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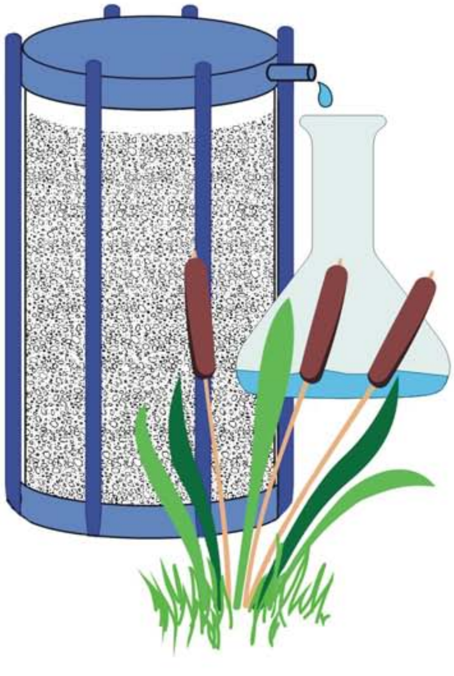
Environmental Sciences Laboratory

Performance of a Permeable Reactive Barrier Using Granular Zero-Valent Iron: FY 2004 Annual Report Durango, Colorado, Disposal Site

September 2004



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Acronym List

DOE	U.S. Department of Energy
LM	Office of Legacy Management
EPA	U.S. Environmental Protection Agency
ESL	Environmental Sciences Laboratory
ft	feet
gal	gallon(s)
gal/min	gallons per minute
in.	inches
MCL	maximum contaminant level
µg/L	micrograms per liter
mg/L	milligrams per liter
ORP	oxidation-reduction potential
PRB	permeable reactive barrier
TIC	total inorganic carbon
UMTRA	Uranium Mill Tailings Remedial Action
yd^3	cubic yards
ZVI	zero-valent iron

Executive Summary

A permeable reactive barrier (PRB) facility was constructed at the Durango, Colorado, Disposal Site in 1995 to test PRB designs for passive remediation of uranium-contaminated ground water. An engineered disposal cell containing uranium mill tailings from an abandoned uranium-ore processing mill is located on the Durango Disposal Site. The PRB facility treats contaminated tailings water issuing from a seep into a collection drain at the downgradient boundary of the Durango Disposal Site. The tailings water is contaminated with uranium and other mill-related constituents. A long-term performance test of a PRB containing granular zero-valent iron (ZVI) has been in progress at this site since July 1999. Previous reports include data from the PRB facility through 2002. This report includes more recent data collected during 2003 and 2004. This study is being conducted by the U.S. Department of Energy (DOE) Office of Legacy Management (LM) at Grand Junction, Colorado.

Effluent water samples from the PRB containing granular ZVI have consistently had higher quality than influent water samples. Concentrations of contaminants in most samples of effluent are below the maximum contaminant levels (MCLs) for the Uranium Mill Tailings Remedial Action (UMTRA) Ground Water Project. Exceptions are molybdenum, which is elevated above the MCL in most samples, and uranium which is occasionally slightly elevated in a few effluent samples. In effluent samples from the most recent sampling (May 2004), concentrations of potential contaminants (e.g., arsenic, cadmium, copper, manganese, molybdenum, selenium, uranium, vanadium, and zinc) are significantly reduced from the influent values.

Gradients of pH and oxidation-reduction potential decreased only slightly in effluent samples since July 1999, indicating that the reactive medium is still chemically active and performing well. A potential problem in using ZVI for water treatment is the generation of high dissolved iron concentrations. Dissolved iron concentrations in the PRB effluent have consistently exceeded 58 milligrams per liter (mg/L) and have been as high as 110 mg/L because of corrosion of ZVI. Dissolved iron concentration in the May 2004 effluent sample was 47.2 mg/L. Carbonate mineral precipitation may be the critical factor limiting the longevity of PRBs. Although calcium concentrations decrease across PRB E,[1] the decrease is not nearly as large as observed at some PRBs at other sites, for example at the Monticello, Utah, PRB. The relatively small chemical gradients for calcium and total inorganic carbon will help extend the effective life of PRB E compared to most other PRBs. Sulfate concentrations also show only modest decreases across PRB E. Treatment costs at present (206,272 gallons [gal]) are about $24 per 1,000 gal. These costs are higher than desired; our goal is to achieve a cost of $10 per 1,000 gal, which will require a treatment volume of about 500,000 gal without changeout of the ZVI.

Tailings water is piped to the Durango PRB facility, thus the flow through the PRB can be accurately controlled and measured in contrast to the inherent uncertainty of flux through PRBs that are placed in subsurface trenches. This controlled situation is ideal in supporting tests of new technologies aimed at increasing the efficiency of PRBs. In 2003, the U.S. Environmental Protection Agency (EPA) funded the Grand Junction DOE Environmental Sciences Laboratory to research chemical and physical methods of removing carbonate minerals from PRBs to improve efficiency. Several chemicals were successful in removing carbonate minerals in the laboratory phase of that study. The Durango PRB facility could be used for a field test of these methods.

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[1] For discussion purposes the PRBs are labeled alphabetically. The material in PRB C was replaced in 1999, and PRB C was renamed PRB E.

Water levels in the collection drain are monitored with data-collecting pressure transducers. Water levels increased rapidly after winter shutdown of the PRB facility from 1996 through 1999. The rate of increase in water levels following winter shutdowns appears to be decreasing. Because of the limited amount of contaminated water, operation of the PRB facility was discontinued in June 2004. If water levels increase sufficiently in 2005 or 2006, PRB E may be operated again to continue to test the longevity of the ZVI.

1.0 Introduction

Uranium (U) and associated constituents have contaminated ground water at many uranium milling sites and nuclear weapons facilities worldwide. Concentrations of these contaminants are elevated to values that may be harmful to human health and the environment.

Pump-and-treat systems, currently the most widely used ground water remediation method, are costly and have not been effective at many sites (National Academy of Sciences 1994). At the time the Durango, Colorado, project was initiated in 1995, permeable reactive barrier (PRB) technology had been developed for passive remediation of ground water contaminated by chlorinated solvents (Gillham et al. 1994), but no PRBs had been installed to treat U and related contaminants. Most PRB installations had been placed below the ground surface without easy access for replacing the reactive material. In 1995, PRBs were installed at the Durango Disposal Site near Durango with a unique design that allowed easy change out of the reactive material. The PRBs were designed and constructed by personnel from Sandia National Laboratories in October 1995 with funding from the U.S. Department of Energy (DOE) Uranium Mill Tailings Remedial Action (UMTRA) Ground Water Project. The Durango PRB project is now administered by DOE Office of Legacy Management (DOE−LM) and is managed by the DOE−LM office at Grand Junction, Colorado.

Laboratory research has shown that when water contaminated with redox-sensitive contaminants such as U and chromium (Cr) contacts zero-valent iron (ZVI), dissolved contaminant concentrations decrease (Cantrell et al. 1995; Dwyer and Marozas 1997; Blowes et al. 1997; Morrison et al. 2002a). The chemical mechanisms that are responsible for the uptake of U are currently being debated in the scientific community (Fiedor et al. 1998; Gu et al. 1998; Matheson and Goldberg 1999; Morrison et al. 2001). Suggested mechanisms include (1) precipitation of reduced minerals such as uraninite (UO_2) and (2) formation of ferric oxyhydroxide [$Fe(OH)_3$] from oxidation of ZVI followed by adsorption of U on the newly formed $Fe(OH)_3$.

The Durango site provided an opportunity to test PRB designs for passive remediation of U-contaminated tailings water. During construction of a uranium mill tailings repository in 1991, a contaminated seep developed that required treatment. The seep water was collected in a gravel drain and piped to a lined retention pond where it was treated with lime and discharged to a drainage system (Figure 1). Four PRBs were later constructed to treat the contaminated water before it entered the retention pond; the material in PRB C was replaced in 1999 and PRB C was renamed PRB E. Inflow and outflow water chemistries have been monitored since 1996. Reactive material in one PRB was changed out when flow ceased after 3 years of operation. This PRB was unearthed and the solids were extensively sampled and analyzed (Morrison et al. 2002b).

