Phase 4 TCE Abiotic Fate and Transport at the Paducah Gaseous Diffusion Plant: Recommendations for Future Monitoring

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# Acronyms

KRCEE - University of Kentucky – Kentucky Research Consortium for Energy and Environment

Tc-99 - technetium-99

VOCs - Volatile Organic CompoundsPGDP - Paducah Gaseous Diffusion Plant

DOE - United States Department of Energy

PCC - Porters Creek Clay

RGA – Regional Gravel Aquifer

UCD – Upper Continental Deposits

UCRS – Upper Continental Recharge System

bgs – below ground surface

amsl – above mean sea level

# Executive Summary

# Introduction

In 1988, radionuclide technetium-99 (Tc-99) and volatile organic compounds (VOCs), including trichloroethene (TCE), were detected in private wells to the north of the Paducah Gaseous Diffusion Plant (PGDP) near Paducah in western Kentucky (KRCEE 2011, 16). Since then, other chlorinated ethenes of concern to the environment and human health (*i.e.*, dichloroethenes [DCEs] and vinyl chloride) have been found in groundwater in and around the PGDP.

In order to successfully remediate the contaminants from the groundwater, the origin, transport and fate of the contaminants must be adequately understood. For TCE and other chlorinated ethenes, this would include identifying the biotic (biological) and abiotic (chemical and physical) processes that control their movement in the subsurface and their degradation (fate). To achieve these goals, the Kentucky Research Consortium for Energy and Environment (KRCEE) led in a TCE Fate and Transport study sponsored by US Department of Energy (DOE) with emphasis on the regional gravel aquifer (RGA), which underlies the PGDP and its immediate vicinity.

As shown in Figure 1, the KRCEE study is divided into four phases. Phase 1 consisted of estimating the first-order TCE degradation rate by normalizing the TCE measurements against the conservative species technetium-99 (Tc-99) and chloride. The purpose of Phase 2 was to identify subsurface microbial processes that are involved in the biotic degradation of TCE. Phase 2 activities were based on screening of general sitewide PGDP geochemical conditions including TCE and degradation products.

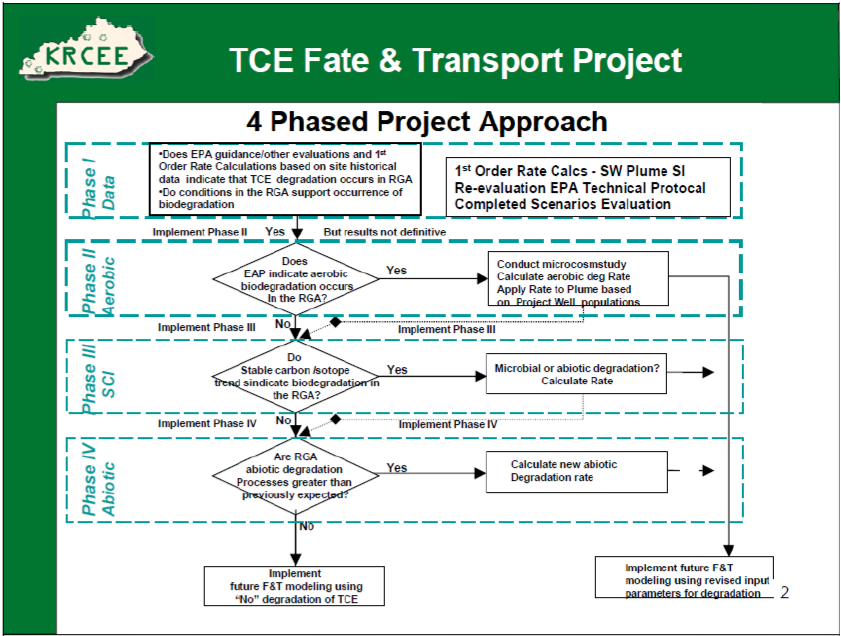


Figure 1. Four phases of the KRCEE TCE fate and transport project

KRCEE (2008) is a summary of the Phase 2 activities. Phase 3 consisted of stable carbon isotope analyses (CSIA) to identify possible abiotic and biotic degradation processes. Lee et al. (2008) is a summary of the Phase 3 results and conclusions. This report is an update of the Phase 4 activities, which involve summarizing the groundwater geochemistry of the RGA, possible sorption mechanisms and investigating possible abiotic (chemical) processes that might be degrading the TCE and other chlorinated ethenes.

# Site Location

The PGDP is a uranium enrichment facility located about 16 kilometers west of Paducah, Kentucky and 6 kilometers south of the Ohio River. The facility is situated in McCracken County in the Purchase area of western Kentucky (KRCEE 2011, 12). The plant is located on DOE property and includes the facility (about 303 hectares), a 333-hectare security zone surrounding the facility, which also includes landfills, and an additional 804 hectares that are leased to the state of Kentucky as part of a wildlife management area (KRCEE 2011, 12). LATA Environmental Services of Kentucky, LLC (LATA) currently manages environmental and waste management activities at the PGDP for DOE.

# General Geology/Hydrogeology of the Site

Details on the stratigraphy and groundwater geology of the PGDP are in KRCEE (2011, 17-28). The bedrock under the PGDP consists of chert-bearing limestones and some shales of Mississippian age (about 318 to 359 million years old) (Figure 2). The Mississippian bedrock is at least 150 meters thick and is located at depths below the surface of about 100-120 meters.

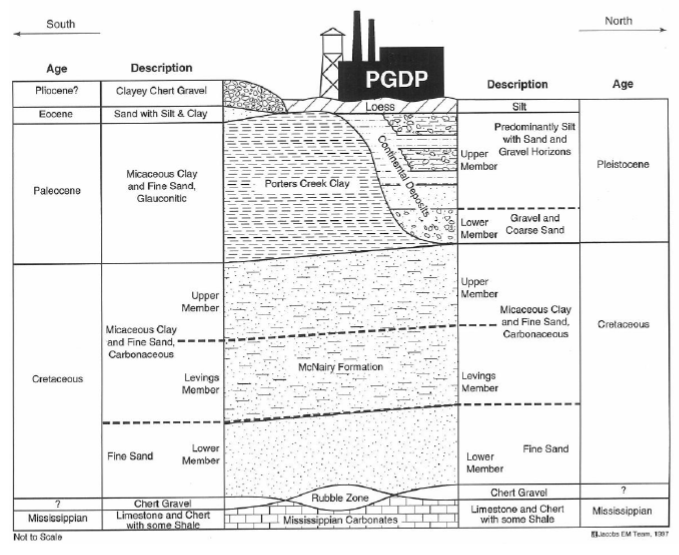
A cherty gravel rubble zone overlies the Mississippian bedrock (KRCEE 2011, 19). The gravel represents the weathered remains of the Mississippian bedrock (Figure 2). The age and lateral extent of the rubble zone is unknown. The rubble zone has a maximum thickness of about 1.5-6 meters.

The Upper Cretaceous (about 65-100 million years ago) McNairy Formation is located above the bedrock and the rubble zone. The formation consists of medium to very fine-grained sand along with some silt and clay (KRCEE 2011, 19). The McNairy Formation is divided into three members: a Lower fine-sand member and the more silt- and clay-rich sands of the intermediate Levings and Upper members (Figure 2; KRCEE 2011, 19). The total thickness of the McNairy Formation is about 60-90 meters.

The McNairy Formation is partially overlain by the Paleocene (about 55-65 million years ago) Porters Creek Clay (Figure 2). The Porters Creek Clay forms a terrace on the south side of the PGDP site (Figure 2) and consists of clay and fine-grained clayey sand (KRCEE 2011, 19). The maximum thickness of the clay is about 60 meters. An Eocene (about 34-55 million years ago) sand overlies the Porters Creek clay south of the PGDP (Figure 2). The sand also includes some silt and clay lenses (KRCEE 2011, 19).

Continental sediments of Pleistocene and possibly Pliocene age (11,000 to 1.8 million years ago and 1.8 to 5.3 million years ago, respectively) overlie the Eocene sand, Porters Creek Clay, and the McNairy Formation (Figure 2). The sediments range in thickness from 0 to 35 meters and cover several paleo topographic valleys and terraces (KRCEE 2011, 19).

Coarse deposits located on ancient terraces to the south of the PGDP are identified as the Terrace Gravel (TG). They overlie the Eocene sand and the Porters Creek Clay (Figure 2). The terrace deposits consist of gravels of possible Pliocene age with a maximum thickness of about nine meters.

Figure 2. Conceptual Cross-section of the subsurface geology of the PGDP (DOE, 2010).

The Lower member of the Continental Deposits consists of poorly sorted sands and gravels, pebbles, and occasional cobbles (KRCEE 2011, 19). Lower Continental Deposits are located in paleo valleys adjacent to the terraces and extend north to the Ohio River (Figure 2). The regional gravel aquifer (RGA) is the major aquifer at the PGDP and refers to sands and gravels of the Pleistocene Lower Continental Deposits and discrete areas of contiguous upper McNairy Formation sands that underlie the coarse deposits. A nearly continuous veneer of sand and silty sand occurs at the top of the RGA immediately below the silt/clay confining unit at the base of the Upper Continental Deposits (KRCEE 2011, 27).

The Upper Continental Deposits are Pleistocene in age. The deposits consist of saturated and unsaturated soils and sediments. The surface of the PGDP is also covered by Pleistocene loess (wind-blown silts). The sediment clasts of the Upper Continental Deposits are predominantly finer-grained materials than the Lower Continental Deposits and consist of upper silt and clay layers, an intermediate interval of sand and gravel, and a lower silt and clay interval (KRCEE 2011, 21-22).

The Upper Continental Deposits are classified as the Upper Continental Recharge System (UCRS) (Figure 2; KRCEE 2011, 25). The PGDP water table is very variable in elevation in the Upper Continental Deposits (KRCEE 2011, 25). The primary hydrologic system function of the UCRS is vertical recharge of groundwater from the ground surface and shallow subsurface anthropogenic losses to the RGA.

# PGDP and Groundwater Contamination

Construction on the PGDP began in 1951 and uranium enrichment operations were initiated in 1952 (KRCEE 2011, 16). From 1953-1977, the PGDP’s primary activity was the enrichment of uranium-235 from natural uranium and the re-enrichment of spent uranium fuel rods from reactors at the DOE Hanford and Savannah River facilities (KRCEE 2011, 16).

Uranium processing operations occurred in C-410 complex buildings. Uranium was complexed with fluorine gas to produce enrichment process feedstock. Enrichment of U-235 was accomplished by passing gaseous UF6 through 1700 “cascade” stages of high temperature and high pressure molecular separation (KRCEE 2011, 16).

Nearly 400 miles of enrichment process piping and other components of the enrichment process required routine cleaning to maintain process efficiencies. The cleaning was accomplished in the C-400 building utilizing the industrial solvent trichloroethylene (TCE). TCE was introduced to the PGDP subsurface and groundwater via wastewater losses and losses of pure TCE during transfer and storage activities.

Spent uranium fuel rod materials contained the fission product Tc-99. Tc-99 occurs as the pertechnetate ion which is very mobile in water and groundwater and has a half-life of about 210,000 years (KRCEE 2011, 36). Tc-99 was released to the PGDP subsurface and groundwater during cleaning and waste disposal operations.

Losses of TCE from C-400 area operations, burial grounds, and waste disposal facilities to the shallow subsurface resulted in storage and vertical transport of TCE and dissolved TCE through the UCRS to the RGA. In the RGA, TCE losses resulted in the development of three TCE groundwater plumes at the PGDP: the Northwest, Northeast and Southwest Plumes. The Northwest TCE-99Tc Plume extends approximately three and half miles from the C-400 building to the south side of Tennessee Valley Authority (TVA) property near the Ohio River. The Northwest Plume exits the northwest corner of PGDP industrial area. The Northeast Plume exits the PGDP industrial area along the eastern PGDP industrial area and extend approximately The Southwest Plume also contains technetium-99 in addition to TCE. The southwest plume is generally contained on DOE industrial site and DOE reservation property.

## Technetium-99 (Tc-99)

In oxygenated near neutral pH water, such as RGA groundwater, technetium should exist in the +7 valence state. TcO4- is one of the more common aqueous Tc (VII) species (Icenhower et al. 2010, p. 728). TcO4- is extremely soluble in water, very mobile in most aerobic groundwater and is usually resistant to co-precipitation and sorption (Icenhower et al. 2010, 723, 730; Bolsunovskii et al. 2010, 1220; Kumar et al. 2007, 229). However, observations of the Tc-99 groundwater plumes at the PGDP, groundwater flow rates and the porosities of the subsurface materials suggest that the Tc-99 is not moving as quickly through the subsurface as it should if it were indeed extremely soluble and non-sorptive (“conservative”). So, some, albeit minor, sorption of Tc-99 on subsurface rocks, sediments and soils is probably occurring.

## Trichloroethene (TCE)

TCE and TCE degradation products *cis*-1,2-dichlorethene (*cis*-DCE), *trans*-1,2-dichlorethene (*trans*-DCE), 1,1-dichloroethene (1,1-DCE) and vinyl chloride, are among the major contaminants of concern at the PGDP. Typical treatment methods for TCE-contaminated groundwater include pump and treat with effluent treatment, air stripping, sparging, iron nanoparticles, carbon sorption, and surface bioreactors. TCE contaminated soils and sediments in shallow unsaturated zones are typically vented or excavated. In-situ bioremediation may be done on subsurface materials above and below the water table (Tlusty 1999). Relative to PGDP aquifer TCE contamination, initial remediation efforts involved the installation of four pump-and-treat wells in the extensive northwestern plume in 1995. The main purpose of the wells was not to remediate the groundwater, but to prevent the chlorinated ethenes from spreading further in the subsurface until effective remediation methods could be identified and implemented (KRCEE 2011, 16-17).

Figure 3. Northwest, southwest, and northeast TCE plumes at the PGDP

(LATAKY, 2013; from DOEKRCEE, 200515).

# Data Quality

Since 1988, an enormous amount of environmental and chemical data has been collected from PGDP and vicinity media including groundwater. The data are archived and accessible on-line in the DOE Paducah Environmental Geographic Analytical Spatial Information System (PEGASIS) database (<http://padgis.latakentucky.com/padgis/>).

