gallons per minute
GPR	ground-penetrating radar
in.	inch(es)
ISE	ion selective electrode
ISRM	In Situ Redox Manipulation (barrier)
L	liter(s)
L/min	liter(s) per minute
m	meter(s)
MCL	Maximum Contaminant Level
NIST	National Institute of Standards and Technology
NTU	nephelometric turbidity unit(s)
OD	outside diameter
PNNL	Pacific Northwest National Laboratory
PV	pore volume
RCRA	*Resource Conservation and Recovery Act of 1976*
TOC	total organic carbon

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1.0 Introduction

Pacific Northwest National Laboratory (PNNL) conducted a treatability test designed to demonstrate that in situ biostimulation can be applied to help meet cleanup goals in the 100-D Area of the U.S. Department of Energy (DOE) Hanford Site. This test is part of a strategy to couple multiple technologies to accelerate cleanup of chromium-contaminated groundwater in the 100 Area at the Hanford Site. The in situ biostimulation concept for this treatability test is intended to provide supplemental treatment upgradient of the In Situ Redox Manipulation (ISRM) barrier by reducing the concentration of the primary oxidizing species in groundwater (i.e., nitrate and dissolved oxygen) and chromate, thereby increasing the longevity of the ISRM barrier.

1.1 Site and Waste Stream Summary

The Hanford Site in southeastern Washington 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 DOE nuclear reactors used for plutonium production between 1943 and 1987. Operations at the Hanford Site now are 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 previous 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 and 100-H reactor areas and the 600 Area between them. The 100-D 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_2CrO_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 (e.g., decontamination, water treatment) 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 contamination in the 100-D Area is the focus of this treatability test.

1.2 Treatment Technology Description

In situ biostimulation has been researched extensively and applied for aquifer remediation over the last 20 years for various contaminants. In situ biostimulation, in the context of this project, is the process of amending an aquifer with a substrate that induces growth and/or activity of indigenous bacteria to induce a desired reaction. For application at the 100-D Area, the purpose of biostimulation is to induce reduction of chromate, nitrate, and oxygen to remove these compounds from the groundwater. Chromate can be biologically reduced to insoluble chromium (III) (e.g., Alam et al. 2006), and in situ chromate reduction has been demonstrated recently using polylactate as a substrate at the 100-H Area of Hanford (Faybishenko et al. 2008; Hubbard et al. 2008). Nitrate can be biologically reduced using a variety of organic substrates including vegetable oil (e.g., Hunter 2001), and in situ nitrate reduction has been demonstrated at the Hanford Site (e.g., Hooker et al. 1998). Biological nitrate reduction occurs as a stepwise process in which the initial intermediate degradation product is nitrite. Under some conditions, nitrite concentrations can accumulate during nitrate reduction, and nitrite must be monitored as a potential unwanted product of nitrate reduction. The final desired product of biological nitrate reduction is nitrogen gas. Dissolved oxygen is readily reduced by a wide variety of bacteria in the presence of a wide variety of organic substrates. These reductive processes are induced by introduction of an organic substrate and the resultant biological processes create geochemically reduced conditions in the aquifer (e.g., a low oxidation–reduction potential).

For implementation of an in situ permeable reactive barrier based on biological reactions, i.e., a biobarrier, a wide variety of available organic substrates are potentially suitable for establishing anaerobic conditions (AFCEE 2004) and thereby reducing dissolved oxygen, nitrate, and chromate. Substrates for the treatability test were selected to provide information about two general approaches for establishing and maintaining an in situ biobarrier. These approaches included 1) use of a soluble (miscible) substrate that is relatively easy to distribute over a large areal extent, is inexpensive, and is expected to have moderate longevity; and 2) use of an immiscible substrate that can be distributed over a reasonable areal extent at a moderate cost and is expected to have increased longevity.

Soluble (miscible) substrates, typically organic acids or sugars, offer the potential for distributing substrate large distances from an injection well. Although consumption of soluble substrates may be relatively rapid, biomass produced from consumption of the substrate can provide long-term reducing conditions as the biomass decays (Sleep et al. 2005; Yang and McCarty 2000). Reduction of sediment iron or sulfate by bacteria may also create additional long-term reducing capacity. Molasses was selected for use in the treatability test (Truex et al. 2007). Molasses has a high solubility and low cost and is representative of the type of secondary waste substrates that may be available to minimize the long-term cost of the barrier (e.g., carbohydrate wastes). Use of molasses is a commercially available approach for field-scale biostimulation (ARCADIS 2009) and has shown favorable results to support anaerobic bioremediation (Borden and Rodriguez 2006) and chromate reduction (Gemoets et al. 2003).

Immiscible substrates can maintain reducing conditions over a long period because the substrate consumption is controlled by the rate of dissolution (AFCEE 2004). The immiscible substrate can be injected into an aquifer as a separate phase or as an emulsion. However, injection of a separate phase can cause significant hydraulic conductivity reduction and cannot distribute substrate very far from the injection well (Coulibaly and Borden 2004). Use of stable emulsions offers the potential for distribution over a larger areal extent, and the distributed substrate at a weight percentage on the order of 1% will cause minimal reduction in hydraulic conductivity (Hunter 2001, 2005; Coulibaly and Borden 2004). Because of the large areal extent necessary for full-scale application in the 100-D Area, the treatability test focused on immiscible substrates that can be delivered as an emulsion rather than other immiscible substrates (Truex et al. 2007). Soybean oil can be effectively emulsified (Coulibaly and Borden 2004) and is currently a commercially available bioremediation substrate. A recent study of slow-release substrates for anaerobic bioremediation showed favorable results for soybean oil (Borden and Rodriguez 2006). Hunter (2001, 2005) has shown effective denitrification using soybean oil and that the tested emulsifier does not significantly inhibit denitrification (Hunter 2005). The commercially available

EOS® 598 soybean oil emulsion was selected for the treatability test (EOS Remediation, LLC, www.eosremediation.com). Soybean oil releases long-chain fatty acids and glycerol to the groundwater and these compounds are subsequently degraded producing other daughter products that can be degraded further to support maintaining anaerobic conditions (Borden and Rodriguez 2006). The overall reactions in the groundwater are controlled by rate of dissolution, hydrolysis, and associated solubility for the oil. Because mass transfer processes control the reactions and longevity of the reducing conditions, biomass yield and decay are not as important as they are for the soluble substrates.

An extensive data set for a polylactate substrate is available for use in establishing a biobarrier (Faybishenko et al. 2008; Hubbard et al. 2008). However, the substrates selected for this treatability test offer alternatives to polylactate that have the potential for a larger areal extent of distribution from an injection well, with an expected similar ability for in situ reduction of dissolved oxygen, nitrate, and chromate. Other potential injectable substrates, such as whey (soluble and particulate), chitin (particulate), and others, may also offer performance characteristics similar to those of the tested substrates but were not directly evaluated in this treatability testing effort.

2.0 Objectives

The 100-D Biostimulation Field Test was conducted to evaluate whether an effective in situ permeable reactive barrier based on biological reactions, i.e., a biobarrier, can be installed by injecting either 1) a soluble substrate, i.e., one that is microbially degraded over a relatively short time frame when compared to the desired life span of the barrier, or 2) an immiscible substrate, i.e., one that slowly dissolves and releases substrate for microbial reactions over a long period. Molasses was selected as the soluble substrate, and emulsified vegetable oil was selected as the immiscible substrate for the field test.

Specific objectives to be addressed in the field test are as follows:

- Determine the effective radius of treatment.
- Evaluate the uniformity of substrate distribution.
- Identify operational needs for injection.
- Induce fermentation reactions and reducing conditions and grow biomass.
- Minimize permeability changes due to growth of biomass (assessed through comparison of pre- and post-hydraulic test results).
- Quantify the ability to obtain and maintain low oxygen and nitrate/nitrite concentrations (limit primary electron acceptor flux) and determine longevity of treatment.
- Quantify the ability to obtain and maintain low chromate concentrations (augment chromate treatment) and determine longevity of treatment.
- Compile information required for full-scale design, including a description of the injection process and treatment performance.

3.0 Test Site Description

The test site location, hydrogeologic setting, and groundwater flow system are described in the following sections.

3.1 Test Site Location and Hydrogeologic Setting

The treatability test site is located in the southwestern portion of the 100-D Area within the chromate and nitrate plumes (Figure 3.1 and Figure 3.2, respectively). Although this location is not within the highest concentration portion of the chromium plume, trend data at this location indicate that chromium concentrations (200–400 ppb) are sufficient to meet treatability test objectives. As shown in Figure 3.2, this location is also well within the 45-mg/L nitrate contour. The selected test site location is approximately 300 m upgradient of the existing ISRM barrier. Based on pump-and-treat system capture zone analysis (DOE 2006), the test site is not within the capture zone of well D5-39, the closest pumping well.

The general hydrogeologic setting of the groundwater 100-HR-3 Operable Unit (encompassing the 100-D and 100-H Areas) is described in Lindsey and Jaeger (1993); summaries of the conceptual site models for groundwater contamination in each of these areas are presented in Peterson et al. (1996). The unsaturated (vadose) zone in the 100-D Area lies in the Hanford formation and the upper portion of the Ringold Formation (Figure 3.3). The unconfined aquifer is composed of sandy gravel to silty sandy

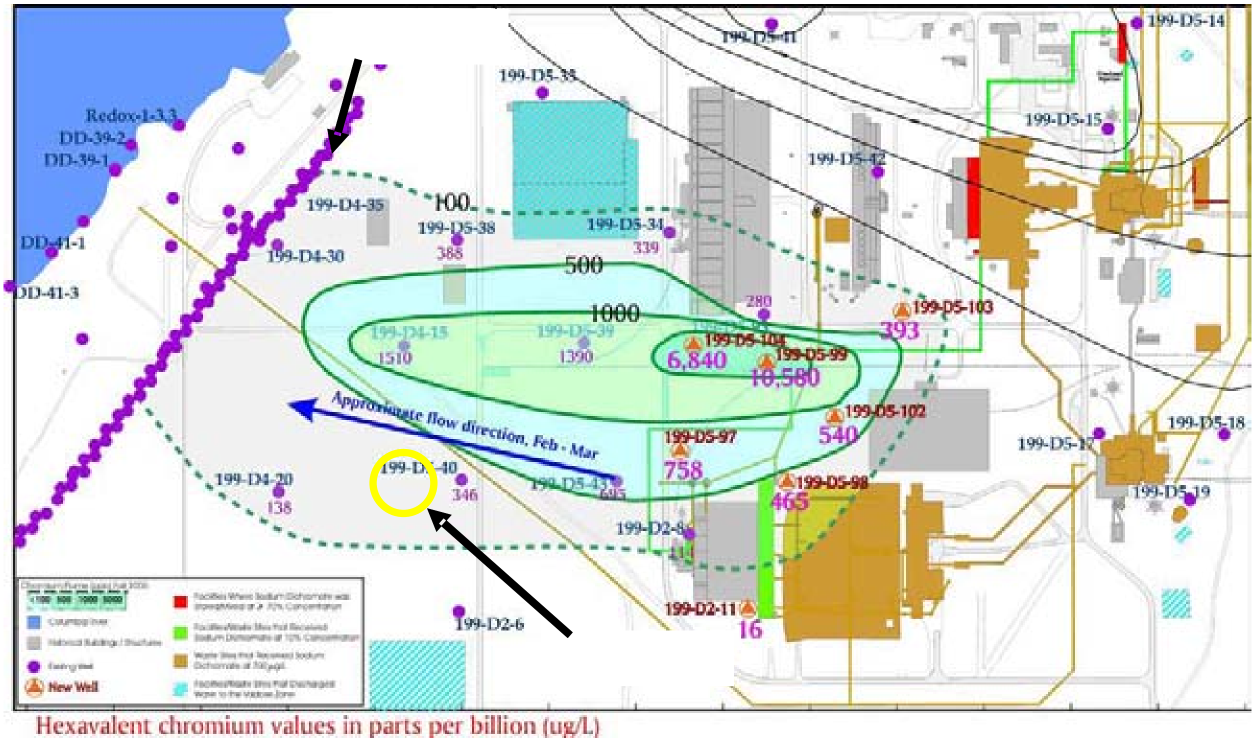

Figure 3.1. Test Location and Recent Chromate Concentration Data for the 100-D Area Unconfined Aquifer (personal communication, Scott Petersen, May 3, 2007)

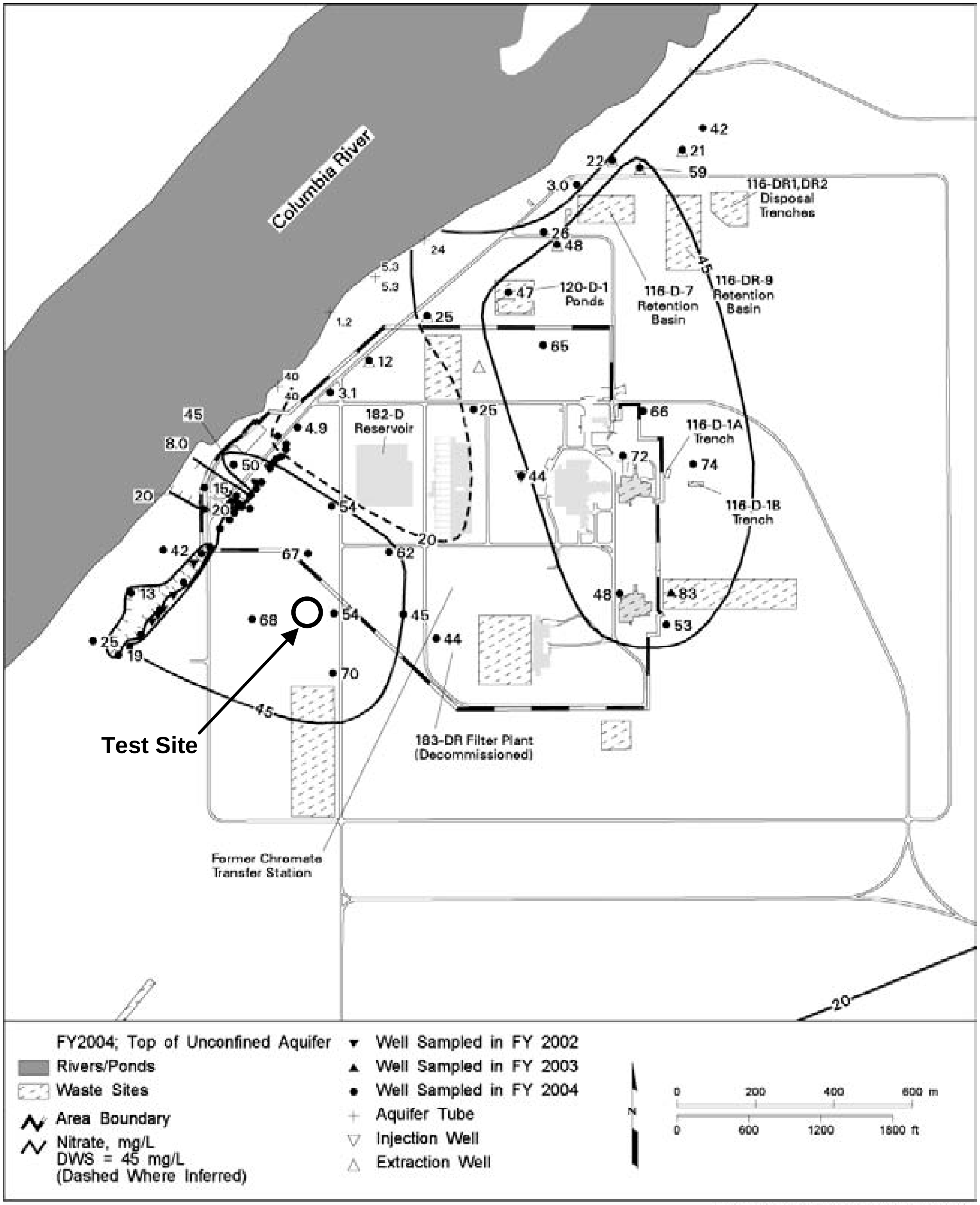

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Figure 3.2. Test Location and Nitrate Concentration Data for the 100-D Area Unconfined Aquifer

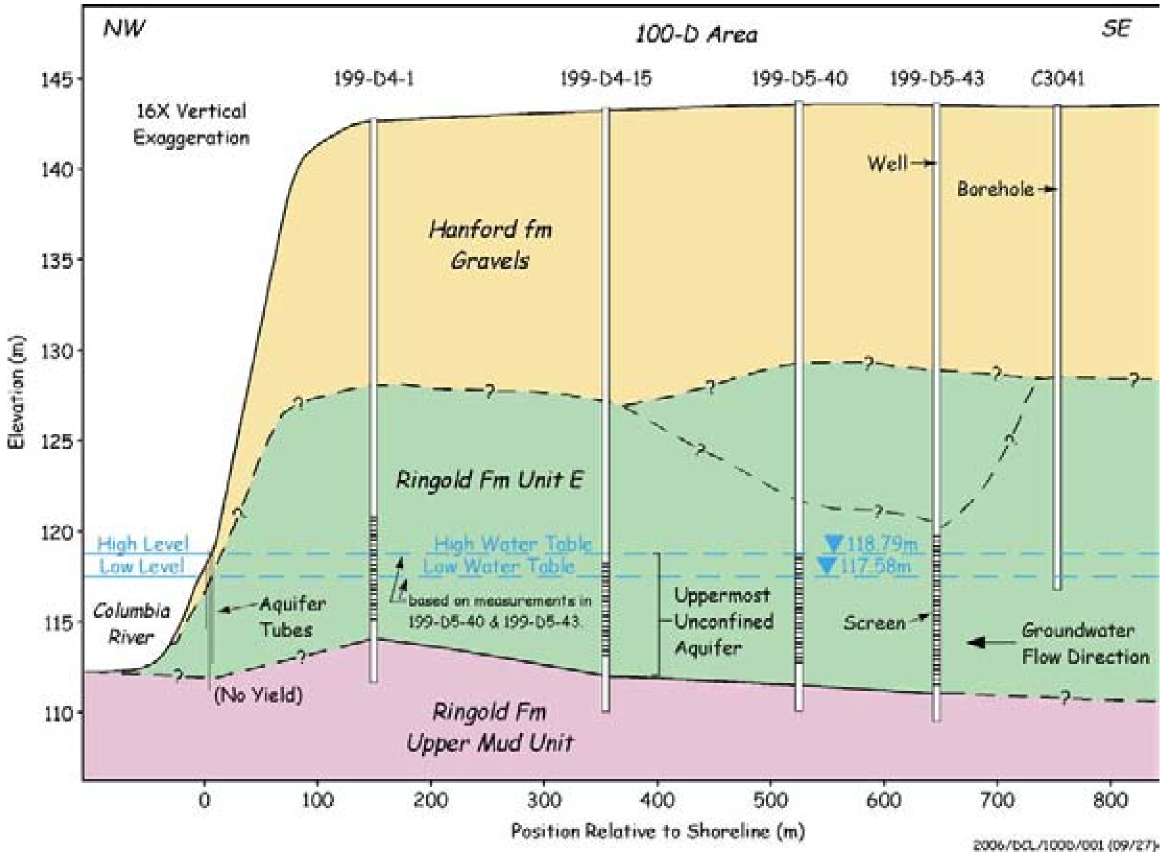


Figure 3.3. 100-D Area Hydrogeologic Cross Section of the Uppermost Aquifer

gravel, ~3 to 9 m thick, which corresponds to Ringold Formation Unit E. Depth to the water table ranges from less than 1 m near the river to ~25 m farther inland. The base of the unconfined aquifer is a fine-grained silty sand to clay overbank interval, designated the Ringold Formation Upper Mud Unit, which is ~15-m thick and generally dips to the west. The deeper Ringold Formation is believed to comprise more layers of clay, silt, and sand based on interpolations between wells elsewhere in the 100 Areas (Hartman 1999).

In the 100-D Area, chromium is the major contaminant of concern in groundwater and flows toward the Columbia River from multiple source areas through the uppermost unconfined aquifer. At the proposed test site location, the unconfined aquifer is contained within the lower Ringold Formation Unit E and is approximately 6.8 to 5.8 m thick (depending on fluctuations occurring in the elevation of the Columbia River); the water table is ~25 m below ground surface (bgs). Groundwater in the unconfined aquifer generally flows northwest and discharges into the Columbia River. Physical property analyses (porosity, bulk density, and particle size distribution by sieve analysis) were previously conducted on 15 split tube samples collected during drilling of ISRM wells. Particle size ranged from 65% to 85% gravel, 14% to 31% sand, and less than 6% fines (silt/clay). Porosity ranged from 5% to 23% with a mean of 14%. Bulk density ranged from 2.1 to 2.4 g/cm^3 with a mean of 2.3 g/cm^3 (Williams et al. 2000).

3.2 Site-Specific Characterization

Site-specific characterization data were collected at the field test site as a baseline for interpreting the field test results. During well installation, borehole logs were prepared and used to generate a geologic cross section of the area (Figure 3.4 and Figure 3.5). Isopach maps showing the top of the underlying confining unit (Figure 3.6) and the saturated thickness of the Ringold formation (Figure 3.7) were prepared and indicate relatively constant elevations across the test area. Detailed borehole logs and well completion diagrams are shown in Appendix A.

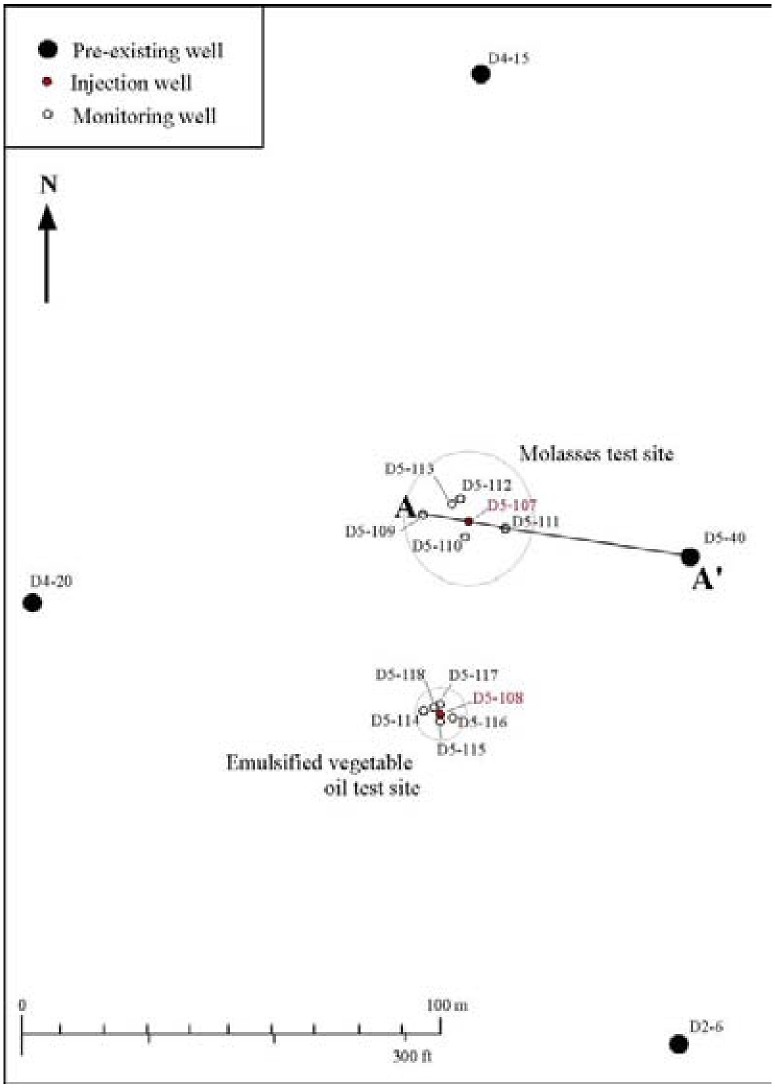


Figure 3.4. Site Wells and Location of Geologic Cross Section

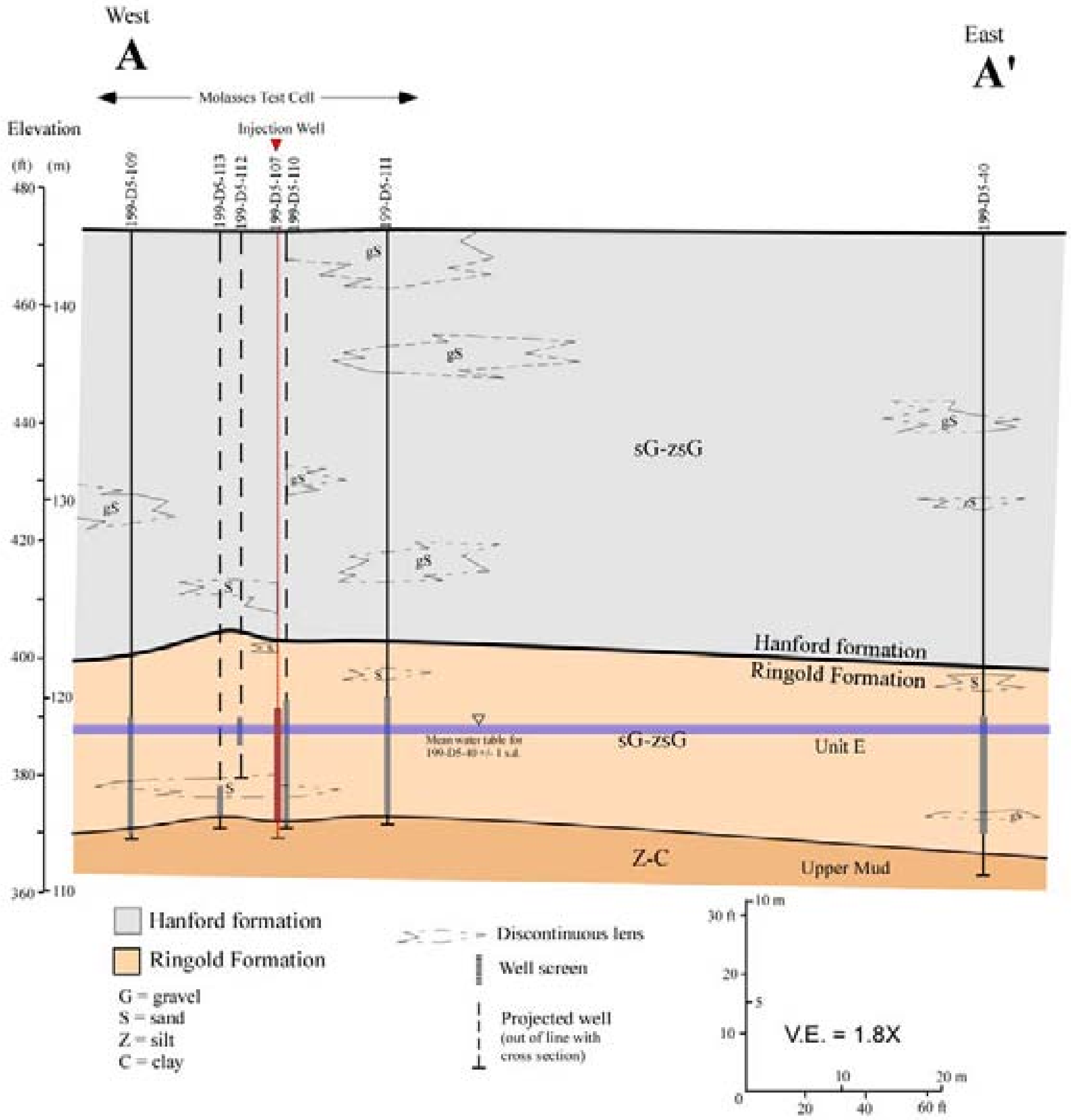


Figure 3.5. Cross Section View of the Field Test Site (see Figure 3.4 for location)

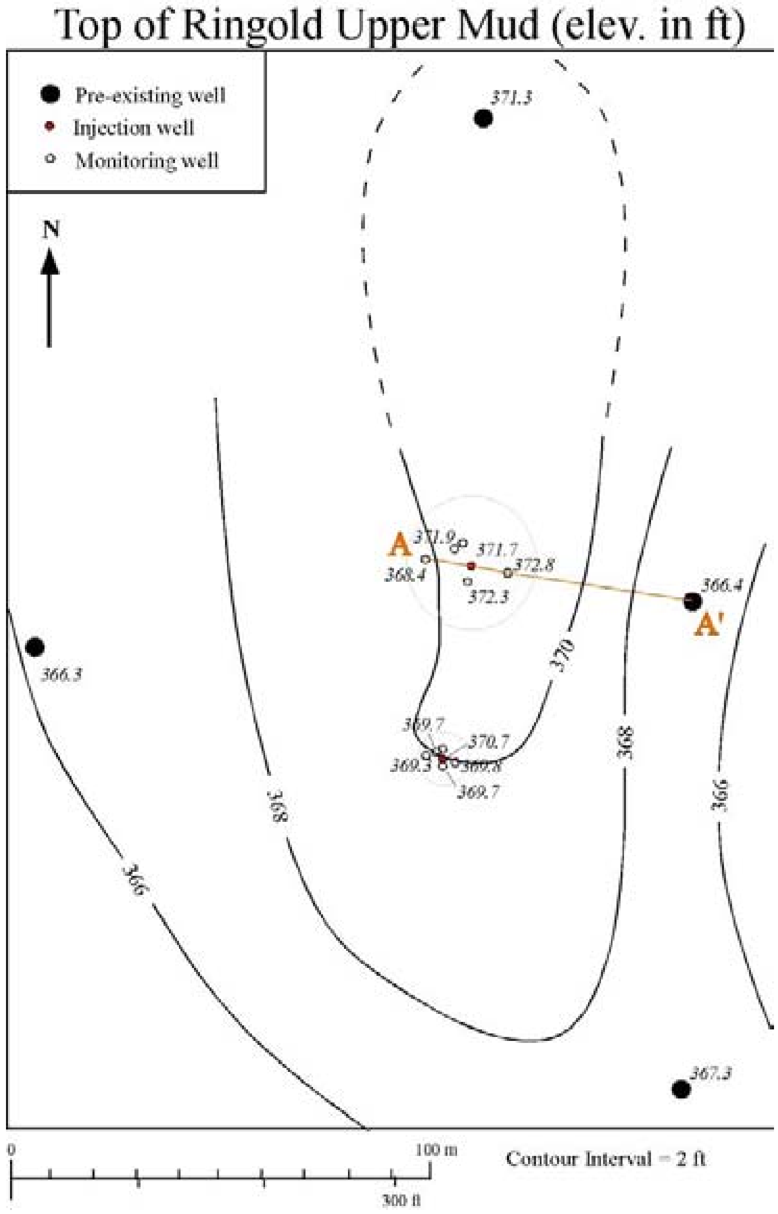


Figure 3.6. Top of Underlying Confining Unit

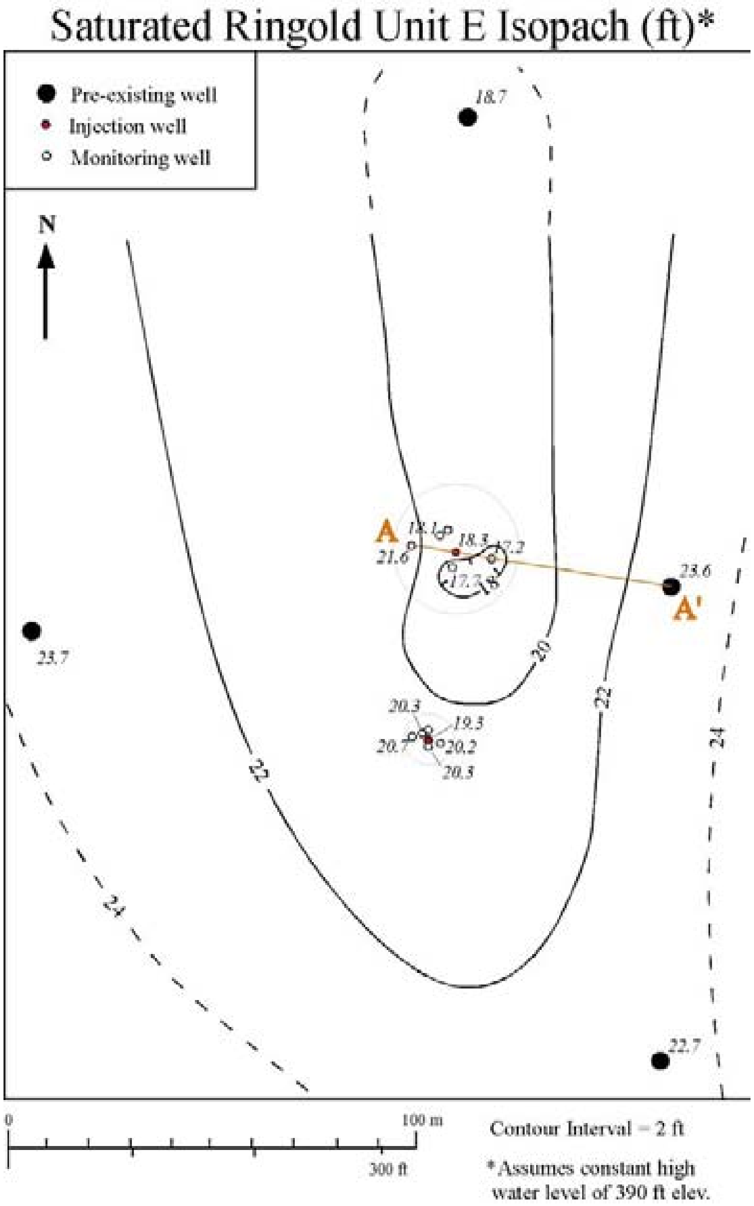


Figure 3.7. Saturated Thickness in the Ringold Formation

3.2.1 Hydraulic Properties

The horizontal hydraulic conductivity in the test area was estimated from a constant rate injection test at the immiscible substrate test site. The constant-rate injection test was performed in well 199-D5-108 for a duration of 360 minutes (6 hours), followed by a recovery monitoring period of several days to obtain site-specific aquifer properties. The pressure recovery data from the test were analyzed to provide an estimated average horizontal hydraulic conductivity of 27.4 m/day (90 ft/day).

3.2.1.1 Test Configuration

Based upon the expected specific capacity of the stress well, the injection rate for the test was specified as 150 L/min (40 gpm). About 70 minutes into the test, the flow rate was adjusted to a new target rate of 130 L/min (35 gpm) in order to maintain more stable flows. Flows were held at this rate for the remainder of the test and fluctuated by less than 2 gpm.

Flow rates were measured using a turbine flowmeter and recorded manually in a field record book. Pressure responses were monitored in the stress well and neighboring monitoring wells using sensors (Model PT2X, Instrumentation Northwest, Kirkland, Washington) with ranges of 5 and 15 psig (0.1% accuracy). These same sensors were installed over the life of the treatability study to provide continuous water-level monitoring data. Manual water-level measurements and depths to bottom for each well were taken at the time of testing using an “e-tape” instrument traceable to standards established by the National Institute of Standards and Technology (NIST).

Five observation wells were used to monitor the pressure response during the test and estimate hydraulic properties of the aquifer. The radial distance between these wells and the stress well ranged between 1.8 and 5.4 m (5.9 and 17.6 ft). The stress well and three of the observation wells were fully screened wells. The other two wells were screened in the lower and upper portion of the aquifer, respectively.

3.2.1.2 Analytical Methods

A comparison of the pressure buildup and recovery data revealed similar patterns. The recovery data were selected for analysis because they provided a smoother, less noisy signal of the pressure response. Prior to analysis, the recovery data were transformed into Agarwal-equivalent drawdown and time, which allows recovery data to be analyzed as an equivalent drawdown (or pressure buildup) response (Agarwal 1980).

Hydraulic properties were estimated using a type-curve fitting method according to the analytical solution of Neuman (1972, 1974, 1975) for an unconfined aquifer with delayed gravity response (specific yield). The analysis also assumes the aquifer is homogeneous, of infinite areal extent, and of uniform thickness, and ignores well-bore storage effects. The pressure response and response derivative data were used for the curve fits. Anisotropy (Kr/Kz) and specific yield (Sy) were prescribed in the analysis at values of 0.1 and 0.15, respectively. Transmissivity (T) and storativity (S) were varied until a satisfactory fit to the data could be made. The analysis assumed the observation wells were fully penetrating and ignored the effects of partial penetration. The analyses were performed using the aquifer testing analysis software package AQTESOLV (HydroSOLVE, Inc., Reston, Virginia).

3.2.1.3 Results

The pressure responses followed a typical delayed-response pattern associated with delayed yield in an unconfined aquifer (Figure 3.8). Pressure responses ranged from 0.15 to 0.5 m (0.5 to 1.7 ft) near the end of the test within the five observation wells. The pressure responses in wells 199-D5-114 and -118 were not used for the analysis for three reasons:

1. The pressure responses show a late time curvature, suggesting a delayed hydraulic response at these locations indicative of poor hydraulic connection or some other formational heterogeneity (e.g., due to the observation well being located in low-permeability material).
2. Data from substrate injection showed only small amounts of substrate delivery to these wells compared to other wells within the radius of influence of the injection. This result is also indicative of poor hydraulic connection with the injection well.
3. The analytical solution assumes the entire area of influence is homogeneous and does not address varying pressure responses due to heterogeneities.

For these reasons, only the pressure responses from the wells 199-D5-115, -116, and -117 were quantitatively fit with type-curves to obtain hydraulic property estimates.

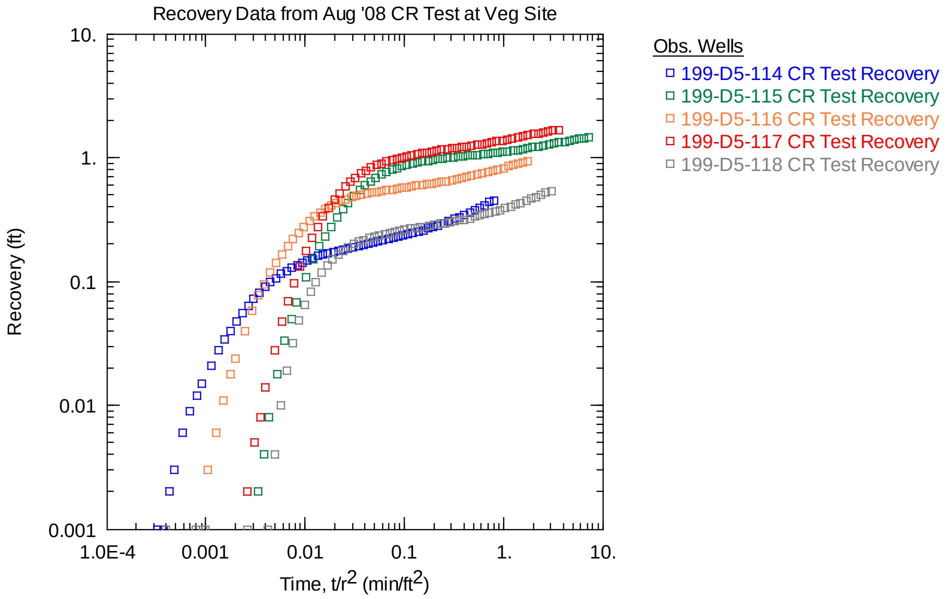


Figure 3.8. Recovery Responses for August 2008 Constant-Rate Test in Well 199-D5-108. Recovery displacement is shown as a function of time divided by the square of radial distance (t/r^2).

The average transmissivity (T) estimate obtained from type-curve fits to the recovery data for wells 199-D5-115, -116, and -117 was 160 m^2/day (1,735 ft^2/day) (Table 3.1). Individual type-curve fits to the data are shown in Figures 3.9 through 3.11. The average aquifer thickness (b) within the emulsified vegetable oil test site at the time of the constant-rate test was 5.9 m (19.3 ft). This calculation is based on the measured well water levels and the borehole geologic logs for the stress well and the five neighboring observation wells. The average hydraulic conductivity (K = T/b) estimate is 27.4 m/day (90 ft/day) (Table 3.1).

Table 3.1. Hydraulic Property Estimates from August 2008 Constant-Rate Test in Well 199-D5-108

Well	Storativity, S	Transmissivity, T (ft^2/day)	Hydraulic Conductivity, K (ft/day)
199-D5-115	0.008	1,830	95
199-D5-116	0.010	2,100	109
199-D5-117	0.010	1,275	66
Avg.	0.009	1,735	90
St. Dev	0.001	421	22

Notes: Specific yield (Sy) and anisotropy (Kr/Kz) were prescribed at values of 0.15 and 0.1, respectively. The average aquifer thickness (b) of the six wells in the test cluster at the time of testing was 19.3 ft.

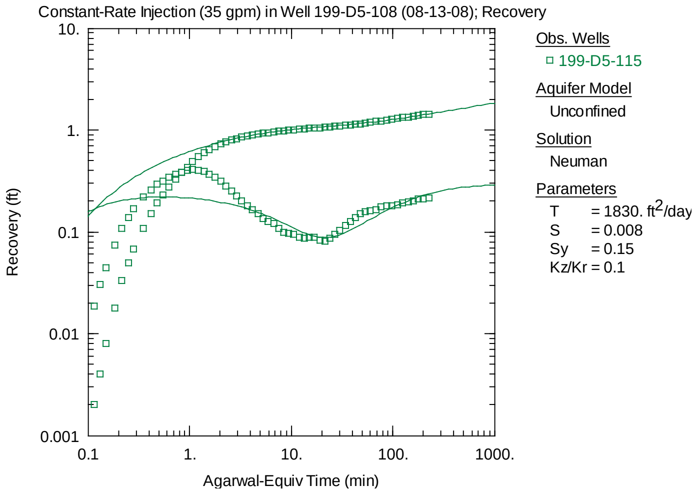


Figure 3.9. Neuman Type-Curve Analysis of Pressure Recovery from Well 199-D5-115 for August 2008 Constant-Rate Injection Test in Well 199-D5-108

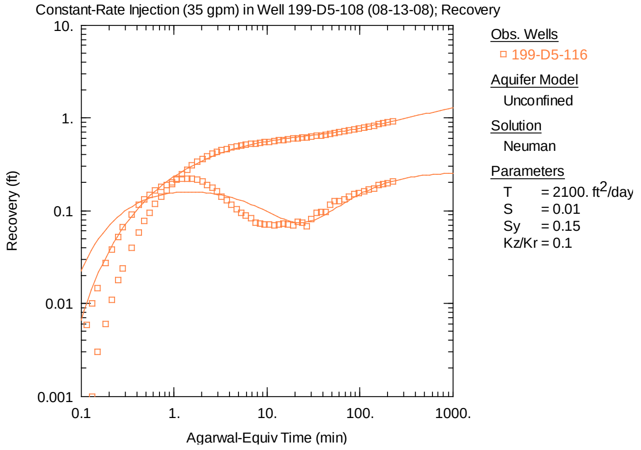


Figure 3.10. Neuman Type-Curve Analysis of Pressure Recovery from Well 199-D5-116 for August 2008 Constant-Rate Injection Test in Well 199-D5-108

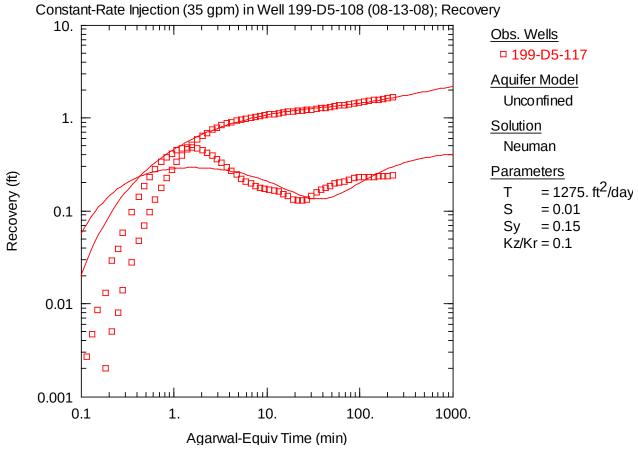


Figure 3.11. Neuman Type-Curve Analysis of Pressure Recovery from Well 199-D5-117 for August 2008 Constant-Rate Injection Test in Well 199-D5-108

3.2.2 Electronic Borehole Flowmeter Summary

The purpose of the electronic borehole flowmeter survey was to characterize the distribution of vertical flow conditions and inferred vertical hydraulic conductivity distribution in the aquifer at the soluble substrate test cell. Electromagnetic borehole flowmeter (EBF) surveys are effective for measuring the vertical groundwater flow velocity distribution in wells. The vertical groundwater-flow velocity measurements can be used to infer the vertical distribution of lateral groundwater flow into a well.

3.2.2.1 Electromagnetic Borehole Flowmeter Survey Description

The theory that governs the operation of the EBF is Faraday's Law of Induction, which states that the voltage induced by a conductor moving at right angles through a magnetic field is directly proportional to the velocity of the conductor moving through the field. Flowing water is the conductor, the electromagnet generates a magnetic field, and the electrodes are used to measure the induced voltage. For sign convention, upward flow represents a positive voltage signal and downward flow represents a negative voltage signal. More detailed descriptions of the EBF instrument system and field test applications are provided in Young et al. (1998).

The concept of the field test design is illustrated in Figure 3.12. The EBF probe consisted of an electromagnet and two electrodes 180 degrees apart inside a hollow cylinder. The inside diameter (ID) of the hollow cylinder was 2.5 cm (1 in.) and the outside diameter (OD) of the probe cylinder was just under 5.1 cm (2 in.). The probe (serial number FMT0605, Quantum Engineering Corporation, Loudon, Tennessee) is capable of measuring flow ranging from 0.04 L/min (0.01 gpm) to 40 L/min (10.6 gpm).

The probe was connected to an electronics box at the surface with a jacketed cable. The electronics attached to the electrodes transmit a voltage signal directly proportional to the velocity of water acting as the conductor. A computer was used to record the voltage signal and convert the signal to a flow rate measurement.

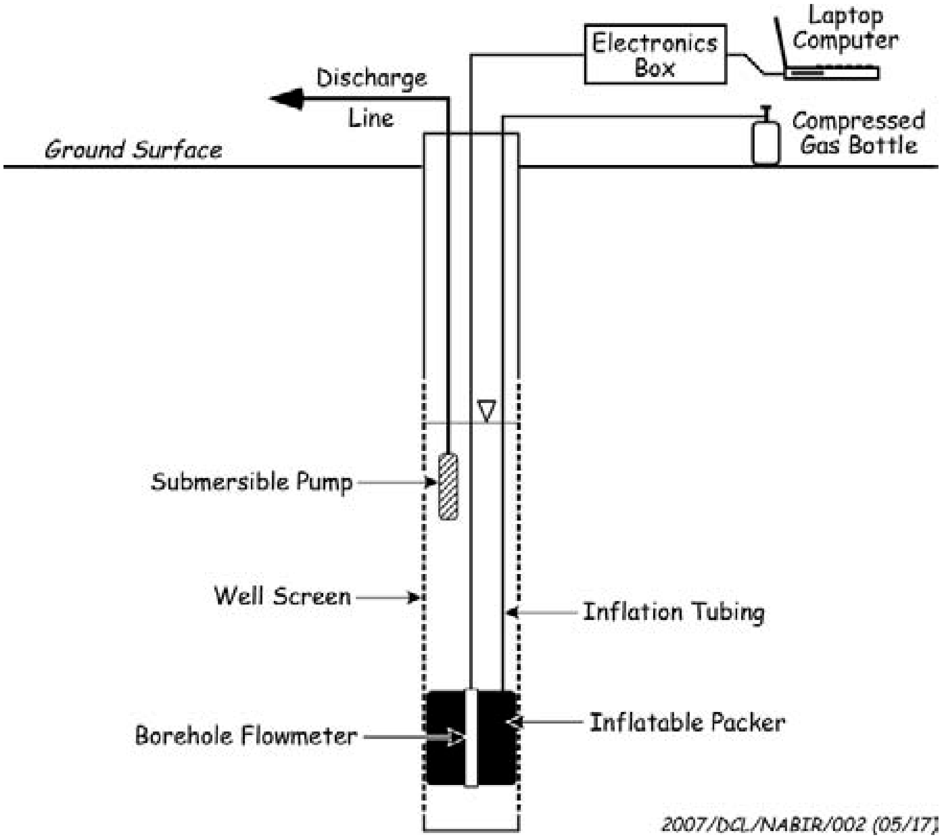


Figure 3.12. Electromagnetic Borehole Flowmeter General Configuration

For the PVC wire-wrap well screens, an inflatable packer was used to minimize bypass flow between the probe and the well screen (Figure 3.12). The inflatable packer consists of a rubber sleeve attached to a stainless steel assembly and is sealed with hose clamps. The EBF probe cylinder was mounted inside the stainless steel assembly. The packer and all fittings were checked for gas leaks at the surface before flowmeter profiling began. At each prescribed depth, inflation of the packer was controlled using compressed nitrogen gas, a regulator, and inflation tubing. After the packer was inflated, the packer seal was checked by pulling the cable for tension. Flow conditions were allowed to re-establish for several minutes due to disturbances caused by movement of the packer/probe assembly. After the flow measurement was recorded, the packer was deflated using a vented valve. The probe was raised (or lowered) very slowly to the next depth, and the measurement procedure was repeated.

3.2.2.2 Data Acquisition and Reporting

Both ambient and dynamic (i.e., pump-induced) flowmeter tests were performed in four wells at the soluble substrate test cell. Ambient flowmeter measurements were acquired every 0.6 to 1.5 m (2 to 5 ft) over the saturated well-screen sections. Dynamic flowmeter measurements were acquired at 0.3-m (1-ft) intervals and at known depths of well-screen solid joints. The locations of the well-screen joints were based on well completion log information (i.e., tubular goods tally) and confirmed in the field by feeling the resistance during raising and lowering of the packer/probe assembly. The purpose of measuring flow at the well-screen joints is to correct for bypass flow between the inflated packer and the well screen. All flowmeter measurements were referenced to the top of the outer protective casing.

During the dynamic flowmeter tests, pumping was extracted from the well and discharged to a portable tank. The discharge rate was 1.89 L/min (0.50 gpm) for all four wells tested and was held constant during each dynamic test. Each well was pumped ~10 to 15 minutes to allow flow conditions to reach near-equilibrium before recording the EBF measurements. The discharge rate was measured and recorded periodically with a calibrated in-line flowmeter. After near-equilibrium conditions were established, EBF measurements were made in succession from bottom to top of the saturated well-screen section. Zero-flow point measurements taken at the bottom of the well provide a reference for the survey measurements.

3.2.2.3 Electromagnetic Borehole Flowmeter Calibration

The EBF probe was calibrated according to the manufacturer's calibration procedure described in Young et al. (1998). Calibration of the instrument was performed over a range of flow rates comparable to flow rates measured in the field. The calibration procedure consisted of establishing a constant uniform flow rate through a vertical PVC pipe containing the EBF probe and comparing the flowmeter measurements (in voltage output) with flow rate measurements at the PVC pipe outlet. Flow rates were maintained at a constant rate by using a power supply box with controller and a 12-V pump. A linear regression plot of the calibration measurements yielded a slope of 3.561 L/min/V (0.9408 gpm/V (Figure 3.13).

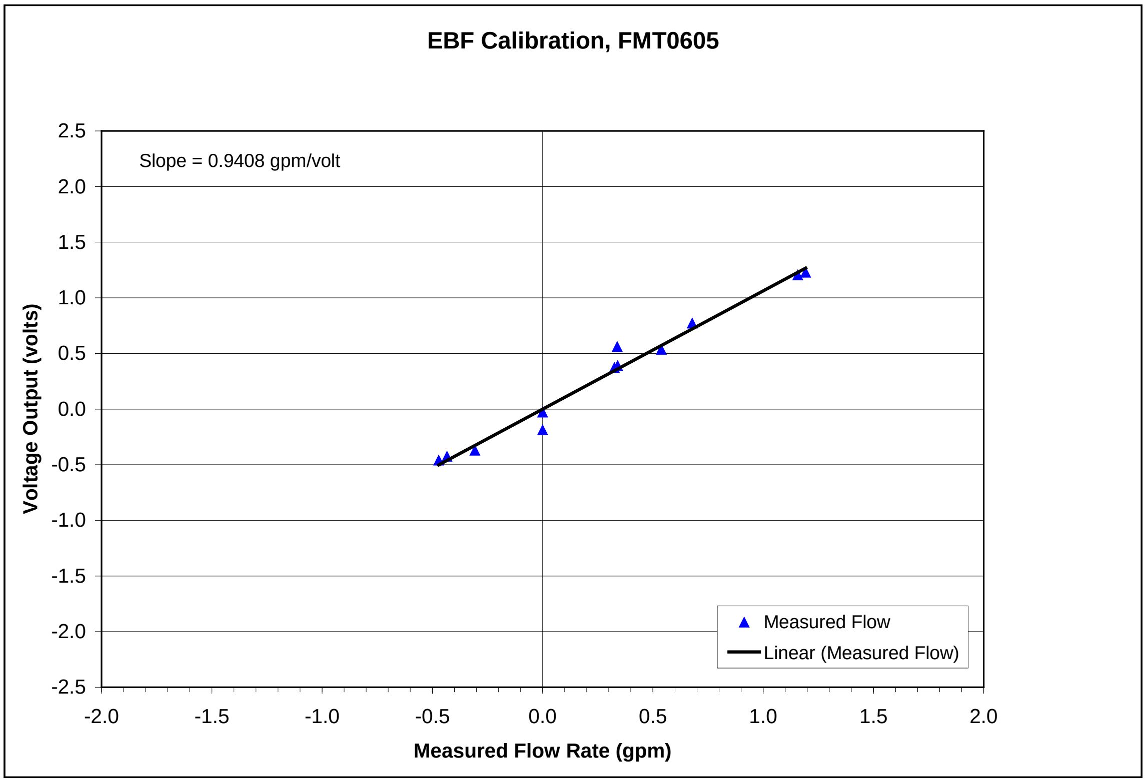


Figure 3.13. Electromagnetic Borehole Flowmeter Calibration Results

3.2.2.4 Electromagnetic Borehole Flowmeter Survey Analyses

For the EBF survey analysis, it is assumed that the aquifer within the well-screen section is composed of a series of horizontal layers, possessing layer-specific hydraulic properties. Under ambient flow conditions (i.e., non-pumping), the difference between two successive well-screen depth measurements is the portion of ambient flow, Δq_i, entering the well screen between depths where the flow measurements were taken. These two depths are assumed to bound layer *i* ($I = 1,2,\ldots,n$). The portion of flow, ΔQ_i, entering the well screen between these successive depths under pump-induced conditions is calculated in the same manner. Ambient-flow survey-profile information is used to correct dynamic flowmeter survey results for background vertical-gradient conditions.

The analytical method used for calculating the vertical distribution of relative hydraulic conductivity from dynamic EBF surveys is summarized in Molz et al. (1994) and Boman et al. (1997). Briefly stated, assuming that a constant pumping rate and pseudo-steady-state conditions are reached during pumping, the normalized relative hydraulic conductivity, K_r, for each *i*th layer within the aquifer can be calculated as follows:

$$K_r = \frac{K_i}{K_{avg}} = \frac{(\Delta Q_i - \Delta q_i)/\Delta z_i}{\sum_i (\Delta Q_i - \Delta q_i)/\sum z_i}; \quad i = 1,2,\ldots,n \tag{3.1}$$

where K_i = absolute horizontal hydraulic conductivity of the *i*th layer

K_{avg} = average horizontal hydraulic conductivity

ΔQ_i = difference in EBF flow measurements at the top and bottom of the *i*th interval under pumping conditions

Δq_i = difference in EBF flow measurements at the top and bottom of the *i*th interval under ambient conditions

Δz_i = *i*th interval thickness.

As indicated in Equation (3.1), the normalized relative hydraulic-conductivity value can be determined directly from measuring specific depth inflow rates as it relates to total flow pumped from the entire test interval. An absolute or actual hydraulic-conductivity-value depth profile (i.e., K_i versus depth), however, can be developed if an estimate of K_{avg} has been determined from a standard hydrologic test method (e.g., constant-rate pumping test). This can be derived by calculating the dimensional values of K_i for each *i*th depth interval by multiplying the net dynamic flowmeter test discharge result relationship (indicated in Equation [3.1]) by the previously determined K_{avg} value.

3.2.2.5 Electromagnetic Borehole Flowmeter Survey Results

Ambient and dynamic EBF surveys were performed in four wells at the biostimulation site. A summary of the pertinent well information is provided in Table 3.2. The following sections provide a description of the flowmeter survey performed at each well and analysis results for the saturated well-screen sections profiled. All depths in the following sections are referenced to ground surface. A summary of the EBF survey information is provided in Table 3.3.

Table 3.2. Summary of Pertinent Well Information

Well Number	Pre-Survey Static Depth to Water (ft bgs)	Pump-Induced Depth to Water (ft bgs)	Depth to Top of Well-Screen Section (ft bgs)	Depth to Bottom of Well-Screen Section (ft bgs)	Measured Depth to Bottom of Well (ft bgs)
199-D5-107	84.02	84.16	82.3	102.3	102.7
199-D5-109	83.94	83.95	82.8	102.8	103.1
199-D5-110	84.17	84.24	80.5	100.5	101.0
199-D5-111	84.09	84.17	80.1	100.1	100.6

Table 3.3. Summary of EBF Survey Information

				EBF Tests Performed		
Well Number	Survey Date(s)	Well Screen ID (in.)	Well Screen Type	Ambient	Dynamic	Discharge Rate (gpm)
199-D5-107	Sept. 21, 2007	6	20 Slot PVC	X	X	0.50
199-D5-109	Sept. 24, 2007	4	20 Slot PVC	X	X	0.50
199-D5-110	Sept. 21–22, 2007	4	20 Slot PVC	X	X	0.50
199-D5-111	Sept. 22, 2007	4	20 Slot PVC	X	X	0.50

Well 199-D5-107. Ambient and dynamic flowmeter surveys were performed on September 21, 2007. The ambient and dynamic flow profiles are shown in Figure 3.14. Ambient measurements ranged from less than detection (i.e., <0.04 L/min [<0.01 gpm]) to 0.34 L/min (0.09 gpm) in the upward direction. The net dynamic flow measurements indicate a generally uniform flow profile over a depth of 25.7 to 30.5 m (84.2 to 100 ft) bgs of the saturated well-screen section. Dynamic flow measurements indicate little flow contribution within the bottom ~0.6 m (~2 ft) of the well screen, which is consistent with the Ringold Formation upper mud unit encountered at a depth of 30.8 m (101 ft) bgs. Bypass flow between the packer/probe assembly and the well screen was estimated to be ~13% of the net dynamic vertical flow. Bypass flow through the sand-pack material surrounding the well screen was estimated to be ~30% of the net flow. A depiction of the inferred normalized hydraulic conductivity profile is shown in Figure 3.15.

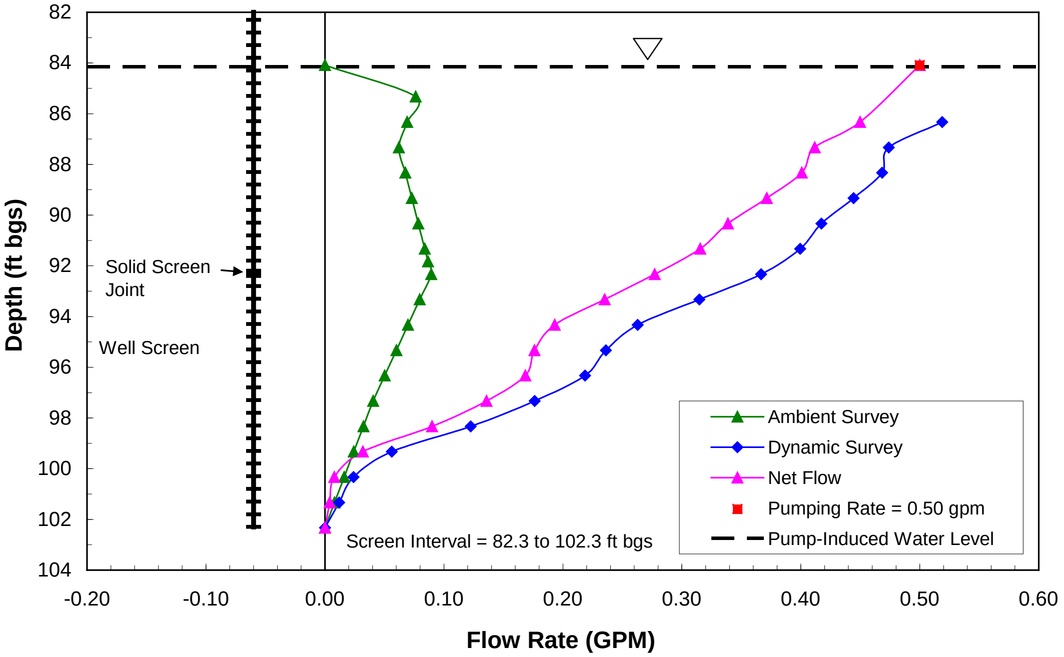


Figure 3.14. Ambient and Dynamic Vertical Flow Profiles, Well 199-D5-107

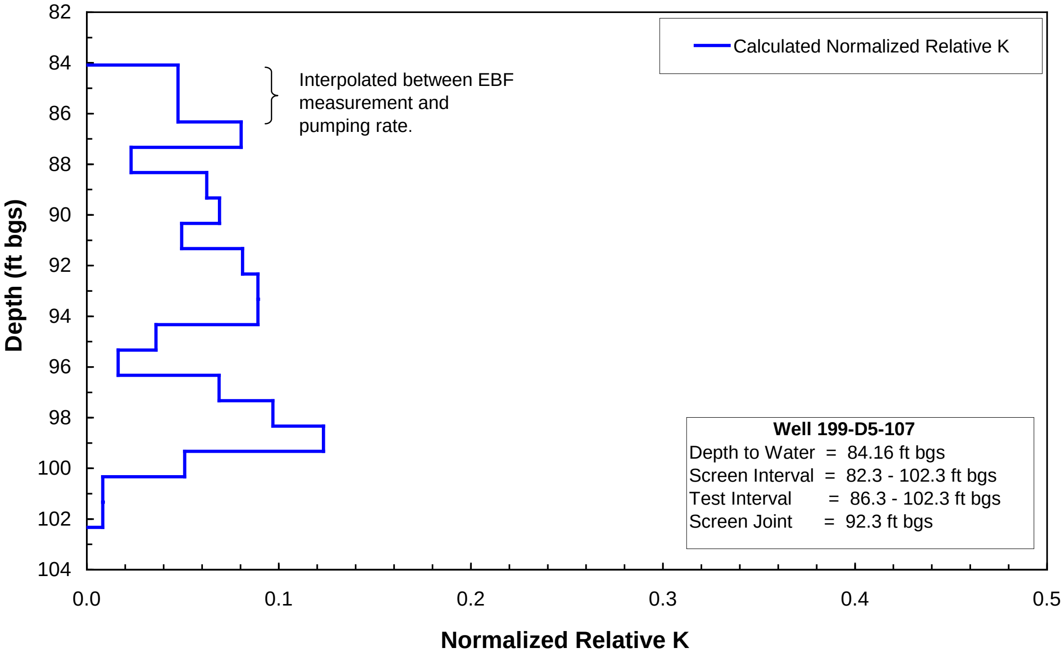


Figure 3.15. Normalized Hydraulic Conductivity Profile, Well 199-D5-107

Well 199-D5-109. Ambient and dynamic flowmeter surveys were performed on September 24, 2007. The ambient and dynamic flow profiles are shown in Figure 3.16. Ambient measurements ranged from less than detection (i.e., <0.04 L/min [<0.01 gpm]) in the middle portion of the well screen to 0.26 L/min (0.07 gpm) upward flow in the upper portion of the well screen. The net dynamic flow measurements indicate a sharp increase in flow contribution between a depth of 29.4 to 30.0 m (96.4 and 98.4 ft) bgs. This 0.6-m (2-ft) depth interval is a high permeable zone that indicates a high relative hydraulic conductivity. The middle portion of the well-screen section between a depth of 27.9 to 29.4 m (91.4 and 96.4 ft) bgs contributes little or no flow over this interval. The dynamic flow profile shows generally uniform flow above 27.9 m (91.4 ft) bgs. Bypass flow between the packer/probe assembly and the well screen was calculated to be ~7% of the measured dynamic vertical flow. Bypass flow through the sand-pack material surrounding the well screen was estimated to be ~18% of the net flow. A depiction of the inferred normalized hydraulic conductivity profile is shown in Figure 3.17.

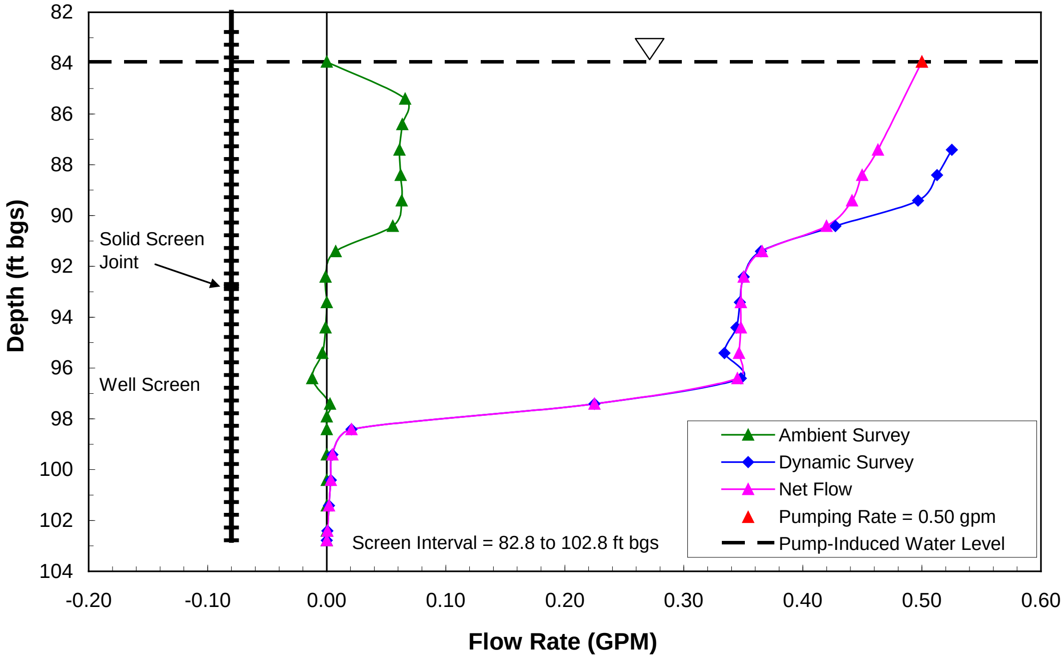


Figure 3.16. Ambient and Dynamic Vertical Flow Profiles, Well 199-D5-109

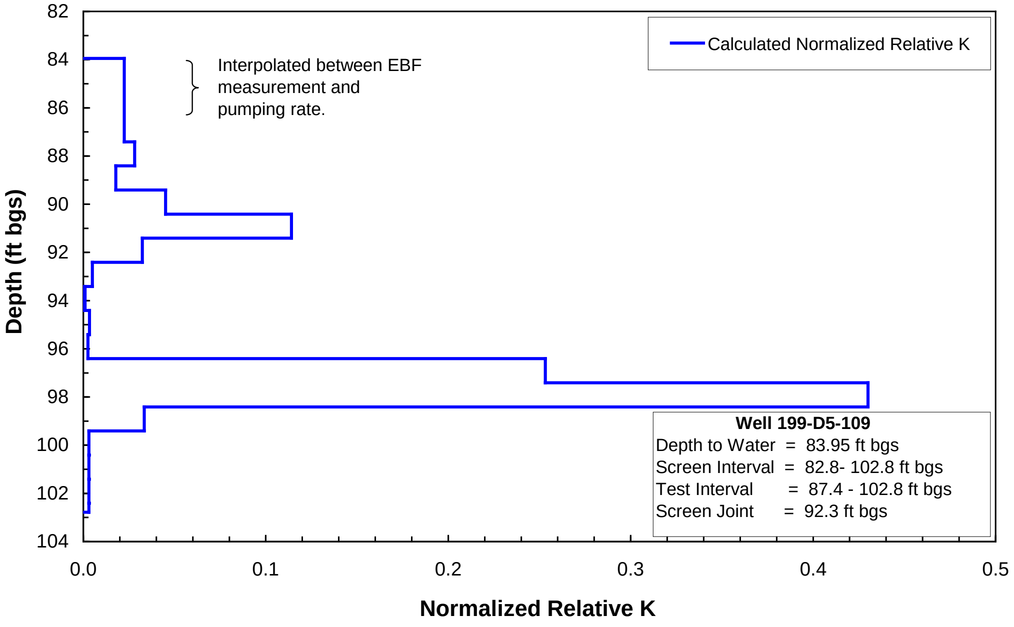


Figure 3.17. Normalized Hydraulic Conductivity Profile, Well 199-D5-109

Well 199-D5-110

Ambient and dynamic flowmeter surveys were performed on September 21-22, 2007. The ambient and dynamic flow profiles are shown in Figure 3.18. Ambient flow measurements were uniform over the saturated well-screen section, with values ranging from 0.23 to 0.26 L/min (0.06 to 0.07 gpm) upward flow. Net dynamic flow measurements also show a generally uniform contribution of flow over a depth of ~27.4 to 30.2 m bgs (~90 to 99 ft bgs) with lower contributions from the lower and upper part of the saturated well-screen section. The normalized hydraulic conductivity profile indicates the highest permeable zone at a depth of 28.8 to 29.4 m bgs (94.6 to 96.6 ft bgs). Bypass flow between the packer/probe assembly and the well screen was estimated to be ~7% of the net dynamic vertical flow. Bypass flow through the sand-pack material surrounding the well screen was estimated to be ~32% of the net flow. A depiction of the inferred normalized hydraulic conductivity profile is shown in Figure 3.19.

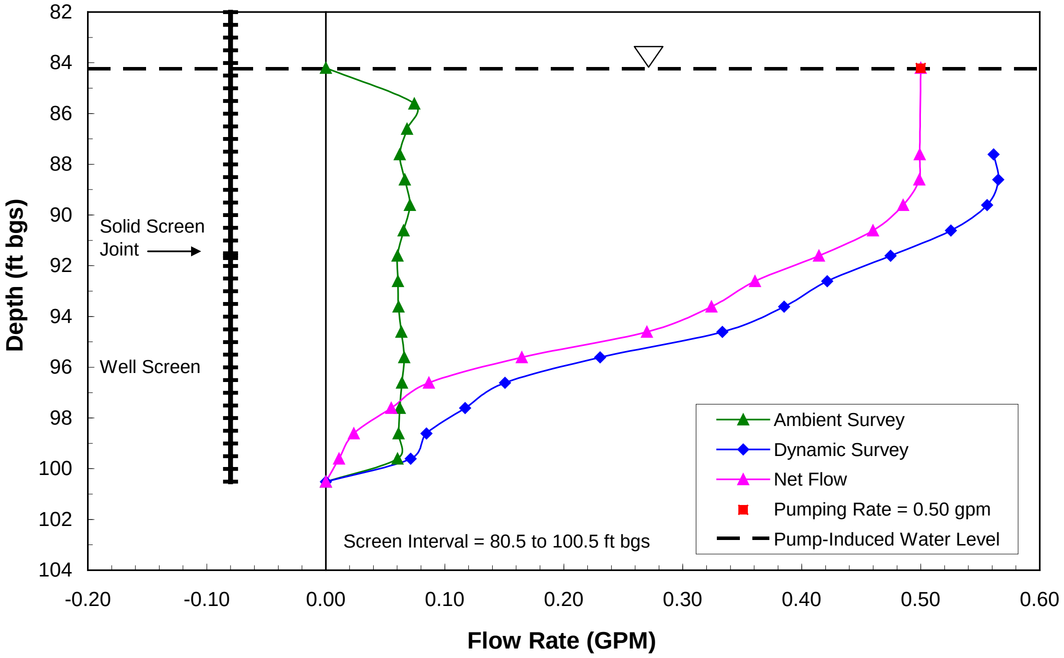


Figure 3.18. Ambient and Dynamic Vertical Flow Profiles, Well 199-D5-110

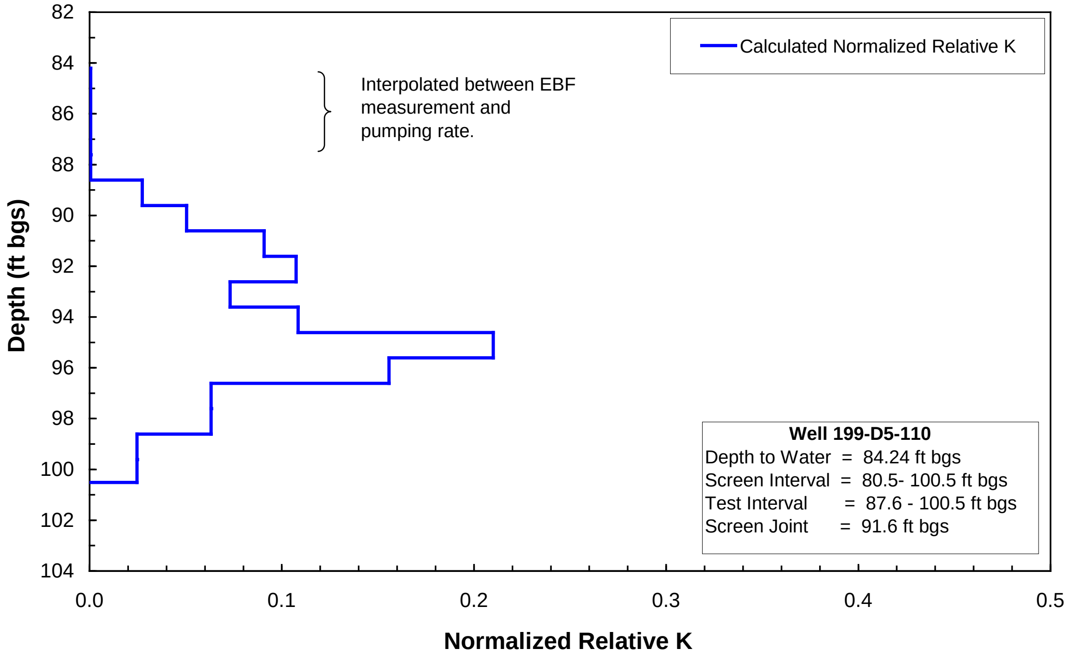


Figure 3.19. Normalized Hydraulic Conductivity Plot, Well 199-D5-110

Well 199-D5-111. Ambient and dynamic flowmeter surveys were performed on September 22, 2007. The ambient and dynamic flow profiles are shown in Figure 3.20. Ambient flow measurements were close to or below the detection limit (i.e., 0.04 L/min [0.01 gpm]) of the instrument, indicating little or no ambient flow. The net dynamic flow measurements indicate a generally uniform flow profile over a depth of 27.3 to 30.5 m (89.6 to 100.1 ft) bgs and a slightly lower, but uniform flow profile above 27.3 m (89.6 ft) bgs. The normalized hydraulic conductivity profile indicates a thin, slightly higher permeable zone occurring at a depth of ~27.4 m (~90 ft) bgs. Bypass flow between the packer/probe assembly and the well screen was estimated to be ~12% of the net dynamic vertical flow. A depiction of the inferred normalized hydraulic conductivity profile is shown in Figure 3.21.

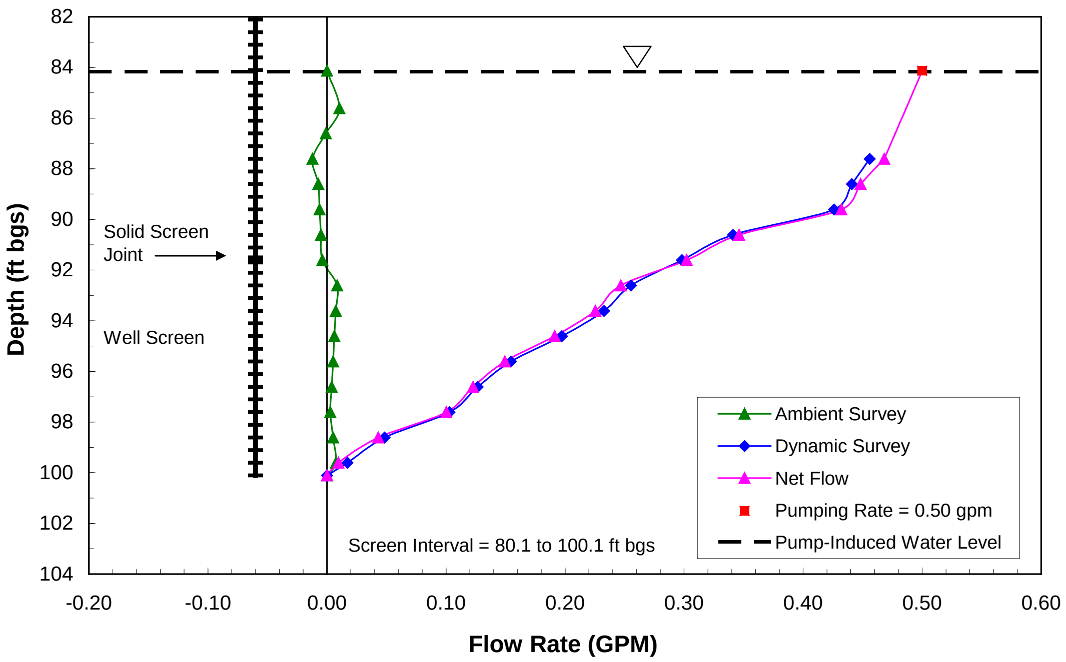


Figure 3.20. Ambient and Dynamic Vertical Flow Profiles, Well 199-D5-111

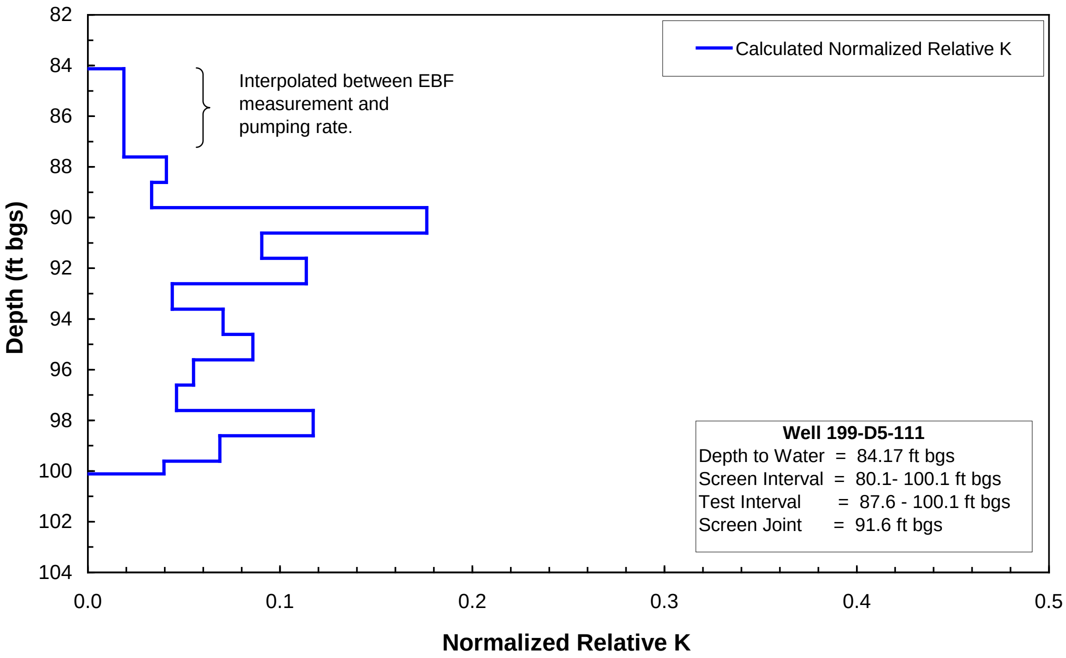


Figure 3.21. Normalized Hydraulic Conductivity Profile, Well 199-D5-111

3.2.2.6 Summary

Analysis results indicate generally uniform lateral flow and relative hydraulic conductivity distribution for saturated well-screen sections in the three wells 199-D5-107, 199-D5-110, and 199-D5-111 surveyed. Analysis results for the fourth well, 199-D5-109, indicate a significantly increased lateral flow and relative hydraulic conductivity over a 0.6-m (2-ft) interval within the lower part of the well-screen section.

3.2.3 Baseline Water Chemistry

Baseline water chemistry data were collected prior to any injection activity. These data are listed in Table 3.4.

Table 3.4. Baseline Water Chemistry at the Upgradient Background Well 199-D5-40. Average of two sampling events in September 2007.

Constituent	Concentration[(a)]	Units
Chromate	70.0	µg/L
Chromium	80.3	µg/L
Nitrate	61.5	mg/L
Nitrite	0.2	mg/L
Dissolved oxygen	5.6	mg/L
Aluminum	100U	µg/L
Antimony	500U	µg/L
Arsenic	1.5	µg/L
Barium	98.1	µg/L
Bismuth	500U	µg/L
Boron	250U	µg/L
Cadmium	0.2	µg/L
Calcium	87307	µg/L
Cobalt	250U	µg/L
Copper	52.2	µg/L
Iron	50.0	µg/L
Lead	53.3	µg/L
Magnesium	18579	µg/L
Manganese	25U	µg/L
Molybdenum	1.2	µg/L
Phosphorus	1250U	µg/L
Potassium	4971	µg/L
Selenium	4.4	µg/L
Silicon	13628	µg/L
Silver	0.03	µg/L
Sodium	11701	µg/L
Sulfur	43849	µg/L
Zinc	894	µg/L
Zirconium	25U	µg/L
Bromide	0.3	mg/L
Chloride	26.0	mg/L
Phosphate	0.1	mg/L
Sulfate	136.5	mg/L
TOC	3.3	mg/L

(a) A “U” designation indicates the analyte was below the detection limit. The number next to the symbol is the detection limit.

3.3 Description of Groundwater Flow System

The hydraulic gradient at and surrounding the field test site was evaluated over time using hydraulic-head triangulation. Figure 3.22 shows the gradient magnitude and direction in August 2007 over an areal extent on the scale of the 100-D Area chromate plume. A series of these figures depicting the gradient magnitude and direction monthly for the period from August 2007 through June 2009 are included in Appendix B. The central triangle in the plume area formed by wells 199-D5-43, -20, and -38 (hereafter, central triangle) was used as the primary indicator of flow in the vicinity of the field test site. Table 3.5 shows the average monthly gradient magnitude and net direction for the central triangle January 2007 through June 2009. Figure 3.23 shows the gradient magnitude and direction for the central triangle plotted with the river stage data over a period of about 2 years. These data show a consistent annual pattern of groundwater flow toward the river for about 10 months and flow for about 2 months which is diverted by high river stages such that flow in the central triangle is more parallel with the direction of river flow.

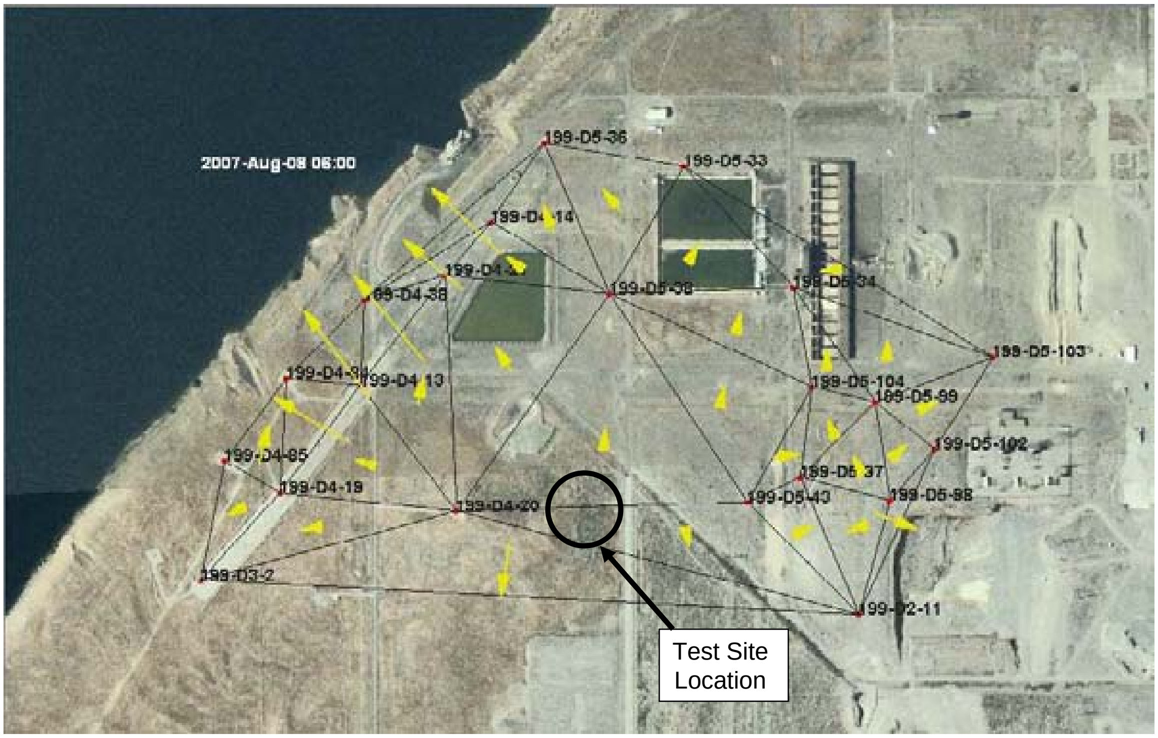


Figure 3.22. Gradient Direction and Relative Magnitude in the 100-D Chromate Plume for August 2007

Groundwater movement through the test area was estimated using the gradient information in Table 3.5 and the hydraulic properties identified for the site (hydraulic conductivity of 27.4 m/day and porosity of 0.14, see Sections 3.1 and 3.2). This analysis estimates that, over a period of about 10 months each year, the groundwater moves toward the river (directional azimuth of between 280^o and 10^o) at a rate of about 38 m/year (125 ft/year). The remainder of the year, the groundwater moves about 8 m/year (26 ft/year) to the northeast, generally parallel with the direction of river flow.

Table 3.5. Groundwater Hydraulic Information for the Monitoring Set of Wells 199-D5-43, 199-D5-20, and 199-D5-38

Time Period	Average Hydraulic Gradient (m/m)	Net Direction (azimuth)	Percentage of Data Missing for the Period	Groundwater Velocity (m/day)[(a)]	Distance in 30 days (m)
July 2007	0.00043	25.3°	0.0	0.0842	2.525
August 2007	0.00041	354.3°	0.0	0.0802	2.407
September 2007	0.00061	315.4°	0.0	0.1194	3.582
October 2007	0.00098	309.8°	0.0	0.1918	5.754
November 2007	0.00090	300.2°	0.0	0.1761	5.284
December 2007	0.00058	291.4°	0.0	0.1135	3.405
January 2008	0.00041	294.3°	0.0	0.0802	2.407
February 2008	0.00044	317.1°	0.0	0.0861	2.583
March 2008	0.00052	313.1°	0.1	0.1018	3.053
April 2008	0.00054	309.9°	0.0	0.1057	3.171
May 2008	0.00034	353.1°	0.0	0.0665	1.996
June 2008	0.00103	76.5°	0.0	0.2016	6.048
July 2008	0.00097	61.0°	0.0	0.1898	5.695
August 2008	0.00072	356.5°	0.0	0.1409	4.227
September 2008	0.00091	324.0°	0.0	0.1781	5.343
October 2008	0.00115	313.1°	0.0	0.2251	6.752
November 2008	0.00103	310.5°	0.0	0.2016	6.048
December 2008	0.00071	313.5°	10.5	0.1390	4.169
January 2009	0.00050	320.2°	26.4	0.0979	2.936
February 2009	0.00045	316.2°	6.2	0.0881	2.642
March 2009	0.00069	304.6°	0.1	0.1350	4.051
April 2009	0.00062	304.7°	0.0	0.1213	3.640
May 2009	0.00026	332.0°	66.4	0.0509	1.527
June 2009	0.00036	74.2°	8.2	0.0705	2.114

(a) Calculated linear velocity using a hydraulic conductivity of 27.4 m/day, the tabulated gradient, and a porosity of 0.14.