The information obtained during previous investigations was used to evaluate the efficiency of PRBs for reducing aqueous concentrations of contaminants, estimating relative uptake rates, and determining the chemistry and mineralogy of material deposited in the PRBs. A long-term performance test of one of the four PRBs (PRB E)[1] is currently being conducted. DOE presented details of the operation of PRB E since its installation in July 1999 through 2002 (DOE 2002). The current report is an update of DOE (2002) and includes data from 2003 and 2004. Sample collection and analyses for this study were conducted by the DOE Environmental Sciences

Laboratory (ESL) at Grand Junction, Colorado. ESL field and laboratory notes are presented in Appendix A.

2.0 Background of Durango PRB Facility

This section describes the PRB facility at the Durango Disposal Site and includes a synopsis of previous results. Additional details on previous efforts are available in several reports and published papers (Dwyer and Marozas 1997; DOE 1998a, 1999, 2000, 2002; Morrison et al. 2002a, 2002b).

A total of 2.5 million cubic yards (yd^3) of uranium mill tailings were relocated to the Durango Disposal Cell located in Bodo Canyon in fall 1990. Contaminated seeps developed along the downgradient slope of the disposal cell shortly after construction. The seep water was collected by a collection drain and piped by gravity flow to a retention pond, where it was regularly treated and then discharged to a nearby wash (Figure 1).

From 1995 to April 23, 2001, contaminated tailings water in the collection drain was diverted to a holding tank (Figure 1). Water from the holding tank flowed to a manifold that distributed the water to the PRB facility. A valve was installed between the collection drain and the holding tank adjacent to a sampling port and flow meter. A large wooden box protected the valve, flow meter, and sampling port. In September 1999, the wooden valve box was replaced with a shed. On April 23, 2001, the system was replumbed to pipe water directly from the collection drain to the PRB, bypassing the holding tank. Since the replumbing, water levels measured in the inlet riser provide data on the head gradient driving water through the PRB. On that same date, a sampling port was added at the bottom of quadrant 2 of PRB E (see below).

Four PRBs (PRBs A, B, C, and D)[1] were installed in October 1995 (Table 1). Construction details are presented in Dwyer and Marozas (1997). The PRBs had two purposes: (1) to help treat the seep water to meet discharge standards and (2) to test the efficiency of PRBs for remediation of U and metals. ZVI was used as the reactive media in all four PRBs. Two types of ZVI were used initially, steel wool and ZVI foam plates. ZVI foam plates were manufactured by Cercona of America (Dayton, Ohio) by binding fine-grained ZVI with aluminosilicate. Two of the PRBs were constructed similar to septic leach fields; one contained only steel wool (PRB A) and one contained steel wool and copper wool (PRB B). The other two PRBs were constructed in steel tanks with baffles that forced the water to flow up and down through the PRB (see Figure 2 for cross section of PRB E). One of the baffled tanks contained ZVI foam plates (PRB C) and the other contained steel wool (PRB D). The baffled tanks are 72 inches (in.) long, 36 in. wide, and 50 in. deep. In July 1999, the ZVI foamed plates in PRB C were replaced with granular ZVI (Peerless Metals Products, mesh size –8 +20), and it was renamed PRB E. PRB E is approximately 90 percent full of ZVI and has about 6 to 10 in. of void space at the top (Figure 2). The cover is bolted down, and a gasket compound is used to seal the cover to the tops of two of the baffles.

Because of the low flow conditions (usually less than 0.7 gallon per minute [gal/min]), only one PRB was operated at any given time; PRB A has never been operated. PRB C operated intermittently from May 1996 through May 1999 and treated 129,000 gallons (gal) (Figure 3). PRB B treated 118,000 gal, and PRB D treated 30,000 gal. Through June 2004, PRB E has treated 206,272 gal of contaminated tailings water. Because access is difficult in the winter, the system is shut down from about November through April. The amount of contaminated water available to operate the PRBs has been decreasing. The water ceased flowing in 2003 before a sample could be collected. In 2004, only one sampling round was conducted before the flow ceased. The PRB system will not be operated in 2005, and water will be allowed to accumulate in the collection drain. The rate of water level increases during the next 1 to 3 years will provide information needed to determine if the water will reach an unacceptable level that will require corrective action. If the water level rises sufficiently, the PRBs may be operated again.

3.0 Methods

Flow rates were adjusted with the valve located in the shed, and were measured with an in-line flow meter. A peristaltic pump was used to collect samples from the inlet riser, the bottom of PRB quadrant 2, and the outflow riser of PRB E. Samples collected from quadrant 2 are labeled “Q2”. At least a gallon was purged prior to collecting samples. Sampling and preservation methods are described in DOE (1998b). Samples were analyzed by Paragon Laboratories, Ft. Collins, Colorado. Analytical laboratory methods and ESL field methods are listed in Table 2.

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4.0 Results and Discussion

PRB E, containing granular ZVI, has operated seasonally since July 1999 and has treated 206,272 gal of tailings water as of June 10, 2004 (Table 3). The flux of contaminated feed water is highest (usually 1 to 2 gal/min) just after spring startup but decreases as water levels in the collection drain decrease. Flow usually stops because of water shortage before November (Table 3).

Hydraulic Conductivity. Hydraulic conductivity is expected to decrease in PRBs because of precipitation of carbonate and oxide minerals (Morrison et al. 2001, 2002a). The water level in the inlet riser can be used to indicate the driving force required to cause flow through the reactive media. On the basis of water elevation measurements in the inlet riser, there appears to be a slight trend toward lower hydraulic conductivity values within the PRB. The head required to produce 0.2 gal/min was 1.71 feet (ft) on November 5, 2001, but increased to 2.02 ft by May 21, 2002 (Table 3). On May 13, 2004, 2.81 ft of head was required for flow at 0.35 gal/min. The measurements at this low flux are somewhat imprecise, and additional data are needed to confirm this apparent trend.

Ground Water Chemistry. Uranium concentrations in the influent water vary from 5,250 to 8,740 micrograms per liter (µg/L) (Figure 4). Most of the U is removed from solution as the water passes from the inlet pipe to the sampling port at the bottom of quadrant 2 and remains low in samples collected from the effluent. For the samplings collected in July 2001, May 2002, and May 2004, the U concentration was higher in the effluent water samples than in the water samples collected at the bottom of quadrant 2. This anomalous situation may be caused by some water flowing between the cover and the flow baffles (Figure 2).

Water in the effluent from PRB E is of much higher quality than the influent. Concentrations of contaminants in most samples of effluent are below the UMTRA maximum contaminant levels (MCLs) (Table 4). Exceptions are molybdenum (Mo) concentrations that are elevated above the MCL in most samples and U concentrations that are elevated in a few effluent samples. In effluent samples from the most recent sampling (May 2004), concentrations of potential contaminants of concern (e.g., arsenic, cadmium, copper, manganese, molybdenum, selenium, uranium, vanadium, and zinc) are significantly reduced (Table 4). Consistent with other published studies, effluent concentrations of Mo and manganese (Mn) are higher relative to influent values, suggesting solubility control by ferrous or carbonate mineral precipitation, respectively (Morrison et al. 2002a).

The corrosion of ZVI causes an increase in pH values and a decrease in oxidation state. These parameters can be used to help evaluate the performance of PRB E. The increase in pH values from influent to effluent of 6.7 to 7.42 in the May 2004 samples is similar to the increase from 6.51 to 7.28 in the initial sampling. Similarly, the oxidation-reduction potential (ORP) decrease (from +233.8 mV influent to –170.2 mV effluent) in May 2004 is reasonably consistent with the initial sampling (+168 mV influent to –234 mV effluent). The relatively small decreases in pH values and ORP gradients over time suggest that the ZVI system is still chemically active and performing well.

