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**Hydrogen Release Compound (HRC<sup>®</sup>) Barrier  
Application at the North of Basin F Site,  
Rocky Mountain Arsenal**

**Innovative Technology Evaluation Report**

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Rocky Mountain Arsenal**

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Prepared for:

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## NOTICE

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## FOREWORD

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This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Sally C. Gutierrez, Director  
National Risk Management Research Laboratory

## ABSTRACT

This Innovative Technology Evaluation Report documents the results of a demonstration of the hydrogen release compound (HRC<sup>®</sup>) barrier technology developed by Regenesi Bioremediation Products, Inc., of San Clemente, California. HRC<sup>®</sup> is a proprietary, food-quality glycerol polylactate ester that slowly releases lactic acid when injected into groundwater aquifers. The HRC<sup>®</sup> enhances natural anaerobic degradation of organic contaminants in the groundwater. The technology was evaluated from February 2001 to October 2002 at the North of Basin F site at the Rocky Mountain Arsenal (RMA) in Commerce City, Colorado. The demonstration evaluated the technology's ability to treat groundwater containing contaminants generated during the processing of chemical warfare agents and during commercial production of pesticides.

The technology evaluation was conducted in an alluvial, surficial aquifer consisting of an upper 1- to 3-foot interval of well-graded sand/gravel and a lower 7- to 8-foot interval of unconsolidated sand to poorly cemented sandstone; the aquifer overlays the claystone of the Denver Formation. A 50-foot by 30-foot L-shaped permeable barrier of HRC<sup>®</sup> was installed; each leg of the barrier consisted of three staggered rows of injection points on 6-foot centers. HRC<sup>®</sup> was injected from the bottom up using direct-push methods at a dose rate of about 10 pounds per foot over a 10-foot interval (from about 44 to 54 feet below ground surface). A total of 4,200 pounds of HRC<sup>®</sup> was injected in 42 points. Groundwater samples were collected from an array of monitoring wells to evaluate the technology's performance. The wells were located upgradient, within, and downgradient from the HRC<sup>®</sup> barrier.

The primary objective of the technology evaluation was to determine the ability of the technology to significantly reduce the primary contaminants of concern (COC) in the North of Basin F plume study area. The primary COCs consisted of di-isopropylmethylphosphonate (DIMP), chlorophenylmethyl sulfide, chlorophenylmethyl sulfone, dieldrin, dicyclopentadiene (DCPD), chloroform, methylene chloride, and tetrachloroethene (PCE). Benzene, trichloroethene (TCE), 1,2-dibromo-3-chloropropane, and n-nitroso-dimethylamine were evaluated as secondary COCs. Results of the evaluation showed decreasing trends for the following COCs: PCE, TCE, DIMP, DCPD, and benzene. Percent reductions for these COCs were generally in the 50 to 80 percent range at multiple downgradient wells, although higher percent reductions were observed for PCE and DCPD (90 to 95 percent). Downgradient concentrations of PCE, DCPD, and benzene were also reduced over the course of the evaluation to below applicable site-specific remediation goals.

An economic analysis of the HRC<sup>®</sup> technology indicated that costs can vary considerably and are based on several factors, including the type and scale of the application, contaminant types and levels, regulatory criteria, and various site-specific factors. The estimated cost for the scenario in the economic analysis section of this report, which incorporates actual costs for 1 year of treatment under conditions similar to those encountered at RMA, was approximately \$0.55 per gallon of treated water. Over a longer period of time, this unit cost would likely be significantly reduced.

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## ACRONYMS AND ABBREVIATIONS

AEA	Atomic Energy Commission
APC	Applied Power Concepts, Inc.
ARAR	Applicable or relevant and appropriate requirement
bgs	Below ground surface
CAA	Clean Air Act
CDPHE	Colorado Department of Public Health and Environment
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
cfu/mL	Colony forming units per milliliter
COC	Contaminant of concern
CPMS	Chlorophenylmethyl sulfide
CPMSO <sub>2</sub>	Chlorophenylmethyl sulfone
CWA	Clean Water Act
DCE	Dichloroethene
DCPD	Dicyclopentadiene
DIMP	Di-isopropylmethylphosphonate
DNAPL	Dense nonaqueous-phase liquid
DO	Dissolved oxygen
EPA	U.S. Environmental Protection Agency
FDEP	Florida Department of Environmental Protection
ft/day	Feet per day
GAC	Granular activated carbon
HRC <sup>®</sup>	Hydrogen release compound
IDW	Investigation-derived waste
IP	HRC <sup>®</sup> injection points
ITER	Innovative Technology Evaluation Report
LCS/LCSD	Laboratory control sample/laboratory control sample duplicate
L/min	Liters per minute
µg/L	Micrograms per liter
µmol	Micromole
mg/L	Milligrams per liter
MS/MSD	Matrix spike/matrix spike duplicate
mV	Millivolts
NAPL	Nonaqueous-phase liquid
NJDEP	New Jersey Department of Environmental Protection
NPDES	National Pollutant Discharge Elimination System
NRC	Nuclear Regulatory Commission
NRMRL	National Risk Management Research Laboratory
ORP	Oxidation-reduction potential
OSHA	Occupational Safety and Health Administration
OSWER	Office of Solid Waste and Emergency Response
PCE	Tetrachloroethene
POTW	Publicly owned treatment works
QAPP	Quality assurance project plan