In 2013-2014, groundwater data from monitoring wells at 1,201 station locations along and near the northwest plume (Figure 3) were downloaded from the PEGASIS database. Information on detection limits and other quality control and assurance data are in the database. As further discussed in Appendices A-C, additional data evaluations were performed with a temporarily available, scaled-down academic version of Geochemist’s Workbench®. Geochemist’s Workbench®, which was developed by Aqueous Solutions L.L.C. of Champaign, Illinois, USA (<http://www.gwb.com/>), is a computer software program that can solve a variety of problems in aqueous geochemistry.

## TCE Degradation Products

## Redox

Temperature, pH, and most other chemical and physical parameters that are required to determine the transport and fate of contaminants in groundwater are usually convenient to define and measure. Reduction-oxidation (redox) measurements are the exception. Platinum electrodes are sometimes used to obtain redox or Eh measurements for water samples. Unfortunately, such measurements are often inaccurate (Drever 1997, 135-136, 181-182; Minnesota Degradation Guidelines 2006, 6-7). Groundwater may contain a number of different chemical species that participate in redox reactions, such as: Fe(III)/Fe(II), sulfate/sulfide, nitrate/nitrite, and various trace elements, such as arsenic, manganese and selenium. Frequently, platinum electrodes will not rapidly respond to the kinetics of many paired reactions that control redox conditions, such as:

* O2-H2O
* SO42- - H2S
* CO2 - CH4
* NO3- - N2
* N2 - NH4+
* many other reactions involving solid phases (Drever 1997, 136).

Unless all redox reactions are all in equilibrium with each other, platinum Eh electrodes cannot obtain a single and accurate Eh measurement for a water sample (Drever 1997, 135-136, 181-182). In natural samples, many of the competing redox reactions are hindered from attaining equilibrium by biological organisms and/or slow chemical reaction kinetics. As an example, the sluggishness of the iron redox reactions often explains why magnetite (Fe3O4) is found in oxidizing beach sands. According to thermodynamic calculations, magnetite should not be stable in the presence of air. At equilibrium, hematite (Fe2O3), goethite (FeOOH) or other Fe(III) compounds, and not magnetite, should be present in the beach sands. However, slow chemical kinetics result in the presence of metastable magnetite.

## Estimating Redox Conditions in the RGA at the PGDP

Figure 4 shows a poor correlation between the log10 dissolved oxygen concentrations (micrograms per liter, μg/L) and Eh measurements with a platinum electrode (millivolts, mV) for the RGA samples, including samples from the lower, middle and upper RGA. The Pearson (*r*) correlation coefficient for the dissolved oxygen concentrations versus the Eh measurements is only 0.032 for 7,217 data points. As alternatives to platinum electrode measurements, redox conditions in groundwater may be estimated with dissolved oxygen measurements or comparisons between the concentrations of various paired dissolved redox species, such as Fe(II)/Fe(III), sulfide/sulfate, or nitrite/nitrate. Very few detectable measurements of sulfide, nitrite, and Fe(II) are available for the RGA groundwater. A dissolved oxygen concentration of 1,000 μg/L may be used as a boundary between aerobic and anaerobic conditions (KRCEE 2011; Minnesota Degradation Guidelines 2006). As shown in Figure 4, the majority of dissolved oxygen measurements in the RGA are above 1,000 μg/L, which indicates that the groundwater are generally oxidizing. Under oxidizing conditions, nitrite, Fe(II) and sulfide should be absent.

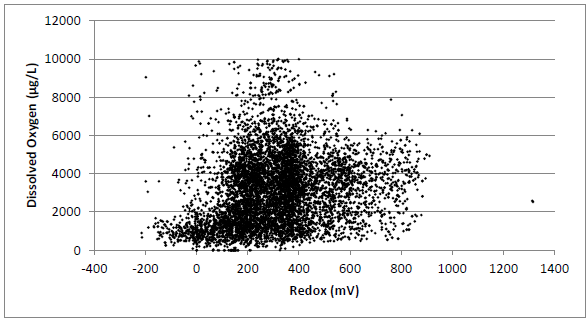


Figure . Log dissolved oxygen concentrations (μg/L) versus Eh measurements

Table 1 shows the average dissolved oxygen concentrations for RGA monitoring wells located in or near the northwest TCE plume for 1996-2006 (KRCEE 2011) and 2007-2015 (also see Figure 5). MW-194 and MW-197 are control wells well outside the plume. With the exceptions of the 1996-2006 average for MW-20 and the 2007-2015 average for control well MW-197, the average dissolved oxygen concentrations are above 1,000 μg/L and conditions are considered aerobic. As shown in Figure 6, for unknown reason(s), the groundwater in MW-197 has become less aerobic since 1993. Although their averages were above 1,000 μg/L, MW-242 and MW-262 had some dissolved oxygen measurements below 1,000 μg/L until 2008 for MW-242 and 2010 for MW-262 (Table 1; Figure 7).

MW-20 is located in the upper RGA (URGA) near site J-14 of the northwest plume (Figure 5) and shows an unusually variable pattern of dissolved oxygen measurements over the last two decades. Figure 8 shows all of the individual dissolved oxygen measurements for MW-20. The dissolved oxygen measurements for MW20 were initially aerobic, but dropped below 1,000 μg/L from March, 1996 to December, 2000. From December, 2000 through November, 2009, dissolved oxygen concentrations fluctuated between 180-1,710 μg/L. Between November, 2009 and April, 2013, the dissolved oxygen concentration dramatically increased from 410 to 3,700 μg/L and has remained well above 3,000 μg/L through the most recently available measurement taken in June, 2012. At this point, the cause(s) for the dissolved oxygen fluctuations are unclear.

### Iron(II)

Iron (II) or ferrous iron is generally very soluble in circum-neutral pH water and forms from the reduction of Fe(III) under anaerobic conditions. The presence of dissolved Fe(II) (Fe2+) is also an indicator of anaerobic degradation of TCE and other chlorinated ethenes (KRCEE 2008, 14-15, also see below). Although the RGA is generally oxidizing, Fe2+ has been detected in RGA groundwater in several MW wells as shown in Table 2. Most of the measurements were performed in 2004-2006. Figure 9 shows that most of the Fe2+ measurements were in groundwater with more than 1,000 μg/L dissolved oxygen and that the Fe2+ concentrations were highly variable. Under these oxidizing conditions, the Fe2+ should be metastable. Sufficient analyses are not available for the RGA to obtain correlations between Fe2+ and nitrite, sulfide, or total organic carbon, all of which may occur under anaerobic conditions.

Table 1. Average dissolved oxygen concentrations PGDP Northwest Plume.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Monitoring Well | Aquifer | Range Dissolved Oxygen (μg/L), 1996-2006, KRCEE (2011) | | Range Dissolved Oxygen (μg/L), 2007-2015 | Average Dissolved Oxygen (μg/L), 1996-2006 KRCEE (2011) | Average Dissolved Oxygen (μg/L), 2007-2015 |
| MW-194 | MRGA | 3,330 – 7,180 | | 2,100 – 5,450 | 5,354 | 4,242 |
| MW-197 | URGA | 510 – 4,340 | | 500 – 2,400 | 1,532 | 901 |
|  |  |  | |  |  |  |
| MW-20 | URGA | 180 – 1,790 | | 410 – 7,030 | 772 | 2,962 |
| MW-65 | LRGA | 3,020 – 4,950 | | 3,000 – 5,700 | 3,886 | 4,091 |
| MW-66 | URGA | 2,150 – 9,200 | | 3,830 – 7,560 | 6,385 | 5,583 |
| MW-125 | LRGA | 1,020 – 4,660 | | 1,580 – 4,960 | 3,156 | 3,212 |
| MW-152 | LRGA | 3,630 – 5,350 | | 3,080 – 11,600 | 4,587 | 4,899 |
| MW-168 | URGA | 850 – 6,960 | | 1,210 – 4,610 | 3,810 | 2,908 |
| MW-185 | MRGA | 1,080 – 5,180 | | 1,680 – 2,420 | 2,124 | 2,025 |
| MW-234 | LRGA | 2,470 – 6,700 | | --- | 4,426 | --- |
| MW-236 | LRGA | 1,430 – 5,260 | | 2,780 – 6,070 | 3,260 | 3,565 |
| MW-242 | MRGA | 690 – 4,480 | | 660 – 5,760 | 1,630 | 3,267 |
| MW-243 | MRGA | 930 – 6,030 | | 3,580 – 9,210 | 4,366 | 5,274 |
| MW-262 | LRGA | 610 – 3,810 | | 600 – 2,490 | 1,774 | 1,076 |
| MW-333 | MRGA | 570 – 4,750 | | 1,050 – 3,700 | 1,844 | 1,902 |
| MW-340 | LRGA | 1,420 – 5,400 | | 1,830 – 4,870 | 3,415 | 3,338 |
| MW-381 | MRGA | | --- | 2,920 – 6,070 | --- | 3,659 |

Average dissolved oxygen concentrations in μg/L for RGA monitoring wells located in or near the northwest TCE plume for 1996-2006 (KRCEE 2011) and 2007-2015. LRGA, MRGA, and URGA indicate the lower, middle and upper regional gravel aquifer, respectively. The groundwater in MW-234 has not been measured for dissolved oxygen since 2002. KRCEE (2011) did not provide results for MW-381.



Figure 5. Monitoring wells along the northwest TCE plume at the PGDP (KRCEE 2008, 66).

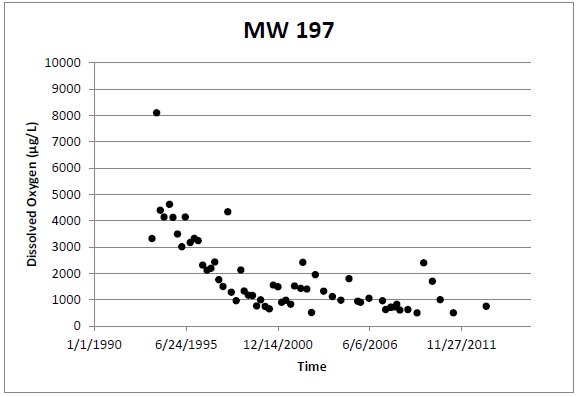
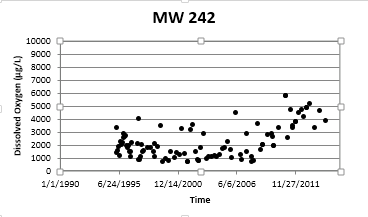


Figure 6. RGA MW-197 temporal dissolved oxygen measurements (μg/L)



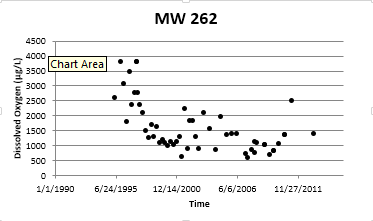


Figure 7. RGA MW-242 and MW-262 Dissolved oxygen measurements (μg/L)

*The groundwater in the wells has periodically exhibited dissolved oxygen concentrations below 1000 μg/L after 2006.*

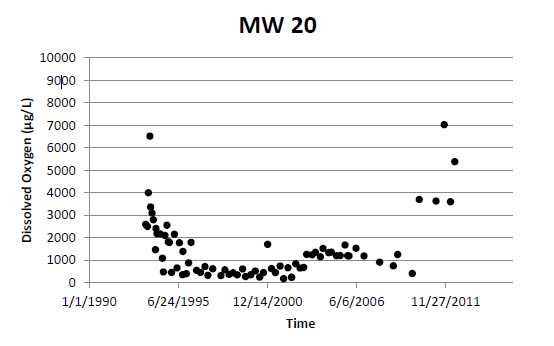
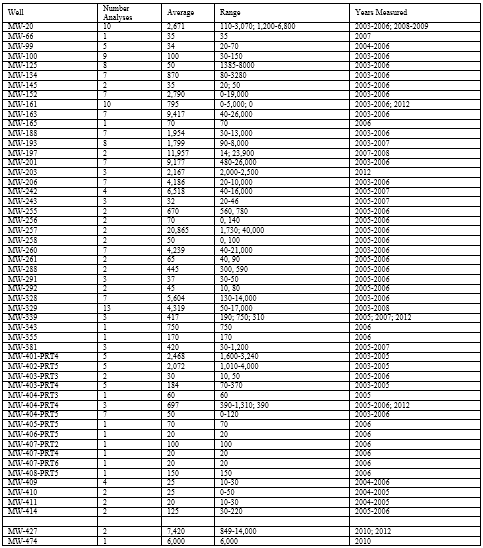


Figure 8. Dissolved oxygen measurements for RGA MW-20 (μg/L).

Table 2. Dissolved iron (II) concentrations in μg/L in MW wells at PGDP



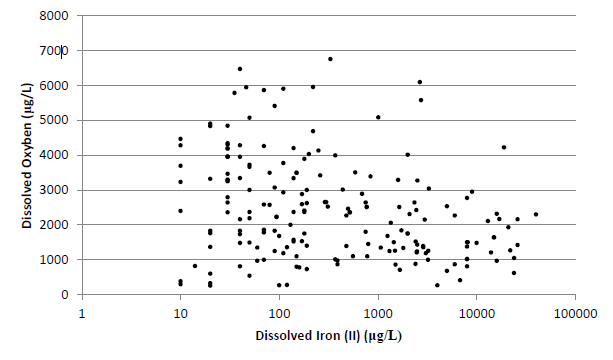


Figure 9. Dissolved iron (II) versus dissolved oxygen measurements in RGA groundwater samples.

### Chemistry of Trichloroethene (TCE) and Other Chlorinated Ethenes

TCE and most other chlorinated ethenes are dense non-aqueous phase liquids (DNAPLs), which means that they are mostly immiscible (“insoluble”) in water and would tend to sink in the subsurface and collect on impermeable layers below unconfined aquifers. Although TCE and other chlorinated ethenes are mostly “insoluble” in water, enough of these compounds can dissolve in groundwater to easily exceed their MCLs (Table 3). Furthermore, chlorinated ethenes will leave droplets in both aquifers and deeper unsaturated soils and sediments that are not exposed to surface volatilization. Enough TCE and other chlorinated ethenes will remain in groundwater, soils and sediments to present potential environmental and human health problems.