Dissolution of ZVI can lead to high concentrations of dissolved Fe in effluent from PRBs. Effluent-dissolved iron (Fe) concentrations from PRB E have consistently exceeded 40 milligrams per liter (mg/L) and have been as high as 110 mg/L. The effluent Fe concentration in May 2004 was 47.2 mg/L (Table 4). The effluent is discharged to a settling pond where the high Fe concentrations cause reddish-orange coloration of the water before settling out. At other PRB sites, discharge of the Fe-bearing water may be problematic because it can cause environmental harm or aesthetic issues.

Calcium carbonate minerals commonly precipitate in ZVI-based PRBs because of the increase in pH values during corrosion. Carbonate mineral precipitation may be the critical factor limiting the longevity of PRBs. Although calcium (Ca) concentrations decrease as the tailings water traverses across PRB E, the decrease is not as large as observed at some PRBs, such as the Monticello, Utah, PRB (Morrison et al. 2001). Total inorganic carbon (TIC) also displays a modest decrease from influent to effluent (Table 4). In addition to forming calcium carbonate, some of the TIC could be combining with Fe to form iron carbonate minerals. The relatively small chemical gradients for Ca and TIC will help extend the effective life of the PRB. Sulfate concentrations also show a modest decrease across PRB E (e.g., from 1,710 to 1,630 mg/L in May 2004), which could be due to sulfate reduction or incorporation of sulfate in newly formed minerals.

Treatment Costs. The approximate cost of installing a water treatment system like PRB E is $5,000 (Table 5). Treatment costs are calculated from installation cost and the volume of water treated (costs of sampling and final disposal are not included). Treatment costs after treatment of 206,272 gal are about $24 per 1,000 gal. Our goal is to achieve $10 per 1,000 gal, which will require a treatment volume of about 500,000 gal (Table 5). If the supply of contaminated tailings water from the collection drain is sufficient, PRB E will be restarted to determine if this goal can be achieved.

Water Levels in the Collection Drain. A data-recording transducer has been used since 1996 to track the water level in the collection drain. This transducer was installed directly in the collection drain at location NVP just upgradient from the holding pond (Figure 5). Two additional transducers were installed later in the tailings upgradient of the collection drain to record the water level changes in the tailings that are due to dewatering by the drain (locations MW-1 and P7, Figure 5). Water levels in the collection drain since 1996 (see Figure 1 for schematic of the collection drain) and in the tailings have been declining (Figure 6). Water levels increased rapidly after winter shutdown of the PRB system in years 1996 through 1999. The rate of increase after winter shutdown (as indicated by shallower slopes on Figure 6) appears to have been declining since 1999. Modeling conducted by Jacobs (1996) indicates that water levels can increase to 7,055 ft elevation before causing any detrimental release to ground water.

5.0 Conclusions and Outlook for Durango PRB Facility

PRB E continues to perform well at treating contaminated tailings water to a reasonable water quality; concentrations, in most cases, are less than MCLs. Data also indicate only minor mineral precipitation, and the expectations for an extended life span of the ZVI are good. If sufficient contaminated water is available, operation of PRB E will continue in the future with a goal of assessing long-term treatment efficiency. EPA is funding DOE to research chemical and physical methods of removing carbonate minerals from PRBs. If successful in the laboratory phase, the Durango PRB facility could be used to field test promising methods.

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6.0 References

Blowes, D.W., C.J. Ptacek, and J.L. Jambor, 1997. "In-Situ Remediation of Cr(VI)-Contaminated Groundwater Using Permeable Reactive Walls: Laboratory Studies," *Environ. Sci. Technol.*, **31**, pp. 3348-3357.

Cantrell, K.J., D.I. Kaplan, and T.W. Wietsma, 1995. "Zero-Valent Iron for the In Situ Remediation of Selected Metals in Groundwater," *J. Hazardous Materials*, **42**, pp. 201-212.

Dwyer, B.P., and D.C. Marozas, 1997. "In Situ Remediation of Uranium Contaminated Groundwater," in *Conference Proceedings of the International Containment Technology Conference*, February 9-12, 1997, St. Petersburg, Florida, cosponsored by U.S. Department of Energy, DuPont Company, and U.S. Environmental Protection Agency, pp. 844 –850.

Fiedor, J.N., W.D. Bostick, R.J. Jarabek, and J. Farrell, 1998. "Understanding the Mechanism Of Uranium Removal From Groundwater by Zero-Valent Iron Using X-Ray Photoelectron Spectroscopy," *Environ. Sci. Technol.*, **32**, pp. 1466-1473.

Gu, B., L. Liang, M.J. Dickey, X. Yin, and S. Dai, 1998. "Reductive Precipitation of Uranium (VI) by Zero-Valent Iron," *Environ. Sci. Technol.*, **32**, 3366-3373.

Gillham, R.W., D.W. Blowes, C.J. Ptacek, and S.F. O'Hannesin, 1994. "Use of Zero-Balent Metals in In-Situ Remediation of Contaminated Ground Water," in *In-Situ Remediation: Scientific Basis for Current and Future Technologies*, Eds. Gee, G.W. and N.R. Wing, 913-930, Battelle Press, Columbus, Ohio.

Jacobs, 1996. *Long-Term Surveillance Plan for the Bodo Canyon Disposal Site, Durango, Colorado*, Report No. DOE/AL/62350-77 Rev. 2, U.S. Department of Energy, Albuquerque, New Mexico.

Matheson, L.J., and W.C. Goldberg, 1999. "Spectroscopic Studies to Determine Uranium Speciation in ZVI Permeable Reactive Barrier Materials From the Oak Ridge Reservation, Y-12 Plant Site and Durango, CO PeRT wall C," in *Supplement to EOS, Transactions 1999 Fall Meeting*, p. F366, American Geophysical Union, Washington, DC.

Morrison, S.J., D.R. Metzler, and C.E. Carpenter, 2001. "Uranium Precipitation in a Permeable Reactive Barrier by Progressive Irreversible Dissolution of Zero-Valent Iron," *Environ. Sci. Technol.*, **35**, pp.385-390.

Morrison, S.J., D.R. Metzler, and B.P. Dwyer, 2002a. "Removal of As, Mn, Mo, Se, U, V, and Zn from Groundwater by Zero-Valent Iron in a Passive Treatment Cell: Reaction Progress Modeling," *J. Contam. Hydrol.*, v. 56, pp. 99-116.

———, 2002b. "Collection Drain and Permeable Reactive Barrier for Treating Uranium and Metals from Mill Tailings near Durango, Colorado," in *Handbook of Groundwater Remediation Using Permeable Reactive Barriers Applications to Radionuclides, Trace Metals, and Nutrients*, D.L. Naftz, S.J. Morrison, C.C. Fuller, and J.A. Davis, eds., Academic Press.

National Academy of Sciences, 1994. *Alternatives for Ground Water Cleanup*, Report of the National Academy of Science Committee on Ground Water Cleanup Alternatives, Washington, DC, National Academy Press.

STO 210. *Environmental Sciences Laboratory Procedures Manual*, S.M. Stoller Corporation, under contract to U.S. Department of Energy, Grand Junction, Colorado, continuously updated.

U.S. Department of Energy (DOE), 1998a. *Activities Report for FY 1998 Durango, Colorado, UMTRA Project Permeable Reactive Treatment (PeRT) Wall Facility*, GJO-98-63-TAR, prepared by MACTEC-ERS for the U.S. Department of Energy Grand Junction Office, Grand Junction, Colorado.

———, 1998b. *Sampling and Analysis Plan for the UMTRA Ground Water Project*, MAC-GWADM 19.1-1 Rev. 3, prepared by MACTEC-ERS for the U.S. Department of Energy Grand Junction Office, Grand Junction, Colorado.

———, 1999. *Analysis of Solids from a Permeable Reactive Barrier, Durango, Colorado, Bodo Canyon Site*, Report Number ESL-RPT-99-08, prepared by MACTEC-ERS for the U.S. Department of Energy Grand Junction Office, Grand Junction, Colorado.