## ACRONYMS AND ABBREVIATIONS (Continued)

QC	Quality control
RCRA	Resource Conservation and Recovery Act
Regenesis	Regenesis Bioremediation Products, Inc.
RMA	Rocky Mountain Arsenal
ROD	Record of Decision
RVO	Remediation Venture Office
SDWA	Safe Drinking Water Act
SITE	Superfund Innovative Technology Evaluation
SOP	Standard operating procedure
SVOC	Semivolatile organic compound
TCE	Trichloroethene
TER	Technology Evaluation Report
Tetra Tech	Tetra Tech EM Inc.
UIC	Underground injection control
VOC	Volatile organic compound

## CONVERSION FACTORS

	<i>To Convert From:</i>	<i>To:</i>	<i>Multiply By:</i>
Length:	inch	centimeter	2.54
	foot	meter	0.305
	mile	kilometer	1.61
Area:	square foot	square meter	0.0929
	acre	square meter	4,047
Volume:	gallon	liter	3.78
	cubic foot	cubic meter	0.0283
	cubic foot	gallon	7.48
	cubic foot	cubic centimeter	28,317
Mass:	pound	kilogram	0.454
Temperature:	(°Fahrenheit - 32)	°Celsius	0.556
Time	days	minutes	1440

## ACKNOWLEDGMENTS

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The HRC<sup>®</sup> technology evaluation was a cooperative effort that involved the following personnel from the EPA SITE Program, EPA Region VIII, Colorado Department of Public Health and the Environment (CDPHE), Remediation Venture Office (RVO), U.S. Fish and Wildlife Service (USFWS), and the U.S. Army, Rocky Mountain Arsenal (RMA):

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Mr. Terrence Lyons	EPA, NRMRL, Task Order Manager
Mr. Scott Jacobs	EPA, NRMRL, Quality Assurance Manager
Mr. Larry Kimmel	EPA Region VIII, Federal Facilities
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Mr. Stephen Smith	RVO, USFWS
Mr. Stan Lynn	Tetra Tech
Mr. Tom James	U.S. Army, RMA

## EXECUTIVE SUMMARY

This Innovative Technology Evaluation Report documents the results of an evaluation of the hydrogen release compound (HRC<sup>®</sup>) barrier technology developed by Regenesi Bioremediation Products, Inc., of San Clemente, California. HRC<sup>®</sup> is a proprietary, food-quality glycerol polylactate ester that slowly releases lactic acid when injected into groundwater aquifers. The HRC<sup>®</sup> enhances natural anaerobic degradation of organic contaminants in the groundwater. Other microorganisms use the controlled slow production of hydrogen to enhance their capability of reductive dechlorination, which is recognized as one of the primary attenuation mechanisms by which groundwater contaminated with chlorinated solvents can be remediated.

The technology was evaluated from February 2001 to October 2002 at the North of Basin F site at the Rocky Mountain Arsenal (RMA) in Commerce City, Colorado. The demonstration evaluated the technology's ability to treat groundwater containing contaminants generated during the processing of chemical warfare agents and during commercial production of pesticides. The primary contaminants in groundwater at the North of Basin F site consisted of di-isopropylmethylphosphonate (DIMP), chlorophenylmethyl sulfide, chlorophenylmethyl sulfone, dieldrin, dicyclopentadiene (DCPD), chloroform, methylene chloride, tetrachloroethene (PCE), benzene, trichloroethene (TCE), 1,2-dibromo-3-chloropropane, and n-nitroso-dimethylamine.

The primary objective for the evaluation was to determine the technology's ability to significantly reduce the concentrations of each of the contaminants of concern (COC) in the North of Basin F plume. Secondary objectives included (1) evaluating the technology's ability to achieve site-specific remediation goals, and (2) monitoring time-plots of the concentrations of treatment-derived products and parameters that might indicate anaerobic conditions.

The statistical evaluation of the analytical data collected from downgradient wells during the evaluation found decreasing concentrations for the following COCs as a result of HRC<sup>®</sup> injection: PCE, TCE, DIMP, DCPD, and benzene. Percent reductions for TCE, DIMP, and benzene were between 50 and 80 percent at multiple downgradient wells, while percent reductions for PCE and DCPD were higher at 90 to 95 percent. Analytical data for the remaining COCs did not show any well-defined or consistent decreasing trends, suggesting that degradation of the remaining COCs was not accelerated by injection of HRC<sup>®</sup>. Downgradient concentrations of PCE, DCPD, and benzene were consistently reduced to below applicable remediation goals for the site.