TCE may abiotically or biotically degrade in anaerobic natural environments into DCEs, vinyl chloride and ethene (Figure 10). DCEs are potential carcinogens and exposure can harm the central nervous system in humans. Among the DCEs, 1,1-DCE is greatest health threat to humans, as indicated by its lower MCL (Table 3).

Vinyl chloride is a known carcinogen and, as indicated by its very low MCL (Table 3), is considered a greater human health threat than TCE (Mattes et al. 2010, 446). Small amounts of vinyl chloride may naturally form through abiotic reactions in soils (Mattes et al. 2010, 446).

Besides forming from the decomposition of chlorinated ethenes, ethene (ethylene, C2H4) also forms naturally and is an important plant hormone and food source for microbes (Mattes et al. 2010, 445). Ethene mostly occurs in the atmosphere and photochemical reactions result in a half-life of ethene of only about 56 hours in air (Mattes et al. 2010, 445).

Table 3. *Chemical Characteristics and MCLs for chlorinated ethenes.*

Aqueous solubility, boiling point, density, and US federal Maximum Contaminant Levels (MCLs) in μg/L for chlorinated ethenes (Tobiszewski and Namieśnik, 2012).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Compound | Aqueous Solubility (μg/L at 25oC) | Boiling Point (oC) | Density  (mg/kg at 20oC) | MCL (μg/L) |
| 1,1-dichloroethylene | 2,250 | 31.6 | 1.21 | 7 |
| *cis*-1,2-dichloroethylene | 3,500 | 60.1 | 1.28 | 70 |
| *trans*-1,2-dichloroethylene | 6,260 | 48.7 | 1.26 | 100 |
| Trichloroethylene (TCE) | 1,000 | 88 | 1.46 | 5 |
| Vinyl chloride (VC) | 2,700 | -13.9 | 0.99 | 2 |

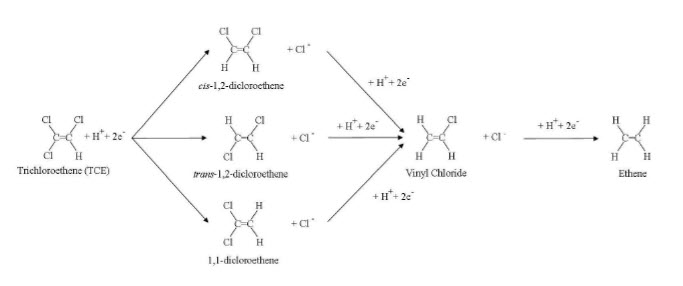


Figure 10. Degradation pathways for the reductive dechlorination of TCE

(see text).

The pathways may be either abiotic or biotic, but they are expected to occur under anaerobic conditions.

## Transport and Fate of TCE and other Chlorinate Ethenes

The transport and fate of TCE and other chlorinated ethenes in the subsurface are influenced by a number of physical, chemical and biological factors. Physical processes involve surbsurface transport or phase changes in contaminants without chemical reactions or the involvement of biological organisms. Examples would include the volatilization of an organic liquid into a gas or the movement of a contaminant in the subsurface by groundwater flow (advection). Substances may also chemically (abiotically) react and produce new substances, which may involve chemical precipitation or the formation of colloids. The sorption of contaminants onto mineral or other solid surfaces would involve both chemical and physical processes. Changes in pH, temperature, and other conditions may also desorb contaminants from solid surfaces and possibly revive environmental problems. In biotic processes, plants, animals or microorganisms may degrade or transform contaminants into new phases or substances. As discussed below, both abiotic (chemical) and biotic (microbial) processes are capable of degrading TCE into DCEs and vinyl chloride (Figure 10).

### Physical Processes

#### Volatilization

As shown by their relatively low boiling points in Table 3, chlorinated ethenes, and especially vinyl chloride, are volatile organic compounds. Volatilization is expected to be most significant in unsaturated soils and sediments, and especially near surface where solar heating, flowing air, and biological activity are common. The depth of the top of the RGA averages about 17 meters under the PGDP (KRCEE 2011, 28). The flow rate of the RGA groundwater is about 0.3-1 m/day (KRCEE 2011, 26). Temperatures for the RGA groundwater are generally 5-27oC. With the possible exception of vinyl chloride, the volatilization of TCE and other chlorinated ethenes is expected to be minimal under the conditions in the RGA. Indeed, TCE and other chlorinated ethenes are known to persist in aquifers for decades (O’Carroll et al. 2013, 104).

#### Advection, Diffusion and Dispersion

The movement of TCE and other contaminants in groundwater involves advection, dispersion and diffusion. Advection refers to groundwater flow, which may carry water-soluble contaminants and colloids. At the PGDP, advection is extremely important because of the possibility of groundwater transporting Tc-99 and chlorinated ethenes towards Bayou and Little Bayou Creeks, the Ohio River and other surface waters.

Dispersion refers to the mixing of contaminants in flowing groundwater (Drever 1997, 356, 361). In very slow moving groundwater where advection and dispersion are insignificant, the thermal motion of water molecules still allows contaminants to diffuse from areas of higher concentration to lower through differences in chemical potential (Fetter 1993, 43; Drever 1997, 357). In diffusion, charge balances are maintained and single ions cannot diffuse without oppositely charged ions diffusing with them or ions with the same charge diffusing in the opposite direction (Drever 1997, 357).

MW-194 and MW-197 are located outside of the main RGA groundwater flow in the northwest plume (Figure 5). However, groundwater in the wells contains low concentrations of TCE, which are thought to have originated from the slow diffusion of TCE from the plume (KRCEE 2008, 64).

Ideally, a conservative chemical in groundwater moves through advection and diffusion without sorbing onto surfaces, volatilizing out of the groundwater or undergoing chemical reactions. Chloride and bromide are very conservative. As discussed earlier, Tc(VII) tends to be very soluble and conservative in water under aerobic conditions (Icenhower et al. 2010, 723, 730; Bolsunovskii et al. 2010, 1220; Kumar et al. 2007, 229).

In the RGA, chloride may not be an entirely suitable conservative tracer because it would be a byproduct of any biotic or abiotic reductive dechlorination of TCE and other chlorinated ethenes (Figure 10). Observations of the Tc-99 groundwater plume at the PGDP, the porosities of the subsurface materials, and groundwater flow rates suggest that the Tc-99 is not moving as quickly through the subsurface as it should if it were indeed extremely soluble and conservative. Nevertheless, the Tc-99 does appear to be fairly conservative in the aerobic environments of the RGA. Figure 11 shows a fairly linear log10-1og10 distribution between Tc and TCE in monitoring wells along the northwest plume. When their concentrations are plotted over time for individual MW wells in the northwest plume, the distributions of Tc-99 and TCE are often very parallel. Two typical examples shown in Figure 12 indicate that TCE and Tc-99 are behaving similarly in the RGA, which suggests that the transport of TCE in the northwest plume, like Tc-99, is largely controlled by advection, dispersion, and diffusion, with minimal sorption.

#### Sorption

“Sorption” is a broad term that includes the adsorption and/or absorption of chemicals with minerals and other solid materials. Although the results, such as those shown in Figure 12, appear to minimize the role of sorption in the transport of TCE, there is currently not enough detailed information on the mineralogy and chemistry of the RGA to define the role, if any, of sorption on the transport and fate of TCE and other chlorinated ethenes. The remediation of TCE with zero valent iron and other iron compounds, on the other hand, suggests that iron minerals and surface coatings in aquifers could contribute to the sorption and abiotic degradation of TCE and other chlorinated ethenes. Detailed X-ray diffraction (XRD) and scan electron microscopy (SEM) studies of RGA sediments would be required to identify and estimate the concentrations of any iron or manganese compounds, which could sorb or contribute to the abiotic dechlorination of TCE or other chlorinated ethenes. Light microscopy would be required to identify possible amorphous iron or manganese (oxy)(hydr)oxide surface coatings.

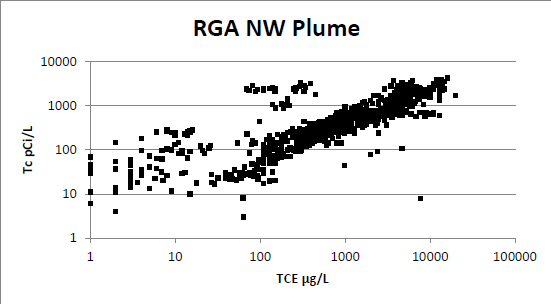


Figure 11. Log10-log10 plot of northwest plume Tc-99 and TCE in RGA

Only limited studies are available on the adsorption of TCE in rocks and sediments, especially under aerobic conditions. In general, organic carbon has a greater ability to adsorb TCE than carbonate minerals, quartz, or clay. In a study with a caliche soil, Akyol et al. (2011) concluded that the soil organic matter had about a 100 times greater ability to adsorb TCE concentrations of 1-1,300 mg/L than the carbonate minerals. He et al. (2012) also found that organic carbon favored the adsorption of TCE more than minerals. Furthermore, increases in ionic strength increased the adsorption capacity of organic carbon in the Chinese soils. In the He et al. (2012) study, TCE adsorption was not influenced by changes in soil pH or moisture. In laboratory column and batch studies, the adsorption of TCE onto two sandy soils from Poland was low (Kret et al. 2015). Kret et al. (2015, 9879) concluded that the sorption of TCE mostly depends on the organic content and the amount of clay- and silt-sized particles in the aquifer. In another study, Li et al. (2012) concluded that humic acid was more effective in adsorbing TCE than quartz or kaolinite clay.

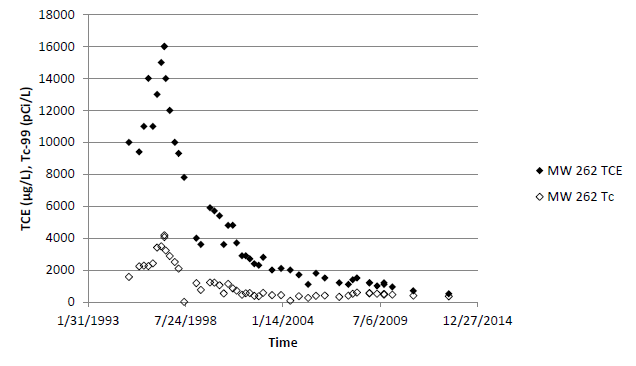


Figure 12. (MW-234 and NW-262) Northwest Plume RGA TCE and Tc-99.

MW-262 is relatively close to the TCE source and MW-234 is more distant (Figure 5).

### Degradation of Trichloroethene (TCE) and Other Chlorinated Ethenes

DCEs, vinyl chloride and ethene have been detected in the groundwater of the RGA, although few ethene analyses have been done. The DCEs, vinyl chloride and ethene probably resulted from the degradation of TCE in the subsurface rather than occurring as impurities in the original TCE, forming from natural materials at the site, or originating from other chemicals utilized at the PGDP.

Previous studies summarized in KRCEE (2008) have already concluded that microbes are at least partially responsible for the degradation of TCE. At concentrations of 700 mg/L, such as what occurs in the RGA near the C-400 building, the TCE is a likely biocide of bacteria that could aerobically degrade TCE (KRCEE 2011, 40). However, enzymes released by bacteria feeding on other organic compounds in the groundwater would degrade TCE (KRCEE 2008). Once TCE degrades, bacteria are capable of degrading *cis*-DCE and other TCE degradation products. TCE and its degradation products may also degrade through abiotic (non-biological) chemical reactions (Tobiszewski and Namieśnik 2012).

Tobiszewski and Namieśnik (2012) discuss a number of chemical (abiotic) reactions that can degrade TCE. However, only the hydrogenolysis (reductive dechlorination) pathways shown in Figure 10 adequately explain the presence of DCEs, vinyl chloride and some ethene in the groundwater of the RGA. *Trans-* and *cis-*DCEs may also degrade to acetylene (C2H2) (Tobiszewski and Namieśnik 2012), which has not been measured in the RGA.

Although the dechlorination pathways in Figure 10 may be biotic or abiotic, they occur under reductive (anaerobic) conditions (Tobiszewski and Namieśnik 2012; Mattes et al. 2010). Abiotic dechlorination requires the presence of reduced compounds in the host materials, such as zero valent iron or Fe(II) and sulfide minerals (Tobiszewski and Namieśnik 2012; Liang et al. 2007; Minnesota Degradation Guidelines 2006, 14). For example, 1,1-DCE is the prominent abiotic dechlorination product of TCE in the presence of sulfide (Kastner, 1991). Although biotic dechlorination of TCE may produce *trans*-DCE and 1,1-DCE, *cis*-DCE tends to be prominent (Vogel et al. 1987; Wiedemeier et al. 1999). Biotic processes with microbes are also faster than abiotic dechlorination, but the abiotic degradation of chlorinated ethenes is more likely to go to completion (Tobiszewski and Namieśnik 2012), which is important if the formation of carcinogenic vinyl chloride is to be avoided. Abiotic processes may become important if the concentrations of chlorinated ethenes are high and subsurface microbial populations are low, especially in impermeable rocks (Tobiszewski and Namieśnik 2012). Both abiotic and biotic degradation are generally enhanced with increasing groundwater temperatures (Morrison et al. 2014, 262).

KRCEE (2008, 13) found evidence three lines of evidence for the biodegradation of TCE and other chlorinated ethenes: 1) first-order rate calculations, which indicate that TCE half-lives in the RGA range from 3 to 26 years, 2) enzyme activity probes and genetic profiling assisted in identifying the biotic processes that were degrading the TCE, and 3) stable carbon isotope analyses (CSIA) indicated that aerobic biodegradation was occurring. The TCE was not directly degraded by microbes. Rather, the aerobic microbes consumed natural organic matter or less chlorinated organic contaminants and produced enzymes that degraded the TCE, which is called aerobic co-metabolic degradation (KRCEE 2008, 13). Although limited dissolved organic carbon analyses of the RGA groundwater were relatively low (1-6 mg/L) and consistent with low nutrient groundwater, KRCEE (2008, 15) concluded that dissolved organic carbon concentrations in the RGA must be adequate enough to support the microbial populations that were identified with enzyme activity probe analyses. The authors of KRCEE (2008, 17) note that the RGA is not entirely aerobic and that the presence of DCEs and other dechlorination byproducts in the RGA indicate that suitable anaerobic conditions must be locally present for reductive dechlorination (Figure 10).