———, 2000. *Kinetic Tests of Permeable Reactive Barriers*, Report Number ESL-RPT-2000-01, prepared by MACTEC-ERS for the U. S. Department of Energy Grand Junction Office, Grand Junction, Colorado.

———, 2002. *Performance of a Permeable Reactive Barrier Using Granular Zero-Valent Iron, Durango, Colorado, Disposal Site*, Report Number ESL-RPT-2002-06, prepared by S.M. Stoller for the U.S. Department of Energy Grand Junction Office, Grand Junction, Colorado.

Table 1. Features of PRBs at Durango PRB Facility

Identifier	Design Type	ZVI Type
PRB A	Leach Field	Steel Wool
PRB B	Leach Field	Steel Wool and Copper Wool
PRB C	Baffled Tank	Cast ZVI Foam Plates
PRB D	Baffled Tank	Steel Wool
PRB E	Baffled Tank	Granular ZVI

Table 2. Analytical Methods

Analyte	Procedure	Description[a]
Alkalinity	AP (Alk–1)[b]	Titration
As	SW846 6020	ICP-MS
Ba	SW846 6010B	ICP-AES
Ca	SW846 6010B	ICP-AES
Cd	SW846 6020	ICP-MS
Cl	MCAWW 300.0A	Ion Chromatography
Conductivity	AP (EC–1)[b]	Electrical Resistivity
Cr	SW846 6010B	ICP-AES
Cu	SW846 6010B	ICP-AES
DO Probe	AP (DO–1)[b]	Membrane Diffusion
Fe	SW846 6010B	ICP-AES
K	SW846 6010B	ICP-AES
Mg	SW846 6010B	ICP-AES
Mn	SW846 6010B	ICP-AES
Mo	SW846 6010B	ICP-AES
Na	SW846 6010B	ICP-AES
NH_3	MCAWW 350.1	Spectrophotometry
NO_3	MCAWW 353.1	Ion Chromatography
pH	AP (pH–1)[b]	Potentiometric
Se	SW846 6020	ICP-MS
Si	SW846 6010B	ICP-AES
SO_4	MCAWW 300.0A	Ion Chromatography
Sr	SW846 6010B	ICP-AES
TDS	MCAWW 160.1	Evaporation
TIC	SW846 9060	CO_2 Emission
TOC	SW846 9060	Ampule Oxidation
U	SW846 6020	ICP-MS
V	SW846 6010B	ICP-AES
Zn	SW846 6010B	ICP-AES

[a] AA = atomic absorption; DO = dissolved oxygen; ICP-AES = Inductively Coupled Plasma - Atomic Emission Spectroscopy; ICP-MS = Inductively Coupled Plasma - Mass Spectrometry

[b] ESL procedure (STO 210), all other procedures are from Paragon Laboratories.

Table 3. Contaminated Tailings Water Flow Data for PRB E

Date	Cumulative Volume Treated (gal)	Flux (gal/min)	Head at Inlet[a] (ft)
7/26/1999	0		
7/29/1999	1,117	0.95	
8/13/1999	3,402	<0.01	
11/4/1999	5,144		
4/12/2000	6,058	1.75	
4/18/2000	17,933	1.12	
4/19/2000	18,629	0.57	
4/25/2000	28,941	0.30	
4/26/2000	29,191	0.47	
5/24/2000	42,193	0.28	
6/14/2000	48,932	0.19	
6/27/2000	50,821	0.00	
6/29/2000	50,927	0.10	
4/23/2001	51,215	2.00	
4/30/2001	65,454	1.25	
5/1/2001	66,815	1.50	
5/29/2001	86,038	0.40	
7/26/2001	102,929	0.16	
8/29/2001	113,164	0.25	
9/8/2001	115,989	0.23	1.63
9/20/2001	118,125	0.20	
11/5/2001	129,780	0.20	1.71
4/9/2002	129,780	0.96	2.49
4/24/2002	143,170	0.60	
5/21/2002	157,400	0.20	2.02
6/5/2002	158,605		
7/31/2002	158,862	<0.01	1.50
6/3/2003	159,660	0.72	3.02
6/24/2003	169,214	<0.01	
4/27/2004	191,956	0.40	
5/13/2004	196,325	0.35	2.81
6/10/2004	206,272	<0.01	

[a] Elevation that water in inlet pipe rises above the outlet pipe.

Table 4. 2004 PRB E Sampling Results

	May 13, 2004			CDPHE Discharge Limit[a]	UMTRA MCL
	Flow Rate = 0.35 gal/min				
	Influent	Quadrant 2	Effluent		
Alkalinity (mg/L $CaCO_3$)	619	623	629		
Ammonia as N (µg/L)	297	<50	<50		
Arsenic (µg/L)	178	3.2	<1.9	500	50
Barium (µg/L)	28.3	13.7	14.2		1,000
Cadmium (µg/L)	16.3	1.3	1.6		10
Calcium (mg/L)	567	496	526		
Chloride (mg/L)	140	134	135		
Chromium (µg/L)	<2.1	<2.1	<2.1		50
Copper (µg/L)	<1.7	<1.7	<1.7		
Conductivity (µS/cm)	3,871	3,757	3,822		
DO (mg/L)	2.62	0.69	1.50		
ORP (mV)	233.8	-138.8	-170.2		
pH	6.7	7.51	7.42		
Temperature (deg C)	11.26	11.21	11.80		
Iron (mg/L)	0.0829	37.5	47.2		
Magnesium (mg/L)	80.3	82.2	82.0		
Manganese (mg/L)	11.00	5.20	6.31		
Molybdenum (µg/L)	950	525	651		100
Nitrate as N (mg/L)	<0.05	<0.05	<0.05		44
Potassium (mg/L)	20.5	19.2	20.6		
Selenium (µg/L)	359	7.6	8.2		10
Silicon (mg/L)	23.5	16.6	18.0		
Sodium (mg/L)	325	324	326		
Strontium (mg/L)	3.11	3.00	3.09		
Sulfate (mg/L)	1,710	1,650	1,630		
TDS (mg/L)	3,450	8,190[b]	3,210		
TIC (mg/L)	162	139	140		
TOC (mg/L)	9.6	9.2	8.9		
Uranium (µg/L)	8,740	72.2	104	2,000	44
Vanadium (µg/L)	7,750	116	98.6		
Zinc (µg/L)	1,470	3.7	4.1	500	

[a] Colorado Department of Public Health and Environment (CDPHE) standards for discharging treated water to the creek at Bodo Canyon.

[b] Suspected analytical error.

Table 5. Estimated Costs of Installing a Baffled-Tank PRB and Treatment Costs (volume of PRB is 75 ft^3; cost of ZVI delivered to the site is about \$33/ft^3; cost of ZVI = \$2,491)

Component	Cost
ZVI	$2,491
PRB Box	$1,000
Excavation	$ 800
Misc Hardware etc.	$ 709
TOTAL	**$5,000**

Volume Treated (gal)	$/1000 gal
50,000	$100
100,000	$ 50
150,000	$ 33
200,000	$ 25
250,000	$ 20
300,000	$ 17
400,000	$ 13
500,000	$ 10