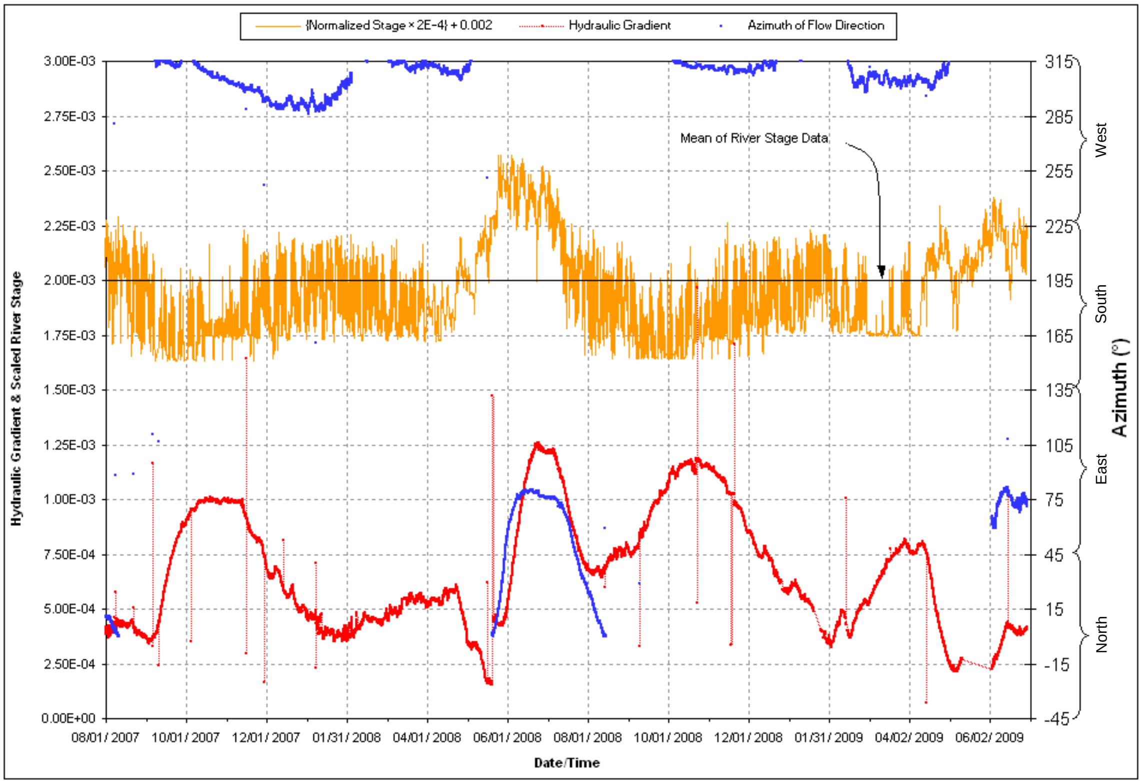


Figure 3.23. Gradient Magnitude and Direction from Triangulation Analysis with Wells 199-D5-43, 199-D5-20, and 199-D5-38 and River Stage Data

4.0 Testing Approach

The treatability test was conducted according to the treatability test plan (Truex et al. 2007). Two test cells were installed at the test site, each consisting of an injection well surrounded by monitoring wells (Figure 4.1). The test cells were located such that existing well 199-D5-40 could be used as an upgradient, unimpacted monitoring location for both test cells. During well installation, sediment samples were collected and used in laboratory microcosm studies to confirm that the substrates induce chromate, nitrate, and dissolved oxygen reduction and for bench-scale studies of emulsion transport. Site characterization information were used to refine the field test design. Field test operations were conducted by injecting the substrate using process water from the 100-D Area pressurized water supply as the carrier solution. The injected water/substrate displaced chromate- and nitrate-contaminated groundwater during the injection. However, this displacement was used to assist in evaluating the longevity of the treatment. Because chromate and nitrate were initially absent in the treatment area, the injection and monitoring locations were used to evaluate the breakthrough of chromate and nitrate at these locations as a means to assess when the reductive capacity was exhausted.

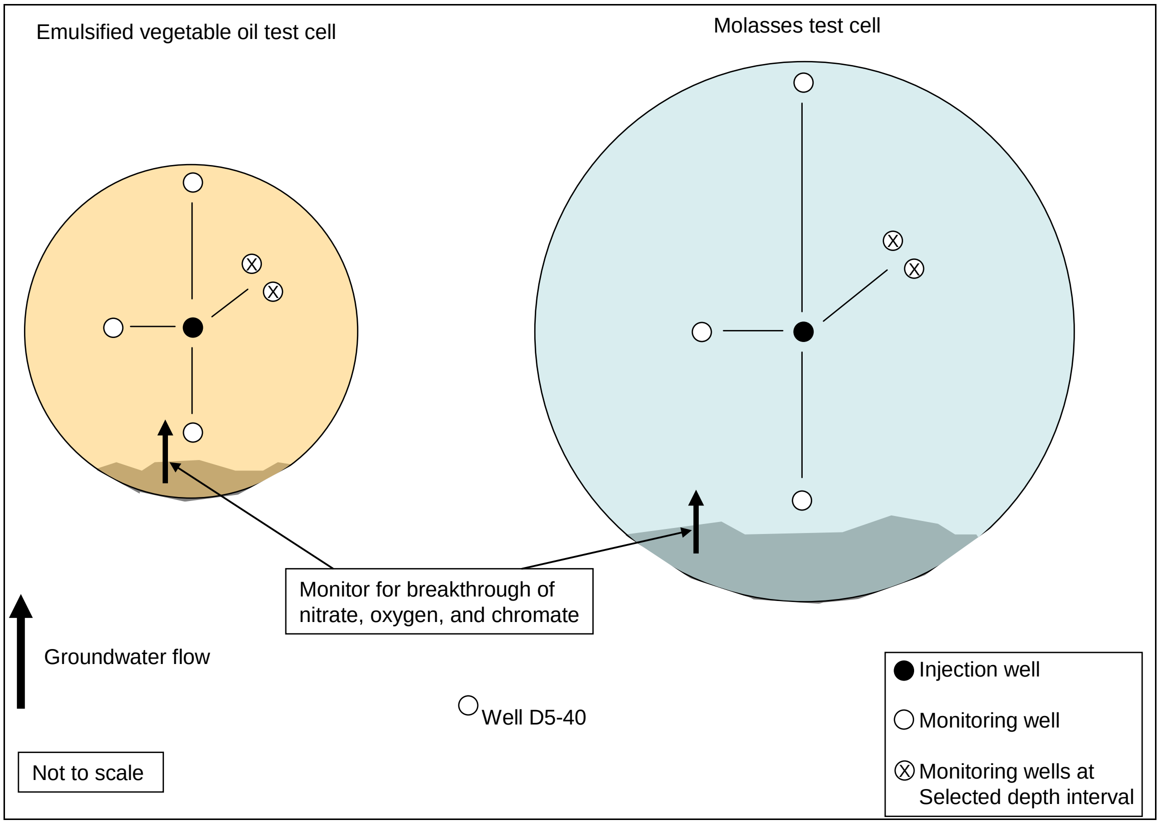


Figure 4.1. Conceptual Layout of Test Cells

This monitoring process is shown conceptually on Figure 4.1. These data address the effectiveness and implementability objectives for the test. Distribution of the substrates was assessed using geophysical methods and through monitoring of groundwater total organic carbon, turbidity, and a conservative tracer at the monitoring locations during and just after injection. These data and the operational aspects of the test address the implementability objectives for the test. The design and operational aspects of conducting the test in conjunction with the performance and distribution data were used to evaluate system scale-up and estimate cost for full-scale application, thereby addressing the cost objective of the test.

Through testing of the two different types of potential substrates (immiscible and soluble), the treatability test was intended to enable evaluation of how each substrate performs under field conditions (e.g., in the presence of field-scale heterogeneities) at the large scale necessary for a biobarrier to provide supplemental treatment upgradient of the ISRM barrier. The following sections summarize the test operations, hydraulic testing approach, data collection and management, and deviations from the test plan.

4.1 Test Operations

4.1.1 Site Layout

The test site is located just south of the 100-D reactor complex. Figure 4.2 and Figure 4.3 show the well layout for the soluble substrate and immiscible substrate tests, respectively. The field site included an exclusion zone during active chemical injection operations where no unauthorized personnel were allowed. The area contained sampling lines, cabling for water level measurement, sampling pump control lines, and the make-up water feed line. The laboratory trailer was located just outside this exclusion zone. The sampling manifold and other sampling equipment were located in the laboratory trailer. All water-level monitoring transducer cabling was routed into this trailer for real-time observations during testing. The process trailer was located in the exclusion zone and contained the water and chemical injection piping and control systems. Two 1,890-L (500-gal) tanks were located outside the exclusion zone for purge water storage.

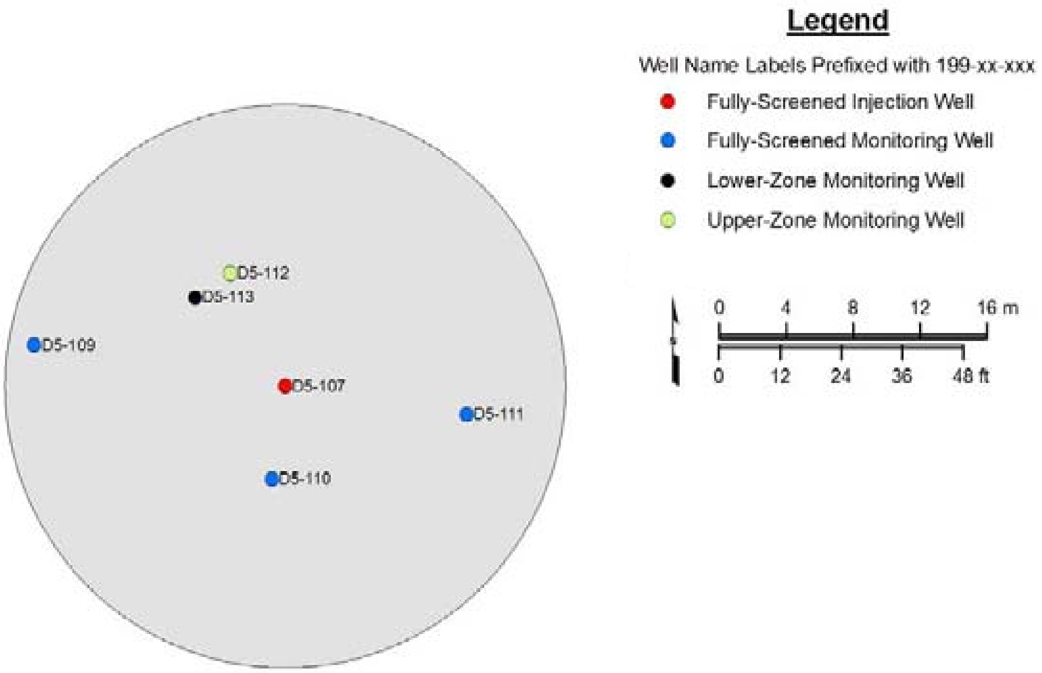


Figure 4.2. Well Layout for the Soluble Substrate Field Test

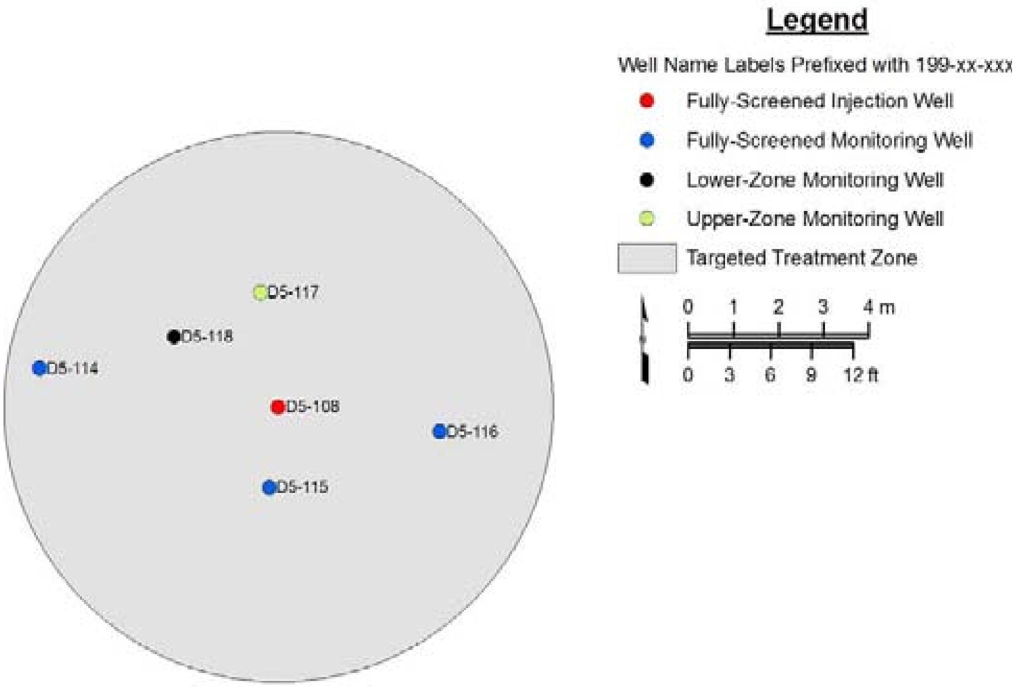


Figure 4.3. Well Layout for the Immiscible Substrate Test

4.1.2 Water Supply

Process water for the injections was obtained from the 100-D Area water supply system. The closest available access point was located approximately 200 m north of the injection site. A backflow preventer was installed to prevent any inadvertent siphoning of injection process water back into the water supply piping system. The water was routed to the test site through 7.6-cm (3-in.) lay-flat hose. The pressure loss through the hose was small enough that the pressurized water supply had sufficient capacity to achieve the specified flow rate.

4.1.3 Injection Equipment

Process water was routed into the injection manifold located inside the process trailer. The injection manifold (Figure 4.4) consisted of 5-cm (2-in.) stainless steel piping, valving, a pump, and flow rate monitoring equipment. For the soluble substrate test, the tracer solution also included a nitrogen nutrient. The manifold was used for diversion/shutoff and flow control of the process water and for dilution of the concentrated feed stock solutions to achieve the desired injection concentrations. The tracer and substrate solutions were fed into the manifold system using a chemical metering pump (Model QD, Fluid Metering, Inc., Syosset, New York) and double-diaphragm pump (Sandpiper, Warren Rupp, Mansfield, Ohio), respectively. Flow rate of the tracer was maintained with manual adjustments as necessary. The substrate feed rate was controlled by manually adjusting the stroke rate of the double diaphragm pump. The feed rate was monitored and recorded using a Campbell CR10X data logger (Campbell Scientific, Logan, Utah). The process water and total solution feed rates were measured with stainless steel turbine flowmeters (FTB-900, Omega Scientific, Stamford, Connecticut) and recorded with a Campbell CR10X data logger. The solution feed rate was also monitored on a qualitative basis using an in-line rotameter (Model 7500, King Instrument Company, Garden Grove, California).

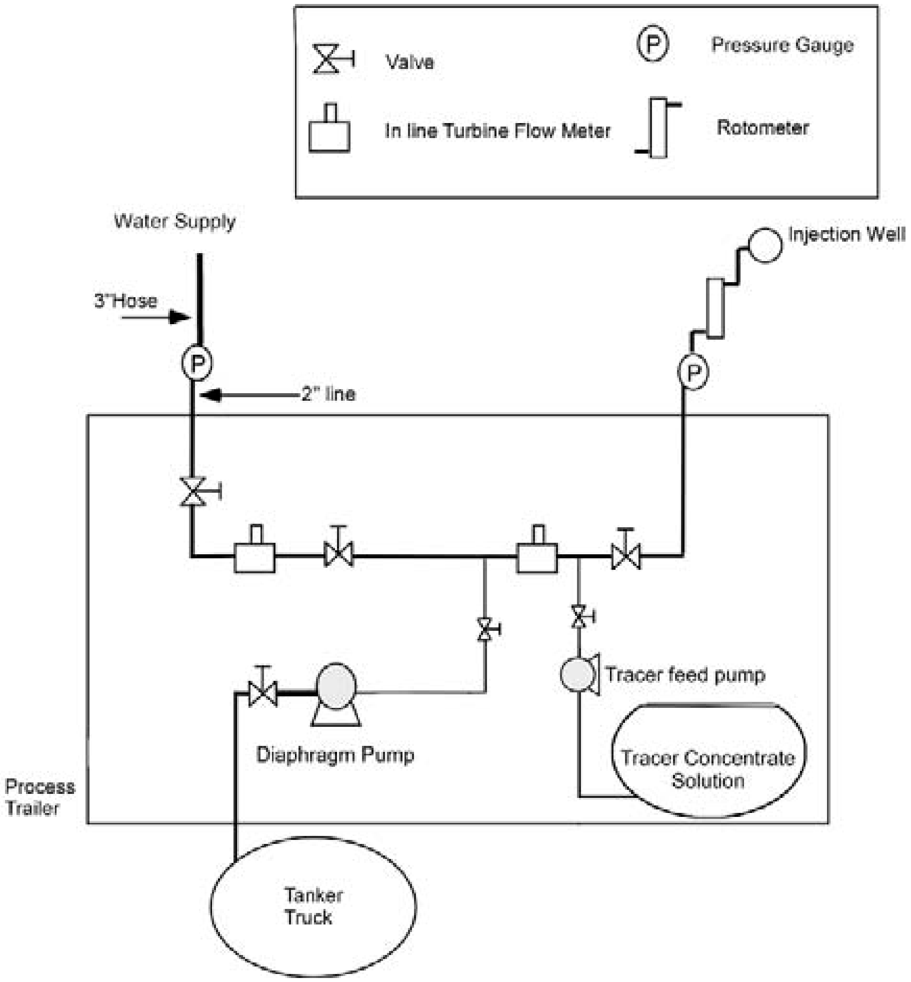


Figure 4.4. Injection Manifold with the Make-Up Water and all Other Necessary Components

Two pressure gauges were located in the system; one at the inlet and one at the outlet of the injection manifold (Figure 4.4). The injection well was outfitted with an injection pipe consisting of 32 m (105 ft) of 5-cm (2-in.) schedule 40 PVC pipe with the bottom section capped. Holes were drilled into the pipe over a 6.1-m (20-ft) interval corresponding to the screened interval of the injection well.

4.1.4 Monitoring Equipment

Dedicated Grundfos Redi-flow2 sampling pumps (Instrumentation Northwest, Kirkland, Washington) capable of providing sample flows rates up to 7.6 L/min (2 gpm) were installed in all site monitoring wells. The sample tubing (0.95-cm [0.375-in.] polyethylene) from each of these sampling pumps was routed inside the laboratory trailer and connected to a sampling manifold. A single variable-frequency power supply (Redi-flo VFD, Instrumentation Northwest) provided power for the sampling pumps. A multichannel interface (pump switchbox) was used to allow a single power supply/controller arrangement to provide power to all sampling pumps.

A sampling manifold was used to collect samples from the various monitoring wells. This approach routes all sample streams into a central manifold for monitoring field parameters (in a flow-through monitoring assembly) and collecting groundwater samples (Figure 4.5). The advantage of this type of system is that all field parameter measurements are made using a single set of electrodes, which improves data quality and comparability of spatially distributed measurements. Consistent labeling between the sampling manifold and pump switch box simplified selection of the well to be sampled and reduced the chance of operator error during the frequent sampling associated with the injection tests. To further help reduce the potential for collecting sample from the wrong well, the pump switch box included a series of low-voltage light-emitting diode indicator lights on the sample manifold. When a pump was turned on, a light came on to indicate which pump was operating and which valve on the manifold should be opened.

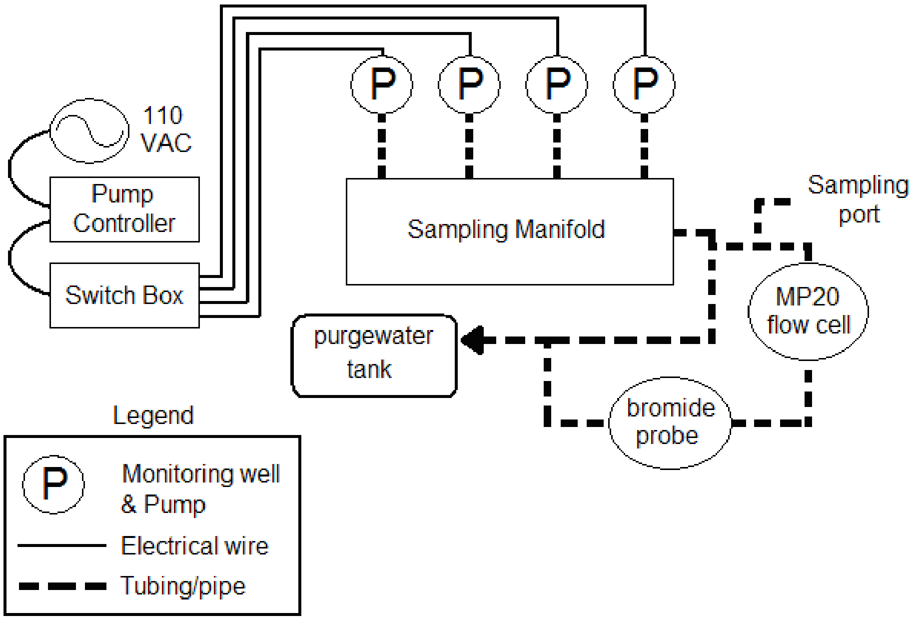


Figure 4.5. Groundwater Sample Acquisition System

Field parameters (specific conductance, temperature, dissolved oxygen, pH, and oxidation reduction potential) were monitored using an MP20 flow cell (QED Environmental Systems, Ann Arbor, Michigan). The flow-through nature of the flow cell assembly minimizes the amount of dead space within the monitoring chamber.

To monitor real-time tracer arrivals, bromide ion selective electrodes (ISE) were used in a flow-through assembly for pumped samples and in selected monitoring wells for downhole measurements. The ISE probe (TempHion, Instrumentation Northwest) was plumbed in series with the MP20 flow cell, providing real-time estimates of bromide concentration in the field. Prior to sampling, it was determined that the housing for the bromide probe required a 3.78-L (1-gal) purge volume for readings to stabilize. ISE measurements were logged using a Campbell Scientific CR10X data logger programmed to record data at a frequency ranging from 5 to 30 minutes.

Purge rates during groundwater sampling were maintained at 3.78 L (1 gal) per minute to minimize drawdown in the monitoring wells and, based on volumetric calculations and field observations, it was determined that a 2-minute purge time was sufficient to ensure adequate purging of the sample lines, manifold, and flow cells. During field operations, flow cell readings generally stabilized in less than 1 minute, indicating that the 2-minute purge time was adequate. The sensors used to measure field parameters during this test meet the specifications shown in Table 4.1.

Table 4.1. Field Parameter Monitoring Electrode Specifications

Parameter	Manufacturer/Model No.	Range	Accuracy
pH	QED/MP20	2 to 12 pH units	±0.2 pH
Oxidation reduction potential	QED/MP20	−999 to 999 mV	±25 mV
Temperature	QED/MP20	5 to 50°C	±0.2°C
Specific conductance	QED/MP20	0 to 100 mS/cm	±1%
Dissolved oxygen	QED/MP20	0 to 50 mg/L	±0.2 mg/L
Bromide	Instrumentation Northwest/ TempHion	Calibrate to specified range	±5% of range

4.1.5 Soluble Substrate Operations

Pretest Monitoring. Before the test injection, hydraulic testing and baseline aqueous sampling were conducted. Hydraulic testing included slug and slug interference testing, electronic borehole flowmeter testing in each fully screened well, and a geophysical survey. Additional pretest monitoring included water-level measurements at test cell wells and other selected locations, to determine hydraulic gradients. Baseline aqueous monitoring included analyses for total organic carbon (TOC), organic acids, nitrate, nitrite, sulfate, chromate, major cations and anions, metals covered by the *Resource Conservation and Recovery Act of 1976* (RCRA), and dissolved oxygen concentration. Baseline monitoring was performed in all test cell monitoring and injection wells and at well 199-D5-40, the upgradient monitoring well.

Substrate Injection. The substrate injection was conducted using process water injected at approximately 40 gpm amended with approximately 40 g/L molasses, 100 mg/L ammonium chloride, and 100 mg/L sodium bromide. Samples of the injected solution and at the test cell monitoring wells were collected periodically during injection and were analyzed for bromide, TOC, organic acids, nitrate, nitrite, sulfate, and chromate. At the end of the substrate injection, process water was injected for approximately an hour to clear the injection system of substrate and flush the wellbore. The decline in hydraulic head at the monitoring locations was monitored after injection flow was terminated to provide data to help evaluate hydraulic properties of the test zone. After the injection was completed, the injection system was disconnected and the injection well was converted to a monitoring location. Details of the sampling schedule are included in Section 4.3.

Process Monitoring. Process monitoring was conducted after injection to assess the formation of a reducing barrier. Samples were collected at each well in the test cell weekly for 8 weeks and analyzed for TOC, organic acids, nitrate, nitrite, sulfate, chromate, oxygen, oxidation reduction potential, bromide, and pH. To assess the impact of the injected solutions, slug tests and additional geophysical surveys were conducted during the process monitoring phase. Details of the sampling schedule are included in Section 4.3.

Performance Monitoring. After the process monitoring phase was completed, the test cell was monitored to assess its performance as a reducing barrier. The goal of this monitoring phase was to evaluate the conditions within the reducing zone and to determine when nitrate, chromate, and oxygen breakthrough occurs as an indication of barrier longevity. This performance monitoring consisted of samples collected periodically for 21 months at each well in the test cell and at the upgradient monitoring well (199-D5-40). Samples were analyzed for TOC, organic acids, bromide, nitrate, nitrite, sulfate, chromate, total chromium, oxygen, oxidation reduction potential, and pH. Additionally, major cations and anions, RCRA metals, and methane were monitored for comparison to the baseline water quality determined in the pretest monitoring. Details of the sampling schedule are included in Section 4.3.

4.1.6 Immiscible Substrate Operations

Pretest Monitoring. Before the test injection, hydraulic testing and baseline aqueous sampling were conducted. Hydraulic testing included slug and slug interference testing, electronic borehole flowmeter testing in each fully screened well, an injection/recovery test, and a geophysical survey. Additional pretest monitoring included water-level measurements at test cell wells and other selected locations, to determine hydraulic gradients. Baseline aqueous monitoring included analyses for TOC, organic acids, nitrate, nitrite, sulfate, chromate, major cations and anions, metals covered by RCRA, and dissolved oxygen concentration. Baseline monitoring was performed in all test cell wells and at well 199-D5-40, the upgradient monitoring well. A short-duration injection test using process water was conducted with monitoring of the pressure buildup and recovery after injection to help estimate the bulk hydraulic properties for the test cell.

Substrate Injection. The substrate injection was conducted over a period of 17 hours using process water injected at approximately 40 gpm amended with approximately 60 g/L emulsion (EOS® 598 product) and 100 mg/L sodium bromide. Emulsion amendment was not continuous during this time but occurred in seven discrete pulses, with a total emulsion injection time of 10.5 hours. Samples of the injected solution and at the test cell monitoring wells were collected periodically during injection and were analyzed for bromide, TOC, nitrate, nitrite, sulfate, and chromate. At the end of the substrate injection, process water was injected for approximately 3 hours to clear the injection system of substrate. After the injection was completed, the injection system was disconnected and the injection well was converted to a monitoring location. Details of the sampling schedule are included in Section 4.3.

Process Monitoring. Reporting for the process monitoring was combined with that for the performance monitoring phase for the immiscible substrate injection because of the similar monitoring frequency.

Performance Monitoring. After injection, the test cell was monitored to assess its performance as a reducing barrier. The goal of this monitoring was to evaluate the conditions within the reducing zone and to determine when nitrate, chromate, and oxygen breakthrough occurs as an indication of barrier longevity. This performance monitoring consisted of samples collected periodically for 10 months at each well in the test cell and at the upgradient monitoring well (199-D5-40). Samples were analyzed for TOC, bromide, nitrate, nitrite, sulfate, chromate, total chromium, oxygen, oxidation reduction potential, and pH. Additionally, major cations and anions, RCRA metals, and methane were monitored for comparison to the baseline water quality determined in the pretest monitoring. To assess the impact of the injected solutions on geohydrologic properties, slug tests and additional geophysical surveys were conducted during the process monitoring phase. Details of the sampling schedule are included in Section 4.3.

4.2 Hydraulic Testing to Evaluate Permeability Changes

Permeability changes due to the injected materials and biomass production were evaluated using slug testing and geophysical testing. The two techniques are described in Sections 4.2.1 and 4.2.2, respectively.

4.2.1 Hydraulic Slug Testing Methods

A series of slug tests was performed in 10 of the 12 wells located within the molasses and emulsified vegetable oil treatment test sites to evaluate changes in aquifer hydraulic properties after bioremediation treatment. The two upper-zone monitoring wells, 199-D5-112 and 199-D5-117, were not tested because they did not contain sufficient water column for slug testing. Baseline slug tests were conducted in August 2007 prior to any injection treatment activities. Post-treatment slug tests were performed in the molasses well cluster in two separate campaigns, once in November 2007 and again in November 2008. In the emulsified vegetable oil well cluster, post-treatment slug testing was performed once in November 2008. The responses from the pre- and post-treatment slug tests were then used to evaluate changes in formation permeability.

4.2.1.1 Well Development

Insufficiently developed wells may have a low-K skin around the screen. This negatively impacts the slug test response, and the K estimate will be biased low. Well development was performed by the drilling contractor in two separate phases using a double-disc surge block. During well completion, surging was performed within 3-m (10-ft) intervals for a minimum of 1 hour per interval, with development considered complete when the filter pack sand had finished settling. Fines pulled into the well during surging were then bailed/pumped out of the wellbore. After well completion, additional surging was performed within the screened interval until minimal fines were detected. The wells were then pumped at flow rates up to 130 L/min (35 gpm) with a submersible pump until turbidity levels were below 5 NTU.

Based on reproducibility in the slug test results, it appears that the wells were sufficiently developed prior to performing the pre-treatment slug tests. Changes in the response between repeat tests can indicate a dynamic skin effect, which is indicative of the need for additional development in the well (Butler 1998). Except for the post-treatment tests in the two injection wells (199-D5-107 and 199-D5-108), no dynamic skins were observed. It should be noted that, although the absence of dynamic skin does provide indication that the well has been developed to the extent possible for stress levels comparable to that provided by the slug tests, it does not provide confirmation that no skin exists.

4.2.1.2 Field Methods

Slug testing was performed using three different slugging rods of known dimensions. The 6-in.-diameter injection wells were slug-tested using 3- and 4.5-in.-OD slugging rods, and the 4-in.-diameter wells were tested with 2- and 3-in.-OD rods. Table 4.2 contains summary information for the different slugging rods used. For each test, the slugging rod was rapidly submerged into the water column within the test well, creating falling-head conditions. Water levels were allowed to recover to static conditions after the slug-injection test. The slugging rod was then rapidly withdrawn from the water column, creating a rising-head test. As time permitted, many of the wells were tested using multiple slugging rods of different volumes, to vary the initial stress level as well as to repeat tests with the same slugging rod. Butler (1998) recommends doing this to identify non-ideal test conditions such as changing effective screen length and dynamic skin effects. In general, the responses were reproducible and independent of magnitude of initial stress.

Table 4.2. Slugging Rod Information

Outside Diameter, in.	Volume, ft^3	Theoretical Initial Stress (H_o^*), ft of H_2O	
		6-in. Well	4-in. Well
2.0	0.13	Not used	1.50
3.0	0.33	1.68	3.77
4.5	0.74	3.77	Not used

Pressure responses were monitored in the stress well and neighboring monitoring wells for each test using sensors (Model PT2X, Instrumentation Northwest, Kirkland, Washington) with ranges of 5 and 15 psig (0.1% accuracy). Manual water-level measurements and depths to bottom for each well were taken at the beginning and end of each day of testing using an “e-tape” instrument traceable to standards established by NIST. It was noted that no wells experienced any significant infilling with fine-grained material as a result of the slug-testing activities, providing further indication that the wells were effectively development prior to slug testing.

4.2.1.3 Wells Screened Across the Water Table

Most of the wells within the test sites are screened across the water table and exhibited associated impacts to the early-time responses. The highly permeable filter pack sand and the surrounding developed zone act as an effectively larger well casing, resulting in an observed initial stress (H_o) that is lower than expected based on the volume of the slugging rod and the nominal well casing radius. In situations such as these, where the filter pack material and surrounding developed zone have a higher K than the undisturbed aquifer material, the slug test response has a characteristic “double straight-line” pattern on a semi-log plot (Bouwer 1989). This type of response is characterized by an initially steeper section of data indicative of the high-K filter pack (inner zone), followed by a flatter formational response in later time (outer zone). An example of this is illustrated in Figure 4.6.

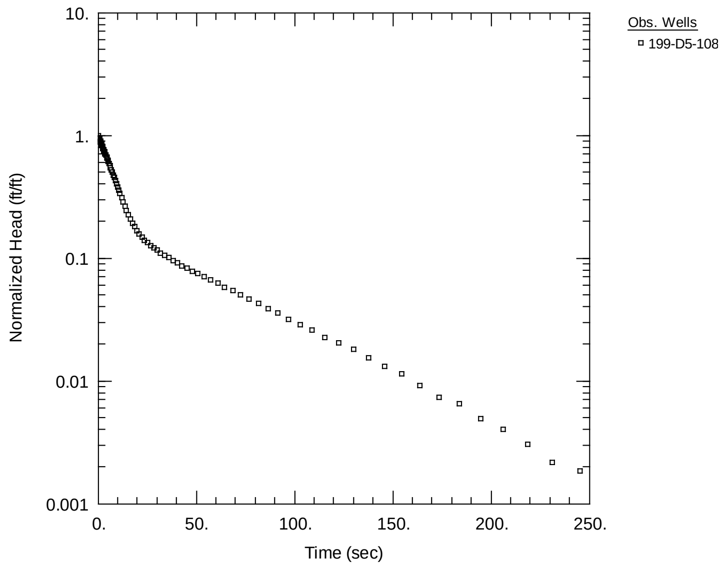


Figure 4.6. Slug Test Response for Well 199-D5-109 (August 2007) Showing an Example of the "Double-Straight Line" Effect (Bouwer 1989) Observed on Semi-Log Plots for Wells Screened Across the Water Table

The combination of being screened across the water table and having a highly permeable filter pack has the effect of increasing the effective radius of the well. This results in the observed initial stress (H_o) being lower than the theoretical initial stress (H_o^*) calculated from the slugging rod volume and nominal well casing radius (r_c). The additional pore volume of the filter pack increases the effective casing volume. Butler (1998) recommends empirically calculating the r_c term for each response with a mass-balance approach:

$$r_e = r_c \sqrt{\frac{H_o^{\ *}}{H_o}} \tag{4.1}$$

For wells screened across the water table, the effective casing radius (r_e) was calculated using Equation (4.1) and used in place of the nominal casing radius (r_c) in the analytical models. The inner and outer zone portions of the slug test responses were analyzed separately by the methods detailed below in an effort to address the heterogeneous responses in wells screened across the water table (Bouwer 1989; Butler 1998; Spane and Newcomer 2008).

4.2.1.4 Analytical Methods

The slug test responses were analyzed with standard methods for estimating aquifer hydraulic properties in unconfined aquifers. Although considerable effort was made in the field to initiate each slug test instantaneously, some of the very early-time ($t \leq 5$ seconds) data required minimal processing prior to analysis due to signal noise or the effects of non-instantaneous slug withdrawal. This involved the translation and projection of time and initial stress (H_o) according to the approach described in Butler (1998).

For wells screened across the water table, the inner/outer zone responses were analyzed using the type-curve model of Hyder et al. (1994), commonly referred to as the KGS model (Butler 1998), as well as the straight-line method of Bouwer and Rice (1976). Both methods are appropriate for over-damped responses such as those observed. Due to its empirical nature and analytical simplicity, the Bouwer and Rice (1976) method is very commonly used. However, the KGS type-curve method avoids some of the weaknesses and limitations inherent in the Bouwer and Rice (1976) method (Butler 1998). Estimates were made using both methods to provide comparison and a range of values, but the results from the KGS model are considered more representative, given the non-ideal test conditions and heterogeneous (inner vs. outer zone) responses associated with being screened across the water table.

The over-damped responses observed in the two lower-zone monitoring wells (199-D5-113 and 199-D5-118) followed a more typical (homogeneous) pattern because they were not screened across the water table. For these two wells, the entire response was fit by a single straight line (Bouwer and Rice) or curve (KGS model) rather than separate inner/outer zone analyses.

Slug-test responses in well 199-D5-109 showed very rapid responses (recovery in less than a few seconds) that were critically damped. Critically damped responses are identified by a characteristic concave-downward pattern on a semi-log plot (Butler 1998). In critically damped responses, the initial portion of the data is affected by inertial effects of the water column as water flows rapidly into the well bore from a highly permeable formation. Using the Bouwer and Rice and KGS methods on critically damped responses can lead to incorrect K estimates. Accordingly, these responses were analyzed also using the Springer and Gelhar (1991) high-K variant of the Bouwer and Rice method in which the inertial effects of water are addressed.

Slug tests impart a more localized stress to the aquifer than other larger-scale hydraulic characterization methods such as tracer and constant-rate pumping tests. Near-well conditions have a large influence on slug test responses, as mentioned earlier. For this and other reasons (e.g., anisotropy and heterogeneity) K estimates from slug tests should be considered “lower bound” (Butler 1998) K estimates for the formation. Results from the constant-rate pumping test conducted in August 2008 are more representative of the large-scale aquifer at the site. However, pre- and post-treatment slug testing using consistent field and analytical methods provides an assessment tool for evaluating potential changes in permeability within the treatment zone.

All slug test responses were analyzed using the aquifer testing analysis software package AQTESOLV (HydroSOLVE, Inc.).

4.2.2 Geophysical Testing Methods

Time-lapse geophysical data sets have the potential to provide information about the distribution of amendments injected into the subsurface for remediation purposes. The ability to geophysically distinguish pore fluid replacement by an injected amendment at the field scale is a function of many factors, including the geophysical contrast between the pore fluid and the injected amendment, the additional impact on the geophysical signature by biogeochemical transformations that occur as a response to the biostimulation, and scaling factors. Through linking laboratory and field-scale investigations, Hubbard et al. (2008) illustrated the potential of time-lapse geophysical methods for imaging the spatiotemporal distribution of an injected polylactate as well as remediation-induced biogeochemical transformations at the Cr(VI)-contaminated Hanford 100-H site.

Laboratory and field experiments have been performed at the Hanford 100-D site to determine the utility of geophysical methods for assessing 1) the effective radius and 2) the uniformity of the injected soluble substrate (molasses) and immiscible substrate (emulsified vegetable oil). In addition to addressing the objectives of the project, the study also focused on identifying which geophysical method (or suite of methods) was most useful for imaging the two different amendments.

A very brief background of the different geophysical methods that were used for this study and petrophysical relationships that can be used to interpret geophysical measurements in terms of amendment distribution is provided in Appendix C. The following paragraphs briefly review the geophysical methods as well as laboratory and field experimental approaches that were employed for the treatability test.

4.2.2.1 Laboratory Experiments

The laboratory experiments consisted of obtaining seismic, radar, and complex electrical measurements of the individual fluid components (water and amendments) as well as performing flow-through column experiments wherein bioremediation was induced via introduction of the different amendments in saturated sediments. Although the primary objective was to document the geophysical signature of the initial phase of the experiment—the pore water replacement with the amendment—the geophysical signatures at later times were also recorded to assess if subsequent biogeochemical reactions are also likely to influence the geophysical signatures.

The experimental electrical conductivity fluid component measurements for the treatability test were (in microsiemens per meter) groundwater ~ 22, molasses = 246, and vegetable oil = 30.4. The experimental dielectric constant values for the fluid components were groundwater = 80, molasses = 79.7, and vegetable oil = 3. These batch measurements suggest that pore water replacement by vegetable oil should be detectable using radar time-lapse methods, and that electrical methods should be able to track the pore water replacement of both molasses and vegetable oil, with the molasses providing the most significant contrast.

The molasses and vegetable oil flow-through column biostimulation experiments were conducted over approximately 1 month using acrylic columns. For each experiment, separate columns were instrumented with different types of sensors for making radar, seismic, and complex electrical measurements (Figure 4.7). The columns were carefully packed using sieved, predominantly quartz sand sediments that had been recently retrieved from the Ringold Formation in the 100-Area. Microbial inoculation was not performed; instead, the biostimulation experiments relied on the ability of the attached community to utilize the introduced substrate. To circumvent environmental health and safety issues associated with using Cr(VI)-contaminated groundwater from the 100-D site for the column experiments, a synthetic groundwater was made using a recipe that replicated the Hanford 100-D geochemistry less the Cr(VI).

The synthetic groundwater was introduced from the same influent vessel to the base of all columns. To facilitate comparison between the geophysical signatures over time in these different-width columns, the flow rates during the vegetable oil experiment were adjusted so that the pore water velocities would be similar to each other and to flow rates at the Hanford 100-D site. A rate of 0.034 mL/min was used for the wider time domain reflectometry (TDR) column; a flow rate of 0.765 mL/min was used for the other smaller-diameter columns (electrical, seismic, and geochemical).

Figure 4.7. Geophysical Measurement Columns Used in the Laboratory Experiments. Left: complex resistivity, four-electrode column. Middle: seismic column. Right: time domain reflectometry column.

After the columns were flushed for several days with the synthetic groundwater, store-bought molasses and ammonium (60 mg/L) were injected into the columns intended for testing the geophysical response of the miscible substrate. Ammonium was added as a readily available supply of nitrogen for cell growth (and, once oxidized to NO_3, to mimic the concentration in the 100-D groundwater). Molasses injection proceeded for 5 days, followed by continuous flushing with synthetic groundwater for almost 2 months.

Synthetic groundwater was also flushed through the columns intended for testing the geophysical response to the vegetable oil. Flushing occurred for several days, followed by introduction of the EOS 598 emulsion, which proceeded for 12 days. Continuous flushing with synthetic groundwater proceeded after the amendment introduction for almost 2 months. For the molasses and vegetable oil column experiments, effluent samples were analyzed for organic carbon, chloride, nitrate, and sulfate at 1- to 2-day intervals during the initiation of the experiments and less frequently thereafter. The molasses effluent samples were also assessed for bromide concentrations. Total organic carbon was measured as acetate using an ion chromatograph, and anions were measured using ion chromotography.

Geophysical measurements were made before, during, and after amendment introduction. Electrical conductivity measurements were made using a YSI Model 35 conductance meter, dielectric constant measurements were made using a Trase TDR system with 8-cm prongs, and seismic measurements were made using two fluid-coupled 1,000-kHz piezoelectric transducers at three locations along the column length. The column geophysical measurements were interpreted to obtain estimates of geophysical attributes as a function of time relative to amendment injection. The TDR waveform amplitudes were analyzed using the tangent method to estimate dielectric constant. Seismic velocity and amplitudes were determined for each of the three locations using the first arrival time and the maximum peak-to-peak voltage surrounding that first arrival, respectively, following Peterson et al. (1985). Electrical phase, imaginary conductivity, and real conductivity measurements were assessed over the acquisition frequency range. These measurements were subsequently interpreted in terms of Cole-Cole parameters of chargeability and time constant, following the stochastic method given by Chen et al. (2008).

Geochemical analyses of aqueous effluent samples are shown in Figure 4.8; the geophysical attributes associated with the molasses flow-through experiments are shown in Figure 4.9. On all graphs, the shaded region indicates the duration of the molasses injection. Comparison of the organic carbon and bromide measurements suggested that the molasses remained in the column slightly longer than the conservative tracer. Analysis of the geophysical signatures suggested that

- Electrical conductivity is significantly increased and tracks the organic carbon.
- The Cole-Cole electrical parameters (tau and chargeability) indicate the leading and trailing edges of the injectate 'plume.'
- The molasses severely attenuates the seismic amplitudes.

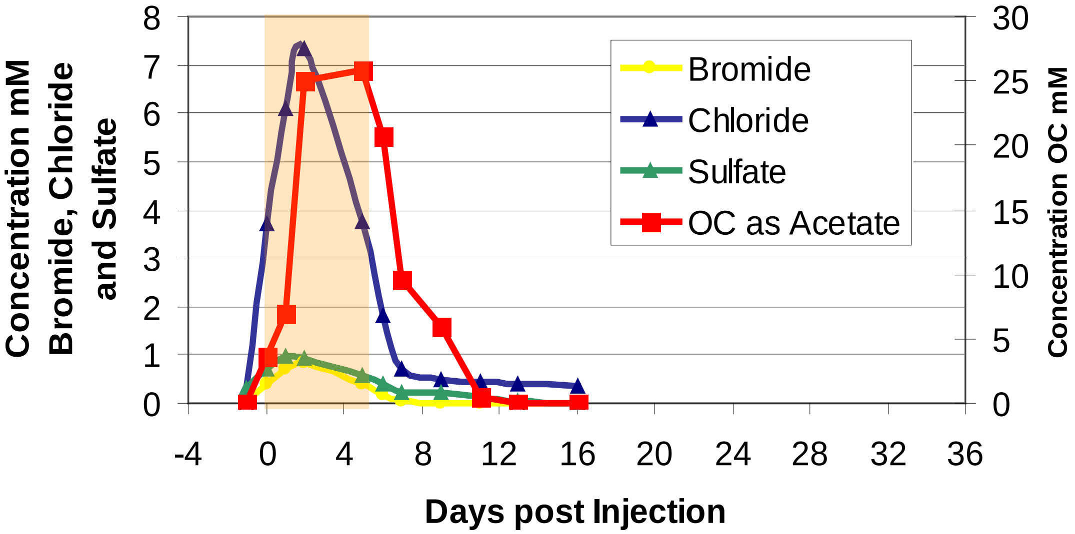


Figure 4.8. Geochemical Analysis of Effluent Fluid Samples from the Molasses Experimental Column Study. The shaded region represents the duration of the molasses injection. The large chloride spike is associated with the store-bought molasses. Comparison of the bromide and organic carbon signatures suggest that the residence time of the molasses in the system is just slightly longer than that of the conservative tracer.

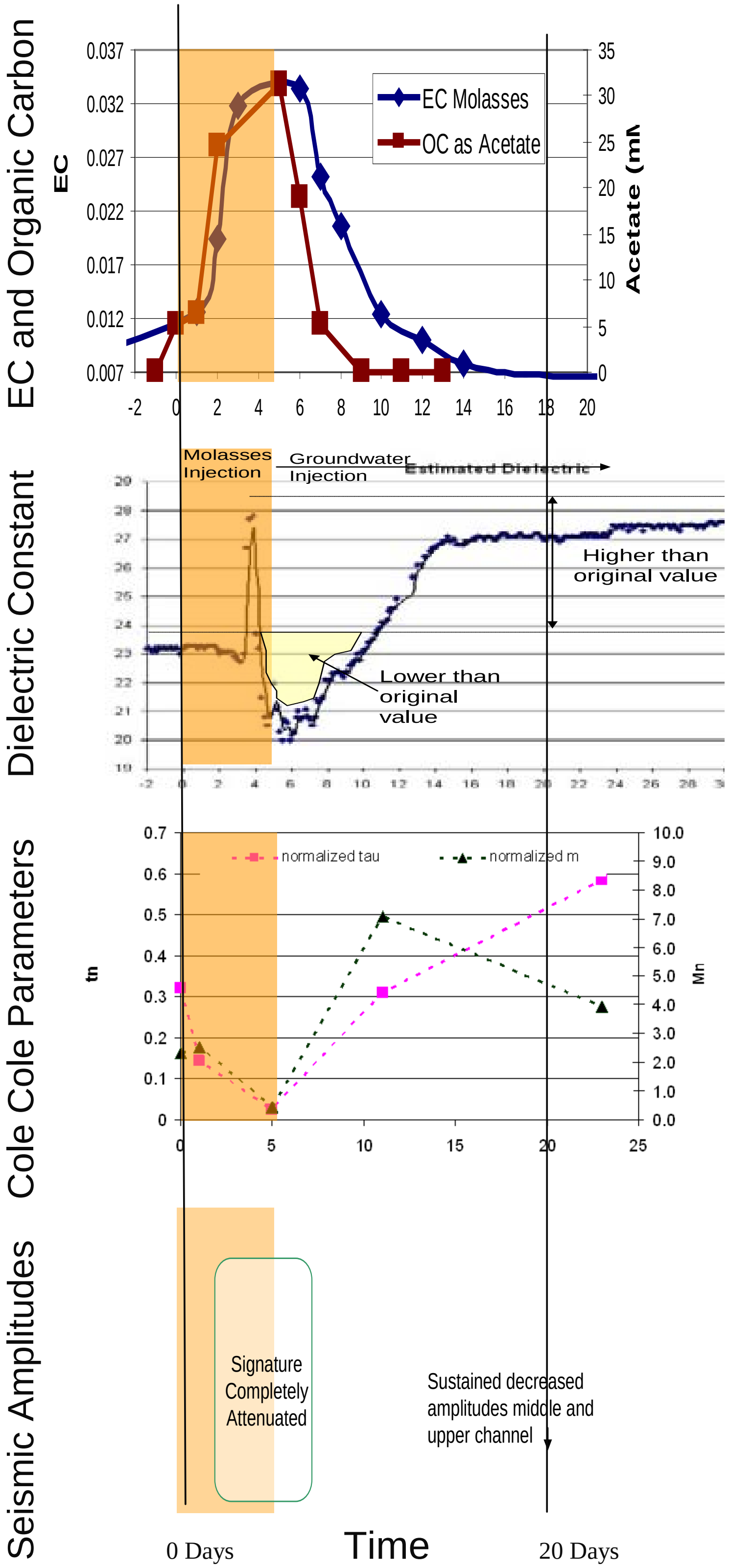


Figure 4.9. Geophysical Responses Associated with Molasses Flow-Through Biostimulation Column Experiment

The dielectric constant changes after the molasses is almost through the system: it initially increases, then decreases, and then increases again to ~20% higher than baseline. Because the dielectric constant of the molasses (79) is very similar to that of water (80), and because the changes occur after the amendment has passed through the system, the dielectric changes are interpreted as a response to remediation-induced biogeochemical transformations rather than the pore fluid replacement with the amendment. In particular, we interpret the decrease to be due to the formation of nitrogen/CO_2 gas bubbles (which were visible during the laboratory experiment). The increase in dielectric constant at later times could be caused by an increased grain dielectric constant or to enhanced porosity (refer to Appendix C).

These laboratory experiments suggest that the electrical methods should provide excellent information about the molasses distribution, and that the presence of the amendment should severely attenuate the seismic signature. Although time-lapse radar methods are not expected to be able to track the amendment, they should respond to subsequent biogeochemical transformations.

Geochemical and geophysical analyses of the vegetable oil column experiments are shown in Figure 4.10. The shaded portion indicates the period during which vegetable oil was introduced into the flow-through column; the saturating fluid during other times is the synthetic groundwater. Different from the miscible amendment, some of the largest geophysical responses lag in time behind the amendment pulse, suggesting that some of the amendment remains in the system, as would be expected. Analysis of the geophysical responses suggests that the pore fluid replacement by the vegetable oil leads to

- a decrease in electrical conductivity
- a change in Cole-Cole parameters, including a sustained increase in normalized tau and decrease in normalized chargeability after vegetable oil was introduced
- a decrease in seismic velocity
- an initial increase in dielectric constant and then an approximately 11% decrease in dielectric constant in later times as groundwater (k = 80) was replaced by vegetable oil (k ~ 3).

These experiments suggest that all three geophysical methods should provide information about the vegetable oil distribution.

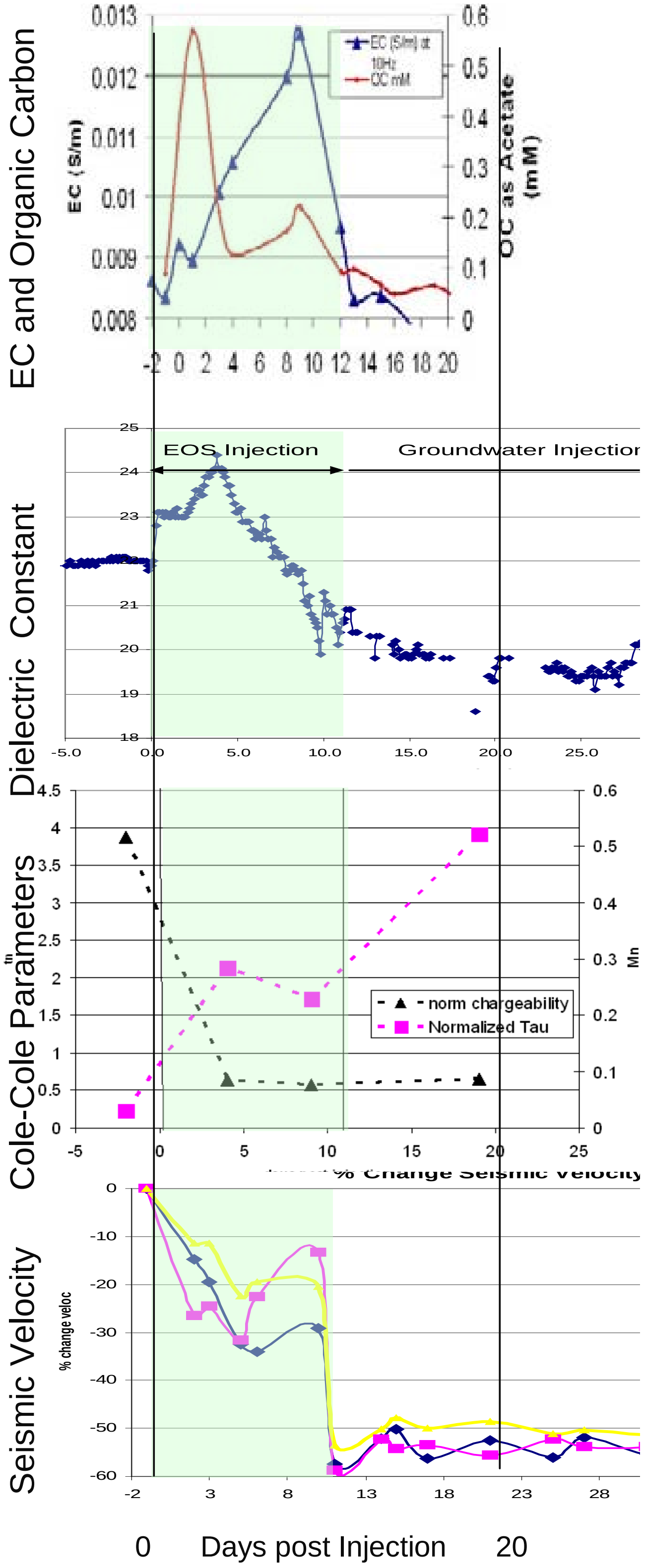


Figure 4.10. Results of Vegetable Oil Biostimulation Flow-Through Column Experiments. The green shaded area indicates the duration of the vegetable oil injection into the column.

4.2.2.2 Field Data Acquisition and Inversion

Tomographic ground-penetrating radar (GPR), electrical time domain reflectometer (TDR), and seismic data were collected between several of the monitoring wellbores at both the miscible and immiscible test cells following the acquisition schedules shown in Table 4.3 and Table 4.4.

Table 4.3. Tomographic Data Acquisition Schedule, Molasses Field Experiment

Date	Well Pair	GPR	Seismic	ERT	Comments
5-Sep-07	111-107	X	X		ERT failed
‘Baseline’	110-107	X	X		
	109-107	X	X		
	113-107	X	X		
	113-110	X	X		
	109-113	X	X		
	111-110	X	X		
26-Sept-07	**Mol. Injection Initiated**				
10-Oct-07	109-113	X	X		Seismic attenuated
	All Others	X	X		GPR & seismic attenuated
13-Nov-07	113-107	X	X		Seismic attenuated
	109-113	X	X		Seismic attenuated
	All Others	X	X		GPR & seismic attenuated
25-Apr-08	113-107	X	X		Seismic attenuated
	109-113	X	X		Seismic attenuated
	All Others	X	X		GPR & seismic attenuated
20-Aug-08	109-113	X	X		Seismic attenuated
	All Others	X	X		GPR & seismic attenuated
5-May-09	113-107	X	X		Seismic attenuated
	109-113	X	X		Seismic attenuated
	110-107	X	X		Seismic attenuated
	All Others	X	X		GPR & seismic attenuated

Radar tomographic data were collected using a PulseEKKO 100 system, with 100-MHz central frequency antennas and a transmitter and receiver spacing of 0.125 m in the wellbores. Radar data were collected from several meters above the water table through the saturated intervals. Radar travel time and amplitude picking, pre-inversion quality control steps, and inversion procedures were performed following Peterson (2001). The changes in radar attributes as a function of time were determined by inverting the differences in the travel times and amplitudes between the baseline and subsequent data sets instead of differencing the inverted velocity or attenuation values. This approach tends to minimize error associated with borehole and station effects and also may minimize mathematical error because only one inversion procedure is performed. Estimates of radar velocity (and changes in velocity) were converted to dielectric constant estimates as described in Appendix C.

Seismic tomographic data were collected in only the saturated section using a Geometrics Geode seismic system, an LBNL piezoelectric source, and an ITI hydrophone sensor string that was lowered down the wellbores. The central frequency of the pulse was 4000 Hz with a bandwidth from approximately 1000 to 7000 Hz. The source and geophone spacing in the wellbores was 0.125 m. Travel times and associated amplitudes were picked for all source–receiver pairs and inverted for seismic velocity and amplitude (or associated changes) using a 0.25-m by 0.25-m discretization, following Peterson et al. (1985).

Table 4.4. Tomographic Data Acquisition Schedule, Vegetable Oil Field Experiment

Date	Well Pair	GPR	Seismic	ERT	Comments
5-Sep-07	114-108	X	X		
	116-108	X	X		
	118-115	X	X		
	118-116	X	X		
	115-114	X	X		
	115-116	X	X		
	115-108	X	X		
10-Oct-07	118-115	X			
14-Nov-07	114-108		X		
	116-108		X		
	118-108		X		
	118-115	X	X		
	118-116		X		
	115-114		X		
	115-116		X		
	118-114		X		
	115-108		X		
18-Aug-08	118-115	X	X	X	Considered as
	118-116	X	X	X	Baseline
	115-114	X	X	X	Measurements
	115-116	X	X	X	
	118-114	X	X	X	
	116-114	X	X	X	
20-Aug-08	**Vegetable Oil Injected**				
22-Aug-08	118-115	X	X	X	
	118-116	X	X	X	
	115-114	X	X	X	
	115-116	X	X	X	
	118-114	X	X	X	
	116-114	X	X	X	
25-Aug-08	118-115	X	X	X	
	118-116	X	X	X	
	115-114	X	X	X	GPR failed
	115-116	X	X	X	GPR failed
	118-114	X	X	X	
	116-114	X	X	X	GPR failed
19-Nov-08	118-115	X	X	X	
	118-116	X	X	X	Seismic attenuated
	115-114	X	X	X	
	115-116	X	X	X	
	118-114	X	X	X	Seismic attenuated
	116-114	X	X	X	Seismic attenuated
6-May-09	118-115	X	X	X	Seismic attenuated
	118-116	X	X	X	Seismic attenuated
	115-114	X	X	X	Seismic attenuated
	115-116	X	X	X	Seismic attenuated
	118-114	X	X	X	Seismic attenuated
	116-114	X	X	X	Seismic attenuated

Electrical data were collected using an MPT/ERT2004 system (Multi-Phase Technologies, LLC, Sparks, Nevada) using 15 electrodes per well, each separated by 0.4 m. Inversions were performed using EarthImager software (Advanced Geosciences, Inc., Austin, Texas) to yield estimates of electrical conductivity.

Results of the field investigation are reported along with the other field data in Sections 5 (soluble substrate) and 6 (immiscible substrate).

4.3 Test Data Collection and Management

Data were collected during the injection, process monitoring, and performance monitoring phases of the field test according to the treatability test plan (Truex et al. 2007). Specific sampling dates and analytes are listed in Table 4.5 (soluble substrate) and Table 4.6 (immiscible substrate). There were no data quality issues that impacted interpretation of the results as presented in this report. Appendix D lists the field test data and data validation reports to support the results reported herein.

Table 4.5. Summary of Sampling for the Soluble Substrate Test

Testing Phase	Sample Date	Analytes
Pre-test	09/10/07	A,C,M,O,T
Pre-test	09/17/07	A,C,M,O,T
Pre-test	09/25/07	A,C,M,O,T
Injection	09/26/07	A,B,T (multiple events)
Injection	09/27/07	A,B,T (multiple events)
Injection	09/28/07	A,B,T (multiple events)
Injection	09/29/07	A,B,T (multiple events)
Process monitoring	10/03/07	A,B,C,O,T
Process monitoring	10/09/07	A,B,C,O,T
Process monitoring	10/17/07	A,B,C,O,T
Process monitoring	10/24/07	A,B,C,O,T
Process monitoring	10/31/07	A,B,C,O,T
Process monitoring	11/08/07	A,B,C,O,T
Process monitoring	11/15/07	A,B,C,O,T
Process monitoring	11/20/07	A,B,C,O,T
Process monitoring	11/28/07	A,B,C,O,T
Performance monitoring	12/05/07	A,C,M,Me,O,T
Performance monitoring	12/18/07	A,C,M,Me,O,T
Performance monitoring	01/08/08	A,C,M,Me,O,T
Performance monitoring	01/30/08	A,C,M,Me,O,T
Performance monitoring	02/13/08	A,C,M,Me,O,T
Performance monitoring	02/27/08	A,C,M,Me,O,T
Performance monitoring	03/19/08	A,C,M,Me,O,T
Performance monitoring	04/15/08	A,C,M,Me,O,T
Performance monitoring	05/13/08	A,C,M,Me,O,T
Performance monitoring	07/09/08	A,C,M,Me,O,T
Performance monitoring	09/18/08	A,C,M,Me,O,T
Performance monitoring	01/07/09	A,C,M,Me,O,T
Performance monitoring	03/11/09	A,C,M,Me,O,T
Performance monitoring	06/22/09	A,C,M,Me,O,T

A = anions, B = bromide, C = hexavalent chromium, M = metals, Me = methane, O = organic acids, T = total organic carbon.

Field parameters were collected at all sample events.

Note: There are some differences in sampling at individual wells; see Appendix D for full details.

Table 4.6. Summary of Sampling for the Immiscible Substrate Test

Testing Phase	Sample Date	Analytes
Pre-Test	08/05/08	A,B,C,T
Pre-Test	08/12/08	A,B,C,T
Injection	08/20/08	A,B,T
Injection	08/21/08	A,B,T
Performance monitoring	09/08/08	A,B,C,M,O,T
Performance monitoring	10/10/08	A,B,C,M,O,T
Performance monitoring	12/19/08	A,B,C,M,O,T
Performance monitoring	03/11/09	A,B,C,M,O,T
Performance monitoring	06/22/09	A,B,C,M,O,T

A = anions, B = bromide, C = hexavalent chromium, M = metals, Me= methane, O = organic acids, T = total organic carbon.

Field parameters were collected at all sample events.

Note: There are some differences in sampling at individual wells; see Appendix D for full details.

4.4 Deviations from the Treatability Test Plan

The treatability test plan includes provisions for a final test design phase with corresponding laboratory experimentation. Thus, there are minor difference between the treatability test plan and the final test implementation because the field design was refined based on characterization information collected at the field test site and from laboratory study results. Minor adjustments were made to the sampling schedule outlined in the treatability test plan in response to observed response and based on analyses conducted as part of the final design effort for the test. Performance of the immiscible substrate test was delayed by 1 year to accommodate additional time for test design and the corresponding laboratory tests for emulsion injection. In particular for the immiscible substrate test, sampling frequencies were reduced based on the anticipation of slower temporal changes in parameters. Additionally, some analytes were mistakenly missed, notably the baseline samples for the immiscible substrate test cell. Table 4.7 summarizes the differences between the planned and actual sampling and analysis schedule.

Table 4.7. Comparison of Actual and Planned Sampling

Parameter	Monitoring Phase	Test Plan Sampling Frequency	Actual Sampling	
			Soluble Substrate	Immiscible Substrate
Major cations: Al, As, B, Ba, Bi, Ca, Co, Fe, K, Mg, Mn, Ni, Zn, Zr, P, Sr, Na, Si, S, Sb	Pretest monitoring	1, 2, and 3 weeks before injection	Same	None
	Performance monitoring	1, 6, and 12 months after injection	More sampling events	More sampling events
RCRA/Trace metals: Cr, Cu, As, Se, Mo, Ag, Cd, Pb, ^{238}U	Pretest monitoring	1, 2, and 3 weeks before injection	Same	None
	Performance monitoring	1, 6, and 12 months after injection	More sampling events	More sampling events
Anions: Cl^-, PO_4^{3-}	Pretest monitoring	1, 2, and 3 weeks before injection	Same	None
	Performance monitoring	1, 6, and 12 months after injection	More sampling events	More sampling events
Methane	Performance monitoring	1, 6, and 12 months after injection	More sampling events	None
Total organic carbon	Pretest monitoring	1, 2, and 3 weeks before injection	Same	Only 2 events
	Substrate injection	Every 4 hours in injection line (soluble), every 2 hours in injection line (immiscible), every 4 hours starting 8 hours before expected arrival at monitoring wells (soluble), every 2 hours starting 4 hours before expected arrival at monitoring wells (immiscible)	Comparable	Only at end
	Process monitoring	Weekly for 8 weeks after injection	Same	Less frequent
	Performance monitoring	Twice per month after end of process monitoring stage	Sampling frequency reduced to enable sampling over a longer total duration	Less frequent
NO_2^-, NO_3^-, SO_4^{2-}	Pretest monitoring	1, 2, and 3 weeks before injection	Same	Only 2 events
	Substrate injection	Every 4 hours in injection line (soluble), every 2 hours in injection line (immiscible), every 4 hours starting 8 hours before expected arrival at monitoring wells (soluble), every 2 hours starting 4 hours before expected arrival at monitoring wells (immiscible)	Comparable	Comparable
	Process monitoring	Weekly for 8 weeks after injection	Same	Less frequent
	Performance monitoring	Twice per month after end of process monitoring stage	Sampling frequency reduced to enable sampling over a longer total duration	Less frequent

Table 4.7. (contd)

Parameter	Monitoring Phase	Test Plan Sampling Frequency	Actual Sampling	
			Soluble Substrate	Immiscible Substrate
Cr^{+6}	Pretest monitoring	1, 2, and 3 weeks before injection	Same	Only 2 events
	Substrate injection	Every 4 hours in injection line (soluble), every 2 hours in injection line (immiscible), every 4 hours starting 8 hours before expected arrival at monitoring wells (soluble), every 2 hours starting 4 hours before expected arrival at monitoring wells (immiscible)	Comparable	Comparable
	Process monitoring	Weekly for 8 weeks after injection	Same	Less frequent
	Performance monitoring	Twice per month after end of process monitoring stage	Sampling frequency reduced to enable sampling over a longer total duration	Less frequent
Bromide	Pretest monitoring	1, 2, and 3 weeks before injection	Same	Only 2 events
	Substrate injection	Every 4 hours in injection line (soluble), every 2 hours in injection line (immiscible), every 4 hours starting 8 hours before expected arrival at monitoring wells (soluble), every 2 hours starting 4 hours before expected arrival at monitoring wells (immiscible)	Comparable	Comparable
	Process monitoring	Weekly for 8 weeks after injection	Same	Less frequent
	Performance monitoring	Twice per month after end of process monitoring stage	Sampling frequency reduced to enable sampling over a longer total duration	Less frequent
Organic Acids	Pretest monitoring	1, 2, and 3 weeks before injection	Same	None
	Substrate injection	End of substrate injection	Same	Same
	Process monitoring	Weekly for 8 weeks after injection	Same	Less frequent
	Performance monitoring	Twice per month after end of process monitoring stage	Sampling frequency reduced to enable sampling over a longer total duration	Less frequent

5.0 Results for the Soluble Substrate Test

Results for the field test are presented for the injection, process monitoring, and performance monitoring phases of the test in the following sections. The supporting laboratory test results are also summarized. The overall results are then presented and discussed with respect to each of the test objectives.

5.1 Injection Description and Results

The concept for the substrate injection process was to obtain an injection radius of about 15 m (50 ft) with a uniform molasses concentration of about 40 g/L. Process water was used as the carrier medium for the substrate. An injection flow rate was selected so the substrate would be delivered over a period of about 3 days. This injection period minimized the possibility of accumulating excessive biomass near the injection well during the injection process. Laboratory tests showed that the lag time before significant microbial growth occurred was on the order of 5 days. A tracer was injected with the substrate to help identify the injection front and for subsequent monitoring of injection solution elution from the test zone.

The injection pressures monitored within the injection wellbore during substrate injection were higher than anticipated based on the observed pressure response during developmental pumping and an initial injection test using only water. The viscosity of the injected solution was 1.5 to 2 cP. Thus, only a small increase in the injection pressure was the result of the somewhat higher viscosity of the molasses-water mixture. It is likely the largest percentage of the increase resulted from incomplete dissolution of the concentrated molasses feed stock that may have initially caused temporary plugging in the injection well. During the first 24 hours of the test, the molasses feed was periodically stopped for short periods of time to allow process water only to pass through the well screen. Each time this operation was performed, injection pressures quickly decreased to below critical levels (i.e., pressures had built up to the point where water in the well bore was near ground surface) and a sustained reduction in injection pressure was realized. This response is consistent with the hypothesis that a film of molasses had accumulated in the screen openings, and potentially further out into the filter pack, thus increasing the pressure drop across this near-well zone. Injecting process water would dissolve any molasses accumulation on the screen. After about 24 hours of injection, the injection pressures stabilized (Figure 5.1), and the injection flow rate could be more readily maintained (Figure 5.2).

After injection was terminated, water levels did not begin recovering toward static conditions for about 25 minutes. A representative recovery response for the observation wells, as seen in well 199-D5-110, is shown in Figure 5.3. The late-time pressure response is about three times lower than predicted (solid blue type curve in Figure 5.3). This delay in pressure recovery is likely associated with recharge of an unknown volume of molasses solution that leaked into the overlying, more permeable Hanford formation during the injection period. Pressures reached as high as 35 psi (80 ft of water buildup) in the injection well during molasses injection. These relatively high pressures could have compromised the bentonite seal and formed preferential vertical pathways along the borehole/filter pack interface, allowing a portion of the injection stream to leak up through the annular space into the more permeable Hanford formation sediments. This volume of water would have drained vertically following the termination of the test, causing the observed delay in recovery to pre-test static conditions – analogous to well-bore storage effects, but on a larger scale and less predictable. The magnitude of this effect was not significant enough to prevent distribution of the molasses in the test cell and subsequent functioning as a permeable reactive barrier. However, the effect should be considered when applying this technology elsewhere.

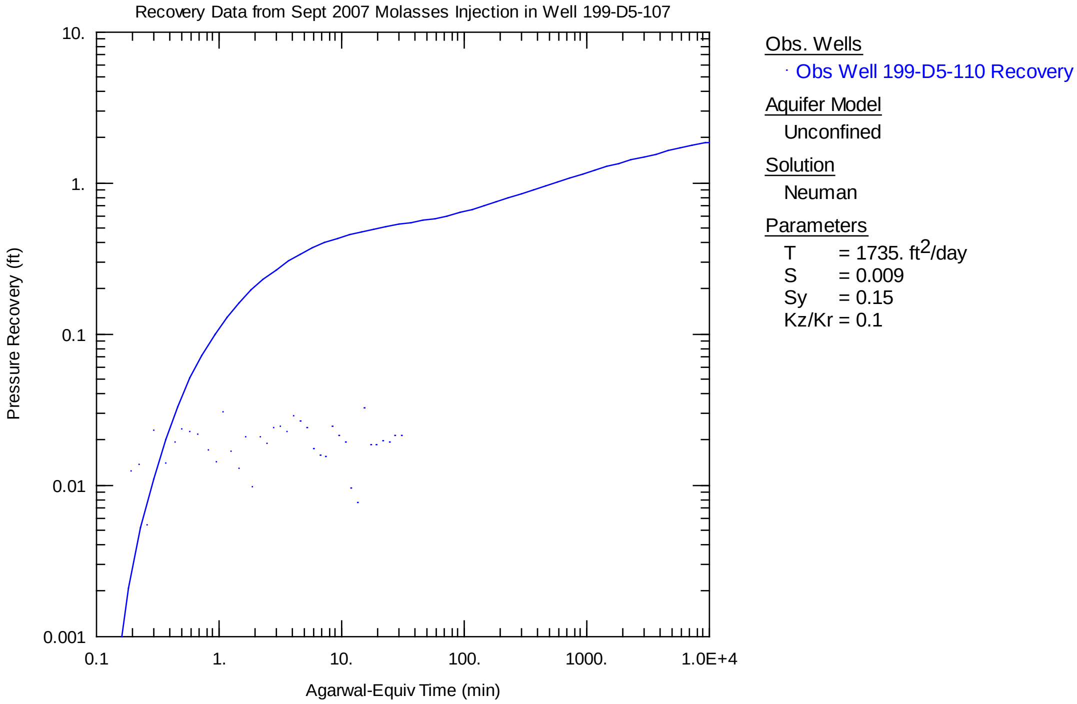


Figure 5.1. Pressure Recovery Response in Observation Well 199-D5-110 Following the September 2007 Molasses Injection

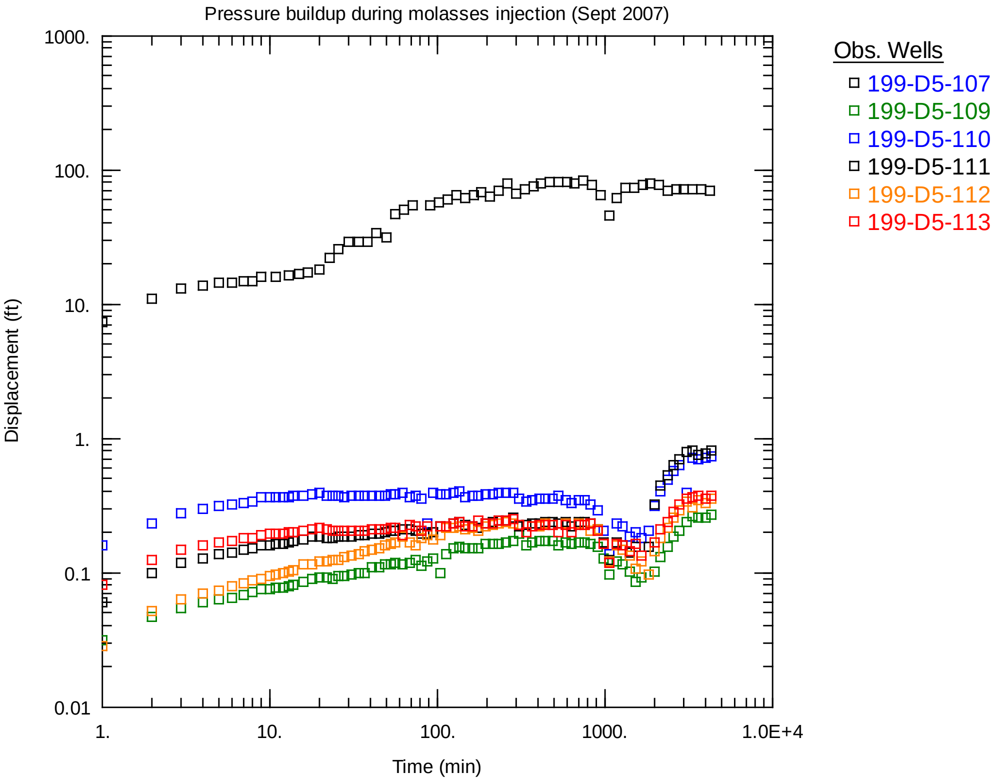


Figure 5.2. Pressure Response at Injection and Monitoring Wells During the Molasses Injection Period

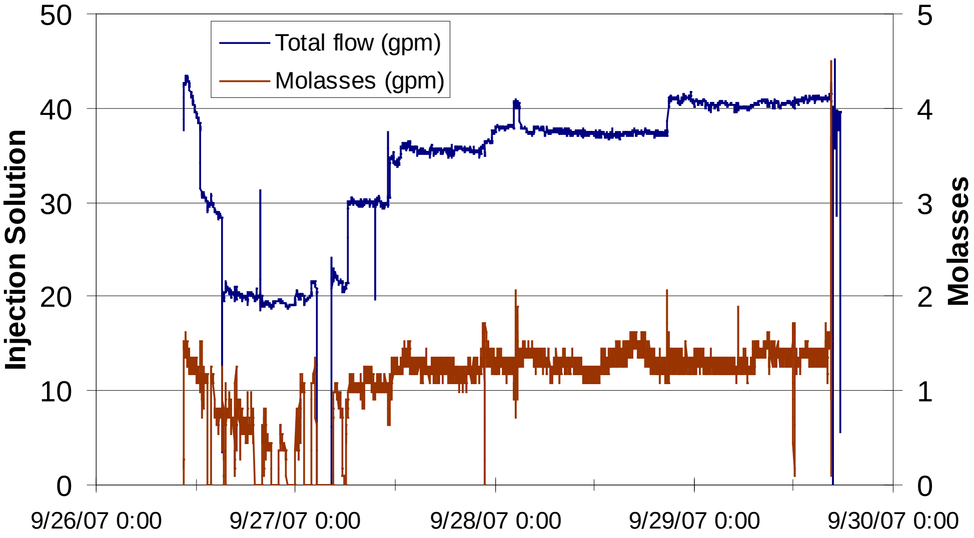


Figure 5.3. Flow Rate of Injected Solution and Molasses During the Injection Period

The following parameters describe the injection process.

- The average injection flow rate (water and all solutes) was approximately 125 L/min (33 gpm).
- The average molasses injection flow rate was approximately 4.2 L/min (1.1 gpm).
- Approximately 19,300 L (5,100 gal) of molasses were injected.
- The total injection volume was about 594,000 L (157,000 gal).
- The average molasses concentration during injection was about 44 g/L.
- The injection duration was 3.25 days.
- Based on the injected volume, estimated aquifer properties (5.6-m [18-ft] thick at the time of injection with a porosity of 0.14), and an idealized radial geometry, the nominal injection radius was 15 m (50 ft).
- About 9400 L (2,500 gal) of water were injected after the molasses injection was terminated, to flush the injection system, injection wellbore, and filter pack.
- About 625 L (165 gal) of sodium bromide tracer solution were injected, resulting in an average solution concentration of 69 mg/L as bromine, based on the measured concentration in the stock solution, the volume of stock solution injected, and the total solution (i.e., water and molasses) volume injected.
- About 625 L (165 gal) of ammonium chloride solution were injected, resulting in an average solution concentration of 171 mg/L based on the measured concentration in the stock solution, the volume of stock solution injected, and the total solution (i.e., water and molasses) volume injected.
- Injection pressure was variable throughout the injection but was typically about 25 psi.

Primary data collected to monitor substrate injection are depicted in Figures 5.4 through 5.9. Note that the tracer and TOC concentration data, which are metrics for the quantity of solution and substrate respectively, follow similar breakthrough curves at each monitoring location, indicating there was no significant retardation of the injected substrate. These figures also show that the oxidation reduction potential dropped quickly with substrate injection. These data, along with the organic acid data presented later, suggest that substrate utilization by the in situ microbial population begins quickly and, subsequently, injection for a longer duration could be problematic because of the potential for excessive biomass formation near the injection well. Under the radial flow system created by this single-well injection, substrate flow is directed outward from the point of injection with flow velocities decreasing with radial distance. The well hydraulics associated with this radial flow system will place an upper bound on the rate at which fluids can be injected, and at the biostimulation treatability test site, 150 L/min (40 gpm) was identified as the maximum rate that could be sustained. Another factor to consider is the volume of water required to increase the injection radius varies with the square of the radius. As an example, for a 150 L/min (40 gpm) injection flow rate into an aquifer with a thickness of 5.6 m (18 ft) and a porosity of 0.14, about 3 days are required to inject to a radius of 15 m (50 ft). However, about 5.25 days would be required to inject to a radius of 20 m (66 ft). The field test data suggest that injection to a radius of 15 m (50 ft) is feasible. Injecting to a significantly larger radius (e.g., 20 m [66 ft]) may not be feasible because of the potential for biofouling.

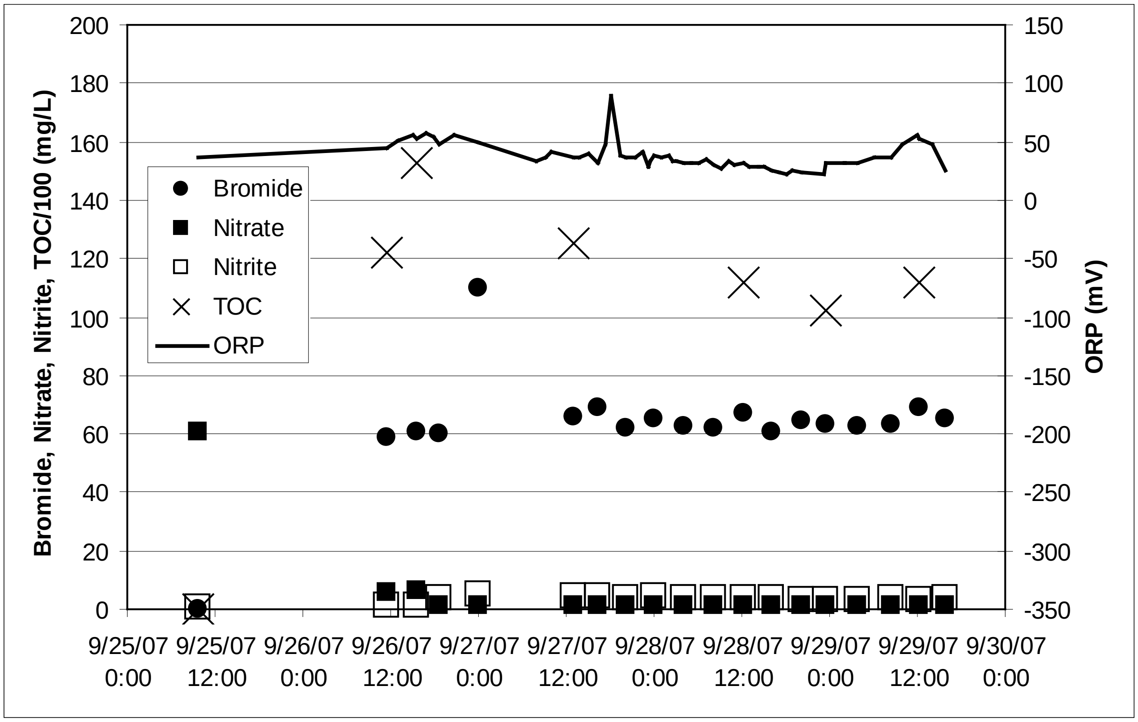


Figure 5.4. Operational Parameters Measured at Injection Well 199-D5-107 During the Injection Phase of the Test

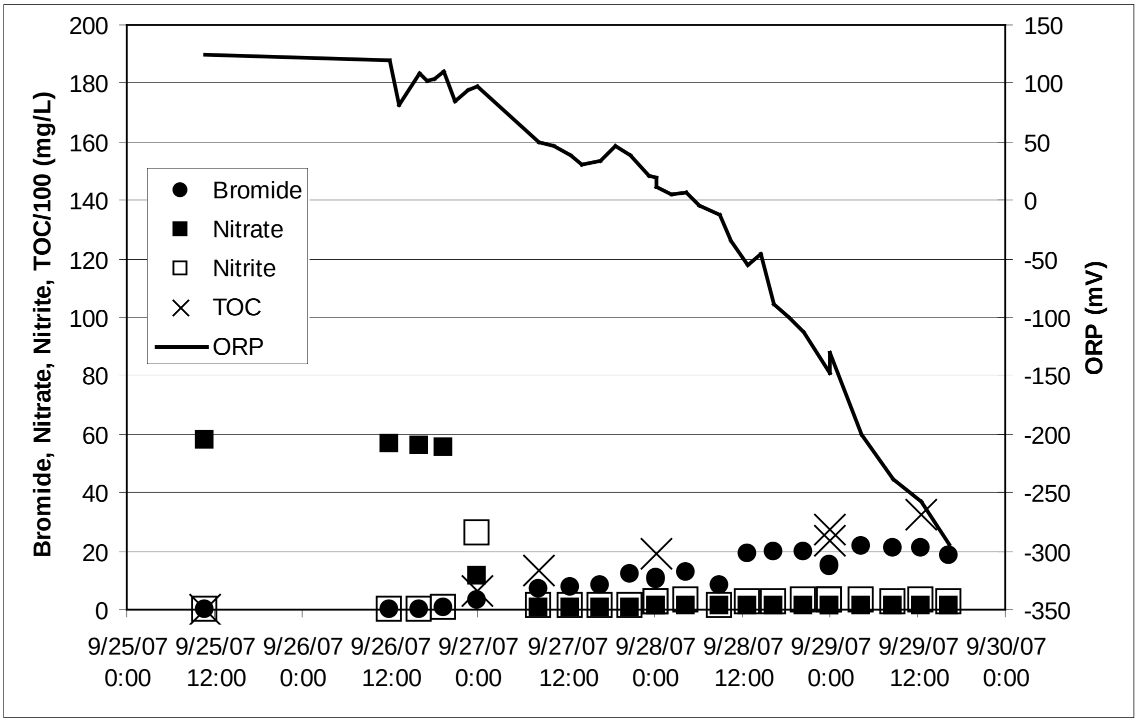


Figure 5.5. Operational Parameters Measured at Monitoring Well 199-D5-109 During Injection in 199-D5-107

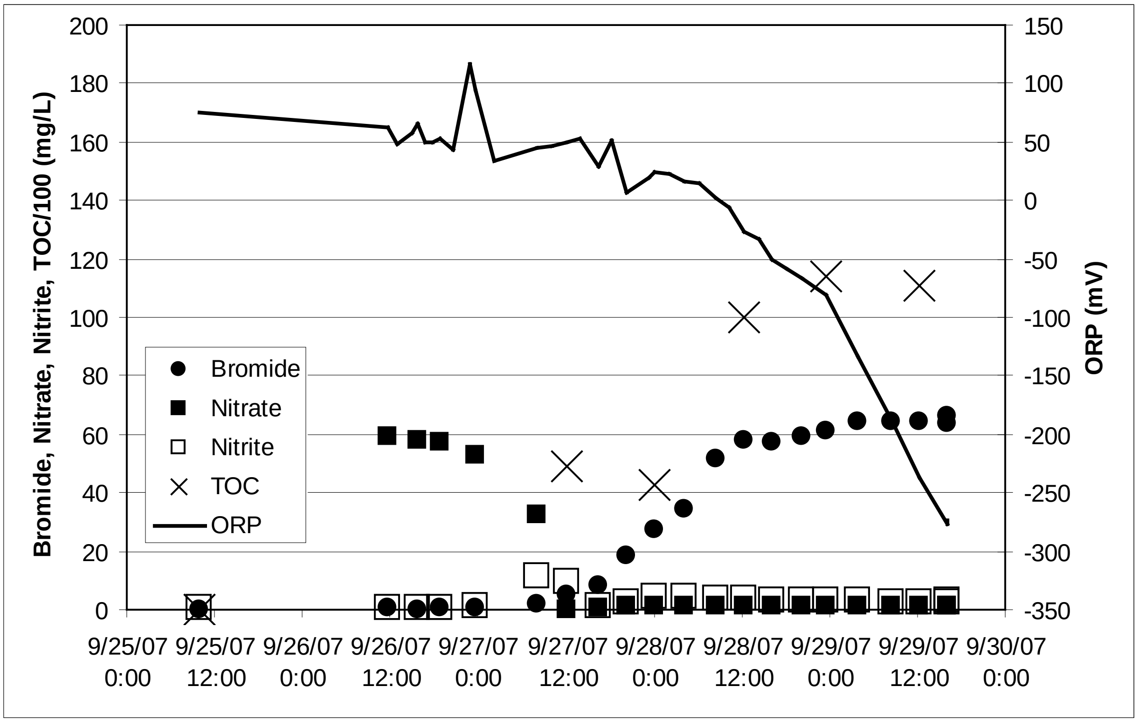


Figure 5.6. Operational Parameters Measured at Monitoring Well 199-D5-110 During Injection in 199-D5-107

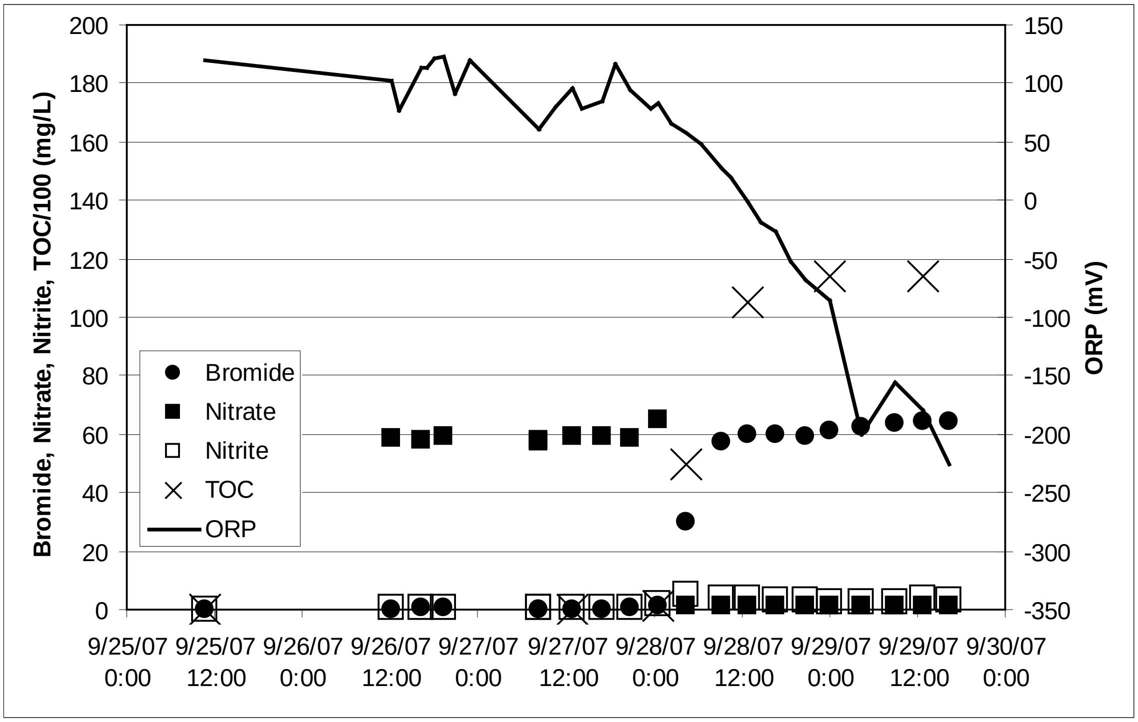


Figure 5.7. Operational Parameters Measured at Monitoring Well 199-D5-111 During Injection in 199-D5-107

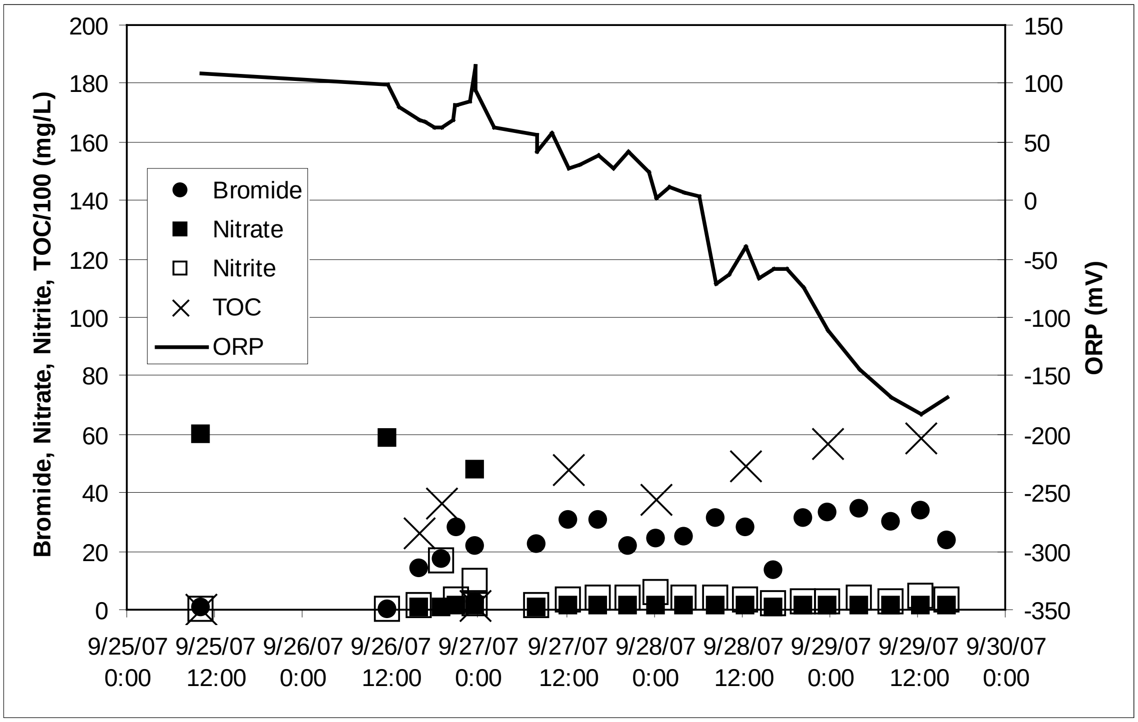


Figure 5.8. Operational Parameters Measured at Monitoring Well 199-D5-112 During Injection in 199-D5-107

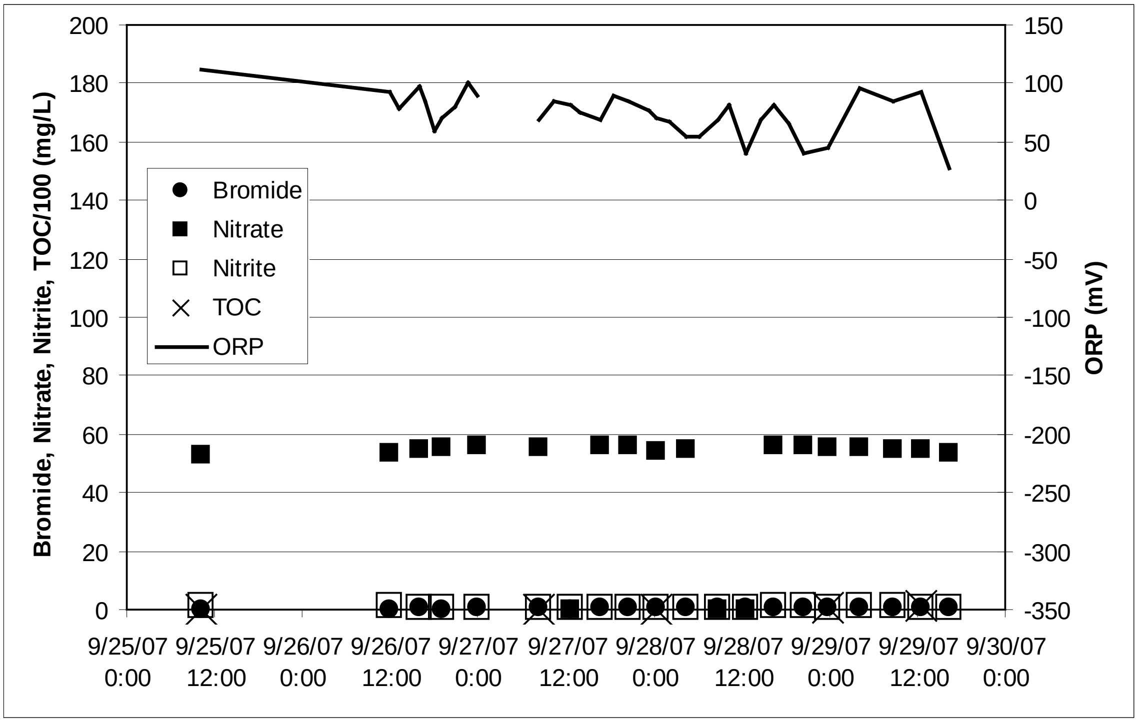


Figure 5.9. Operational Parameters Measured at Monitoring Well 199-D5-113 During Injection in 199-D5-107

Total organic carbon concentrations were monitored intermittently throughout the test, and the measurements collected at the end of the injection process were used to assess the uniformity of substrate distribution. Based on the estimated injection radius of 15 m (50 ft), monitoring wells 199-D5-110, -111, -112, and -113 should have had a TOC concentration comparable to the injected concentration by the end of the injection. Well 199-D5-109 should have been just on the fringe of the substrate injection. As shown in Table 5.1, TOC data at monitoring wells 199-D5-110, -111, and -109 are consistent with what would be expected for the substrate injection. Total organic carbon values are lower than expected at monitoring wells 199-D5-112 (upper zone monitoring) and 199-D5-113 (lower zone monitoring). Characterization data showed that the hydraulic conductivity over the screened interval for well 199-D5-112 was higher than what was observed at other locations. Substrate arrival data indicate that transport in the direction of wells 199-D5-112 and -113 moved predominantly through the upper, more permeable, zone and was diluted or otherwise diverted by this high-conductivity layer, as indicated by the early tracer arrival that never reached full concentration. Very little substrate appeared in the lower interval at well 199-D5-113, although the TOC concentration did increase by a factor of 10 within a week after injection, possibly because of density sinking of the substrate. This information suggests that heterogeneities in the direction of wells 199-D5-112 and -113 impacted the initial distribution of substrate. Further observations during the process monitoring and performance monitoring phases were used to determine how the variability in substrate injection impacts the ability of the bioremediation zone to reduce oxygen, nitrate, and chromate over time.