If present, abiotic dechlorination of TCE and other chlorinated ethenes through the pathways in Figure 10 would require anaerobic conditions or the presence of metastable reduced compounds in the RGA or TCE-contaminated portions of the UCRS that recharge the RGA. Localized anaerobic surface conditions could be associated with sewage disposal, from reactions with buried metal pipes or other equipment, or if metastable reduced-iron or sulfide minerals are present. Wilson et al. (2009) concluded that TCE and *cis*-DCE may be abiotically removed from groundwater under oxidizing conditions if magnetite is present in the host materials. Detailed X-ray diffraction (XRD), light microscopy and scanning electron microscopy (SEM) studies of RGA sediments would be required to identify and estimate the concentrations of any magnetite or other reduced phases in the RGA.

### Distinguishing between Abiotic and Biotic Degradation of Chlorinated Ethenes

Distinguishing biotic from abiotic degradation of chlorinated ethenes is often extremely difficult (Elsner et al. 2010, 79). For example, while the removal of TCE with zero valent iron is considered abiotic, zero valent iron will also stimulate microbial activity and confound the distinction (Elsner et al. 2010, 79). Nevertheless, distinguishing between the abiotic and biotic degradation of chlorinated ethenes is important. While abiotic processes with zero valent iron may thoroughly break down TCE into less harmful ethene or ethane, biotic processes may not go to completion and produce vinyl chloride (Figure 10), which is even more hazardous than TCE (Elsner et al. 2010, 79-80; O’Carroll et al. 2013, 107).

In laboratory or field studies at unidentified locations, Elsner et al. (2010), Liang et al. (2007) and Lojksek-Lima et al. (2012) used carbon stable isotope analyses (CSIA) to distinguish abiotic from biotic degradation of TCE and other chlorinated ethenes. CSIA involves measuring the concentrations of carbon 12 and 13 in the chlorinated ethenes. Because it takes slightly more energy to break a bond with carbon-13 than carbon-12 because of its greater mass, microorganisms tend to metabolize carbon-12 more than carbon-13. This results in abiotic and biotic degradation of chlorinated ethenes having distinctive δ13C results.

A small number of carbon isotope analyses were performed on TCE from groundwater in the northwest plume by Lee et al. (2008), as shown in Table 4. The general slight decrease in the δ13C per mil analyses of TCE between the MW-197 control well and down gradient wells along the northwest plume (Figure 5), as well as other evidence from Phases I and II of the DOE-sponsored study, indicates that aerobic co-metabolic biodegradation of the TCE is occurring (Lee et al. 2008; KRCEE 2008, 13).

To apply the methods in Elsner et al. (2010) and identify any role of abiotic reactions in the dechlorination of TCE and other chlorinated ethenes in the RGA would require additional CSIA analyses on TCE samples. CSIA would also need to be performed on DCEs and vinyl chloride in the contaminated groundwater samples.

Table 4. Stable carbon isotope data on TCE from groundwater wells along the northwest plume.

MW-197 (Figure 5) is the control well (Lee et al. 2008).

|  |  |
| --- | --- |
| Monitoring Well | TCE 13δ per mil (‰) |
| MW-197 (control) | -23.1 |
|  |  |
| MW-168 | -24.8 |
| MW-262 | -25.8 |
| MW-340 | -25.9 |
| MW-185 | -25.9 |
| MW-66 | -25.3 |
| MW-242 | -24.6 |
| MW-125 | -25.6 |
| MW-381 | -25.4 |
| MW-236 | -25.3 |

### Correlations between Chlorinated Ethenes in RGA Groundwater Samples

Correlations between the concentrations of various chlorinated ethenes in the RGA groundwater reveal relationships between them, which may provide further insights into the abiotic and biotic degradation of TCE and other chlorinated ethenes as additional stable carbon isotope and other data are collected. Table 5 shows Pearson correlation results between the various chlorinated ethenes in RGA groundwater samples (including samples from the LRGA, MRGA and URGA). Each of the correlations in Table 5 is followed by the number of sample pairs in the correlation.

The Pearson correlations in Table 5 were tested for significance using the two-tailed t test procedures in Davis (1986, 66-67, 87-92). The null hypothesis for each of the 15 correlations states that the two tested parameters are independent. The results in Table 5 involve a set of comparisons where each parameter is compared with all of the others. The data set in Table 5 introduces a family wise error problem (Keppel 1991, 164-170), where the probability of committing a Type I error at the traditional α = 0.05 with the 15 comparisons in Table 5 is 54%. That is, there is a 54% probability of rejecting a null hypothesis and an accepting a correlation as significant when in reality it is not. To avoid a family wise error, α was reduced to 0.01, which reduces the probability of committing a Type I error to about 14%. Although this increases the chance of committing a Type II error, where significant correlations may be rejected as insignificant, with these data it would be better to miss a correlation than have a high probability of committing a Type 1 error. To better approximate the required normal distributions for the t tests, log10 values were used in the calculations (Davis 1986, 66-67, 87-92).

*Trans*-DCE versus chloride did not contain enough samples to provide any results. The correlations between 1,1-DCE and vinyl chloride and 1,1-DCE and chloride were not significant, which are shaded gray in Table 5. All of the other correlations were significant. Although correlation does not mean causation, it is interesting that except for the trans-DCE and chloride correlation, which had too few samples, all of reductive dechlorination reactants and products from TCE through *cis*-DCE and *trans*-DCE and to vinyl chloride showed correlations (Figure 10). No correlations were found between 1,1-DCE and is dechlorination products, vinyl chloride and chloride. Additional analyses and SCIA may provide additional insight into the meanings of these correlations.

Table 5. Data points for correlations & chlorinated ethene Pearson correlation coefficients (r) for RGA

Gray shading indicates that the correlations contained too few samples or were not significant at α = 0.01.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Compound | TCE | *cis*-DCE | *trans*-DCE | 1,1-DCE | Vinyl Chloride |
| TCE | --- | --- | --- | --- | --- |
| *cis*-DCE | 0.184; 964 | --- | --- | --- | --- |
| *trans*-DCE | 0.283; 51 | 0.134; 77 | --- | --- | --- |
| 1,1-DCE | 0.037; 410 | 0.104; 331 | 0.192; 47 | --- | --- |
| Vinyl Chloride | 0.091; 24 | 0.211; 18 | 0.473; 26 | -0.085; 39 | --- |
| Cl- | 0.079; 2,648 | 0.092; 224 | 0.929; 3 | -0.320; 17 | 0.866; 14 |

# Conclusions and Recommendations

PGDP RGA groundwater data suggests that TCE is degrading into DCEs, vinyl chloride and perhaps ethene through biotic ***reductive dechlorination*** in very localized sites in the RGA and perhaps in the UCRS. The role of abiotic reductive dechlorination is uncertain. The following recommendations will allow researchers to possibly identify abiotic mechanisms and better understand the geochemical processes in the RGA that would assist in remediation efforts:

* The following parameters should be routinely measured on RGA groundwater samples,:

Alkalinity (bicarbonate, carbonate)

Ammonium

Biochemical oxygen demand (BOD)

Calcium

Chloride

Copper

Dichloroethenes (*cis*-1,2-, *trans*-1,2-, 1,1-DCE)

Dissolved oxygen

Ethene

Iron (total, +2, dissolved +3)

Magnesium

Nitrate

Nitrite

Organic carbon – dissolved (DOC) and total (TOC)

pH

Potassium

Sodium

Sulfate

Sulfide

Tc-99

Trichloroethene (TCE)

Temperature

Vinyl chloride

Tc-99 and all chlorinated ethenes of environmental concern should be analyzed, including: TCE, DCEs, and vinyl chloride. Measurements are especially needed on the sparsely investigated northeast and southwest TCE plumes. Ethene (ethylene) analyses may also provide insights into reductive dechlorination.

Local redox conditions in the RGA would be better estimated with dissolved oxygen analyses and possibly sulfide, sulfate, nitrite, nitrate, Fe+2, dissolved Fe+3, and ammonium analyses, if the reducing parameters are present. Alkalinity (bicarbonate, carbonate), calcium, chloride, magnesium, pH, potassium, sodium, sulfate, and temperature are important in developing geochemical models for the RGA, which will allow researchers to better understand the overall abiotic processes in the aquifer.

Dissolved and total organic carbon analyses would yield information on the abundance of the food source for bacteria for either natural attenuation or microbial bioremediation of the chlorinated ethenes. KRCEE (2008, 19) also recommended performing routine copper and biochemical oxygen demand (BOD) analyses. Copper may have biocidal effects on subsurface microorganisms and the BOD analyses, in addition to total and dissolved organic carbon, are indicators of the amount of carbon available for microbial degradation processes (KRCEE 2008, 19). Detection limits should be consistent for each measured parameter and as low as possible.

* To distinguish any abiotic from biotic dechlorination, stable carbon isotope analyses (CSIA) are required on TCE, DCEs and vinyl chloride from all three TCE plumes in the RGA.
* Considering the geochemical history of the groundwater at the site, other inorganic and organic species (e.g., selenium, lead, and 1,1,1-trichloroethane) should only be periodically monitored to ensure that no MCLs are exceeded. If additional contaminants of concern arise in the RGA, they should be added to the list of routinely measured parameters. Redox measurements with platinum electrodes could continue, but would probably not be useful.
* Powder X-ray diffraction (XRD), scanning electron microscope (SEM) analyses, and light microscopy are required to identify the minerals in the contaminated RGA sediments.

The widespread occurrence of DCEs and vinyl chloride in the groundwater of the RGA indicates the presence of reductive dechlorination. Yet, the RGA is mostly oxidizing. The presence of magnetite or other metastable minerals in the sediments of the RGA might explain how reductive dechlorination could occur under otherwise aerobic conditions (*e.g.*, Wilson et al. 2009).

* Efforts should be made to find evidence of localized anaerobic environments in the RGA, (such as near sewage disposal sites) and possibly in the UCRS, which provides recharge to the RGA.
* After information on the mineralogy of the RGA is obtained, laboratory column and batch studies (such as those described in Lewis et al. 2010) are required to better understand the ability of TCE and other chlorinated ethenes to sorb onto the RGA sediments.
* Although databases in Geochemist’s Workbench® do not contain distribution coefficients and other data on chlorinated ethenes, when the distribution coefficients and data become available, they could be entered into the program to model sorption and other transport and fate processes. Obtaining a subscription to Geochemist’s Workbench® would also allow for additional mass balances and other evaluations of the data in PEGASIS. The subscription would cost $US 8,000 per year.

# Acknowledgements

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# Appendix A: Evaluation and Potential Applications of Groundwater Geochemistry Data from the Northwest Plume at the Paducah Gaseous Diffusion Plant

Evaluation and Potential Applications of Groundwater Geochemistry Data from the Northwest Plume at the Paducah Gaseous Diffusion Plant

Evaluation of Data Quality

**Introduction**

In 2013-2014, groundwater data from monitoring wells at 1,201 station locations along and near the northwest plume were downloaded from the PEGASIS database. Information on detection limits and other quality control and assurance data are in the database. Additional data evaluations were performed with a temporarily available, scaled-down academic version of Geochemist’s Workbench®. Geochemist’s Workbench®, which was developed by Aqueous Solutions L.L.C. of Champaign, Illinois, USA (<http://www.gwb.com/>), is a computer software program that can solve a variety of problems in aqueous geochemistry. The KRCEE currently does not have a subscription to the program to evaluate the rest of the PEGASIS database.

**Charge Balances**

If the chemical analyses of a water sample are reliable and complete, the number of cation charges should equal the number of anion charges. The following equation is used to calculate the error in an ion balance analysis of a water sample:

*E*% = [(Σ /z/mc - Σ /z/ma) / (Σ /z/mc + Σ /z/ma)] x 100

where:

*E* = charge balance error in %.

mc = moles of each cation

ma = moles of each anion

/z/ = absolute value of the charge of the ion

Determining the charge balance error of a water sample requires that at least the concentrations of all major (> 1 milligrams per liter, mg/L) and minor (0.1 to 1 mg/L) ions be entered into the equation. Most natural waters contain at least minor concentrations of the following chemical species: dissolved calcium (Ca2+), dissolved magnesium (Mg2+), dissolved potassium (K+), dissolved sodium (Na+), alkalinity (as CaCO3), chloride (Cl-), and dissolved sulfate (SO42-). Because these chemical species are usually at concentrations above 0.1 mg/L, failure to measure any of them often results in poor or at least questionable ion balances. In the initial review of the monitoring well data in and around the northwest plume, any sample that omitted one or more of the following parameters was removed from further consideration and its quality was considered unknown: Ca2+, Mg2+, K+, Na+, pH, temperature, alkalinity, Cl-, and SO42-. This reduced the list of possibly reliable samples down to about 600. Even if the concentrations were below 0.1 mg/L, Ca2+, Mg2+, K+, Na+, alkalinity as CaCO3, Cl- and SO42- were always entered into the charge balance calculations along with pH and temperature. In some samples, fluoride, nitrate, sulfite, and any other ions were measured at concentrations above 0.1 mg/L. With the exception of aluminum, these species were also entered into the charge balance calculations. Aluminum created an unusual problem. For reason(s) that are not exactly known, Geochemist’s Workbench® often failed to calculate a charge balance if aluminum was entered into the program. The problem did not occur with iron, manganese, or other metals.

Based on tradition, the charge balance error (*E*) of a sample is expected to be within +/-5%. However, errors up to +/-10% are usually tolerable. If the charge-balance error for a sample exceeds +/-10%, then:

* a significant error may be present in at least one of the analyses.
* some ions that are usually not in significant concentrations in natural waters may be substantially present in the sample and were overlooked and not measured (such as, boron or fluoride). There are analytical methods that can quickly scan a sample for most of the elements in the periodic table. In general, these screening methods are only qualitative or perhaps semi-quantitative. However, if unusual elements are detected, the sample may be reanalyzed with more precise methods.
* some elements have variable valence states and diverse chemical speciation (*e.g*., iron, selenium, and manganese). Often, chemical analyses only provide the total concentrations of these elements or make assumptions about the chemical speciation. If these assumptions are incorrect, they may contribute significant errors to the charge balance.