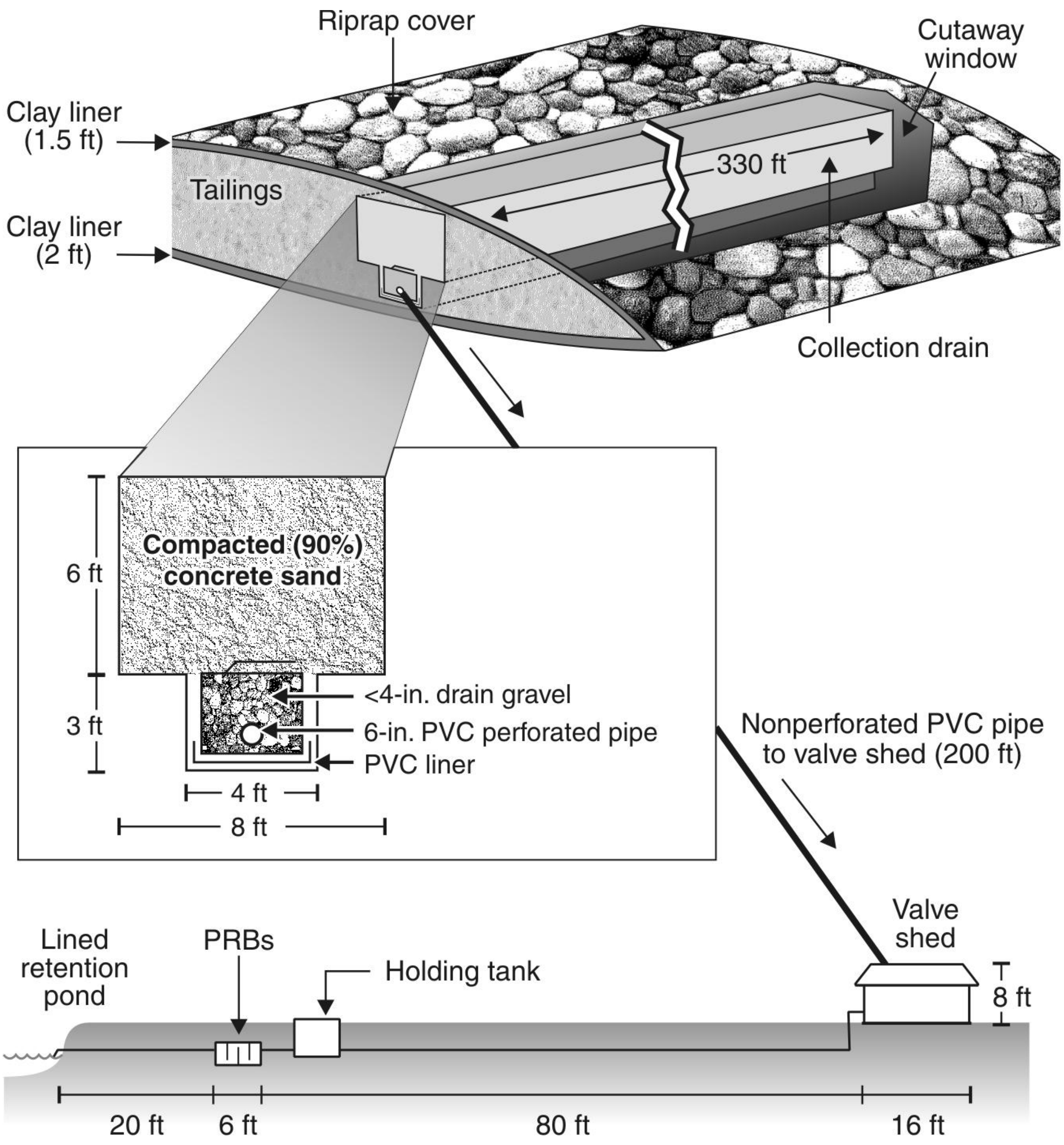


Figure 1. Schematic Showing the Flow of Contaminated Tailings Water From Collection Drain Piping to PRBs

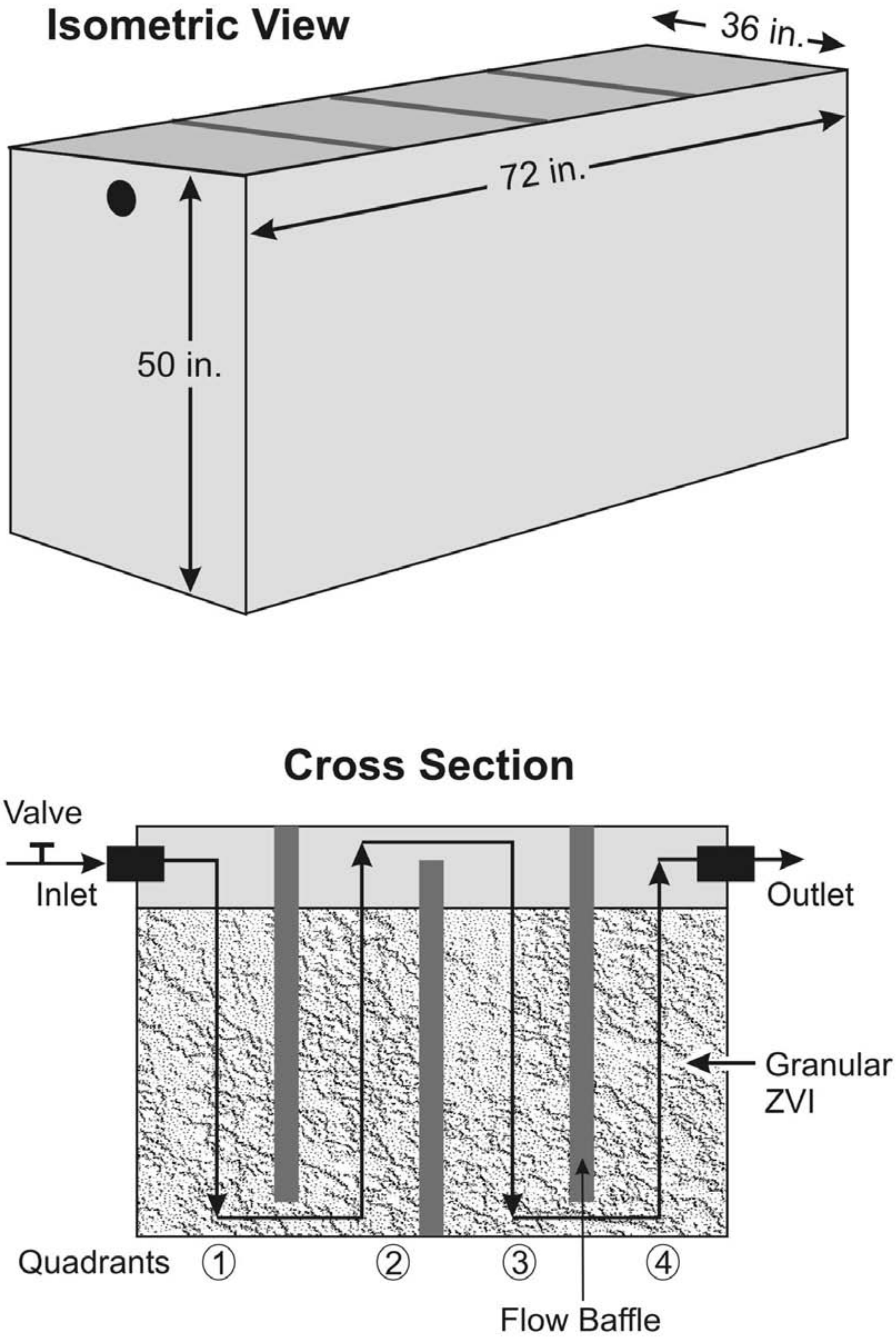


Figure 2. Steel Box With Partitions and Granular ZVI Used for PRB E
The same steel box was used for PRBs C and D.