Table 5.1. Total Organic Carbon Concentrations at the End of the Substrate Injection Period

Well	Total Organic Carbon (g/L)
199-D5-107 (injection well)	11
199-D5-109	2.7
199-D5-110	11
199-D5-111	11
199-D5-112	6
199-D5-113	0.1 (rising to 1.5 shortly after injection terminated)

In summary, the dissolved substrate (molasses) injection provided a large (~15-m radius) zone of substrate distributed around the injection well. Operations were relatively simple, although management of the injection pressure was initially problematic. While there was no apparent biofouling during injection (i.e., the injection mound did not continue to build significantly over time), there are indications that microbial activity had begun. Thus, it is likely that injection to larger radial distances (e.g., 20 m [66 ft]) may not be possible without use of a groundwater recirculation process capable of significantly enhancing interwell groundwater flow rates during an injection.

5.2 Process Monitoring Results

The goals of the process monitoring phase were 1) to assess the anticipated fermentation process induced by the injection of substrate, and 2) to evaluate the “drift” of the substrate and fermentation products downgradient because of the natural groundwater flow. At the end of the substrate injection phase, a suite of analytes was collected to define the starting conditions. These analytes then were monitored weekly over the next 8 weeks. Key analytes are

- organic acids (fermentation products)
- anions including chromate, nitrate, nitrite, sulfate, and bromide (tracer)
- TOC
- field parameters, including pH, specific conductance, dissolved oxygen, and oxidation-reduction potential.

In summary, results from process monitoring indicate that fermentation was rapidly induced through injection of the substrate and much longer than the 8-week process monitoring period. Thus, results of the process monitoring phase are combined with the performance monitoring phase. For reference, Appendix E contains plots of the organic acid concentrations and geochemical indicators during the first 8 weeks of monitoring.

5.3 Performance Monitoring Results

Performance monitoring results with respect to the targeted treatment compounds, hydraulic properties, and overall biogeochemical conditions are presented in this section.

5.3.1 Water Chemistry for Target Compounds

Nitrate, dissolved oxygen, and chromate were the target compounds for treatment in the biobarrier. In summary, low concentrations of nitrate, nitrite, and oxygen were maintained throughout the test duration. Chromium and chromate concentrations, while variable during the period where significant organic acids were present in the test zone, were significantly lower than the background concentrations.

5.3.1.1 Nitrate/Nitrite

Data indicate that nitrate concentration within the test cell remained below 2 mg/L over a duration of 600 days, except for a short period (approximately 3 months) in which concentrations reached up to 10 mg/L at well 199-D5-112. For the duration of the test, nitrite concentrations were generally 2 mg/L or lower. As demonstrated in laboratory experiments, the site microbial population is capable of full denitrification without significant buildup of nitrite as an intermediate compound. Details of the results over the test period are depicted in Figure 5.10 and Figure 5.11.

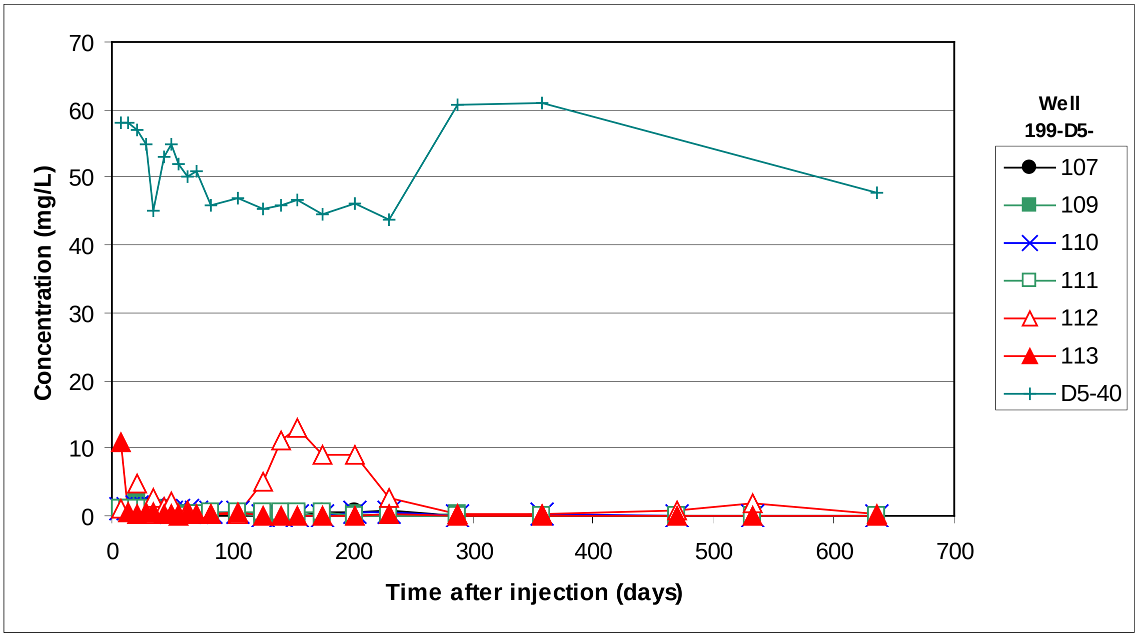


Figure 5.10. Nitrate Concentrations over the Duration of the Test

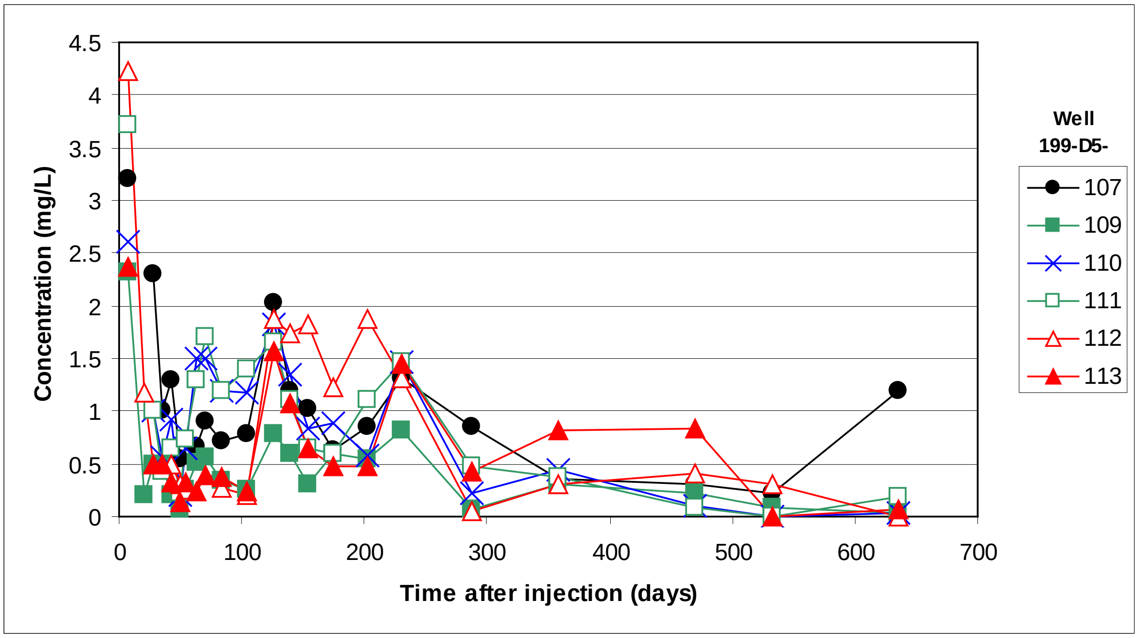


Figure 5.11. Nitrite Concentrations over the Duration of the Test

5.3.1.2 Dissolved Oxygen

Data indicate that dissolved oxygen concentration within the test cell remained below 1 mg/L over the duration of the test at all wells.

5.3.1.3 Chromate/Chromium

Chromate reduction in the test cell was monitored using the measurements of hexavalent chromium (chromate, Cr^{6+}) in the form of the water soluble chromate ion (from onsite spectrophotometric analysis) and total chromium (from laboratory ICP-MS analysis) in water samples. The data indicate that both hexavalent chromium and total chromium concentrations in the test cell were significantly lower than background upgradient concentrations in well 199-D5-40 except for a period from day 50 to 140 where hexavalent chromium measurements varied dramatically from below detection to above ~250 µg/L. During this time period of variation in the data, the pH at all wells in the test cell was below pH 6 and ranged as low as pH 4 due to the presence of organic acids. In contrast, the pH at the background upgradient well 199-D5-40 did not vary significantly (range of 7.1 to 8). Over the same time interval, there were no organic acids present and the hexavalent chromium concentrations at this well remained relatively stable with values between 80 and 140 µg/L. The hexavalent chromium concentrations were stable again, and generally below detection, after day 140 throughout the remainder of the test when pH was generally above pH 6 at most wells and the organic acid concentration had declined substantially. Details of the results over the test period are depicted in Figure 5.12 and Figure 5.13.

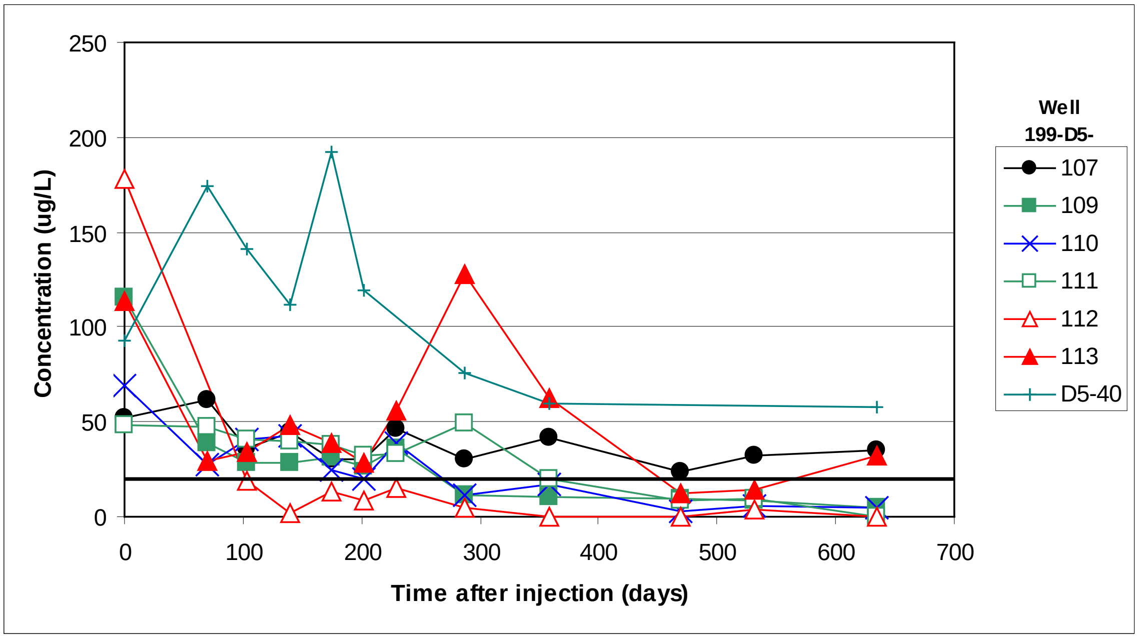


Figure 5.12. Total Chromium Concentrations from Laboratory Analysis (ICP-MS). The target contaminant level for chromate in the Hanford 100-D groundwater is 22 µg/L.

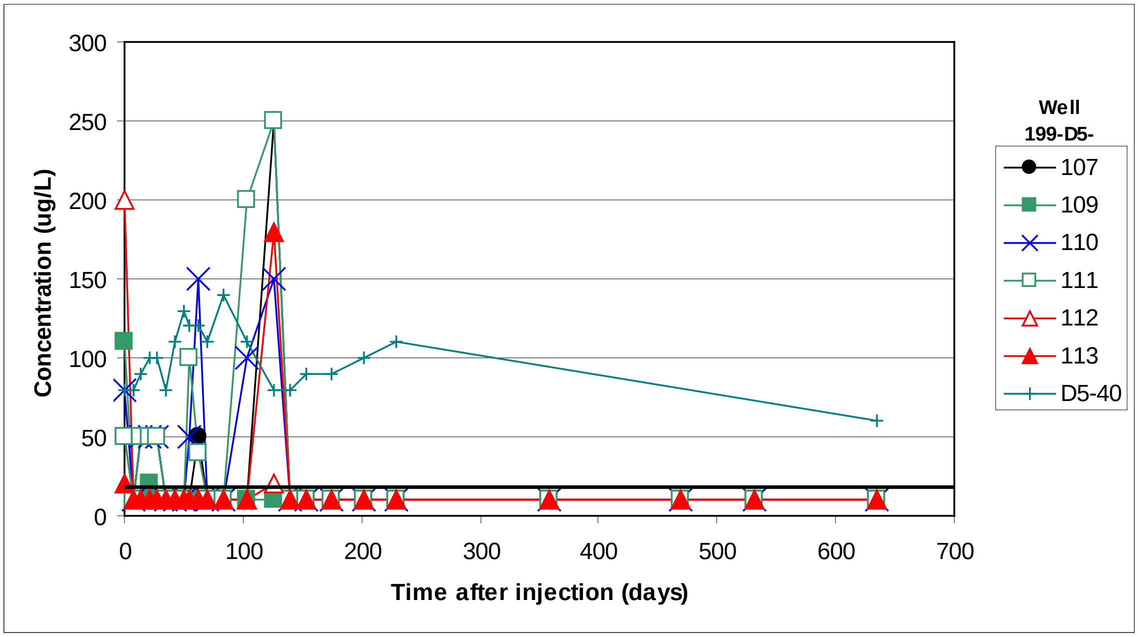


Figure 5.13. Chromate Concentrations Using Spectrophotometric Analysis (field test kit). The target contaminant level for chromate in the Hanford 100-D groundwater is 22 µg/L. Data below the detection limit are plotted at the detection limit for the method.

5.3.2 Hydraulic Conductivity

Hydraulic conductivity was assessed through hydraulic slug testing, geophysical testing, and bromide elution.

5.3.2.1 Hydraulic Slug Test Results

Hydraulic slug testing was conducted prior to injection (August 2007), in November 2007 approximately 60 days after substrate injection, and again in November 2008 approximately 420 days after injection. Table 5.2 shows the results of these tests in terms of the relative hydraulic conductivity of the post-injection tests compared to the pre-injection test. These results show minimal impact from injection of the substrate in the short term. Over the longer term, permeability was reduced, likely due to biomass growth. By the November 2008 test, chemical data show that the organic compound concentrations in the test cell are very low. Thus, the biomass concentration would be expected to slowly decline over time and lead to increased permeability back toward the baseline value. Full details of the hydraulic slug testing are shown in Appendix F.

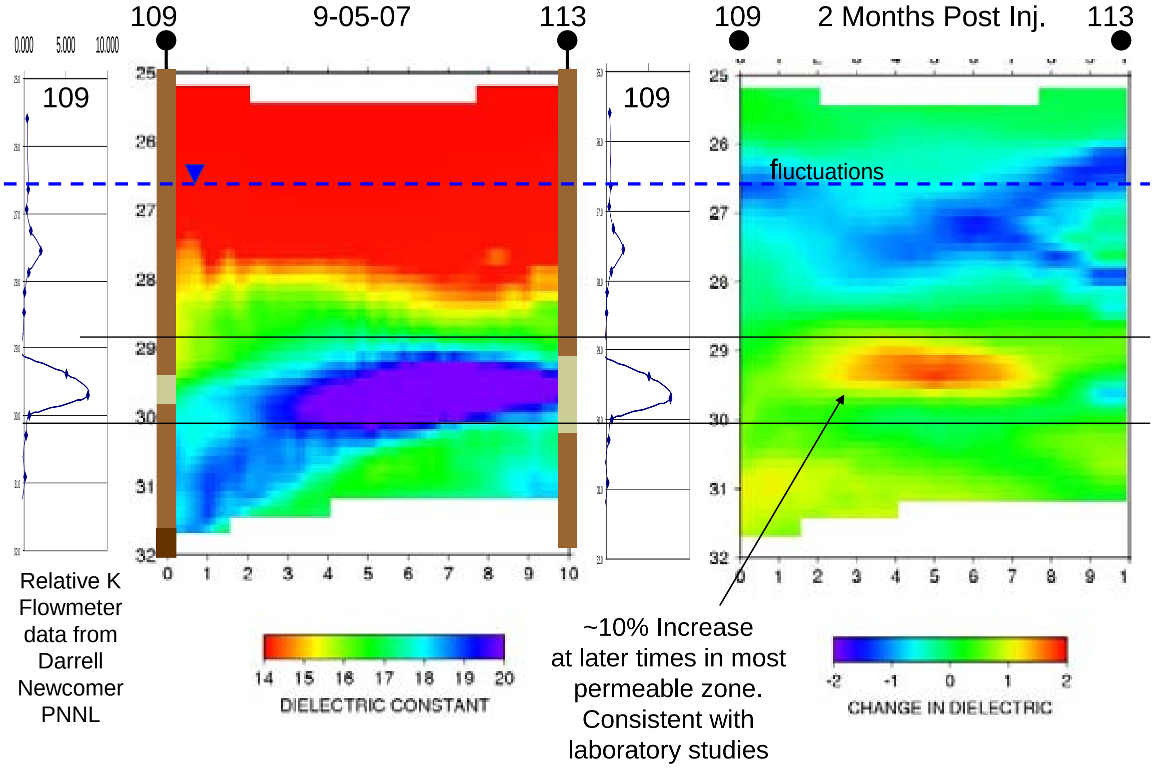
Table 5.2. Permeability Change Results Based on Slug Testing

	Permeability Change (K_{post}/K_{pre})[(a)]	
Well Name	Post 1	Post 2
199-D5-109	1.20	0.02
199-D5-110	0.99	0.28
199-D5-111	1.08	0.23
199-D5-113	0.75	0.55

(a) Post 1 is based on data for the pre-injection result (August 2007) and post-injection result conducted November 2007. Post 2 is based on data for the pre-injection result (August 2007) and post-injection result conducted November 2008.

5.3.2.2 Geophysical Testing Results

Although electrical methods are expected to be the most useful for imaging molasses distribution, the baseline electrical data acquisition failed. Additionally, the attenuation of the seismic amplitudes was so severe that the quality of the post-injection datasets was unusable; this seismic response was expected based on the laboratory response and indicates that all well pair directions were impacted by the injected molasses. However, some of the pre- and post-injection radar tomograms had acceptable data quality. Where acceptable, radar travel times were used to estimate velocity and dielectric constant distribution (see Appendix C). Figure 5.14 shows a baseline radar dielectric constant transect and an associated change in dielectric constant at 2 months post injection. Comparison of the dielectric constant transect with the wellbore geological and hydraulic conductivity flowmeter data suggests that the radar is useful for delineating the hydrological heterogeneity of the injection zone. Comparison of the change in dielectric with the baseline illustrates the impact of heterogeneity on the system: at 2 months post injection, the dielectric has increased ~10% in the most permeable zone. The geophysical imaging suggested that the molasses was distributed a minimum of 16m from the injection well. Heterogeneity significantly influenced the amendment distribution, with more amendment traveling through the more permeable zones.



Relative K Flowmeter data from Darrell Newcomer PNNL

~10% Increase at later times in most permeable zone. Consistent with laboratory studies

Figure 5.14. Baseline Radar Imaging (left) and 'Difference' Radar Imaging (right). Shown are 1) the favorable comparison of the radar tomogram with the geological and hydrological wellbore data and 2) the influence of heterogeneity on the amendment distribution and subsequent biogeochemical transformations. Decreases in dielectric constant near the water table are likely due to water table fluctuations.

5.3.2.3 Bromide Elution

The elution of bromide that was injected with the substrate was used to evaluate groundwater movement through the test cell. Assessment of the bromide response is complicated by the uneven initial distribution (Figure 5.15). Initial bromide concentration at monitoring wells 199-D5-110 and -111 were comparable to the injected bromide concentration. At these wells, bromide was eluted to approximately half the initial concentration within 70 days. Subsequently, the rate of bromide elution decreased substantially. These results are consistent with hydraulic slug testing data showing that the hydraulic conductivity remained comparable to pre-injection values through November 2007 (~60 days), and then decreased less than half of the pre-injection valued by November 2008 (~420 days). Bromide data at the injection well (199-D5-107) and well 199-D5-113 show an increase of bromide concentrations as groundwater redistributed the injected solution within the test cell. These data also indicate that groundwater flux at these locations is slow and/or being fed by an upgradient source of injected solution or potentially through drainage from the unsaturated zone. Both of these wells represent locations where the hydraulic conductivity is expected to be low. The injection well would be expected to have the largest growth of biomass in the test cell and consequently the most significant biomass-related decrease in hydraulic conductivity. Well 199-D5-113 is screened within a low permeability region of the test cell.

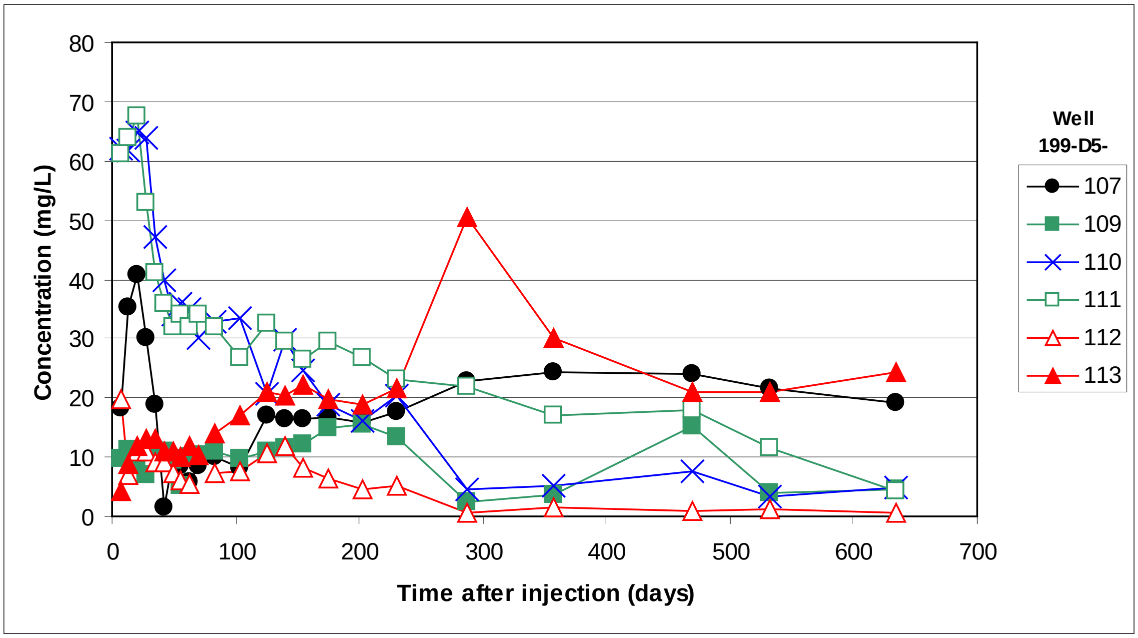


Figure 5.15. Bromide Concentrations over the Duration of the Test

5.3.3 Performance Assessment

The soluble substrate biobarrier maintained low nitrate, nitrite, dissolved oxygen and chromium concentrations over the duration of the monitoring period. During this time, conditions within the test cell changed in response to the addition of the substrate and associated biogeochemical reactions that were induced. Figures 5.16 through 5.22 show the trends in primary biogeochemical parameters, including TOC, glucose, acetate, pH, sulfate, iron, and methane.

Addition of molasses as a soluble substrate induced fermentation to organic acids (see Appendix E). These reactions resulted in decreased total organic carbon and glucose concentrations with time. Acetate concentration increased initially and then declined. The groundwater pH declined and then increased again over the same time interval as the acetate concentration changes as would be expected due to the presence of organic acids at relatively high concentrations. These pH changes were greater than expected based on the laboratory buffering tests conducted prior to the field test. However, the overall performance of the biobarrier did not appear to be significantly diminished due to the transient low pH conditions.

Biological activity also included sulfate reduction, iron reduction, and methanogenesis. These biological processes began occurring several months after substrate injection. Neither process was observed in the relatively short term laboratory tests that were conducted prior to the field test. Sulfate and iron reduction processes create reduced species that have reductive capacity to help maintain the targeted reducing conditions within the biobarrier and may increase the overall effectiveness and longevity of the biobarrier.

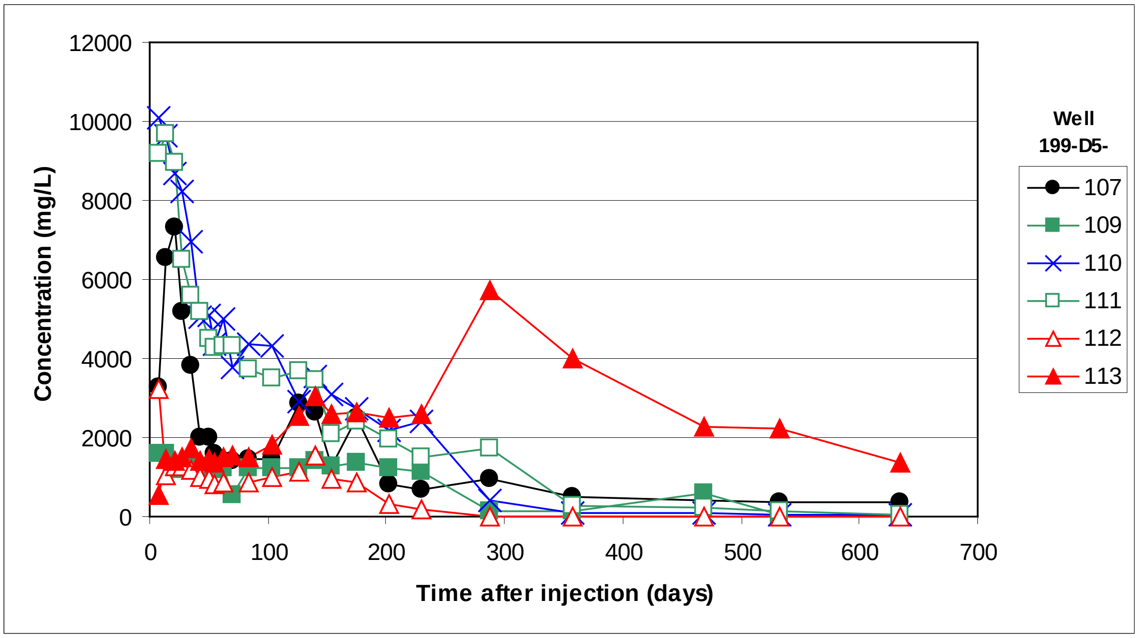


Figure 5.16. TOC Concentrations over the Duration of the Test

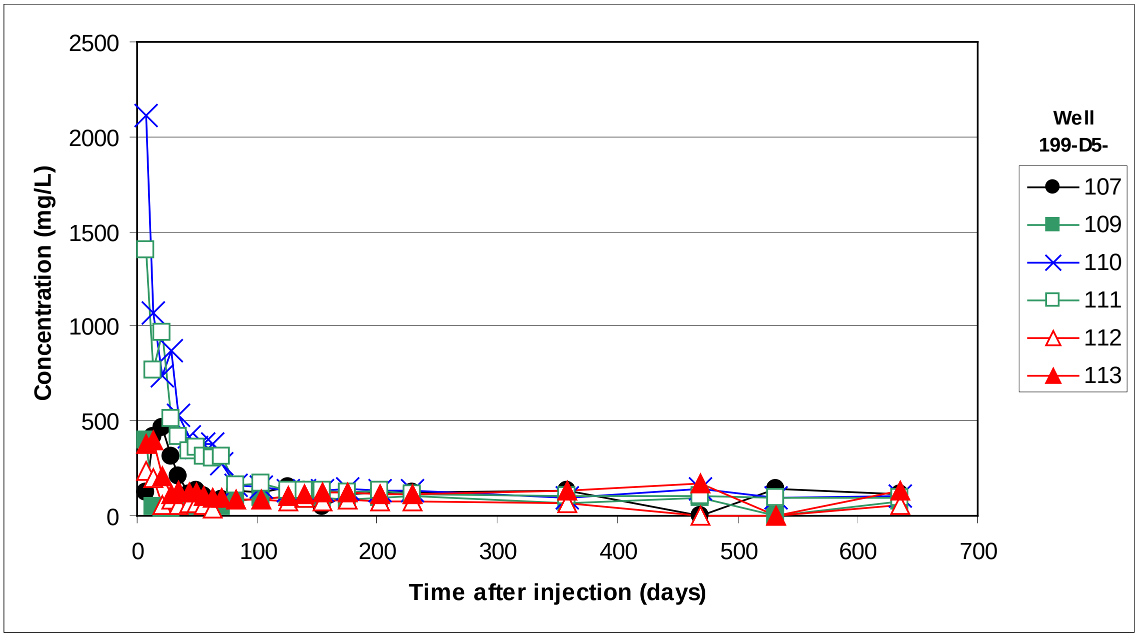


Figure 5.17. Glucose Concentrations over the Duration of the Test

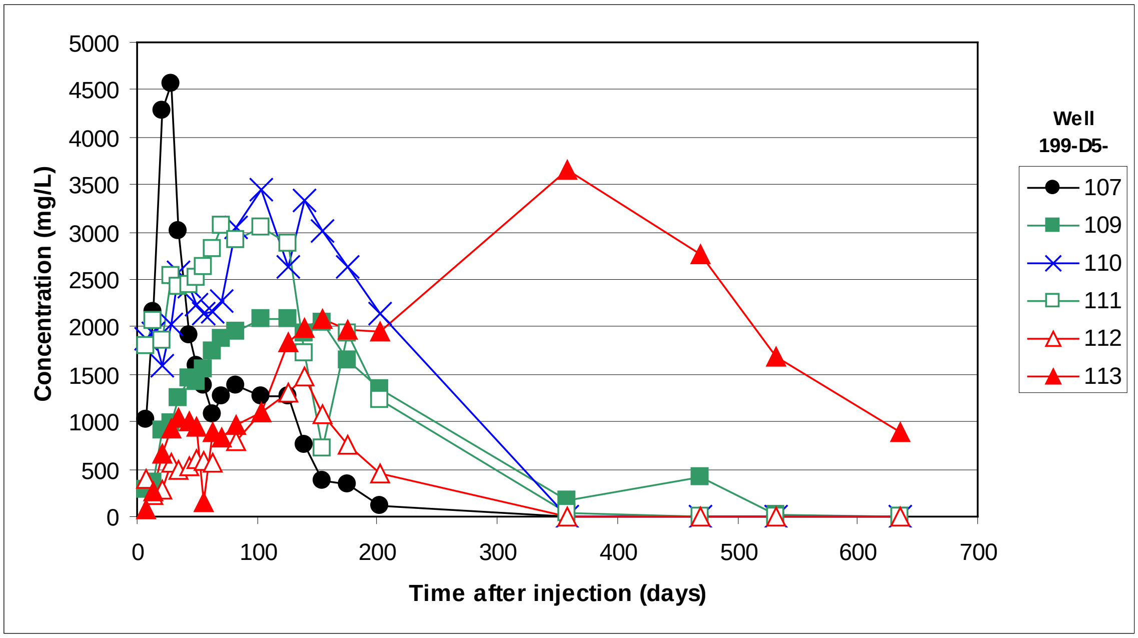


Figure 5.18. Acetate Concentrations over the Duration of the Test

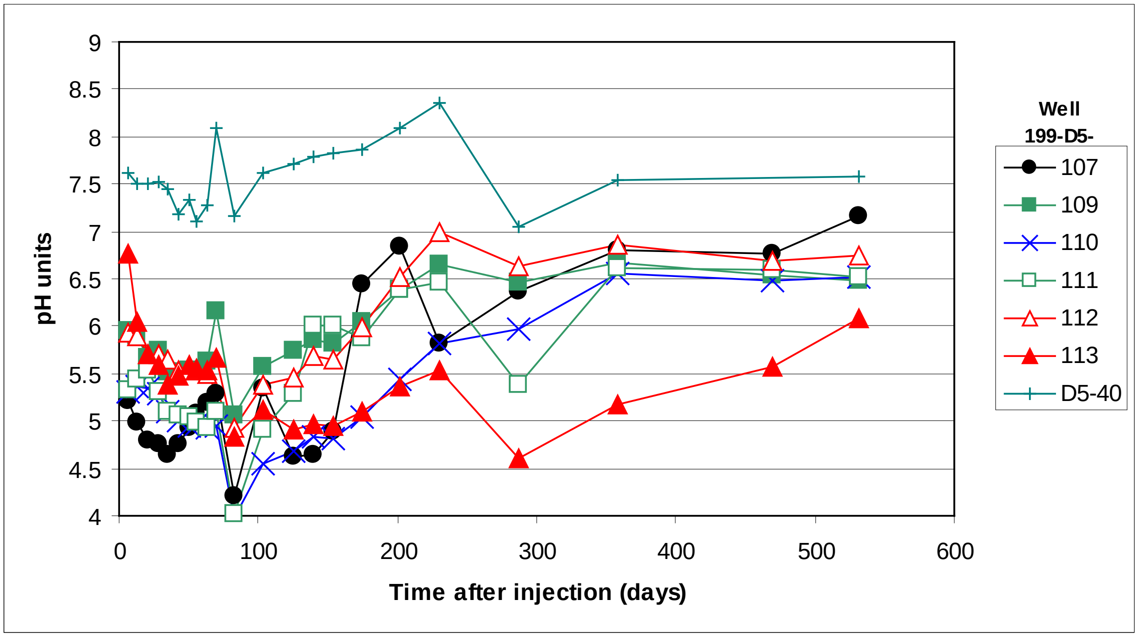


Figure 5.19. pH over the Duration of the Test. Data are not available for the last sampling time (day 635). Data for day 532 for well 199-D5-40 are also not available. The plotted point at day 532 is the average pH over the duration of the test at well 199-D5-40.

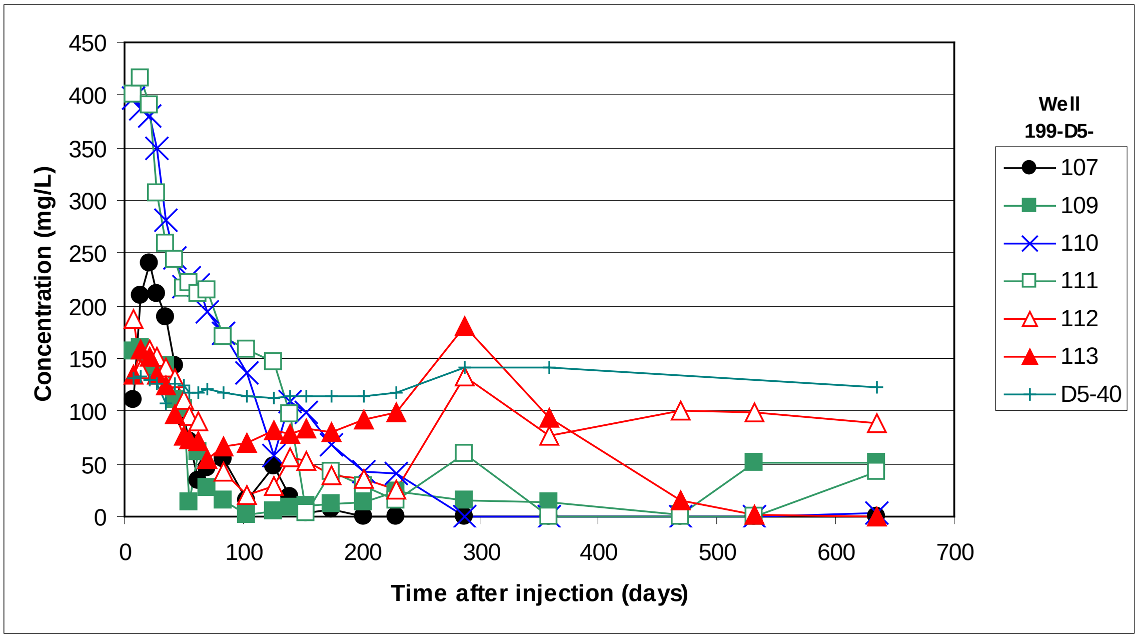


Figure 5.20. Sulfate Concentrations over the Duration of the Test

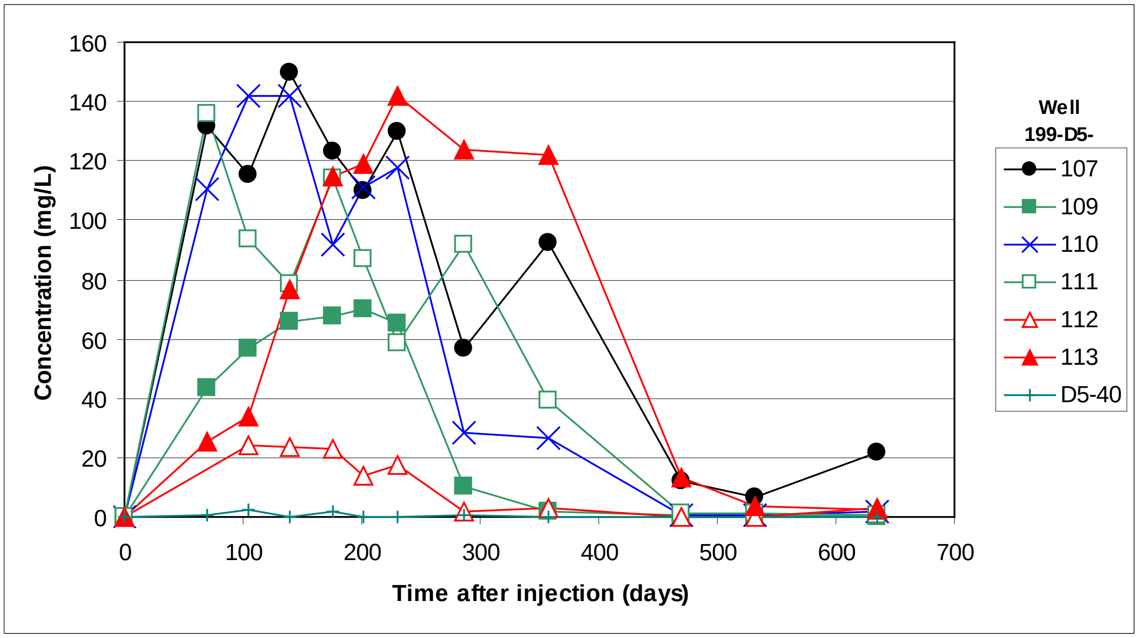


Figure 5.21. Iron Concentrations over the Duration of the Test

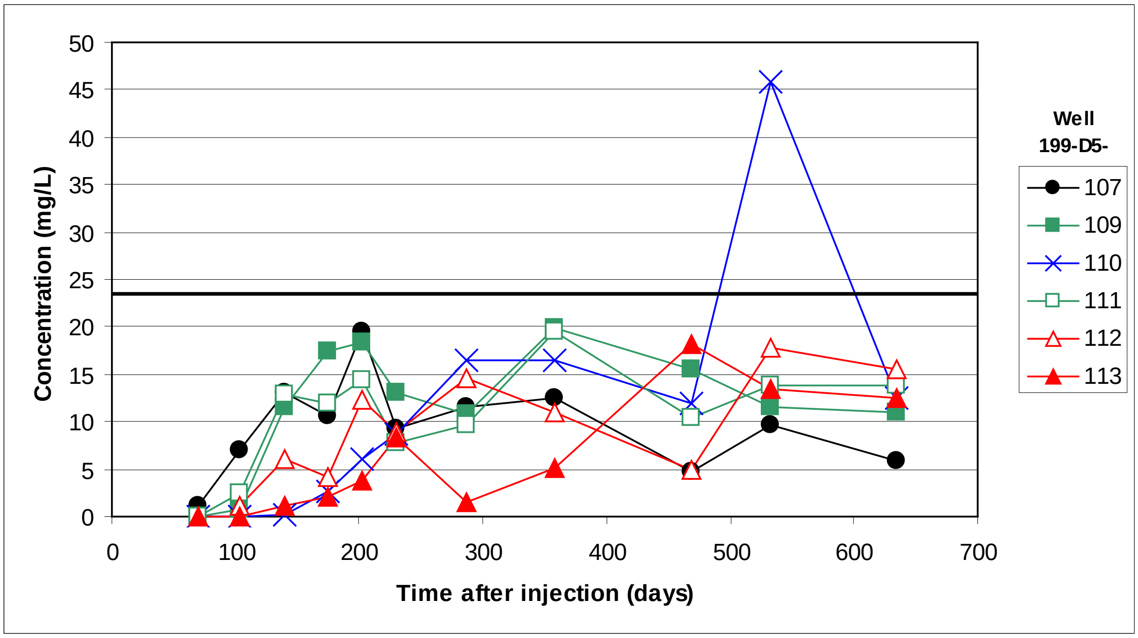


Figure 5.22. Methane Concentrations over the Duration of the Test

By about 300 days after substrate injection, the soluble substrate and associated organic degradation products are essentially depleted. Continued performance of the biobarrier in terms of reducing nitrate, nitrite, dissolved oxygen, and chromate after this time is associated with the presence of reduced iron and sulfur species and cryptic growth of biomass as discussed in the test plan (Truex et al. 2007). It should also be noted that the apparent performance in terms of groundwater constituent reduction is affected by the rate at which constituents are carried into the test cell. Because the hydraulic conductivity was decreased within the test cell, the flow rate through the test cell is slower than initially and the biogeochemical data would therefore evolve more slowly than initially. Although the reduction in hydraulic conductivity was moderate, full scale application of a biobarrier must consider changes to the flow field and associated solute flux through the biobarrier. The decreased flow rate and the continued reductive conditions throughout the duration of the test suggest that continued monitoring would be needed to fully determine the capacity and longevity of the induced biobarrier.

5.3.4 Water Quality

Within the test cell, water quality was negatively impacted by an increase in the concentration of metals and organic constituents and a decrease in the pH, oxidation-reduction potential, and dissolved oxygen concentration. These changes were expected due to the imposed anaerobic conditions required for biological treatment of dissolved oxygen, nitrate, and chromate. Although the concentration of most metals increased, only three, arsenic, barium, and selenium, increased to concentrations consistently above the maximum contamination level. The concentration profiles for these metals are shown in Figures 5.23 through 5.25. The concentration of lead increased to above the maximum contamination level for one sample in well 199-D5-111 and one sample in well 199-D5-113. A biobarrier design requires a downgradient portion of the aquifer where these water quality impacts can recover and this type of recovery region would need to be considered as part of determining the location for biobarrier application.

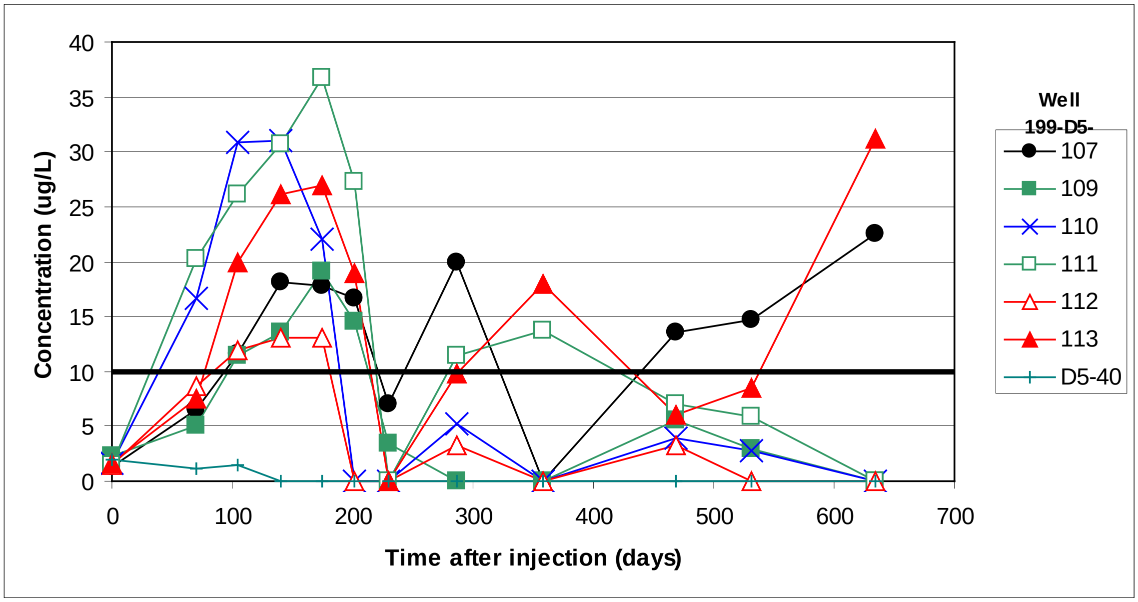


Figure 5.23. Arsenic Concentrations During the Test. The drinking water Maximum Contaminant Level (MCL) for arsenic is 10 µg/L.

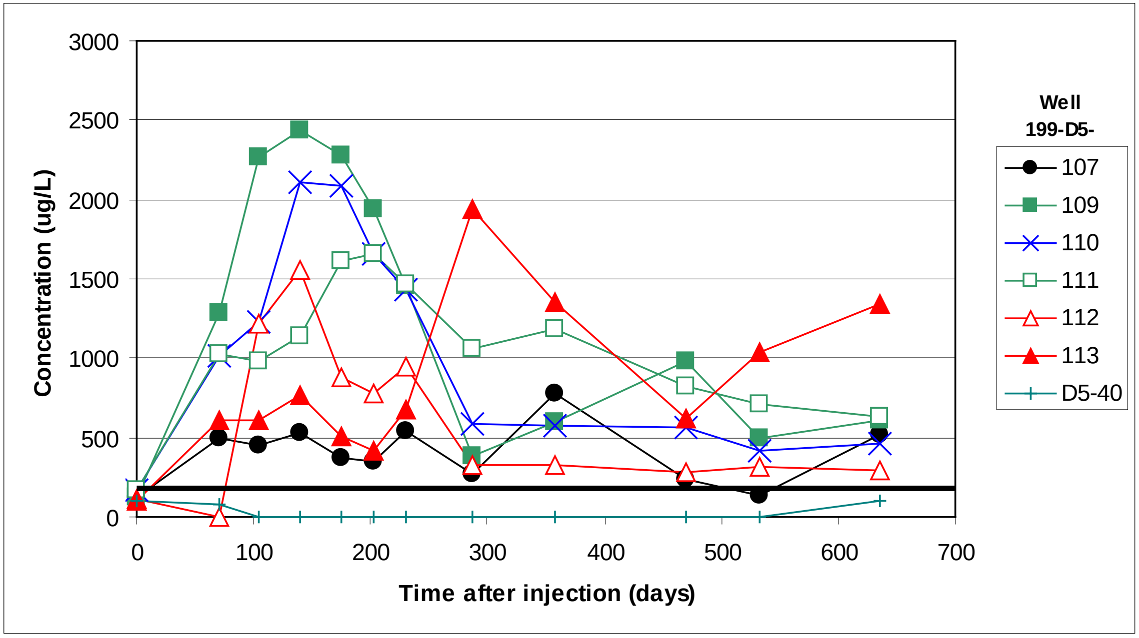


Figure 5.24. Barium Concentrations During the Test. The drinking water Maximum Contaminant Level (MCL) for barium is 200 µg/L.

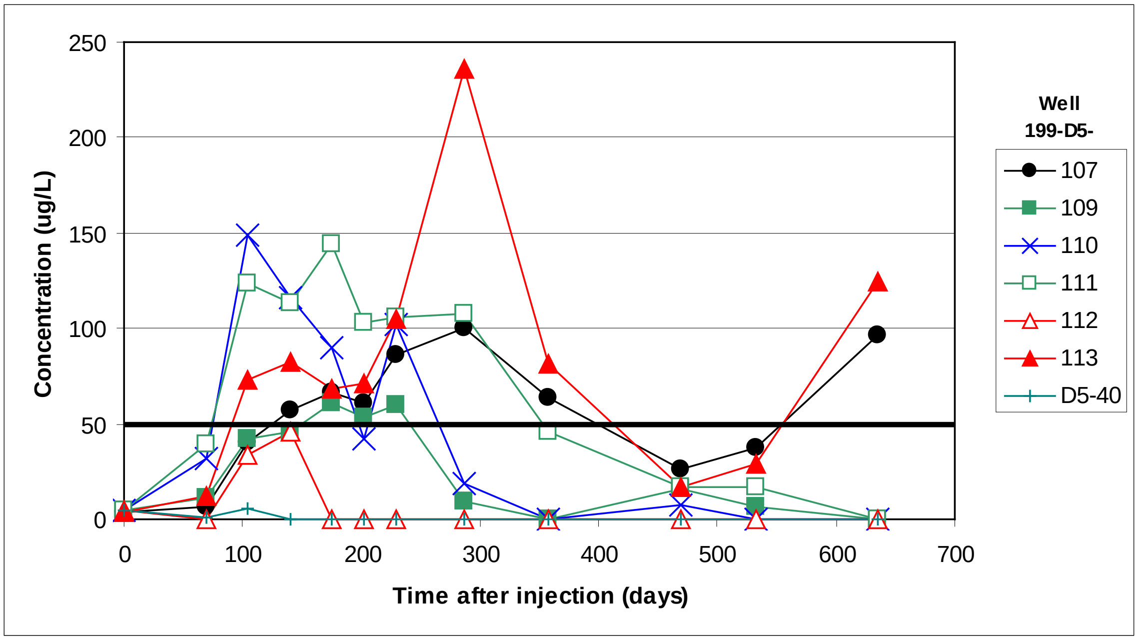


Figure 5.25. Selenium Concentrations During the Test. The drinking water Maximum Contaminant Level (MCL) for selenium MCL is 50 µg/L.

5.4 Summary Comparison of Laboratory Microcosm and Field Test Results

Laboratory microcosm tests showed that dominant products of substrate fermentation varied based on the initial substrate concentration. At an initial substrate concentration similar to the concentration injected at the field test site, the primary products of fermentation included succinate, lactate, propionate, acetate, formate, ethanol, and butyrate, with acetate dominating at the end of the fermentation period. A similar mixture of fermentation products was observed during field test.

Laboratory experiments also evaluated whether additional buffering capacity would be needed during substrate injection. Table 5.3 shows the pH changes occurring as a function of added bicarbonate buffer. Based on these results, no additional buffering was added during substrate injection because it was interpreted that the buffering available in the sediment was sufficient. However, the pH drop observed in the field was larger than expected and generally lowered the pH by 2 pH units during fermentation. The pH remained low for several months and then increased again toward neutral. The pH drop in some of the microcosm experiments conducted after the buffering experiment was also on the order of 2 pH units; however, fermentation and subsequent denitrification were still observed. It is likely the presence of carbonate minerals as buffering materials may be heterogeneously distributed, and the overall buffering capacity was different from what was observed in the initial buffer tests.

Table 5.3. pH Response over One Month of Fermentation with Molasses (45 g/L) and Bicarbonate Buffer Added as Specified in the Table

	Bicarbonate Buffer Concentrations and Resulting pHs			
	1 mM	30 mM	100 mM	300 mM
Initial pH	6.8	6.8	7.6	9
Final pH	6.5	6.5	7.5	8

Figure 5.26 and Figure 5.27 show typical responses for nitrate reduction in microcosm experiments. Note that denitrification occurs without significant production of a nitrite intermediate product. Similar results were observed during the field test where data suggested that nitrate reduction occurred and nitrite concentrations remained very low. Figure 5.26 and Figure 5.27also show no sulfate reduction in the microcosm experiments over a period of about 75 days. In the field, sulfate reduction and methane production was initiated 3-4 months after substrate injection.

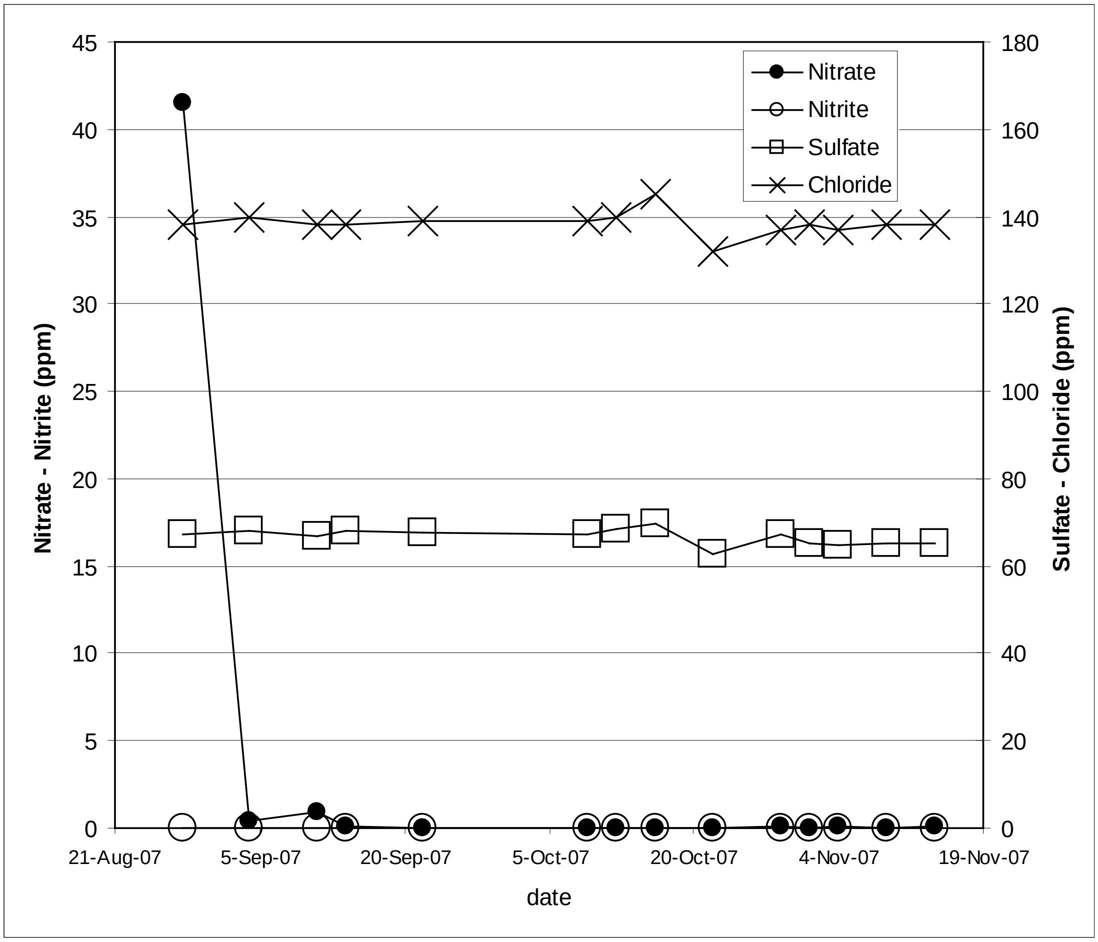


Figure 5.26. Denitrification Observed When Microcosm was Spiked with Nitrate While Acetate Concentration (the dominant remaining organic acid) was Greater Than 30 mM. Sulfate reduction was not observed over a period of about 75 days.

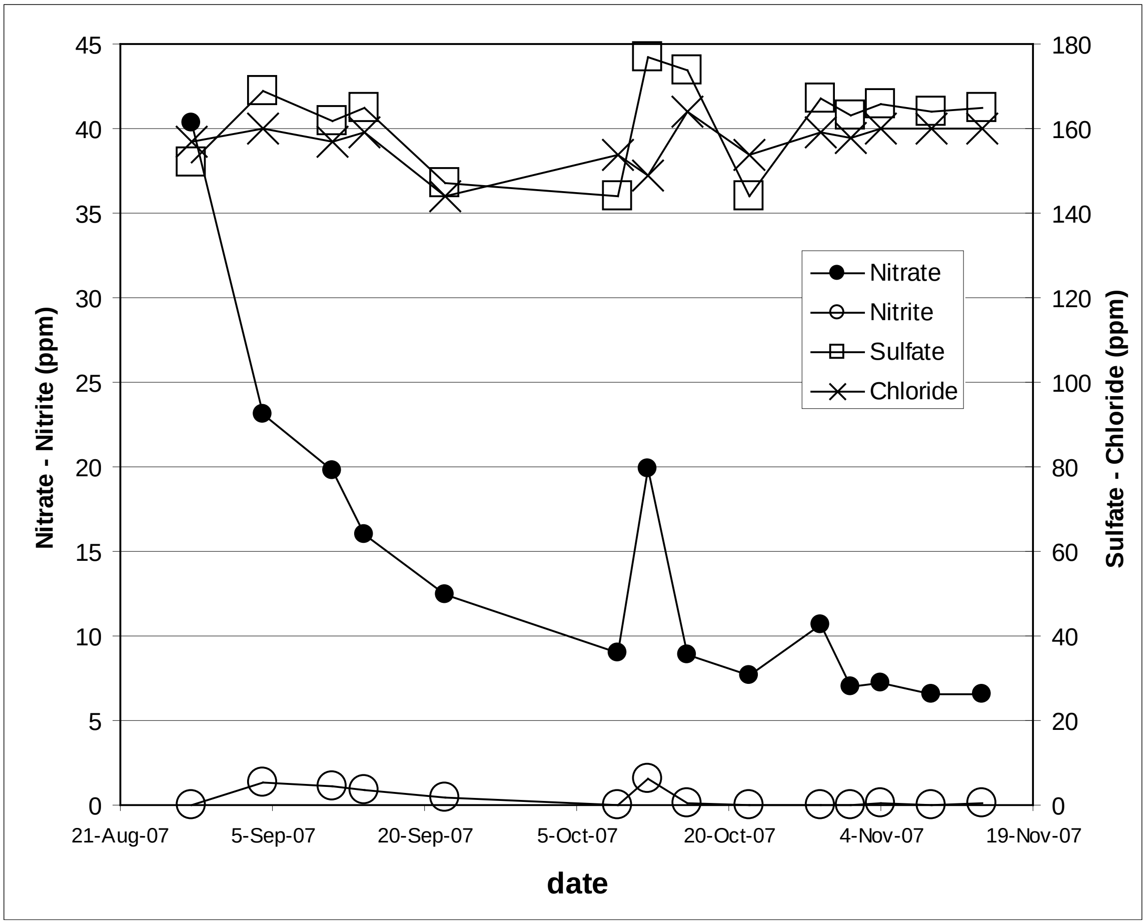


Figure 5.27. Denitrification Observed When Microcosm was Spiked with Nitrate While Acetate Concentration (the dominant remaining organic acid) was Less Than 5 mM. Sulfate reduction was not observed over a period of about 75 days.

5.5 Description of Results Relative to Field Test Objectives

The following is a summary of the field test results with respect to the objectives of the field test.

- Determine the effective radius of injection.

Result: A radius of injection of about 15 m (50 ft) from the injection well for a labile substrate is obtainable. It is unlikely that a radius greater than 20 m (66 ft) could be obtained because of the rapid initiation of microbial reactions and potential for associated biomass buildup near the injection well. However, hydraulic properties would need to be evaluated at any proposed implementation location to determine if a higher injection rate, and thus a larger radial extent of treatment for a given time period, could be sustained. Additionally, use of a groundwater recirculation process that was able to significantly enhance interwell groundwater flow rates during an injection may also enable larger well spacing during full-scale deployment of the technology.

- Evaluate the uniformity of substrate distribution.

  Result: Uniformity of substrate injection is, as expected, dependent on formational heterogeneities within and beyond the targeted treatment zone. However, the field test injection was able to distribute substrate to all of the monitoring locations, although at different concentrations. Subsequent microbial activity and treatment of the target compounds over a period of about 2 years was observed at all locations.

- Identify operational needs for injection.

  Result: Relatively simple operations with the use of process water and substrate supplied in a tanker truck were demonstrated during the injection. One problem encountered was the initial injection pressure increase, which most likely resulted from accumulation of molasses or solids from the molasses tanker on the injection well screen or within the filter pack material. A mitigation approach was developed during the treatability test (i.e., short pulses of process water were used to dissolve molasses buildup on the screen openings), and similar approaches may be required during full-scale deployment of the technology.

- Induce fermentation reactions and reducing conditions and grow biomass.

  Result: Process monitoring data showed that fermentation reactions and associated reducing conditions occurred at all of the monitoring locations. Direct in situ biomass measurement is not possible, but indirect measurements suggest that biomass was produced and helped facilitate treatment of target compounds and maintenance of reducing conditions for about 1 year after the introduced substrate and associated fermentations products were depleted, for a total treatment duration of about 2 years and potentially longer.

- Minimize permeability changes resulting from biomass increases.

  Result: Comparison of pre- and post-injection hydraulic conductivity measurements results show minimal impact from injection of the substrate in the short term. Over the longer term, permeability was reduced, likely due to biomass growth. At most locations, moderate permeability reductions ranging from 0.23 to 0.55 of the initial value were observed. However, at one well, permeability was reduced to 0.02 of the initial value.

- Quantify the ability to obtain and maintain low oxygen and nitrate/nitrite concentrations (limit primary electron acceptor flux) and determine longevity of treatment.

  Result: Low oxygen, nitrate, and nitrite concentrations were maintained over the duration of the test (~2 years) with indications that the treatment duration will be longer than 2 years.

- Quantify the ability to obtain and maintain low chromate concentrations (augment chromate treatment) and determine longevity of treatment.

  Result: Low total chromium and chromate concentrations were maintained over the duration of the test (~2 years), with indications that the treatment duration will be longer than 2 years.

- Quantify the water quality impacts of the treatment.

Result: Within the test cell, water quality was negatively impacted by an increase in the concentration of metals and organic constituents and a decrease in the pH, oxidation-reduction potential, and dissolved oxygen concentration. These changes were expected due to the imposed anaerobic conditions required for biological treatment of dissolved oxygen, nitrate, and chromate. A biobarrier design requires a downgradient portion of the aquifer where these water quality impacts can recover, and this type of recovery region would need to be considered as part of determining the location for biobarrier application.

- Compile information for full-scale design considering the injection process, biobarrier performance, hydrogeology, and electron flux information at 100-D.

  Result: Table 5.4 shows the information available from this treatability test that is suitable for use to support design and cost estimation in a feasibility study.

Table 5.4. Biobarrier Scale-Up Information

Item	Value	Comment
Substrate loading	6.7 kg/m^3	Lower substrate loading may be appropriate for volumetric bioremediation of chromate or for shorter periods of barrier effectiveness.
Substrate cost	0.21 $/kg	Treatability test cost
Nutrient loading	4 mg/m^3	May not be necessary in all bioremediation applications
Nutrient cost	5 $/kg	Treatability test cost for ammonium chloride (may not be needed for some sites)
Injection well spacing (perpendicular to flow)	30 m	Based on 15-m radius of influence. Full-scale spacing may need to consider overlapping of substrate injection zones. Potentially, larger spacing could be obtained with a groundwater recirculation system and may be appropriate, depending on relative cost of recirculation design versus a single well injection design.
Operational labor for injection	250 hours of labor time	Labor for injection during the test
Monitoring frequency	Quarterly to semiannually	Based on the timeframe of observed changes during the test.
Frequency of substrate injection	Every 2 years (observed performance over test duration) Every 3–4 years (estimated based on performance observed over 2-year period)	Barrier performance did not diminish over the 2-year testing period. Groundwater flow conditions should also be considered in determining the frequency of reinjection.

Table 5.4. (contd)

Item	Value	Comment
Primary injection equipment and cost	Substrate feed pump (air-driven diaphragm pump) - $2,500 Nutrient feed pump (peristaltic) - $500 Feedwater pump (centrifugal) - $500 Substrate flowmeter (pulse counter) - $1,000 Nutrient flowmeter (turbine) - $800 Feedwater flowmeter (turbine) - $1,000 In-line mixer - $100 Data logger for flowmeters and feed pump - $3,000 Hose for feedwater - $10/ft Hardware for injection well piping - $400	Equipment used during the test and nominal cost. Injection system design and construction cost is not included. These costs would be best estimated by the contractor performing the scale-up injections.

6.0 Results for the Immiscible Substrate Test

6.1 Injection Description and Results

The concept for the immiscible substrate injection process was to obtain an injection radius of about 8 m (25 ft) with a uniform emulsified oil concentration of about 60 g/L. Process water was used as the carrier medium for the substrate. Emulsion properties were carefully controlled to enable distribution to the target radius and to achieve a targeted oil concentration within the biobarrier. A tracer was injected with the substrate to help identify the injection front and for subsequent monitoring of injection solution elution from the test zone.

Injection flow rate of process water and emulsified oil are shown in Figure 6.1. The pressure response in the injection well and the surrounding monitoring wells during injection are shown in Figure 6.2 and Figure 6.3. The following parameters describe the details of the injection process.

- The average injection flow rate (water and all solutes) was approximately 147 L/min (38.7 gpm).
- The average emulsified oil injection flow rate while oil injection was occurring was approximately 8.6 L/min (2.3 gpm). The average oil injection flow rate during the overall oil injection phase was 5.3 L/min (1.4 gpm).
- Approximately 5,560 L (1470 gal) of emulsified oil were injected.
- The total injection volume was about 157,700 L (41,700 gal), including periods in which only process water was injected but not including process water injection before or after the oil injection phase.
- The average emulsified oil concentration during periods with oil injection was about 60 g/L.
- The injection duration of the oil phase was 17.4 hours, although the total duration of emulsified oil pulses was 10.7 hours.
- Based on the injected volume, estimated aquifer properties (5.6-m [18-ft] thick at the time of injection with a porosity of 0.14), and an idealized radial geometry, the nominal injection radius was 8 m (25 ft).
- About 30,600 L (8,100 gal) of water were injected after the emulsified oil injection was terminated, to flush the injection system, injection wellbore, and filter pack.
- About 67 L (17.7 gal) of concentrated sodium bromide tracer solution were injected (187 g/L Br^-), resulting in an average solution concentration of 75 mg/L as bromine, based on the concentrations measured in the injection well during injection.
- Injection pressure was variable throughout the injection, ranging from 3 to 17 psi.

The injection pressures monitored within the injection wellbore during substrate injection were higher than anticipated, based on the observed pressure response during developmental pumping and an initial injection test using only water. Pressure buildup was mitigated by pulse injection of the emulsion.

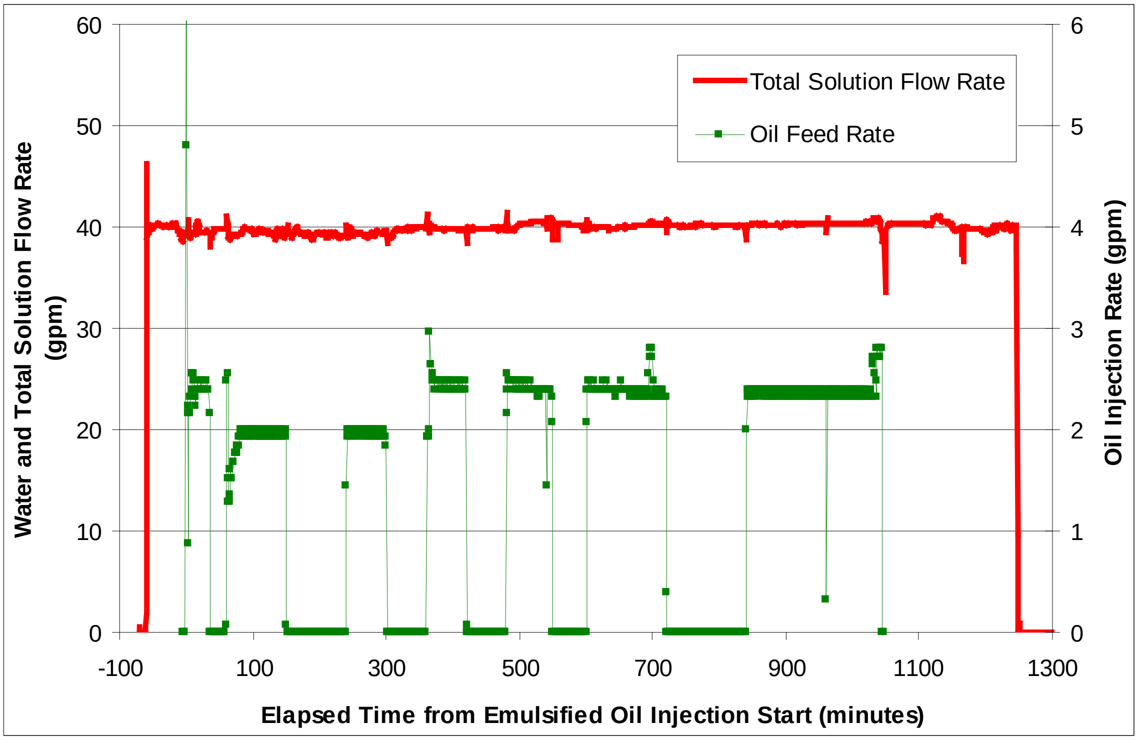


Figure 6.1. Flow Rate of Injected Solution and Emulsified Oil During the Injection Period

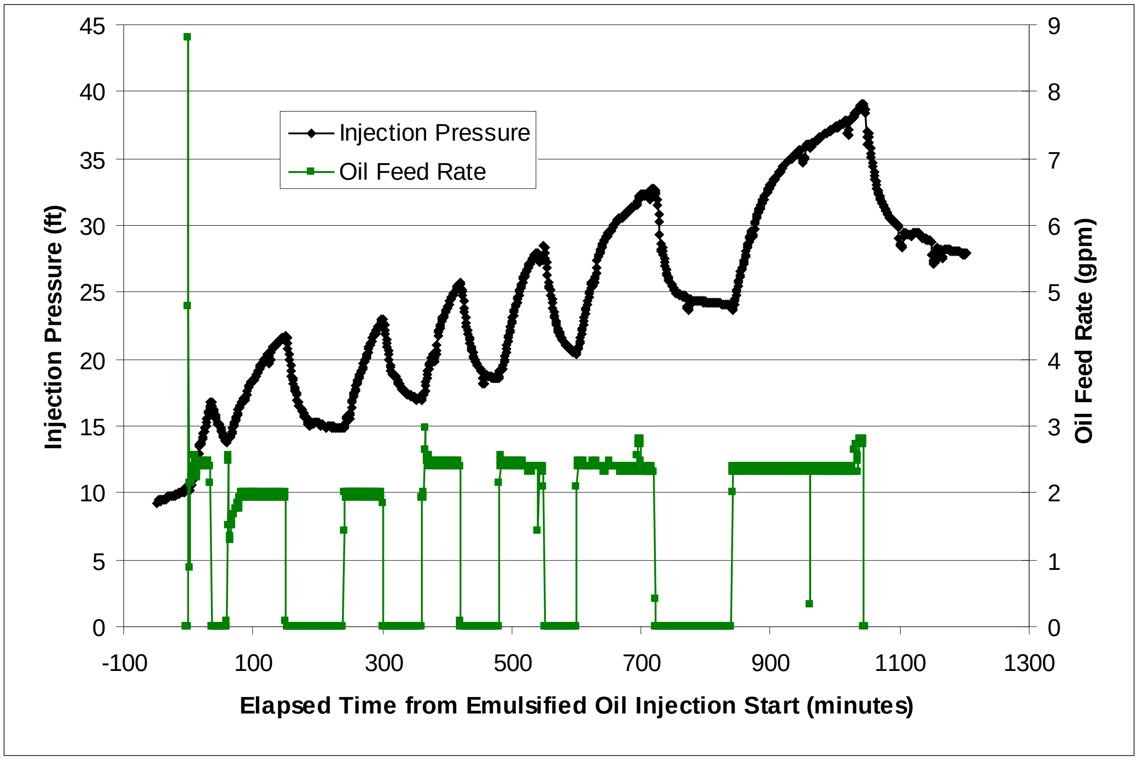


Figure 6.2. Injection Pressure (well 199-D5-108) During Emulsified Oil Injection

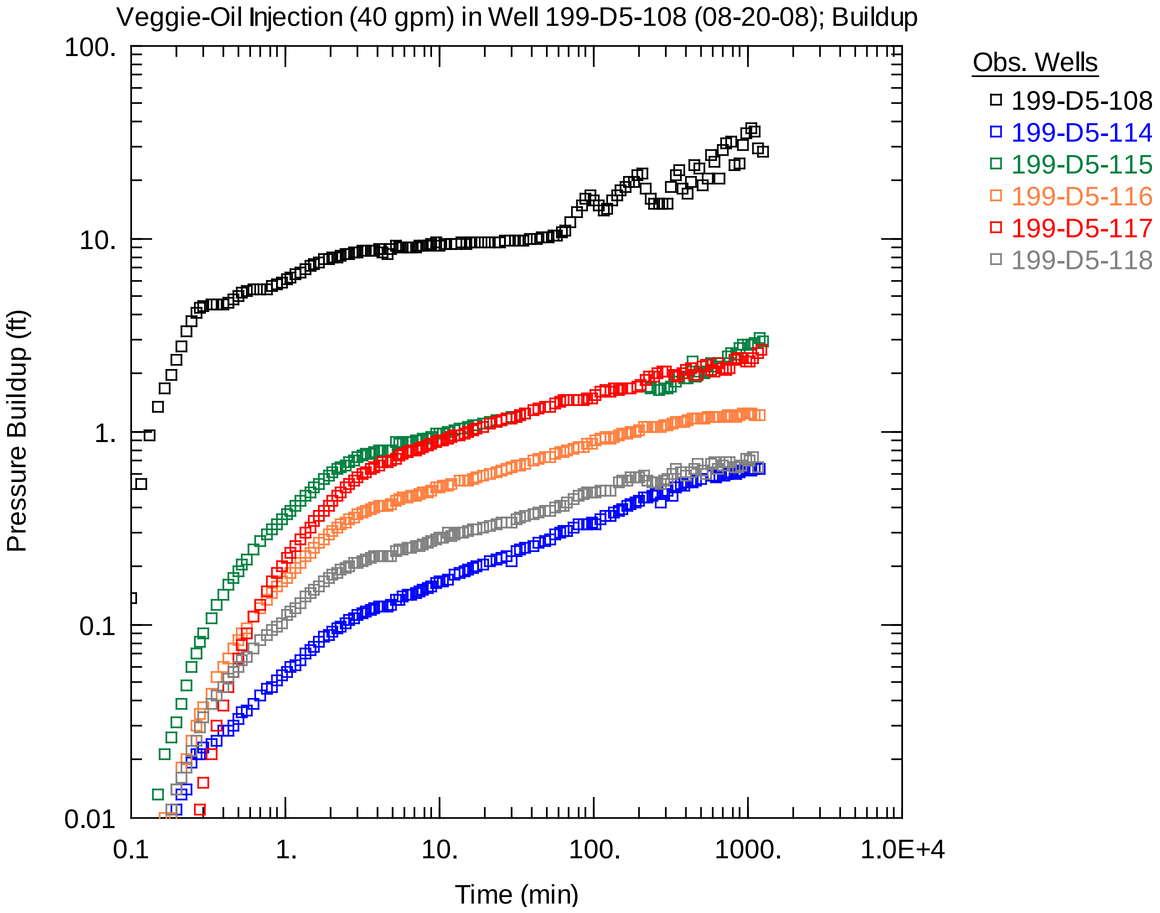


Figure 6.3. Pressure Response at Injection and Monitoring Wells During the Injection Period. Here elapsed time is from the start of water injection. Oil injection began 60 minutes after the start of water injection.

Primary data collected to monitor substrate injection are depicted in Figures 6.4 through 6.9.