Significant errors in cation and anion analyses may cancel each other out. Therefore, a low charge balance error **does not** guarantee the accuracy of the chemical analyses of a water sample.

A total of 255 samples from the PEGASIS database with minimum analyses of Ca2+, Mg2+, K+, Na+, pH, temperature, alkalinity, Cl-, and SO42- provided charge balances within +/-5% and an additional 56 samples were within +/- 5 to 10% (Appendix B). This is a total of 311 samples (Appendices B and C). The 311 samples were taken from wells at 83 station locations.

**Chemistry Plots**

Some of the parameters in the 311 samples are expected to have highly linear correlations (such as: total dissolved solids [TDS] vs. conductivity or dissolved magnesium vs. dissolved calcium). Although a strong correlation does not necessarily indicate a direct cause or relationship, graphs of these paired parameters may be used to identify suspicious outliers in the groundwater measurements.

A total of 247 of the 311 samples had both TDS and conductivity measurements. The coefficient of determination (R2) of a TDS versus conductivity plot of the 247 samples is 0.96. As shown in Figure A-1, three minor outliers are noticeable. They are from sample locations MW255, MW288, and MW404-PRT4 (Table A-1). Although they are suspicious, the three measurements are not radically different from the other samples and they could be valid analyses.

Figure A-1. A plot of total dissolved solids (TDS) versus conductivity for 247 groundwater samples from monitoring wells along or near the northwest plume at the PGDP. The black line is the best fit with a coefficient of determination (R2) of 0.96. Three outliers are circled in red and identified in Table A-1.

Mg2+ and Ca2+ are alkaline earth elements that have very similar chemical properties. Their concentrations often show a strong positive correlation in natural water samples. All 311 samples had dissolved calcium and magnesium measurements. As shown in Figure A-2, dissolved calcium and magnesium have a good positive correlation (R2 = 0.98). No pronounced outliers are seen.

Figure A-2. A plot of Ca2+ versus Mg2+ for 311 groundwater samples from monitoring wells along or near the northwest plume at the PGDP. The black line is the best fit with R2 = 0.98. No pronounced outliers are noticeable.

R2 = 0.98

For some of the 311 samples, both the total and dissolved concentrations of an element were measured. Because the total concentration of any analyte should include its dissolved concentration, the total concentration should equal or exceed its dissolved concentration. Spreadsheets of the 311 samples may be inspected for any samples that have dissolved concentrations that exceed their total concentrations. However, such discrepancies can be more easily identified as outliers on graphs.

Table A-1. Location names, collection dates, and project sample numbers of outliers on various plots of chemical data from among the 311 groundwater samples from monitoring wells along or near the northwest plume at the PGDP. See text for details. Shaded gray samples have charge balance errors (*E*) of +/- 5.0 to 10%.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Figure | Plotted Parameters | Location Name | Date Collected | Sample Number | Charge Balance (*E*%) for the Sample from Appendix A | Likely Cause of Outlier |
| 1 | TDS vs. Conductivity | MW 255 | 11/12/2003 | MW255Q1-04 | -0.5 | Unusual analyses that may be accurate |
| 1 | TDS vs. Conductivity | MW 288 | 11/7/2007 | MW288A1-08 | -5.1 | Unusual analyses that may be accurate |
| 1 | TDS vs. Conductivity | MW 404-PRT4 | 9/30/2008 | MW404P4UGA1-08 | -0.1 | Unusual analyses that may be accurate |
| 3 | Total vs. Dissolved Al | 720-011 | 5/16/1998 | 720011WA120 | 0.1 | Unknown |
| 7 | Total vs. Dissolved Ba | MW 439 | 12/14/2010 | MW439A1-11 | -5.7 | Unknown |
| 5 | Total vs. Dissolved Ca | MW 243 | 11/4/2002 | MW243QS1-03 | 7.9 | Data entered as mg/L rather than µg/L |
| 5 | Total vs. Dissolved Ca | MW 244 | 11/4/2002 | MW244QS1-03 | 9.8 | Data entered as mg/L rather than µg/L |
| 5 | Total vs. Dissolved Ca | MW 248 | 11/4/2002 | MW248QS1-03 | 8.9 | Data entered as mg/L rather than µg/L |
| 5 | Total vs. Dissolved Ca | MW 249 | 11/4/2002 | MW249QS1-03 | 8.3 | Data entered as mg/L rather than µg/L |
| 4 | Total vs. Dissolved Fe | 720-011 | 5/15/1998 | 720011WA085 | 0.1 | Unknown |
| 6 | Total vs. Dissolved Mg | MW 243 | 11/4/2002 | MW243QS1-03 | 7.9 | Data entered as mg/L rather than µg/L |
| 6 | Total vs. Dissolved Mg | MW 244 | 11/4/2002 | MW244QS1-03 | 9.8 | Data entered as mg/L rather than µg/L |
| 6 | Total vs. Dissolved Mg | MW 248 | 11/4/2002 | MW248QS1-03 | 8.9 | Data entered as mg/L rather than µg/L |
| 6 | Total vs. Dissolved Mg | MW 249 | 11/4/2002 | MW249QS1-03 | 8.3 | Data entered as mg/L rather than µg/L |
| 8 | Total vs. Dissolved Zn | 720-019 | 5/5/1998 | 720019WA080 | 1.1 | Unknown |
| 8 | Total vs. Dissolved Zn | MW 255 | 11/17/2004 | MW255Q1-05 | 0.5 | Unknown |

From among the 311 samples, graphs were prepared of elements with at least 30 pairs of total and dissolved results. For most trace elements, modern analytical methods should be able to distinguish between total and dissolved concentrations with differences of greater than 50 µg/L. So, if the dissolved concentration of a trace element exceeded its total concentration by at least 50 µg/L, the sample was identified as an outlier. As shown below, outliers were detected in a number of plots of total versus dissolved concentrations.

Only 39 of the 311 samples had both dissolved and total aluminum measurements. Figure A-3 is a graph of most of the total versus dissolved aluminum concentrations. The black solid 1:1 line in the graph represents equal concentrations of dissolved and total aluminum. All of the data points should be on or above the line. As shown in Figure A-3 and Table A-1, only one sample, 720011WA120 from Station Location 720-011 on May 16, 1998, was below the line and had a dissolved aluminum concentration that exceeded its total aluminum concentration by more than 50 µg/L. To better visualize this outlier, samples with total aluminum concentrations of 1,000 to nearly 60,000 µg/L, all of which are above the black line, are not shown in Figure A-3.

Figure A-3. A plot of total versus dissolved aluminum for samples from among the 311 groundwater samples from monitoring wells along or near the northwest plume at the PGDP. The black line represents equal concentrations of total and dissolved aluminum. For clarity, samples with total aluminum concentrations of 1,000 to nearly 60,000 µg/L are not shown on the graph. However, none of these samples had dissolved concentrations that exceeded their total concentrations. One outlier is identified and is circled in red. See the text and Table A-1 for additional details.

720-011 5/16/1998 WA120

A total of 90 of the 311 samples had both measured total and dissolved iron concentrations. One sample with anomalous iron was identified and, like aluminum, it is from location 720-011 (Figure A-4; Table A-1). The project sample number of the outlier is 720011WA085 and it was collected on May 15, 1998.

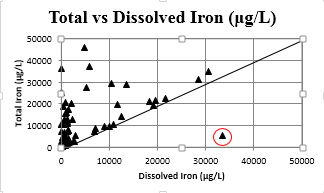


Figure A-4. A plot of total versus dissolved iron for samples from among the 311 groundwater samples from monitoring wells along or near the northwest plume at the PGDP. The black line represents equal concentrations of total and dissolved iron. For clarity, samples with total iron concentrations of 50,000 to 224,000 µg/L are not shown on the graph, but all of them had lower dissolved iron concentrations. One outlier is identified and is circled in red. See the text and Table A-1 for additional details.

All 311 samples had both total and dissolved calcium and magnesium measurements. In many cases, the total concentrations were slightly lower (few mg/L) than the dissolved concentrations as shown in Figures A-5 and A-6. Four samples from locations MW243, MW244, MW248 and MW249 had total calcium and magnesium concentrations about 1000 times lower than their dissolved values (Figures A-5 and A-6; Table A-1). In all cases, the total calcium and magnesium concentrations were probably mistakenly entered into the PEGASIS database as mg/L rather than µg/L values.

The total and dissolved concentrations for barium and zinc also had some outliers. A total of 307 of the 311 samples had both dissolved and total barium measurements. The barium results had one substantial outlier as shown in Table A-1 and Figure A-7. A total of 66 of the 311 samples had total and dissolved zinc analyses. The zinc results had two substantial outliers as shown in Figure A-8 and listed in Table A-1.

Dissolved and total concentrations of antimony, arsenic, beryllium, cadmium, chromium, cobalt, copper, lead, manganese, molybdenum, nickel, selenium and vanadium were also measured in some of the 311 samples. However, the dissolved and total analyses of these elements either showed no significant (> 50 µg/L) outliers or involved less than 30 samples and were not plotted.

Although not all of the chemical data in the PEGASIS database could be readily evaluated, charge balance analyses and data plots provide some indication of the level and limitations of the results in the database. A total of 311 of the samples in the database had complete enough data and yielded a charge balance error (*E*) within +/-10%. Available data plots for several elements, TDS, and conductivity from the 311 samples indicate that the vast majority of these data are reasonably consistent.

Figure A-5. A plot of total versus dissolved calcium for the 311 groundwater samples from monitoring wells along or near the northwest plume at the PGDP. The black line represents equal concentrations of total and dissolved calcium. Four outliers are identified and circled in red. See the text and Table A-1 for additional details.

Figure A-6. A plot of total versus dissolved magnesium for the 311 groundwater samples from monitoring wells along or near the northwest plume at the PGDP. The black line represents equal concentrations of total and dissolved magnesium. Four outliers are identified and circled in red. See the text and Table A-1 for additional details.

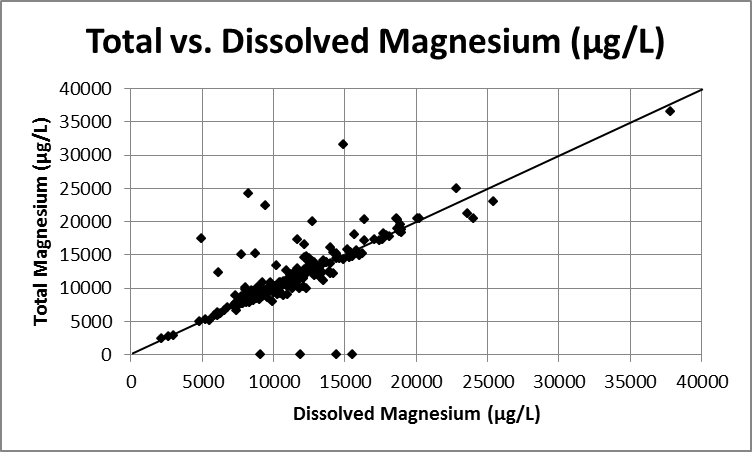


Figure A-7: A plot of total versus dissolved barium for samples from among the 311 samples groundwater samples from monitoring wells along or near the northwest plume at the PGDP. The black line represents equal concentrations of total and dissolved barium. Several samples had barium measurements above 500 µg/L, which for clarity are not shown in the figure. However, none of these samples had dissolved concentrations that exceeded their total concentrations. One outlier, where the dissolved concentration exceeded its total concentration by more than 50 µg/L, is identified and circled in red. See the text and Table A-1 for additional details.

Figure A-8. A plot of total versus dissolved zinc for samples from among the 311 groundwater samples from monitoring wells along or near the northwest plume at the PGDP. The black line represents equal concentrations of total and dissolved zinc. Several samples had zinc measurements above 200 µg/L, which for clarity are not shown in the figure. However, none of these samples had dissolved concentrations that exceed their total concentrations. Two outliers, where the dissolved concentrations exceeded their total concentrations by more than 50 µg/L, are identified and circled in red. See the text and Table A-1 for additional details.

Appendices B and C

Appendix B: Ion Balance Errors (*E*%) for 311 Groundwater Analyses from PGDP

Samples with +/- 5-10% *E* values are shaded gray

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Station Name** | **Date Collected** | **Lab Sample ID** | **Project Sample ID** | **Ion Balance, *E*%** | **Notes** |
| 001-175 | 5/12/1998 | 981335-1 | 001175WA065 | 3.4 |  |
| 001-176 | 5/29/1998 | 981466-10 | 001176WA065 | -1.5 |  |
| 001-176 | 5/29/1998 | 981466-9 | 001176WA070 | -1.6 |  |
| 001-176 | 5/29/1998 | 981466-8 | 001176WA075 | -0.1 |  |
| 001-176 | 5/29/1998 | 981477-9 | 001176WA080 | 4.0 |  |
| 001-176 | 5/29/1998 | 981477-14 | 001176WD080 | 1.0 |  |
| 001-177 | 5/21/1998 | 981477-19 | 001177WA065 | -1.9 |  |
| 001-177 | 5/26/1998 | 981477-7 | 001177WA085 | 1.4 |  |
| 001-177 | 5/26/1998 | 981477-17 | 001177WD080 | 2.0 |  |
| 001-177 | 5/26/1998 | 981477-4 | 001177WD085 | 9.6 |  |
| 001-177 | 6/10/1998 | 981642-10 | 001177WA090 | 2.2 |  |
| 001-177 | 6/10/1998 | 981642-17 | 001177WA095 | 1.8 |  |
| 001-177 | 6/10/1998 | 981642-3 | 001177WA105 | -0.2 |  |
| 001-177 | 6/11/1998 | 981642-2 | 001177WA120 | -1.5 |  |
| 001-177 | 6/11/1998 | 981642-14 | 001177WA140 | -2.7 |  |
| 001-180 | 6/2/1998 | 981548-1 | 001180WA060 | -1.4 |  |
| 001-180 | 6/2/1998 | 981548-2 | 001180WA065 | -0.5 |  |
| 001-182 | 6/11/1998 | 981642-13 | 001182WA070 | -0.1 |  |
| 001-182 | 6/11/1998 | 981642-12 | 001182WD070 | -3.1 |  |
| 720-011 | 5/15/1998 | 981334-6 | 720011WA075 | -0.03 | Dissolved Al concentration not used, see text |
| 720-011 | 5/15/1998 | 981334-10 | 720011WA080 | -4.1 |  |
| 720-011 | 5/15/1998 | 981334-9 | 720011WA085 | 0.1 | Dissolved Al concentration not used, see text |