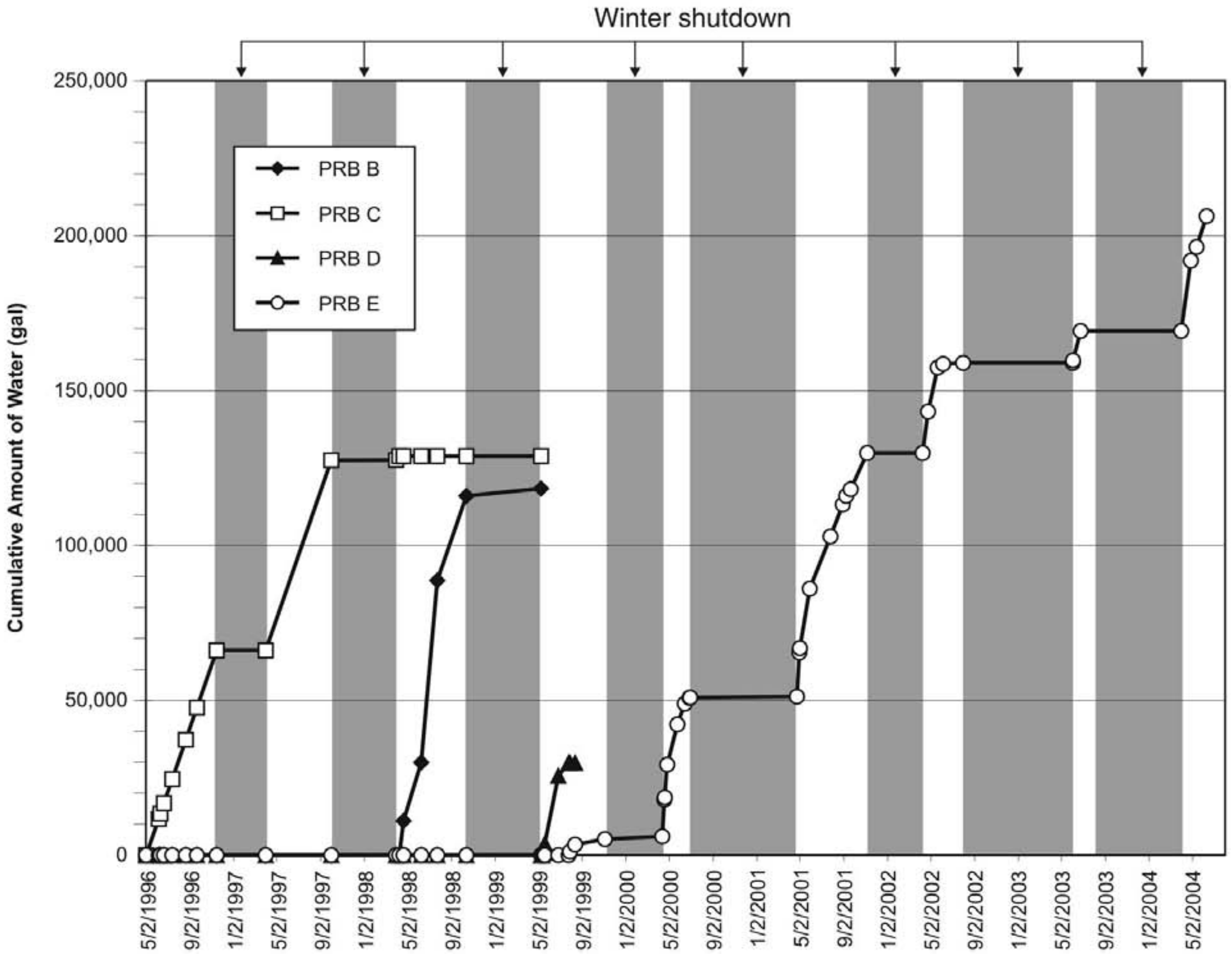


Figure 3. History of Operation of PRBs

(PRB A was never operated; Shaded areas are winter shutdowns)

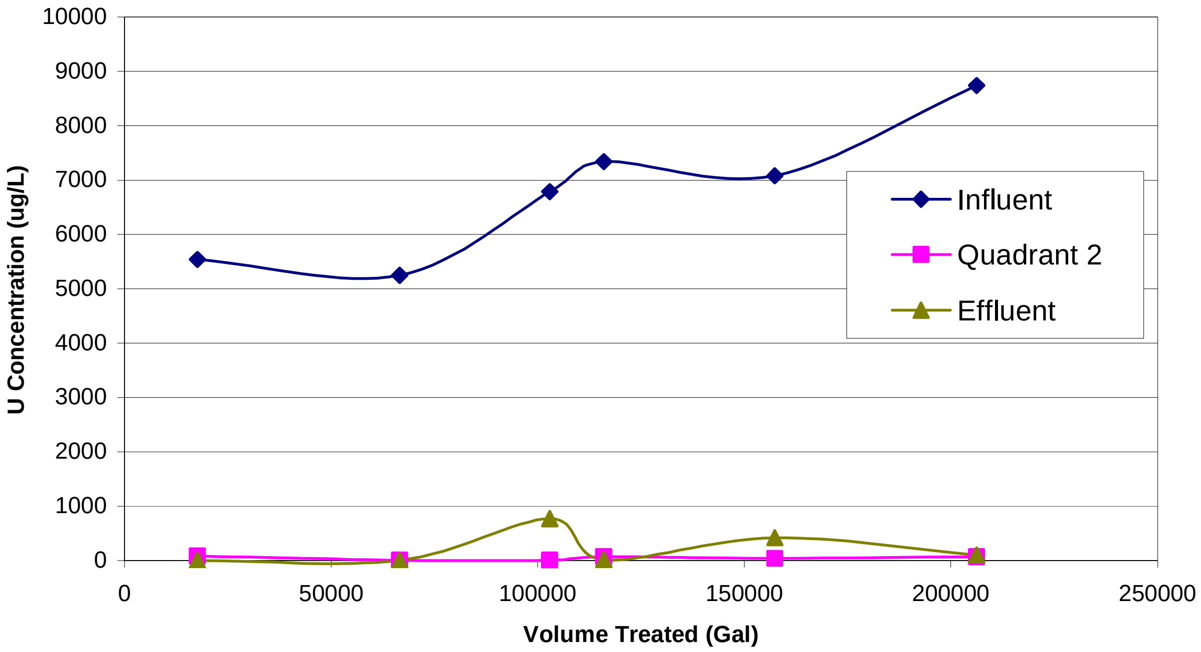


Figure 4. Uranium Concentrations in Samples of Influent, Quadrant 2, and Effluent for PRB E