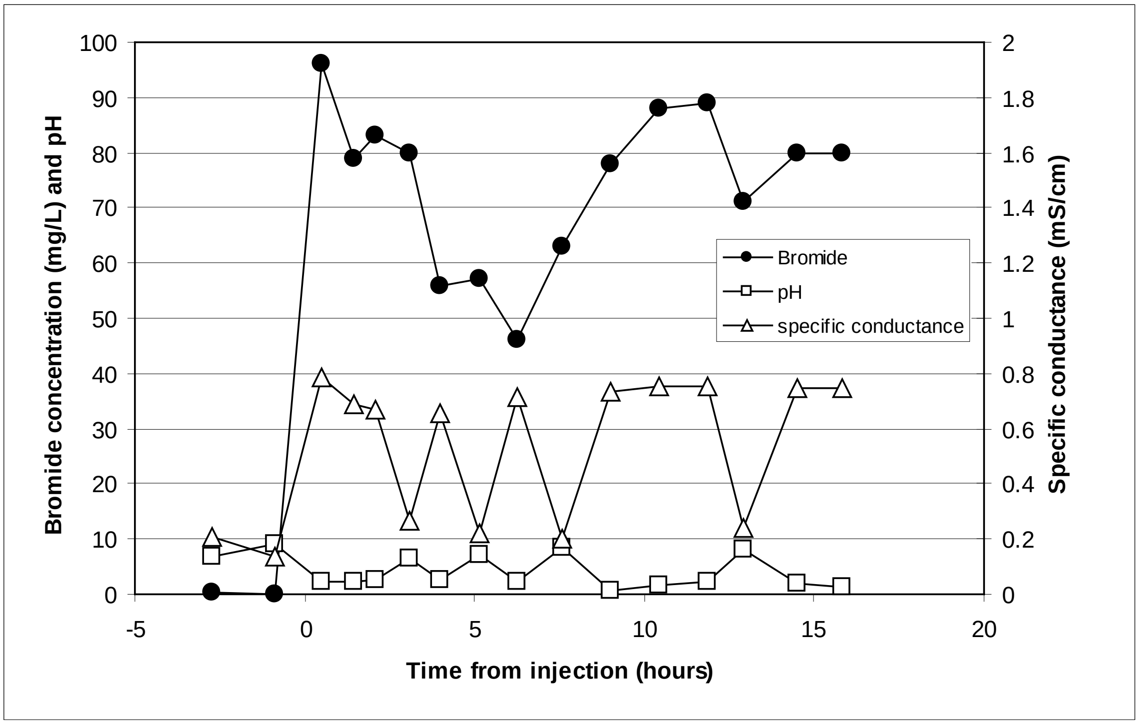


Figure 6.4. Operational Parameters Measured at Injection Well 199-D5-108 During the Injection Phase of the Test

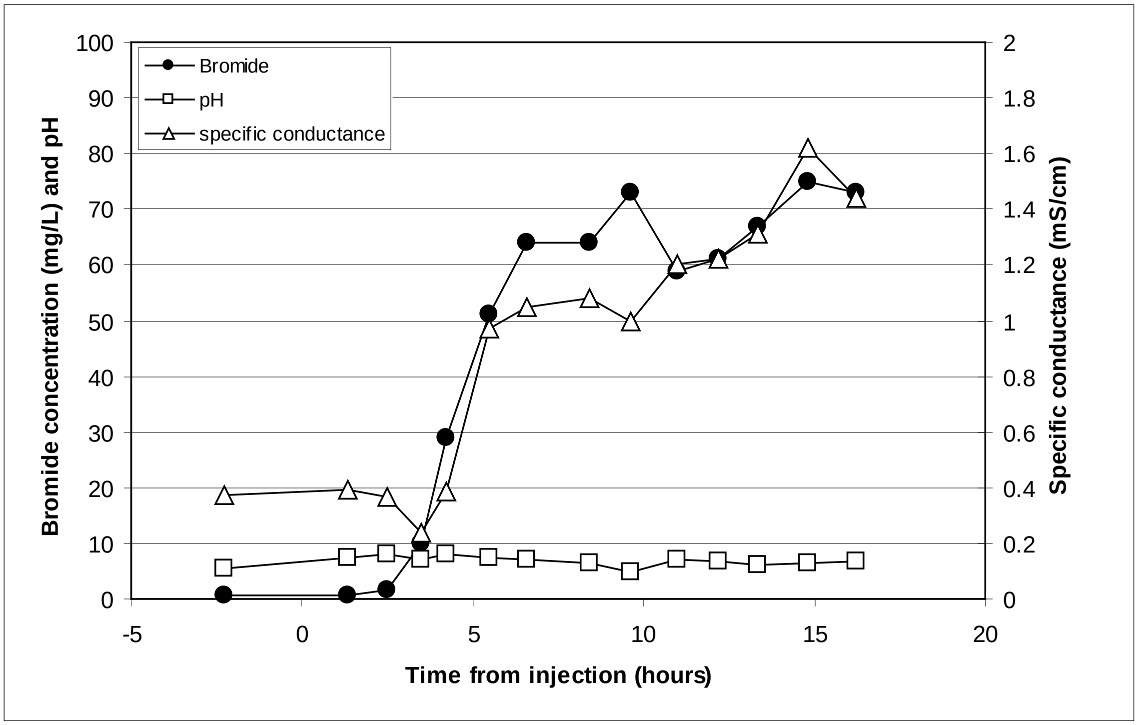


Figure 6.5. Operational Parameters Measured at Monitoring Well 199-D5-114 During Injection in 199-D5-108

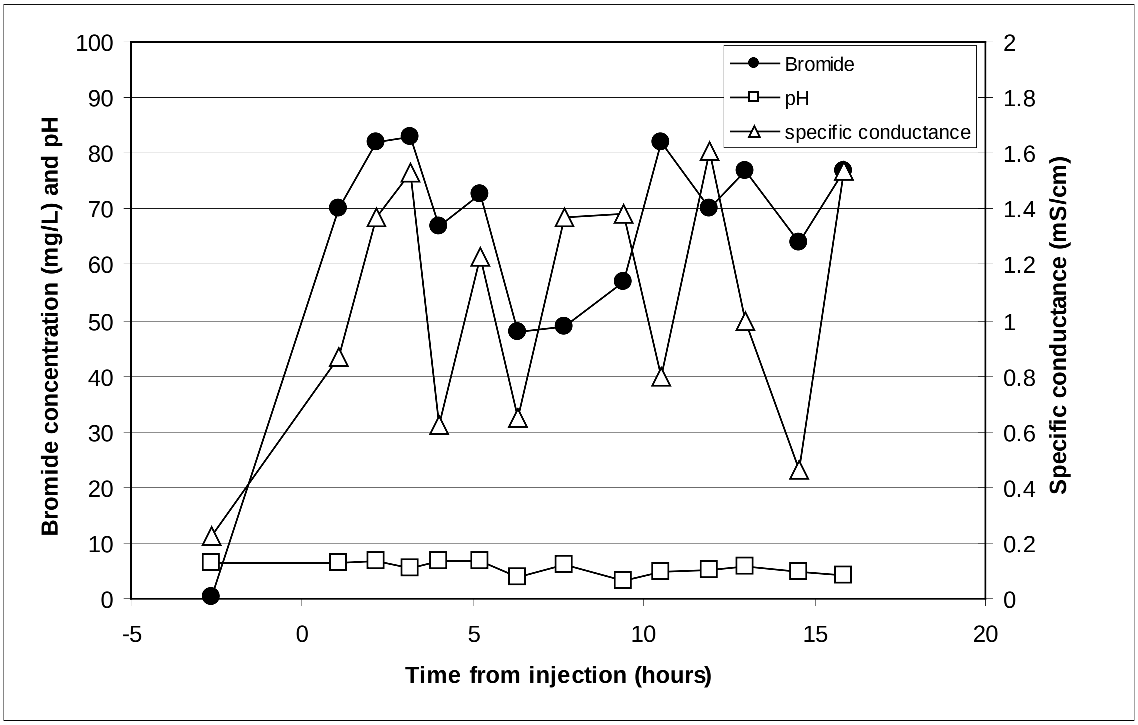


Figure 6.6. Operational Parameters Measured at Monitoring Well 199-D5-115 During Injection in 199-D5-108

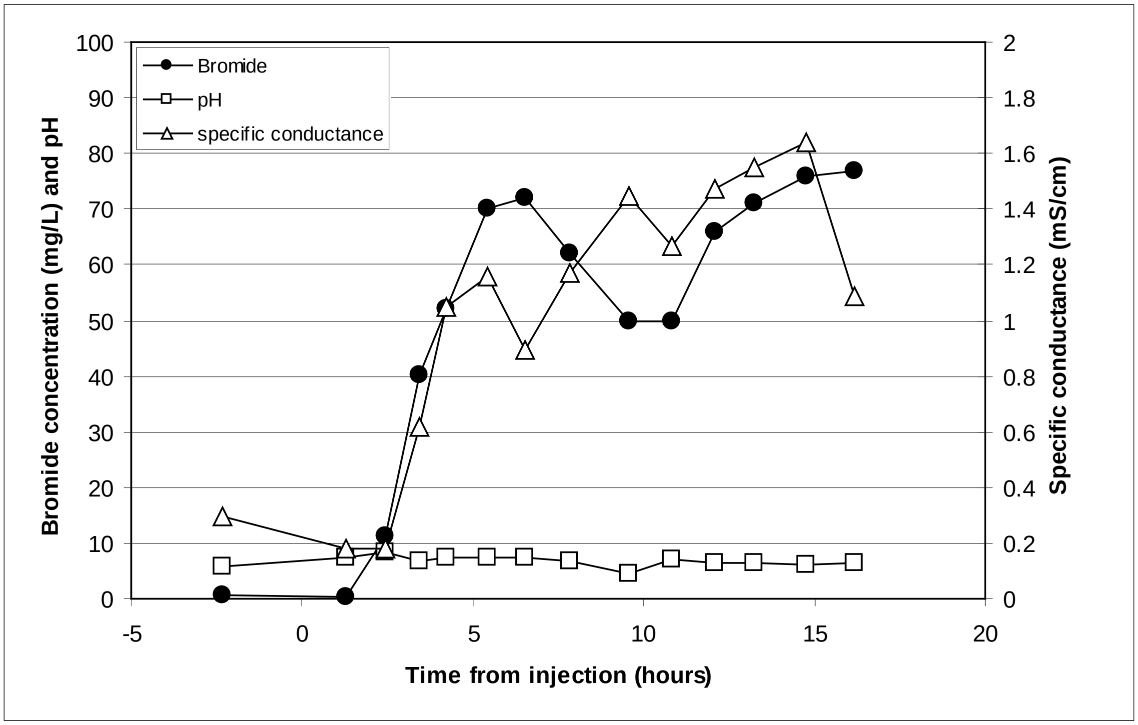


Figure 6.7. Operational Parameters Measured at Monitoring Well 199-D5-116 During Injection in 199-D5-108

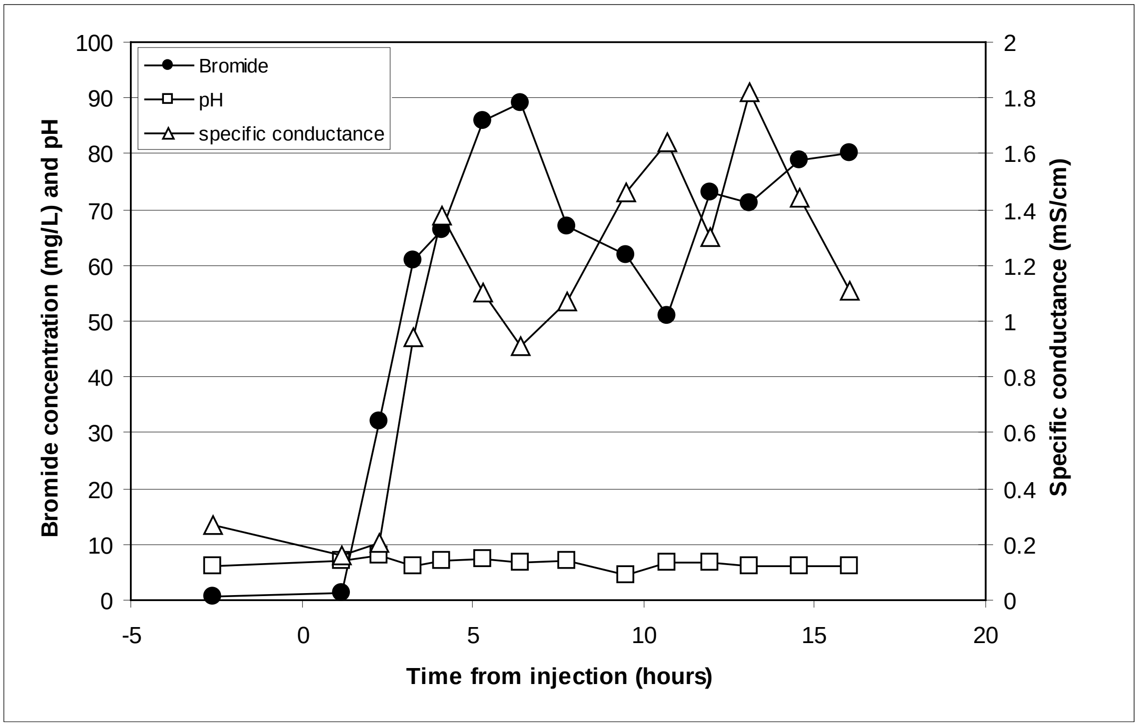


Figure 6.8. Operational Parameters Measured at Monitoring Well 199-D5-117 During Injection in 199-D5-108

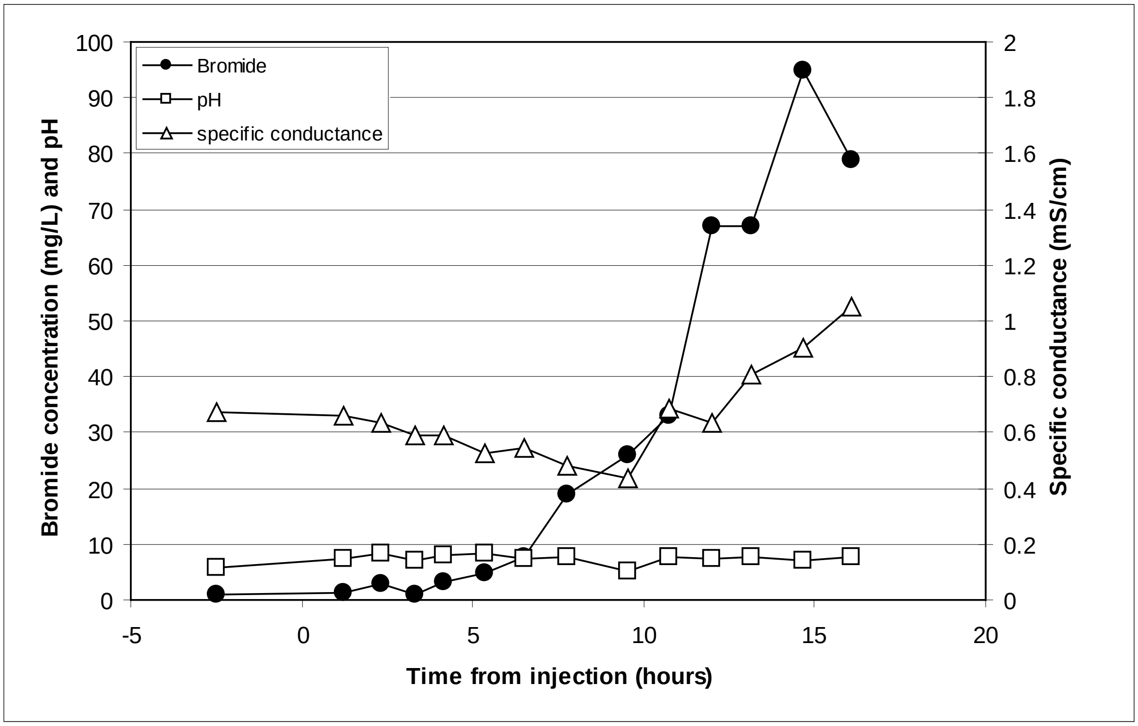


Figure 6.9. Operational Parameters Measured at Monitoring Well 199-D5-118 During Injection in 199-D5-108

Total organic carbon concentrations measured at the end of the injection process were used to assess the uniformity of substrate distribution. Based on the injected volume and the corresponding estimated injection radius of 8 m (25 ft), all monitoring wells should have had a TOC concentration comparable to the injected concentration by the end of the injection. As shown in Table 6.1, TOC data at monitoring wells 199-D5-115, and -117 are consistent with what would be expected for the substrate injection. Total organic carbon values are lower than expected at monitoring well 199-D5-116 and significantly lower than expected at wells 199-D5-114 and 199-D5-118 (lower zone monitoring).

Table 6.1. Total Organic Carbon Concentrations at the End of the Substrate Injection Period

Well	Total Organic Carbon (g/L)
199-D5-108 (injection well)	14.8[(a)]
199-D5-114	0.8
199-D5-115	10.2
199-D5-116	2.6
199-D5-117	12.2
199-D5-118	0.6

(a) Average during entire period when oil was injected.

In summary, the dissolved emulsified oil injection provided a large (~8 m radius) zone of substrate distributed around the injection well. Operations were relatively simple, although pulse injection was necessary to manage injection pressure. It is likely that injection to larger radial distances may be possible.

6.2 Performance Monitoring Results

Performance monitoring results with respect to the targeted treatment compounds, hydraulic properties, and overall biogeochemical conditions are presented in this section.

6.2.1 Water Chemistry for Target Compounds

Nitrate, dissolved oxygen, and chromate were the target compounds for treatment in the biobarrier. In summary, low concentrations of nitrate, nitrite, chromium and oxygen were maintained throughout the test duration.

6.2.1.1 Nitrate/Nitrite

Data indicate that nitrate concentration within the test cell remained below 1 mg/L over a duration of 10 months. During this time, nitrite concentrations did not increase to above 1 mg/L. As demonstrated in laboratory experiments, the site microbial population is capable of full denitrification without buildup of nitrite as an intermediate compound. Details of the results over the test period are depicted in Figure 6.10 and Figure 6.11.

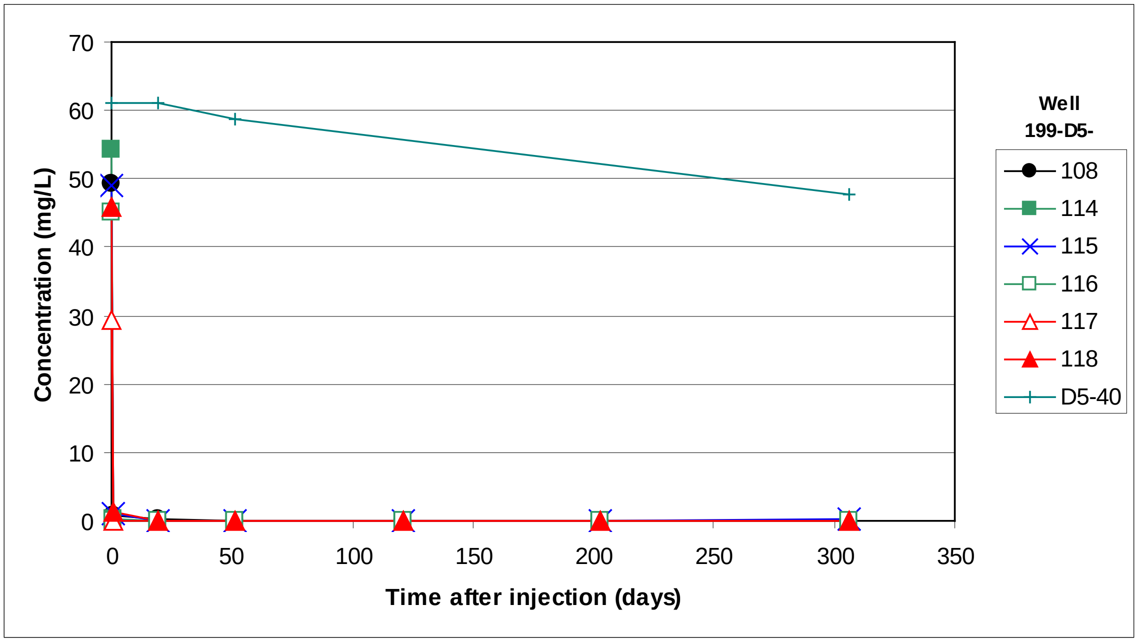


Figure 6.10. Nitrate Concentrations over the Duration of the Test

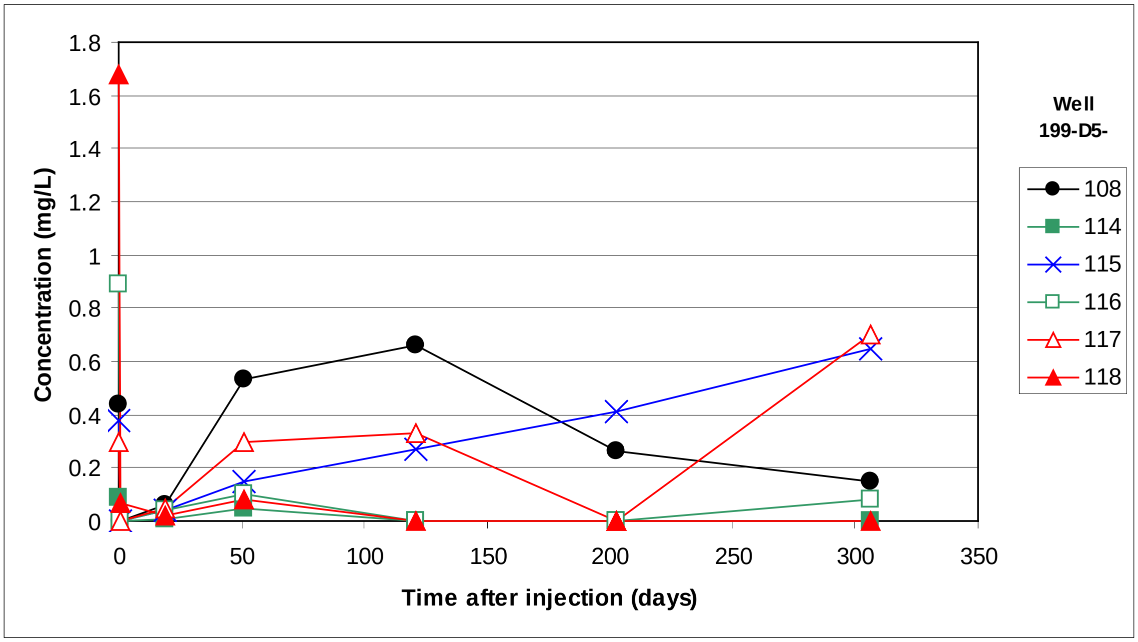


Figure 6.11. Nitrite Concentrations over the Duration of the Test

6.2.1.2 Dissolved Oxygen

Data indicate that dissolved oxygen concentration within the test cell remained below 1 mg/L over a duration of 10 months at all wells.

6.2.1.3 Chromate/Chromium

Chromate reduction in the test cell was monitored using measurements of total chromium (from laboratory inductively coupled plasma mass spectrometry analysis) in water samples. The data indicate that total chromium concentrations in the test cell were significantly lower than background upgradient concentrations in well 199-D5-40. Details of the results over the test period are depicted in Figure 6.12.

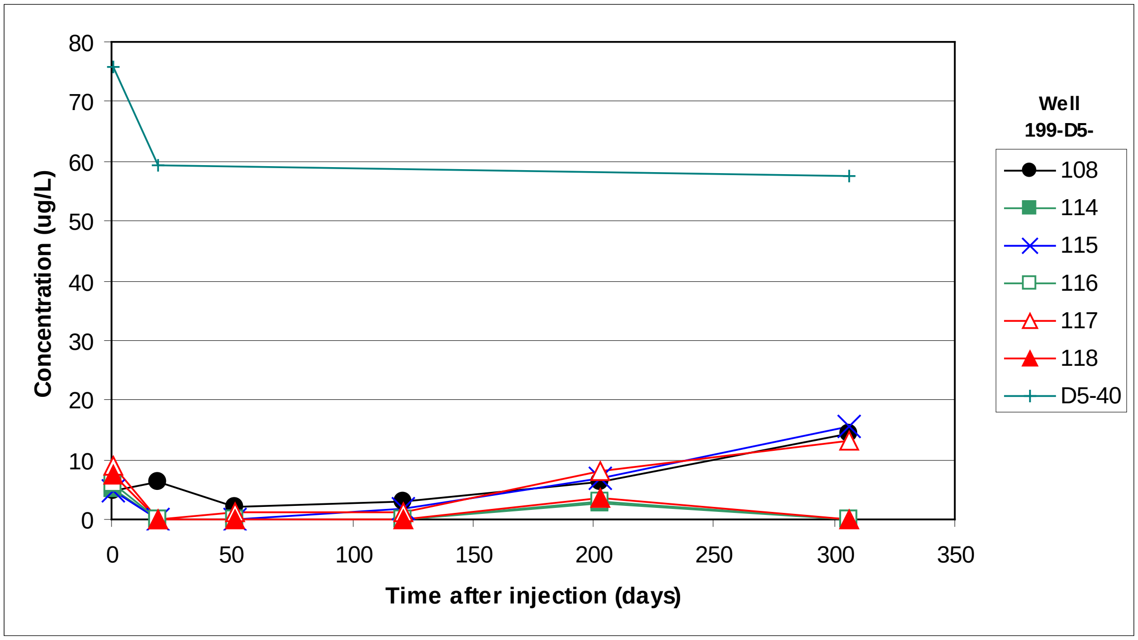


Figure 6.12. Total Chromium Concentrations over the Duration of the Test

6.2.2 Hydraulic Conductivity

Hydraulic conductivity was assessed through hydraulic slug testing, geophysical testing, and bromide elution.

6.2.2.1 Hydraulic Slug Test Results

Hydraulic slug testing was conducted prior to injection (August 2007) and in November 2008 approximately 90 days after substrate injection. Table 6.2 shows the results of these tests in terms of the relative hydraulic conductivity of the post-injection test compared to the pre-injection test. In contrast to the molasses injection, permeability in the immiscible substrate test cell changed quickly and appears to be due to the presence of the injected oil rather than due to significant biomass growth. Because of the slow dissolution of substrate over time, additional permeability reduction is not expected. Full details of the hydraulic slug testing are shown in Appendix F.

Table 6.2. Permeability Change Results Based on Slug Testing

Well Name	Permeability Change (K_{post}/K_{pre})[a]
199-D5-114	0.57
199-D5-115	0.32
199-D5-116	0.36
199-D5-118	0.70

(a) Results are based on data for the pre-injection result (August 2007) and post-injection result conducted November 2008.

6.2.2.2 Geophysical Testing Results

Time-lapse electrical and radar tomograms associated with the vegetable oil test cell are shown in Figure 6.13 and Figure 6.14, respectively. Comparison of the baseline electrical image (Figure 6.13a) and the one collected 2 days post-injection (Figure 6.13b) shows that there is a 10–70% decrease in resistivity (or increase in electrical conductivity), which is consistent with the laboratory studies. Both Figure 6.13b and Figure 6.13c illustrate the influence of heterogeneity on the amendment distribution—most of the electrical conductivity changes occurred near the water table and in the unit at ~30 m bgs that is likely more permeable. The time-lapse images show that the amendment becomes more distributed over time: at 2 days after injection, much of the amendment is near the water table and in the presumably higher-permeability zones but is more completely distributed at 2 months post-injection.

The baseline and time-lapse radar tomograms (Figure 6.14b) reveal behavior similar to that observed with the electrical data. Consistent with laboratory experiments, the post-injection images reveal ~10% decreases in dielectric constant. They also show that the amendment appears to be distributed most near the water table and within the unit located at ~30 m bgs. The seismic data (not shown) were not as useful. On the baseline data, some of the amplitudes near the water table were attenuated (likely due to trapped gas associated with a fluctuating water table), and the amplitudes on the data sets collected post-injection were also attenuated, likely due to evolved gasses (such as N_2 and CO_2). The geophysical imaging reveals that the radius of influence of the substrate injection extended at least 6 m from the injection well.

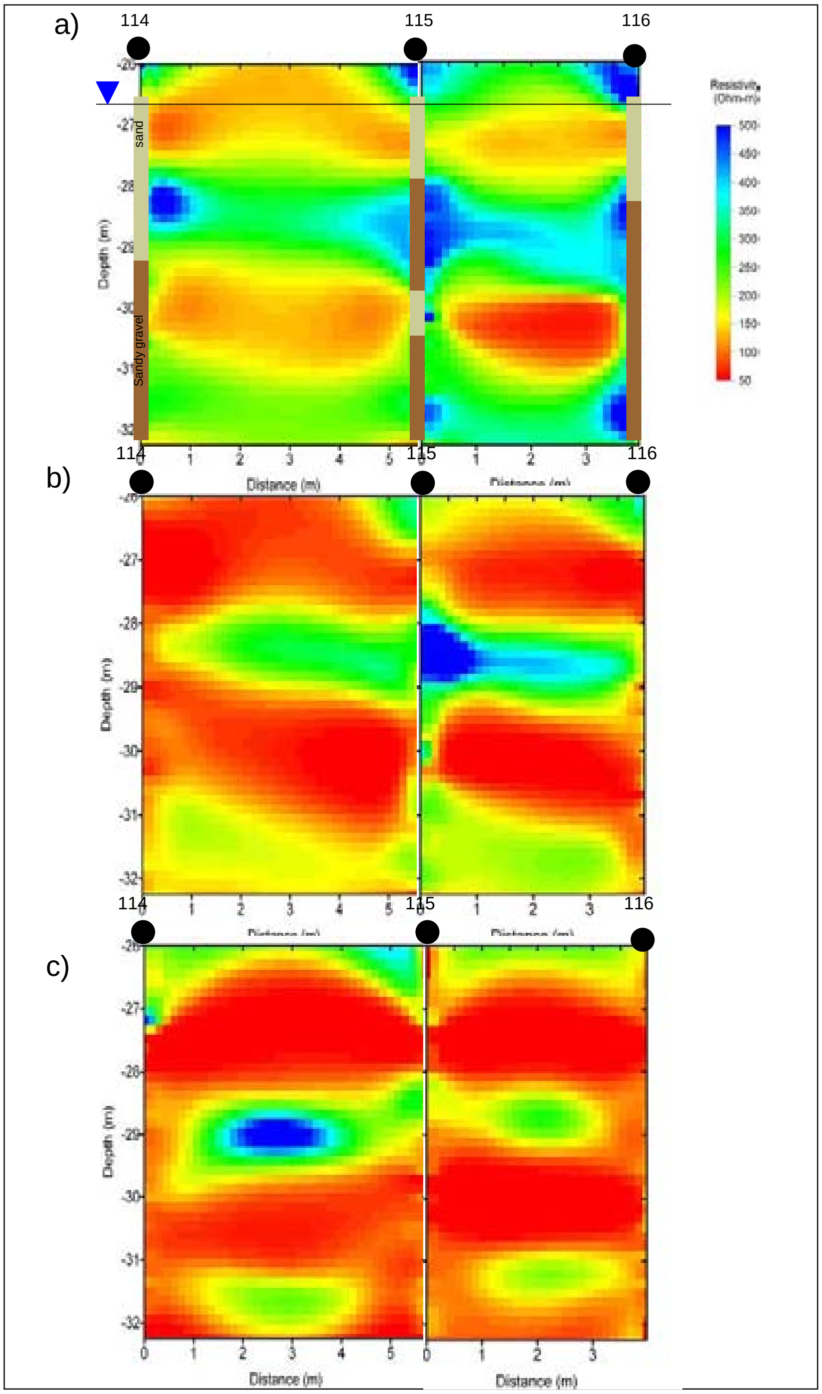


Figure 6.13. Electrical Resistivity Tomagraphy Inversions Showing Electrical Conductivity Along Two Transects (wells 114-115 and 115-116). (a) Prior to injection (August 19, 2008); (b) 2 days post-injection (August 22, 2008); (c) 3 months post-injection (November 18, 2008).

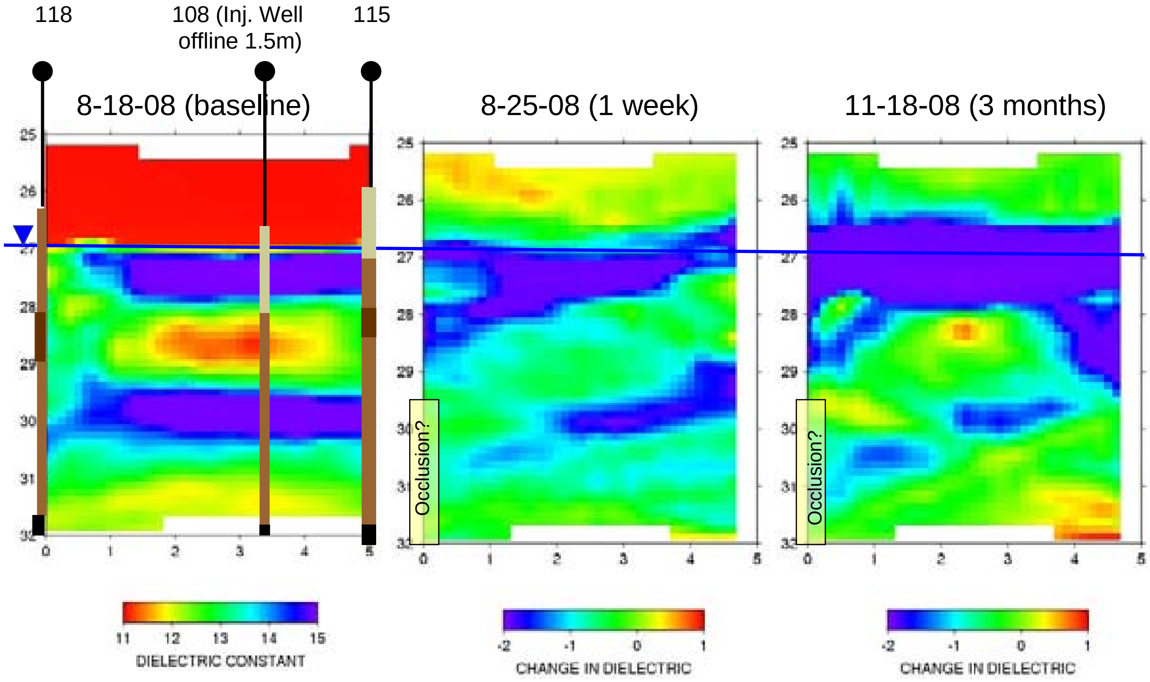


Figure 6.14. Baseline Radar Tomogram (left) and Difference Tomograms (middle and right) Indicating Change in Dielectric Constant Post-Injection Along Transect 118-115

6.2.2.3 Bromide Elution

Bromide concentrations at the test cell monitoring wells show only slow elution where only 2 wells have eluted bromide to concentrations at or below 50% of the initial concentration through 306 days of monitoring. The two wells showing the greatest elution are the downgradient well, 199-D5-114, with 50% concentration by day 121 and the upgradient well, 199-D5-116, with 50% elution by day 306. Using the hydraulic conductivity reduction measured in the post-injection hydraulic slug test analysis and the average hydraulic gradient over the test duration, the average groundwater movement through the test cell would be about 19.5 m in 306 days. The average groundwater movement suggests that one pore volume would have moved through the test cell over the 306 day monitoring period whereas the bromide elution data suggest less movement.

6.2.3 Performance Assessment

The immiscible substrate biobarrier maintained low nitrate, nitrite, dissolved oxygen and chromium concentrations over the duration of the monitoring period (10 months). During this time, conditions within the test cell changed in response to the addition of the substrate and associated biogeochemical reactions that were induced. Figures 6.15 through 6.20 show the trends in primary biogeochemical parameters, including total organic carbon, acetate, pH, and sulfate. Although all of these changes indicate that appropriate reactions are occurring. The monitoring period is short compared to 1) the time required for groundwater to travel through the test cell and 2) the expected duration of the oil substrate. Both the hydraulic conductivity assessment and bromide elution data suggest that groundwater flow through the test cell is slow. Thus, continued monitoring would be needed to evaluate the capacity and longevity of the induced biobarrier.

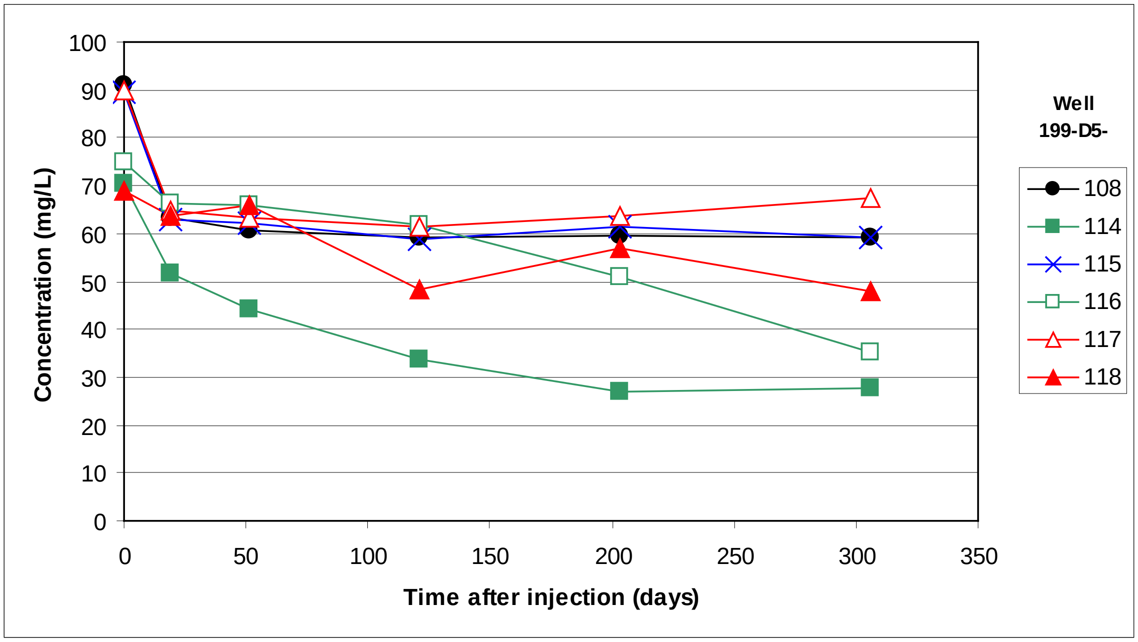


Figure 6.15. Bromide Concentrations over the Duration of the Test

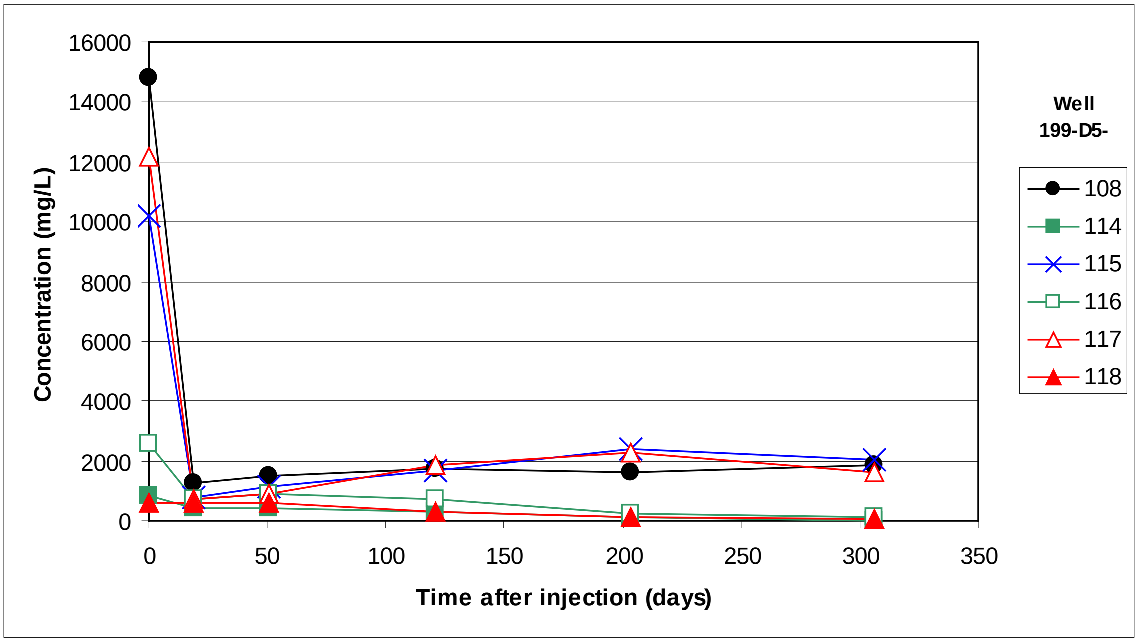


Figure 6.16. TOC Concentrations over the Duration of the Test

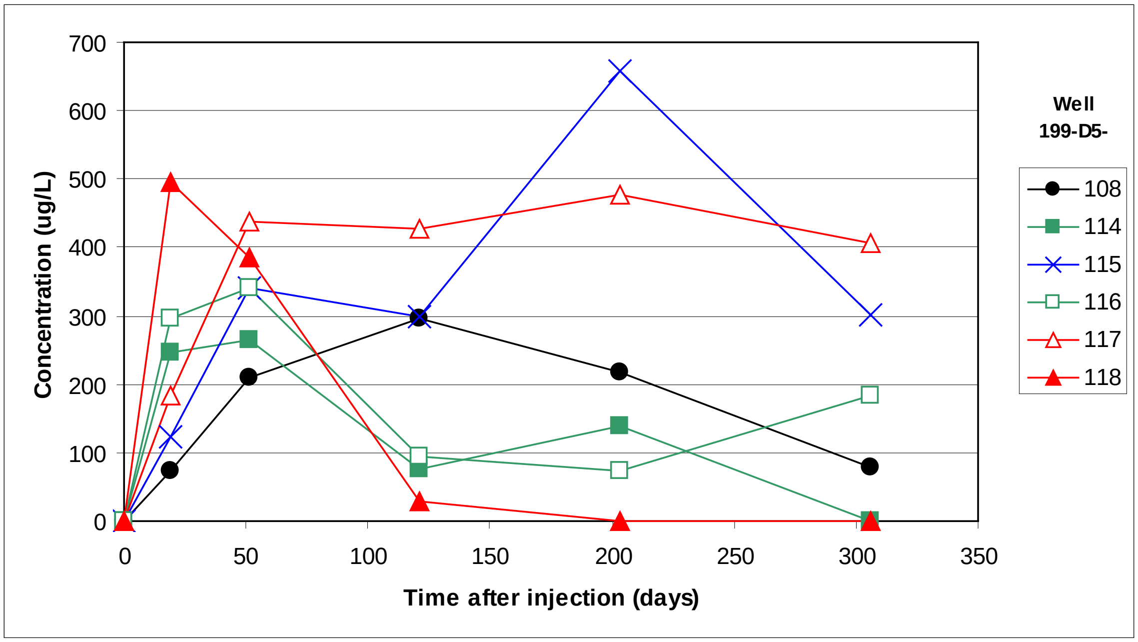


Figure 6.17. Acetate Concentrations over the Duration of the Test

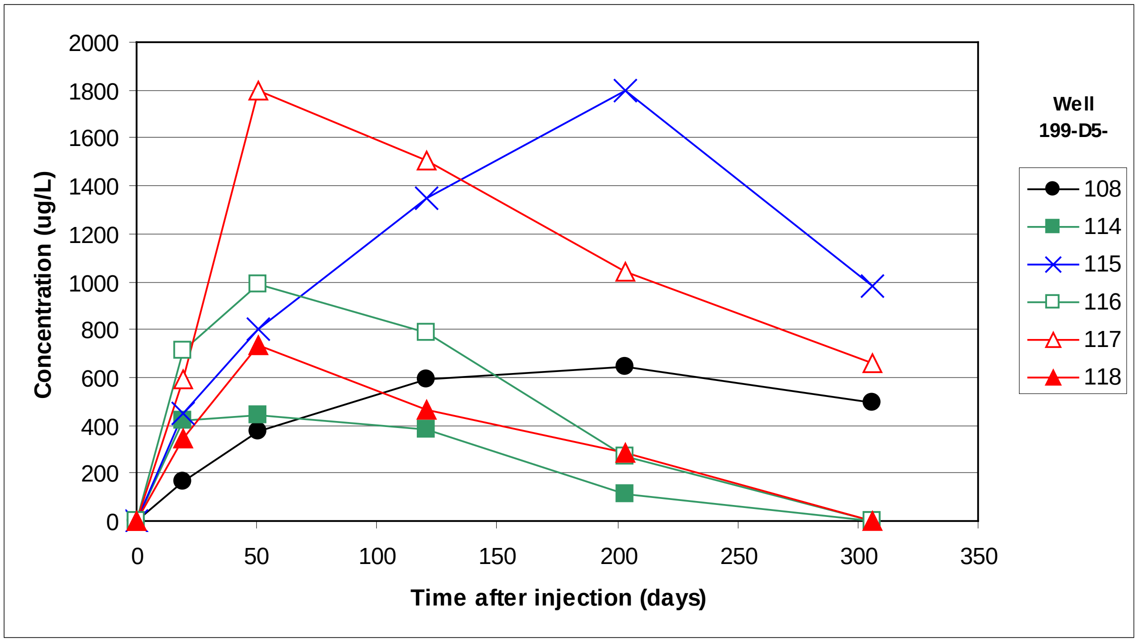


Figure 6.18. Propionate Concentrations over the Duration of the Test

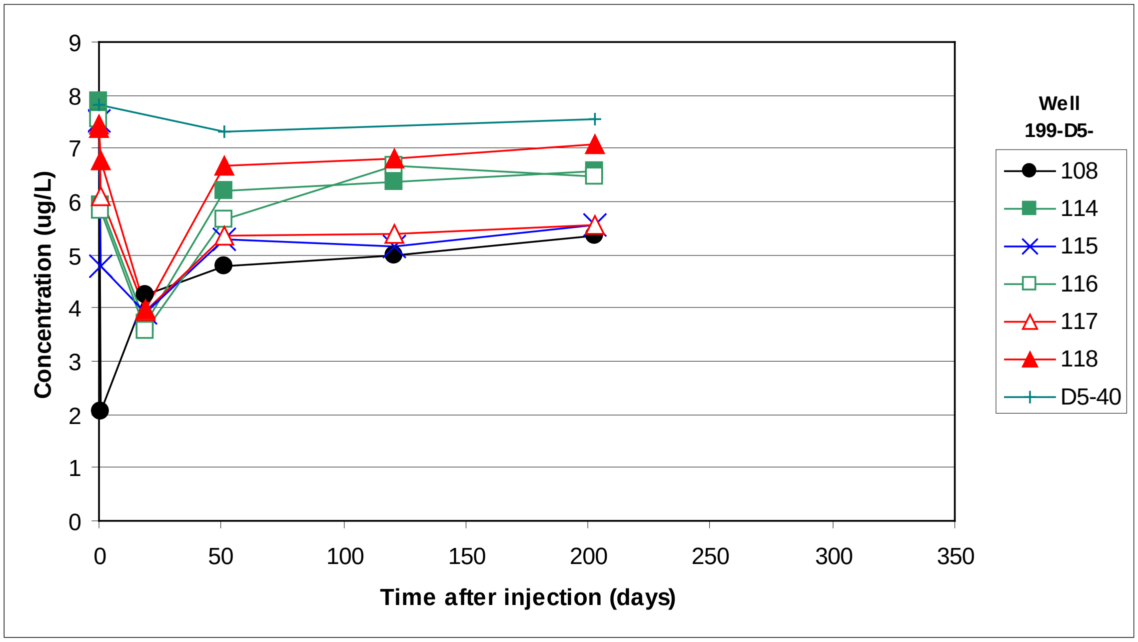


Figure 6.19. pH over the Duration of the Test. Data are not available for the last sampling time (day 306). Data for day 203 for well 199-D5-40 are also not available. The plotted point at day 203 is the average pH over the duration of the test at well 199-D5-40.

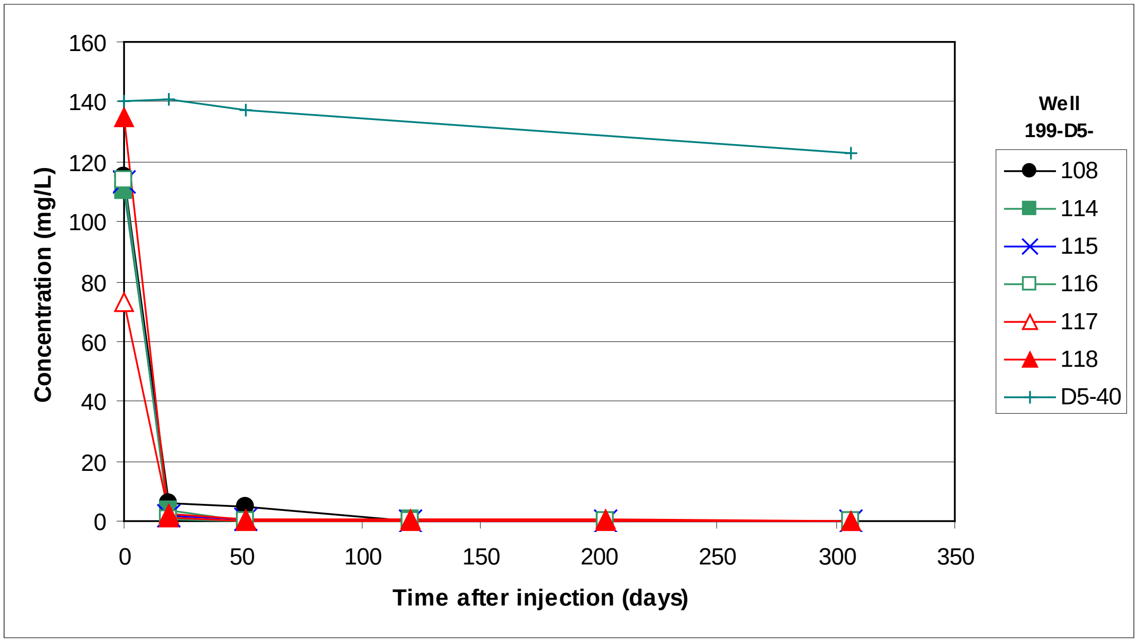


Figure 6.20. Sulfate Concentrations over the Duration of the Test

Several early trends in the data are noteworthy. The total organic carbon declined rapidly as oil droplets became attached to sediment surfaces. However, the total organic carbon concentrations are then maintained in wells 199-D5-108, -115, and -117 at nearly 2 g/L. The total organic carbon concentrations appear to correspond to the summation of propionate and acetate concentrations. These two organic acids are typical fermentation products of lactate. The emulsified oil solution contained 4% lactic acid. The initial pH decline was expected due to the acidic nature of the injected solution (i.e., lactic acid). The pH of the groundwater is beginning to recover, but is slowly evolving, potentially due to the slow groundwater flow conditions.

As with the soluble substrate test cell, the apparent performance in terms of nitrate, dissolved oxygen, and chromate reduction is affected by the rate at which constituents are carried into the test cell. Because the hydraulic conductivity decreased within the test cell, the flow rate through the test cell is slow and the biogeochemical data will therefore evolve slowly. The reduction in hydraulic conductivity occurred rapidly, indicative of a physical effect rather than a biological effect. Full scale application of a biobarrier should consider changes to the flow field and associated solute flux through the biobarrier. The decreased flow rate suggests that continued monitoring would be needed to fully determine the capacity and longevity of the induced biobarrier.

6.2.4 Water Quality

Within the test cell, water quality was negatively impact by an increase in the concentration of metals and organic constituents and a decrease in oxidation-reduction potential and dissolved oxygen concentration. These changes were expected due to the imposed anaerobic conditions required for biological treatment of dissolved oxygen, nitrate, and chromate. Although the concentration of most metals increased, only three, arsenic, barium, and selenium, increased to concentrations consistently above the maximum contamination level. The concentration profiles for these metals are shown in Figures 6.21 through 6.23. A biobarrier design requires a downgradient portion of the aquifer where these water quality impacts can recover and this type of recovery region would need to be considered as part of determining the location for biobarrier application.

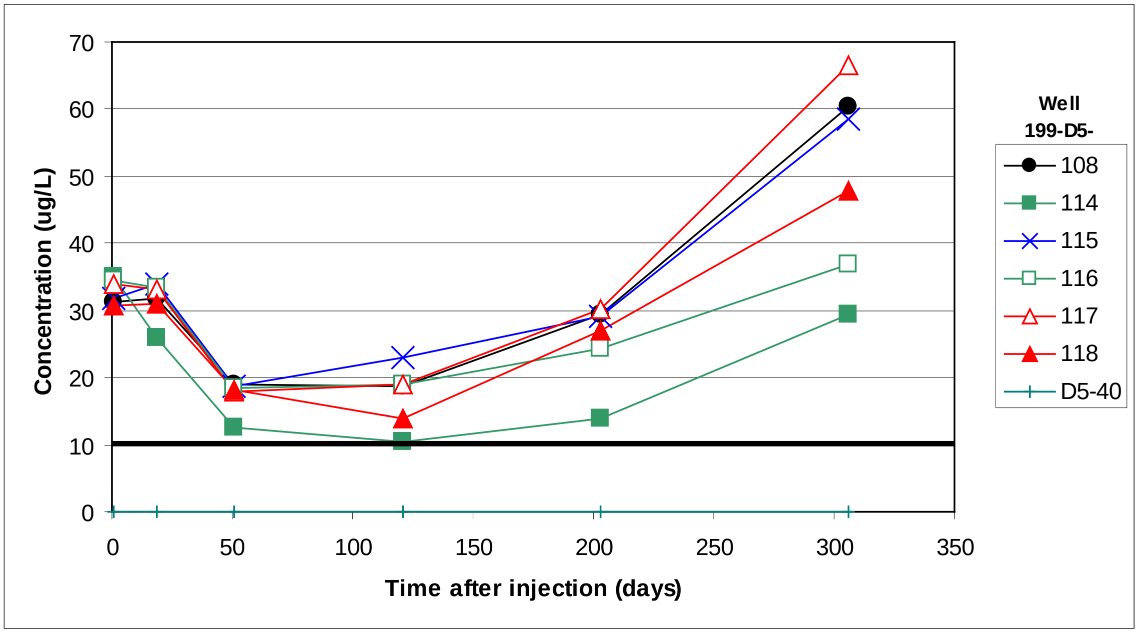


Figure 6.21. Arsenic Concentrations During the Test. The drinking water Maximum Contaminant Level (MCL) for arsenic is 10 µg/L.

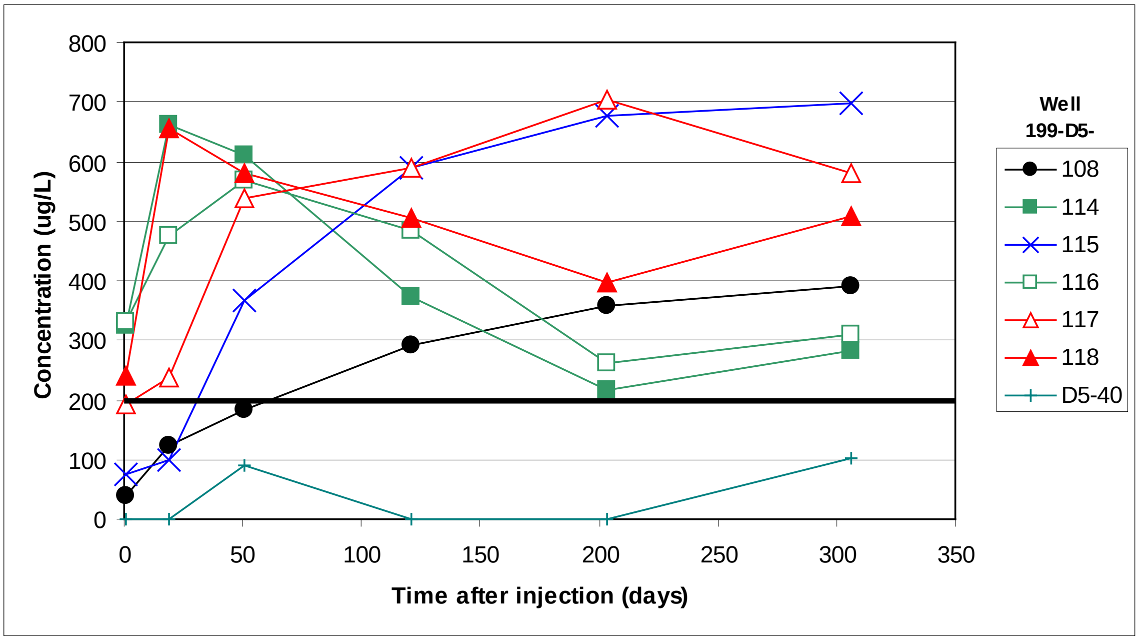


Figure 6.22. Barium Concentrations During the Test. The drinking water Maximum Contaminant Level (MCL) for barium is 200 µg/L.

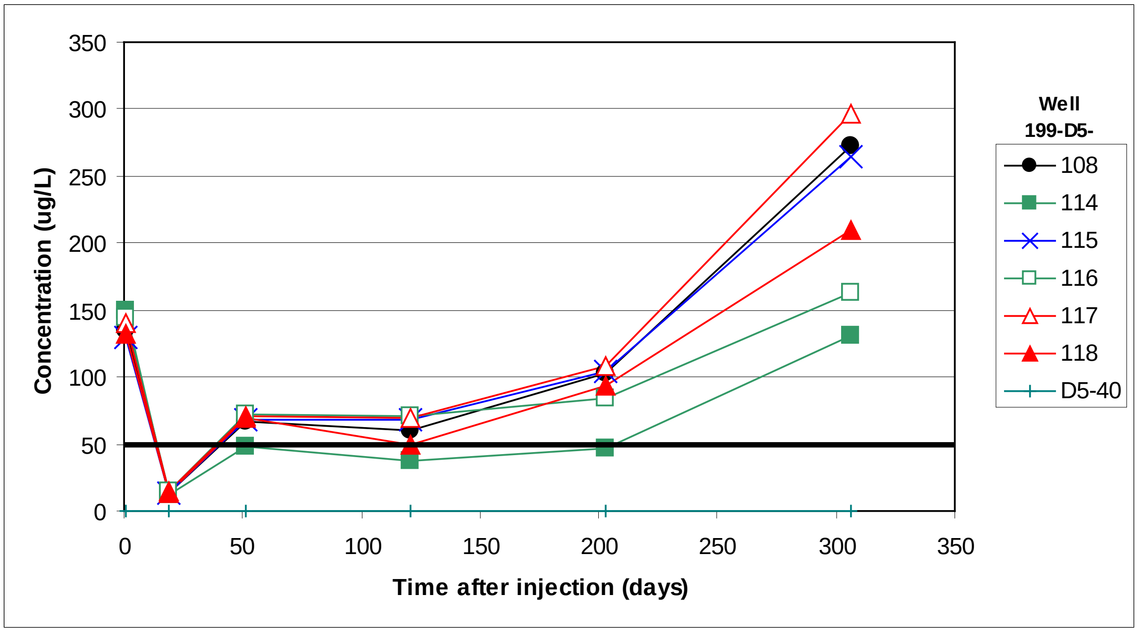


Figure 6.23. Selenium Concentrations During the Test. The drinking water Maximum Contaminant Level (MCL) for selenium is 50 µg/L.

6.3 Summary of Laboratory Emulsion Experiments

Laboratory experiments were conducted to evaluate the distribution and retention of emulsified oil as a function of sediment properties relevant to the Hanford field test. Emulsified oil offers potential advantages for biobarrier application due to its potential for creating a long-lasting barrier. However, because emulsified oil is a nonaqueous phase substance delivered as small droplets, distribution of emulsified oil within the subsurface is controlled by parameters different from those for distribution of a soluble substrate. In addition, a sufficient quantify of the oil must be delivered and retained within the targeted biobarrier to promote long barrier life and adequate contaminant treatment. Results of the laboratory testing and their relationship to the Hanford field test are presented in the following subsections.

6.3.1 Methods

A series of experiments was conducted with three different laboratory-grade Accusands (Table 6.3). Detailed properties of these porous media can be found in Schroth et al. (1996). The 70, 40/50, and 20/30-mesh sands are classified as a fine-, medium-, and coarse-grained sand, respectively. The 1-m-long rectangular columns, with a cross-sectional area of 30 cm^2, were packed under saturated conditions to obtain average porosities listed in Table 6.4. Simulations were conducted to help interpret the experimental results using the STOMP code. Details of the simulations are described by Oostrom.[1]

The oil-emulsion used in the experiments had properties similar to those of the emulsion used by Borden (2007). The emulsion (EOS 598, www.EOSRemediation.com) contains 59.8% by weight emulsified soybean oil, food-grade surfactants (10.1%), and lactate (4%). The emulsion was prepared using high-energy mixing with nonionic surfactants to obtain an emulsion with a relatively mean uniform droplet size of 1.9 µm (standard deviation = 0.8 µm). The statistics of the droplets were determined microscopically using a standard particle analysis technique. For the experiments, the EOS 598 was diluted by a factor 5, to obtain an injection oil concentration of 0.12 g/cm^3. This concentration was used by Borden (2007) and Coulibaly (2006) in their column experiments. For each sand, three experiments were conducted with injections of 1, 0.1, and 0.05 pore volumes (PVs) of the emulsion, followed a flush of 4 PVs of tapwater. Pore volume values are listed in Table 6.4. The injection rate for all experiments was 10 cm^3/min. Effluent samples were collected every 30 min. After the experiment was completed, the column was immediately divided into 10-cm-long sections. Three approximately 50-g samples were obtained from each section, and the oil concentration was determined using high-temperature ignition.

The maximum oil retention, $C_{im}^{\max}$, for each sand was determined independently by flushing a 30-cm-long, 2.54-cm-internal diameter column with emulsion for 10 PVs, followed by a 10-PV tapwater flush. After the flushes, all the sand in the column was collected, and five approximately 50-g samples were obtained. The samples were first dried, followed by ignition at 550°C. The gravimetric oil concentrations resulting from this procedure were assumed to be representative of the maximum oil retention and are listed in Table 6.4. The equivalent collector diameter, d_c, was assumed to be equal to the d_{10} value and was extracted from Schroth et al. (1996). The only parameter not independently obtained was the empty bed collision efficiency, α. The value in Table 6.4 was taken from Borden (2007), as it represents an efficiency for similar soybean emulsion in a sandy porous medium.

Table 6.3. Emulsion Column Experiments Overview

Experiment	Sand Type (mesh)	Emulsion Injection Duration
A1	70	1 PV
A2	70	0.1 PV
A3	70	0.05 PV
B1	40/50	1 PV
B2	40/50	0.1 PV
B3	40/50	0.05 PV
C1	20/30	1 PV
C2	20/30	0.1 PV
C3	20/30	0.05 PV

Table 6.4. Overview of Parameter Values for the Three Laboratory Sands

Parameter	70-mesh	40/50 mesh	20/30 mesh
Porosity	0.42	0.33	0.35
Dry bulk density (g/cm^3)	1.54	1.78	1.72
Pore volume (cm^3)	1260	990	1050
Equivalent collector diameter, d_c(m)	2.0×10^{-4}	3.1×10^{-4}	6.2×10^{-4}
Empty bed collision efficiency, α	2.5×10^{-5}	2.5×10^{-5}	2.5×10^{-5}
Emulsion mean droplet size, d_n (m)	1.9×10^{-6}	1.9×10^{-6}	1.9×10^{-6}
Maximum oil retention, $C_{im}^{\max}$ (g/g)	0.0038	0.0022	0.0010
Emulsion injection concentration (g/cm^3)	0.12	0.12	0.12
Oil density (g/cm^3)	0.95	0.95	0.95

6.3.2 Results

Experimental and simulated results for experiments A1, A2, and A3 in the fine-grained 70-mesh sand are shown in Figures 6.24, 6.25, and 6.26, respectively. For the 1-PV injection (Figure 6.24), emulsion breakthrough concentrations are close to the injection concentration of 0.12 g/cm^3. The sediment concentrations throughout the column are predicted to be at the maximum level. For the listed dry bulk density, the total emulsion mass remaining in the column after flushing amounts to 17.1 g. Because the 1-PV of oil emulsion used for the injection contained 148.8 g oil, this result is according to expectation. The experimental data follow the trends of the predictions. The observed scatter is consistent with the relatively large errors associated with the ignition method and the relatively low oil concentrations

A reduction of the injected oil volume for experiments A2 and A3 resulted in much smaller emulsion concentration effluent peaks. For these experiments with 0.1- and 0.05-PV injections, almost all the injected oil mass is predicted to remain in the sediment. Again, the experimental data follow the trends predicted by the simulator. For experiment A3, the effluent concentrations were too small for meaningful experimental observation. The sediment concentrations shown in Figure 6.25 indicate that for the 0.05-PV injection, the emulsion volume was barely sufficient to transport out to the top of the column.

Experimental and simulated results for experiments B1, B2, and B3 in the medium-grained 40/50-mesh sand are shown in Figures 6.27, 6.28, and 6.29, respectively. The maximum oil retention for this sand is almost a factor of two smaller than for the 70-mesh sand. As a result, compared to the experiments for the 70-mesh sand, more oil was flushed through the columns. The experimental sediment emulsion and breakthrough concentrations are again consistent with the simulated results.

Experimental and simulated results for experiments C1, C2, and C3 in the coarse-grained 20/30-mesh sand are shown in Figures 6.30, 6.31, and 6.32, respectively. For this coarse sand, the maximum oil retention is only about 25% of the 70-sand retention. As a result, even for the 0.05-PV injection, the added emulsion mass is sufficient to maximize the retained oil concentration in the sediment.

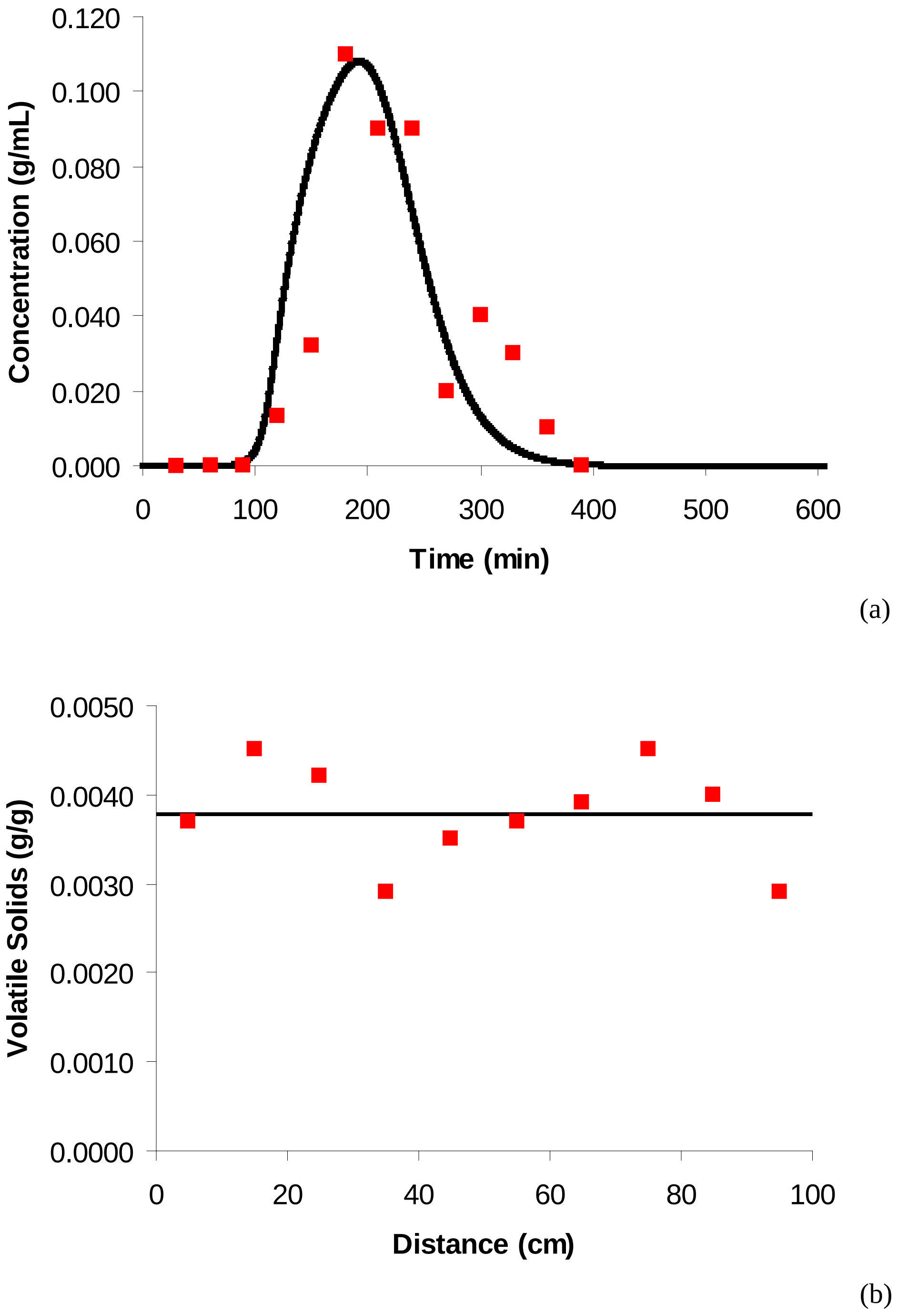


Figure 6.24. Comparison of Simulated and Observed Volatile Solids Concentrations for Experiment A1. (a) column effluent, and (b) sediment after completion of the experiment. Points represent the experimental data. The solid line represents the simulated values.

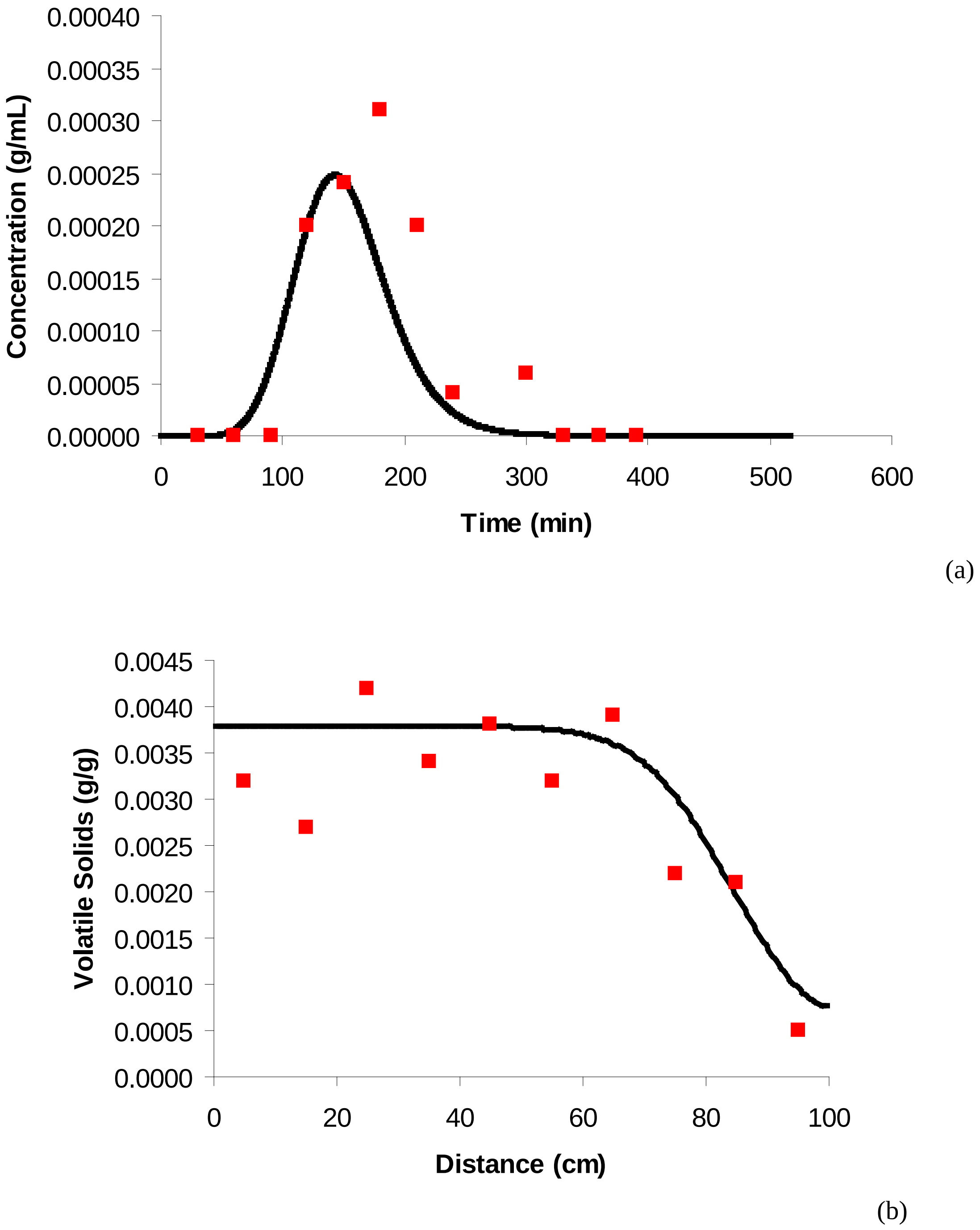


Figure 6.25. Comparison of Simulated and Observed Volatile Solids Concentrations for Experiment A2. (a) column effluent, and (b) sediment after completion of the experiment. Points represent the experimental data. The solid line represents the simulated values.

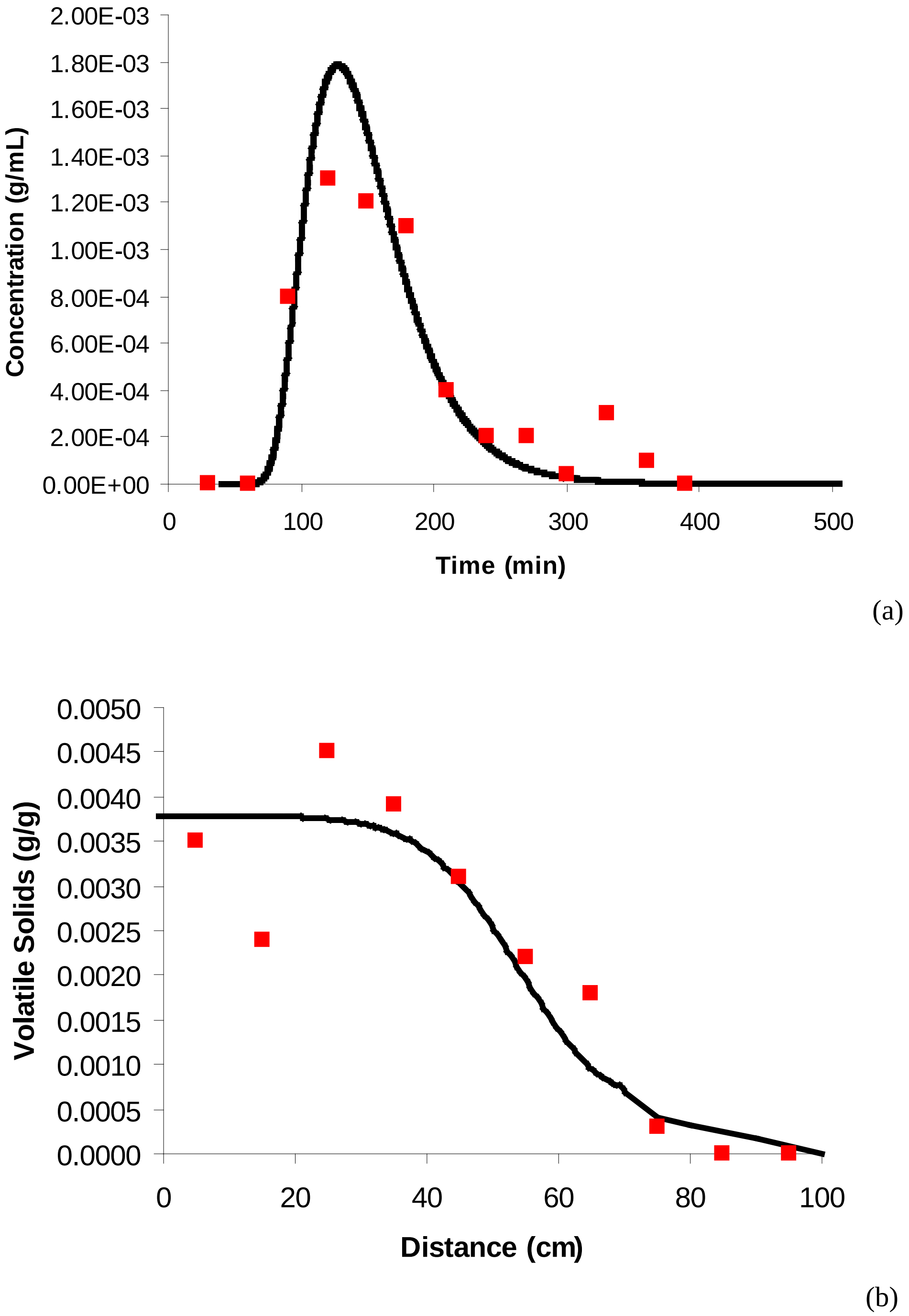


Figure 6.26. Comparison of Simulated and Observed Volatile Solids Concentrations for Experiment A3. (a) column effluent and (b) sediment after completion of the experiment. Points represent the experimental data. The solid line represents the simulated values.

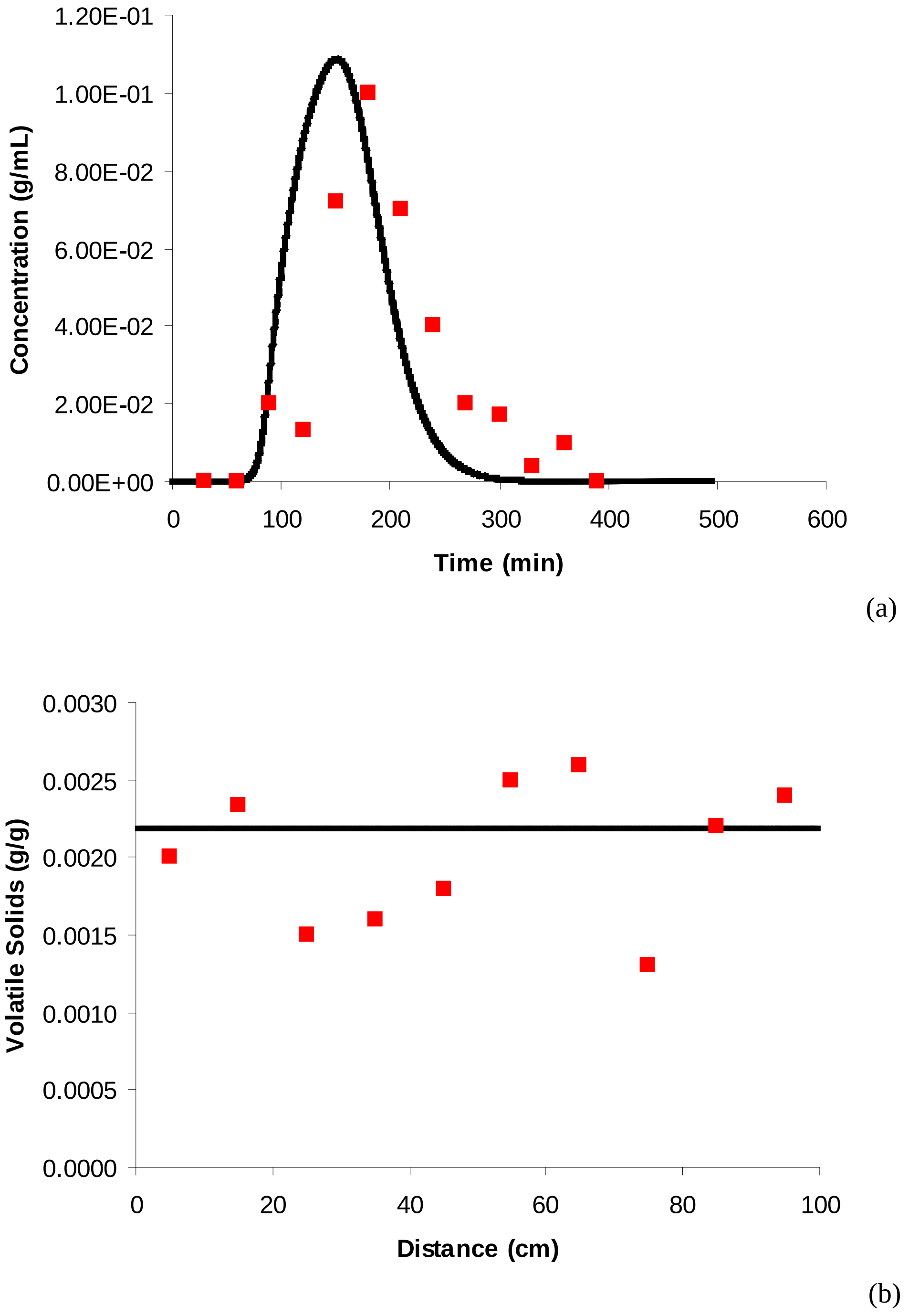
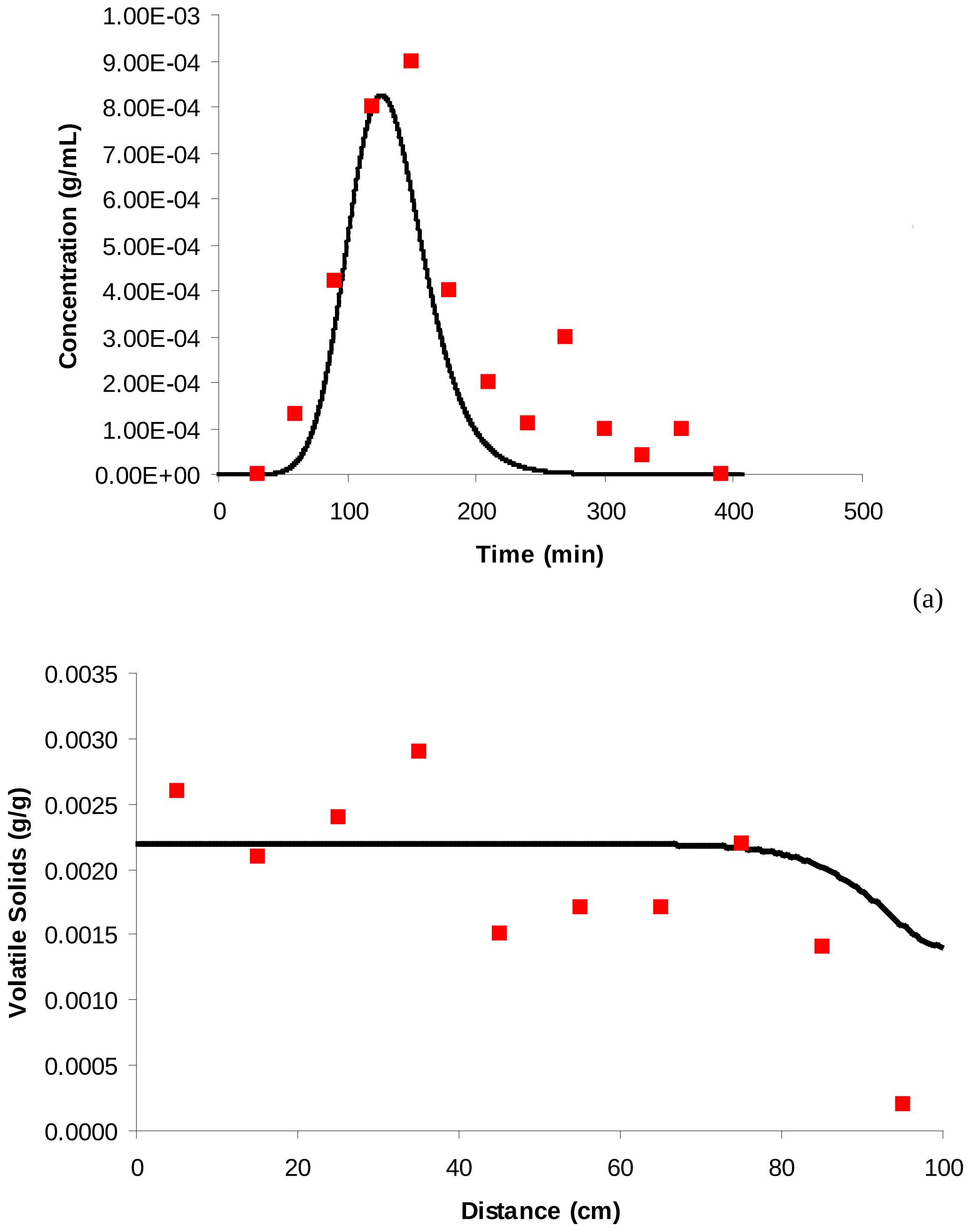


Figure 6.27. Comparison of Simulated and Observed Volatile Solids Concentrations for Experiment B1. (a) column effluent and (b) sediment after completion of the experiment. Points represent the experimental data. The solid line represents the simulated values.



(a)

(b)

Figure 6.28. Comparison of Simulated and Observed Volatile Solids Concentrations for Experiment B2. (a) column effluent and (b) sediment after completion of the experiment. Points represent the experimental data. The solid line represents the simulated values.

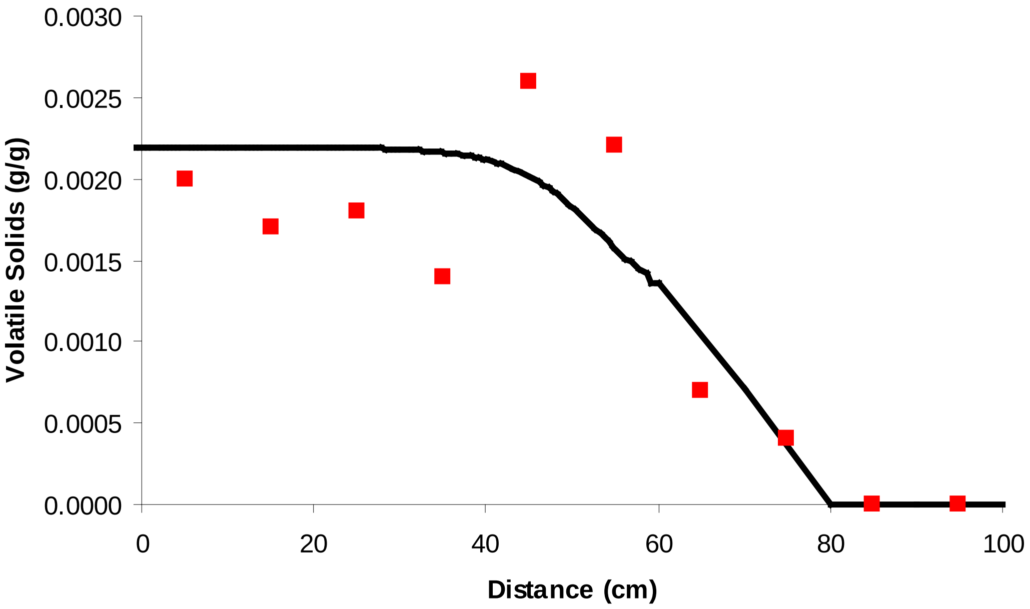


Figure 6.29. Comparison of Simulated and Observed Sediment Volatile Solids Concentrations after Completion of Experiment B3. Points represent the experimental data. The solid line represents the simulated values.

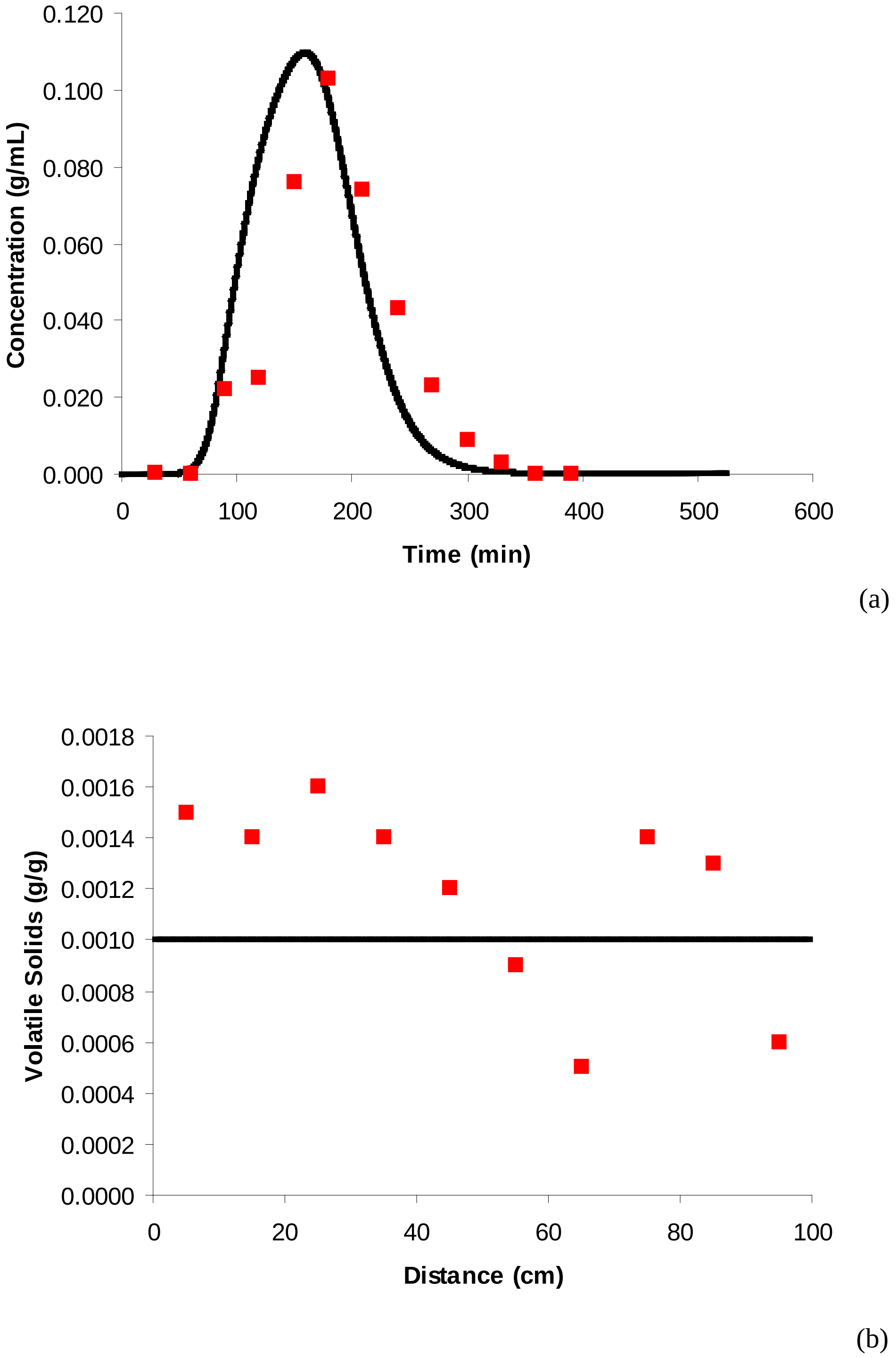
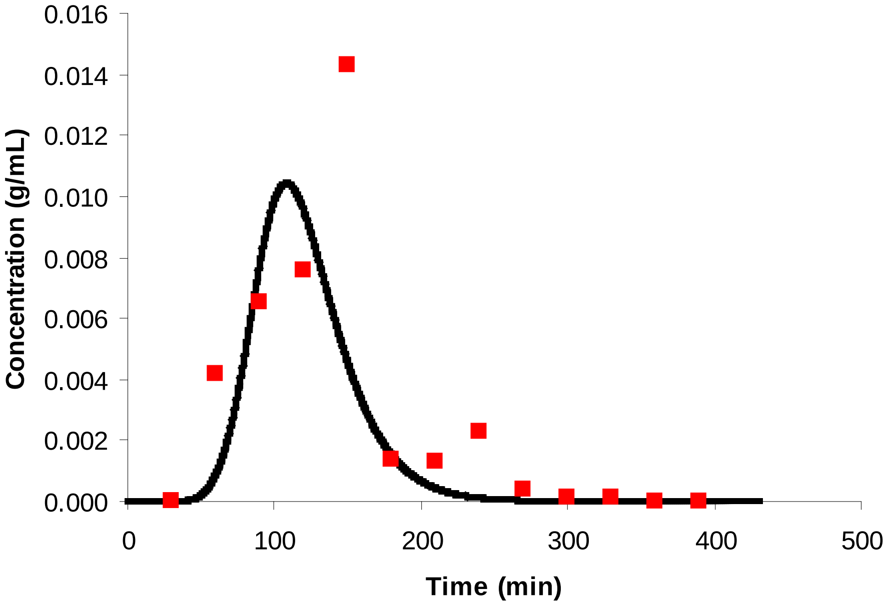
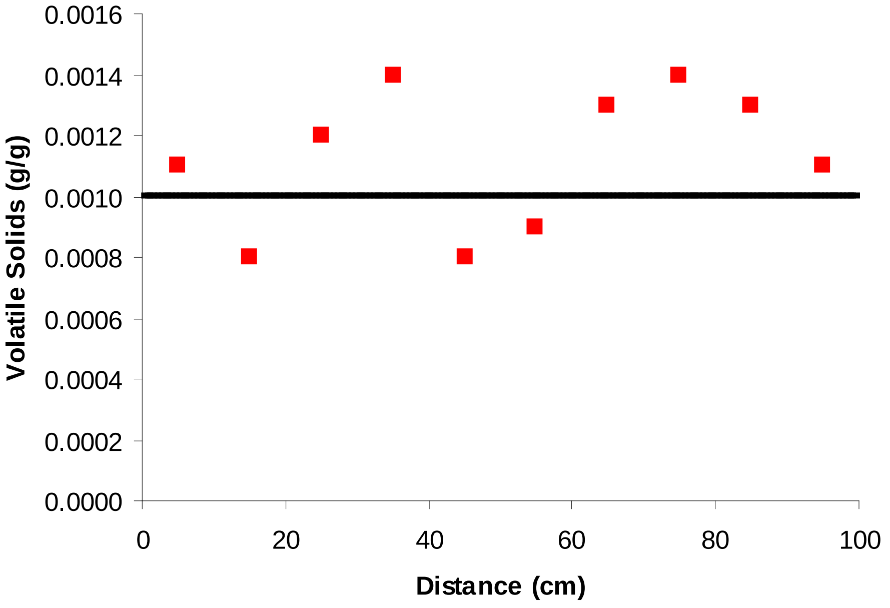


Figure 6.30. Comparison of Simulated and Observed Volatile Solids Concentrations for Experiment C1. (a) column effluent and (b) sediment after completion of the experiment. Points represent the experimental data. The solid line represents the simulated values.



(a)



(b)

Figure 6.31. Comparison of Simulated and Observed Volatile Solids Concentrations for Experiment C2. (a) column effluent and (b) sediment after completion of the experiment. Points represent the experimental data. The solid line represents the simulated values.

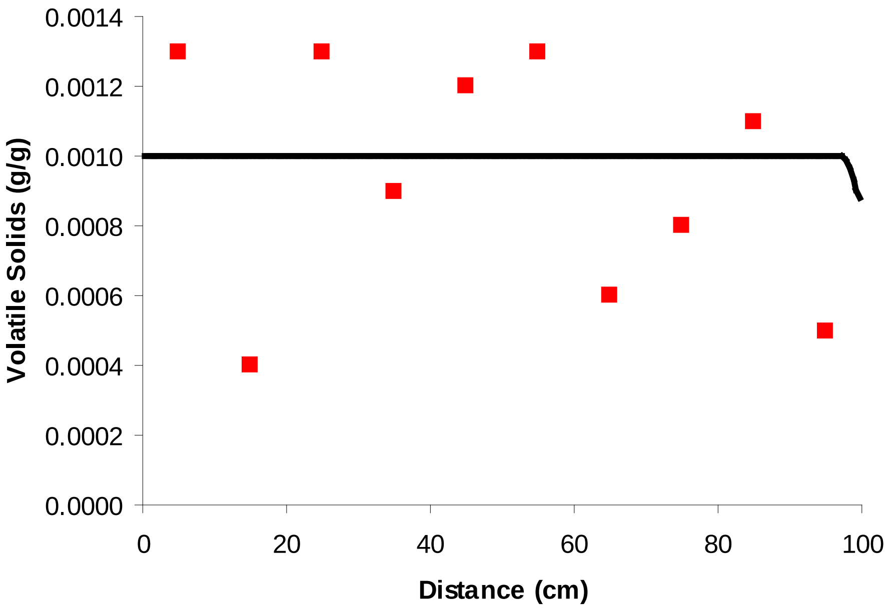


Figure 6.32. Comparison of Simulated and Observed Sediment Volatile Solids Concentrations after Completion of Experiment C3. Points represent the experimental data. The solid line represents the simulated values.