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Station Name** | **Date Collected** | **Lab Sample ID** | **Project Sample ID** | **Ion Balance, *E*%** | **Notes** |
| 720-011 | 5/16/1998 | 981376-1 | 720011WA090 | 0.1 | Dissolved Al concentration not used, see text |
| 720-011 | 5/16/1998 | 981376-2 | 720011WA095 | 7.2 | Dissolved Al concentration not used, see text |
| 720-011 | 5/16/1998 | 981376-3 | 720011WA100 | 0.1 | Dissolved Al concentration not used, see text |
| 720-011 | 5/16/1998 | 981376-4 | 720011WA120 | 0.1 | Dissolved Al concentration not used, see text |
| 720-011 | 5/16/1998 | 981376-5 | 720011WA140 | 2.0 |  |
| 720-013 | 4/29/1998 | 981214-21 | 720013WA070 | -2.0 |  |
| 720-013 | 4/30/1998 | 981214-20 | 720013WA075 | -0.5 |  |
| 720-013 | 4/30/1998 | 981203-2 | 720013WA080 | -1.7 |  |
| 720-013 | 4/30/1998 | 981214-19 | 720013WA085 | -0.1 | Dissolved Al concentration not used, see text |
| 720-013 | 4/30/1998 | 981214-18 | 720013WA090 | 0.01 | Dissolved Al concentration not used, see text |
| 720-013 | 4/30/1998 | 981214-17 | 720013WA120 | -5.2 |  |
| 720-017 | 5/2/1998 | 981214-22 | 720017WA075 | -0.02 | Dissolved Al concentration not used, see text |
| 720-017 | 5/4/1998 | 981246-2 | 720017WA080 | 1.4 |  |
| 720-017 | 5/4/1998 | 981246-4 | 720017WA085 | 0.6 |  |
| 720-017 | 5/4/1998 | 981246-7 | 720017WA090 | -0.05 | Dissolved Al concentration not used, see text |
| 720-017 | 5/4/1998 | 981246-6 | 720017WA095 | 1.2 |  |
| 720-017 | 5/4/1998 | 981246-1 | 720017WA120 | 6.5 |  |
| 720-017 | 5/4/1998 | 981246-3 | 720017WA140 | 0.3 |  |
| 720-019 | 5/5/1998 | 981246-8 | 720019WA075 | 0.1 | Dissolved Al concentration not used, see text |
| 720-019 | 5/5/1998 | 981246-9 | 720019WA080 | 1.1 |  |
| 720-019 | 5/5/1998 | 981246-5 | 720019WA085 | 2.8 |  |
| 720-019 | 5/5/1998 | 981243-8 | 720019WA090 | -6.4 |  |
| 720-026 | 5/20/1998 | 981412-4 | 720026WA080 | 1.1 |  |
| 720-026 | 5/20/1998 | 981412-6 | 720026WA085 | 1.3 |  |
| 720-026 | 5/20/1998 | 981412-5 | 720026WD085 | 0.9 |  |
| 720-028 | 6/2/1998 | 981548-3 | 720028WA070 | -0.3 |  |
| 720-028 | 6/2/1998 | 981548-4 | 720028WA080 | 0.1 |  |
| **Station Name** | **Date Collected** | **Lab Sample ID** | **Project Sample ID** | **Ion Balance, *E*%** | **Notes** |
| 720-028 | 6/3/1998 | 981548-5 | 720028WA085 | 0.1 |  |
| 720-028 | 6/3/1998 | 981599-3 | 720028WA090 | 3.1 |  |
| 720-028 | 6/3/1998 | 981548-7 | 720028WA100 | 0.8 |  |
| 720-028 | 6/3/1998 | 981599-6 | 720028WA120 | 6.0 |  |
| 720-028 | 6/3/1998 | 981599-5 | 720028WD090 | 2.4 |  |
| 720-029 | 5/27/1998 | 981466-5 | 720029WA060 | -3.3 |  |
| 720-029 | 5/28/1998 | 981477-11 | 720029WA080 | 0.9 |  |
| 720-029 | 5/29/1998 | 981477-15 | 720029WA095 | 1.4 |  |
| 720-029 | 5/29/1998 | 981477-22 | 720029WA100 | 4.0 |  |
| 720-029 | 5/29/1998 | 981477-21 | 720029WA120 | 1.9 |  |
| 720-029 | 5/29/1998 | 981477-16 | 720029WD095 | 0.5 |  |
| 720-029 | 5/30/1998 | 981477-20 | 720029WA140 | -1.1 |  |
| MW100 | 11/6/2007 | C073100112 | MW100A1-08 | -3.8 |  |
| MW100 | 9/8/2008 | C082530002 | MW100UGA1-08 | -1.2 |  |
| MW100 | 12/15/2008 | C08350035001 | MW100A1-09 | -0.3 |  |
| MW100 | 11/9/2009 | C09313026005 | MW100A1-10 | -2.5 |  |
| MW124 | 11/14/2001 | C013180045 | MW124Q1-02 | -4.1 |  |
| MW124 | 11/11/2002 | C023160005 | MW124Q1-03 | 5.7 |  |
| MW124 | 11/17/2003 | C033210103 | MW124Q1-04 | 0.1 |  |
| MW124 | 11/18/2004 | C043240003 | MW124Q1-05 | -1.5 |  |
| MW125 | 11/21/2006 |  | MW125A1-07 | 9.1 |  |
| MW125 | 11/6/2007 | C073100079 | MW125A1-08 | -3.6 |  |
| MW125 | 9/9/2008 | C082530030 | MW125UGA1-08 | -2.3 |  |
| MW125 | 12/10/2008 | C08345016002 | MW125A1-09 | -1.0 |  |
| MW125 | 11/9/2009 | C09313026003 | MW125A1-10 | -1.6 |  |
| MW126 | 11/12/2002 | C023170002 | MW126Q1-03 | 6.3 |  |
| MW126 | 11/17/2003 | C033210104 | MW126Q1-04 | 2.8 |  |
| **Station Name** | **Date Collected** | **Lab Sample ID** | **Project Sample ID** | **Ion Balance, *E*%** | **Notes** |
| MW126 | 11/18/2004 | C043240004 | MW126Q1-05 | -1.7 |  |
| MW134 | 11/6/2007 | C073100080 | MW134A1-08 | -3.6 |  |
| MW134 | 9/16/2008 | C082600208 | MW134UGA1-08 | -1.7 |  |
| MW134 | 12/10/2008 | C08345016003 | MW134A1-09 | -2.7 |  |
| MW134 | 11/9/2009 | C09313026002 | MW134A1-10 | -1.7 |  |
| MW145 | 12/10/1998 | C983450002 | 5733-98 | 1.4 |  |
| MW145 | 11/17/1999 | C993210085 | MW145Q1-00 | -2.5 |  |
| MW145 | 11/13/2000 | C003190005 | MW145Q1-01 | -3.2 |  |
| MW145 | 11/13/2002 | C023170076 | MW145DQ1-03 | 4.0 |  |
| MW145 | 11/13/2002 | C023170077 | MW145Q1-03 | 4.7 |  |
| MW145 | 11/12/2003 | C033170058 | MW145DQ1-04 | -4.4 |  |
| MW145 | 11/12/2003 | C033170057 | MW145Q1-04 | -1.5 |  |
| MW145 | 11/23/2004 | C043280024 | MW145DQ1-05 | -1.2 |  |
| MW145 | 11/23/2004 | C043280023 | MW145Q1-05 | -1.1 |  |
| MW145 | 11/6/2007 | C073100203 | MW145A1-08 | 0.1 |  |
| MW145 | 9/17/2008 | C082610054 | MW145UGA1-08 | -1.4 |  |
| MW145 | 12/10/2008 | C08345016001 | MW145A1-09 | -2.1 |  |
| MW145 | 11/4/2009 | C09308037001 | MW145A1-10 | -1.9 |  |
| MW152 | 11/6/2007 | C073100204 | MW152A1-08 | -4.5 |  |
| MW152 | 9/8/2008 | C082530000 | MW152UGA1-08 | -3.1 |  |
| MW152 | 11/19/2008 | C08325001001 | MW152A1-09 | -8.2 |  |
| MW152 | 11/5/2009 | C09309011002 | MW152A1-10 | -2.8 |  |
| MW161 | 12/7/2005 |  | MW161A1-06 | 4.6 |  |
| MW161 | 11/8/2007 | C073120081 | MW161A1-08 | -2.0 |  |
| MW161 | 10/1/2008 | C082760003 | MW161UGA1-08 | 0.6 |  |
| MW161 | 11/18/2008 | C08323017003 | MW161A1-09 | -3.1 |  |
| MW161 | 11/12/2009 | C09316037003 | MW161A1-10 | -1.5 |  |
| **Station Name** | **Date Collected** | **Lab Sample ID** | **Project Sample ID** | **Ion Balance, *E*%** | **Notes** |
| MW163 | 11/5/2007 | C073090074 | MW163A1-08 | -2.5 |  |
| MW163 | 9/11/2008 | C082550119 | MW163UGA1-08 | -2.4 |  |
| MW163 | 11/18/2008 | C08323017001 | MW163A1-09 | -1.8 |  |
| MW163 | 11/12/2009 | C09316037002 | MW163A1-10 | -0.5 |  |
| MW179 | 3/14/1994 | 940315-010 | 4813-94 | -2.8 |  |
| MW188 | 11/11/2009 | C09315016003 | MW188A1-10 | -1.8 |  |
| MW193 | 11/6/2007 | C073100111 | MW193A1-08 | -2.8 |  |
| MW193 | 9/10/2008 | C082540117 | MW193UGA1-08 | -2.4 |  |
| MW193 | 12/17/2008 | C08352015001 | MW193A1-09 | -1.0 |  |
| MW193 | 11/9/2009 | C09313026004 | MW193A1-10 | -2.5 |  |
| MW20 | 9/21/1993 | 930923-092 | 6860-93 | -0.3 |  |
| MW201 | 11/6/2007 | C073100110 | MW201A1-08 | -3.2 |  |
| MW201 | 9/9/2008 | C082530031 | MW201UGA1-08 | -3.4 |  |
| MW201 | 12/10/2008 | C08345011001 | MW201A1-09 | -2.3 |  |
| MW201 | 11/10/2009 | C09314022001 | MW201A1-10 | -4.4 |  |
| MW206 | 12/7/2005 |  | MW206A1-06 | 3.5 |  |
| MW206 | 11/5/2007 | C073090075 | MW206A1-08 | -2.0 |  |
| MW206 | 9/22/2008 | C082660085 | MW206UGA1-08 | -1.8 |  |
| MW206 | 11/18/2008 | C08323017002 | MW206A1-09 | -0.5 |  |
| MW206 | 11/9/2009 | C09313028002 | MW206A1-10 | -3.1 |  |
| MW233 | 11/6/2002 | C023100084 | MW233QN1-03 | 9.3 |  |
| MW233 | 11/5/2003 | C033090033 | MW233QN1-04 | -0.9 |  |
| MW233 | 11/4/2004 | C043090148 | MW233QN1-05 | -0.7 |  |
| MW236 | 11/6/2002 | C023100085 | MW236QN1-03 | 9.0 |  |
| MW236 | 11/5/2003 | C033090034 | MW236QN1-04 | -1.6 |  |
| MW236 | 11/4/2004 | C043090149 | MW236QN1-05 | -0.5 |  |
| MW237 | 11/5/2003 | C033090055 | MW237QN1-04 | 5.9 |  |
| **Station Name** | **Date Collected** | **Lab Sample ID** | **Project Sample ID** | **Ion Balance, *E*%** | **Notes** |
| MW238 | 11/6/2002 | C023100086 | MW238QN1-03 | 4.6 |  |
| MW238 | 11/8/2004 | C043130027 | MW238QN1-05 | -0.4 |  |
| MW239 | 11/4/1999 | C993080154 | MW239QN1-00 | -8.4 |  |
| MW239 | 11/5/2003 | C033090056 | MW239QN1-04 | -4.7 |  |
| MW239 | 11/4/2004 | C043090140 | MW239QN1-05 | -9.7 |  |
| MW240 | 11/5/2002 | C023090087 | MW240DQN1-03 | 7.9 |  |
| MW240 | 11/5/2002 | C023090086 | MW240QN1-03 | 9.3 |  |
| MW240 | 11/3/2003 | C033080004 | MW240DQN1-04 | -6.8 |  |
| MW240 | 11/3/2003 | C033080003 | MW240QN1-04 | -5.6 |  |
| MW240 | 11/8/2004 | C043130028 | MW240DQN1-05 | -2.0 |  |
| MW240 | 11/8/2004 | C043130029 | MW240QN1-05 | -1.6 |  |
| MW241 | 11/5/2002 | C023090090 | MW241QN1-03 | 7.3 |  |
| MW241A | 11/3/2003 | C033080005 | MW241AQN1-04 | -1.4 |  |
| MW241A | 11/4/2004 | C043090139 | MW241AQN1-05 | 0.2 |  |
| MW242 | 11/6/2003 | C033100060 | MW242QS1-04 | -3.4 |  |
| MW242 | 11/10/2004 | C043150059 | MW242QS1-05 | 2.0 |  |
| MW242 | 11/20/2006 |  | MW242A1-07 | 4.2 |  |
| MW242 | 11/7/2007 | C073110057 | MW242A1-08 | -2.6 |  |
| MW242 | 9/10/2008 | C082540115 | MW242UGA1-08 | -1.3 |  |
| MW242 | 11/17/2008 | C08323007001 | MW242A1-09 | -0.4 |  |
| MW242 | 11/4/2009 | C09308041001 | MW242A1-10 | -2.3 |  |
| MW243 | 11/4/2002 | C023080048 | MW243QS1-03 | 7.9 |  |
| MW243 | 11/10/2003 | C033140186 | MW243QS1-04 | 2.4 |  |
| MW243 | 11/9/2004 | C043150000 | MW243QS1-05 | 0.0 |  |
| MW243 | 11/8/2007 | C073120082 | MW243A1-08 | -2.4 |  |
| MW243 | 9/10/2008 | C082540116 | MW243UGA1-08 | -3.9 |  |
| MW243 | 12/16/2008 | C08351020001 | MW243A1-09 | 0.3 |  |
| **Station Name** | **Date Collected** | **Lab Sample ID** | **Project Sample ID** | **Ion Balance, *E*%** | **Notes** |
| MW243 | 11/4/2009 | C09308041002 | MW243A1-10 | -3.4 |  |
| MW244 | 11/6/2003 | C033100061 | MW244QS1-04 | -3.5 |  |
| MW244 | 11/8/2004 | C043140044 | MW244QS1-05 | -0.4 |  |
| MW245 | 11/8/2004 | C043140045 | MW245QS1-05 | 7.2 |  |
| MW248 | 11/4/2002 | C023080049 | MW248QS1-03 | 8.9 |  |
| MW248 | 11/10/2003 | C033140185 | MW248QS1-04 | -0.6 |  |
| MW248 | 11/9/2004 | C043150003 | MW248QS1-05 | -1.3 |  |
| MW249 | 11/7/2001 | C013120004 | MW249QS1-02 | -3.6 |  |
| MW249 | 11/4/2002 | C023080051 | MW249QS1-03 | 8.3 |  |
| MW249 | 11/10/2003 | C033140184 | MW249QS1-04 | -0.7 |  |
| MW249 | 11/9/2004 | C043150004 | MW249QS1-05 | 1.9 |  |
| MW250 | 11/10/2003 | C033140187 | MW250QS1-04 | 2.6 |  |
| MW250 | 11/10/2004 | C043150058 | MW250QS1-05 | 0.6 |  |
| MW255 | 11/17/1999 | C993210086 | MW255Q1-00 | -1.3 |  |
| MW255 | 11/13/2002 | C023170075 | MW255Q1-03 | 6.8 |  |
| MW255 | 11/12/2003 | C033170061 | MW255Q1-04 | -0.5 |  |
| MW255 | 11/17/2004 | C043230015 | MW255Q1-05 | 0.5 |  |
| MW255 | 11/7/2007 | C073110092 | MW255A1-08 | -1.1 |  |
| MW255 | 10/1/2008 | C082750073 | MW255UGA1-08 | 0.3 |  |
| MW255 | 11/18/2008 | C08324001001 | MW255A1-09 | -2.1 |  |
| MW255 | 11/9/2009 | C09313028001 | MW255A1-10 | -1.5 |  |
| MW256 | 11/13/2002 | C023170074 | MW256Q1-03 | 6.8 |  |
| MW256 | 11/12/2003 | C033170060 | MW256Q1-04 | -2.6 |  |
| MW256 | 11/17/2004 | C043230014 | MW256Q1-05 | 0.6 |  |
| MW256 | 11/7/2007 | C073110091 | MW256A1-08 | -4.6 |  |
| MW256 | 10/1/2008 | C082750072 | MW256UGA1-08 | 0.3 |  |