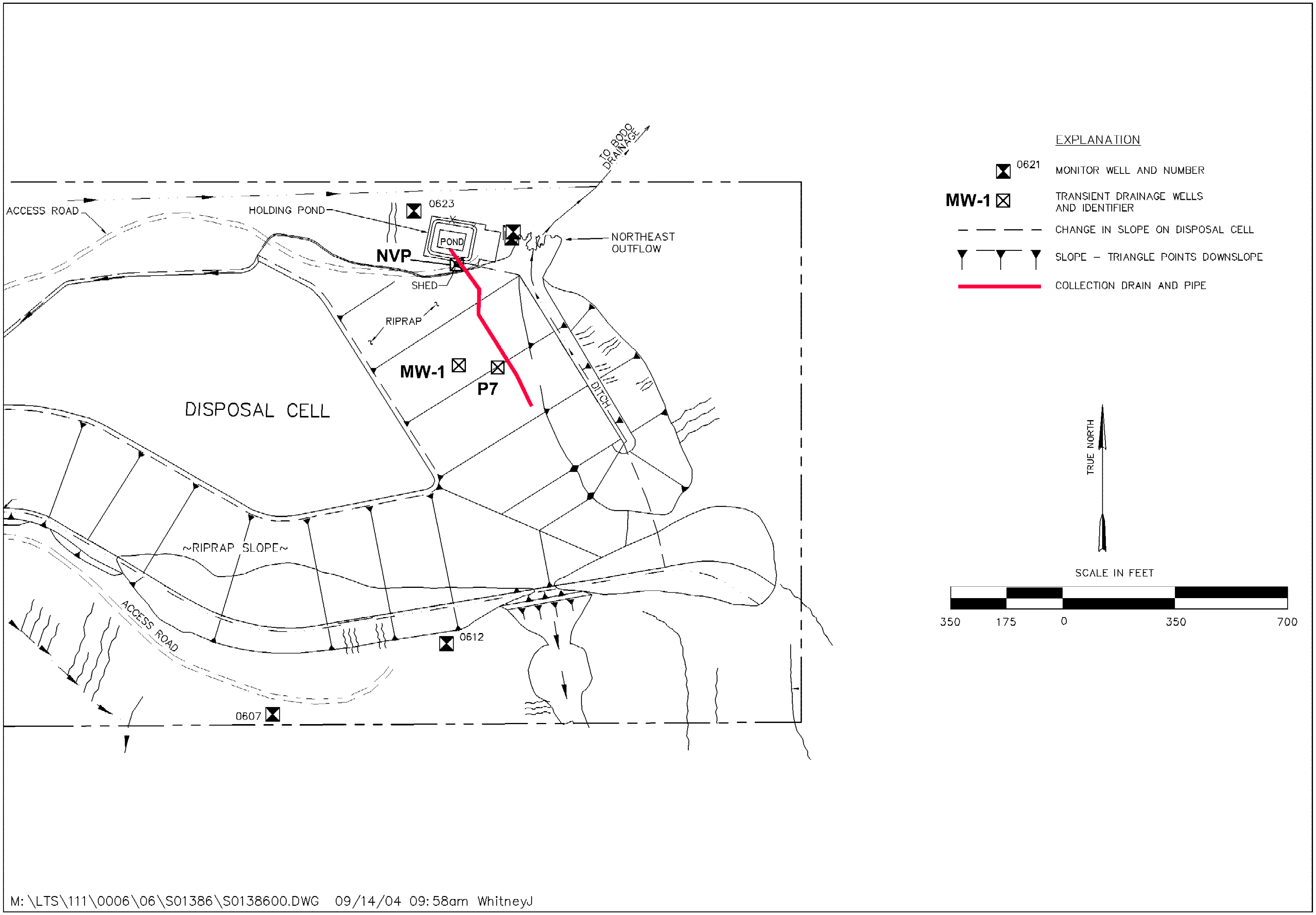
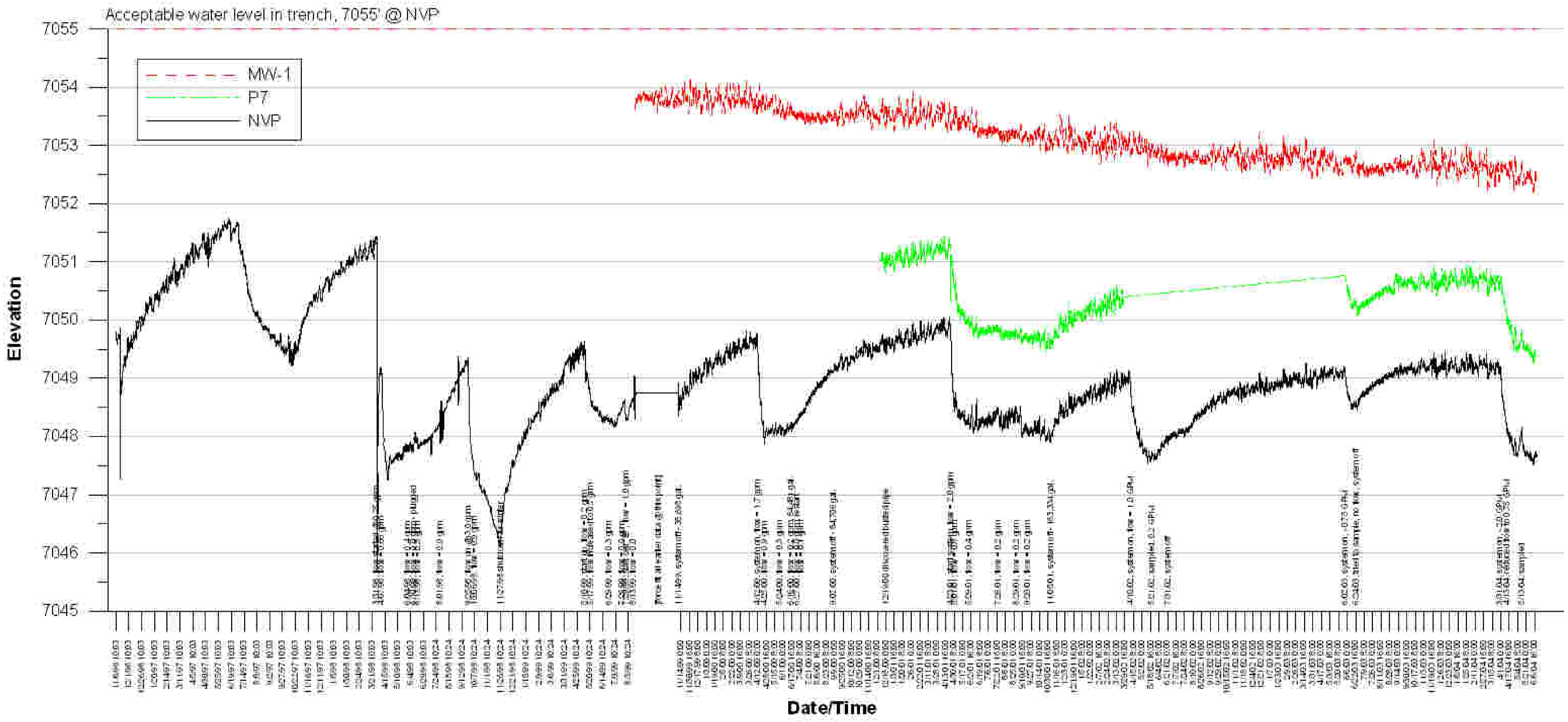


Figure 5. Locations of Collection Drain Monitoring Points NVP, P7, and MW-1



F:\HDMB\G50708\LTS\MDJR\water_levels.GRF

Figure 6. Collection Drain Water Elevations

Appendix A

Environmental Sciences Laboratory Field and Laboratory Notes

DUR01-10-01

Durango PeRT Box sampling

6/24/03 Arrive on site @ 1230. Cut thistles around wells/sampling ports.

Check totalizer. reads 202768 gal. No flow being registered. Slight trickle of H_2O from pipe into pond

Check water levels

EIS 4.75'
6.22' TD sounds hollow. Card slightly wet

EQ2S 4.55'
8.15 TD sounds hollow Card slightly wet

EOS 5.33' TD dry

Try pumping EQ2S. No flow - wet bubbles. Shifted tubes, changed depth still no flow

Pump EIS some minimal flow. Check totalizer while pumping. Indicates ~0.4 gpm D/C pumping totalizer indicates ~0.2 gpm

Try pumping EQ2S again. ≅125 ml/50 sec = 0.033 gpm totalizer indicates 0.3 gpm

Try EIS again, no flow obtained but totalizer indicates ≅0.2 gpm while pumping.

1425 Pressure has remained @ 18.5 oz/in² / 30 in H_2O
Shut gate valve (red handle) Totalizer reads 202781 gal.

1430 Water level @ EIS 5.15' Total TX gallons this season - 9554

Note: Sampling tube is still down EQ2S. Need to take long needle nose pliers next visit

Durango PeRT Box

DUR01-11-01

5/12/2004 1835. Arrive on site. Weather clear, wind calm. Gates much easier to open

Pond level is high. Outlet pipe from pert box is completely submerged and hard to view through murky water.