6.3.3 Conclusions

As suggested by these results and literature data (e.g., Borden 2007; Coulibaly 2006), transport and retention of emulsified oil is strongly influenced by the relative sediment porous media pore size and oil droplet size. For the Hanford application, the Ringold Formation contains a wide range of sediment particle sizes with the characteristic that the pore spaces between the large particles are filled with small particles. This type of packing is reflected in the relatively low porosities observed in the Ringold Formation. Under these conditions, emulsion transport and retention would be controlled by the small particle sizes and associated small pores. Thus, the target oil retention for the field test was estimated based on the results for the 70 sand.

Additionally, design information from the emulsion supplier (EOS Remediation, LLC) and the results of laboratory testing indicate that transport of the emulsion is significantly hindered as the droplet size of the emulsion increases. In tests with larger droplet sizes, oil transport was minimal in the experimental columns. Thus, results were not depicted. For the field test, emulsion product properties similar to the emulsion properties in the laboratory experiments were desired. An emulsion product delivery specification was used to ensure that the emulsion product was suitable for injection. Optical microscopy of product samples was used to ensure that the emulsified material had a mean droplet size of less than 2.5 μm with a standard deviation of less than 1 μm. The EOS 598 met these specifications on delivery for the field test.

6.4 Description of Results Relative to Field Test Objectives

The following is a summary of the field test results with respect to the objectives of the field test.

- Determine the effective radius of injection.

  Result: A radius of injection of about 8 m (25 ft) from the injection well for the emulsified oil substrate was obtainable. Potentially, a greater injection radius is possible Additionally, use of a groundwater recirculation process that was able to significantly enhance interwell groundwater flow rates during an injection may also enable larger well spacing during full-scale deployment of the technology.

- Evaluate the uniformity of substrate distribution.

  Result: Uniformity of substrate injection is, as expected, dependent on formational heterogeneities within and beyond the targeted treatment zone. However, the field test injection was able to distribute substrate to all of the monitoring locations, though at different concentrations. Subsequent microbial activity and treatment of the target compounds over a period of about 10 months was observed at all locations.

- Identify operational needs for injection.

  Result: Relatively simple operations with the use of process water and substrate supplied in a tanker truck were demonstrated during the injection. A pulsed injection strategy was used to mitigate pressure buildup during injection, although continuous injection may have been possible.

- Induce fermentation reactions and reducing conditions and grow biomass.

  Result: Process monitoring data showed that fermentation reactions and associated reducing conditions occurred at all of the monitoring locations. Direct in situ biomass measurement is not possible, but indirect measurements suggest that biomass was produced and helped facilitate treatment of target compounds and maintenance of reducing conditions.

- Minimize permeability changes resulting from biomass increases.

  Result: In contrast to the molasses injection, permeability in the immiscible substrate test cell changed quickly and appears to be due to the presence of the injected oil rather than due to significant biomass growth. Because of the slow dissolution of substrate over time, additional permeability reduction is not expected.

- Quantify the ability to obtain and maintain low oxygen and nitrate/nitrite concentrations (limit primary electron acceptor flux) and determine longevity of treatment.

  Result: Low oxygen and nitrate/nitrite concentrations were maintained over the duration of the test (~10 months) with indications that the treatment duration will be longer.

- Quantify the ability to obtain and maintain low chromate concentrations (augment chromate treatment) and determine longevity of treatment.

  Result: Low total chromium and chromate concentrations were maintained over the duration of the test (~10 months) with indications that the treatment duration will be longer.

- Quantify the water quality impacts of the treatment.

  Result: Within the test cell, water quality was negatively impact by an increase in the concentration of metals and organic constituents and a decrease in the pH, oxidation-reduction potential, and dissolved oxygen concentration. These changes were expected due to the imposed anaerobic conditions required for biological treatment of dissolved oxygen, nitrate, and chromate. A biobarrier design requires a downgradient portion of the aquifer where these water quality impacts can recover and this type of recovery region would need to be considered as part of determining the location for biobarrier application.

- Compile information for full-scale design considering the injection process, biobarrier performance, hydrogeology, and electron flux information at 100-D

  Result: Table 6.5 shows the information available from this treatability test that is suitable for use to support design and cost estimation in a feasibility study.

Table 6.5. Biobarrier Scale-Up Information

Item	Value	Comment
Substrate loading	5 kg/m^3	Lower substrate loading may be appropriate for volumetric bioremediation of chromate or for shorter periods of barrier effectiveness.
Substrate cost	4.1 $/kg	Treatability test cost
Nutrient loading	Not applicable	Deemed unnecessary for the emulsified oil substrate.
Injection well spacing (perpendicular to flow)	16 m	Based on 8 m radius of influence. Full-scale spacing may need to consider overlapping of substrate injection zones. Potentially, larger spacing could be obtained with a longer injection period or with a groundwater recirculation system and may be appropriate depending on relative cost of recirculation design versus a single well injection design.
Operational labor for injection	90 hours of labor time	Labor for injection during the test
Monitoring frequency	Quarterly to semiannually	Based on the timeframe of observed changes during the test.

Table 6.5. (contd)

Item	Value	Comment
Frequency of substrate injection	Every 5 years	Estimated based on design calculation from emulsion provider. Barrier performance did not diminish over the 10-month testing period. Groundwater flow conditions should be considered in determining the frequency of reinjection.
Primary injection equipment and cost	Substrate feed pump (air-driven diaphragm pump) - $2,500 Feedwater pump (centrifugal) - $500 Substrate flowmeter (pulse counter) - $1,000 Feedwater flowmeter (turbine) - $1000 In-line mixer - $100 Data logger for flowmeters & feed pump- $3,000 Hose for feedwater- $10/ft Hardware for injection well piping- $400	Equipment used during the test and nominal cost. Injection system design and construction cost is not included. These costs would be best estimated by the contractor performing the scale-up injections.

7.0 Conclusions and Recommendations

Pacific Northwest National Laboratory conducted a treatability test designed to demonstrate that in situ biostimulation can be applied to help meet cleanup goals in the Hanford Site 100-D Area. The in situ biostimulation technology is intended to provide supplemental treatment upgradient of the In Situ Redox Manipulation (ISRM) barrier previously installed in the Hanford 100-D Area and, thereby increase the longevity of the ISRM barrier. Substrates for the treatability test were selected to provide information about two general approaches for establishing and maintaining an in situ biobarrier. These approaches included 1) use of a soluble (miscible) substrate that is relatively easy to distribute over a large areal extent, is inexpensive, and is expected to have moderate longevity and 2) use of an immiscible substrate that can be distributed over a reasonable areal extent at a moderate cost and is expected to have increased longevity.

The results of the treatability test demonstrate that biostimulation is a viable approach to create a permeable reactive barrier for reducing nitrate, oxygen, and chromate concentrations in the groundwater at the Hanford 100-D Area. A single injection of substrate can create a permeable reactive barrier that lasts at least 2 years and likely longer. It is reasonable to extend these results to support the conclusion that biostimulation is also a viable approach to treating nitrate and chromate within a targeted volume of the aquifer in the Hanford 100-D Area, although the approach to application would likely be somewhat different than the design of the permeable reactive barrier application in the treatability test.

For the soluble substrate test, substrate was successfully distributed and induced a biobarrier that treated nitrate, oxygen, and chromate over a radius of about 15 m (50 ft) from the injection well. Low oxygen, nitrate, and chromium concentrations were maintained for the approximately 2-year duration of monitoring. Aquifer permeability reduction within the test zone was moderate and likely due to growth of bacteria. The injected substrate and associated organic degradation products persisted for about 1 year. Over the second year of barrier monitoring, organic substrate concentrations were low; the continued effectiveness of the treatment zone is attributed to recycling of organic compounds associated with the biomass that was produced during the first year. Thus, the soluble substrate approach met the test performance objectives. Scale-up parameters were determined based on the test data and are available for use in subsequent feasibility studies, as needed.

The immiscible substrate was successfully distributed to a radius of about 8 m (25 ft) from the injection well. Subsequent microbial activity and ability to reduce the targeted species were observed throughout the monitored zone, and low oxygen, nitrate, and chromium concentrations were maintained for the approximately 10-month duration of monitoring. Aquifer permeability reduction within the test zone was moderate and occurred quickly after substrate injection, likely due to physical effects from the presence of immiscible liquid in the aquifer. The monitoring period for the immiscible test was short compared to the expected longevity of the substrate. Initial indications from the immiscible substrate injection are favorable, however, additional monitoring would be necessary to determine the longevity of the treatment and verify acceptable performance relative to all of the test objectives. Scale-up parameters were determined based on the test data and are available for use in subsequent feasibility studies, as needed.

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Appendix A

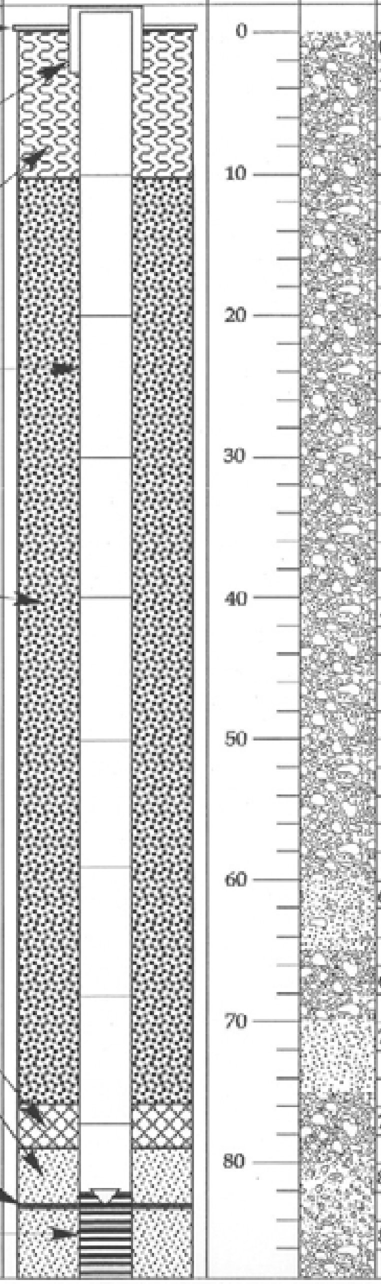
Borehole Logs and Well Completion Diagrams for the Test Site Wells

WELL SUMMARY SHEET	Start Date: 05/02/07 Finish Date: 05/18/07	Page 1 of 2

Well ID: C5577	Well Name: 199-D5-107
Location: West of DR reactor, near 100-D Gate	Project: Biostimulation Test Wells at 100-D Area
Prepared By: Erika Rincon — Date: 07/02/07	Reviewed By: L.D. Walker — Date: 7/25/07
Signature: Erika	Signature:

CONSTRUCTION DATA | **GEOLOGIC/HYDROLOGIC DATA**

Description | Diagram | Depth in Feet | Graphic Log | Lithologic Description/Groundwater Sample Depths (ft bgs)



6-in Concrete Pad

8-in I.D. Type 304/304L Stainless Steel Protective Casing: +2.32 ft ags

Portland Cement Type I/II: 0 - 10.2 ft

6-in I.D., Sch. 40, Polyvinyl Chloride (PVC) Casing: +1.36 - 82.3 ft

Granular Bentonite Crumbles: 10.2 - 75.9 ft

3/8-in Bentonite Pellets: 75.9 - 79.1 ft

Primary Filter Pack 10-20 Mesh Colorado Silica Sand: 79.1 - 102.7 ft

Static Water Level: 83.00 ft bgs (05-16-2007)

6-in I.D. Polyvinyl Chloride (PVC), 20 Slot (0.020-in) Screen: 82.3 - 102.3 ft

0-1 Gravel; G (Fill)

1-40 Silty Sandy Gravel; msG

40-50 Sandy Gravel; sG

60-65 Gravelly Sand; gS

65-70 Silty Sandy Gravel; msG

70-75 Sand; S

75-80 Silty Sandy Gravel; msG

80-85 Gravely Silty Sand; gmS

85-93 Sandy Gravel; sG

WELL SUMMARY SHEET

Start Date: 05/02/07
Finish Date: 05/18/07
Page 2 of 2

Well ID: C5577
Well Name: 199-D5-107
Location: West of DR reactor, near 100-D Gate
Project: Biostimulation Test Wells at 100-D Area
Prepared By: Erika Rincon
Date: 07/02/07
Reviewed By: L.D. Walker
Date: 7/25/07
Signature:
Signature:

CONSTRUCTION DATA

Description

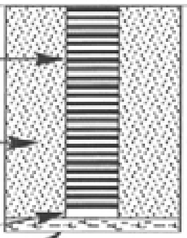
6-in I.D. Polyvinyl Chloride (PVC), 20 Slot (0.020-in) Screen: 82.3 - 102.3 ft

Primary Filter pack 10-20 Mesh Colorado Silica Sand: 79.1 - 102.7 ft

6-in, I.D. Polyvinyl Chloride (PVC) End Cap: 102.3 - 102.7 ft

Natural Backfill: 102.7 - 104.0 ft

Diagram



All depths are in feet below ground surface.

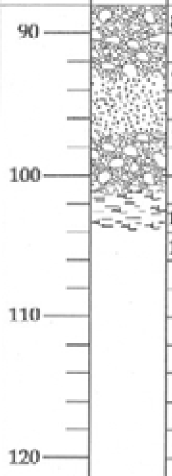
Borehole drilled with 10 1/4 x 11 3/4-inch casing.

All temporary drill casing was removed from the ground.

GEOLOGIC/HYDROLOGIC DATA

Depth in Feet

Graphic Log



Lithologic Description/Groundwater Sample Depths (ft bgs)

85-93 Sandy Gravel; sG

93-97 Sand; S

97-101 Sandy Gravel; sG

101-104 MUD

104 Total Depth Drilled (05-14-2007)

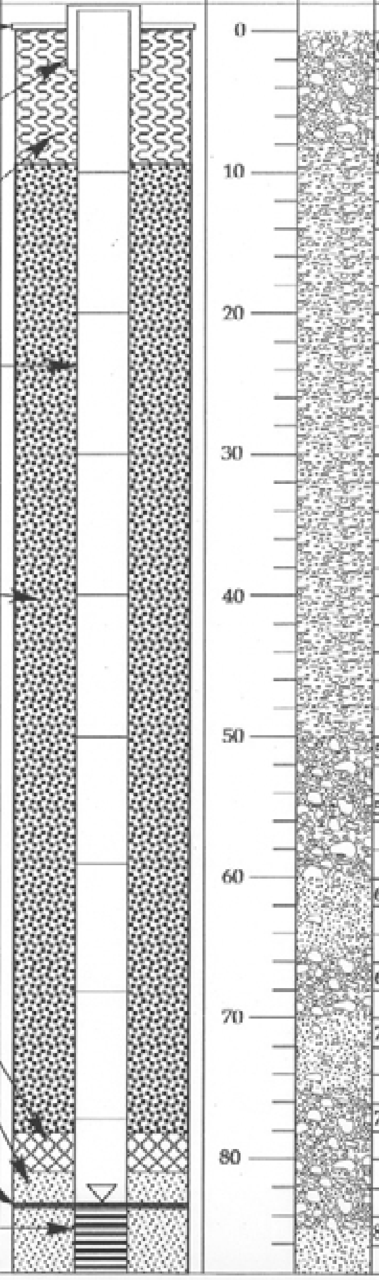
WELL SUMMARY SHEET

Start Date: 06/01/07
Finish Date: 06/08/07
Page 1 of 2

Well ID: C5578	Well Name: 199-D5-108
Location: West of DR reactor, near 100-D Gate	Project: Biostimulation Test Wells at 100-D Area
Prepared By: Erika Rincon Date: 07/02/07	Reviewed By: L.D. Walker Date: 7/26/07
Signature: Erika R	Signature: LD Walker

CONSTRUCTION DATA | **GEOLOGIC/HYDROLOGIC DATA**

Description | Diagram | Depth in Feet | Graphic Log | Lithologic Description/Groundwater Sample Depths (ft bgs)



6-in Concrete Pad

8-in I.D. Type 304/304L Stainless Steel Protective Casing: +2.55 ft ags

Portland Cement Type I/II: 0 - 9.3 ft

6-in I.D., Sch. 40, Polyvinyl Chloride (PVC) Casing: +1.43 - 83.8 ft

Granular Bentonite Crumbles: 9.3 - 78.0 ft

3/8-in Bentonite Pellets: 78.0 - 80.7 ft

Primary Filter Pack 10-20 Mesh Colorado Silica Sand: 80.7 - 106.0 ft

Static Water Level: 83.58 ft bgs (06-07-2007)

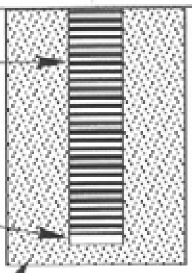
6-in I.D. Polyvinyl Chloride (PVC), 20 Slot (0.020-in) Screen: 83.8 - 103.8 ft

0-1.5 Gravel; G (Fill)
1.5-8 Sandy Gravel; sG
8-50 Silty Gravel; mG
50-55 Silty Sandy Gravel; msG
55-60 Sandy Gravely Silt; smG
60-65 Gravely Sand; gS
65-70 Sandy Gravel; sG
70-75 Gravely Sand; gS
75-85 Sandy Gravel; sG
85-90 Sand; S

WELL SUMMARY SHEET	Start Date: 06/01/07 Finish Date: 06/08/07	Page 2 of 2

Well ID: C5578	Well Name: 199-D5-108
Location: West of DR reactor, near 100-D Gate	Project: Biostimulation Test Wells at 100-D Area
Prepared By: Erika Rincon Date: 07/02/07	Reviewed By: L.d. Walker Date: 7/26/07
Signature: Erika R	Signature:

CONSTRUCTION DATA

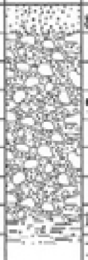
Description	Diagram
6-in I.D. Polyvinyl Chloride (PVC), 20 Slot (0.020-in) Screen: 83.8 - 103.8 ft 6-in, I.D. Polyvinyl Chloride (PVC) End Cap: 103.8 - 104.2 ft Primary Filter pack 10-20 Mesh Colorado Silica Sand: 80.7 - 106.0 ft	

All depths are in feet below ground surface.

Borehole drilled with 10 1/4 x 11 3/4 - inch casing.

All temporary drill casing was removed from the ground.

GEOLOGIC/HYDROLOGIC DATA

Depth in Feet	Graphic Log	Lithologic Description/Groundwater Sample Depths (ft bgs)
90		85-90 Sand; S 90-103 Sandy Gravel; sG 103-106 MUD 106 Total Depth Drilled (06-06-2007)
100		
110		
120		

WELL SUMMARY SHEET

Start Date: 05/02/07
Finish Date: 05/16/07
Page 1 of 2

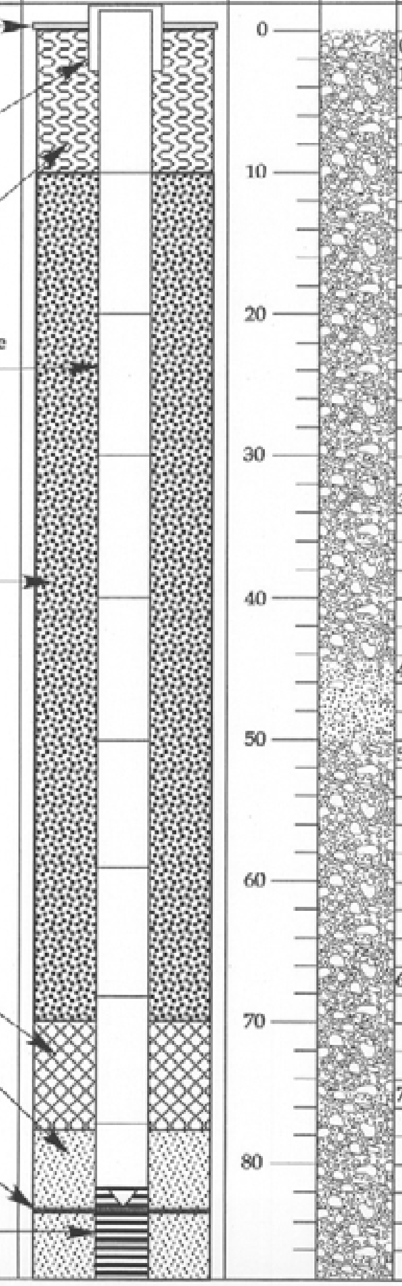
Well ID: C5579
Well Name: 199-D5-109
Location: West of DR reactor, near 100-D Gate
Project: Biostimulation Test Wells at 100-D Area
Prepared By: Erika Rincon
Date: 06/11/07
Reviewed By: L.D. Walker
Date: 7/26/07
Signature: Erika R
Signature: LD Walker

CONSTRUCTION DATA

Description | Diagram

GEOLOGIC/HYDROLOGIC DATA

Depth in Feet | Graphic Log | Lithologic Description/Groundwater Sample Depths (ft bgs)



6-in Concrete Pad

6-in I.D. Type 304/304L Stainless Steel Protective Casing: +2.53 ft ags

Portland Cement Type I/II: 0 - 10.2 ft

4-in I.D., Sch. 40, Polyvinyl Chloride (PVC) Casing: +1.68 - 82.9 ft

Granular Bentonite Crumbles: 10.2 - 70.2 ft

3/8-in Bentonite Pellets: 70.2 - 77.5 ft

Primary Filter Pack 10-20 Mesh Colorado Silica Sand: 77.5 - 104.1 ft

Static Water Level: 83.03 ft bgs (05-16-2007)

4-in I.D. Polyvinyl Chloride (PVC), 20 Slot (0.020-in) Screen: 82.9 - 102.9 ft

0-1 Gravel; G (Fill)
1-34 Silty Sandy Gravel; msG
34-45 Sandy Gravel; sG
45-50 Gravelly Sand; gS
50-65 Sandy Gravel; sG
65-75 Silty Sandy Gravel; msG
75-94 Sandy Gravel; sG

WELL SUMMARY SHEET	Start Date: 05/02/07 Finish Date: 05/16/07	Page 2 of 2

Well ID: C5579	Well Name: 199-D5-109
Location: West of DR reactor, near 100-D Gate	Project: Biostimulation Test Wells at 100-D Area
Prepared By: Erika Rincon — Date: 06/11/07	Reviewed By: L.D. Walker — Date: 7/26/07
Signature:	Signature:

CONSTRUCTION DATA

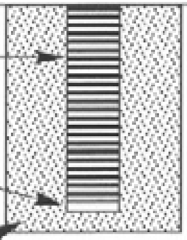
Description

4-in I.D. Polyvinyl Chloride (PVC), 20 Slot (0.020-in) Screen: 82.9 - 102.9 ft

4-in, I.D. Polyvinyl Chloride (PVC) End Cap: 102.9 - 103.2 ft

Primary Filter pack 10-20 Mesh Colorado Silica Sand: 77.5 - 104.1 ft

Diagram



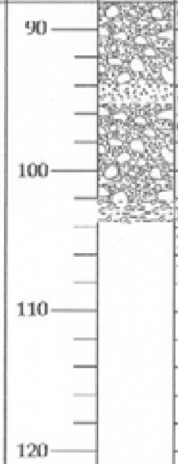
All depths are in feet below ground surface.

Borehole drilled with 7 1/2 x 8 5/8 -inch casing.

All temporary drill casing was removed from the ground.

GEOLOGIC/HYDROLOGIC DATA

Depth in Feet — Graphic Log



Lithologic Description/Groundwater Sample Depths (ft bgs)

75-94 Sandy Gravel; sG

94-95 Sand; S

95-102 Sandy Gravel; sG

102-104.1 Silty Gravel; mG

104.1 Sandy Silt; sM

104.1 Total Depth Drilled (05-07-2007)

WELL SUMMARY SHEET

Start Date: 05/22/07
Finish Date: 05/29/07
Page 1 of 2

Well ID: C5580
Well Name: 199-D5-110
Location: West of DR reactor, near 100-D Gate
Project: Biostimulation Test Wells at 100-D Area
Prepared By: Erika Rincon
Date: 06/11/07
Reviewed By: L. D. Walker
Date: 7/26/07
Signature: Erika R
Signature: LD Walker

CONSTRUCTION DATA

Description | Diagram

6-in Concrete Pad

6-in I.D. Type 304/304L Stainless Steel Protective Casing: +2.46 ft ags

Portland Cement Type I/II: 0 - 9.0 ft

4-in I.D., Sch. 40, Polyvinyl Chloride (PVC) Casing: +1.54 - 80.5 ft

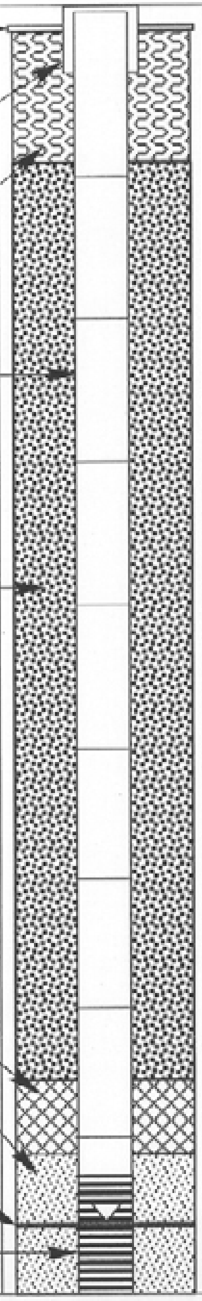
Granular Bentonite Crumbles: 9.0 - 73.6 ft

3/8-in Bentonite Pellets: 73.6 - 78.3 ft

Primary Filter Pack 10-20 Mesh Colorado Silica Sand: 78.3 - 102.5 ft

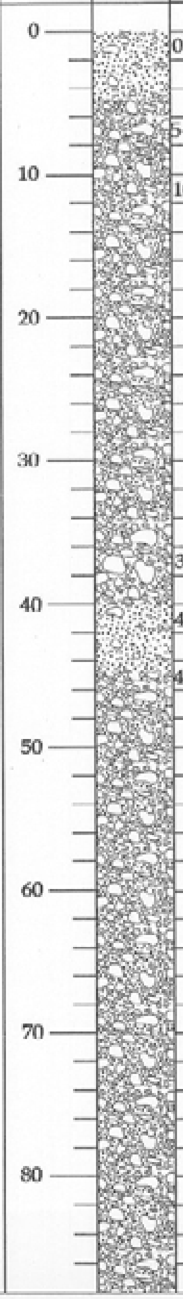
Static Water Level: 83.27 ft bgs (06-14-2007)

4-in I.D. Polyvinyl Chloride (PVC), 20 Slot (0.020-in) Screen: 80.5 - 100.5 ft



GEOLOGIC/HYDROLOGIC DATA

Depth in Feet | Graphic Log | Lithologic Description/Groundwater Sample Depths (ft bgs)



0-5 Gravelly Sand; gS

5-10 Silty Sandy Gravel; msG

10-35 Sandy Gravel; sG

35-40 Gravel; G

40-45 Gravelly Sand; gS

45-90 Sandy Gravel; sG

WELL SUMMARY SHEET

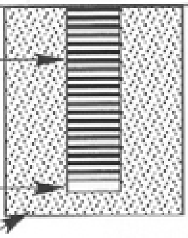
Start Date: 05/22/07
Finish Date: 05/29/07

Page 2 of 2

Well ID: C5580
Location: West of DR reactor, near 100-D Gate
Prepared By: Erika Rincon   Date: 06/11/07
Signature: Erika R

Well Name: 199-D5-110
Project: Biostimulation Test Wells at 100-D Area
Reviewed By: L.D. Walker   Date: 7/26/07
Signature:

CONSTRUCTION DATA

Description	Diagram
4-in I.D. Polyvinyl Chloride (PVC), 20 Slot (0.020-in) Screen: 80.5 - 100.5 ft 4-in, I.D. Polyvinyl Chloride (PVC) End Cap: 100.5 - 101.0 ft Primary Filter pack 10-20 Mesh Colorado Silica Sand: 78.3 - 102.5 ft	

All depths are in feet below ground surface.

Borehole drilled with 7 1/2 x 8 5/8 -inch casing.

All temporary drill casing was removed from the ground.

GEOLOGIC/HYDROLOGIC DATA

Depth in Feet	Graphic Log	Lithologic Description/Groundwater Sample Depths (ft bgs)
90		90-95 Silty Sandy Gravel; msG
		95-96.5 Sand; S
		96.5-100 Gravelly Sand; gS
100		100-100.5 Silty Sandy Gravel; msG
		100.5-102.5 MUD; M
		102.5 Total Depth Drilled (05-24-2007)
110		
120		

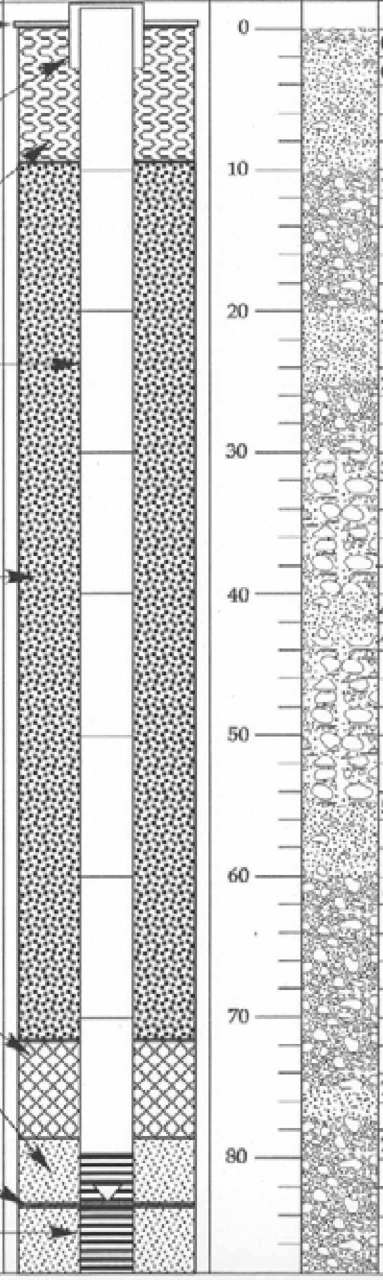
WELL SUMMARY SHEET

Start Date: 05/07/07
Finish Date: 05/14/07
Page 1 of 2

Well ID: C5581
Well Name: 199-D5-111
Location: West of DR reactor, near 100-D Gate
Project: Biostimulation Test Wells at 100-D Area
Prepared By: Erika Rincon
Date: 06/11/07
Reviewed By: L.D. Walker
Date: 7/23/07
Signature:
Signature:

CONSTRUCTION DATA

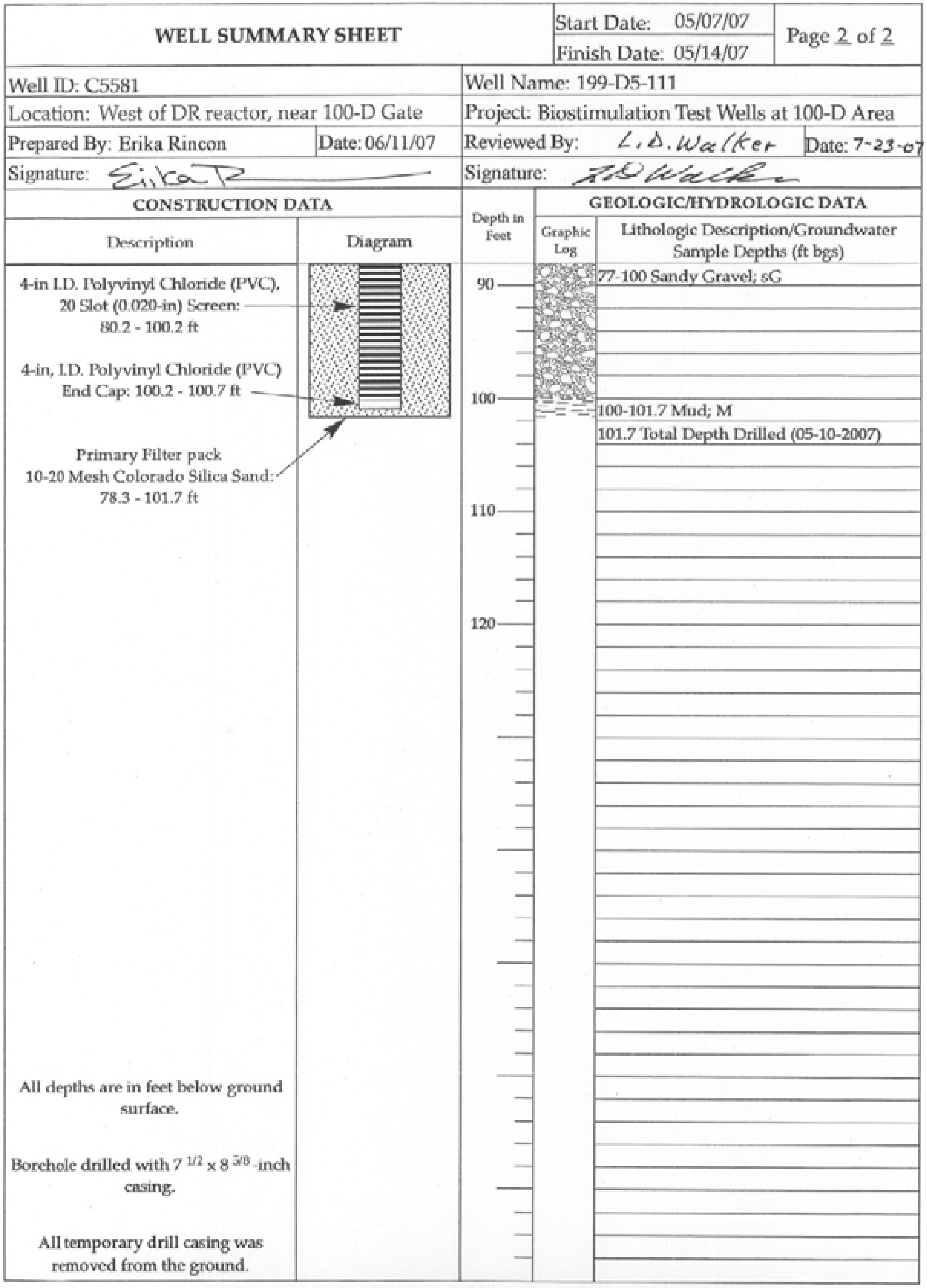
Description	Diagram
6-in Concrete Pad	
6-in I.D. Type 304/304L Stainless Steel Protective Casing: +2.55 ft ags	
Portland Cement Type I/II: 0 - 9.6 ft	
4-in I.D., Sch. 40, Polyvinyl Chloride (PVC) Casing: +1.56 - 80.2 ft	
Granular Bentonite Crumbles: 9.6 - 72.0 ft	
3/8-in Bentonite Pellets: 72.0 - 78.3 ft	
Primary Filter Pack 10-20 Mesh Colorado Silica Sand: 78.3 - 101.7 ft	
Static Water Level: 83.37 ft bgs (05-14-2007)	
4-in I.D. Polyvinyl Chloride (PVC), 20 Slot (0.020-in) Screen: 80.2 - 100.2 ft	



GEOLOGIC/HYDROLOGIC DATA

Lithologic Description/Groundwater Sample Depths (ft bgs)

0-0.5 Gravel; G (Fill)
0.5-10 Gravelly Sand; gS
10-20 Sandy Gravel; sG
20-25 Gravelly Sand; gS
25-30 Sandy Gravel; sG
30-40 Silty Sandy Gravel; msG
40-43 Gravelly Sand; gS
43-55 Silty Sandy Gravel; msG
55-60 Gravelly Sand; gS
60-75 Sandy Gravel; sG
75-77 Sand; S
77-100 Sandy Gravel; sG



WELL SUMMARY SHEET

Start Date: 05/07/07
Finish Date: 05/14/07
Page 2 of 2

Well ID: C5581
Well Name: 199-D5-111
Location: West of DR reactor, near 100-D Gate
Project: Biostimulation Test Wells at 100-D Area
Prepared By: Erika Rincon
Date: 06/11/07
Reviewed By: L.D. Walker
Date: 7-23-07
Signature: Erika R
Signature: LD Walker

CONSTRUCTION DATA

Description	Diagram
4-in I.D. Polyvinyl Chloride (PVC), 20 Slot (0.020-in) Screen: 80.2 - 100.2 ft 4-in, I.D. Polyvinyl Chloride (PVC) End Cap: 100.2 - 100.7 ft Primary Filter pack 10-20 Mesh Colorado Silica Sand: 78.3 - 101.7 ft	

All depths are in feet below ground surface.

Borehole drilled with 7 1/2 x 8 5/8 -inch casing.

All temporary drill casing was removed from the ground.

GEOLOGIC/HYDROLOGIC DATA

Lithologic Description/Groundwater Sample Depths (ft bgs)

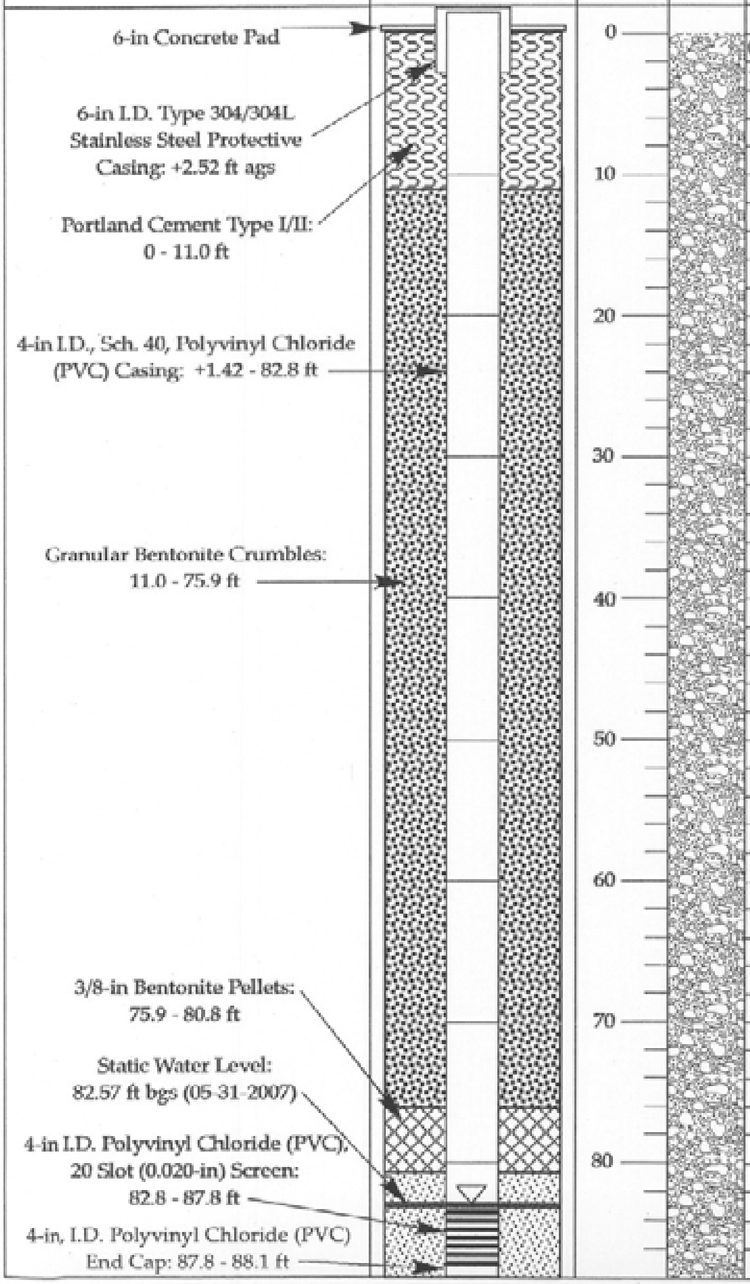
77-100 Sandy Gravel; sG
100-101.7 Mud; M
101.7 Total Depth Drilled (05-10-2007)

WELL SUMMARY SHEET

Start Date: 05/25/07
Finish Date: 05/31/07
Page 1 of 2

Well ID: C5582
Well Name: 199-D5-112
Location: West of DR reactor, near 100-D Gate
Project: Biostimulation Test Wells at 100-D Area
Prepared By: Erika Rincon
Date: 06/11/07
Reviewed By: L. D. Walker
Date: 7/24/07
Signature: Erika R
Signature:

CONSTRUCTION DATA | **GEOLOGIC/HYDROLOGIC DATA**



Lithologic Description/Groundwater Sample Depths (ft bgs)

0-1 Gravel; G (Fill)
1-93 Sandy Gravel; sG

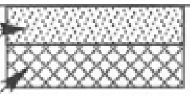
WELL SUMMARY SHEET

Start Date: 05/25/07
Finish Date: 05/31/07
Page 2 of 2

Well ID: C5582
Well Name: 199-D5-112
Location: West of DR reactor, near 100-D Gate
Project: Biostimulation Test Wells at 100-D Area
Prepared By: Erika Rincon
Date: 06/11/07
Reviewed By: L. D. Walker
Date: 7/24/07
Signature: Erika R
Signature:

CONSTRUCTION DATA

Description / Diagram



Primary Filter Pack
10-20 Mesh Colorado Silica Sand:
80.8 - 90.5 ft

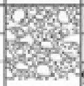
3/8-in Bentonite Pellets:
90.5 - 93.9 ft

All depths are in feet below ground surface.

Borehole drilled with 7 $^{1/2}$ x 8 $^{5/8}$ inch casing.

All temporary drill casing was removed from the ground.

GEOLOGIC/HYDROLOGIC DATA

Depth in Feet	Graphic Log	Lithologic Description/Groundwater Sample Depths (ft bgs)
90		1-93 Sandy Gravel; sG
		93.9 Total Depth Drilled (05-30-2007)
100		
110		
120		

WELL SUMMARY SHEET

Start Date: 05/17/07

Finish Date: 05/25/07

Page 1 of 2

Well ID: C5583

Well Name: 199-D5-113

Location: West of DR reactor, near 100-D Gate

Project: Biostimulation Test Wells at 100-D Area

Prepared By: Erika Rincon

Date: 06/11/07

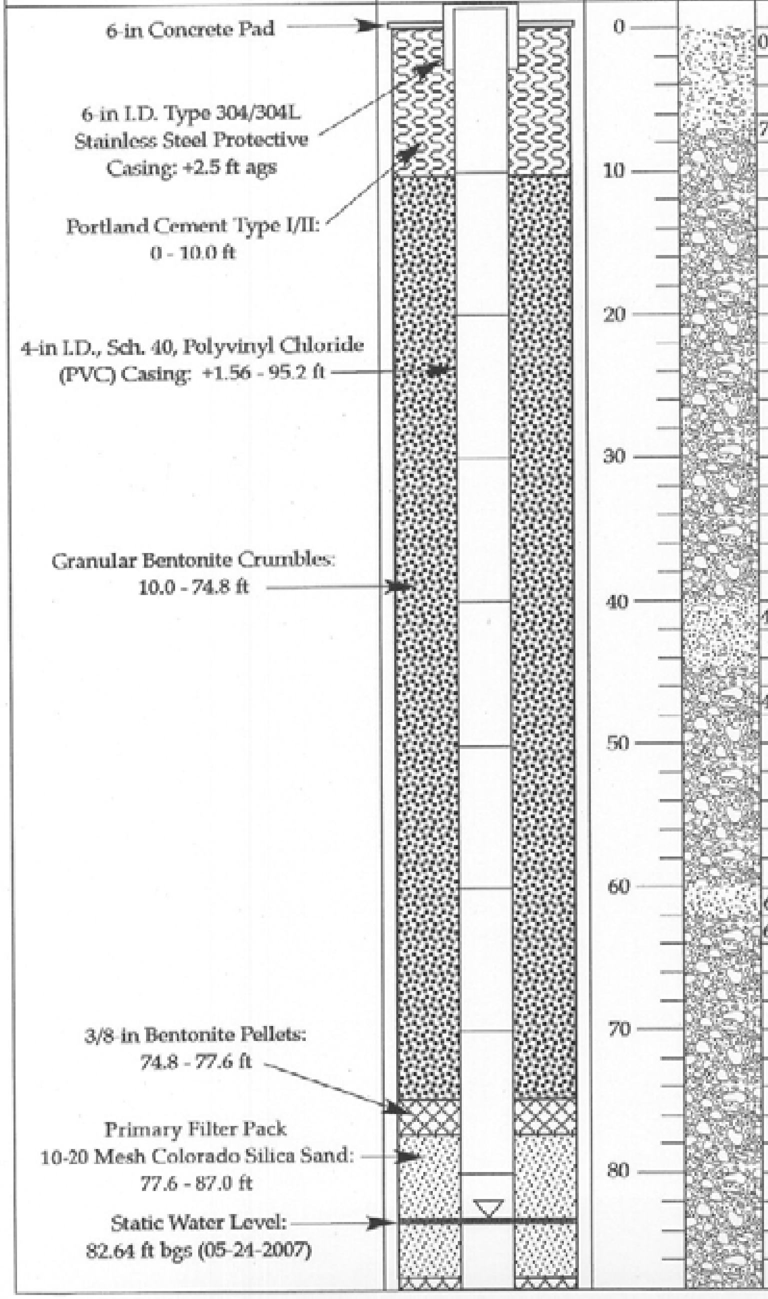
Reviewed By: L.D. Walker

Date: 7/24/07

Signature:

Signature:

CONSTRUCTION DATA			GEOLOGIC/HYDROLOGIC DATA	
Description	Diagram	Depth in Feet	Graphic Log	Lithologic Description/Groundwater Sample Depths (ft bgs)



6-in Concrete Pad

6-in I.D. Type 304/304L Stainless Steel Protective Casing: +2.5 ft ags

Portland Cement Type I/II: 0 - 10.0 ft

4-in I.D., Sch. 40, Polyvinyl Chloride (PVC) Casing: +1.56 - 95.2 ft

Granular Bentonite Crumbles: 10.0 - 74.8 ft

3/8 in Bentonite Pellets: 74.8 - 77.6 ft

Primary Filter Pack 10-20 Mesh Colorado Silica Sand: 77.6 - 87.0 ft

Static Water Level: 82.64 ft bgs (05-24-2007)

0-7 Gravelly Silty Sand; gmS

7-40 Sandy Gravel; sG

40-45 Gravelly Sand; gS

45-60 Sandy Gravel; sG

60-62 Sand; S

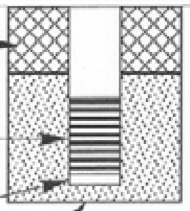
62-93.5 Sandy Gravel; sG

WELL SUMMARY SHEET

Start Date: 05/17/07
Finish Date: 05/25/07
Page 2 of 2

Well ID: C5583
Well Name: 199-D5-113
Location: West of DR reactor, near 100-D Gate
Project: Biostimulation Test Wells at 100-D Area
Prepared By: Erika Rincon
Date: 06/11/07
Reviewed By: L. D. Walker
Date: 7/24/07
Signature: Erika R

CONSTRUCTION DATA

Description	Diagram
3/8-in Bentonite Pellets: 87.0 - 93.3 ft 4-in I.D. Polyvinyl Chloride (PVC), 20 Slot (0.020-in) Screen: 95.2 - 100.2 ft 4-in, I.D. Polyvinyl Chloride (PVC) End Cap: 100.2 - 100.5 ft Primary Filter pack 10-20 Mesh Colorado Silica Sand: 93.3 - 102.0 ft	

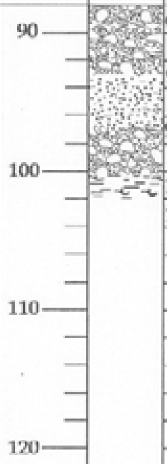
All depths are in feet below ground surface.

Borehole drilled with 7 1/2 x 8 5/8-inch casing.

All temporary drill casing was removed from the ground.

GEOLOGIC/HYDROLOGIC DATA

Depth in Feet | Graphic Log | Lithologic Description/Groundwater Sample Depths (ft bgs)



62-93.5 Sandy Gravel; sG
93.5-97 Sand; S
97-100.5 Sandy Gravel; sG
100.5-102 Mud; M
102 Total Depth Drilled (05-21-2007)

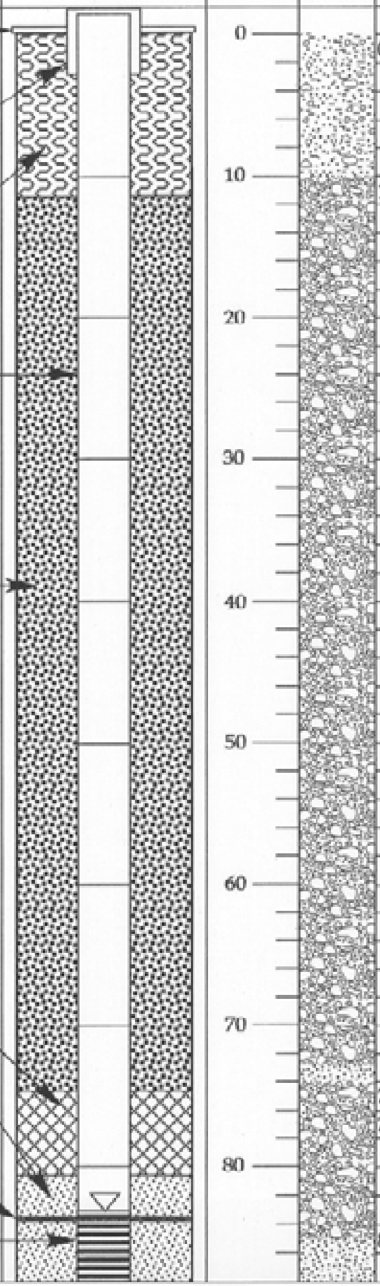
WELL SUMMARY SHEET

Start Date: 06/01/07
Finish Date: 06/12/07
Page 1 of 2

Well ID: C5584
Well Name: 199-D5-114
Location: West of DR reactor, near 100-D Gate
Project: Biostimulation Test Wells at 100-D Area
Prepared By: Erika Rincon
Date: 07/11/07
Reviewed By: L.S. Walker
Date: 7/27/07
Signature: ErikaR
Signature:

CONSTRUCTION DATA

Description
6-in Concrete Pad
6-in I.D. Type 304/304L Stainless Steel Protective Casing: +2.55 ft ags
Portland Cement Type I/II: 0 - 11.1 ft
4-in I.D., Sch. 40, Polyvinyl Chloride (PVC) Casing: +1.34 - 83.2 ft
Granular Bentonite Crumbles: 11.1 - 75.1 ft
3/8-in Bentonite Pellets: 75.1 - 80.3 ft
Primary Filter Pack 10-20 Mesh Colorado Silica Sand: 80.3 - 104.3 ft
Static Water Level: 83.53 ft bgs (06-12-2007)
4-in I.D. Polyvinyl Chloride (PVC), 20 Slot (0.020-in) Screen: 83.2 - 103.2 ft



GEOLOGIC/HYDROLOGIC DATA

Lithologic Description/Groundwater Sample Depths (ft bgs)
0-10 Gravelly Silty Sand; gmS
10-73 Sandy Gravel; sG
73-74 Sand; S
74-85 Sandy Gravel; sG
85-93 Sand; S

WELL SUMMARY SHEET

Start Date: 06/01/07
Finish Date: 06/12/07

Page 2 of 2

Well ID: C5584

Well Name: 199-D5-114

Location: West of DR reactor, near 100-D Gate

Project: Biostimulation Test Wells at 100-D Area

Prepared By: Erika Rincon

Date: 07/11/07

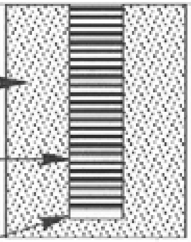
Reviewed By: L. D. Walker

Date: 7/27/07

Signature: Erika R

Signature: LD Walker

CONSTRUCTION DATA

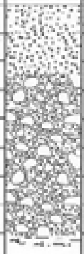
Description	Diagram
Primary Filter pack 10-20 Mesh Colorado Silica Sand: 80.3 - 104.3 ft 4-in I.D. Polyvinyl Chloride (PVC), 20 Slot (0.020-in) Screen: 83.2 - 103.2 ft 4-in, I.D. Polyvinyl Chloride (PVC) End Cap: 103.2 - 103.5 ft	

All depths are in feet below ground surface.

Borehole drilled with $7^{1/2} \times 8^{5/8}$-inch casing.

All temporary drill casing was removed from the ground.

GEOLOGIC/HYDROLOGIC DATA

Depth in Feet	Graphic Log	Lithologic Description/Groundwater Sample Depths (ft bgs)
90		85-93 Sand; S
		93-104.3 Sandy Gravel; sG
100		
		104.3 Mud; M
		104.3 Total Depth Drilled (06-06-2007)
110		
120		

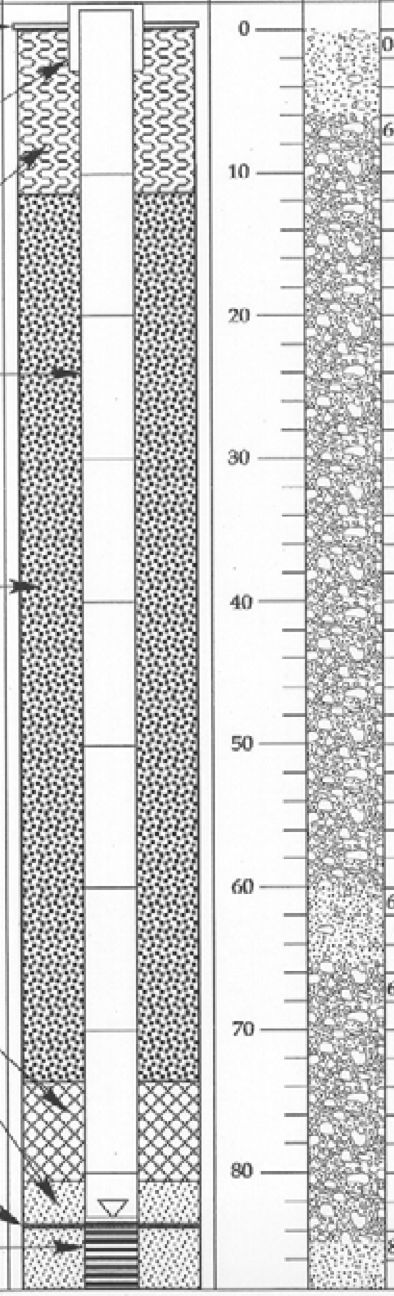
WELL SUMMARY SHEET

Start Date: 07/02/07
Finish Date: 07/10/07
Page 1 of 2

Well ID: C5585
Well Name: 199-D5-115
Location: West of DR reactor, near 100-D Gate
Project: Biostimulation Test Wells at 100-D Area
Prepared By: Jeff Fetters
Date: 07/19/07
Reviewed By: L.D. Walker
Date: 7/27/07
Signature:
Signature:

CONSTRUCTION DATA

Description	Diagram



6-in Concrete Pad

6-in I.D. Type 304/304L Stainless Steel Protective Casing: +2.61 ft ags

Portland Cement Type I/II: 0 - 10.9 ft

4-in I.D., Sch. 40, Polyvinyl Chloride (PVC) Casing: +1.36 - 83.3 ft

Granular Bentonite Crumbles: 10.9 - 73.8 ft

3/8-in Bentonite Pellets: 73.8 - 80.5 ft

Primary Filter Pack 10-20 Mesh Colorado Silica Sand: 80.5 - 105.0 ft

Static Water Level: 83.82 ft bgs (07-10-2007)

4-in I.D. Polyvinyl Chloride (PVC), 20 Slot (0.020-in) Screen: 83.3 - 103.3 ft

GEOLOGIC/HYDROLOGIC DATA

Lithologic Description/Groundwater Sample Depths (ft bgs)

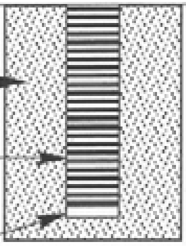
0-6 Gravelly Silty Sand; gmS
6-60 Sandy Gravel; sG
60-65 Gravely Sand; gS
65-85 Sandy Gravel; sG
85-89 Sand; S

WELL SUMMARY SHEET

Start Date: 07/02/07
Finish Date: 07/10/07
Page 2 of 2

Well ID: C5585
Well Name: 199-D5-115
Location: West of DR reactor, near 100-D Gate
Project: Biostimulation Test Wells at 100-D Area
Prepared By: Jeff Fetters
Date: 07/19/07
Reviewed By: L.D. Walker
Date: 7/27/07
Signature:
Signature:

CONSTRUCTION DATA

Description	Diagram
Primary Filter pack 10-20 Mesh Colorado Silica Sand: 80.5 - 105.0 ft 4-in I.D. Polyvinyl Chloride (PVC), 20 Slot (0.020-in) Screen: 83.3 - 103.3 ft 4-in, I.D. Polyvinyl Chloride (PVC) End Cap: 103.3 - 103.6 ft	

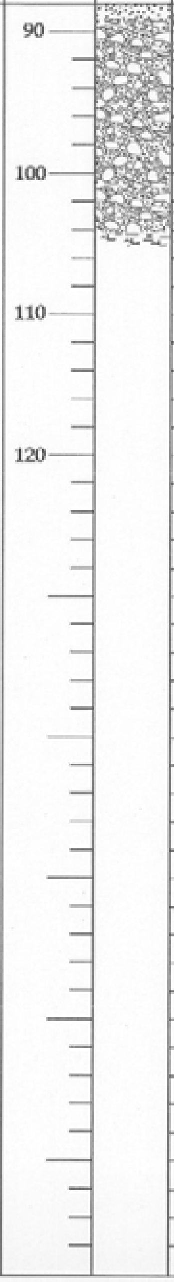
All depths are in feet below ground surface.

Borehole drilled with 7 $^{1/2}$ x 8 $^{5/8}$-inch casing.

All temporary drill casing was removed from the ground.

GEOLOGIC/HYDROLOGIC DATA

Depth in Feet | Graphic Log | Lithologic Description/Groundwater Sample Depths (ft bgs)



85-89 Sand; S
89-104 Sandy Gravel; sG
104-105 Silt; M
105.0 Total Depth Drilled (07-06-2007)

WELL SUMMARY SHEET

Start Date: 06/25/07

Finish Date: 06/29/07

Page 1 of 2

Well ID: C5586

Well Name: 199-D5-116

Location: West of DR reactor, near 100-D Gate

Project: Biostimulation Test Wells at 100-D Area

Prepared By: Erika Rincon

Date: 07/11/07

Reviewed By: L.D. Walker

Date: 7/27/07

Signature: Erika R

Signature: LD Walker

CONSTRUCTION DATA

Description

6-in Concrete Pad

6-in I.D. Type 304/304L Stainless Steel Protective Casing: +2.53 ft ags

Portland Cement Type I/II: 0 - 8.7 ft

4-in I.D., Sch. 40, Polyvinyl Chloride (PVC) Casing: +1.52 - 83.3 ft

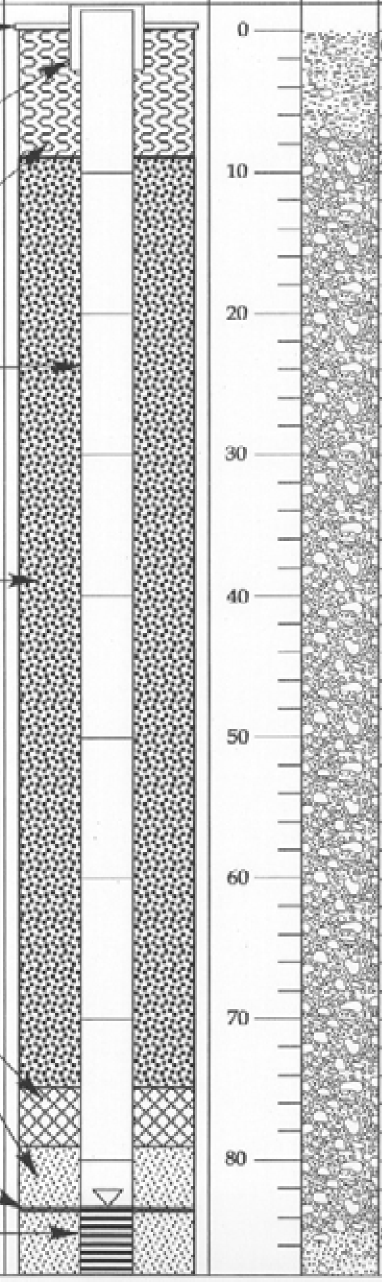
Granular Bentonite Crumbles: 8.7 - 74.7 ft

3/8-in Bentonite Pellets: 74.7 - 79.1 ft

Primary Filter Pack 10-20 Mesh Colorado Silica Sand: 79.1 - 104.5 ft

Static Water Level: 83.65 ft bgs (06-29-2007)

4-in I.D. Polyvinyl Chloride (PVC), 20 Slot (0.020-in) Screen: 83.3 - 103.3 ft



GEOLOGIC/HYDROLOGIC DATA

Lithologic Description/Groundwater Sample Depths (ft bgs)

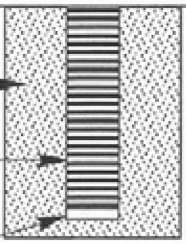
0-7 Gravelly Sandy Silt; gsM

7-85 Sandy Gravel; sG

85-90 Gravely Sand; gS

WELL SUMMARY SHEET	Start Date: 06/25/07 Finish Date: 06/29/07	Page 2 of 2	
Well ID: C5586		Well Name: 199-D5-116	
Location: West of DR reactor, near 100-D Gate		Project: Biostimulation Test Wells at 100-D Area	
Prepared By: Erika Rincon	Date: 07/11/07	Reviewed By: L.D. Walker	Date: 7/27/07
Signature: Erika R		Signature: LDWalker	

CONSTRUCTION DATA

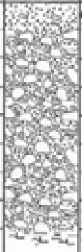
Description	Diagram
Primary Filter pack 10-20 Mesh Colorado Silica Sand: 79.1 - 104.5 ft 4-in I.D. Polyvinyl Chloride (PVC), 20 Slot (0.020-in) Screen: 83.3 - 103.3 ft 4-in, I.D. Polyvinyl Chloride (PVC) End Cap: 103.3 - 103.6 ft	

All depths are in feet below ground surface.

Borehole drilled with $7^{1/2} \times 8^{5/8}$-inch casing.

All temporary drill casing was removed from the ground.

GEOLOGIC/HYDROLOGIC DATA

Depth in Feet	Graphic Log	Lithologic Description/Groundwater Sample Depths (ft bgs)
90		90-104 Sandy Gravel; sG
		104-104.5 Mud; M
		104.5 Total Depth Drilled (06-27-2007)
100		
110		
120		

WELL SUMMARY SHEET	Start Date: 06/12/07 Finish Date: 06/18/07	Page 1 of 2

Well ID: C5587

Well Name: 199-D5-117

Location: West of DR reactor, near 100-D Gate

Project: Biostimulation Test Wells at 100-D Area

Prepared By: Erika Rincon Date: 07/11/07

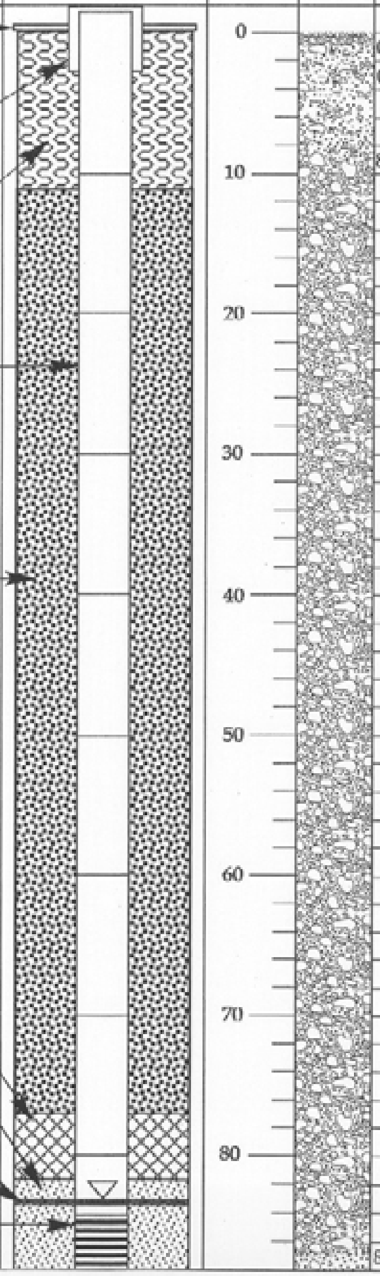
Reviewed By: L. D. Walker Date: 7/27/07

Signature:

Signature:

CONSTRUCTION DATA — Description / Diagram

GEOLOGIC/HYDROLOGIC DATA — Depth in Feet / Graphic Log / Lithologic Description/Groundwater Sample Depths (ft bgs)



6-in Concrete Pad

6-in I.D. Type 304/304L Stainless Steel Protective Casing: +2.56 ft ags

Portland Cement Type I/II: 0 - 10.7 ft

4-in I.D., Sch. 40, Polyvinyl Chloride (PVC) Casing: +1.56 - 84.2 ft

Granular Bentonite Crumbles: 10.7 - 77.3 ft

3/8-in Bentonite Pellets: 77.3 - 81.8 ft

Primary Filter Pack 10-20 Mesh Colorado Silica Sand: 81.8 - 90.2 ft

Static Water Level: 83.53 ft bgs (06-18-2007)

4-in I.D. Polyvinyl Chloride (PVC), 20 Slot (0.020-in) Screen: 84.2 - 89.2 ft

0-0.5 Gravel; G (Fill)

0.5-8.5 Gravely Silty Sand; gmS

8.5-87 Sandy Gravel; sG

87-90 Gravely Sand; gS

WELL SUMMARY SHEET

Start Date: 06/12/07
Finish Date: 06/18/07
Page 2 of 2

Well ID: C5587
Well Name: 199-D5-117
Location: West of DR reactor, near 100-D Gate
Project: Biostimulation Test Wells at 100-D Area
Prepared By: Erika Rincon
Date: 07/11/07
Reviewed By: L. D. Walker
Date: 7/27/07
Signature: Erika R
Signature: LD Walker

CONSTRUCTION DATA

Description

Primary Filter pack
10-20 Mesh Colorado Silica Sand:
81.8 - 90.2 ft

4-in, I.D. Polyvinyl Chloride (PVC)
End Cap: 89.2 - 89.5 ft

Natural Fill: 90.2 - 91.6 ft

Diagram

All depths are in feet below ground surface.

Borehole drilled with 7 1/2 x 8 5/8-inch casing.

All temporary drill casing was removed from the ground.

GEOLOGIC/HYDROLOGIC DATA

Depth in Feet	Graphic Log	Lithologic Description/Groundwater Sample Depths (ft bgs)
90		87-90 Gravely Sand; gS
		90-91.6 Sandy Gravel; sG
		91.6 Total Depth Drilled (06-15-2007)
100		
110		
120		

WELL SUMMARY SHEET

Start Date: 06/19/07

Finish Date: 06/26/07

Page 1 of 2

Well ID: C5588

Well Name: 199-D5-118

Location: West of DR reactor, near 100-D Gate

Project: Biostimulation Test Wells at 100-D Area

Prepared By: Jeff Fetters

Date: 06/29/07

Reviewed By: L. D. Walker

Date: 7/27/07

Signature:

Signature:

CONSTRUCTION DATA

Description | Diagram

6-in Concrete Pad

6-in I.D. Type 304/304L Stainless Steel Protective Casing: + 2.46 ft ags

Portland Cement Type I/II: 0 - 10.1 ft

4-in I.D., Sch. 40, Polyvinyl Chloride (PVC) Casing: +1.36 - 98.15 ft

Granular Bentonite Crumbles: 10.1 - 73.0 ft

3/8-in Bentonite Pellets: 73.0 - 78.8 ft

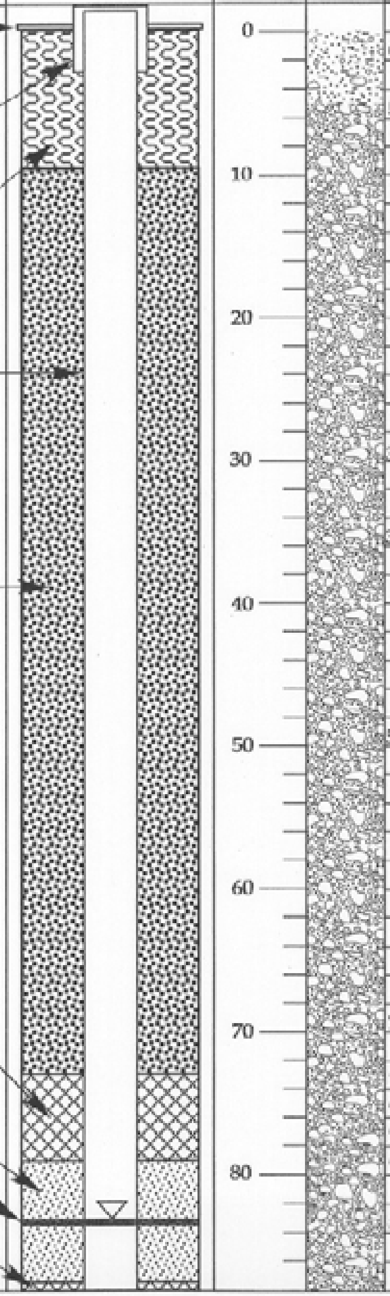
10-20 Mesh Colorado Silica Sand: 78.8 - 89.6 ft

Static Water Level: 83.35 ft bgs (06-26-2007)

3/8-in Bentonite Pellets: 89.6 - 96.2 ft

GEOLOGIC/HYDROLOGIC DATA

Depth in Feet | Graphic Log | Lithologic Description/Groundwater Sample Depths (ft bgs)



0-5 Gravelly Silty Sand; gmS

5-30 Sandy Gravel; sG

30-35 Sandy Gravel; sG

35-50 Sandy Gravel; sG

50-70 Sandy Gravel; sG

70-73.5 Sandy Gravel; sG

73.5 Hanford / Ringold contact

70-75 Sandy Gravel; sG

75-77 Sandy Gravel; sG

77-84 Silty Sandy Gravel msG

84-90 Sandy Gravel; sG

WELL SUMMARY SHEET	Start Date: 06/19/07 Finish Date: 06/26/07	Page 2 of 2

Well ID: C5588		Well Name: 199-D5-118	
Location: West of DR reactor, near 100-D Gate		Project: Biostimulation Test Wells at 100-D Area	
Prepared By: Jeff Fetters	Date: 06/29/07	Reviewed By: L. D. Walker	Date: 7-27-07
Signature:		Signature:	

CONSTRUCTION DATA

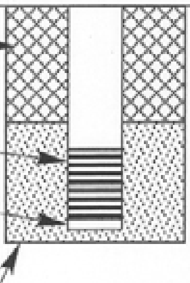
Description	Diagram

3/8-in Bentonite Pellets:
89.6 - 96.2 ft

4-in I.D. Polyvinyl Chloride (PVC),
20 Slot (0.020-in) Screen:
98.15 - 103.13 ft

4-in, I.D. Polyvinyl Chloride (PVC)
End Cap:
103.13 - 103.44 ft

Primary Filter pack
10-20 Mesh Colorado Silica Sand:
96.2 - 104.5 ft



All depths are in feet below ground surface.

Borehole drilled with 7 1/2 x 8 5/8 -inch casing.

All temporary drill casing was removed from the ground.

GEOLOGIC/HYDROLOGIC DATA

Depth in Feet	Graphic Log	Lithologic Description/Groundwater Sample Depths (ft bgs)

84-90 Sandy Gravel; sG
90-93 Silty Sandy Gravel msG
93-104 Sandy Gravel; sG
104-104.5 Mud; M
104.5 Total Depth Drilled (06-22-2007)

BOREHOLE LOG

0502714

Page 1 of 4

Date: 4/26/99

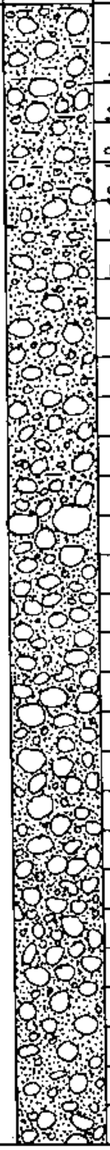
Well ID: B8749

Well Name: 199-D5-40

Location: At the 100-D Area South Gate

Project: 1999 100-D Area Drilling

Reference Measuring Point: Ground Surface

Depth (Ft.)	Sample		Graphic Log	Sample Description	Comments:
	Type No.	Blows Recovery		Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HC1	Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
0				0' → 8' : Silty Sandy GRAVEL (msG);	10" ODEX bit drills
	Air Rotary (Tubex)	NA		60% gravel, 30% sand, 10% silt; gravel	12" hole; 10¾" OD
				20% v.cse, 20% cse, 40% med, 20% fn-v.fn,	CS casing
				sand 40% v.cse-cse, 30% med, 30% fn-v.fn;	
				gryish brn (10YR, 5/2), dry, poorly sorted,	0-5 ft: drill rate
5				gravel sub-round, sand sub-angular; sand	~1 min/ft, then slow
				and gravel 80% basalt, 20% qtz and other,	to ~5 min/ft
				max gravel size 5-6 cm; occ. caliche coating	
				on gravel w/ strong HCl rxn.	
				- 5-7 ft: silt content decreasing -	
10	Cr+6			8' → 31' : Sandy GRAVEL (sG); 70%	*10 Ft: grab sample
	Grab			gravel, 25-30% sand, tr-5% silt; gravel	for PNNL Cr+6 analysis
				tr cobble (12-14 ft), 30% v.cse, 30% cse peb,	
				40% med-v.fn; sand 30% v.cse, 40% cse-	injecting water for
				med, 30% fn-v.fn; gray (7.5YR, 5/1) dry,	dust control and
15				poorly sorted; gravel sub-round to sub-ang,	aiding drilling -
				sand sub-angular; gravel 75% basalt, 25%	about 1-2 gpm
				granitic & other; sand 80% basalt, 20%	
				qtz & other; max gravel ≈20 cm (lg. cob.)	15 ft: very poor
				common weak HCl rxn.	returns
20					
	Cr+6				*20 ft: grab sample
	Grab				for PNNL Cr+6 anal.
					20-25 ft: very poor
25				Most of air circulation lost	returns.
				into formation	

Reported By: L.D. Walker

Title: Geologist

Signature: LD Walker

Date: 4/26/99

Reviewed By: E.C. Rafuse

Title: Field Engineer (BHI)

Signature: E.C. Rafuse

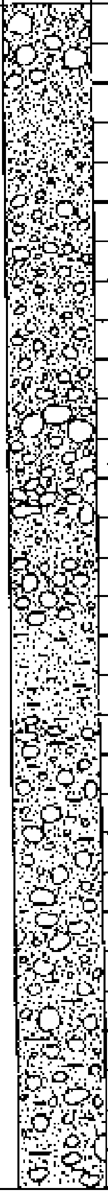
Date: 05/03/99

BHI-EE-183 (12/97)

BOREHOLE LOG

Page 2 of 4
Date: 4/26/99

Well ID: 88749
Well Name: 199-D5-40
Location: South Gate of 100-D Area
Project: 1999 100-D Area Drilling
Reference Measuring Point: Ground Surface

Depth (Ft.)	Sample		Graphic Log	Sample Description	Comments:
	Type No.	Blows Recovery		Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
30		NA		31'→33.5': Gravelly SAND (gS); Fines	10" ODEX bit drills
	Cr^{+6} Grab			up to a clear contact at 31'; 20% gravel,	12" hole; 10¾" OD
				80% sand; gravel predom. fn-v.fn, sand	CS casing.
	Air Rotary (Tubex)			30% v.cse, 50% cse, 20% med-v.fn; gray	
				(7.5YR, 5/1); dry; mod sorted, sand sub-	*30 Ft: grab sample
35				angular; 80% basalt, 20% qtz/other, max	PNNL Cr^{+6} analysis
				gravel ≈1 cm, no HCl rxn.	
				33.5'→42' : Sandy GRAVEL (sG);	
				50% gravel, 50% sand, tr silt; gravel is	
				tr cse-v.cse peb, 50% med, 40% fn, 10%	
40				v. fn, sand 30% v.cse, 40% cse, 30% med-v.	
	Cr^{+6} Grab			fn; gray (7.5YR, 5/1), dry, mod-poorly	*40 Ft: grab sample
				sorted; gravel sub-round, sand sub-	PNNL Cr^{+6} analysis
				ang; gravel 60% basalt, 40% granitic,	
				metamorphic, other; sand 75% basalt,	
45				25% qtz/other; max gravel ≈ 5 cm	
				(39-40 ft: drilling indicates cobbles	
				over 10 cm).	
				42'→43' : Gravelly SAND (gS); similar	
				to gS 31'→33.5'	
50				43'→45' : Sandy GRAVEL (sG)	*50 Ft: grab sample
	Cr^{+6} Grab			similar to 33.5'→42' sG	PNNL Cr^{+6} analysis
				45'→47' : Silty SAND (mS); 5% gravel	
				60% sand 35% silt; sand is basalt	α, β, γ ≈< detect
				rich med-cse., weak HCl rxn.	
55				47'→74' : Silty Sandy GRAVEL (msG);	
				60% gravel, 30% sand, 10% silt; gravel	
				tr cob, 10% v.cse peb, 30% cse, 50% med,	
				10% fn-v.fn; sand 20% v.cse-cse, 50% med,	
				30% fn-v.fn; grayish brn (10YR, 5/2); moist;	

Reported By: L. D. Walker
Title: Geologist
Signature:
Date: 4/26/99

Reviewed By: EC Rafuse
Title: Field Engineer (BHI)
Signature: EC Rafuse
Date: 5/03/99

3

BOREHOLE LOG

Page ~~1~~ of 4

Date: 4/26/99

Well ID: B8749

Well Name: 199-D5-40

Location: At 100-D Area South Gate

Project: 1999 100-D Area Drilling

Reference Measuring Point: Ground Surface

Depth (Ft.)	Sample: Type No.	Sample: Blows Recovery	Graphic Log	Sample Description: Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HC1	Comments: Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
60	Cr^{+6}	NA		(msG) - continued.	10" ODex bit drills
	Grab			poorly sorted; gravel round - sub round,	12" hole; 10¾" OD
	Air			Sand sub ang; gravel 40% basalt, 60%	CS casing.
	Rotary			granitic and other - possible some	
	(Tubex)			re-worked Ringold gravel; sand 60%	*60 ft: grab sample
65				basalt, 40% qtz/other; max gravel ≈	PNNL Cr^{+6} analysis
				7 cm; no HCl rxn	
70	Cr^{+6}				*70 ft: grab sample
	Grab				PNNL Cr^{+6} anal.
				74 ft: Change in sand mineralogy -	
				Hanford / Ringold contact	
75				74'→75': Silty Sandy GRAVEL (msG)	
				75'→ 78': SAND (S); 5% gravel, 95%	
				sand, tr silt; gravel fn - v. fn, Sand 10%	
				v. cse - cse, 30% med, 40% fn, 20% v. fn; lt	*78 ft: grab sample
	Cr^{+6} Grab			brownish gray (10YR, 6/2), dry, well sorted,	CHI Cr^{+6} analysis
80	Cr^{+6}			ang to sub angular; 80% qtz, 15% basalt,	
	Grab			5% other; max gravel ~ 1 cm, no HCl rxn	*80 ft: grab sample
					PNNL Cr^{+6} analysis
				78'→ 98': Sandy GRAVEL (sG);	
				65% gravel, 35% sand, tr silt; gravel	End 4/26/99
85	SS	Rec.		20% v. cse - cse peb, 20% med, 40% fn, 20% v. fn,	Begin 4/27/99
	84.4'→	90%		Sand 10% v. cse - cse, 20% med, 50% fn, 20%	*84.4'→ 86.4': Split
	86.4'			v. fn; grayish brn (10YR, 5/2), damp, poorly	Spoon for Sieve analysis
				sorted; gravel rnd - sub rnd, sand sub ang, gravel	* Water Sample B0V165
				30% basalt, 70% other, Sand 75% qtz, 20% basalt, 5% other.	↳ Cr^{+6} = 7 ppb

Reported By: L.D. Walker

Title: Geologist

Signature: LD Walker

Date: 4/27/99

Reviewed By: E C Rafuse

Title: Field Engineer (BHI)

Signature: E C Rafuse

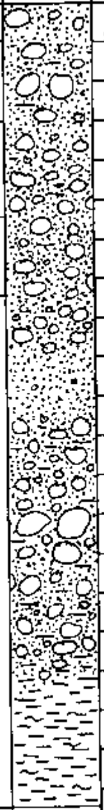
Date: 5/3/99

BHI-EE-183 (12/97)

BOREHOLE LOG

Page ~~1~~ 7 of 4
Date: 4/27/99

Well ID: B8749
Well Name: 199-D5-40
Location: 100-D Area South Gate
Project: 1999 100-D Area Drilling
Reference Measuring Point: Ground Surface

Depth (Ft.)	Sample		Graphic Log	Sample Description	Comments:
	Type No.	Blows Recovery		Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HC1	Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
90				88'→89': Silt content 5-10%, then back	10" ODEX bit drills
	SS 90.0'→ 92.0'	Rec. 60%		to trace amounts;	12" hole; 10¾" OD
				90 ft: Silt ~5%, weak Rxn to HCl	CS casing.
				tr mica	
					*90.0'→92.0': Split
95	SS 94.5'→ 96.5'	Rec. 70%			Spoon sample for sieve
					analysis.
	Air Rotary (Tubex)	NA		98'→99.5': Gravelly SAND (gS); 10% gravel	*94.5'→96.5': Split
				90% sand, tr silt; gravel 40% med, 60%	Spoon for sieve analysis
				Fn-v.fn; Sand is 10% v.cse-cse, 30%	
100				med, 50% fn, 10% v.fn; lt. brnish gray	W.L. = 83.2' (4/27 a.m.)
				(10YR, 6/2) well-mod sorted, gravel rnd	→when drive shoe @85'
				sand sub-angular; sand 80% qtz, 20%	
				basalt/other, tr mica, no rxn to HCl	102'→103': drilling
				99.5' → 106': Silty Sandy GRAVEL (msG)	indicates lg. cobbles
105				60% gravel, 30% sand, 10% silt; similar	
				to sandy gravel above with more silt.	
				106'→109.5': SILT (M); with clay;	
				90% silt, 10% clay, pale brown (10YR, 7/3)	
110				strong HCl rxn; small lumps of clay	TD = 109.5 feet
				(<5mm) med. plasticity.	
115					

Reported By: L.D. Walker
Title: Geologist
Signature: LD Walker
Date: 4/27/99

Reviewed By: EC RaFuse
Title: Field Engineer (BHI)
Signature: EC Rafuse
Date: 5/3/99

BHI-EE-183 (12/97)

0510307

WELL SUMMARY SHEET

Page 1 of 1
Date: 04/26/99

Well ID: B 8749
Well Name: 199-D5-40
Location: 100-D Area South Gate
Project: 1999 100-D Area Drilling
Prepared By: L.D. Walker / J.M. Faurote
Date: 4/29/99
Reviewed By: E.C. Lafax
Date: 05/03/99
Signature: L.D. Walker / J.M. Faurote
Signature: E.C. Lafax

CONSTRUCTION DATA

Description

Protective casing is 1.0' above permanent riser pipe.

Portland Type I, II, V Cement (with Quik Gel) Grout from the surface to 66.9'

6" ID carbon-steel riser from +2' bgs to 82.53'

Colorado Silica Sand (10-20 mesh) from 66.9' to 109.5

▼ @ 82.31' on 4/29/99

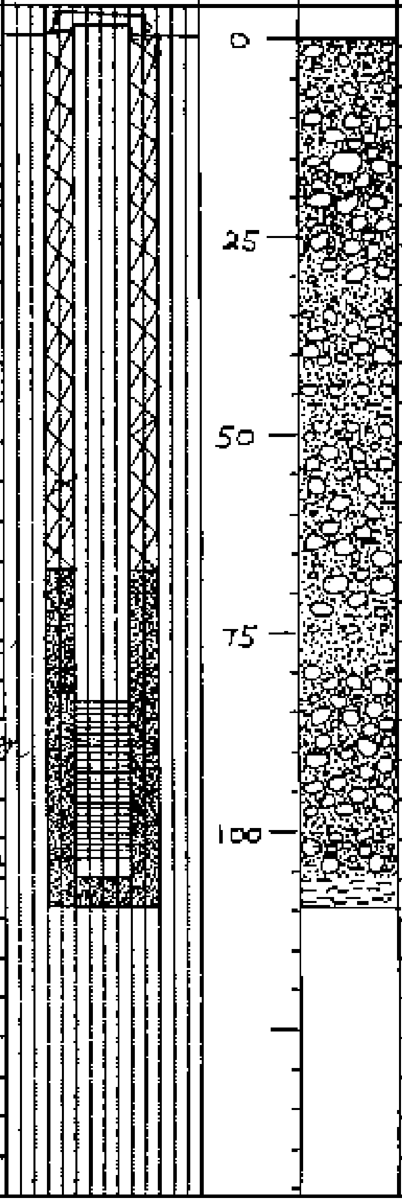
6" ID SS304 .020 slot Screen from 102.54' to 82.53'

SS304 tailpipe 105.56 - 102.54

total pipe 107.56

All temporary casing was removed.

All depths are below ground surface.



GEOLOGIC/HYDROLOGIC DATA

Lithologic Description

0'→8': Silty Sandy GRAVEL

8'→31': Sandy GRAVEL

31'→33.5': Gravelly SAND

33.5'→42': Sandy GRAVEL

42'→43': Gravelly SAND

43'→45': Sandy GRAVEL

45'→47: Silty SAND

47'→74': Silty Sandy GRAVEL

74 ft: Hanford / Ringold contact

74'→75': Silty Sandy GRAVEL

75'→78': SAND

78'→98': Sandy GRAVEL

98'→99.5': Gravelly SAND

99.5'→106': Silty Sandy GRAVEL

106'→109.5': SILT w/ clay

TD = 109.5 feet

BHI-EE-159 (12/97)

BOREHOLE LOG

Page 1 of 3

Date: 5-2-07

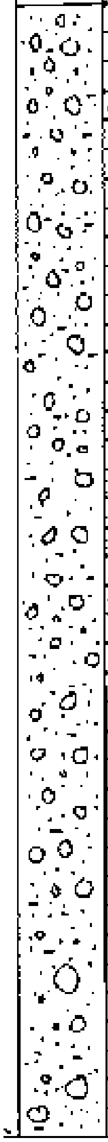
Well ID: C5571

Well Name: 199-D5-107

Location: N&E of DR reactor, near 100-D Area gate

Project: Biostimulation test wells

Reference Measuring Point: ground surface

Depth (Ft)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
0					Cable Tool drill rig
				0-1 gravel (fill) - drill pad	Drive barrel method
				1-15' silty sandy GRVL msG; 20% silt 40% snd	
				40% gvl; gvl 90% basalt 10% other, SR-SA, 0.5-7cm;	grab samples (archive)
				snd vf-vc sub-silt 80% basalt 20% other; 2.5Y 5/1 gray	every 5 ft.
5	grab			strong rxn HCL, dry	
10	grab				
15	grab			15-20 lith same as above	
				weak rxn HCL	
20	grab			20-30 lith. same as above	
15	grab				
30	grab			30-35 lith. same as above / coarser sand	
35	grab			35-40 lith same as above / increase in fine sand	

Reported By: Erika Rincon

Title: geologist

Date 5-2-07

Reviewed By L.D. Walker

Title: Geologist

Date: 7/25/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 2 of 3

Date: 5-2-07

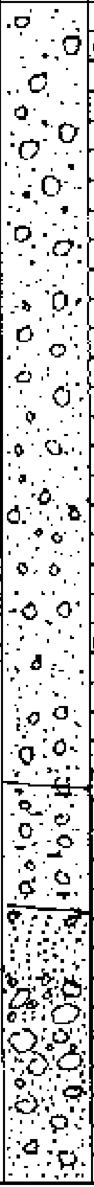
Well ID: C5577

Well Name: 199-D5-107

Location: West of DR reactor, near 100-D Area gate.