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Station Name** | **Date Collected** | | **Lab Sample ID** | | **Project Sample ID** | | **Ion Balance, *E*%** | | **Notes** | |
| MW256 | 11/5/2009 | | C09309023003 | | MW256A1-10 | | -3.1 | |  | |
| MW257 | 11/7/2007 | | C073110093 | | MW257A1-08 | | -3.7 | |  | |
| MW257 | 9/23/2008 | | C082670077 | | MW257UGA1-08 | | 0.4 | |  | |
| MW257 | 11/18/2008 | | C08324001002 | | MW257A1-09 | | -1.8 | |  | |
| MW257 | 11/11/2009 | | C09315016004 | | MW257A1-10 | | -0.5 | |  | |
| MW258 | 11/18/1999 | | C993230018 | | MW258DQ1-00 | | -1.9 | |  | |
| MW258 | 11/18/1999 | | C993230017 | | MW258Q1-00 | | -1.3 | |  | |
| MW258 | 11/13/2002 | | C023170073 | | MW258Q1-03 | | 4.3 | |  | |
| MW258 | 11/12/2003 | | C033170059 | | MW258Q1-04 | | -5.4 | |  | |
| MW258 | 11/23/2004 | | C043280022 | | MW258Q1-05 | | -2.6 | |  | |
| MW258 | 11/7/2007 | | C073110090 | | MW258A1-08 | | -2.2 | |  | |
| MW258 | 9/17/2008 | | C082610055 | | MW258UGA1-08 | | -0.1 | |  | |
| MW258 | 11/19/2008 | | C08324018001 | | MW258A1-09 | | 0.9 | |  | |
| MW258 | 11/4/2009 | | C09308037002 | | MW258A1-10 | | -0.5 | |  | |
| MW260 | 11/5/2007 | | C073090065 | | MW260A1-08 | | -2.0 | |  | |
| MW260 | 11/5/2007 | | C073090066 | | MW260DA1-08 | | -3.3 | |  | |
| MW260 | 9/11/2008 | | C082550118 | | MW260UGA1-08 | | -2.9 | |  | |
| MW260 | 11/19/2008 | | C08324018003 | | MW260A1-09 | | -1.1 | |  | |
| MW260 | 11/19/2008 | | C08324018004 | | MW260DA1-09 | | -1.6 | |  | |
| MW260 | 11/11/2009 | | C09315016001 | | MW260A1-10 | | -1.5 | |  | |
| MW260 | 11/11/2009 | | C09315016002 | | MW260DA1-10 | | -0.3 | |  | |
| MW261 | 11/8/2007 | | C073120080 | | MW261A1-08 | | -1.0 | |  | |
| MW261 | 9/23/2008 | | C082670078 | | MW261UGA1-08 | | 1.4 | |  | |
| MW261 | 11/18/2008 | | C08324001003 | | MW261A1-09 | | 1.1 | |  | |
| MW261 | 11/11/2009 | | C09315016005 | | MW261A1-10 | | -3.7 | |  | |
| MW283 | 11/13/2002 | | C023170027 | | MW283Q1-03 | | 5.2 | |  | |
| MW283 | 11/13/2003 | | C033180000 | | MW283Q1-04 | | -1.7 | |  | |
| **Station Name** | **Date Collected** | | **Lab Sample ID** | | **Project Sample ID** | | **Ion Balance, *E*%** | | **Notes** | |
| MW284 | 11/13/2002 | | C023170028 | | MW284Q1-03 | | 5.9 | |  | |
| MW284 | 11/13/2003 | | C033180001 | | MW284Q1-04 | | -0.8 | |  | |
| MW284 | 11/23/2004 | | C043280025 | | MW284Q1-05 | | -2.1 | |  | |
| MW288 | 11/11/2002 | | C023160007 | | MW288Q1-03 | | 4.1 | |  | |
| MW288 | 11/13/2003 | | C033180002 | | MW288Q1-04 | | 0.4 | |  | |
| MW288 | 11/18/2004 | | C043240001 | | MW288Q1-05 | | -1.4 | |  | |
| MW288 | 11/7/2007 | | C073110088 | | MW288A1-08 | | -5.1 | |  | |
| MW288 | 9/17/2008 | | C082620002 | | MW288UGA1-08 | | -1.3 | |  | |
| MW288 | 12/16/2008 | | C08351020003 | | MW288A1-09 | | -0.8 | |  | |
| MW288 | 11/4/2009 | | C09308025001 | | MW288A1-10 | | -3.5 | |  | |
| MW291 | 11/11/2002 | | C023160006 | | MW291Q1-03 | | 6.5 | |  | |
| MW291 | 11/13/2003 | | C033180003 | | MW291Q1-04 | | -0.4 | |  | |
| MW291 | 11/17/2004 | | C043230022 | | MW291Q1-05 | | -0.2 | |  | |
| MW291 | 11/20/2006 | |  | | MW291A1-07 | | 8.9 | |  | |
| MW291 | 11/20/2006 | |  | | MW291DA1-07 | | 9.4 | |  | |
| MW291 | 11/7/2007 | | C073110087 | | MW291A1-08 | | -4.4 | |  | |
| MW291 | 9/17/2008 | | C082620001 | | MW291UGA1-08 | | -1.8 | |  | |
| MW291 | 12/16/2008 | | C08351020002 | | MW291A1-09 | | -1.0 | |  | |
| MW292 | 11/11/2002 | | C023160008 | | MW292Q1-03 | | 3.5 | |  | |
| MW292 | 11/17/2003 | | C033210102 | | MW292Q1-04 | | 2.1 | |  | |
| MW292 | 11/18/2004 | | C043240002 | | MW292Q1-05 | | -0.4 | |  | |
| MW292 | 11/7/2007 | | C073110089 | | MW292A1-08 | | -3.0 | |  | |
| MW292 | 9/9/2008 | | C082530032 | | MW292UGA1-08 | | 0.1 | |  | |
| MW292 | 12/16/2008 | | C08351020004 | | MW292A1-09 | | -1.6 | |  | |
| MW292 | 11/4/2009 | | C09308025002 | | MW292A1-10 | | -1.3 | |  | |
| MW293 | 11/13/2002 | | C023180006 | | MW293Q1-03 | | 3.7 | |  | |
| MW293A | 11/13/2003 | | C033180004 | | MW293AQ1-04 | | 1.9 | |  | |
| **Station Name** | **Date Collected** | | **Lab Sample ID** | | **Project Sample ID** | | **Ion Balance, *E*%** | | **Notes** | |
| MW294 | 11/13/2002 | | C023180007 | | MW294Q1-03 | | 7.8 | |  | |
| MW294A | 11/13/2003 | | C033180005 | | MW294AQ1-04 | | 2.6 | |  | |
| MW294A | 11/23/2004 | | C043280026 | | MW294AQ1-05 | | -1.4 | |  | |
| MW328 | 11/5/2007 | | C073090098 | | MW328A1-08 | | -3.4 | |  | |
| MW328 | 9/4/2008 | | C082480073 | | MW328UGA1-08 | | -2.4 | |  | |
| MW328 | 12/11/2008 | | C08346020001 | | MW328A1-09 | | 0.2 | |  | |
| MW328 | 11/5/2009 | | C09309023002 | | MW328A1-10 | | -2.2 | |  | |
| MW329 | 11/5/2007 | | C073090097 | | MW329A1-08 | | 0.7 | |  | |
| MW329 | 9/4/2008 | | C082480045 | | MW329DUGA1-08 | | -1.9 | |  | |
| MW329 | 9/4/2008 | | C082480044 | | MW329UGA1-08 | | -2.3 | |  | |
| MW329 | 12/11/2008 | | C08346020002 | | MW329A1-09 | | -0.6 | |  | |
| MW329 | 11/5/2009 | | C09309023001 | | MW329A1-10 | | -1.0 | |  | |
| MW339 | 11/8/2007 | | C073130040 | | MW339A1-08 | | -1.7 | |  | |
| MW339 | 9/23/2008 | | C082670079 | | MW339UGA1-08 | | -1.0 | |  | |
| MW339 | 12/15/2008 | | C08350028001 | | MW339A1-09 | | -1.1 | |  | |
| MW339 | 11/12/2009 | | C09316037004 | | MW339A1-10 | | -0.4 | |  | |
| MW343 | 11/8/2007 | | C073120079 | | MW343A1-08 | | -2.3 | |  | |
| MW343 | 10/1/2008 | | C082760002 | | MW343UGA1-08 | | 0.1 | |  | |
| MW343 | 12/11/2008 | | C08346022001 | | MW343A1-09 | | -1.9 | |  | |
| MW343 | 11/12/2009 | | C09316037001 | | MW343A1-10 | | 0.7 | |  | |
| MW380 | 11/5/2002 | | C023090091 | | MW380QN1-03 | | 9.1 | |  | |
| MW380 | 11/5/2003 | | C033090057 | | MW380QN1-04 | | -1.2 | |  | |
| MW380 | 11/4/2004 | | C043090153 | | MW380QN1-05 | | 0.1 | |  | |
| MW381 | 11/5/2002 | | C023090088 | | MW381QN1-03 | | 8.9 | |  | |
| MW381 | 11/5/2003 | | C033090035 | | MW381QN1-04 | | -1.0 | |  | |
| MW381 | 11/4/2004 | | C043090152 | | MW381QN1-05 | | -0.5 | |  | |
| MW381 | 11/7/2007 | | C073110058 | | MW381A1-08 | | -3.5 | |  | |
| **Station Name** | | **Date Collected** | | **Lab Sample ID** | | **Project Sample ID** | | **Ion Balance, *E*%** | | **Notes** |
| MW381 | | 12/16/2008 | | C08351021002 | | MW381A1-09 | | -0.7 | |  |
| MW381 | | 11/10/2009 | | C09314022002 | | MW381A1-10 | | -3.8 | |  |
| MW403-PRT3 | | 11/5/2007 | | C073090096 | | MW403P3A1-08 | | -3.5 | |  |
| MW403-PRT3 | | 9/30/2008 | | C082740184 | | MW403P3UGA1-08 | | -2.0 | |  |
| MW403-PRT3 | | 12/17/2008 | | C08352011001 | | MW403P3A1-09 | | -4.7 | |  |
| MW403-PRT3 | | 11/16/2009 | | C09320023001 | | MW403P3A1-10 | | -0.5 | |  |
| MW404-PRT3 | | 11/5/2007 | | C073090067 | | MW404P3A1-08 | | -9.4 | |  |
| MW404-PRT3 | | 9/30/2008 | | C082740185 | | MW404P3UGA1-08 | | -1.7 | |  |
| MW404-PRT4 | | 9/30/2008 | | C082740186 | | MW404P4UGA1-08 | | -0.1 | |  |
| MW404-PRT5 | | 11/5/2007 | | C073090069 | | MW404P5A1-08 | | -6.2 | |  |
| MW404-PRT5 | | 9/30/2008 | | C082740187 | | MW404P5UGA1-08 | | 0.7 | |  |
| MW409 | | 11/6/2007 | | C073100081 | | MW409A1-08 | | -2.8 | |  |
| MW409 | | 9/15/2008 | | C082590086 | | MW409DUGA1-08 | | -3.0 | |  |
| MW409 | | 9/15/2008 | | C082590085 | | MW409UGA1-08 | | -2.9 | |  |
| MW409 | | 12/15/2008 | | C08350035002 | | MW409A1-09 | | -1.1 | |  |
| MW409 | | 11/16/2009 | | C09320023002 | | MW409A1-10 | | -2.2 | |  |
| MW414 | | 11/21/2006 | |  | | MW414A1-07 | | 7.5 | |  |
| MW414 | | 11/6/2007 | | C073100169 | | MW414A1-08 | | -3.6 | |  |
| MW414 | | 9/22/2008 | | C082660086 | | MW414UGA1-08 | | -0.9 | |  |
| MW414 | | 12/11/2008 | | C08346022002 | | MW414A1-09 | | -2.8 | |  |
| MW414 | | 11/12/2009 | | C09316037005 | | MW414A1-10 | | -0.4 | |  |
| MW427 | | 12/14/2010 | | C10348027001 | | MW427A1-11 | | 3.5 | |  |
| MW439 | | 6/1/2010 | | C10152022004 | | MW439A1-10 | | -0.9 | |  |
| MW439 | | 12/14/2010 | | C10348022002 | | MW439A1-11 | | -5.7 | |  |
| MW441 | | 6/1/2010 | | C10152022005 | | MW441A1-10 | | -2.0 | |  |
| MW441 | | 12/14/2010 | | C10348022001 | | MW441A1-11 | | -9.5 | |  |
| MW447 | | 6/1/2010 | | C10152022006 | | MW447A1-10 | | 0.2 | |  |
| **Station Name** | | **Date Collected** | | **Lab Sample ID** | | **Project Sample ID** | | **Ion Balance, *E*%** | | **Notes** |
| MW447 | | 12/14/2010 | | C10348027004 | | MW447A1-11 | | -8.1 | |  |
| MW468 | | 6/1/2010 | | C10152024001 | | MW468A1-10 | | -1.0 | |  |
| MW468 | | 6/1/2010 | | C10152024002 | | MW468DA1-10 | | -0.7 | |  |
| MW468 | | 12/14/2010 | | C10348025001 | | MW468A1-11 | | -6.9 | |  |
| MW473 | | 6/1/2010 | | C10152024003 | | MW473A1-10 | | -1.7 | |  |
| MW473 | | 12/14/2010 | | C10348025003 | | MW473A1-11 | | -8.5 | |  |
| MW474 | | 12/14/2010 | | C10348025002 | | MW474A1-11 | | -6.1 | |  |
| MW490 | | 6/1/2010 | | C10152022003 | | MW490A1-10 | | -0.5 | |  |
| MW490 | | 12/14/2010 | | C10348027005 | | MW490A1-11 | | -7.5 | |  |
| MW99 | | 12/6/2005 | |  | | MW99A1-06 | | 7.1 | |  |
| MW99 | | 11/6/2007 | | C073100205 | | MW99A1-08 | | -4.6 | |  |
| MW99 | | 9/8/2008 | | C082530001 | | MW99UGA1-08 | | -3.0 | |  |
| MW99 | | 11/19/2008 | | C08325001002 | | MW99A1-09 | | -1.6 | |  |
| MW99 | | 11/5/2009 | | C09309011001 | | MW99A1-10 | | -4.7 | |  |