1845 Open main valve completely. Totalizer reading @229457

Initial flowrate = 1.65 gpm

1852 Rate = 1.50 gpm T= 229468

1900 Rate = 0.5 gpm T= 229472

1910 Rate = 0.5 gpm T= 229477

Trim weeds

5/13/2004 0830 Arrive on site

0905 Rate = 0.35 gpm T= 229817 pressure gauge = 23 (inside circle of gauge)

0910 E1S WL = 4.00

EQ2S WL = 3.62

EOS TD ~~WL~~ = 5.35 no sounding @TD can hear water trickling

1000 Sample E1S NDZ 128 start pump @ 0935

1015 Start pump EQ2S

1030 Sample EQ2S NDZ 129

DUR01-11-02

5/13/2004 1040 Start pump @ EOS Initial water dark with iron flecks.
cleared after 3"

1055 Sample EOS NDZ130

1135 flow rate = 0.35 gpm Totalizer 229879
1150 lock gates leave site

DUR01-11-03

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Durango PeRT Box sampling												
2	5/12-13/2004												
3													
4	5/12/2004 Open valve to box @ 1845. Totalizer = 229457 gal. Rate initially = 1.65 gpm. Drops to 0.5 gpm in 30 minutes												
5													
6	5/13/2004 Sample PeRT box. Rate at 0.35gpm												
7													
8													
9	Location	Date	Time	Water	Sample	Temp	Conductivity	pH	ORP	DO	DO	Alk (UF)	Alk (F)
10				Level	Ticket	(C)	(uS/cm)		(mV)	(%)	(mg/L)	(mg/L as	(mg/L as
11				(ft. below)	Number							CaCO3)	CaCO3)
12													
13	EIS	5/13/2004	950	4.00	NDZ 128	11.26	3871	6.7	233.8	24.6	2.62	600	619
14	EQ2S	5/13/2004	1026	3.62	NDZ 129	11.21	3757	7.51	-138.8	6.5	0.69	563	623
15	EOS	5/13/2004	1055	5.35	NDZ 130	11.8	3822	7.42	-170.2	14.2	1.5	620	629
16													
17													
18													
19	Rate still at 0.35 gpm. Totalizer = 229879 gal.												

Water Sampling Field Data

Date 5/13/2004 Project Location Durango Peat Box Well / Location No. EOS

Sequence Number ______ Sample Number

NDZ 130

DUR01-11-04

Well Purging Information

Depth to water 5.35 Casing Diameter ______

Depth of well 5.35 Casing Volume 1X 3X 10X (gal.) 2"=.163, 4"=.653g/ft.

Depth of water ______ Borehole Volume ______ Low Flow Purge Volume ______

Sampling Equipment. *Grundfos 12V Submersible Peristaltic Other:*

Measurement Equipment *YSI 3500, Hach 2100P Turbidimeter, Hach alkalinity, Other:*

Calibration Information

Cal @ GJO 5/12/2004

Conductivity

Time of calibration check 0930

Temperature of calibration standard ______

Conductivity reading 1004

Conductivity reading at 25° C ______

pH

Time of two-buffer calibration ______

Temperature of buffer solutions ______

Buffers used for calibration 7 check

Turbidity

Time of operational check NA

Gelex Standards

Assigned Value.	Actual Reading

Dissolved Oxygen

Time of last check with $NaSO_3$ solution ______

Atmospheric pressure 588 mmHg. Altitude ______

Temperature of calibration chamber ______

DO saturation 70%

Correction Factor ______

Calibration Value ______

ORP

Temperature of Zobell solution ______

ORP of Zobell solution 232 mV

Final Sample Data

Measurement conditions: In situ ( ) Open container ( ) Air exclusion ( )

Time	Temp	Conductivity	Conductivity ATC	pH	ORP	Turbidity	D.O.
1055	11.8°C		3822 µS/cm	7.42	-170.2	NA	14.2 % 1.5 mg/L

Alkalinity

Time 1050 **Unfiltered** Total alkalinity 620 ppm as $CaCO_3$

Time 1105 **Filtered** Total alkalinity 629 ppm as $CaCO_3$

Hach kit method: Titration cartridge 1.6 N H_2SO_4

Phenolphthalein alkalinity (for pH 8.3 or greater) Unfiltered: ______ Filtered: ______

Filters

Number of 0.45 µ disposable filters used ______

Water Sampling Field Data

Date 5/13/2004 Project Location Durango Pert Well / Location No. E/S

Sequence Number ______ Sample Number NDZ 128

DUR01-11-08

Well Purging Information

Depth to water 4.00

Casing Diameter ______

Depth of well ______

Casing Volume 1X 3X 10X ______ (gal.) 2"=.163, 4"=.653g/ft.

Depth of water ______

Borehole Volume ______ Low Flow Purge Volume ______

Sampling Equipment. Grundfos 12V Submersible Peristaltic Other:

Measurement Equipment YSI 3500, Hach 2100P Turbidimeter, Hach alkalinity, Other:

Calibration Information

Cal @ GJO – 5/12/2004

Conductivity

Time of calibration check 0930

Temperature of calibration standard ______

Conductivity reading ______

Conductivity reading at 25° C ______

pH

Time of two-buffer calibration ______

Temperature of buffer solutions ______

Buffers used for calibration 7 check

Turbidity

Time of operational check ______

Gelex Standards

Assigned Value	Actual Reading

Dissolved Oxygen

Time of last check with $NaSO_3$ solution ______

Atmospheric pressure 588.4 mmHg. Altitude ______

Temperature of calibration chamber ______

DO saturation 70%

Correction Factor ______

Calibration Value ______

ORP

Temperature of Zobell solution ______

ORP of Zobell solution ______ mV

Final Sample Data

Measurement conditions: In situ ( ) Open container ( ) Air exclusion ( ) flow cell

Time	Temp	Conductivity	Conductivity ATC	pH	ORP	Turbidity	D.O.
0950	11.26 °C	3871 µS/cm		6.70	233.8	NA	24.6% ← YSI 650 2.62 mg/L

Alkalinity

Time 1010 Unfiltered Total alkalinity 600 ppm as $CaCO_3$

Time 1005 Filtered Total alkalinity 619 ppm as $CaCO_3$

Hach kit method: Titration cartridge 1.6 N H_2SO_4

Phenolphthalein alkalinity (for pH 8.3 or greater) Unfiltered: ______ Filtered: ______

Filters

Number of 0.45 µ disposable filters used 1

Water Sampling Field Data

Date 5/13/2004 Project Location Durango Pert Well / Location No. EQ25

Sequence Number ______ Sample Number — **NDZ 129**

DUR01-11-06

Well Purging Information

Depth to water 3.62 Casing Diameter ______

Depth of well ______ Casing Volume 1X 3X 10X (gal.) 2"=.163, 4"=.653g/ft.

Depth of water ______ Borehole Volume ______ Low Flow Purge Volume ______

Sampling Equipment. Grundfos 12V Submersible Peristaltic Other:

Measurement Equipment YSI 3500, Hach 2100P Turbidimeter, Hach alkalinity, Other:

Calibration Information

Cal @ GJO 5/12/04

Conductivity

Time of calibration check 0930

Temperature of calibration standard ______

Conductivity reading ______

Conductivity reading at 25° C ______

pH

Time of two-buffer calibration ______

Temperature of buffer solutions ______

Buffers used for calibration 7 check

Turbidity

Time of operational check ______

Gelex Standards

Assigned Value	Actual Reading

Dissolved Oxygen

Time of last check with $NaSO_3$ solution ______

Atmospheric pressure 588 mmHg. Altitude ______

Temperature of calibration chamber ______

DO saturation 70%

Correction Factor ______

Calibration Value ______

ORP

Temperature of Zobell solution ______

ORP of Zobell solution ______ mV

Final Sample Data

Measurement conditions: In situ ( ) Open container ( ) Air exclusion ( )

Time	Temp	Conductivity	Conductivity ATC	pH	ORP	Turbidity	D.O.
1026	11.21°C	3757 µS/cm		7.51	-138.8		6.5% 0.69 mg/L

Alkalinity ✓

Time 1025 **Unfiltered** Total alkalinity 563 ppm as $CaCO_3$

Time 1030 **Filtered** Total alkalinity 623 ppm as $CaCO_3$

Hach kit method: Titration cartridge 1.6 N H_2SO_4

Phenolphthalein alkalinity (for pH 8.3 or greater) Unfiltered: Filtered:

Filters

Number of 0.45 µ disposable filters used 1

Durango PeRT Box

DUR01-12-01

6/14/04 During sampling @ Durango T. Franzone checked flow rate @ PeRT box. Flow has ceased on 6/10/04

Checked flow meter x 5" and no movement detected.

totalizer reading 239826 gal

pressure gauge = 22

Valve still open.