Project: Biostimulation Test Wells

Reference Measuring Point: ground surface



Depth (Ft.)	Sample: Type No.	Sample: Blows Recovery	Sample Description: Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments: Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
40	grab		40-50 sandy GRAVEL sG; 60% snd 40% gvl; gvl 60% basalt, 40% other, SR-SA, 0.5-7cm; snd 60% basalt 40% other, f-vc, 2.5Y 6/2 light brownish gray; no rxn HCl, dry	Cable Tool drill rig Drive Barrel method grab samples (archive) every 5 ft.
45	grab			
50	grab		50' same lith. as above 2.5Y 4/2 dk grayish brn	
55	grab			
60	grab		60-65 gravelly SAND gS; 95% snd 5% gvl gvl 0.5-2cm, SR-SA 50% basalt 50% other snd - lith. same as above	
65	grab		65-70 silty sandy GRAVEL msG; 40% gvl 40% snd 20% silt; gvl 50% basalt 50% qtz, SR-SA, 0.5-4cm; snd 50% basalt 50% other, f-c; strong rxn HCl 2.5Y 6/2 light brownish gray, dry	
70	GRAB		70-75 SAND <5% GRAVEL (P&C MIXED) M-F SA. WELL SORTED SUB ROUNDED QTZ ABUNDANT Fe Ox STAINED ON QTZ. NO HCl [illegible] [illegible] DOCUMENTED TO DESCRIPTION AS ABOVE	
75	GRAB		75' DESCRIPTION AS PER 65'	

Reported By: Erika Rincon G L Hartza

Title: geologist

Signature: Erika R

Date: 5-11-07

Reviewed By: L. D. Walker

Title: Geologist

Date: 7/25/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 2 of 3

Date: 5-9-07

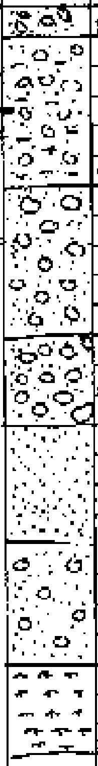
Well ID: C5577

Well Name: 199-D5-107

Location: Biostim Test Site - 100 D Area

Project: Biostim Test Wells

Reference Measuring Point: GS

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
				80' GRAVELLY SILTY SAND gmS DRY	
80	Grab			20% G, TR COBB. 3" VARIOUS LITH SR,	SPLIT SPOON" / 82-84.5
	55	graph/ 200 lbs		30% SILT, 60% SAND SA-A, C-VF	9/2-9.15 DRIVE
				SALT-PEPPER, WELL SORTED WEAK HCl Rxn	206 BLOWS
		18/2		2.5Y 6/2 LIGHT BROWNISH GRAY AS REC'D	SW1 82.5' bgs (6-13-07)
				85' SOIL IS MOIST	84-86 split-spoon-PNNL
85		226 blows #25.5/100% Rec		85 SAMPLE WET ~~@85~~ SG 60% G, PEC	
				COBBLES TO +3" SR VARIOUS LITH	86-88 split-spoon (PNNL)
				40% SAND SA-A C-VF WELL SORTED	
				WEAK HCl RXN 2.5Y 4/3 OLIVE BROWN	
				WHEN WET	88-90 split-spoon (PNNL)
90	grab			90' Sandy gravel (sG) 70% gvl 30% sand: GVL: 4mm-	
				3mm (sc-vfp), 70% qtz 10% basalt, R-SR; Sand: c-vf	90-92 split-spoon (PNNL)
				Predom. m-VF, 90% qtz 10% basalt, A-SA, wk Rxn	
				HCl, 2.5y 3/2, vDark grayish brown.	
95	grab			93-97 Sand (S) m-VF, Predom med.	93-95 split-spoon (PNNL)
				grained, 80% qtz/other 20% basalt, A-SA	
				no Rxn HCl, 2.5y 4/3 olive brown, high	96-98 split-spoon (PNNL)
				mica content	
				97' Sandy gravel	
100	grab			101' Ringold upper mud, 100% clay/mud	
				2.5y 4/2 dk grayish brown, moist, wk	
				Rxn HCl	
					TD 104' bgs (5-14-07)

Reported By: G.L. Kasza/Jeff Rivers

Title: Geologist

Date: 6/14/07

Reviewed By: L.D. Walker

Title: Geologist

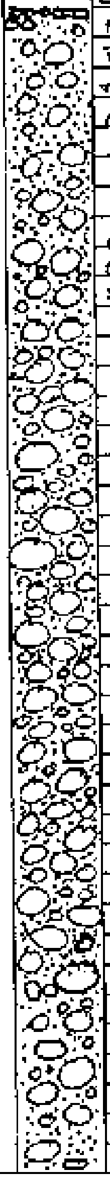
Date: 7/25/07

A-6003-642 (03/00)

BOREHOLE LOG

Page 1 of 3
Date: 5-31-2007

Well ID: C5578
Well Name: 199-D5-108
Location: Biostim Test Site
Project: Wells to Support Biostimulation Test
Reference Measuring Point: Ground Surface @ Top of Pad.



Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description: Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments: Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
0				0-1.5' PAD GRAVEL (CRUSHED)	CABLE TOOL 7" DRIVE
				1.5-8' G SANDY GRAVEL	BARREL
				70% G PEBBLE-COBBLE, COBBLES	
				TO 4" POOR SORTING FINE PEBBLES	GRAB SAMPLES FOR
				MAINLY BASALT-COBBLES MIXED LITHOLOGY	1 PT ARCHIVE JAR
				30% SILTY SAND DRY VF-M GR. SG	CHIPTRAY 1
5	GRAB			STRONG HCl RXN 10YR 6/3 PALE BRN	PHOTOGRAPH OF
					CUTTINGS
				8-n G SILTY GRAVEL 70% G	
				COBBLES TO +4", RANDOM. BASALT	
				SAND, 10% F-V FINE, 30% SILT	
10	GRAB			NO HCl RXN	
15	GRAB			15' AS ABOVE	
20	GRAB			20' AS ABOVE	
25	GRAB			25' AS ABOVE	
30	GRAB			30' AS ABOVE	
				33' 8" Ø COBBLE IN CUTTINGS	
35	GRAB			35' AS ABOVE	

Reported By: Greg L. Kasza
Title: Geologist
Signature: Greg Kasza
Date: 5-31-07

Reviewed By: L.D. Walker
Title: Geologist
Signature: L.D. Walker
Date: 7/26/07

A-6003-647 (03/03)

BOREHOLE LOG

Page 2 of 3

Date: 5-31-07

Well ID: C5578

Well Name: 199-05-108

Location: Biostim Test Site 100 D

Project: Injection Well to Support Biostimulation Test

Reference Measuring Point: GS @ Top of Pad

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description: Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments: Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
40	Grab			40' Same as Above	Cable Tool 7" Drive Barrel Grab Samples for 1 PT Archive Jar Chiptray & Photograph
45'	Grab			45' Same As Above	
50	grab			50-55 silty sandy GRAVEL msG; 30% silt, 30% gvl 40% snd; snd - 80% basalt 20% other, vf-vc; gvl - 80% basalt 20% other; 0.5-3cm, SR-SA; 2.5Y 5/1 gray, dry mod. rxn HCl	
55	grab			55-60 sandy gravelly SILT; sgM; 50% silt 30% gvl 20% snd; snd 80% basalt 20% other, vf-c, 2.5Y 4/1 gray; gvl 80% basalt 20% other, SR-SA, 0.5-3cm; dry, mod. rxn HCL	
60	grab			60-65 gravelly sand gS; 30% gvl 70% snd; snd - 50% basalt 50% other, vc-vf, 2.5Y 5/1 gray gvl - 50% basalt 50% other, SR-SA, 0.5-7cm, strong rxn HCl, dry	
65	grab			65-70 sandy GRAVEL sG; 50% gvl 50% snd lith. same as above	
70	grab			70-75 gravelly SAND gS; 15% gvl 85% snd lith same as above	
75	grab			75-78 sandy GRAVEL sG; 50% gvl 50% snd; gvl - 50% basalt 50% other, SR-SA, 0.5-6cm; snd 30% basalt 70% other f-vc, 2.5Y 6/2 light brownish gray; slight rxn HCl, dry	75' ↓ drilling rate

Reported By: Erika Rincon Cascade

Title: geologist

Signature: Erika R

Date: 6-1-07

Reviewed By: L.D. Walker

Title: Geologist

Signature:

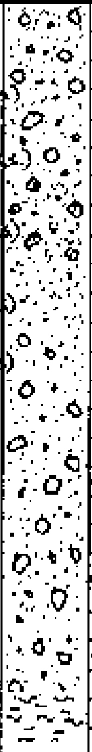
Date: 7/26/07

A 6003 642 (03/03)

BOREHOLE LOG

Page 3 of 3
Date: 6-4-07

Well ID: C5578
Well Name: 199-D5-108
Location: West of DR reactor, near 100-D gate
Project: Biostimulation Test Wells
Reference Measuring Point: ground surface

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description: Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments: Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
80	grab			78-85 sandy GRAVEL sG; 60% snd 40% gvl; gvl-	(CableTool-Drive Barrel
		PNNL grab(ss)		50% basalt 50% other, 0.5-5cm, SR-SA; snd-vf-vc,	grab samples every 5ft
				90% qtz/other 10% basalt; 2.5Y 6/2 light brownish	for archive
				gray, no rxn HCL, dry	81-83' grab-PNNL-split
83 bgs ▽		PNNL grab(ss)		83-85 same as above, wet	spoon
85	grab				83'-85' grab-PNNL split
		PNNL grab(ss)		85-90 SAND S; 100% sand; f-m, 10YR 4/3	spoon
				brown, 20% basalt 80% other, mod. rxn HCL, wet	85.5-87.5' grab-PNNL-split
		PNNL grab(ss)			spoon
					88-90' grab-PNNL-split
					spoon
90	grab	PNNL grab(ss)		90-95 sandy GRAVEL sG; 60% gvl 40% snd;	
				gvl: 30% basalt 70% qtz/other, 0.5-6cm, SR-SA; snd-	
				10% basalt 90% qtz/other, f-m; 2.5Y 4/2 dark grayish	90-92' grab-PNNL split
		PNNL grab (ss)		brn, no rxn HCL	spoon
95	grab				
		PNNL grab (s.s.)		95 - sandy Gravel (sG) - 65% gravel, 30%	93-95 s.s. grab PNNL
				sand, 5% silt - gravel - FP-CP, 30% basalt	
		PNNL grab (s.s.)		70% qtz-rich, SR-R, sand VFs-VCs, predom med,	
				20% basalt 80% qtz / 2.5Y 4/2 dark grayish brown.	
100	grab	PNNL grab (s.s.)		wet, no rxn HCl!	95-97 s.s. grab PNNL
					97-99 s.s. grab PNNL
		PNNL grab (s.s.)		100' - Sandy Gravel (sG) - as above	
					99-101 s.s. grab PNNL
				102' - Mud (M) - clay-rich mud,	101-102.5 s.s. grab PNNL
				brown 10YR 5/3, no rxn HCl.	
					Clay rip-up clast noted
					@ 102'
					T.D. 106' bgs (6-6-07)

Reported By: Erika Rincon	Reviewed By: L.D. Walker
Title: geologist	Title: Geologist
Signature: Erika R Date: 6-6-07	Signature: Date: 7/26/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 1 of 3

Date: MAY 2, 2007

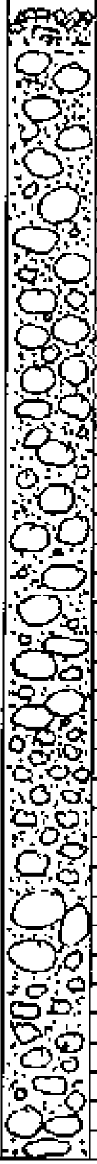
Well ID: C5579

Well Name: 199-D5-109

Location: BIOSTIM TEST SITE @100 D-AREA

Project: 12 WELLS FOR BIOSTIMULATION TEST

Reference Measuring Point: GROUND SURFACE

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description: Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments: Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
0				0'~1' PAD BASE - CRUSHED	CABLE TOOL W/
				GRAVEL & SCREENED PIT RUN	DRIVE BARREL
				1'-1.6' SOIL/HORIZON-PLANT	
				MATERIAL - SILT & FINE SAND	GRAB SAMPLES FOR
				1.6'-35.5'± msG, SILTY	ARCHIVE PINT JAR
5	GRAB			SANDY GRAVEL; 70% GRAVEL	AND CHIP TRAY
				COBBLES TO ~4" SR-RND	
				LITHOLOGY IS MAINLY BASALT	
				~10% SAND FINE-MED GRAIN	
				SA QTZ DOMINANT,	
10	GRAB			20-30% SILT-VFSAND	
				SA-SR NO HCl RXN. DRY	
				10YR 7/1 LT GRAY	
15	GRAB			15' SAMPLE AS ABOVE	
20	GRAB			20' AS ABOVE	
25	GRAB			25' ↑ % GRAVEL BUT MAX	
				SIZE ≈ 2"	
30	GRAB			30' COARSE AGAIN	
				33' SALT-PEPPER SAND FRACTION (INCREASE DARKS)	
				34-38 sG TO gS FINING	
35	GRAB			38 COARSENING SEQUENCE	
				COBBLES TO 6" AGAIN	
				ABUNDANT ROCK FLOUR &	
				FRESH ANGULAR FRAGMENTS	
				IN CUTTINGS	

Reported By: GREG L HASZA

Title: GEOLOGIST

Signature:

Date: 5-2-07

Reviewed By: L.D. Walker

Title: Geologist

Signature:

Date: 7/26/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 2 of 3
Date: MAY-2,3 2007

Well ID: C5579
Well Name: 199-D5-109
Location: 100 HR3 OU BIOSTIM TEST SITE
Project: 100-HR 3-OU BIOSTIM TEST
Reference Measuring Point: GS

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
				SALT-PEPPER COLOR	Cable tool with
40	GRAB			10% SILTS	drive barrel
				DRY 2.5Y 4/1 DARK GRAY	
				FINING TO:	
				45' gS 20% PEBBLES TO 2"	
45	GRAB			80% SAND AS DESCRIBED ABOVE	
				COARSENING TO	
				50' sG 80% PEBBLE-COBBLE	
50	GRAB			TO +4"	
				FINING TO	
				55' sG 80% PEBBLES TO 2"	
55	GRAB				
				60'	
				AS ABOVE MINOR HCl RXN	
60'	GRAB			ONLY ON FEW(?) CLASTS W/	
				CO_3 CEMENT ON SURFACE	
				63' FINING TO S (90%)	
				65' mcS 20% G TO 2" S.R	
65	GRAB			VARIOUS MIXED LITHOLOGIES	
				80% SAND ~~[illegible]~~ 20% SILT	
				SAND M-VFGRAIN	
				NO RXN 10YR 6/1 GRAY	HARDER DRILLING -
				70' AS ABOVE	CHANGE TO
70	GRAB			SOME IRON STAIN ON QTZ IN SAND	SMALLER DIA DRIVE
				FRACTION - DRY	BARREL & SHORTER (2')
		H			HANFORD @ 73' BGS
		R		73' COARSENING TO W/ COLOR CHANGE;	RINGOLD
				75 SG SANDY GRAVEL 60% G 40% S	
75	GRAB			GRAVEL-COBBLES TO +4" VARIOUS LITHOLOGIES	
				SR. SAND M-VFGR FeOx STAINING QTZ	
				SALT/PEPPER SC +ANGULAR SUBROUND	
				CO_3 COATING CLASTS 10YR 6/2 LT BROWNISH GRAY	

Reported By: GREG L PASZA
Title: GEOLOGIST
Signature:
Date: 5-3-07

Reviewed By: L.D. Walker
Title: Geologist
Signature: LD Walk
Date: 7/27/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 3 of 3

Date MAY 3, 4

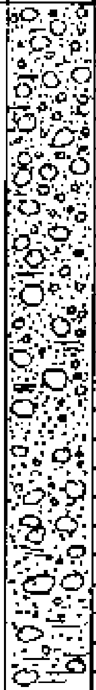
Well ID: C5577

Well Name: 199-D5-109

Location: 100 HR 3 OU BIOSTIM TEST SITE

Project: BIOSTIMULATION TEST

Reference Measuring Point: GS

Depth (Ft.)	Sample		Graphic Log	Sample Description	Comments
	Type No.	Blows Recovery		Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
80	GRAB	5GAL FOR PNNL		AS ABOVE SG 40% G .5R TO 3"	HARD DRILLING
				VARIOUS LITHOLOGIES. 60% SAND	CHANGE TO 5½" OD
				M-VF GR DRY TRACE MICA	DRIVE BARREL; PREVIOUS
				TRACE SILT No CO$_3$ RXN	WAS BROKEN USED.
				10YR 5/3 AS RECEIVED 10YR 3/2 AS DAMPED	
85	GRAB	5GAL		85 · AS ABOVE W/ MORE VISIBLE	85- SAMPLE IS WET
				MICA	
					COLLECTING 5GAL
					BUCKET SIZE
90	GRAB	5GAL		90' AS ABOVE 10YR 3/4 V. DK GRAYISH	SAMPLE FOR
				BROWN AS RECEIVED W/ No CaCO$_3$	PNNL REQUEST
				RXN	
				94 S	
95				95 GS TO SG	
	GRAB	5GAL		96.5 SG 60% G COBBLES TO 3"	
				40% SAND VF-M gr 10YR 4/3 BROWN	
				W/ MOD WET, TR MICA, WELL SORTED	
				SUB-R No HCl RXN	
100				100 AS ABOVE COLOR IN SITU 10YR 4/4	
	GRAB	5GAL		DK YELLOWISH BRN NOT SAMPLED.	
				DISCOLORED W/ CRUSHED BASALT	
				ROCK FLOUR	
				102 mG SILTY GRAVEL COBBLES -(4.5")	ROM CONTACT 102.3
105	GRAB	5GAL 103-104		GRADED TO <1/2" VARIOUS LITHS	
				GROUNDMASS 10YR 5/4 LT YELLOWISH BRN	
				SANDY SILTY CLAY SAND 40%	
				NO HCl RXN MASSIVE BEDDED	
				104.1 T.D sM SAND 20%	
110				F-VF GR SA QTZ BLACK MINS	
				OLIVE SILT CLAY SEMI PLASTIC	
				WEAK HCl RXN. 10YR 5/3 BROWN	
115					

Reported By: GREG L KASZA

Title: GEOLOGIST

Signature:

Date: 5-4-07

Reviewed By: L.D. Walker

Title: Geologist

Signature:

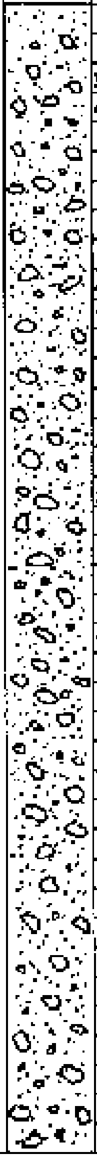
Date: 7/26/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 1 of 3
Date: 5-20-07

Well ID: C5580
Well Name: 199-D5-110
Location: W of DR Reactor / Near 100-D Area
Project: Biostimulation Test Wells
Reference Measuring Point: Ground Surface

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
					Cable Tool - Drive Barrel
0				0-5' Gravelly sand - to - sandy gravel	
5	ARCHIVE GRAB			5' - silty sandy Gravel (msG) - 10% silt, 40% sand, 50% gravel, sand VFS-VCS-predom. VFS-FS, gravel VFP-VCP- up to 60 mm, predom FP-MP, dry, brown 10YR 4/3, no rxn HCl.	Boulder @ 5.0'.
10	ARCHIVE GRAB			10' - sandy Gravel (sG) - 30% sand 70% gravel, sand VFS-VCS predom. FS-MS, 70% basalt, 30% qtz/lithics, SA-SR, gravel VFP-VCP, occasional cobble/boulder - 80% basalt 20% qtz granitic, dry, dark gray 10YR 4/1, no rxn HCl	
15	ARCHIVE GRAB			15' - sandy Gravel (sG) - as above. 20' - sandy Gravel (sG) - as above increase gravel fraction to 75-80%	
20	ARCHIVE GRAB			25' - Sandy Gravel (sG) - as above 30' - sandy Gravel (sG) - as above less VFS - FS in sand fraction, otherwise same, 100 mm cobble noted	
25	ARCHIVE GRAB			35' - Gravel (G) 15% sand 85% gravel sand - VFS-FS VCS, pred MS-VCS, 70% basalt 30% qtz, SA-SR, gravel VFP-50, pred. MP-CP, 70% basalt, 30% granitic, dry, very dark gray 10YR 3/1, no rxn HCl, unconsolidated.	
30	ARCHIVE GRAB				
35	ARCHIVE GRAB				

Reported By: STEVE AIRHART
Title: GEOLOGIST
Signature:
Date: 5-22-07

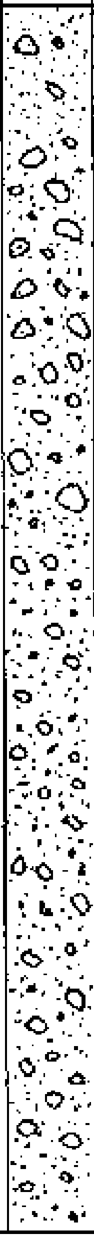
Reviewed By: L.D. Walker
Title: Geologist
Signature:
Date 7/26/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 2 of 3
Date: 5-23-07

Well ID: C5580
Well Name: 199-D5-110
Location: W of DR Reactor / near 100-D gate
Project: Biostimulation test site
Reference Measuring Point: ground surface

Depth (Ft.)	Sample: Type No.	Sample: Blows Recovery	Graphic Log	Sample Description: Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments: Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
40	ARCHIVE GRAB			40'- gravelly Sand (gS) 25% gravel 75% sand gravel - VFP - SC , 60% basalt 40% granitic other, SE-R, sand VFS - VCS predom MS, 50% basalt 50% qtz (salt&pepper), SA-SR, dry, gray 10YR5/1, no rxn HCl,	
45	ARCHIVE GRAB			45'- sandy Gravel (sG) 40% sand 60% gravel, sand VFS-VCS - predom MS-CS, 50% basalt 50% qtz, gravel VFP-SC - up to 100 mm noted, 60% basalt 40% granitic (other), SA-R, dark gray 10YR4/1, dry, no rxn HCl	
50	ARCHIVE GRAB			50'- sandy Gravel (sG)-as above	
55	ARCHIVE GRAB			55'- Sandy Gravel (sG)-as above > clast size. , >200 mm cobble/boulder noted.	
60	ARCHIVE GRAB			60'- sandy Gravel (SG)-as above < clast size	
65	ARCHIVE GRAB			65'- sandy Gravel (sG) - as above, weak rxn HCl. , more brown overall 10YR 3/2 very dark grayish brown < basalt overall	Δ color - more brown, > consolidation @ 68-68.5' significant Δ color < basalt (Ringold)
70	ARCHIVE GRAB			70'- Sandy Gravel (sG) - 40% sand, 60% gravel , sand MS-VCS, predom CS, 90% qtz 10% basalt, SA-SR, gravel VFP-VCP, predom CP, SA-R, dry, 50% basalt, 50% granitic (other), 10YR 6/2, light brownish gray, No rxn HCl (general) - $CaCO_3$ noted in some clasts.	
75	ARCHIVE GRAB			75'- sandy Gravel (sG) - as above 150 mm granitic clast noted	

Reported By: STEVE AIRHART
Title: GEOLOGIST
Signature:
Date: 5.22.07

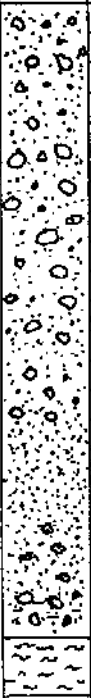
Reviewed By: L.D. Walker
Title: Geologist
Signature: LD Walker
Date: 7/26/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 3 of 3
Date: 5-23-07

Well ID: C5580
Well Name: 199-D5-110
Location: W of DR Reactor / Near 100-D Gate
Project: Biostimulation Test Site
Reference Measuring Point: Ground Surface

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
80	ARCHIVE GRAB			80' - sandy Gravel (sG) - 5% silt, 30%,	
				sand, 65% gravel, sand VFS-MS,	
				predom FS (well sorted), 95% qtz 5% mafic,	SWL 82.87' bgs (5-29-07)
				gravel VFP-CP, predom. MP 70% qtzite,	
				granite, 30% basalt, dry, 10YR 6/2 light	
85	ARCHIVE GRAB			brownish gray, mod rxn HCl	
				85' - sandy Gravel (sG) - as above	wet sediment
				wet color olive brown 2.5Y 4/3.	
					> fines between 85-90'
90	ARCHIVE GRAB			90' - ~~silty~~ muddy sandy Gravel (msG) -	
				10% silt/clay, 30% sand, 60% gravel	
				sand VCS-VFS, predom CS, 85% qtz 15%	
				mafic, gravel VFP-MP, predom FP,	
				SR-R, 65% granite/qtzite 35% basalt, wet,	
95	ARCHIVE GRAB			olive brown 2.5Y 4/3, strong rxn HCl.	
					93.5' sand contact
				95' - Sand (S) - trace silt, >95% sand	96.5' ~~sandy gravel~~ SPA gravelly sand contact
				- well sorted MS-CS, wet, dark	
				grayish brown 10YR 4/2, No rxn HCl,	
100	ARCHIVE ~~GRAB~~ GRAB			sand 90% qtz 10% mafic	
				96.5-99.5' gravelly Sand (gS)	
	TD=102.5'		TD		
				100' - Muddy sandy Gravel (msG)	
				10% silt/clay, 30% sand, 60% gravel	
105				sand VFS-VCS poorly sorted, 85% qtz	> clay @ 100.5' -
				15% mafic, gravel VFP-MP, SR-R, 65%	confirm as clay contact
				qtz-rich 35% mafic, No rxn HCl	Large cobble noted @
					contact.
110				100.5' - Mud (m) Clay-rich mud -	
				light brownish gray 10YR 6/2 - to -	
				grayish brown 10YR 5/2, $CaCO_3$-rich	
				nodules react strongly to HCl, general	
				matrix no rxn dry-to-moist	
115					
				NOT USED SPA	

Reported By: STEVE AIRHART
Title: GEOLOGIST
Signature: SPA
Date: 5-24-07

Reviewed By: L.D. Walker
Title: Geologist
Signature: LD Walker
Date: 7/26/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 1 of 3

Date: 5-7-07

Well ID: C5581	Well Name: 199-D5-111	Location: 100 HR 3 OU Biostim Test Site
Project: REF CGW-33308 REV 0 Biostimulation Wells		Reference Measuring Point: G.S

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
0				0-0.5' Crushed / Pit Run Gravel.	Cable Tool. Drill Bay
				0.5 -0.8 Native Soil with Vegetation Matter	Moisture Stops @ -3'
				0.5 - GS 30% SubR Gravel to +3"	
				Various Lithologies 70% S	grab samples every
				VF-Med SA Dry Well Sorted Disc	5feet for archive
				5 Salt/Pepper No HCl Rxn.	
5	Grab				
					grab samples in 5 gallon
					buckets every 10ft for
					PNNL
10	Igrab- grab	PNNL			
				10-20 sandy GRAVEL sG; 80% snd 50%gvl	
				snd - 90% basalt 10% other, vf-vc; gvl - 90% basalt,	9-10' grab sample PNNL
				10% other, 0.5-4cm, SR-SA; 2.5Y5/1 gray, dry; no	
				rxn HCl	
15	grab				
20	Igrab- grab	PNNL			
				20-25 gravelly SAND gS; 70% snd 30% gvl	19-20' grab sample PNNL
				gvl - 90% basalt 10% other, 0.5-6cm, SR-SA; snd - 80%	
				basalt, 10% other, vf-vc (mostly course), 2.5Y 5/1 gray	
				slight mottled, dry	
25	grab				
				25-30 sandy GRAVEL sG; 60% gvl 40% snd	
				lith. same as above	
30	grab				
	grab-	PNNL		30-40 silty sandy GRAVEL msG; 30% silt 30% snd	30-34' grab sample PNNL
				40% gvl; snd vf-c with silt, 80% basalt 20% other,	
				gvl 0.5-4cm 90% basalt, SR-SA; 2.5Y5/1 gray, dry	
				no rxn HCl	
35	grab				

Reported By: Erika Rincon		Reviewed By: L.D. Walker	
Title: geologist		Title: Geologist	
Signature: ErikaR	Date: 5-8-07	Signature:	Date: 7/23/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 2 of 3
Date: 5-8-07

Well ID: C5581
Well Name: 199-D5-111
Location: West of DR reactor, near 100-D gate
Project: Biostimulation Test Wells, 100-D Area
Reference Measuring Point: ground surface

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
	I grab-grab	PNNL			Cable Tool - Drive Barrel
40				40-43 gravelly SAND gS; 95% snd 5% gvl	39-40' grab sample PNNL
				gvl 50% basalt 50% qtz/other, SR, 0.5-3cm;	grab samples every 5 ft
				snd 50% basalt 50% qtz/other, m-vc, 2.5Y 4/1 dark gray	for achive
				no rxn HCL, dry	
				43-55 silty sandy GRAVEL msG; 35% silt 35% snd	grab samples every 10 ft
45	grab			30% gvl; snd vf-c with silt 75% basalt 25% other;	for PNNL
				gvl 0.5-7cm poorly sorted, SR-SA, 80% basalt 20% other	
				2.5Y 5/1 gray, mod. rxn HCL, dry	
	I grab-grab	PNNL			
5					49-50' grab sample (PNNL)
55	grab			55-60 gravelly SAND gS 95% snd 5% gvl, gvl-50%	
				basalt 50% qtz/other, SR, 0.5-9cm; snd 50% basalt 50% other	
				m-vc, 2.5Y 4/1 dark gray no rxn HCL, dry	
60	I grab-grab	PNNL		60-70 sandy GRAVEL sG; 60% snd 40% gvl; gvl-50%	59-60' grab sample PNNL
				basalt, 50% qtz/other, 0.5-9cm, SR-SA; snd-50% basalt	
				50% qtz/other, vf-c; 2.5Y 5/2 grayish brn. slight rxn HCL, dry	
65	grab				
70	I grab-grab	PNNL			69-70 grab sample PNNL
				70-75 sandy GRAVEL sG; 50% gvl 50% snd	
				gvl - 80% qtz/other 20% basalt, 0.5-8cm, SR-SA; snd -	
				50% qtz/other 50% basalt, m-vc; 2.5Y 6/4 light yellowish	
				brn no rxn HCL, dry	
75	grab			75-77 SAND S; 100% sand; 15% basalt 85%	
				other, m-c, [illegible] 2.5Y 6/3 light yellowish brn	
				mod. rxn HCL dry	

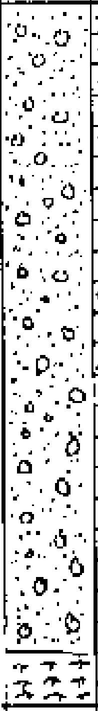
Reported By: Erika Rinon		Reviewed By: L.D. Walker	
Title: geologist		Title: Geologist	
Signature:	Date: 5-9-07	Signature:	Date: 7/23/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 3 of 3
Date: 5-9-2007

Well ID: C5581
Well Name: 199-D5-111
Location: west of DR reactor, near 100-D gate
Project: Biostimulation Test Wells, 100-D Area
Reference Measuring Point: ground surface

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description: Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments: Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
80	I grab - grab	PNNL		77-83 sandy GRAVEL sG; 60%snd 40%gvl; gvl-50%	Cable Tool-Drive Barrel
				basalt 50% other, SR-SA, 0.5-5cm; snd-85%other 15%basalt	79-80 grab sample (PNNL)
				vf-c, 2.5Y 6/2 light brownish gray; strong rxn HCl, dry	grab samples every 5 ft for achive
				83-88 same as above; wet	SWL 83.37 bgs (5-14-07)
85	grab				
					grab sample every 10 ft for PNNL.
				88-100 sandy GRAVEL sG; 50%gvl 50%snd; gvl-	
90	I grab - grab	PNNL		20% basalt 80% qtz/other, 0.5-6cm, SR; snd-80% qtz/other	
				20% basalt, c-vc, 2.5Y 5/4 light olive brown no rxn HCl, dry	89-90 grab sample PNNL
95	grab				
100	I grab - grab	PNNL		100-101.7 Clay/Mud (100%); 2.5Y 6/4 light yellowish	99-100 grab sample PNNL
				brown, strong rxn HCl	
					101.7' T.D. (5-10-2007)
105					

Reported By: Erika Rincon
Title: geologist
Signature: Erika R
Date: 5-10-07

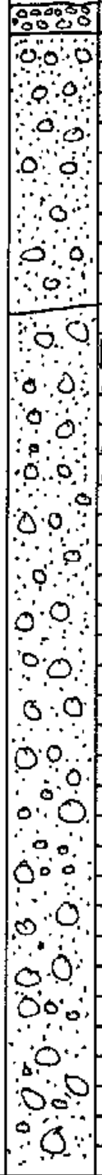
Reviewed By: L.D. Walker
Title: Geologist
Date: 7/23/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 1 of 3
Date: 5-25-07

Well ID: C5582
Well Name: 199-D5-112
Location: West of DR reactor, near 100-D gate
Project: Biostimulation Test Wells, 100-D Area
Reference Measuring Point: ground surface

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description: Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments: Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
0					Cable Tool-Drive Barrel
				0-1 gravel fill	
				1-10' sandy GRAVEL sG; 40% gvl 60% snd; gvl - 90% basalt 10% other, SA, 0.5-12cm; snd - 80% basalt 20% other, vf-vc some silt, 2.5Y 5/2 grayish brn, strong rxn HCl, dry	grab samples every 5 ft for achive
5	grab				
10	grab	grab PNNL			9-11' grab sample for PNNL
				10-13 sandy GRAVEL sG; 60% gvl 40% snd; gvl - 80% basalt 20% qtz&other, SR-SA, 0.5 - 7cm; snd - 60% basalt 40% other, vf-vc, 2.5Y 6/1, gray, strong rxn HCl, dry	
15	grab			13-45 sandy GRAVEL sG; 50% gvl 50% snd; gvl - same as above; snd 70% basalt 30% other, vf-vc, 2.5Y 6/1 gray slight rxn HCl, dry	
20	grab	grab PNNL			19-23' grab sample for PNNL
25	grab				
30	grab	grab PNNL			30-33' grab sample for PNNL
35	grab				

Reported By: Erika Rincon
Title: geologist
Signature: ErKa
Date: 5-29-07

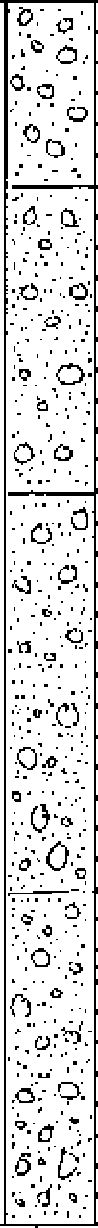
Reviewed By: L. D. Walker
Title: Geologist
Signature: LD Walker
Date: 7/24/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 2 of 3
Date: 5-29-07

Well ID: C5582
Well Name: 199-D5-112
Location: West of DR reactor, near 100-D Area gate
Project: Biostimulation Test Wells, 100-D Area
Reference Measuring Point: ground surface

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description: Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments: Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
40	grab	grab PNNL			Cable Tool - Drive Barrel grab samples every 5ft for archive
					36-42' grab sample for PNNL
45	grab			45-55 sandy GRAVEL sG; 65% sd 35% gvl; gvl - 70% basalt 30% qtz/other, SR-SA, .5-4cm; snd - vf-c, 70% basalt 30% other, 2.5Y 5/1 gray; slight rxn HCl, dry	
		grab PNNL			48-50' grab sample for PNNL
50	grab				
55	grab			55-68 sandy GRAVEL 60% snd 40% gvl; gvl - 50% basalt 50% qtz/other, SR-SA, .5-3cm; snd - f-vc, 60% basalt 40% other, 2.5Y 5/2 grayish brn, weak rxn HCl, dry	
60	grab	grab PNNL			58-60' grab sample PNNL.
65	grab				66' ↓ drilling rate
				68-85 sandy GRAVEL sG; 50% snd 50% gvl; gvl - 50% basalt 50% qtz/other, SR-SA, .5-5cm; snd - 30% basalt 70% qtz/other, m-C, 2.5Y 6/3 light yellowish brn, no rxn w HCl, moist	
70	grab				
75	grab				

Reported By: Erika Rincon
Title: geologist
Signature: Erika R
Date: 5-29-07

Reviewed By: L. D. Walker
Title: Geologist
Signature: LD Walker
Date: 7/24/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 3 of 3
Date: 5-30-07

Well ID: C5582 | Well Name: 199-D5-112 | Location: West of DR reactor, near 100-D Area gate

Project: Biostimulation Test Wells, 100-D Area | Reference Measuring Point: ground surface

Depth (Ft.)	Sample		Graphic Log	Sample Description	Comments
	Type No.	Blows Recovery		Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
80	grab				Cable Tool - Drive Barrel
					grab samples every
					5feet for achive
				83-90 sandy GRAVEL sG; 60% snd 40% gvl; gvl-30%	
				basalt 70% qtz/other, SR-SA, .05-5cm; snd 20% basalt	SWL 82.57' bgs (5-31-07)
85	grab			80% other, 2.5Y 5/3 light olive brn, strong rxn HCl, wet	
90	grab			90-93 sandy GRAVEL sG; 80% gvl 20% snd; gvl-50%	
				basalt, 50% qtz/other, 0.5-9cm, SR-SA; snd-50% basalt	
				50% other, c-vc, 2.5Y 3/2 v dk grayish brn, no rxn	
				HCL, wet	
95					T.D. 93.85' bgs (5-30-07)
100					

Reported By: Erika Rincon | Reviewed By: L. D. Walker

Title: geologist | Title: Geologist

Signature: Erika R | Date: 5-30-07 | Signature: | Date: 7/24/07

A-6003-842 (03/03)

BOREHOLE LOG

Page 1 of 3
Date: 5-17-07

Well ID: C5583
Well Name: 199-D5-113
Location: west of DR reactor, near 100-D entrance
Project: Biostimulation Test Wells, 100-D
Reference Measuring Point: ground surface

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
0					Cable Tool-Drive Barrel
				0-7 gravelly silty SAND gmS; 70%snd, 20% silt	grab samples every 5ft
				10%gvl; gvl-80% basalt 20% other, 0.5-5cm, mostly	for above.
				pea-size, SR-SA; snd vf-vc with silt, mostly fine,	
				50% basalt 50% other, 10YR 4/3 brown, slight rxn HCl	
5	grab			dry, some organic matter (roots)	
				7-13 sandy GRAVEL sG; 45%gvl [illegible] 55% snd;	
				gvl - 90% basalt 10% other, SR-SA, 0.5-7cm; snd - vf-c,	
10	grab			mostly fine, 80% basalt 20% other; 25Y6/1 gray, slight rxn	
				HCl, dry	
				13-25 same as above, increase in coarse sand	
15	grab				
20	grab				
25	grab				
				25-35 sandy GRAVEL sG; 50% snd 50% gvl	
				gvl-90% basalt 10% other, SR-SA, 0.5-7cm; snd-vf-vc	
				80% basalt 20% other; 25Y6/1gray, dry, no rxn HCL	
30	grab				
35	grab				
				35-40 sandy GRAVEL sG 35% gvl 65% snd	
				lith. same as above.	

Reported By: Erika Rincon
Title: geologist
Signature: Erika R
Date 5-17-07

Reviewed By: L.D. Walker
Title: Geologist
Signature:
Date: 7/24/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 2 of 3

Date: 5-17-07

Well ID: C5585

Well Name: 199-D5-113

Location: West of DR reactor, near 100-D Area gate

Project: Biostimulation Test Wells, 100-D Area

Reference Measuring Point: ground surface

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
40	grab			40-45 gravelly SAND gS; 30%gvl 70%snd gvl 0.5-4cm, SR-SA, 80% basalt 20% other; snd-f-vc, 50% basalt 50% qtz/other, 2.5Y 5/2 grayish brn, dry no rxn HCL	Cable Tool - Drive barrel / grab samples every 5ft for archive
45	grab			45-60 sandy GRAVEL sG; 40%gvl 60%snd; gvl - 70% qtz/other 30% basalt, SR-SA, 0.5-3cm; snd 50% basalt 50% qtz/other, vf-vc, mostly coarse; 2.5Y 5/2 grayish brn, no rxn HCL, dry	
50	grab				
55	grab				
60	grab			60-62 SAND S; 95%snd 5%gvl; snd - 65% basalt 35% qtz/other, c-vc, 2.5Y 2.5/1 black, no rxn HCL, dry 62-65 increasing gravels 90% snd 10% gvl	
65	grab			65-68 sandy GRAVEL sG; 40%gvl 60%snd; gvl - 0.5-4cm, SR-SA, 80% qtz/other 20% basalt; snd - f-vc, 50% basalt 50% other, 2.5Y 5/2 grayish brn, strong rxn HCL, dry	67 ↓ rate of drilling
70	grab			68-75 sandy GRAVEL sG; 50%gvl 50% snd; gvl 0.5-8cm, 80% qtz/other 20% basalt, SR-SA; snd - m-c some clay, 80% qtz/other 20% basalt, no rxn HCL, dry 2.5Y 6/3 light yellowish brn	68 consolidated sediment
75	grab				

Reported By: Erika Rivron

Title: geologist

Signature:

Date: 5-15-07

Reviewed By: L.D. Walker

Title: Geologist

Signature:

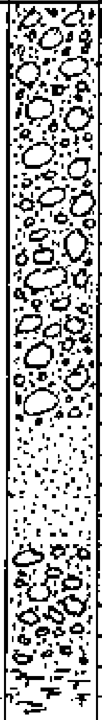
Date: 7/24/07

A-9003-842 (03/03)

BOREHOLE LOG

Page 2 of 1
Date: 5-18, 21 2007

Well ID: C5583
Well Name: 199-D5-113
Location: Biostim Test Site 100 D Area
Project: Biostimulation Test Wells, 100-D Area
Reference Measuring Point: G.S.

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
80	GRAB			FROM ABOVE	CABLE TOOL - DRIVE
					BARREL, GRAB SAMPLE
					FOR ARCHIVE
					81' DAMP FRONT
					83' WET SAMPLE
85	GRAB			85 SANDY GRAVEL SG 60% G –	
				P-C C TO 3" SUBROUND, VARIOUS	SWL 82.64' bgs (5-24-07)
				LITH 40% SAND M-VFN GR.	
				SA-SR SALT-PEPPER ABUNDANT FeOx	
				STAIN ON QTZ TR MICA NO HCl	
90	GRAB			RXN. TR SILT 10YR 5/3	
				BROWN, MOIST - AS RECOVERED	
				90 AS ABOVE W COBBLES TO 4"	
				93.5 - 97 SAND S M-VFN	
				GR. SA-SR, FeOx STAIN ON QTZ	
95	GRAB			TR MICA NO HCl RXN	
				97 - 100.5 SG SANDY GRAVEL	
				70% P-C COBBLES TO 4"	
100	GRAB			SR VARIOUS LITH. 50% PEBBLES	
				OF 1/2-1" ANGULAR RANDOM BASALT	
102	GRAB	-T.D-		30% MS SAND AS ABOVE	
T.D				TR SILT GRAY MILD HCl RXN	
				100.5 - 101 M CLAY TR. INCORPORATED	
				BASALT PEBBLES STRONG HCl RXN	
				2.5Y 7/2 LT GRAY DRY AS RECEIVED	
				101.5 - 102 M CLAY MOD HCl RXN	
				MASSIVE 2.5Y (5/4) 5/3 LT OLIVE BRN	Total Depth 102' bgs (5-21-07)
				MOIST SEMI-PLASTIC	
				102 T.D.	

Reported By: Greg L. Kasza
Title: Geologist
Signature:
Date: 5-21-07

Reviewed By: L.D. Walker
Title: Geologist
Signature:
Date: 7/24/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 1 of 3

Date: 6-1-07 / 6-4-07

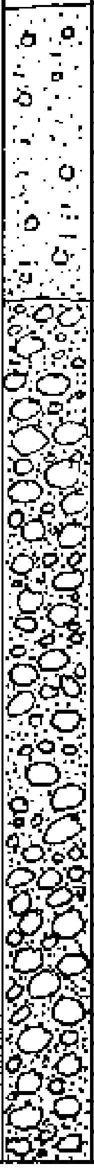
Well ID: C5584

Well Name: 199-D5-114

Location: West of DR reactor, near 100-D gate

Project: Biostimulation Test Wells, 100-D Area

Reference Measuring Point: groundsurface

Depth (Ft.)	Sample Type No.	 Blows Recovery	Graphic Log	Sample Description Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
0					Cable Tool-Drive Barrel
				0-10 gravelly silty SAND gmS; 70% snd 20% silt	
				10% gvl; gvl-80% basalt 20% other, SR-SA, 0.5-5cm	grab sample every 5 ft
				mostly pea-size; snd-50% basalt 50% other, vf-vc	for archive
				mostly fine with silt, 10YR 4/3 brn, strong rxn HCl	LPT, FAC, CHIP TRAY
5	grab			dry	& PHOTO
10	grab			10- sandy GRAVEL sG; 60% gvl 40% snd	
				gvl-80% basalt 20% other, SR-SA, 0.5-7cm; snd-	
				60% basalt 40% other, vf-vc, 2.5Y 5/1, gray; dry,	
				no rxn HCL	
15	GRAB				
				15' AS ABOVE	
20	GRAB			20' AS ABOVE	
25	GRAB			25' AS ABOVE FINING TO 40% GRAVEL	
				60% SAND	
30	GRAB			30' AS ABOVE COARSENING TO 70%	
				GRAVEL, 30% SAND	
35	GRAB			35' AS ABOVE 60% G - 40% S	

Reported By: Erika Rincon   Greg Kasza

Title: Geologist   Geologist

Signature: Erika R   G Kasza

Date: 6-4-07

Reviewed By: L. D. Walker

Title: Geologist

Signature:

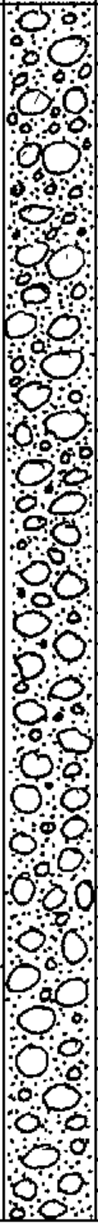
Date: 7/27/07

A 6003 642 (03/03)

BOREHOLE LOG

Page 2 of 3
Date: 6-4-2007

Well ID: C5584
Well Name: 199-05-114
Location: BIOSTIM TEST SITE, 100-D
Project: WELLS FOR BIOSTIMULATION TEST
Reference Measuring Point: G.S.

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description: Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments: Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
40	GRAB			SANDY GRAVEL sG 60% G-40%	CABLE TOOL w/
				S. GRAVEL - PEBBLE COBBLE CLASTS	DRIVE BARREL
				TO 6" ON LONG AXIS. PREDOM BASALT SR-SA	
				SAND 50% BASALT 50% QTZ & OTHER VF-VC	
				TR SILT 2.5Y 5/1 GRAY AS ROCK	
45	GRAB			DRY, NO HCl RXN	
				45 AS ABOVE	
50	GRAB			50' AS ABOVE FINING. 50% GVL	
				50% SAND	
55	GRAB			55' AS ABOVE	
60	GRAB			60' AS ABOVE	
65	GRAB			65' AS ABOVE	
70	GRAB			70' AS ABOVE w/ SEVERAL FRIABLE	
				CONCRETIONS w/ STRONG HCl RXN	73-74 HANFORD
				73 S - SAND 10% G, 90% SAND	RINGOLD CONTACT
				LITHOLOGY AS ABOVE DRILLER INDICATES	
				MUCH HARDER DRILLING; NO MICA	
75	GRAB			NO FeOx ON QTZ	
				74 - sG SANDY GRAVEL G 50% S-50%	
				PEBBLES TO 3", MIXED LITHOLOGY	
				SR-SA SAND - VF-MED GR TR SILT	
				70% QTZ 30% DARKS TR FEOx ON QTZ	

Reported By: Greg L. Kasza
Title: Geologist
Signature:
Date: 6-4-07

Reviewed By: L.D. Walker
Title: Geologist
Signature: LD Walker
Date: 7/27/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 3 of 3

Date: 6-1, 5, 6 -07

Well ID: C5584

Well Name: 199-D5-14

Location: BIOSTIM TEST SITE 100D AREA

Project: BIOSTIMULATION TEST WELLS

Reference Measuring Point: GS

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description: Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments: Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
80	GRAB			TR MICA 10YR 6/3 AS REC'D PALE BR	
				10YR 7/2 (DRY) LT GRAY MOD SORTED	
		∇		TR MINOR HCl RXN	Very hard/slow
					drilling last 5'.
				80' sandy Gravel (sG) - 35% sand 65%	
85	GRAB			gravel, sand, VFS-VCS predom. FS,	
				95% qtz 5% basalt, mafic SA-SR, gravel	
				VFP-VCP - up to 65 mm, 90% qtzite, chert	
				10% basaltic, SR-R, $CaCO_3$ cement noted on	
				clast surfaces, mod-to-strong rxn HCl.	83' CONTINUED HARD
90	GRAB			10YR 7/2 light gray, dry	DRILLING - MOISTURE
				85 CUTTINGS DAMP.	FRONT
				85 SAND (S) 90% SAND-10% GRVL	
				VFS - MS 95% QTZ 5% BASALT & OTHER	
				SA-A ABUNDANT FeOx STAIN ON QTZ	
95	GRAB			TR MICA PEBBLES AS ABOVE	
				10YR 4/3 BROWN - DAMP	
				90 AS ABOVE - WET	
				93- SG SANDY GRAVEL	
				95 SG SANDY GRAVEL 20% SAND 80%	
100	GRAB			GRAVEL - PEBBLE-COBBLE TO 2", PREDOM	
				LIGHT COLORS - 70% BASALTS SR-R	
				WELL SORTED. SAND VF-C, PREDOM QTZ	
				SA-SR TR. MICA ABUNDANT FeOx ON	
				QTZ, MINOR HCl RXN 10YR 4/2 DK GRAYISH BRN	
104.3	GRAB	104.3		WET, AS RECEIVED.	
				96- SG 50% SAND 50% GRAVEL	
				98.5 SG 25% SAND 75% GRAVEL	
				100' AS ABOVE 6" COBBLE IN	
				SAMPLE	
				101.5 SAME AS ABOVE	
				102.5 " " "	
				103.5 SAME AS ABOVE	
				104 TRANSITION TO RUM $CaCO_3$ NODULES	
				THIN STRINGERS BRN CLAY AND MIXED WITH GRAVEL FROM ABOVE	
				104.3 RUM CONTACT M - CLAY	
				MASSIVE 10 YR 6/4 LT YELLOWISH	
				BROWN SLIGHT HCl RXN.	TD @ 104.3' BGS

Reported By: GREG L. KAGZA

Title: GEOLOGIST

Signature: Greg Kagza

Date: 6-6-07

Reviewed By: L.D. Walker

Title: Geologist

Signature: LD Walker

Date: 7/27/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 1 of 3
Date: 7/2/07

Well ID: C5585
Well Name: 199-D5-115
Location: West of DR reactor, near 100-D gate
Project: Biostimulation test well, 100-D
Reference Measuring Point: Ground Surface

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
0					Cable Tool - Drive Barrel
					archive grab samples
					every 5 ft
				0-6 gravelly sandy SILT (gsM): gvl-	
5	Grab			90% basalt, 10% other, .5-4.0 cm; sand	
				vf-c, 30% basalt, 70% other; 10YR 6/3 pale	
				brown, strong rxn HCl	
10	Grab			6-30 sandy GRAVEL (sG) 60%	
				gvl 40% sand; gvl 70% basalt, 30%	
				other; sand f-vc, 70% basalt, 30% other,	
				10YR 4/2 dark grayish brown, slight rxn HCl	
				gvl .5-5.0 cm	
15	Grab				
				Same as above, no rxn HCl	
				10YR 4/1 dark gray	
20	Grab			Same lithology as above	
25	Grab			same lithology as above	
30	Grab			30-60 sandy GRAVEL (sG) 75%	
				gvl, 25% sand; Gvl 85% basalt, 15%	
				other, .5-5.0 cm SA-R; sand 30% basalt	
				70% other, f-vc, no rxn HCl, dry	
				10YR 4/1 dark gray	
35	Grab				
				lithology same as above; 40 gvl,	
				60% sand	

Reported By: Brett Mayhew Patrick Cobbage
Reviewed By: L.D. Walker
Title: Geologist
Title: Geologist
Signature: Brett Mayhew
Date: 7/2-07
Signature:
Date: 7/22/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 2 of 3

Date: 7/2/07

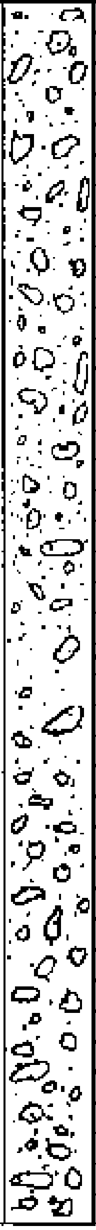
Well ID: C5585

Well Name: 199-D5-115

Location: West of DR reactor near 100-D gate

Project: Biostimulation test wells 100-D

Reference Measuring Point: ground surface

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
40	Grab			Same lithology as above	Cable tool with drive barrel
45	Grab			60% gvl, 40% sand; lithology same as above; sand: vf-c; moderate rxn HCl	
50	Grab			50% gvl, 50% sand, lithology same as above; moist	
55	Grab			Same as above	Driller commented on crushed rock
60	Grab			60-65 gravelly SAND (gS); 30% gvl, 70% sand; gvl: 75% basalt, 25% other, 0.5-7.5cm, SA-SR; sand: 60% basalt, 40% other, vf-c; slight rxn HCl; 10YR 5/1 grey	
65	Grab			65-73 sandy GRAVEL (sG); 60% gvl, 40% sand; lithology same as above; strong rxn HCl	
70	Grab			Same as above	72' - decreased drilling rate, changed drive barrel
	Grab			73-85 sandy GRAVEL (sG); 80% gvl, 20% sand; gvl: 25% basalt, 75% other, 0.5-4.5 cm, SA-SR; sand: 20% basalt, 80% other, vf-c; slight rxn HCl; 10YR 5/2 grayish brown	73 - approximate Hanford - Ringold contact
75	Grab				

Reported By: Patrick Cobbage / Brett Myers

Title: Geologist

Signature: Patrick Cobbage Brett M

Date: 7/3/07

Reviewed By: L. D. Walker

Title: Geologist

Date: 7/27/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 2 of 3
Date: 7/3/07
Well ID: C5585
Well Name: 199-D5-115
Location: West of DR reactor, near 100-D gate
Project: Biostimulation test wells, 100-D
Reference Measuring Point: Ground Surface

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
80	Gmb			same as above, moist	Cable tool
					w/ cable tool
					84.18' water level (bgs)
85	Gmb			85-89 SAND (S) 70% granitic/other, 30% basalt, vf-c, moist, no rxn HCl, dark yellowish brown, 10YR 4/4	
					89' heaving sands
90	Gmb			89-104 sandy GRAVEL (sG) 75% gvl, 25% sand; gvl 65% basalt, 35% other .5-7.0cm, sand 40% basalt, 60% other f-c, wet, no rxn HCl, brown 10YR 4/3	
95	Gmb			Same lithology as above moist, very dark grayish brown 10YR 3/2	multiple large cobbles
					more sand between 95-98'
100	Gmb			same lithology as above	
104	Gmb			104-105 SILT (M) 100% silt, Dark grayish brown 10YR 4/2, moist no rxn HCl	
105	Gmb				Final depth 105'
				105 same as above, wet	

Reported By: Brett Myler Patrick Cabbage
Title: Geologist
Date: 7/7/07

Reviewed By: L.D. Walker
Title: Geologist
Date: 7/27/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 1 of 3

Date: 6/25/07

Well ID: C5586

Well Name: 199-D5-116

Location: West of DR Reactor, near 100-D Grade

Project: Biostimulation test wells at 100 D

Reference Measuring Point: Ground Surface

Depth (Ft.)	Sample: Type No	Sample: Blows Recovery	Graphic Log	Sample Description: Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments: Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
0				0-7 gravelly sandy SILT (gsM): gvl-90% basalt, 10% other, 0.5-3cm; sand-vf-c, 30% basalt, 70% other; 10YR 4/3, brn, strong rxn HCl	Cable Tool Drive Barrel Grab Samples for Archive every 5'
5	Grab				
				7-15 sandy GRAVEL: gvl-85% basalt, 15% other, 0.5-6.5cm; sand-vf-vc, 75% basalt, 25% other, 10YR 4/1, gray, moderate rxn HCl	
10	Grab				
15	Grab			~~sandy G~~ 15-45 sandy GRAVEL, gvl: lithology same as above; Sand: same as above, 10YR 5/1 grey, moderate rxn HCl	
20	Grab			Same as above	
25	Grab			Same as above	
30	Grab			Same as above	
35	Grab			Same as above	

Reported By: Patrick Cabbage

Title: Geologist

Signature: Patrick P. Cabbage

Date 6/25/07

Reviewed By: L.D. Walker

Title: Geologist

Date: 7/27/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 2 of 3
Date: 6/25/07

Well ID: C5586
Well Name: 199-D5-116
Location: West of DR Reactor, near 100-D gate
Project: Biostimulation test wells at 100-D
Reference Measuring Point: Ground Surface

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
40	Grab			Same as above	Cable Tool Drive Barrel Grab samples for archive every 5'
45	Grab			45-50 sandy GRAVEL (sG); 50% gvl, 45% sand, 5% silt; gvl: 70% basalt, 30% other, 0.5-8.5cm, SR-SA; sand: 75% basalt, 25% other, vf-c, no rxn HCl, 10YR 4/1 dark gray	
50	Grab			50-55 sandy GRAVEL (sG); 50% gvl, 50% sand; gvl: 60% basalt, 40% other, 0.5-8cm, SR; sand: 70% basalt, 30% other, m-vc; slight rxn HCl, 10YR 3/1 very dark gray	
55	Grab			55-70 sandy GRAVEL (sG); 60% gvl, 40% sand; gvl: 70% basalt, 30% other, SR-SA, 0.5-6.5cm; sand: 60% basalt, 40% other, vf-c; moderate rxn HCl, 10YR 5/1 gray	
60	Grab			lithology same as above	
65	Grab			lithology same as above	
70	Grab			70-74 sandy GRAVEL (sG), gvl sc 30% gvl, 70% sand, lithology same as above	
	Grab			74-75 sandy GRAVEL (sG) 80% gvl, 20% sand; gvl: 70% basalt, 30% other, 0.5-5.0, SR; Sand; 25% basalt, 75% other, m-vc, mod rxn HCL 10YR 6/2 light brownish grey	74' Contact Ringold/Hanford
75	Grab				

Reported By: Patrick Cabbage
Title: Geologist
Signature: Patrick Cabbage
Date: 6/25/07

Reviewed By: L.D. Walker
Title: Geologist
Signature: L.D. Walker
Date: 7/27/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 3 of 3
Date: 6/26/07

Well ID: C5586
Well Name: 199-D5-116
Location: West of DR reactor, near 100D gate
Project: Biostimulation test Wells at 100-D
Reference Measuring Point: Ground Surface

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description: Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments: Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
75	Grab			75-80 sandy GRAVEL (sG) 40% gvl, 60% sand; lithology same as above	Cable Tool Drive Barrel Grab sample for archive every 5'
80	Grab			80-85 Same lithology as above no rxn to HCl	
85	Grab			85-90 gravelly SAND (gS), 15% gvl, 85% sand; gvl: 50% basalt, 50% other, 0.5-8cm, SR; sand: 10% basalt, 90% other, m-c; slight rxn HCl, 10YR 4/3 brown (wet)	~87.5' - added 10 gallons water due to heaving sands ~89' - added 5 gallons water due to heaving sands
90	Grab			90-95 sandy GRAVEL (sG), 60% gvl, 40% sand; gvl: 30% basalt, 70% other, 0.5-7.5 cm, SR; sand: 30% basalt, 70% other, m-vc; no rxn HCl, 10YR 3/2 very dark grayish brown (wet)	
95	Grab			gravelly ~~95-100~~ sandy GRAVEL (sG) 95-100 lithology same as above	96' Added 5 gallons water due to heavy sands
100	Grab			100-104 lithology same as above	
105	Grab			104-104.5 Grab Mud, 100% mud, no rxn HCl, moist, 10YR 5/3 brown	TD: 104.5' bgs 6/27

Reported By: Brett Mayhew Patrick Cobbey
Title: Geologist
Signature: Brett Mayhew
Date: 6/27/07

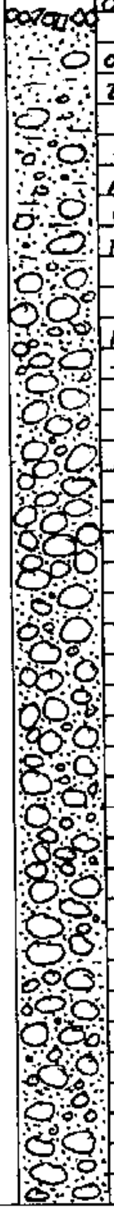
Reviewed By: L.D. Walker
Title: Geologist
Signature: LD Walker
Date: 7/27/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 1 of 3
Date: 6-12, 13, 2007

Well ID: C5587
Well Name: 199-D5-117
Location: Biostimulation Test Site - 100-D
Project: 12 Wells for Biostimulation Test.
Reference Measuring Point: Ground Surface

Depth (Ft.)	Sample: Type No.	Sample: Blows Recovery	Graphic Log	Sample Description: Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size. Reaction to HCl	Comments: Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
0				0-0.5 Gravel for pad cap	Cable Tool w/
				Crushed, Pit Run	Drive Barrels
				0.5-8.5 gmS Gravelly Silty Sand	
				20% G 10% Silt 70% Sand, Gravel	Archive Samples
				Predom Basalt, SR-SA Varying sizes	@ 5' Intervals
				from fine pebble to 2" x 6" x 6" Axial	1 PT Jar, Chip Tray
5	Grab			measurements, Sand 50% Basalt 50 other	& Photograph
				vf-vc SA-SR Tr Mica, Strong HCl	
				Rxn, 10YR 4/3 Brown Dry	
				8.5'-73.5 sG Sandy Gravel	
				60% G - 40% S Gravel - Predom (77%)	
10	Grab			Basalt SA-SR Pebble Cobble to	
				+3" Sand 60% Basalt 40% Other VF-VC	
				No HCl Rxn 2.5Y 5/1 Gray Dry	
15	Grab			15. Same As Above	
20	Grab			20' Same As Above	
25	Grab			25' Same As Above	
30	Grab			30' Same As Above	
35	Grab			35' Same As Above	

Reported By: Greg L. Kasza
Title: Geologist
Signature: Greg L Kasza
Date: 6-13-07

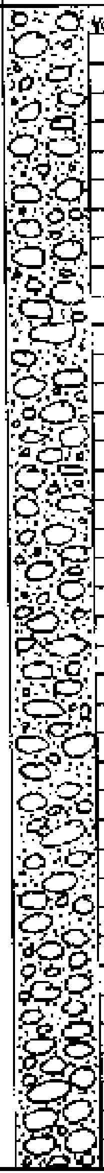
Reviewed By: L.D. Walker
Title: Geologist
Signature: LD Walker
Date: 7/27/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 2 of 3
Date: 6-13-2007

Well ID: C5587
Well Name: 199-D5-117
Location: Biostim Test Site – 100-D Area
Project: 12 Wells for Biostimulation Test
Reference Measuring Point: GS

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sample Size, Water Level
40	Grab			40' Same As Above Hanford Gravel	Cable tool with
				SG Sandy Gravels w/ minor	drive barrel
				variation in % of G vs S.	
				Gravel Fraction SA-SR, Predom Basalt	
				Variable Size Ranging From Fine Pebble	
				to occasional +4" cobbles	
45	Grab			Sand Fraction – Predom Basalt VF-VC	
				SG No HCl rxn occasional moist	
				zones but mostly dry	
				Color is 2.5Y 5/1 - Gray Range	
				45' Same As Above	
50	Grab			50' Same As Above	
55	Grab			55' Same As Above	
60	Grab			60' Same As Above	
65	Grab			65' Same As Above	
70	Grab			70' Same As Above	70.5 Driller reports
					Slower penetration
					rate
					73-74 transition
				74' SG Sandy Gravel 60% G 40% S	~~74 Hanford-Ringold Cnt.~~ Ec
75	Grab			Gravel Cobbles to 12" Average 1-1½"	73.5 Hanford-Ringold
				Various Lithologies SR-R.	Contact
				Sand VFS → MS Tr Mica, Tr	
				FeOx on Qtz SA-SR well sorted	
				Dry as Rec'd Mod HCl rxn BRN	

Reported By: Greg L. Hogan
Title: Geologist
Signature:
Date: 6-13-07

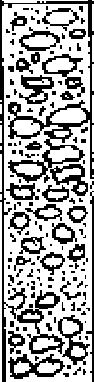
Reviewed By: E.D. Walker
Title: Geologist
Signature:
Date 7/27/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 3 of 3
Date: 6-14/15 2007

Well ID: C5587
Well Name: 199-D5-119
Location: BIOSTIM TEST SITE 100
Project: 12-WELLS FOR BIOSTIMULATION TEST
Reference Measuring Point: G.S

Depth (Ft.)	Sample		Graphic Log	Sample Description	Comments
	Type No	Blows Recovery		Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
				80' SG SANDY GRAVEL 60% G	V. BLOW DRILLING
80	GRAB			40% SAND, GRAVEL ROUND AND PEBBLE	
				COBBLES TO 5" LONG AXIS VARIOUS	
				LITHOLOGIES SR-R SAND VFS-AS	
		83.5'		TR MICA & FeOx STAIN ON QTZ	
		BGS		SA-SR, DRY NO HCl RXN	
85	GRAB	6-12-07		10YR 6/1 GRAY	
				85' SG AS ABOVE 40% G, 60% S	
				WET	
				87-90 95 20% GRAVEL 80% SAND	
				DESCRIPTION AS ABOVE	
90	GRAB			90-91.6 TD SG SANDY GRAVEL	
	→91.6 TD			AS BEFORE 60% G, 40% S,	
				GRAVEL-PEBBLE COBBLE TO ±4"	
				LONG AXIS, VARIOUS LITH SR-R	
95				SANDS VFS-MS TR MICA	
				OCCASIONAL FeOx STAIN ON QTZ	
				SA-SR WET NO HCl RXN	

Reported By: Greg L. Kasza
Title: Geologist
Signature:
Date: 6-15-07

Reviewed By: L.D. Walker
Title: Geologist
Signature:
Date: 7/27/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 1 of 3

Date: 6-19-2007

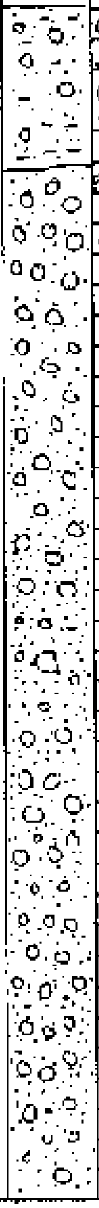
Well ID: C5588

Well Name: 199-D5-119

Location: West of DR reactor, near 100-D Gate.

Project: Biostimulation Test Wells, 100-D

Reference Measuring Point: ground surface.

Depth (Ft.)	Sample Type No	Sample Blows Recovery	Graphic Log	Sample Description: Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments: Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
					Cable Tool - Drive Barrel
0				0-5 gravelly silty SAND (gmS); gvl-80% basalt 20% other, 0.5-2cm, SR-SA; sand-50% basalt, 50% other, vf-vc with silt, 2.5Y5/3 light olive brn, strong rxn HCL, cool matte, dry	archive grab samples every 5 ft
5	grab			5-30 sandy GRAVEL (sG), 50% sand 50% gvl; gvl-80% basalt 20% other, SR-SA, 0.5-6cm; snd-80% basalt 20% other, vf-vc, 2.5Y5/1 gray; no rxn HCL, dry	6.5' ↓ drilling - large boulder
10	grab				
15	grab				
20	grab				
25	grab				
30	grab			30-35 same as above - increase in coarse snd	
35	grab			35-50 sandy GRAVEL (sG) 45% gvl 56% snd; gvl-80% basalt 20% qtz/other, 0.5-7cm, SR-SA; snd-70% basalt, 30% other, vf-c, mottled, 2.5Y5/, gray, mod. rxn HCL, dry	

Reported By: Erika Rivon

Title: geologist

Signature: Erika R

Date: 6-2007

Reviewed By: L. D. Walker

Title: Geologist

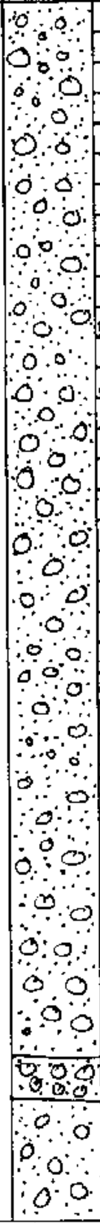
Date: 7/27/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 2 of 3
Date: 6-20-2007

Well ID: C5588
Well Name: 199-D5-118
Location: West of DR reactor, near 100-D Gate
Project: Biostimulation Test Wells, 100-D Area
Reference Measuring Point: ground surface

Depth (Ft.)	Sample Type No.	Sample Blows Recovery	Graphic Log	Sample Description Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Comments Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
40	grab				Cable Tool-Drive Barrel grab samples for achive every 5 ft.
45	grab				
50	grab			50-70 sandy GRAVEL (sG) 50% snd 50% gvl; gvl-80% basalt 20% other, 0.5-5cm, SR-SA; snd-80% basalt, 20% other, vf-vc, 2.5Y 4/1 dk gray, mod. rxn HCL, dry	
55	grab				
60	grab				
65	grab				
70	grab			70-73.5 sandy GRAVEL (sG); 60% snd 40% gvl; gvl-60% basalt 40% qtz/other, 0.5-3 cm, SR-SA; snd-vf-vc, 60% basalt 40% other, 2.5Y 5/1 gray, strong rxn HCL, dry	
	grab				73.5 Hanford/Ringold contact
75	grab			73.5-75 sandy GRAVEL (sG); 65% gvl 35% snd; gvl-30% basalt 70% other, 0.5-3 cm, SR-SA; snd-50% basalt 50% other 2.5Y 6/2 light brownish gray, m rxn HCL, dry cementation	~75 ↓ drilling rate

Reported By: Erika Rincon
Title: geologist
Signature: Erika R
Date: 6-20-07

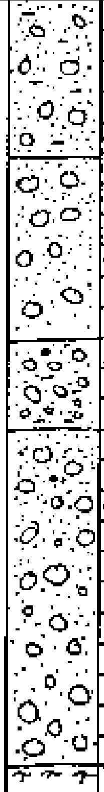
Reviewed By: L.D. Walker
Title: Geologist
Signature: LD Walker
Date: 7/27/07

A-6003-642 (03/03)

BOREHOLE LOG

Page 3 of 3
Date: 6-20-2007

Well ID: C5588
Well Name: 199-D5-118
Location: West of DR reactor, near 100-D Gate
Project: Biostimulation Test Wells, 100-D
Reference Measuring Point: ground surface

Depth (Ft)	Sample		Graphic Log	Sample Description	Comments
	Type No.	Blows Recovery		Group Name, Grain Size Distribution, Soil Classification, Color, Moisture Content, Sorting, Angularity, Mineralogy, Max Particle Size, Reaction to HCl	Depth of Casing, Drilling Method, Method of Driving Sampling Tool, Sampler Size, Water Level
80	grab			75-77 sandy GRAVEL (sG) 60%snd 40% gvl	Cable Tool - Drive Barrel
				gvl - 20% basalt 80% qtz/other, SR-SA, 0.5-3cm; snd -	archive grab samples
				m-c, 20% basalt 80% other, 2.5Y 6/3 light yellowish brn	every 5ft
				strong rxn HCL, dry	
				77-84 silty sandy GRAVEL (msG) 35% gvl 45% snd	
85	grab			20% silt; gvl 20% basalt 80% qtz/other, 0.5-3cm, SR-SA	SWL: 83.24' bgs (6-26-07)
				snd - 10% basalt 90% other, silt-c, 2.5Y 7/2 light gray,	
				strong rxn HCL, dry	
				84-90 sandy GRAVEL (sG) 45% gvl 55% snd;	~84' ↑ drilling rate
				gvl - 20% basalt 80% qtz/other SR-SA, 0.5-3cm; snd - 30%	
90	grab			basalt 70% other, m-c, mod. rxn HCL, 2.5Y 5/3 light	
				olive brn, wet	
				90-93 silty sandy GRAVEL (msG) 60% gvl 30% snd	
				10% silt; gvl 0.5-6cm, poorly sorted, SR, 20% basalt	
				80% other; snd f-c with silt 30% basalt 70% other,	93' heaving formation
95	grab			10YR 4/2 dk grayish brn, no rxn HCL, wet	- added 25 gallons of water -
				93-104 sandy GRAVEL (sG) 50% snd 50% gvl	
				lith. same as above	
100	grab				
	grab			104-104.5 100% MUD	Ringold Upper Mud
105				10YR 6/3 pale brn, slight rxn HCL, wet	
					T.D. 104.5' bgs (6-22-07)

Reported By: Erika Rincon
Title: geologist
Signature: Erika R
Date: 6-22-07

Reviewed By: L. D. Walker
Title: Geologist
Date: 7/27/07

A-6003-642 (03/03)

Appendix B

Gradient Direction and Magnitude in the 100-D Area During the Field Test

Appendix B

Gradient Direction and Magnitude in the 100-D Area During the Field Test

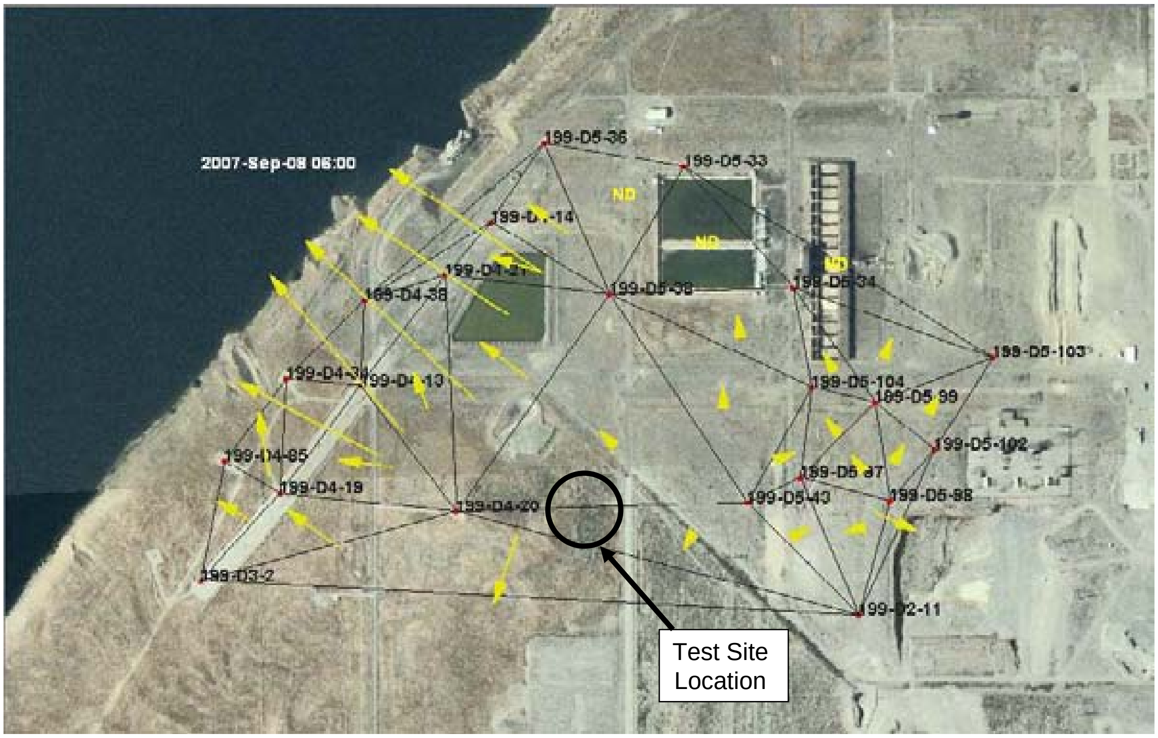


Figure B.1. Gradient Direction and Relative Magnitude in the 100-D Chromate Plume for September 2007

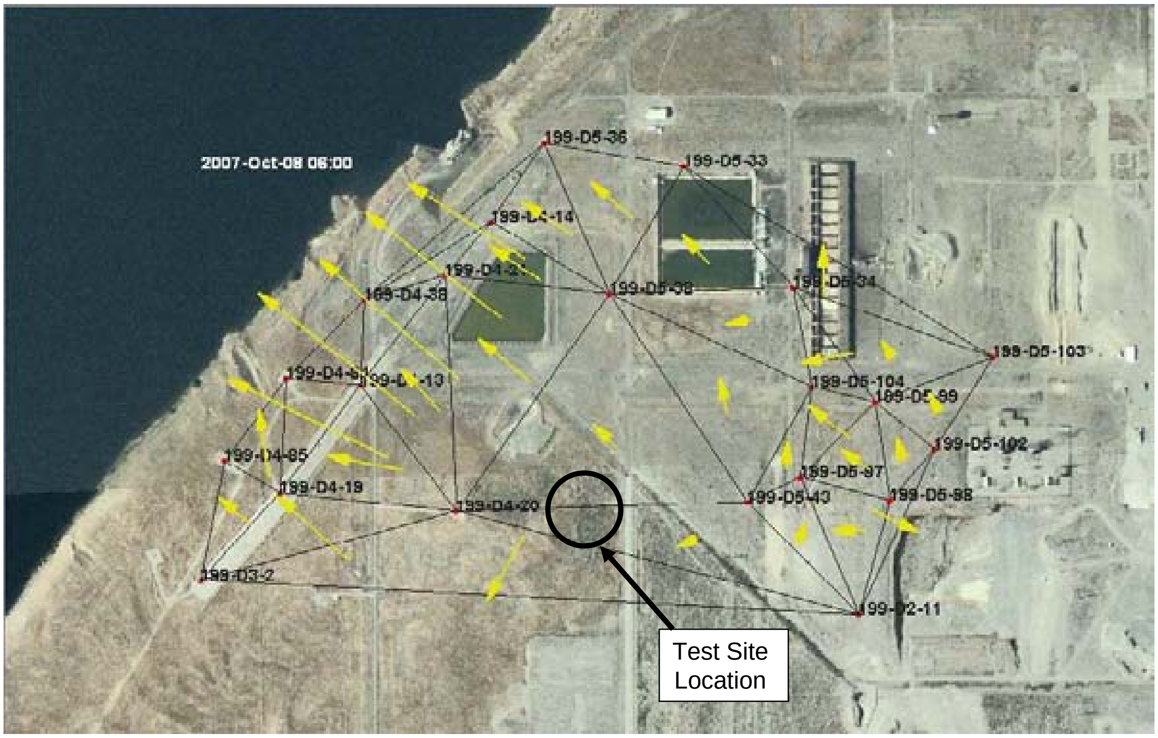


Figure B.2. Gradient Direction and Relative Magnitude in the 100-D Chromate Plume for October 2007

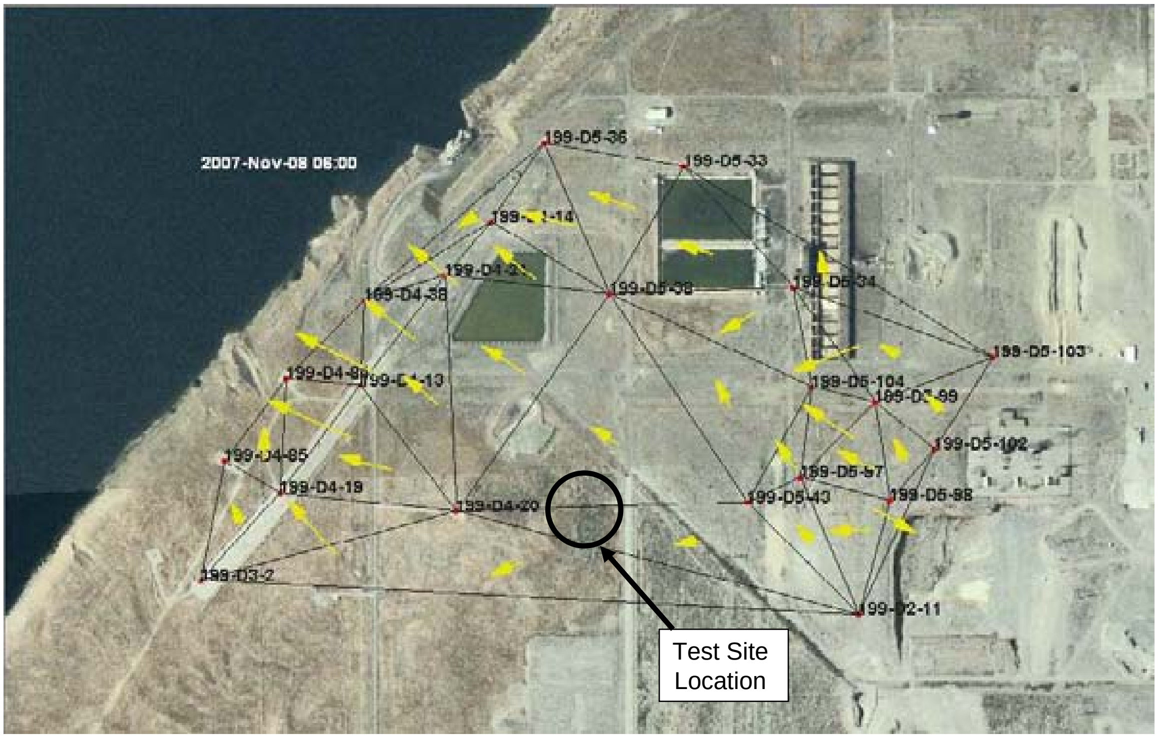


Figure B.3. Gradient Direction and Relative Magnitude in the 100-D Chromate Plume for November 2007

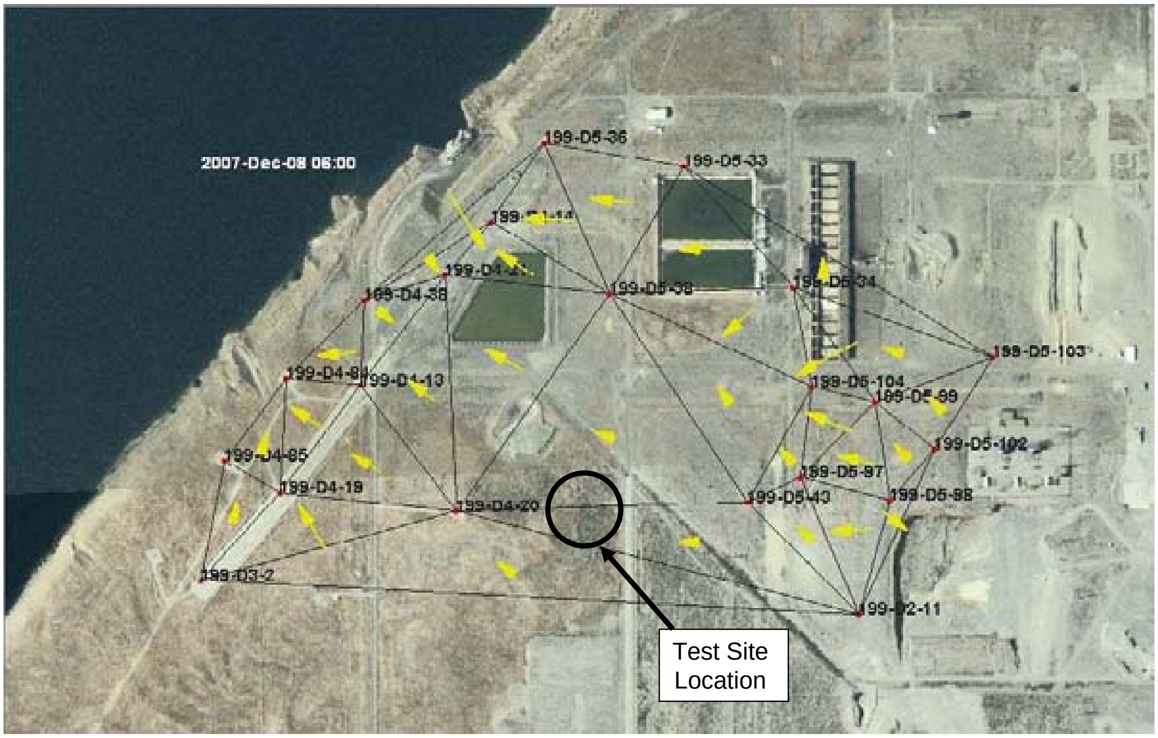


Figure B.4. Gradient Direction and Relative Magnitude in the 100-D Chromate Plume for December 2007

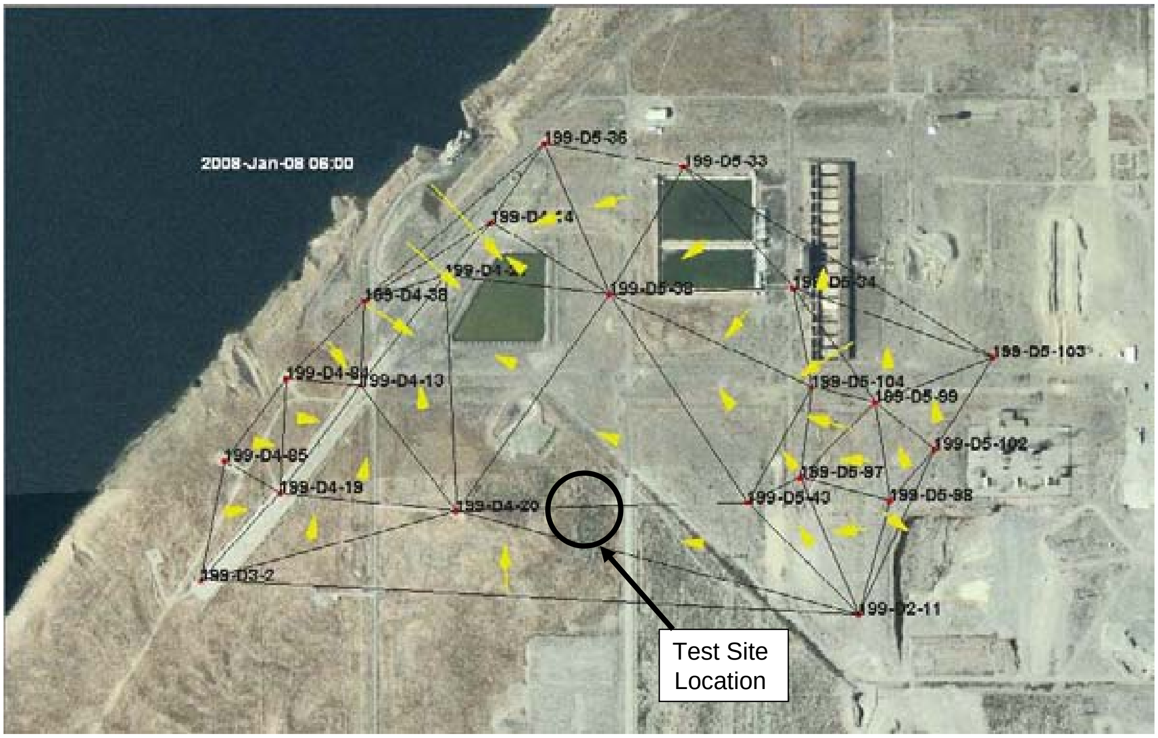


Figure B.5. Gradient Direction and Relative Magnitude in the 100-D Chromate Plume for January 2008

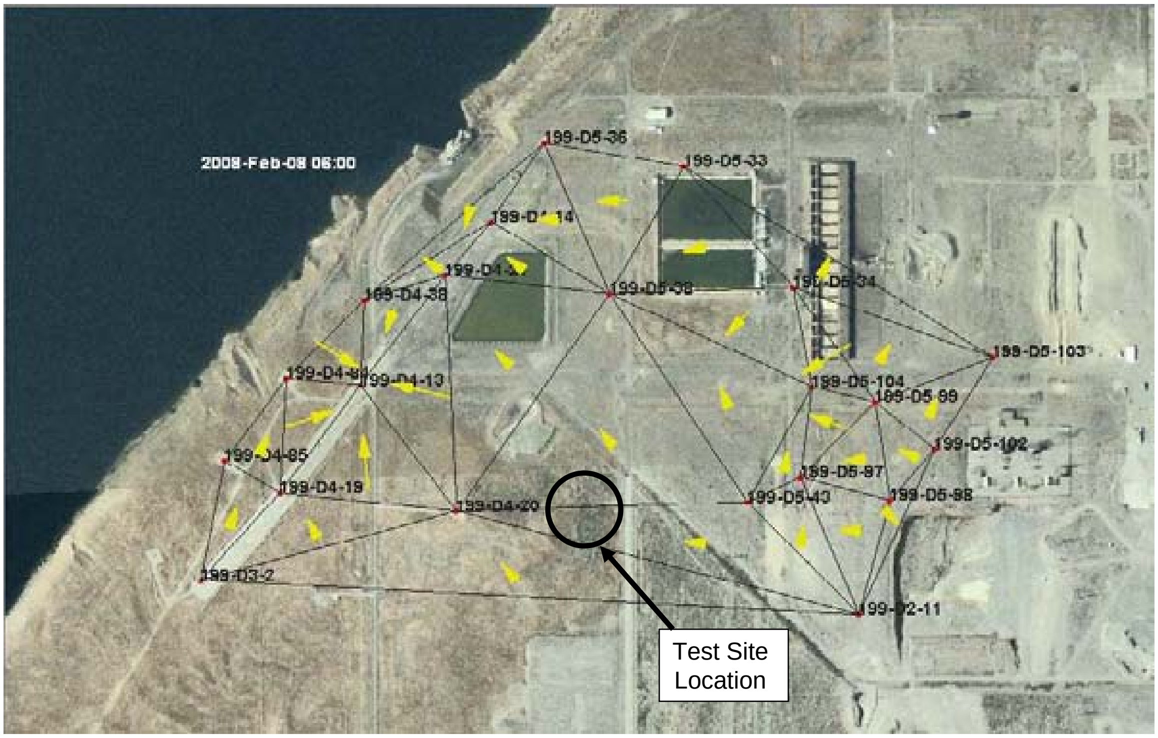


Figure B.6. Gradient Direction and Relative Magnitude in the 100-D Chromate Plume for February 2008