Appendix C: List of Station Names and Sampling Dates of the 311 Groundwater Samples from Monitoring Wells along the Northwestern Plume at the PGDP

Sorted by Station Name:

|  |  |
| --- | --- |
| **STATION NAME** | **DATE COLLECTED** |
| 001-175 | 5/12/1998 |
| 001-176 | 5/29/1998 |
| 001-177 | 5/21/1998 |
| 001-177 | 5/26/1998 |
| 001-177 | 6/10/1998 |
| 001-177 | 6/11/1998 |
| 001-180 | 6/2/1998 |
| 001-182 | 6/11/1998 |
| 720-011 | 5/15/1998 |
| 720-011 | 5/16/1998 |
| 720-013 | 4/29/1998 |
| 720-013 | 4/30/1998 |
| 720-017 | 5/2/1998 |
| 720-017 | 5/4/1998 |
| 720-019 | 5/5/1998 |
| 720-026 | 5/20/1998 |
| 720-028 | 6/2/1998 |
| 720-028 | 6/3/1998 |
| 720-029 | 5/27/1998 |
| 720-029 | 5/28/1998 |
| 720-029 | 5/29/1998 |
| 720-029 | 5/30/1998 |
| MW100 | 11/6/2007 |
| MW100 | 9/8/2008 |
| MW100 | 12/15/2008 |
| MW100 | 11/9/2009 |
| MW124 | 11/14/2001 |
| MW124 | 11/11/2002 |
| MW124 | 11/17/2003 |
| MW124 | 11/18/2004 |
| MW125 | 11/21/2006 |
| MW125 | 11/6/2007 |
| MW125 | 9/9/2008 |
| MW125 | 12/10/2008 |
| MW125 | 11/9/2009 |
| MW126 | 11/12/2002 |
| MW126 | 11/17/2003 |
| MW126 | 11/18/2004 |
| MW134 | 11/6/2007 |
| MW134 | 9/16/2008 |
| MW134 | 12/10/2008 |
| MW134 | 11/9/2009 |
| MW145 | 12/10/1998 |
| MW145 | 11/17/1999 |
| MW145 | 11/13/2000 |
| MW145 | 11/13/2002 |
| MW145 | 11/12/2003 |
| MW145 | 11/23/2004 |
| MW145 | 11/6/2007 |
| MW145 | 9/17/2008 |
| MW145 | 12/10/2008 |
| MW145 | 11/4/2009 |
| MW152 | 11/6/2007 |
| MW152 | 9/8/2008 |
| MW152 | 11/19/2008 |
| MW152 | 11/5/2009 |
| MW161 | 12/7/2005 |
| MW161 | 11/8/2007 |
| MW161 | 10/1/2008 |
| MW161 | 11/18/2008 |
| MW161 | 11/12/2009 |
| MW163 | 11/5/2007 |
| MW163 | 9/11/2008 |
| MW163 | 11/18/2008 |
| MW163 | 11/12/2009 |
| MW179 | 3/14/1994 |
| MW188 | 11/11/2009 |
| MW193 | 11/6/2007 |
| MW193 | 9/10/2008 |
| MW193 | 12/17/2008 |
| MW193 | 11/9/2009 |
| MW20 | 9/21/1993 |
| MW201 | 11/6/2007 |
| MW201 | 9/9/2008 |
| MW201 | 12/10/2008 |
| MW201 | 11/10/2009 |
| MW206 | 12/7/2005 |
| MW206 | 11/5/2007 |
| MW206 | 9/22/2008 |
| MW206 | 11/18/2008 |
| MW206 | 11/9/2009 |
| MW233 | 11/6/2002 |
| MW233 | 11/5/2003 |
| MW233 | 11/4/2004 |
| MW236 | 11/6/2002 |
| MW236 | 11/5/2003 |
| MW236 | 11/4/2004 |
| MW237 | 11/5/2003 |
| MW238 | 11/6/2002 |
| MW238 | 11/3/2003 |
| MW238 | 11/8/2004 |
| MW239 | 11/4/1999 |
| MW239 | 11/5/2003 |
| MW239 | 11/4/2004 |
| MW240 | 11/5/2002 |
| MW240 | 11/3/2003 |
| MW240 | 11/8/2004 |
| MW241 | 11/5/2002 |
| MW241A | 11/3/2003 |
| MW241A | 11/4/2004 |
| MW242 | 11/6/2003 |
| MW242 | 11/10/2004 |
| MW242 | 11/20/2006 |
| MW242 | 11/7/2007 |
| MW242 | 9/10/2008 |
| MW242 | 11/17/2008 |
| MW242 | 11/4/2009 |
| MW243 | 11/4/2002 |
| MW243 | 11/10/2003 |
| MW243 | 11/9/2004 |
| MW243 | 11/8/2007 |
| MW243 | 9/10/2008 |
| MW243 | 12/16/2008 |
| MW243 | 11/4/2009 |
| MW244 | 11/4/2002 |
| MW244 | 11/6/2003 |
| MW244 | 11/8/2004 |
| MW245 | 11/8/2004 |
| MW248 | 11/4/2002 |
| MW248 | 11/10/2003 |
| MW248 | 11/9/2004 |
| MW249 | 11/7/2001 |
| MW249 | 11/4/2002 |
| MW249 | 11/10/2003 |
| MW249 | 11/9/2004 |
| MW250 | 11/10/2003 |
| MW250 | 11/10/2004 |
| MW255 | 11/17/1999 |
| MW255 | 11/13/2002 |
| MW255 | 11/12/2003 |
| MW255 | 11/17/2004 |
| MW255 | 11/7/2007 |
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| MW255 | 11/18/2008 |
| MW255 | 11/9/2009 |
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| MW256 | 11/12/2003 |
| MW256 | 11/17/2004 |
| MW256 | 11/7/2007 |
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| MW256 | 11/19/2008 |
| MW256 | 11/5/2009 |
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| MW258 | 11/18/1999 |
| MW258 | 11/13/2002 |
| MW258 | 11/12/2003 |
| MW258 | 11/23/2004 |
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| MW261 | 11/18/2008 |
| MW261 | 11/11/2009 |
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| MW283 | 11/13/2003 |
| MW283 | 11/17/2004 |
| MW284 | 11/13/2002 |
| MW284 | 11/13/2003 |
| MW284 | 11/23/2004 |
| MW288 | 11/11/2002 |
| MW288 | 11/13/2003 |
| MW288 | 11/18/2004 |
| MW288 | 11/7/2007 |
| MW288 | 9/17/2008 |
| MW288 | 12/16/2008 |
| MW288 | 11/4/2009 |
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| MW291 | 11/17/2004 |
| MW291 | 11/20/2006 |
| MW291 | 11/7/2007 |
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| MW291 | 12/16/2008 |
| MW292 | 11/11/2002 |
| MW292 | 11/17/2003 |
| MW292 | 11/18/2004 |
| MW292 | 11/7/2007 |
| MW292 | 9/9/2008 |
| MW292 | 12/16/2008 |
| MW292 | 11/4/2009 |
| MW293 | 11/13/2002 |
| MW293A | 11/13/2003 |
| MW293A | 11/18/2004 |
| MW294 | 11/13/2002 |
| MW294A | 11/13/2003 |
| MW294A | 11/23/2004 |
| MW328 | 11/5/2007 |
| MW328 | 9/4/2008 |
| MW328 | 12/11/2008 |
| MW328 | 11/5/2009 |
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| MW339 | 12/15/2008 |
| MW339 | 11/12/2009 |
| MW343 | 11/8/2007 |
| MW343 | 10/1/2008 |
| MW343 | 12/11/2008 |
| MW343 | 11/12/2009 |
| MW380 | 11/5/2002 |
| MW380 | 11/5/2003 |
| MW380 | 11/4/2004 |
| MW381 | 11/5/2002 |
| MW381 | 11/5/2003 |
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| MW381 | 12/16/2008 |
| MW381 | 11/10/2009 |
| MW403-PRT3 | 11/5/2007 |
| MW403-PRT3 | 9/30/2008 |
| MW403-PRT3 | 12/17/2008 |
| MW403-PRT3 | 11/16/2009 |
| MW404-PRT3 | 11/5/2007 |
| MW404-PRT3 | 9/30/2008 |
| MW404-PRT4 | 9/30/2008 |
| MW404-PRT5 | 11/5/2007 |
| MW404-PRT5 | 9/30/2008 |
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| MW409 | 9/15/2008 |
| MW409 | 12/15/2008 |
| MW409 | 11/16/2009 |
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| MW414 | 9/22/2008 |
| MW414 | 12/11/2008 |
| MW414 | 11/12/2009 |
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| MW441 | 12/14/2010 |
| MW447 | 6/1/2010 |
| MW447 | 12/14/2010 |
| MW468 | 6/1/2010 |
| MW468 | 12/14/2010 |
| MW473 | 6/1/2010 |
| MW473 | 12/14/2010 |
| MW474 | 12/14/2010 |
| MW490 | 6/1/2010 |
| MW490 | 12/14/2010 |
| MW99 | 12/6/2005 |
| MW99 | 11/6/2007 |
| MW99 | 9/8/2008 |
| MW99 | 11/19/2008 |
| MW99 | 11/5/2009 |

Sorted by Date:

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| **DATE COLLECTED** | **STATION NAME** |
| 9/21/1993 | MW20 |
| 3/14/1994 | MW179 |
| 4/29/1998 | 720-013 |
| 4/30/1998 | 720-013 |
| 5/2/1998 | 720-017 |
| 5/4/1998 | 720-017 |
| 5/5/1998 | 720-019 |
| 5/12/1998 | 001-175 |
| 5/15/1998 | 720-011 |
| 5/16/1998 | 720-011 |
| 5/20/1998 | 720-026 |
| 5/21/1998 | 001-177 |
| 5/26/1998 | 001-177 |
| 5/27/1998 | 720-029 |
| 5/28/1998 | 720-029 |
| 5/29/1998 | 001-176 |
| 5/29/1998 | 720-029 |
| 5/30/1998 | 720-029 |
| 6/2/1998 | 001-180 |
| 6/2/1998 | 720-028 |
| 6/3/1998 | 720-028 |
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| 6/11/1998 | 001-182 |
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| 11/4/1999 | MW239 |
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| 11/4/2002 | MW244 |
| 11/4/2002 | MW248 |
| 11/4/2002 | MW249 |
| 11/5/2002 | MW240 |
| 11/5/2002 | MW241 |
| 11/5/2002 | MW380 |
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| 11/6/2002 | MW233 |
| 11/6/2002 | MW236 |
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| 11/13/2002 | MW258 |
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| 11/3/2003 | MW238 |
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| 11/5/2003 | MW233 |
| 11/5/2003 | MW236 |
| 11/5/2003 | MW237 |
| 11/5/2003 | MW239 |
| 11/5/2003 | MW380 |
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| 11/10/2003 | MW250 |
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| 11/20/2006 | MW291 |
| 11/21/2006 | MW125 |
| 11/21/2006 | MW414 |
| 11/5/2007 | MW163 |
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| 11/5/2007 | MW260 |
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| 11/5/2007 | MW403-PRT3 |
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| 12/14/2010 | MW468 |
| 12/14/2010 | MW473 |
| 12/14/2010 | MW474 |
| 12/14/2010 | MW490 |