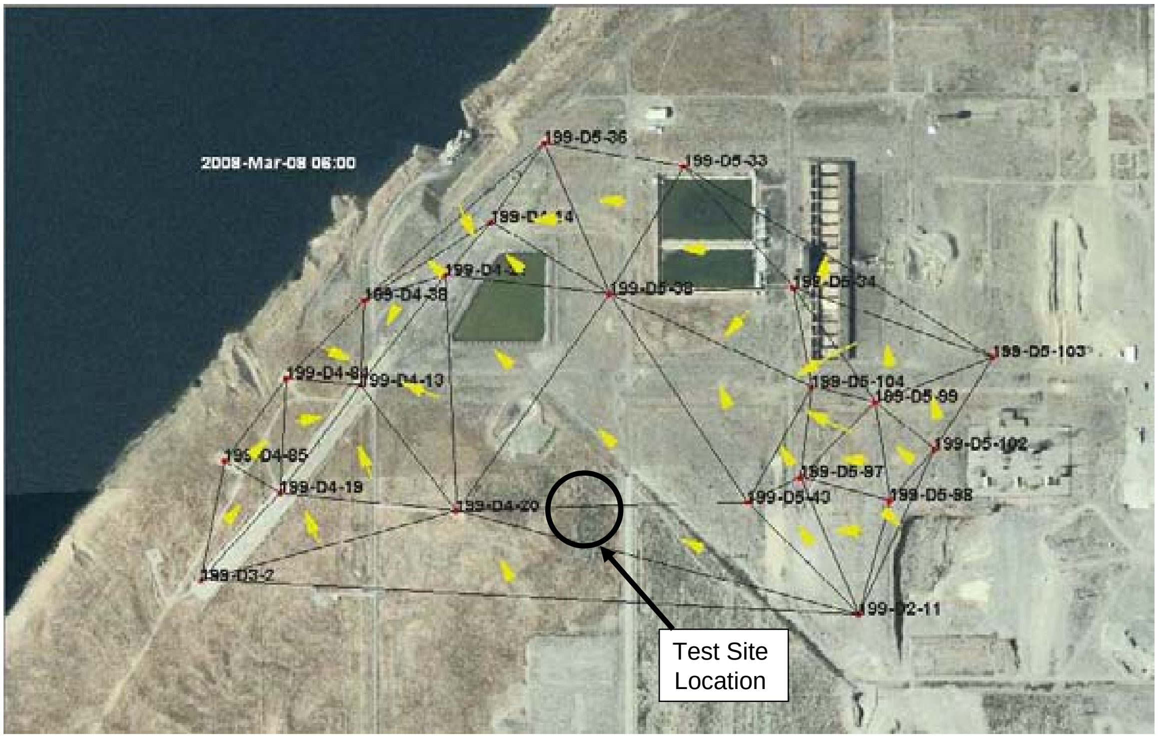


Figure B.7. Gradient Direction and Relative Magnitude in the 100-D Chromate Plume for March 2008

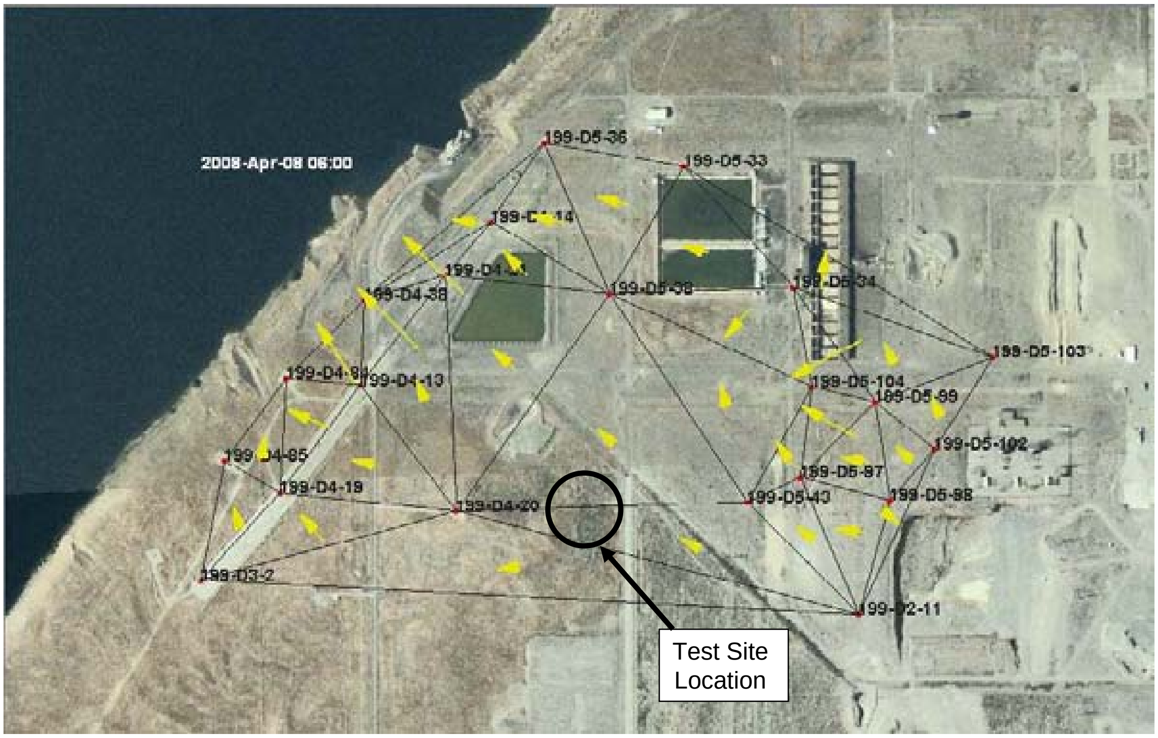


Figure B.8. Gradient Direction and Relative Magnitude in the 100-D Chromate Plume for April 2008

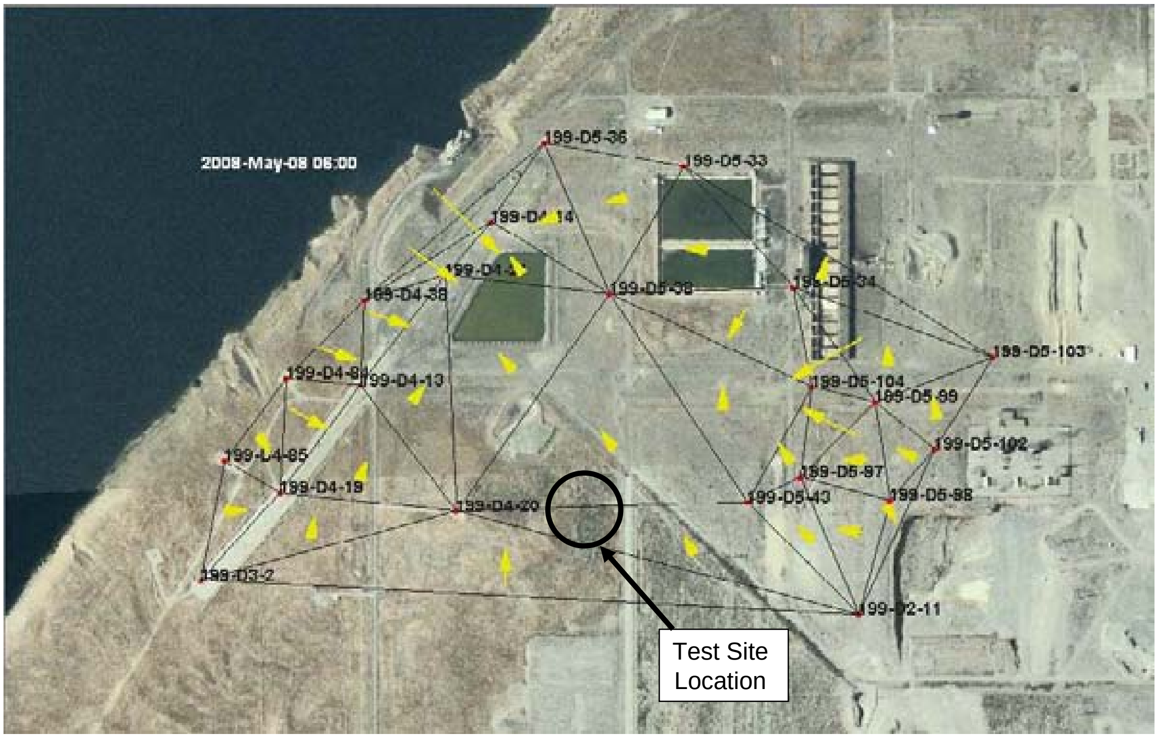


Figure B.9. Gradient Direction and Relative Magnitude in the 100-D Chromate Plume for May 2008

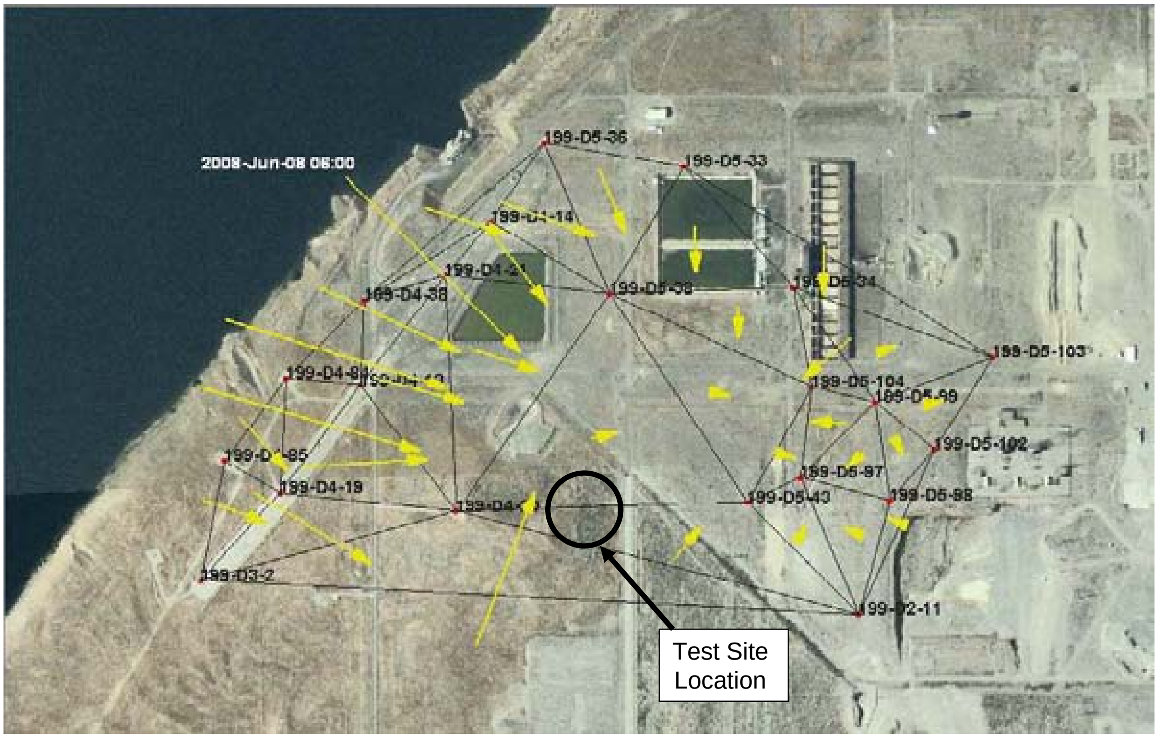


Figure B.10. Gradient Direction and Relative Magnitude in the 100-D Chromate Plume for June 2008

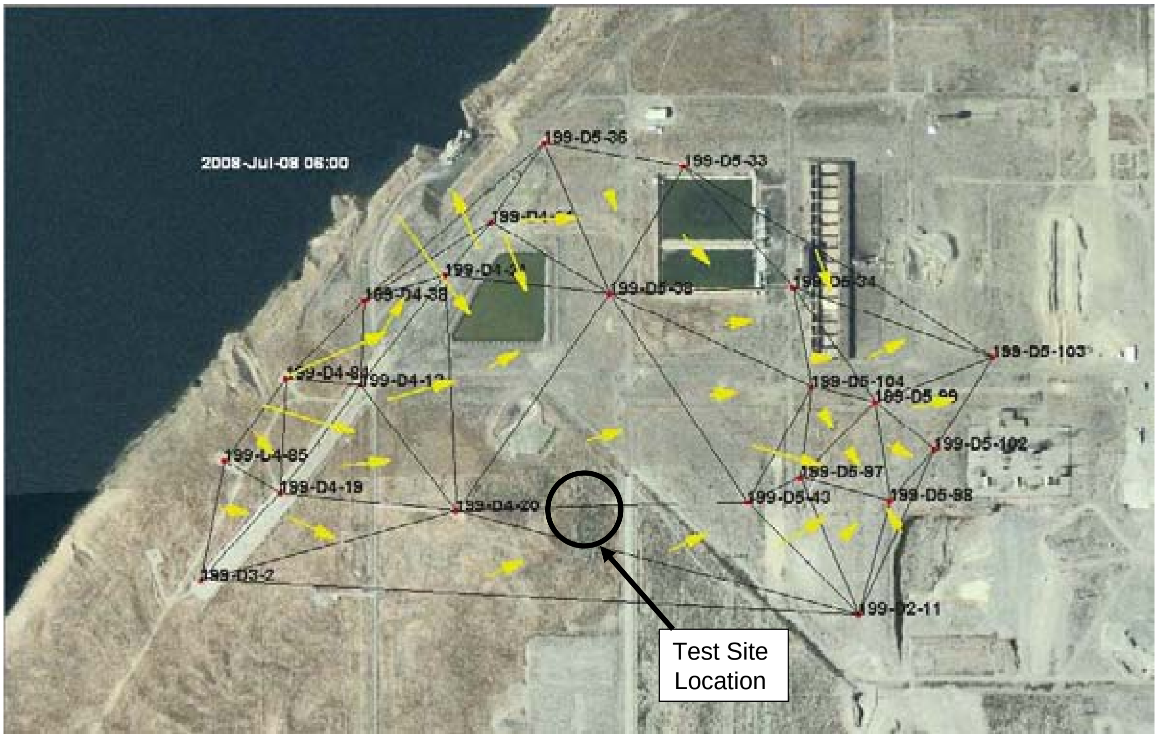


Figure B.11. Gradient Direction and Relative Magnitude in the 100-D Chromate Plume for July 2008

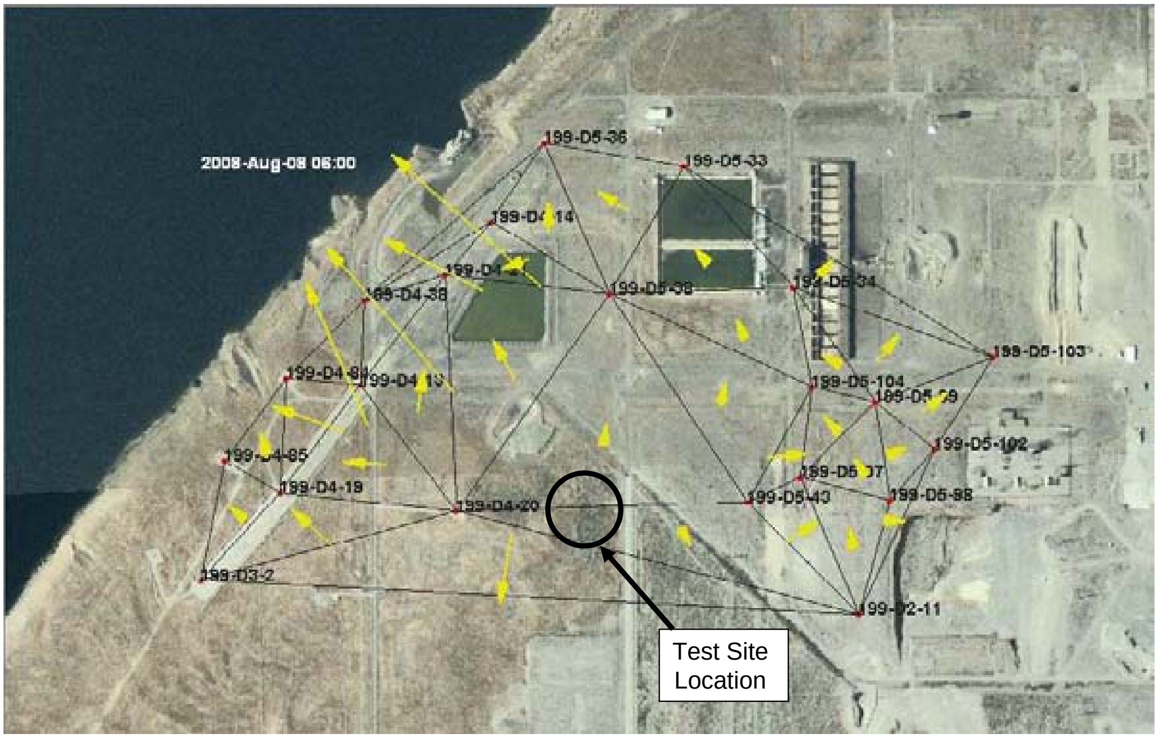


Figure B.12. Gradient Direction and Relative Magnitude in the 100-D Chromate Plume for August 2008

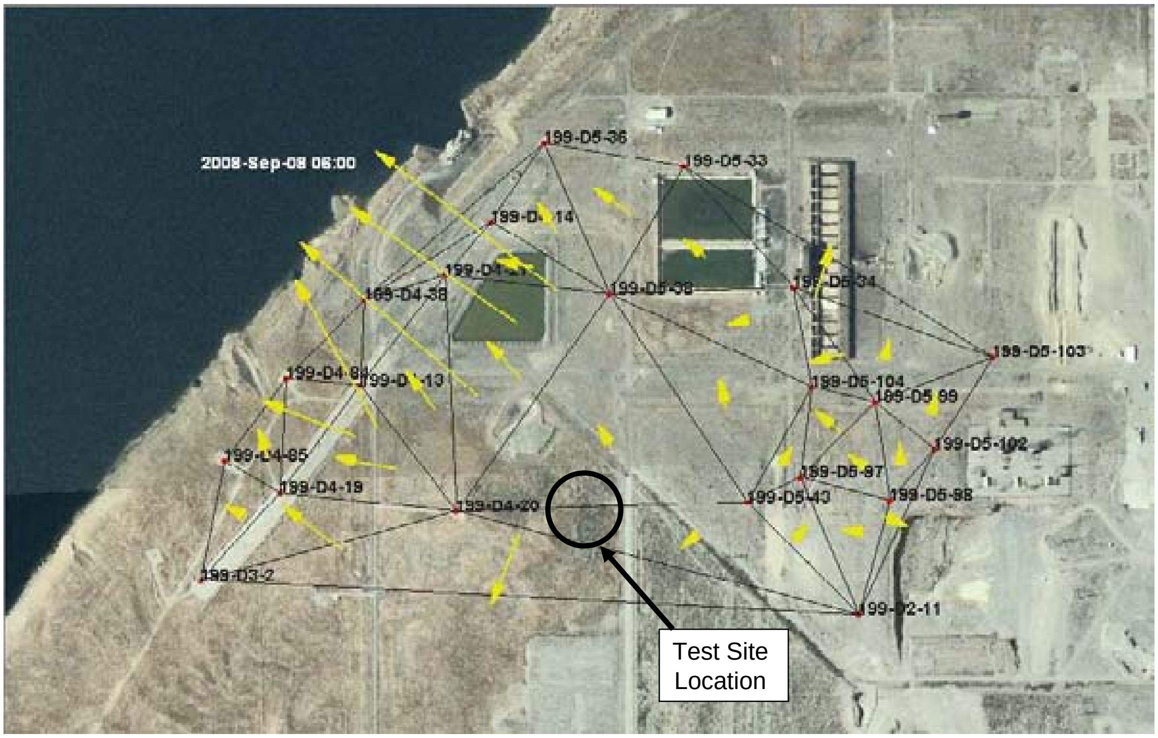


Figure B.13. Gradient Direction and Relative Magnitude in the 100-D Chromate Plume for September 2008

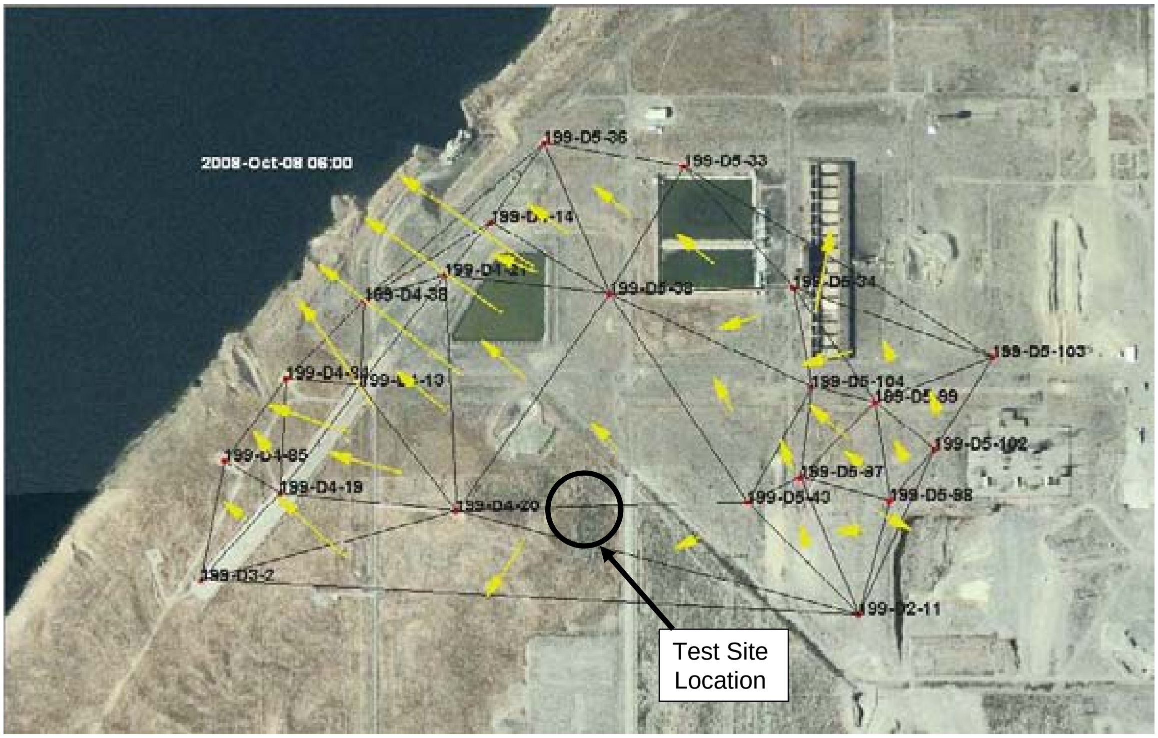


Figure B.14. Gradient Direction and Relative Magnitude in the 100-D Chromate Plume for October 2008

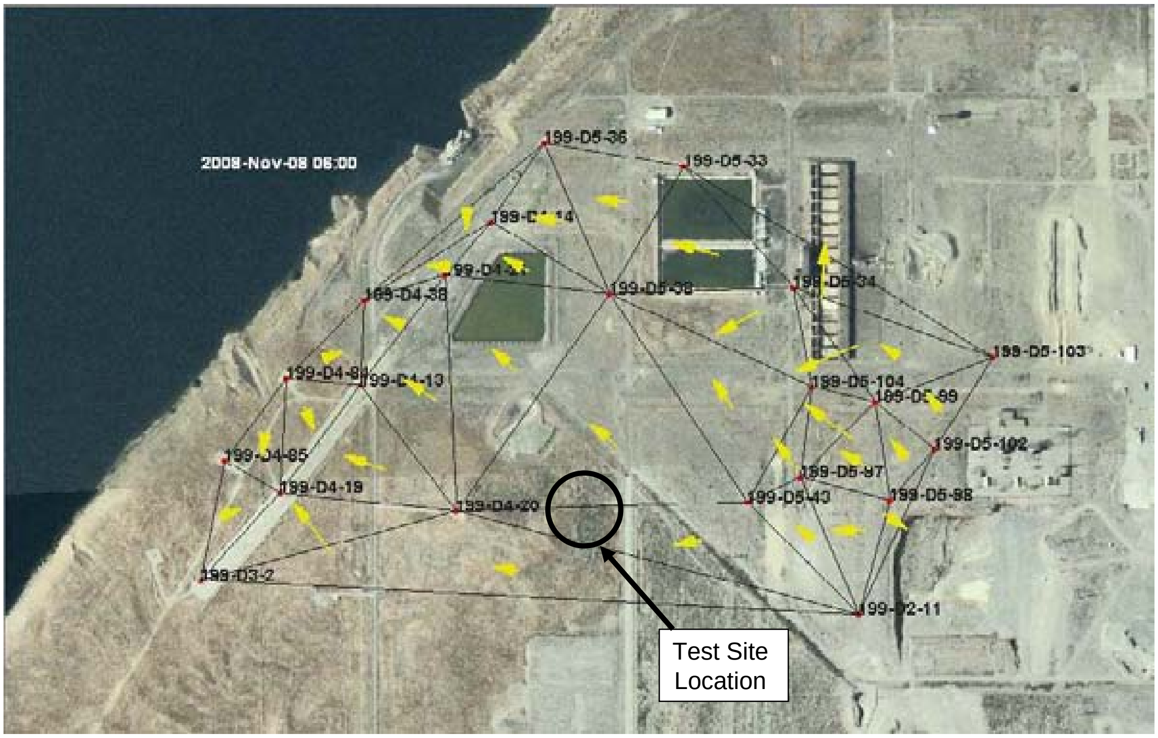


Figure B.15. Gradient Direction and Relative Magnitude in the 100-D Chromate Plume for November 2008

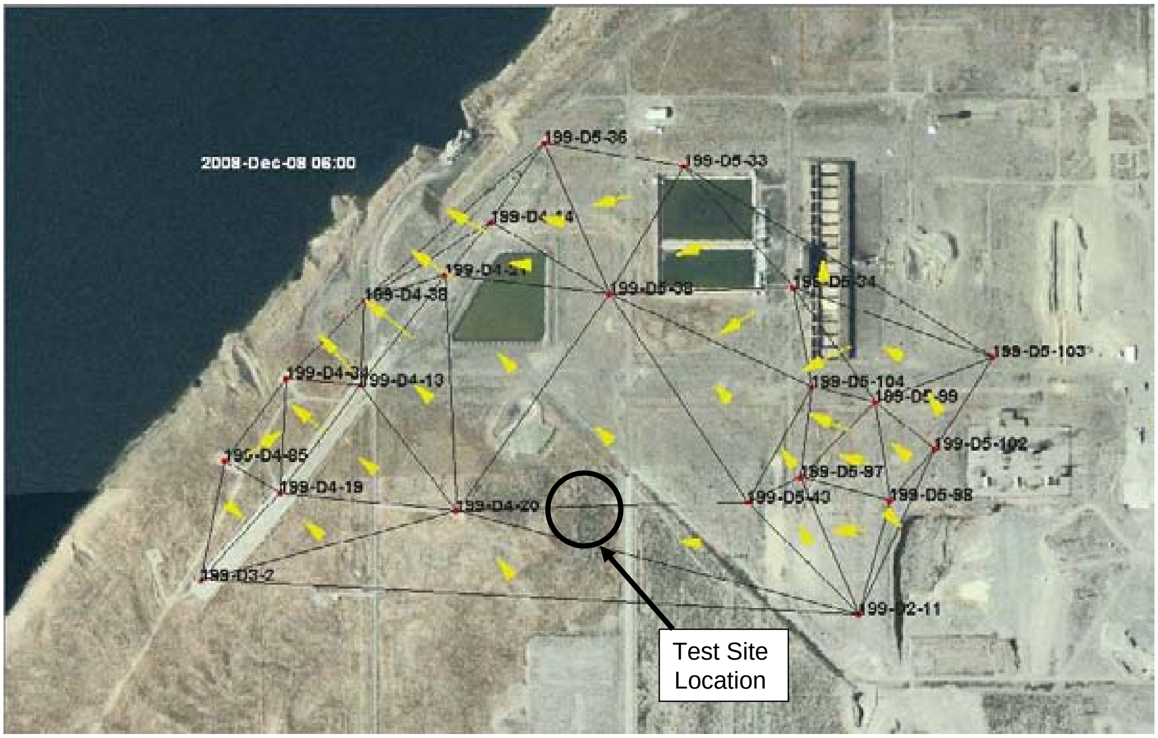


Figure B.16. Gradient Direction and Relative Magnitude in the 100-D Chromate Plume for December 2008

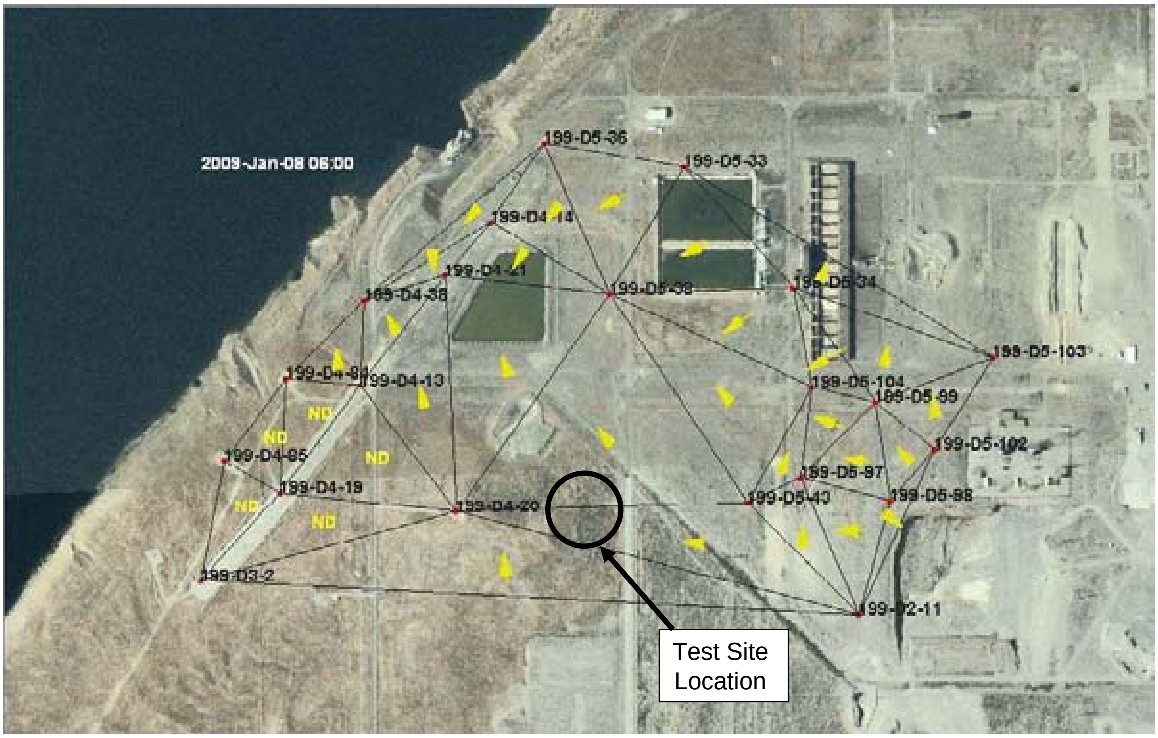


Figure B.17. Gradient Direction and Relative Magnitude in the 100-D Chromate Plume for January 2009

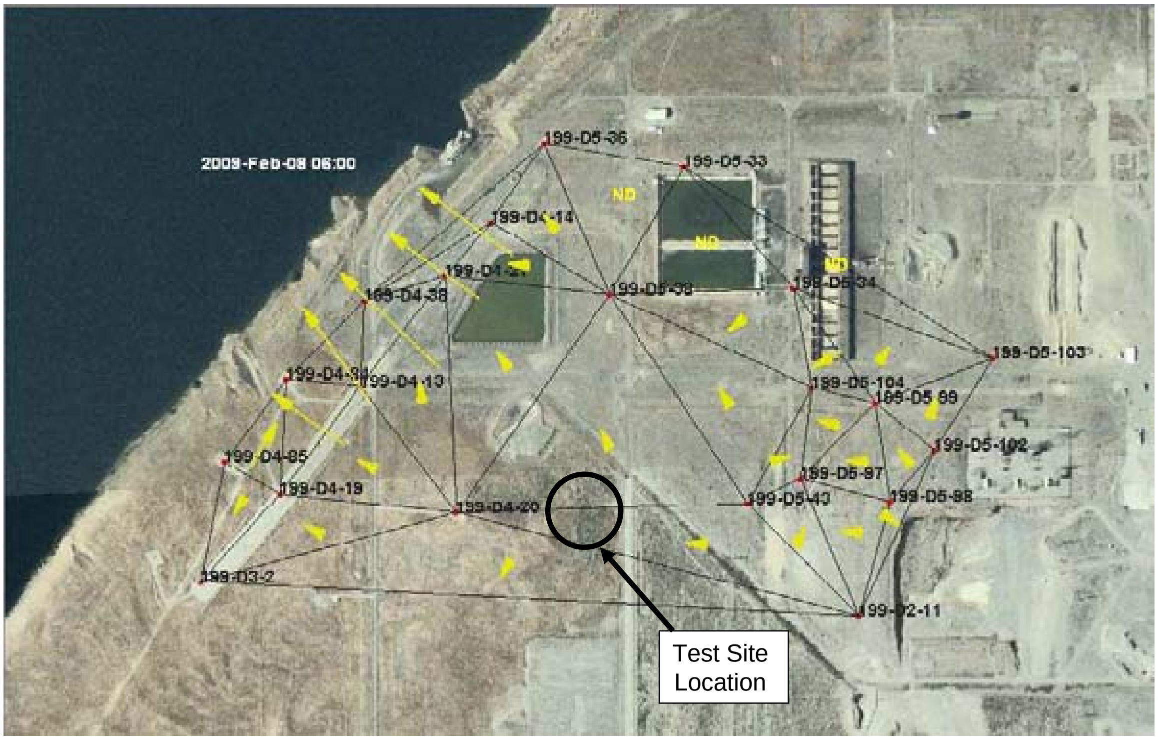


Figure B.18. Gradient Direction and Relative Magnitude in the 100-D Chromate Plume for February 2009

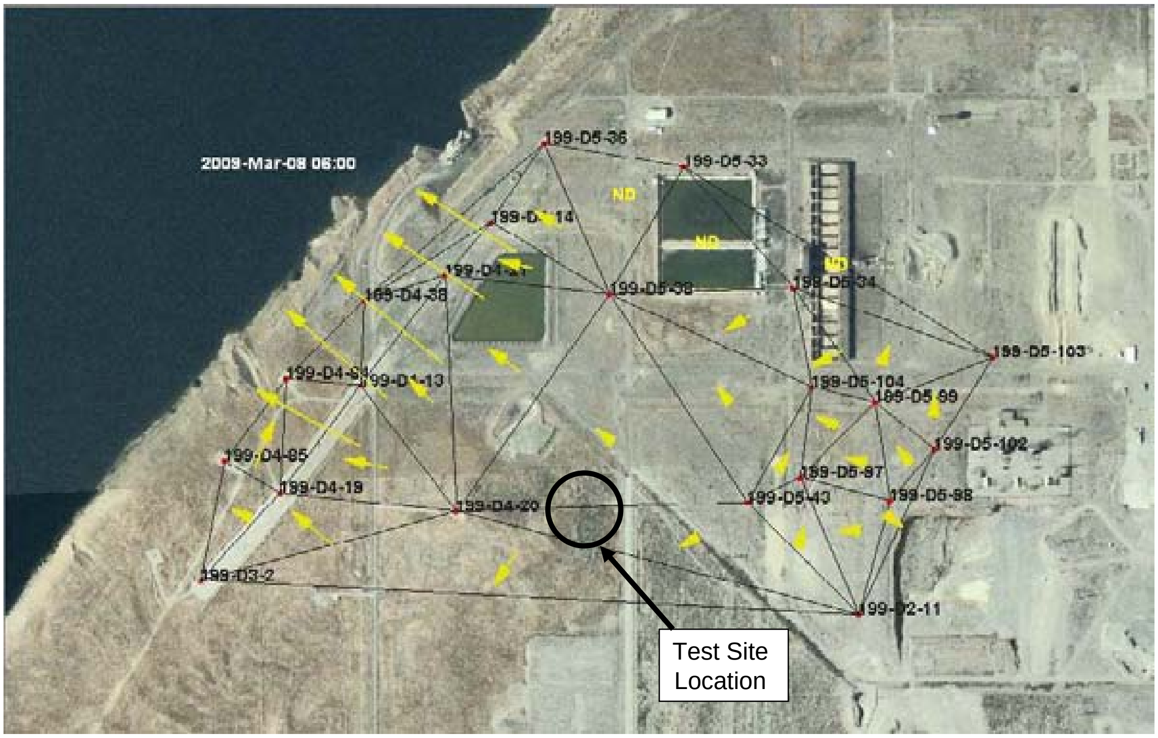


Figure B.19. Gradient Direction and Relative Magnitude in the 100-D Chromate Plume for March 2009

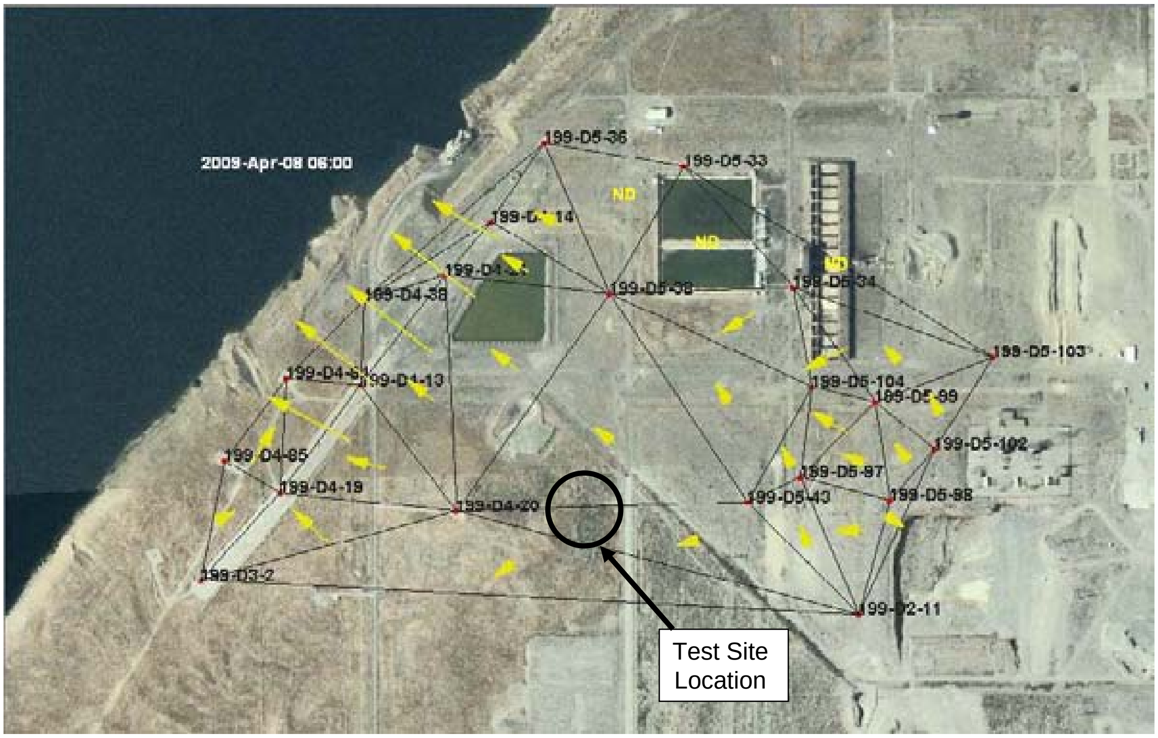


Figure B.20. Gradient Direction and Relative Magnitude in the 100-D Chromate Plume for April 2009

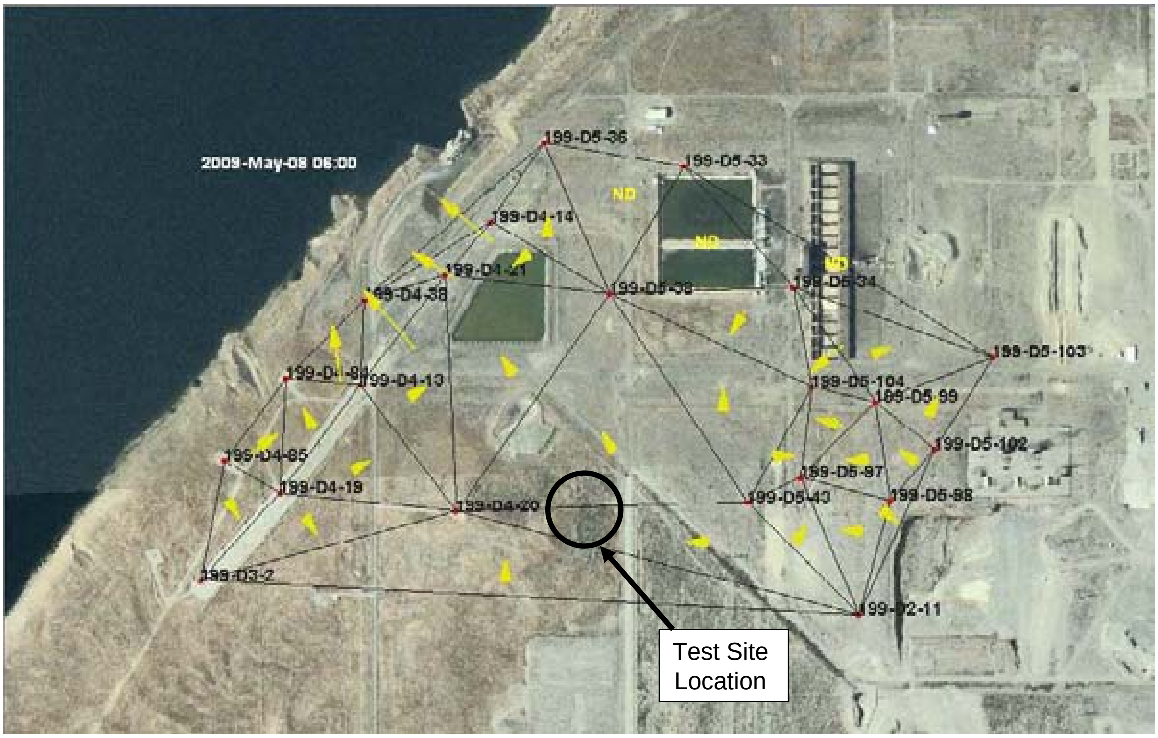


Figure B.21. Gradient Direction and Relative Magnitude in the 100-D Chromate Plume for May 2009

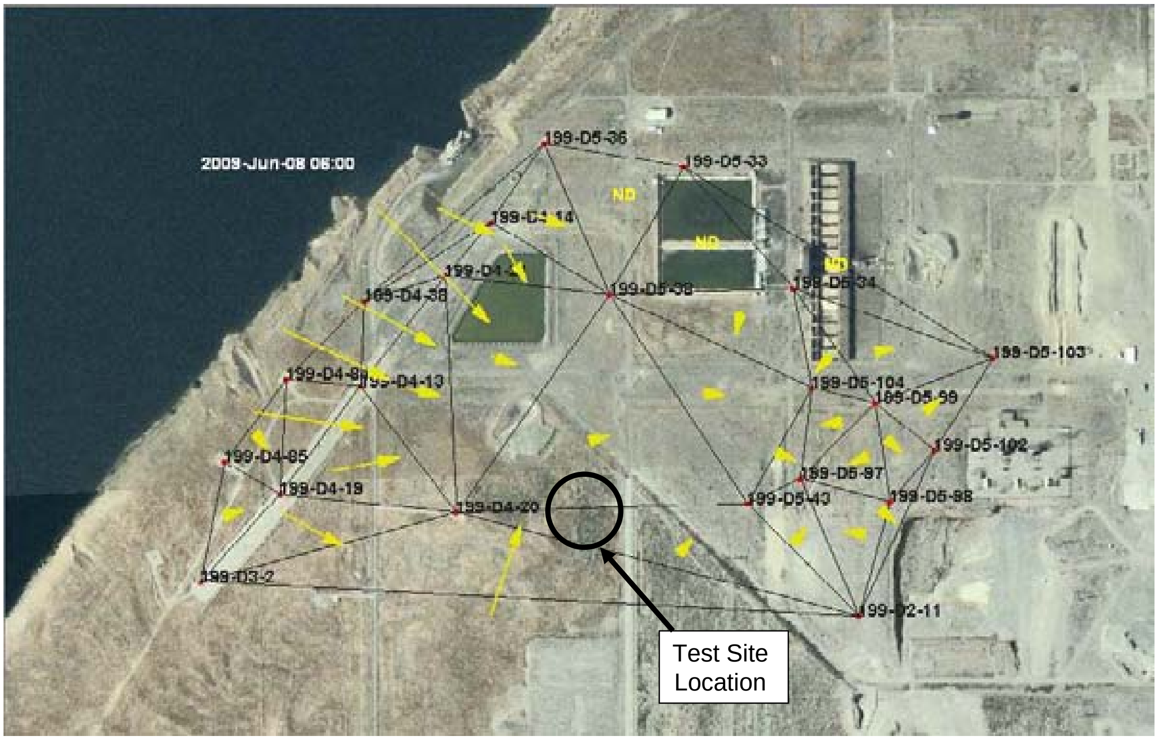


Figure B.22. Gradient Direction and Relative Magnitude in the 100-D Chromate Plume for June 2009

Appendix C

Geophysical Methods Background

Appendix C

Geophysical Methods Background

C.1 Complex Electrical Methods

The complex electrical method was used to measure frequency-dependent electrical responses over the range of 0.1-1000 Hz using non-polarizing Ag/AgCl electrodes. This method involves injecting current of different frequencies into a sample volume and measuring the responses relative to a reference resistor to yield the phase and electrical conductivity as function of frequency. Typically, the obtained electrical conductivity estimate is used to provide information about pore space variations (water content, total dissolved solids) whereas the phase is used to infer information about interactions occurring near the interface of the grains and pore fluids (Binley and Kemna 2005). Archie's Law (Archie 1942) is commonly used to relate the measured effective conductivity (σ_{eff}) to porosity ($\boldsymbol{n}$), the electrical conductivity of the pore water (σ_w), and the electrical conductivity associated with surface conduction ($\sigma_{surface}$) as

$$\boldsymbol{\sigma_{eff} = \sigma_w n^m + \sigma_{surface}}, \tag{1}$$

where m is Archie's exponent. Neglecting changes associated with surface conduction, cementation and porosity, equation (1) suggests that if an amendment having a higher electrical conductivity replaces pore water, the effective electrical conductivity will increase.

Because theoretically based models for predicting spectral induced polarization (SIP) signatures are lacking or difficult to parameterize, phenomenological formulations such as the Cole-Cole relaxation model (Cole and Cole 1941) are often used to model the complex response. Inversion of the complex resistivity data yields estimates of the Cole-Cole parameters chargeability and time constant (e.g., Chen et al. 2008), which can in turn be related to pore and grain geometric characteristics. Interpretation of complex resistivity measurements and obtained parameters in terms of near subsurface biogeochemical properties and processes is a relatively new area of biogeophysical research. Although recent research has interpreted these measurements in terms of remediation-induced end-products such as precipitates (Williams et al. 2005; Chen et al. 2008) and biofilms, to our knowledge the complex resistivity response of pore fluid replacement by remedial amendments has not been documented.

C.2 Radar Methods

Time-domain reflectometer (TDR) methods were used at the laboratory scale, and tomographic ground-penetrating radar (GPR) methods were used at the field scale to measure electromagnetic wave propagation characteristics over the ~100-1000 MHz range. TDR methods involve propagating an electromagnetic signal along waveguides inserted into the material of interest and measuring the velocity and amplitude of the traveling wave (Topp et al. 1980). Tomographic radar data acquisition consists of placing a transmitter and a receiver in separate boreholes, and moving them successively until many transmitter and receiver locations have been occupied. The travel time of the direct arrival and associated amplitude information is extracted from the recorded waveforms, and inversion algorithms are used to transform this information into estimations of velocity and attenuation between the boreholes (Peterson 2001).

At the frequency of operation for TDR and radar systems, the separation (polarization) of opposite electric charges within a material subjected to an external electric fielddominates the electrical response. The dielectric constant ($\boldsymbol{\kappa}$), which used to describe these high-frequency electrical properties; can be approximated from the velocity (*V*) of the radar signal (Davis and Annan 1989) by

$$\kappa \approx \left(\frac{c}{V}\right)^2, \tag{2}$$

where *c* is the propagation velocity of electromagnetic waves in free space. The dielectric constant obtained from travel times is often used within dielectric mixing models to explore the dielectric contribution from a variety of components (Wharton et al. 1980) such as the idealistic expression for a three-component, soil-water-air system:

$$\boldsymbol{\kappa = \left(Sn\kappa_w^{\gamma} + (1-n)\kappa_g^{\gamma} + n(1-S)\kappa_a^{\gamma}\right)^{\frac{1}{\gamma}}}. \tag{3}$$

In Equation (3), *S* is water saturation; *n* is the soil porosity; κ_w, κ_g and κ_a are the unitless dielectric constant values of pore water, soil grains, and air, respectively; and γ is a factor that accounts for the orientation of the electrical field with respect to the geometry of the medium (which is commonly assumed to be 0.5 for an isotropic medium). Given that the dielectric constant of water (80) is high relative to typical values for grains (4-8) and air (1), the mixing formula shown in (3) is commonly used for moisture content estimation. Under saturated conditions and assuming constant porosity, Equation (3) suggests that if a lower dielectric constant amendment replaces the pore water, that the effective dielectric constant will decrease.

C.3 Seismic Methods

Seismic methods use sensitive geophones to measure disturbances that propagate outward from the source as a series of wavefronts. Seismic velocity and attenuation are related to the bulk elastic properties of the sediment and pore fluids, which in turn depend on mineralogy, fluid chemistry, and intergranular structure (Pride 2005). As such, simple expressions, such as those given in (1) and (3), are not available to relate seismic attributes to pore fluid properties. However, as P-wave velocity increases with both fluid viscosity and density, this attribute might be sensitive to pore water replacement by a more viscous or dense amendment.

C.4 References

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Appendix D

Field Test Data

Appendix D

Field Test Data

The field test data are provided on the compact disk bound inside the back cover of the printed copies of this report.

Appendix E

Organic Compound Concentration Data Plots for the Soluble Substrate Test

Appendix E

Organic Compound Concentration Data Plots for the Soluble Substrate Test

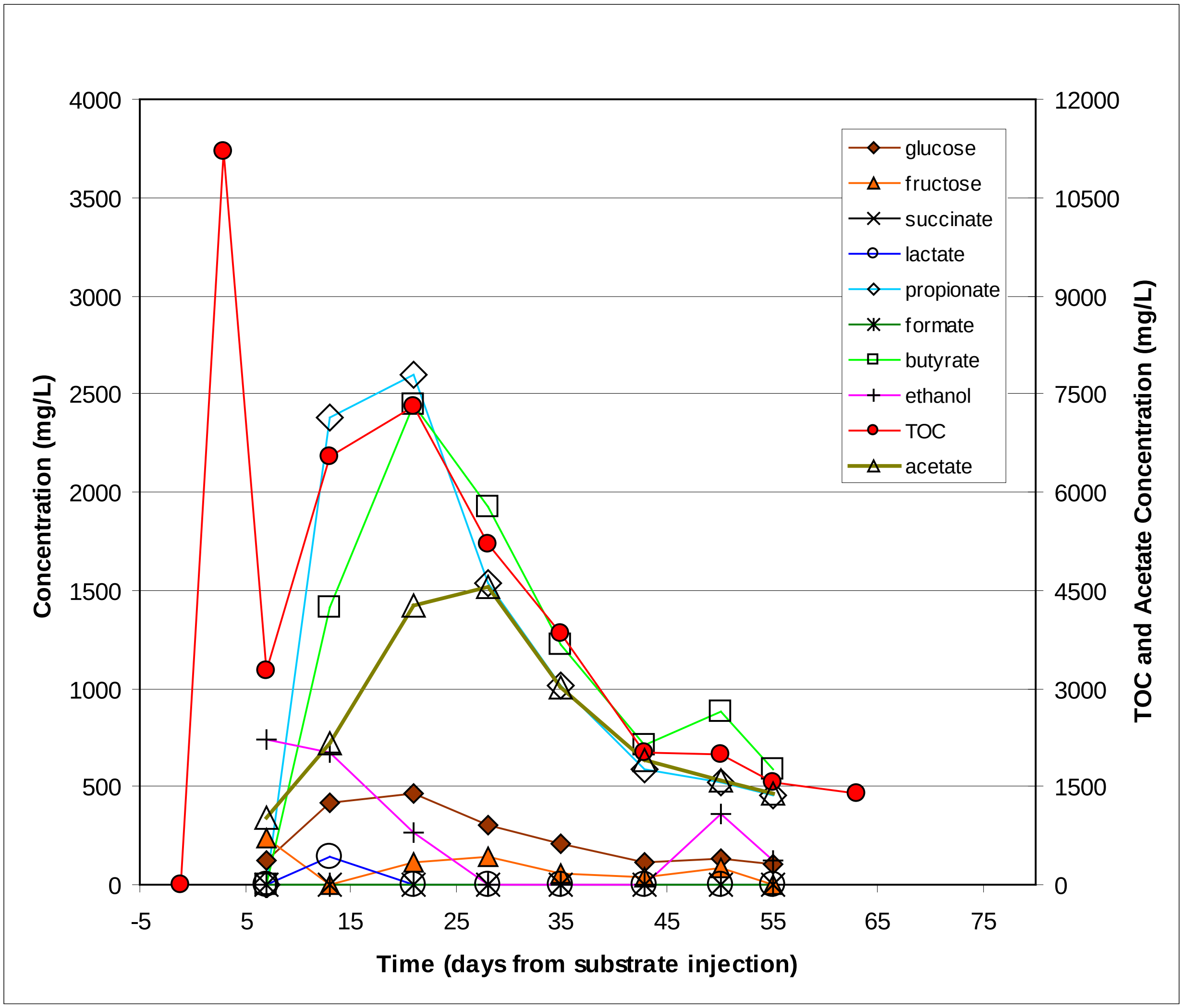

Figure E.1. Organic Compound Concentrations During the Process Monitoring Phase at the Injection Well 199-D5-107

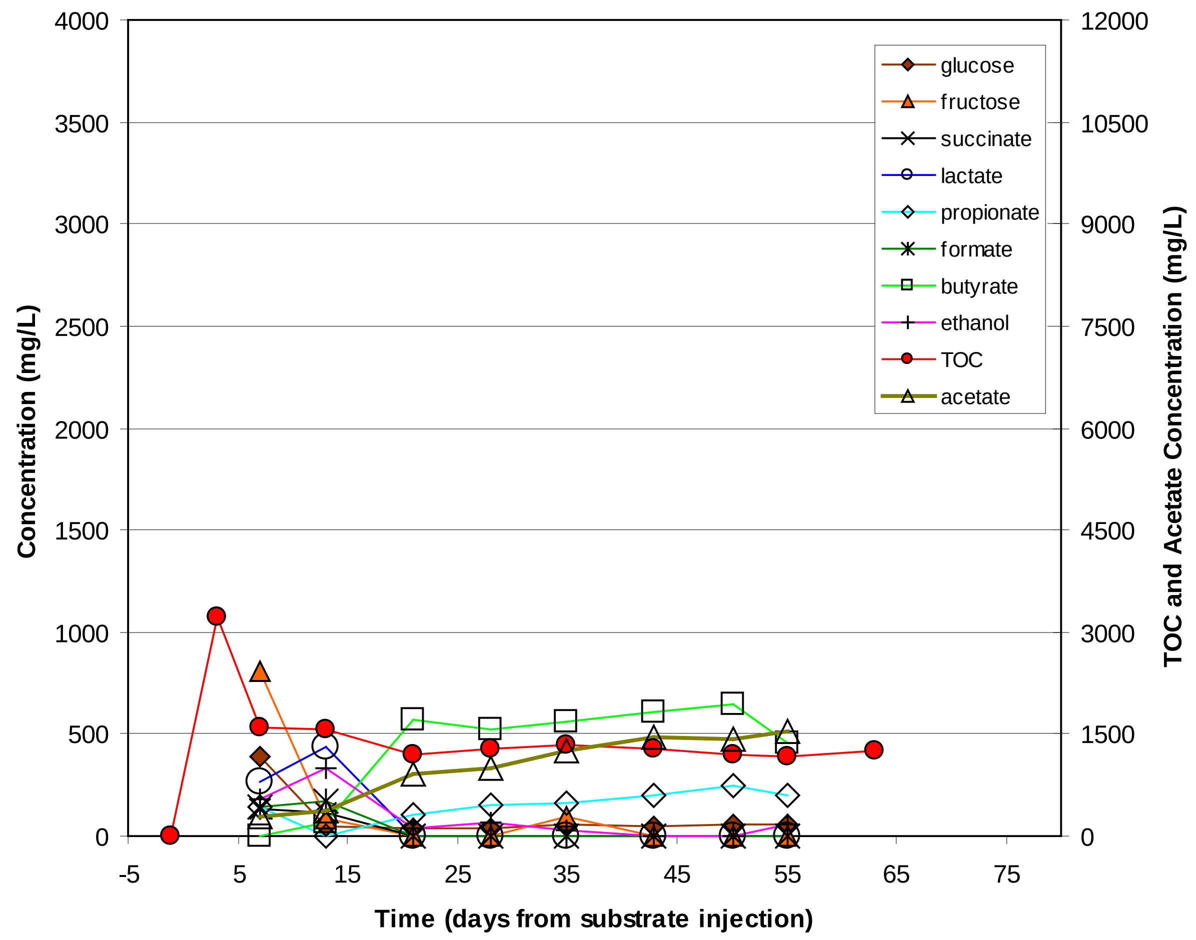

Figure E.2. Organic Compound Concentrations During the Process Monitoring Phase at Monitoring Well 199-D5-109

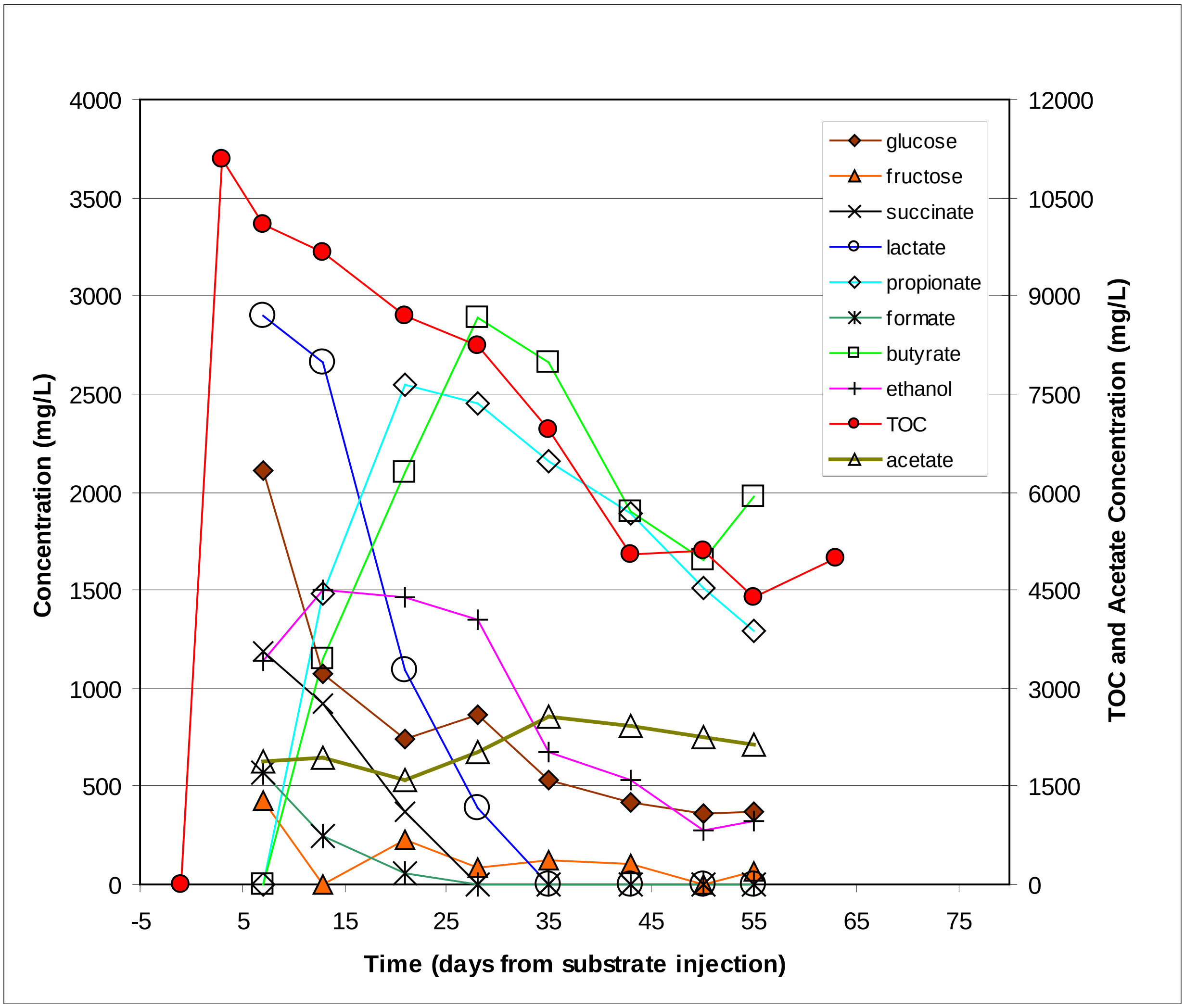

Figure E.3. Organic Compound Concentrations During the Process Monitoring Phase at Monitoring Well 199-D5-110

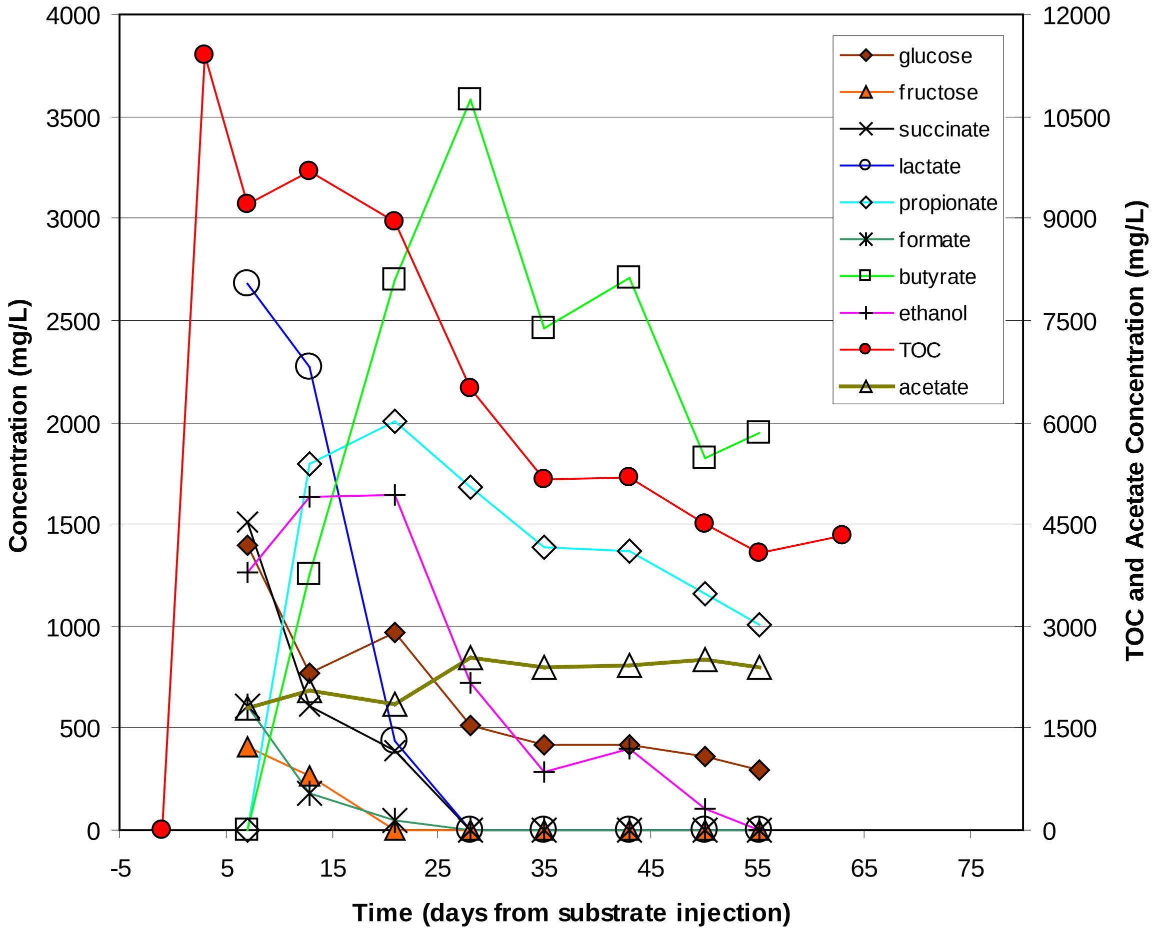

Figure E.4. Organic Compound Concentrations During the Process Monitoring Phase at Monitoring Well 199-D5-111

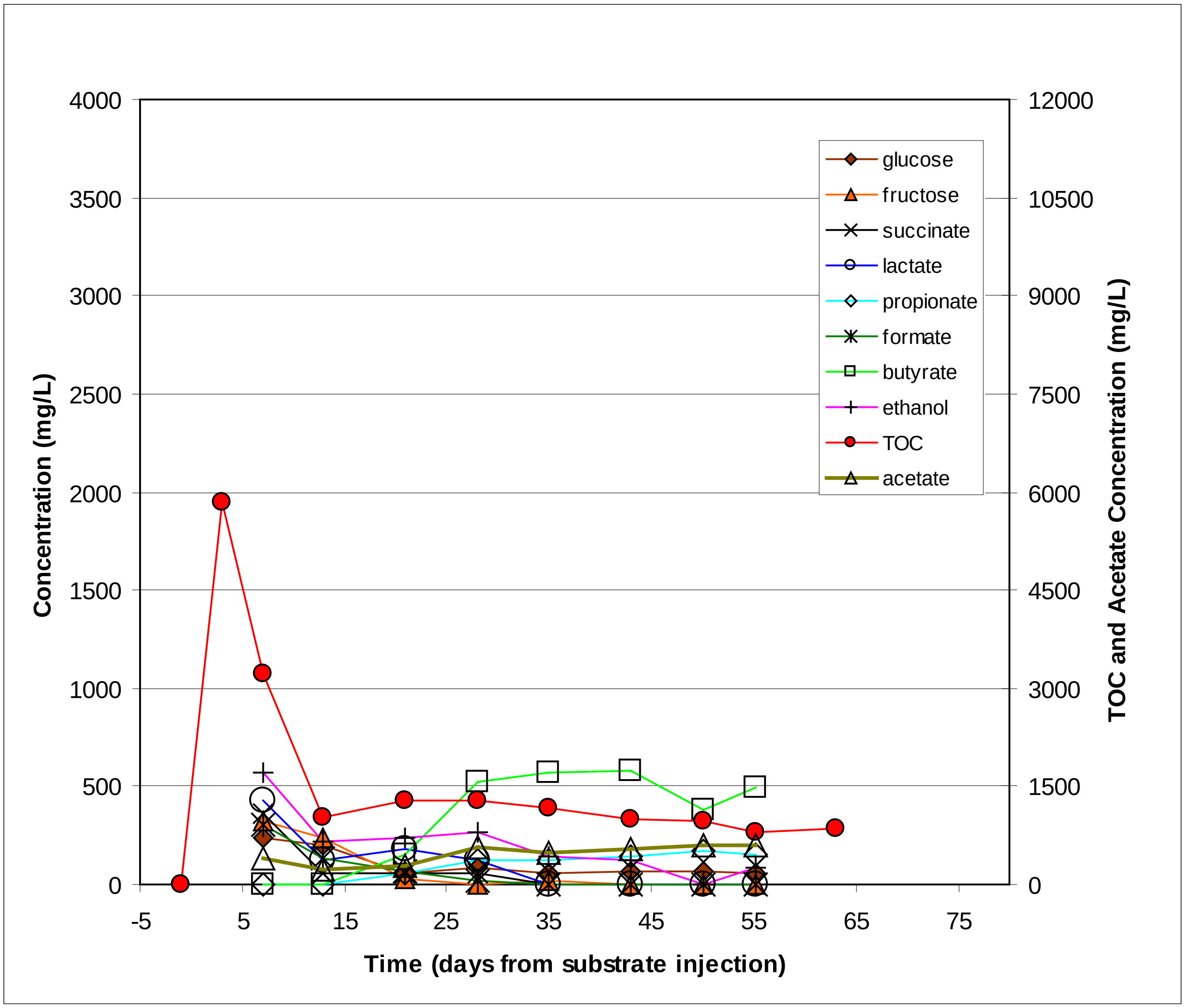

Figure E.5. Organic Compound Concentrations During the Process Monitoring Phase at Monitoring Well 199-D5-112

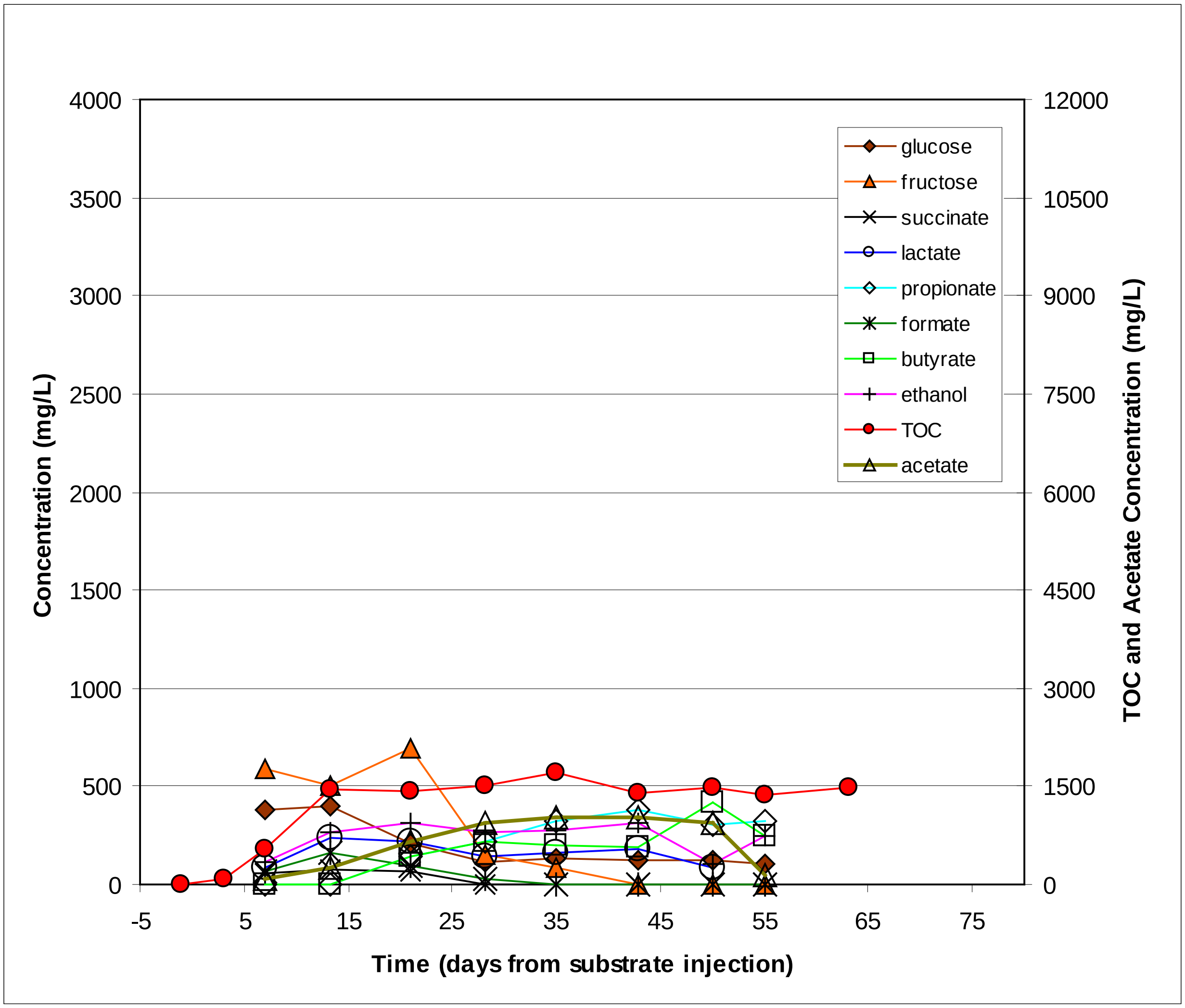

Figure E.6. Organic Compound Concentrations During the Process Monitoring Phase at Monitoring Well 199-D5-113

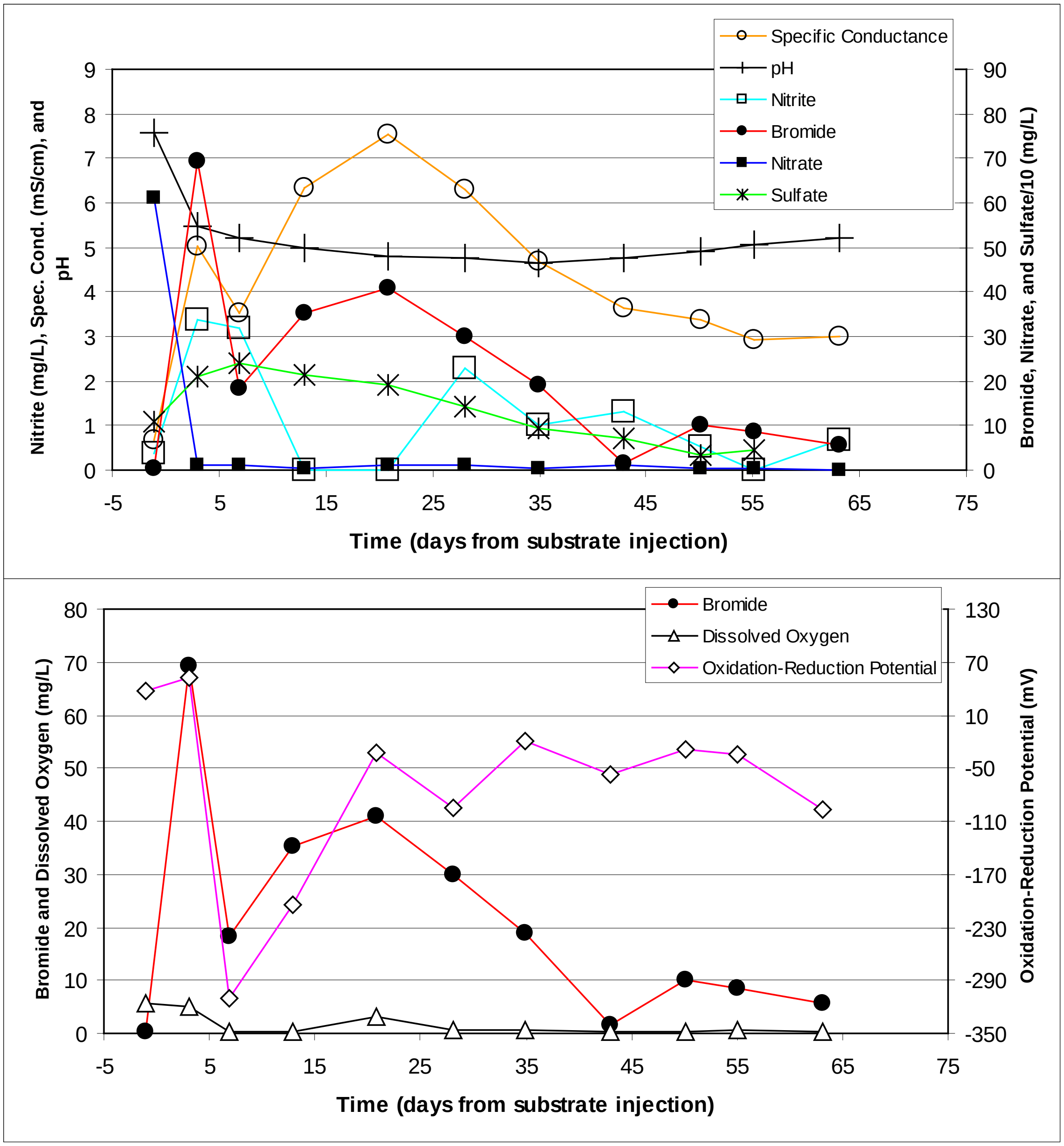

Figure E.7. Process Monitoring Phase Data at Injection Well 199-D5-107

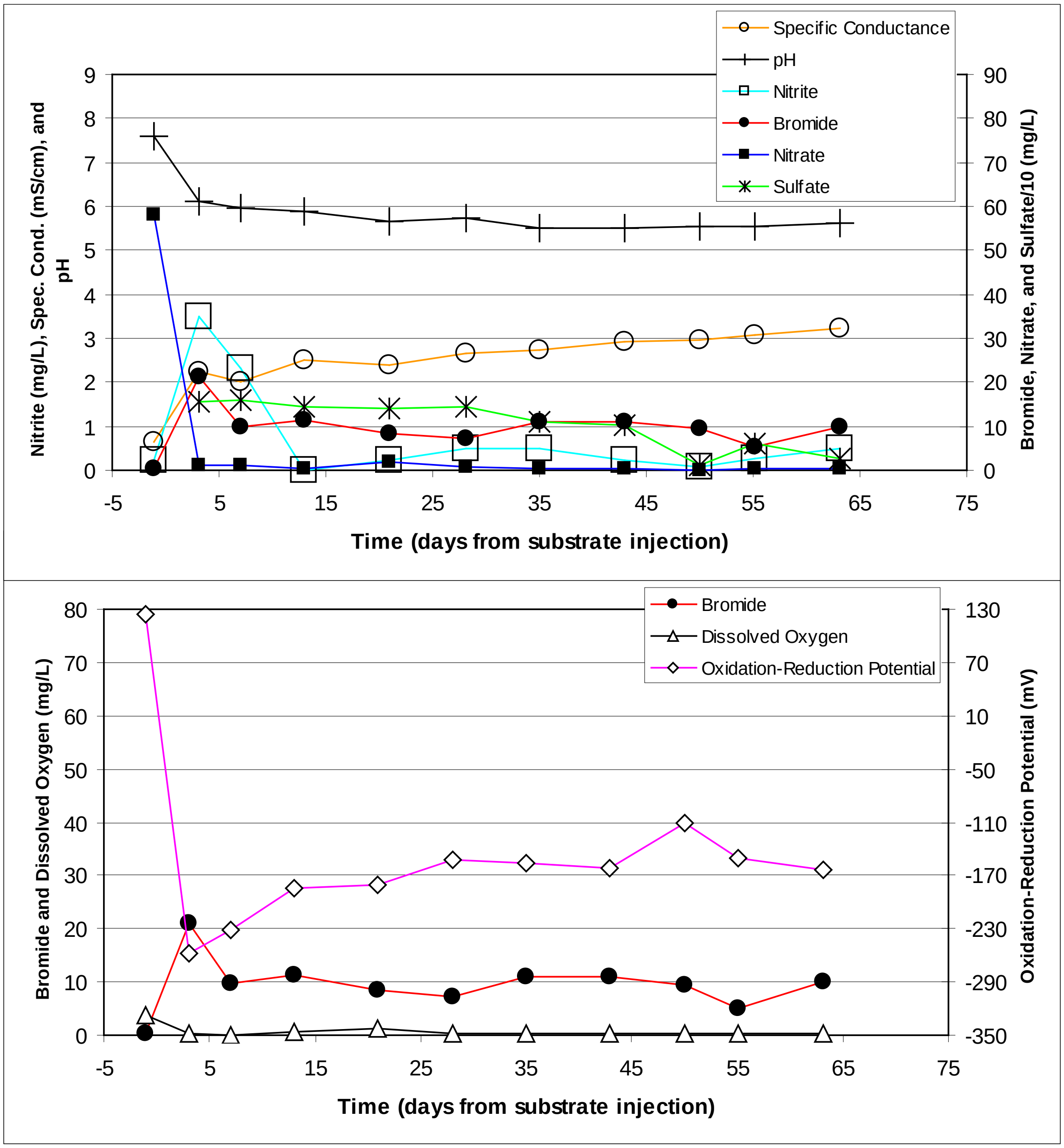

Figure E.8. Process Monitoring Phase Data at Monitoring Well 199-D5-109

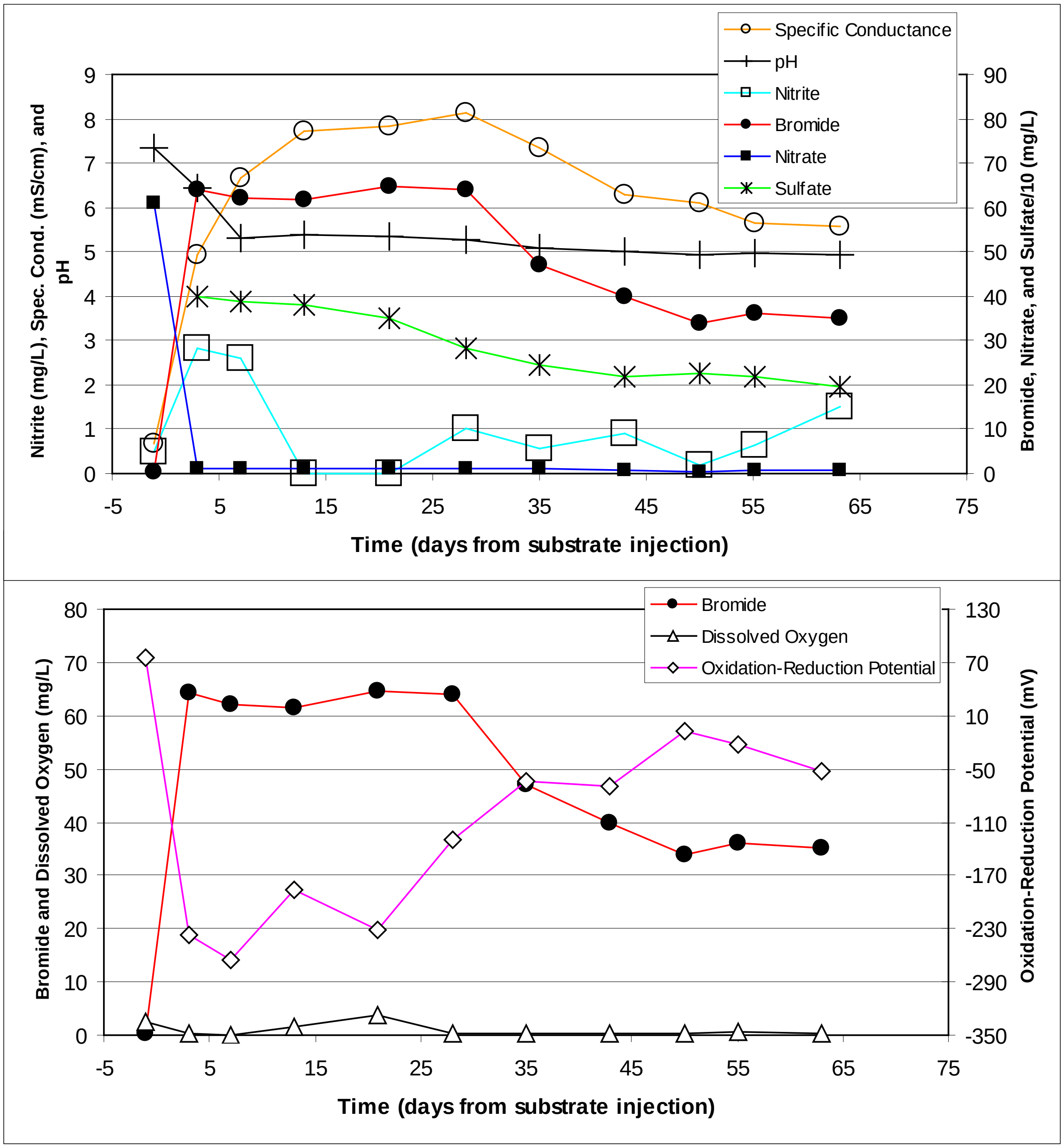

Figure E.9. Process Monitoring Phase Data at Monitoring Well 199-D5-110

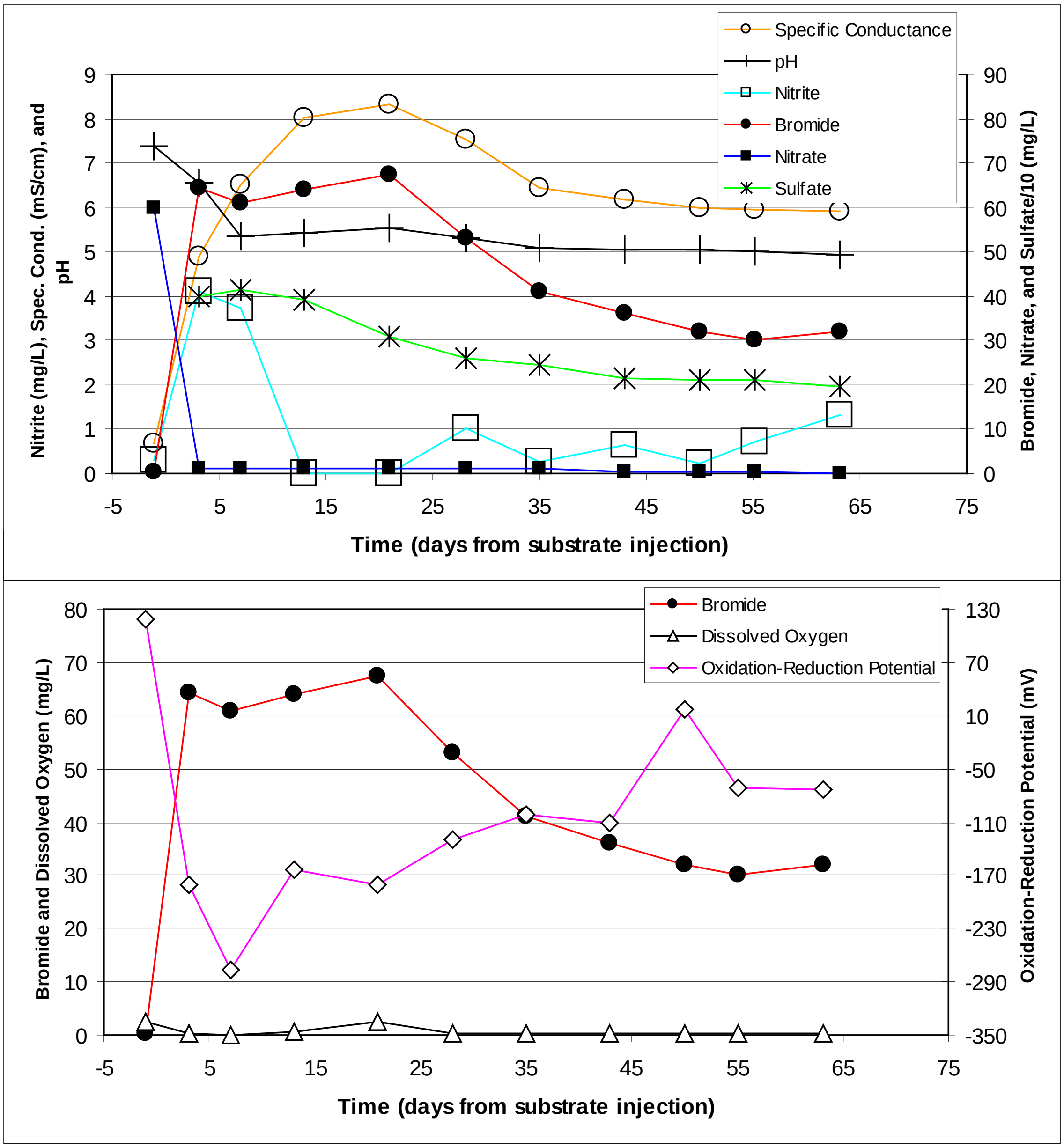

Figure E.10. Process Monitoring Phase Data at Monitoring Well 199-D5-111

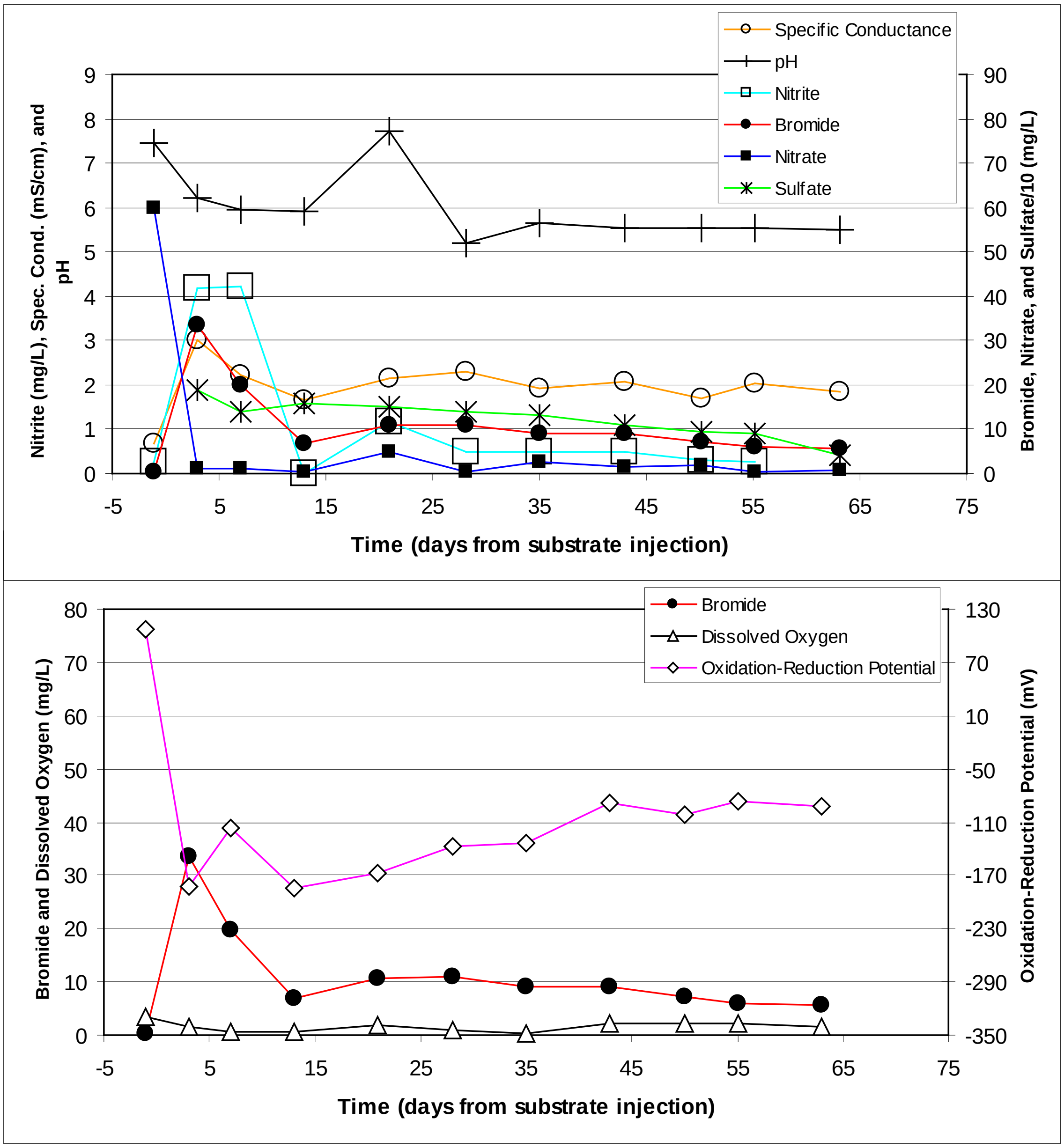

Figure E.11. Process Monitoring Phase Data at Monitoring Well 199-D5-112

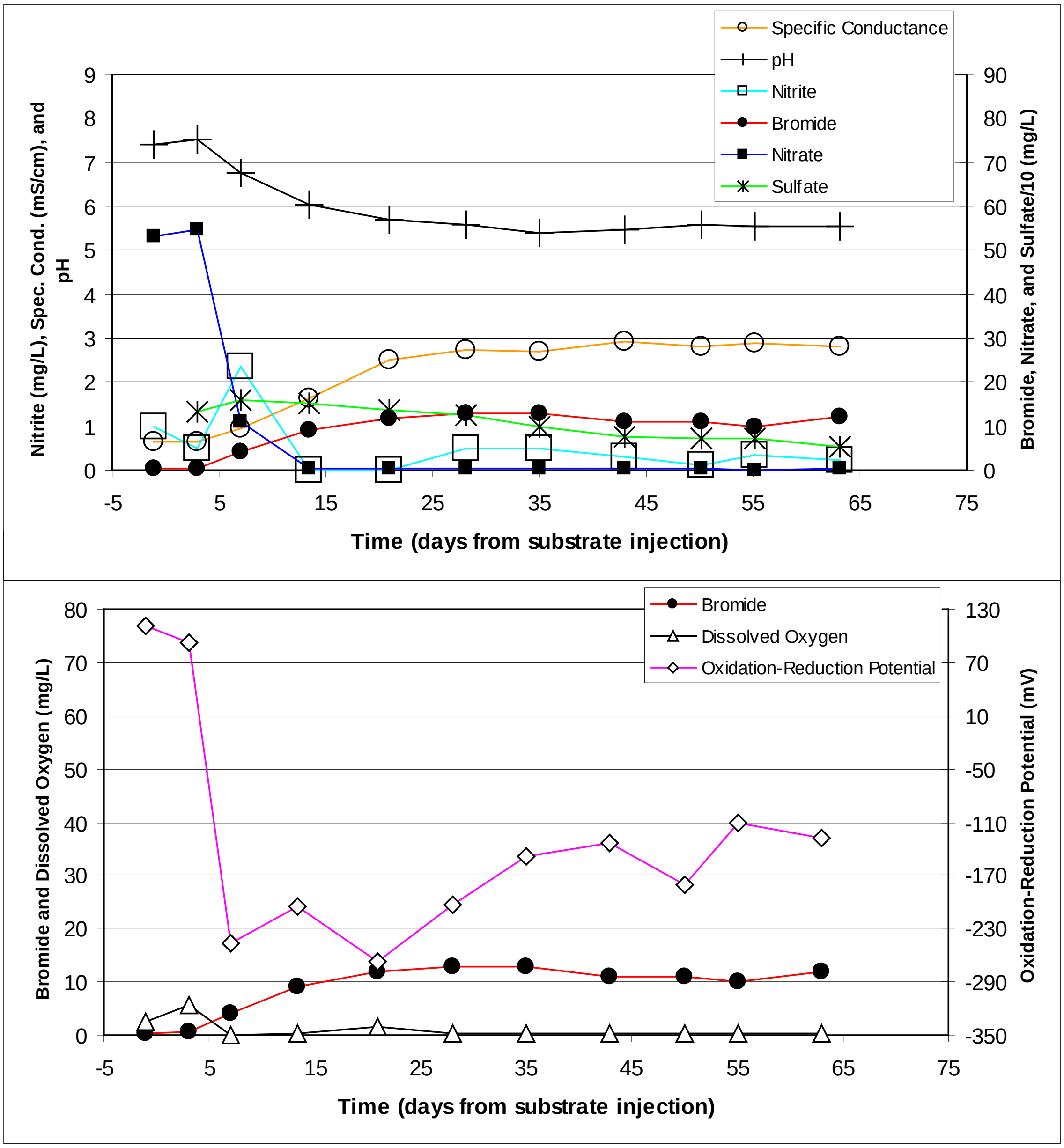

Figure E.12. Process Monitoring Phase Data at Monitoring Well 199-D5-113

The following data plots are the same as Figures 6.1 through 6.6 in the text except that the scale of the vertical axis has been changed to provide for additional interpretation of the data.

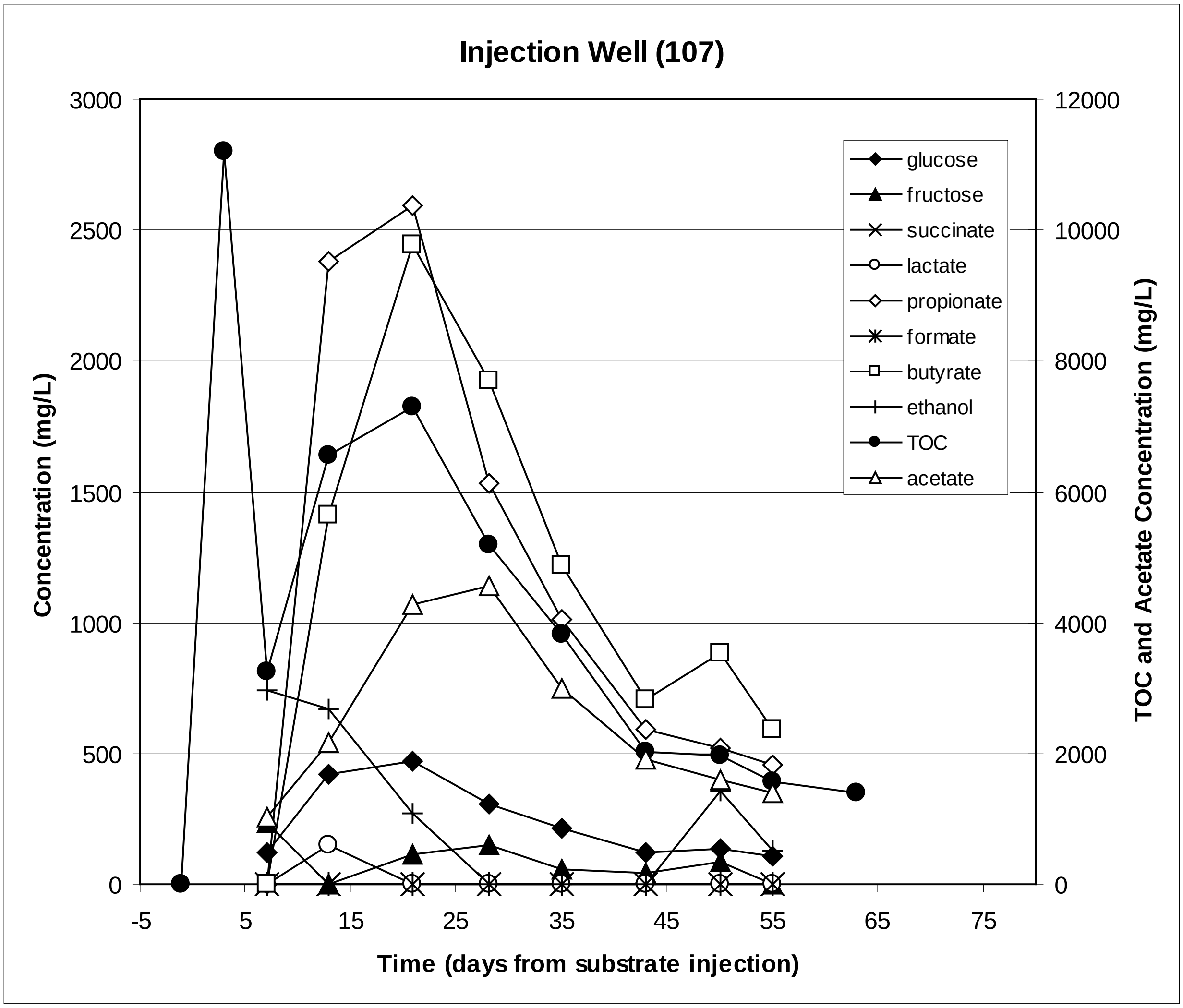

Figure E.13. Organic Compound Concentrations During the Process Monitoring Phase at Injection Well 199-D5-107

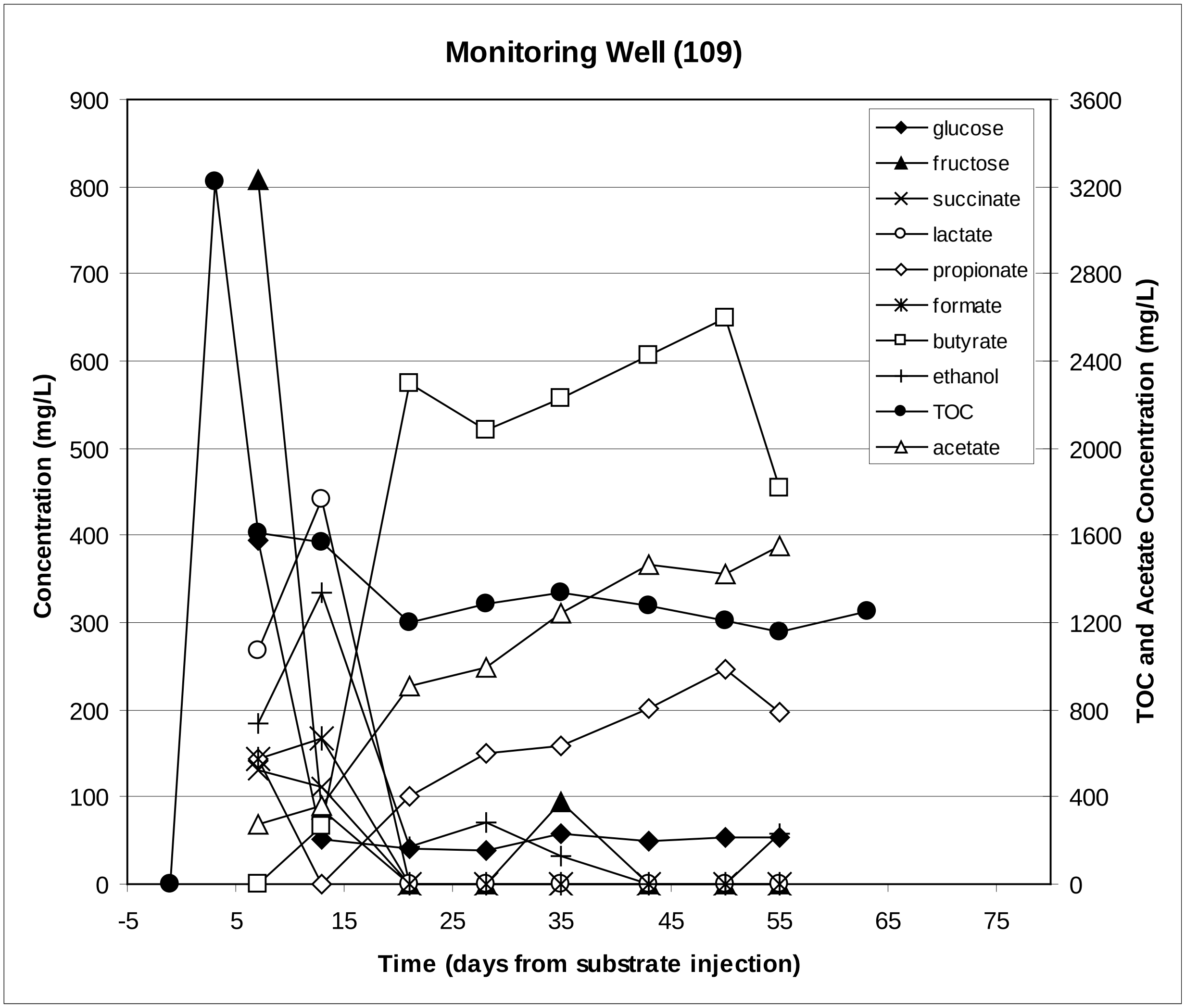

Figure E.14. Organic Compound Concentrations During the Process Monitoring Phase at Process Monitoring Well 199-D5-109

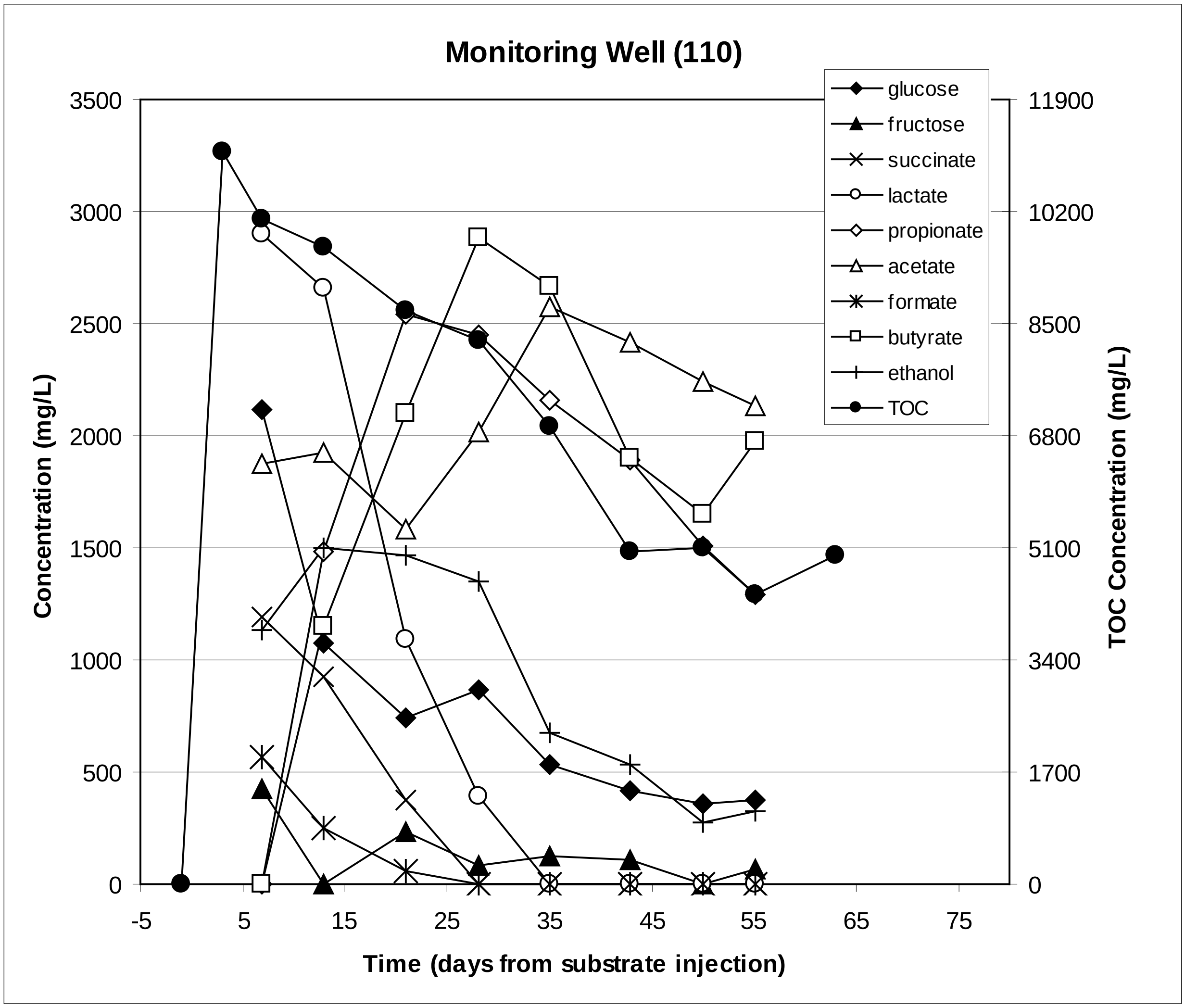

Figure E.15. Organic Compound Concentrations During the Process Monitoring Phase at Process Monitoring Well 199-D5-110

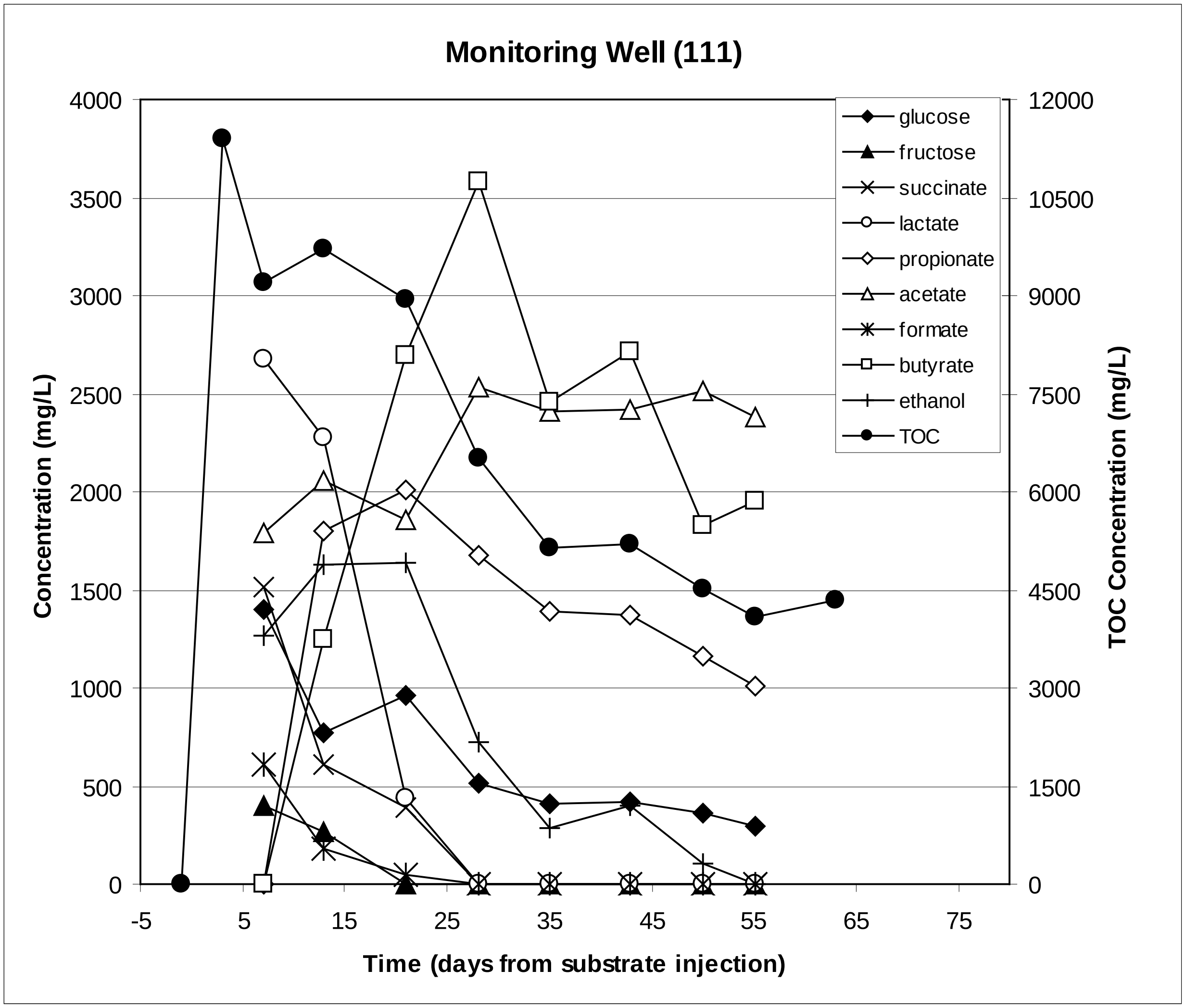

Figure E.16. Organic Compound Concentrations During the Process Monitoring Phase at Process Monitoring Well 199-D5-111

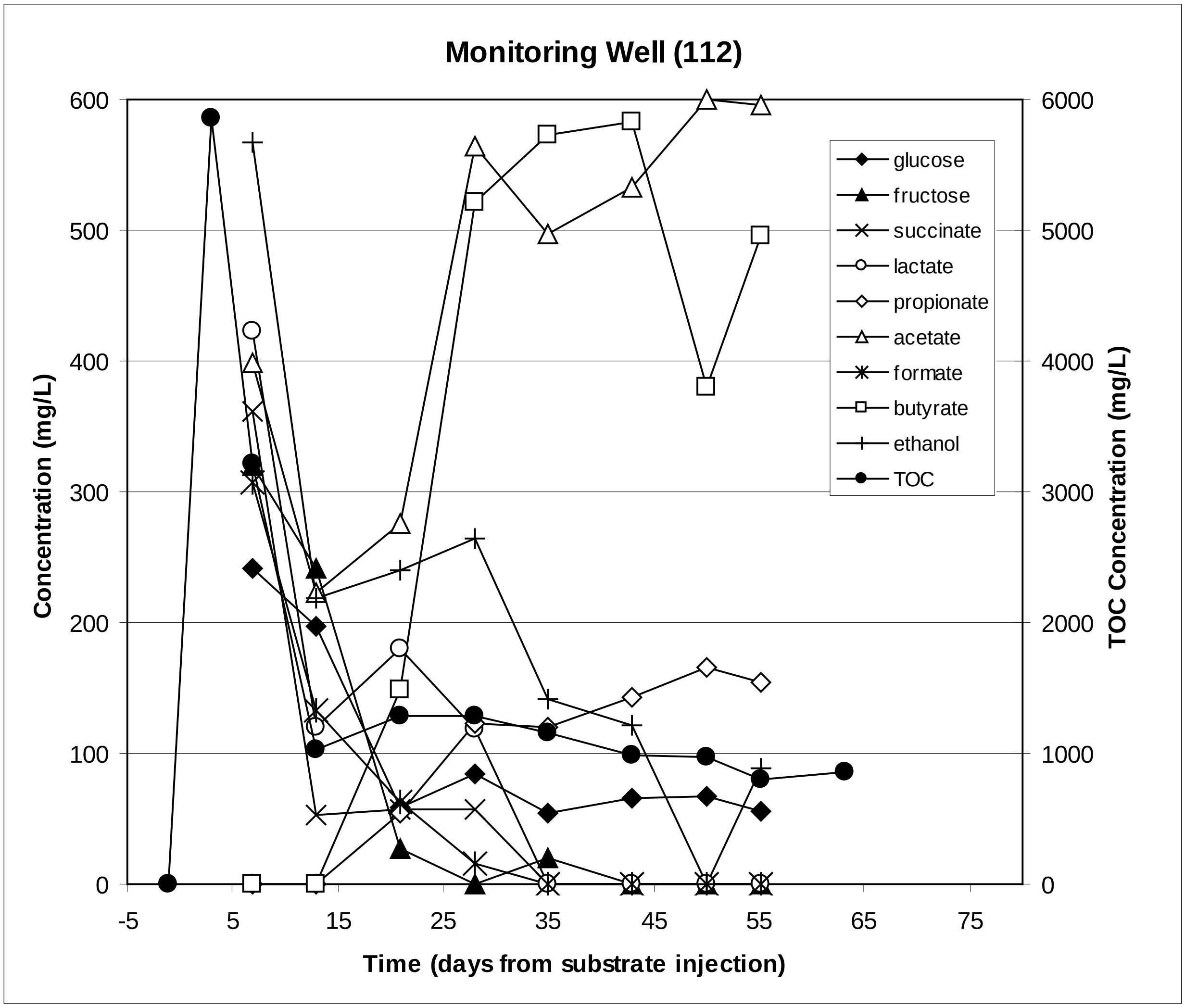

Figure E.17. Organic Compound Concentrations During the Process Monitoring Phase at Process Monitoring Well 199-D5-112

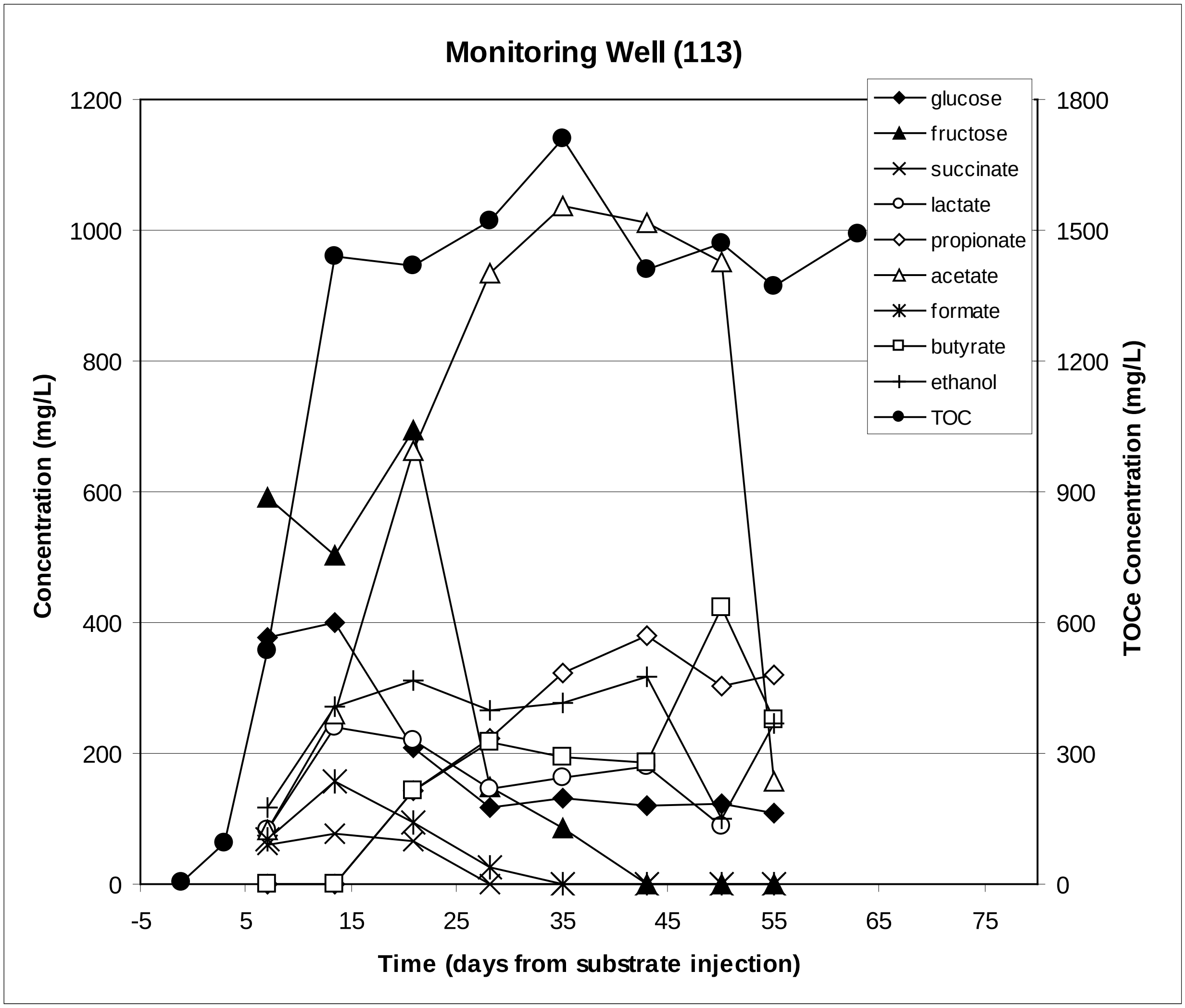

Figure E.18. Organic Compound Concentrations During the Process Monitoring Phase at Process Monitoring Well 199-D5-113

Appendix F

Detailed Slug Testing Results

Appendix F

Detailed Slug Testing Results

A series of slug tests were performed to evaluate potential reduction in permeability in the aquifer associated with the bioremediation treatment activities. Slug test responses were analyzed using multiple analytical methods in order to provide a more complete and comparative analysis.

Table F.1 contains the results from all of the analysis methods; however, it should be noted that only those results obtained using the most appropriate analytical method and representative portions of the responses were selected for use in the permeability reduction calculations. Except for one well (discussed below) estimates obtained using the KGS (Hyder et al. 1994; Butler 1998) are preferred. For the critically-damped responses observed in well 199-D5-109, the Springer and Gelhar (1991) model was deemed most appropriate. Heterogeneous responses were analyzed as inner- and outer-zone responses separately. Both are included here, but the outer-zone estimates are more representative of the undisturbed formation (Bouwer 1989).

Table F.1. Detailed Hydraulic Conductivity Estimates from Pre- and Post-Treatment Slug Tests

			Hydraulic Conductivity in ft/day[a]					
			K_{pre} (08/07)		K_{post-1} (11/2007)		K_{post-2} (11/2008)	
Test Cluster	Well Name	Analysis Method	Inner Zone	Outer Zone	Inner Zone	Outer Zone	Inner Zone	Outer Zone
Molasses	199-D5-107	B&R	40	30	15	4	3	1
		KGS	58	45	20	6	4	1
	199-D5-109	B&R	345		230		2	
		KGS	387		420		3	
		S&G	145		174		Not Used(b)	
	199-D5-110	B&R	53	77	47	73	17	21
		KGS	78	115	71	114	25	32
	199-D5-111	B&R	40	45	41	47	9	10
		KGS	57	66	60	71	13	15
	199-D5-113	B&R	60		43		33	
		KGS	69		52		38	
Emulsified-Vegetable Oil	199-D5-108	B&R	49	50	n/a		12	12
		KGS	72	76			24	25
	199-D5-114	B&R	97	205			83	104
		KGS	109	230			83	132
	199-D5-115	B&R	40	42			15	14
		KGS	44	50			16	16
	199-D5-116	B&R	43	49			18	18
		KGS	46	56			21	20
	199-D5-118	B&R	70				50	
		KGS	80				56	

(a) Best estimates of K for the aquifer used in calculations of permeability change are highlighted in BOLD.
(b) Response for well 199-D5-109 in 11/2008 was overdamped, unlike previous responses.
Abbreviations.
ft = feet, B&R = Bouwer and Rice (1979) straight-line method, KGS = KGS type-curve model (Hyder et al. 1994; Butler 1998), S&G = Springer and Gelhar (1991, pp. 36-40) inertial model.

Table F.2 contains a summary of the calculated permeability change based on the best estimates of hydraulic conductivity for pre- and post-treatment tests. Permeability change was defined as the ratio of post-treatment K to the pre-treatment K (K_{post}/P_{pre}).

TableF.2. Permeability Change Results Based on Slug Test Best Estimates

		K_{pre} (08/07)	K_{post-1} (11/2007)	K_{post-2} (11/2008)	Permeability Change (K_{post}/K_{pre})	
Test Cluster	Well Name	ft/day	ft/day	ft/day	Post 1	Post 2
Molasses	199-D5-107	45	6	1	0.13	0.02
	199-D5-109	145	174	3	1.20	0.02
	199-D5-110	115	114	32	0.99	0.28
	199-D5-111	66	71	15	1.08	0.23
	199-D5-113	69	52	38	0.75	0.55
Emulsified-Vegetable Oil	199-D5-108	76	n/a	25	n/a	0.33
	199-D5-114	230		132		0.57
	199-D5-115	50		16		0.32
	199-D5-116	56		20		0.36
	199-D5-118	80		56		0.70

Figures F.1 through F.25 contain the slug test responses, analytical model fits to the data, and accompanying analytical parameters. They are organized by well, test date, inner/outer zone, and analytical method, in that order.

Well 199-D5-107

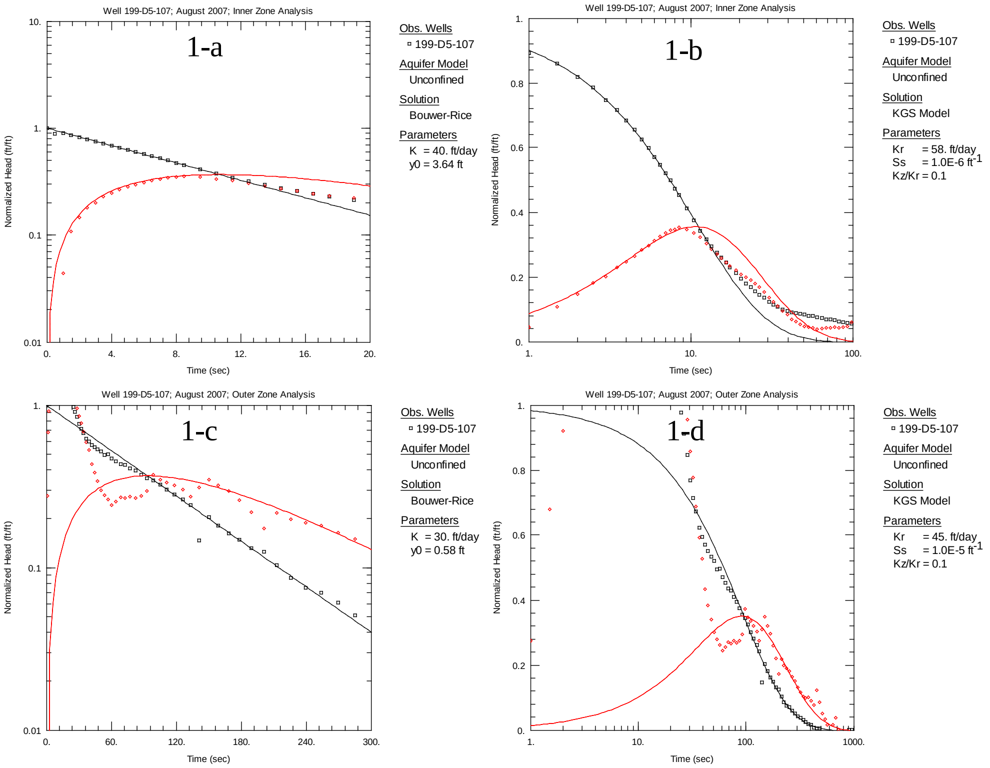

Figure F.1. Responses for Well 199-D5-107 from 11/2007 Tests (derivative shown in red)

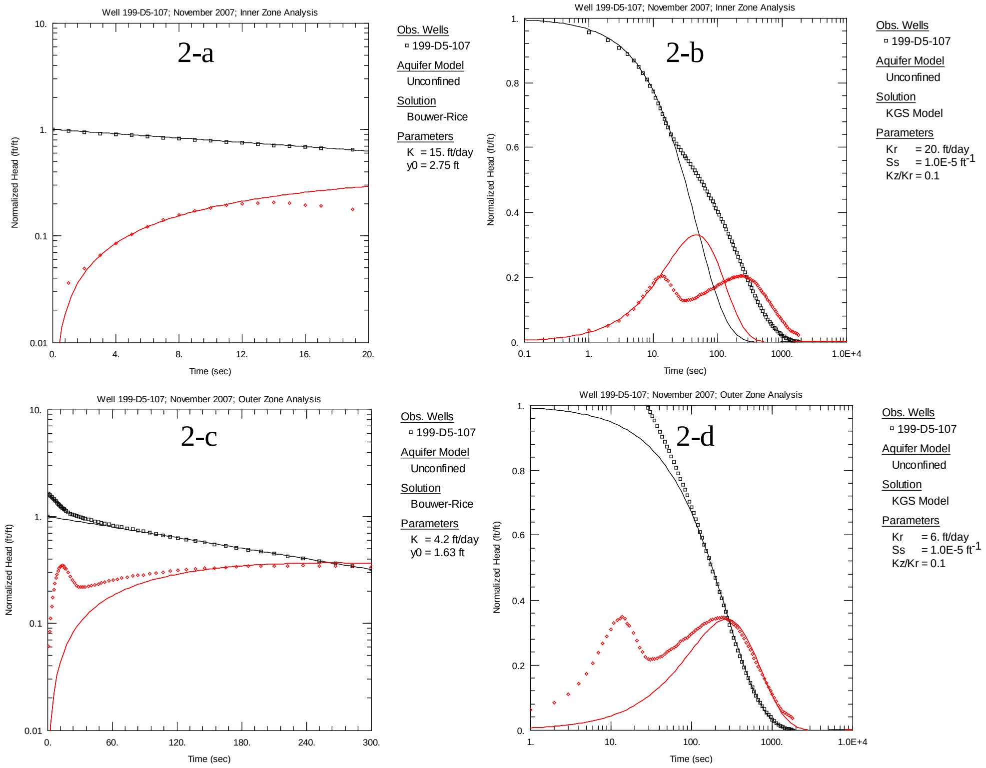

Figure F.2. Responses for Well 199-D5-107 from 11/2007 Tests (derivative shown in red)

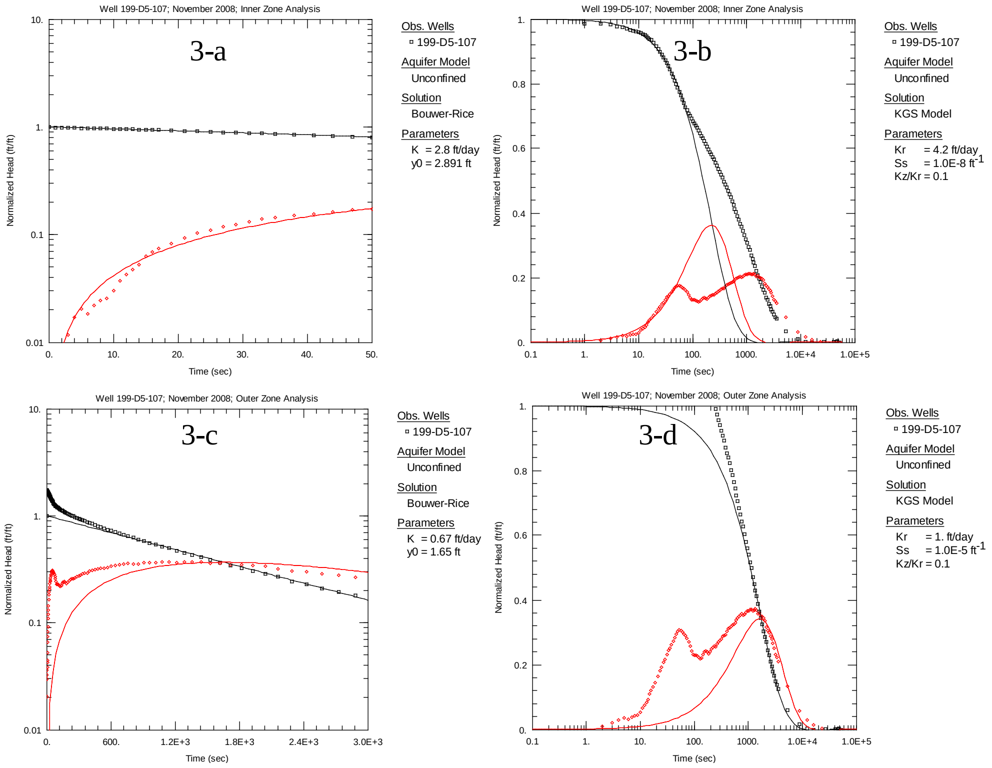

Figure F.3. Responses for Well 199-D5-107 from 11/2008 Tests (derivative shown in red)

Well 199-D5-108

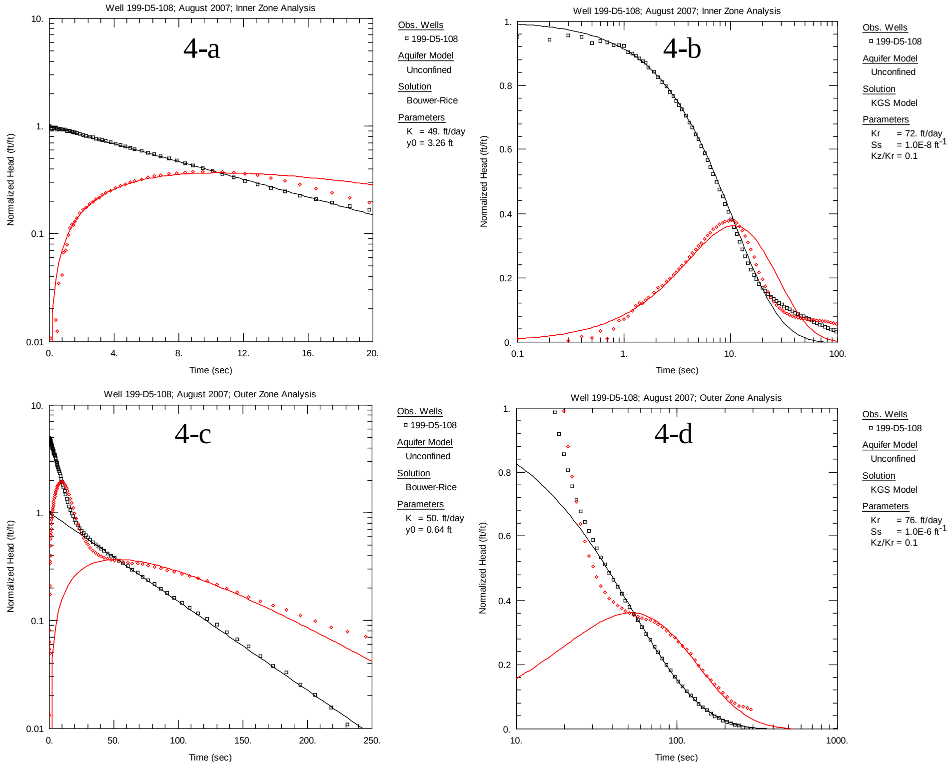

Figure F.4. Responses for Well 199-D5-108 from 08/2007 Tests (derivative shown in red)

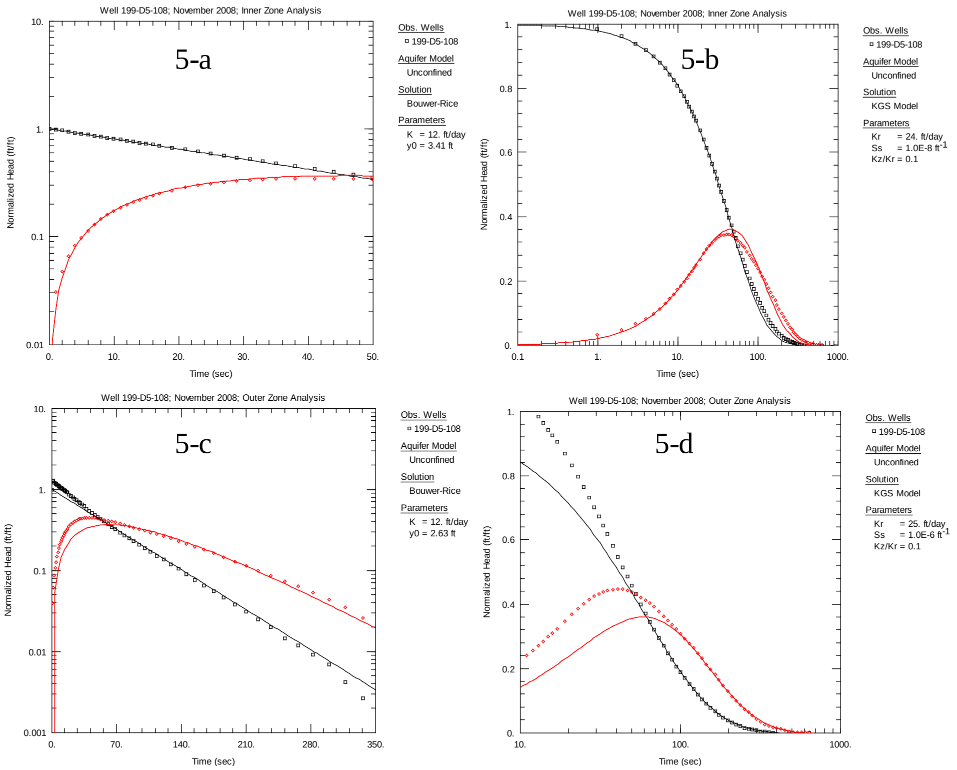

Figure F.5. Responses for Well 199-D5-108 from 11/2007 Tests (derivative shown in red)

Well 199-D5-109

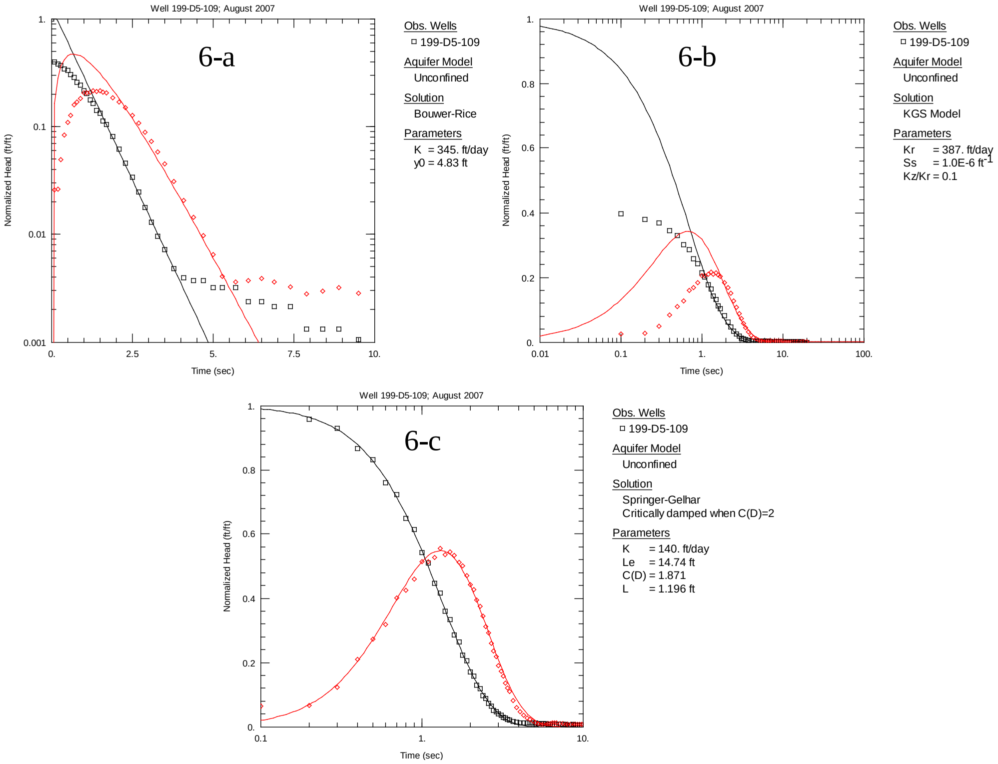

Figure F.6. Responses for Well 199-D5-109 from 08/2007 Tests (derivative shown in red)

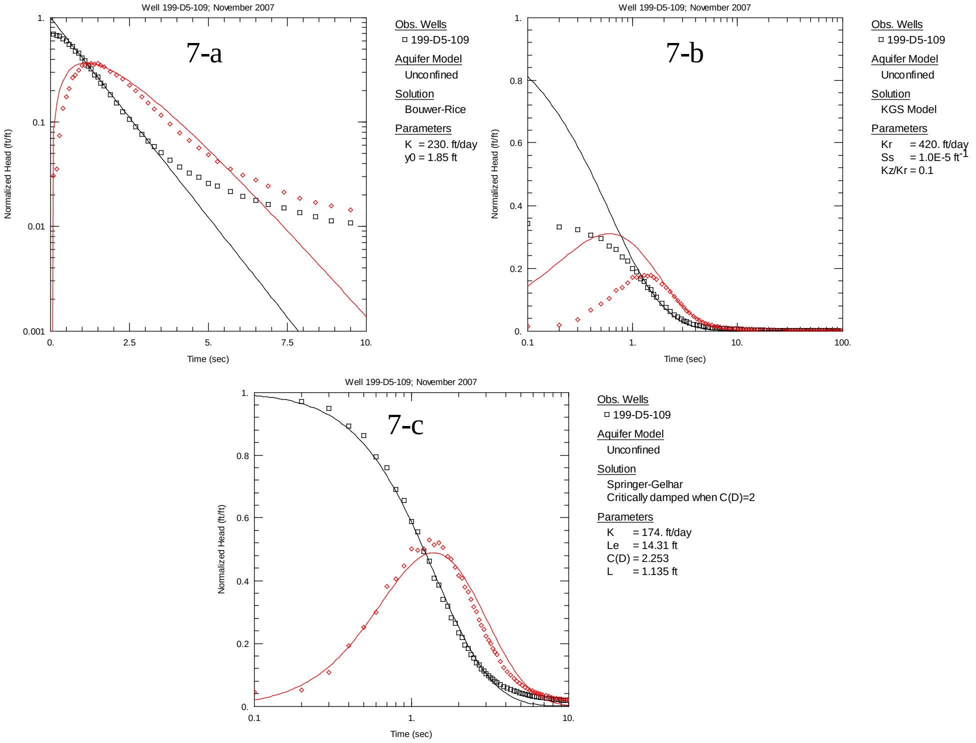

Figure F.7. Responses for Well 199-D5-109 from 11/2007 Tests (derivative shown in red)

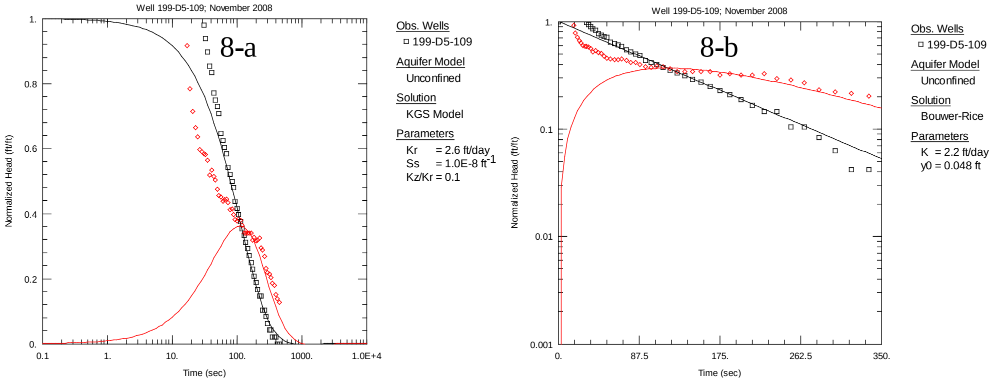

Figure F.8. Responses for Well 199-D5-109 from 11/2008 Tests (derivative shown in red)

Well 199-D5-110

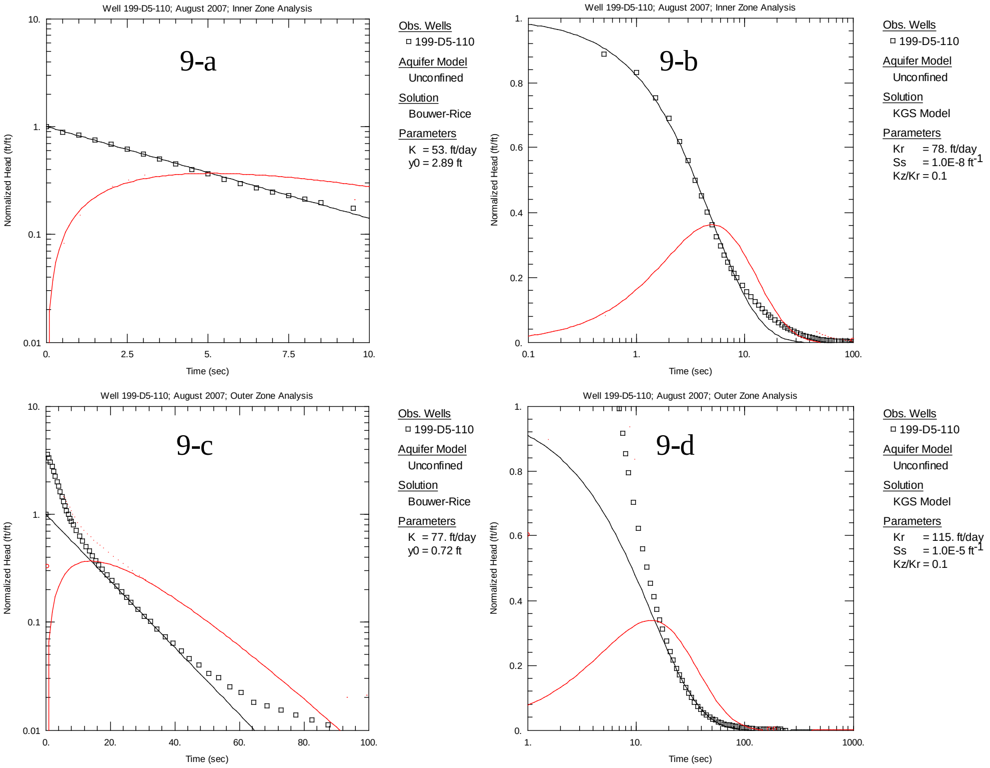

Figure F.9. Responses for Well 199-D5-110 from 08/2007 Tests (derivative shown in red)

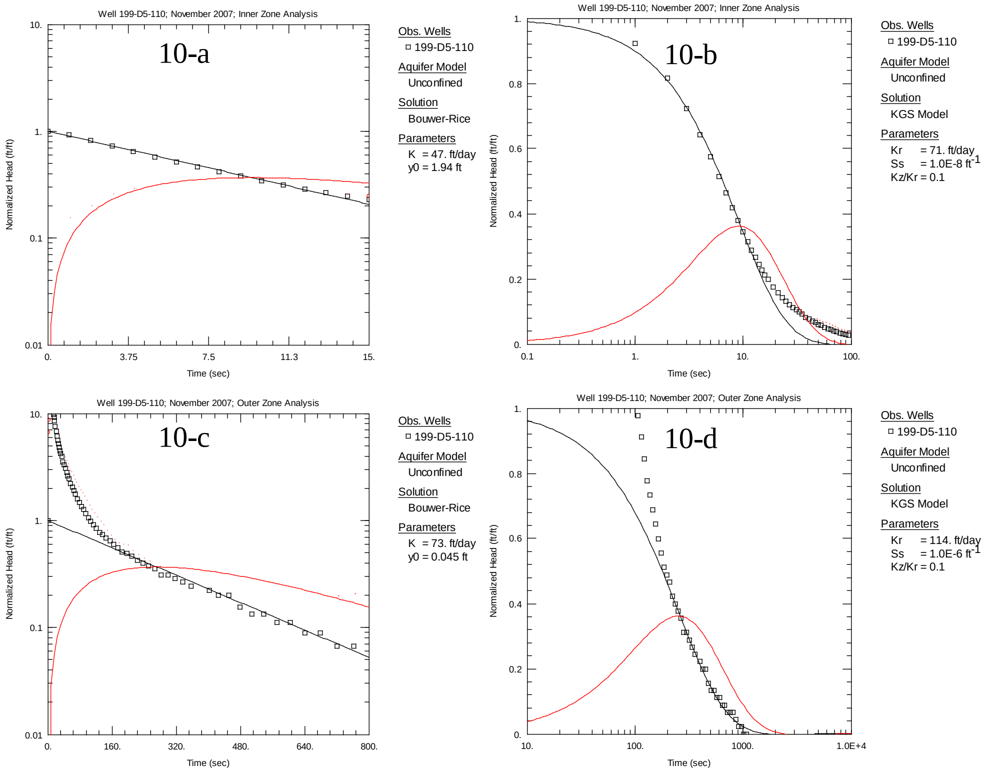

Figure F.10. Responses for Well 199-D5-110 from 11/2007 Tests (derivative shown in red)

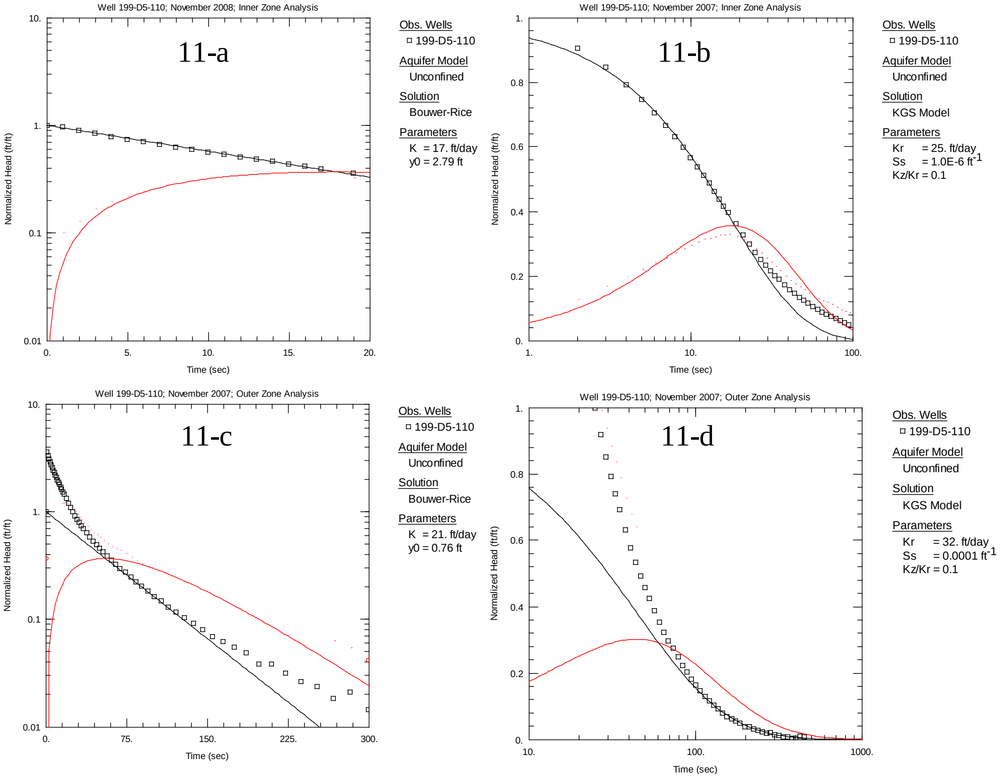

Figure F.11. Responses for Well 199-D5-110 from 11/2008 Tests (derivative shown in red)

Well 199-D5-111

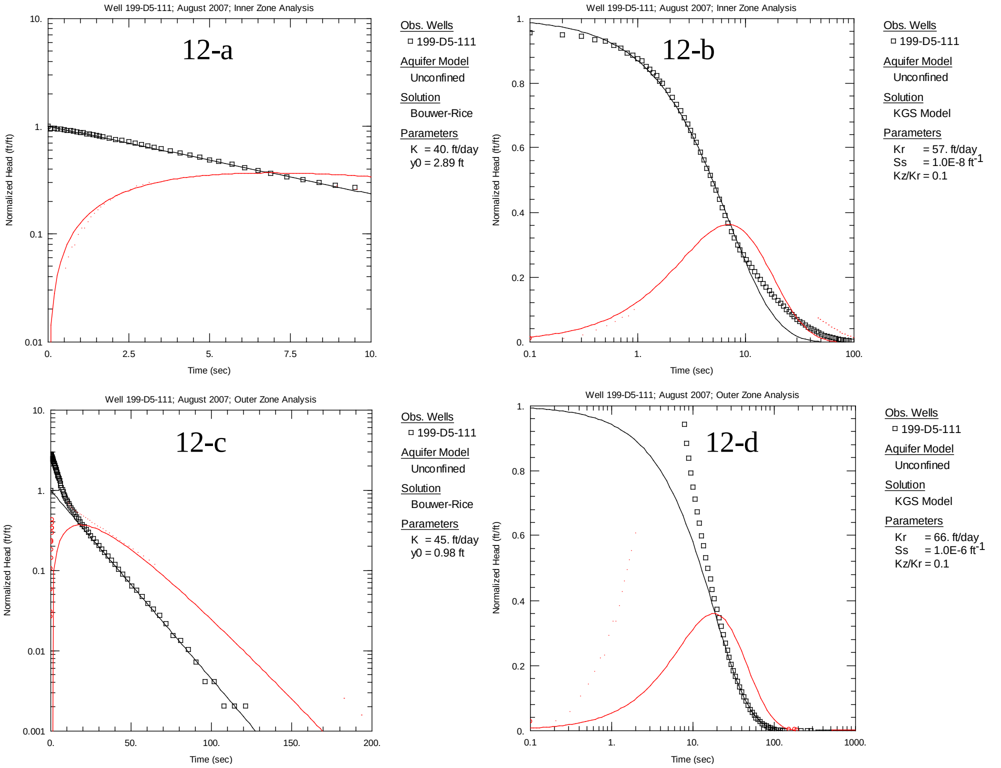

Figure F.12. Responses for Well 199-D5-111 from 08/2007 Tests (derivative shown in red)

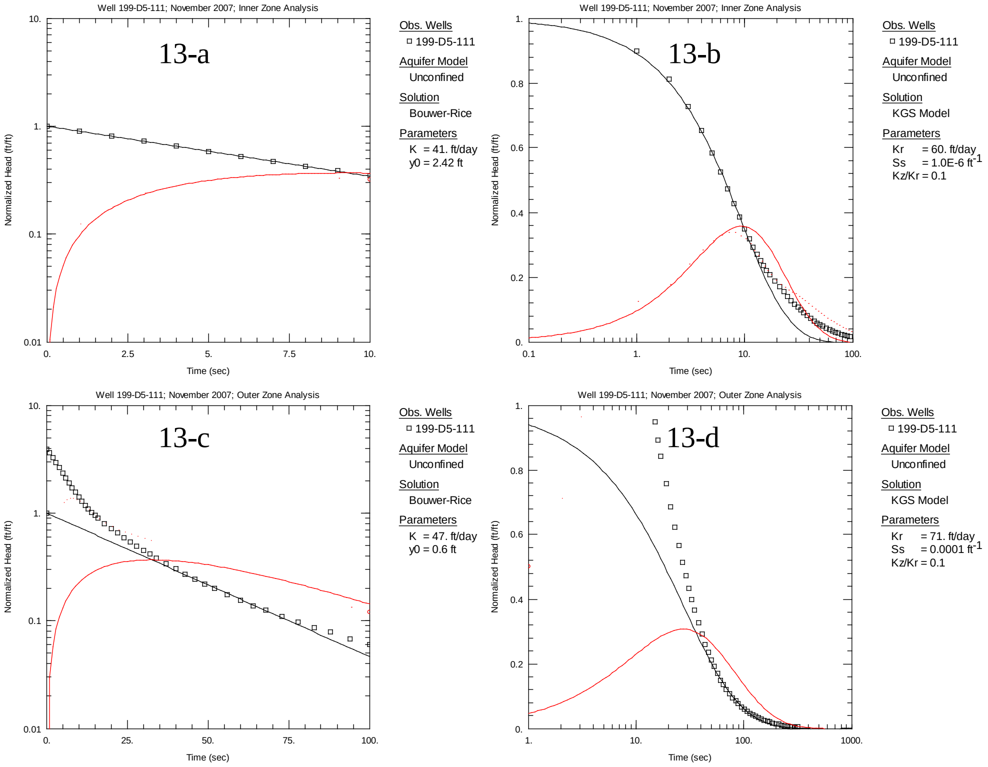

Figure F.13. Responses for Well 199-D5-111 from 11/2007 Tests (derivative shown in red)

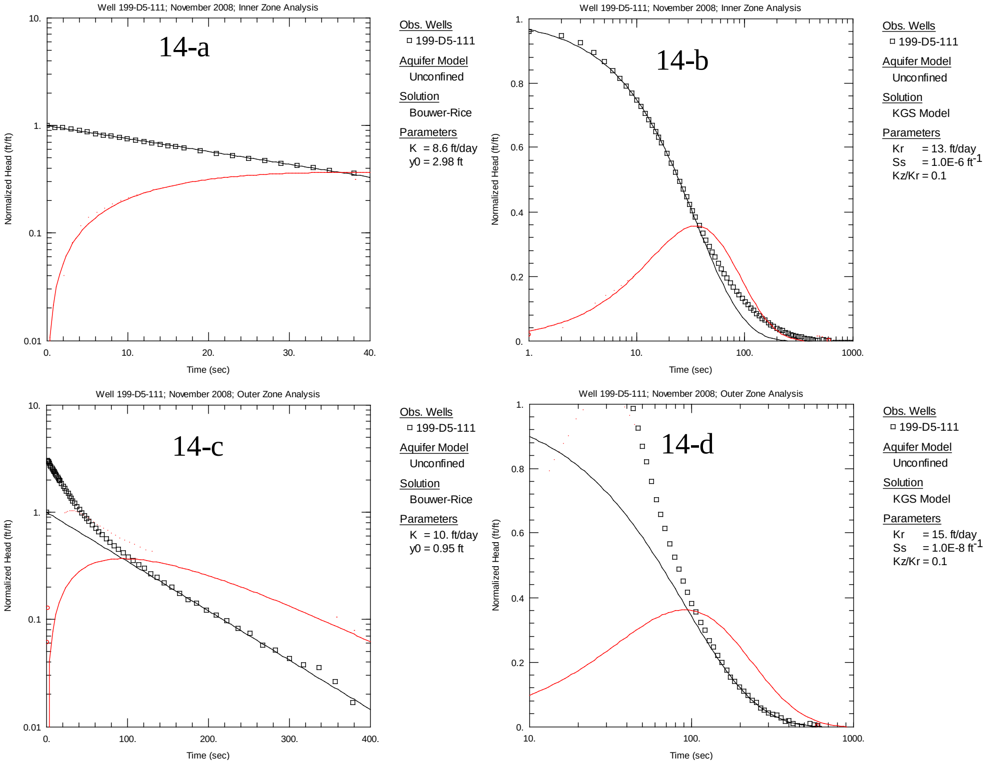

Figure F.14. Responses for Well 199-D5-111 from 11/2008 Tests (derivative shown in red)

Well 199-D5-113

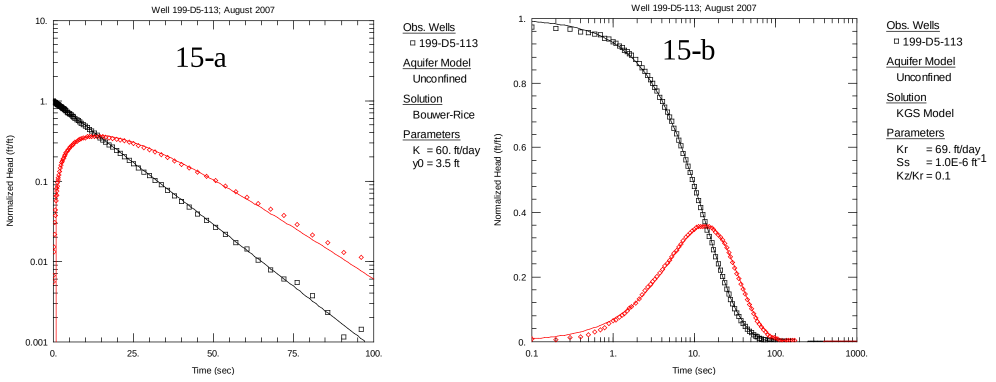

Figure F.15. Responses for Well 199-D5-113 from 08/2007 Tests (derivative shown in red)

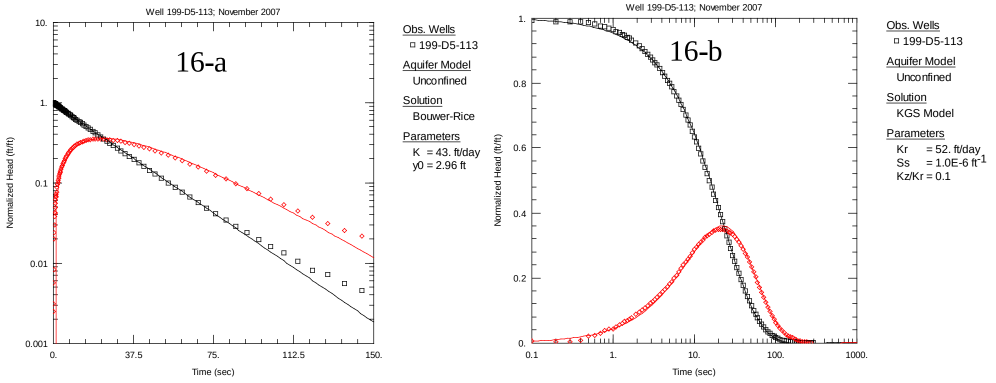

Figure F.16. Responses for Well 199-D5-113 from 11/2007 Tests (derivative shown in red)

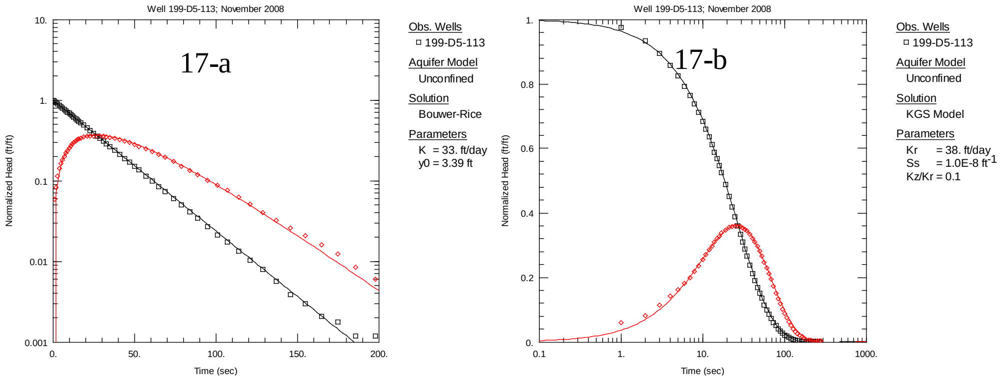

Figure F.17. Responses for Well 199-D5-113 from 11/2008 Tests (derivative shown in red)

Well 199-D5-114

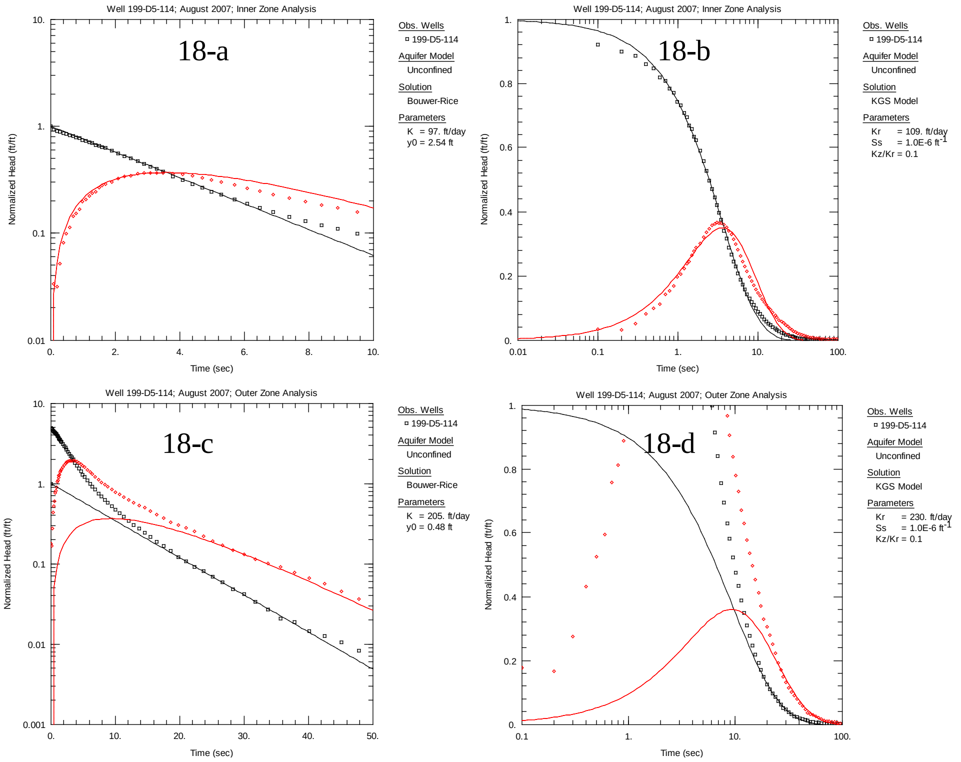

Figure F.18. Responses for Well 199-D5-114 from 11/2007 Tests (derivative shown in red)

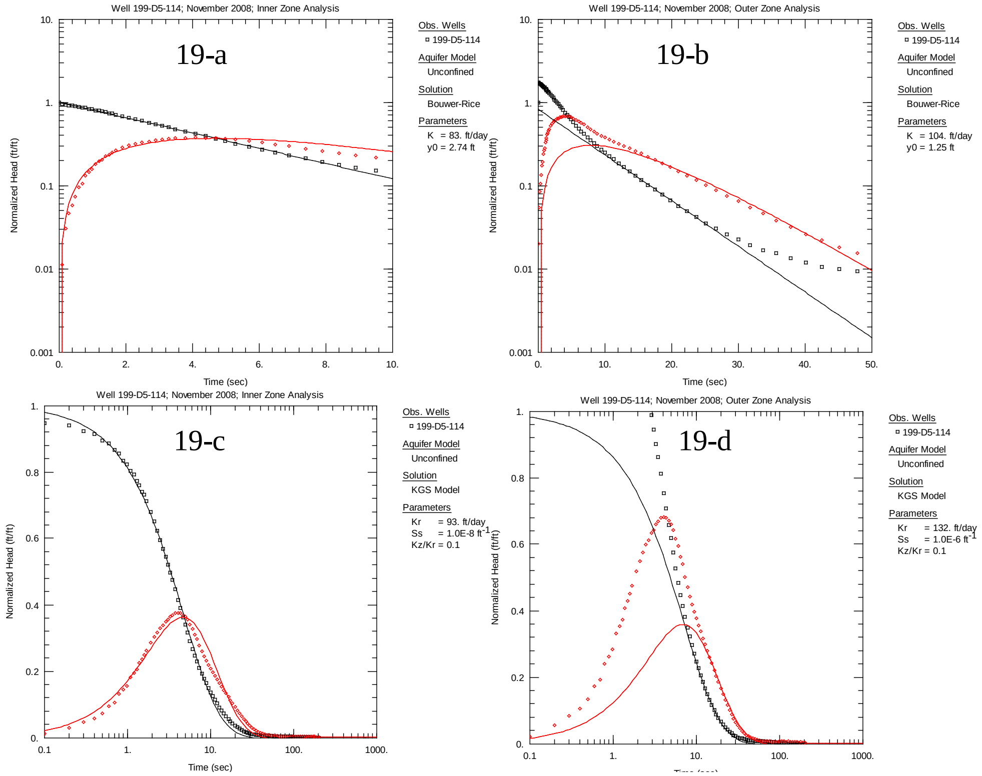

Figure F.19. Responses for Well 199-D5-114 from 11/2008 Tests (derivative shown in red)

Well 199-D5-115

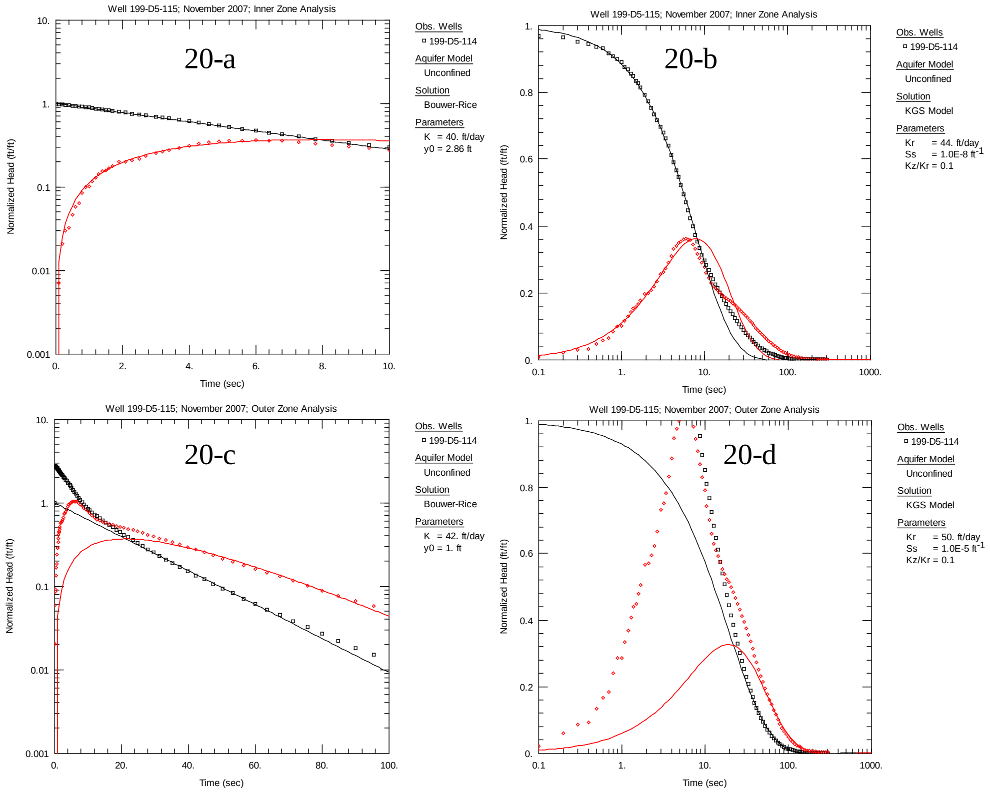

Figure F.20. Responses for Well 199-D5-115 from 11/2007 Tests (derivative shown in red)

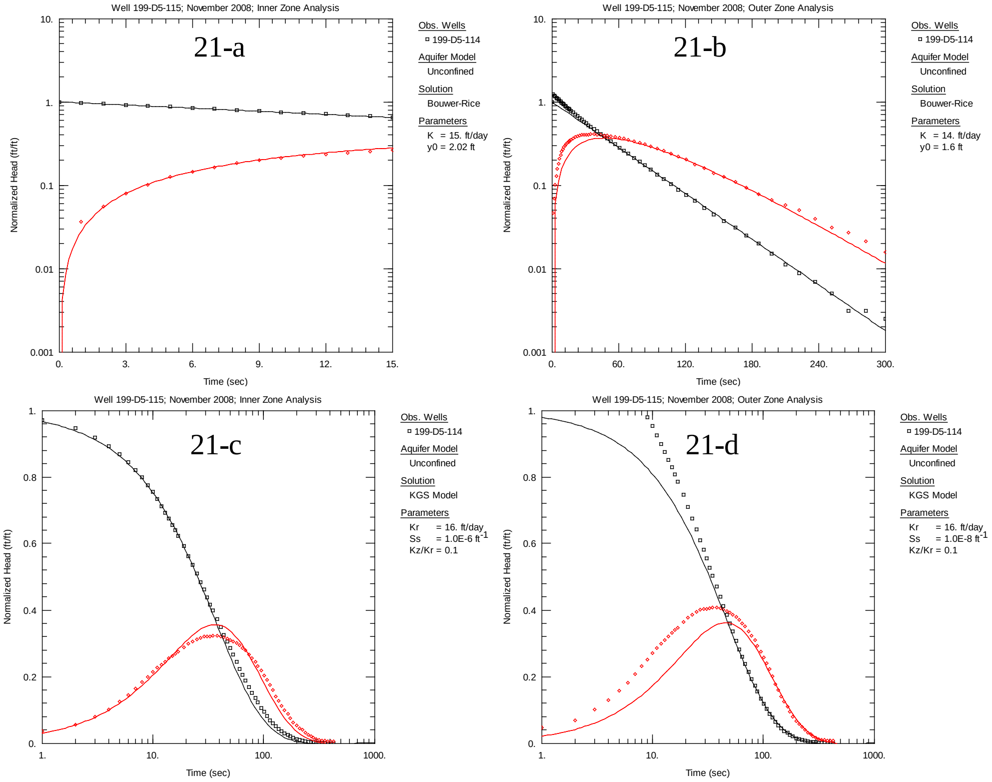

Figure F.21. Responses for Well 199-D5-115 from 11/2008 Tests (derivative shown in red)

Well 199-D5-116

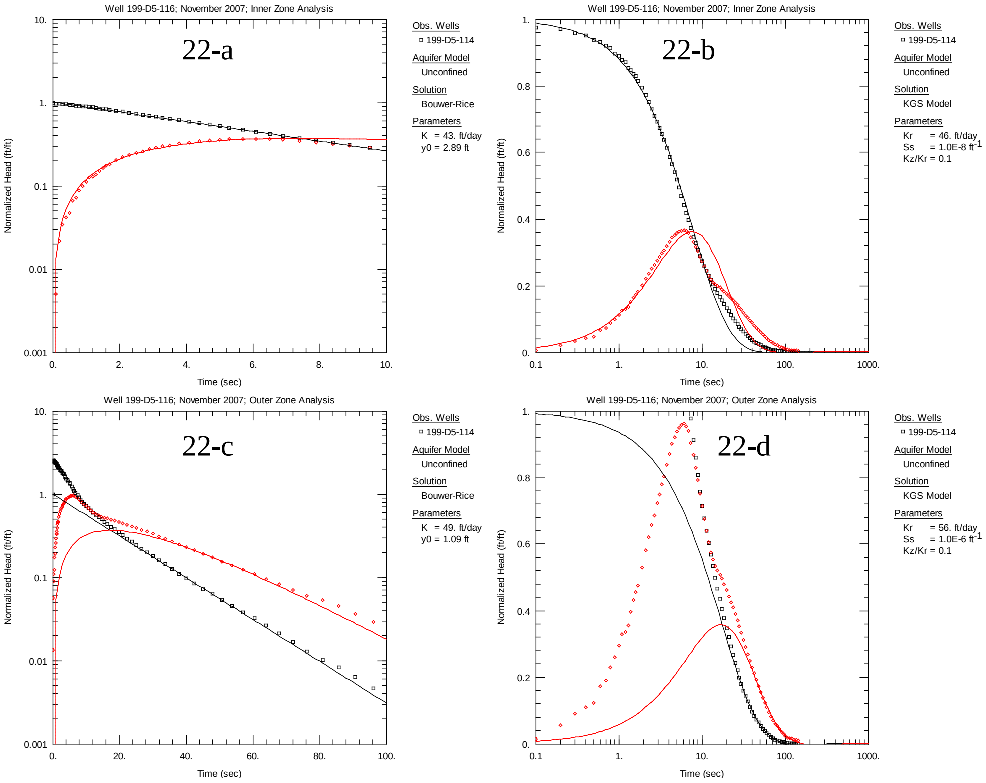

Figure F.22. Responses for Well 199-D5-116 from 11/2007 Tests (derivative shown in red)

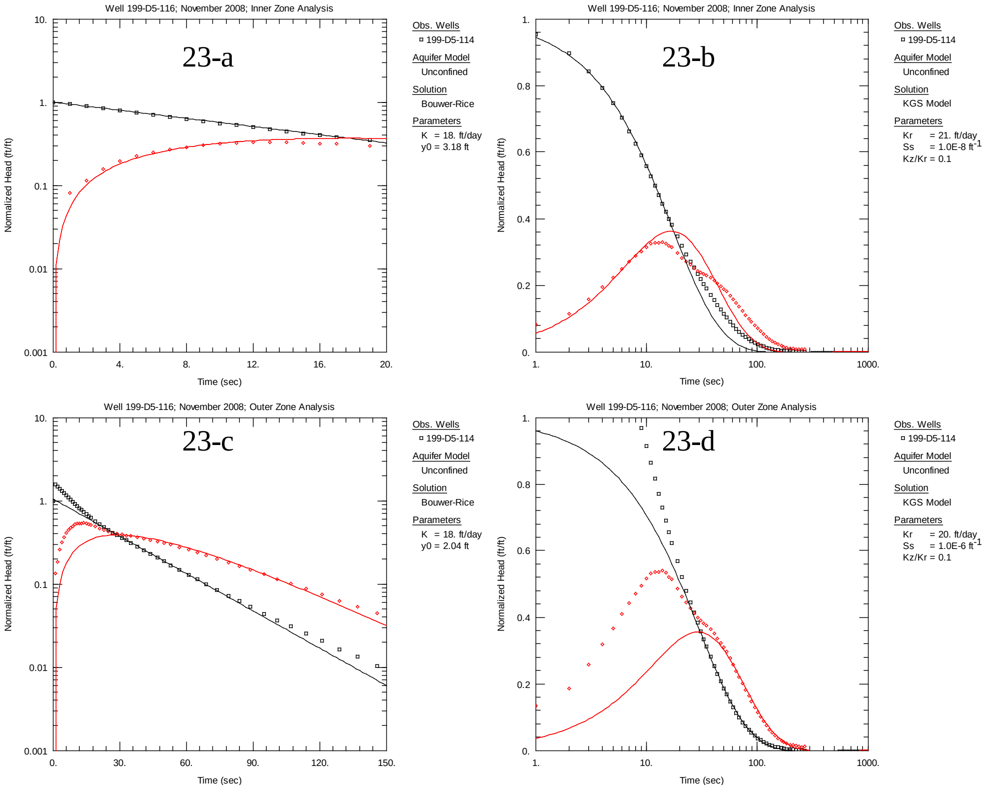

Figure F.23. Responses for Well 199-D5-116 from 11/2008 Tests (derivative shown in red)

Well 199-D5-118

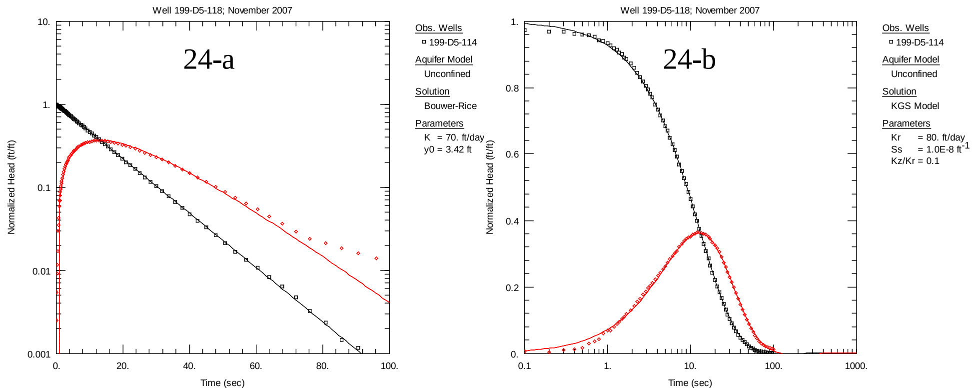

Figure F.24. Responses for Well 199-D5-118 from 11/2007 Tests (derivative shown in red)

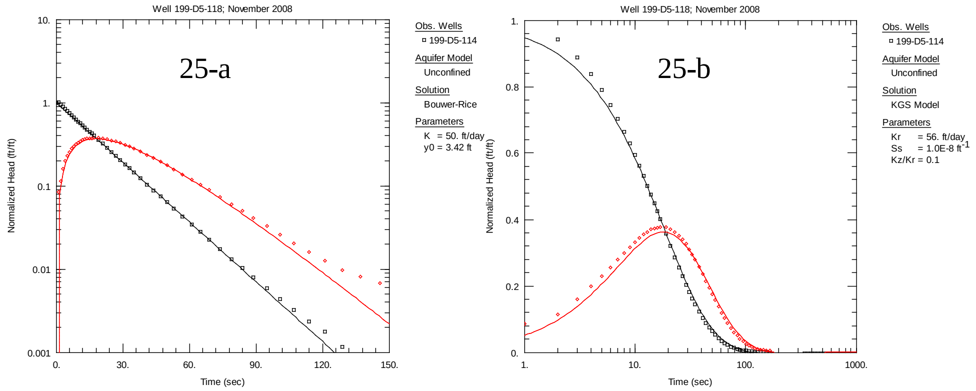

Figure F.25. Responses for Well 199-D5-118 from 11/2008 Tests (derivative shown in red)

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