Several other parameters, including volatile fatty acids, competing electron acceptors, and degradation by-products, were evaluated in groundwater samples collected from downgradient wells to determine if anaerobic conditions were sustained throughout the evaluation period. Analytical data indicated that initial aquifer conditions were only mildly aerobic; however, a high dose of HRC<sup>®</sup> was required to overcome competing electron acceptors, including iron and sulfate. Iron concentrations reached maximum levels about 4 to 5 months following HRC<sup>®</sup> injection, and then declined gradually at most wells. Sulfate concentrations fell from an average baseline concentration of 550 milligrams per liter (mg/L) to less than 100 mg/L. In spite of the high hydrogen demand presented by the competing electron acceptors, sufficient volatile fatty acids (lactic, propionic, butyric, and acetic acid, which are the hydrogen sources), remained after 18 months following HRC<sup>®</sup> injection. Oxidation-reduction potential levels ranged from -50 to -300 millivolts, and groundwater pH was reduced due to the release of the volatile fatty acids, which indicates that anaerobic conditions were sustained and dechlorination continued throughout the evaluation period.



Analytical data from several wells showed a direct correlation between increasing concentrations of cis-1,2-dichloroethene, which is a daughter product from the dechlorination of TCE, and decreasing concentrations of TCE. However, further degradation of cis-1,2-DCE to vinyl chloride and ethene was not observed.

An economic analysis of the HRC<sup>®</sup> technology was conducted for the barrier-based application demonstrated at the RMA North of Basin F site. The cost estimate was primarily based on the assumptions and unit costs provided by Regensis, as well as information obtained during the SITE technology evaluation. The cost estimate was based on actual costs experienced at RMA for 1 year of application. The overall cost for 1 year of treatment and monitoring was estimated to be \$302,360, or \$0.55 per gallon of water treated, based on the estimated groundwater flow velocity for the aquifer. However, most of the costs during the first year are one-time expenses, and the frequency of monitoring would likely decrease in subsequent years, which would lower the costs proportionately if treatment was extended beyond 1 year.

## **1.0 INTRODUCTION**

The Hydrogen Release Compound (HRC<sup>®</sup>) bioremediation technology developed by Regenesi Bioremediation Products, Inc. (Regenesi), of San Clemente, California is designed to enhance natural anaerobic degradation of organic contaminants in groundwater aquifers. A barrier application of this technology was evaluated during a demonstration at the North of Basin F site on the Rocky Mountain Arsenal (RMA) in Commerce City, Colorado. The evaluation was conducted by the U.S. Environmental Protection Agency's (EPA) Superfund Innovative Technology Evaluation (SITE) Program in cooperation with EPA Region VIII, the Colorado Department of Public Health and Environment (CDPHE), and the Remediation Venture Office (RVO) at RMA, which is staffed by representatives from the U.S. Army, Shell Oil Company, and the U.S. Fish and Wildlife Service.

The technology evaluation occurred from February 2001 to October 2002. The technology evaluated the ability of an HRC<sup>®</sup> barrier to treat groundwater containing contaminants generated during the processing of chemical warfare agents by the government and during commercial production of pesticides. This Innovative Technology Evaluation Report (ITER) summarizes the results of that evaluation and provides other pertinent technical and cost information for potential users of the technology. A separate Technology Evaluation Report (TER) provides detailed information regarding the evaluation, including all data and associated statistical evaluations. For additional information about the technology, the evaluation site, and the SITE Program; refer to key contacts listed at the end of this section.

### **1.1 PURPOSE AND ORGANIZATION OF THE ITER**

Information presented in the ITER is intended to assist decision-makers in evaluating specific technologies for treatment of contaminated media. The ITER represents a critical step in the development and commercialization of a treatment technology. The report discusses the effectiveness and applicability of the technology and analyzes costs associated with its application. The technology's effectiveness is evaluated based on data collected during the evaluation. The applicability of the technology is discussed in terms of waste and site characteristics that could affect technology performance, material handling requirements, technology limitations, and other factors.

The purpose of this ITER is to present information that will assist decision-makers in evaluating the HRC<sup>®</sup> technology for application to a particular site cleanup. This report provides background information and introduces the HRC<sup>®</sup> bioremediation technology (Section 1.0), analyzes the technology's effectiveness in treating contaminated groundwater at the RMA North of Basin F site (Section 2.0), analyzes the economics of using the HRC<sup>®</sup> technology to treat contaminated groundwater (Section 3.0), analyzes the technology's applications (Section 4.0), summarizes the technology's status (Section 5.0), and presents a list of references used to prepare the ITER. Vendor's claims for the HRC<sup>®</sup> technology are presented in Appendix A.

### **1.2 DESCRIPTION OF THE EVALUATION SITE**

This section provides background information on the RMA and describes the North of Basin F site at RMA. Figure 1-1 shows the location of this site and the surrounding features at RMA.

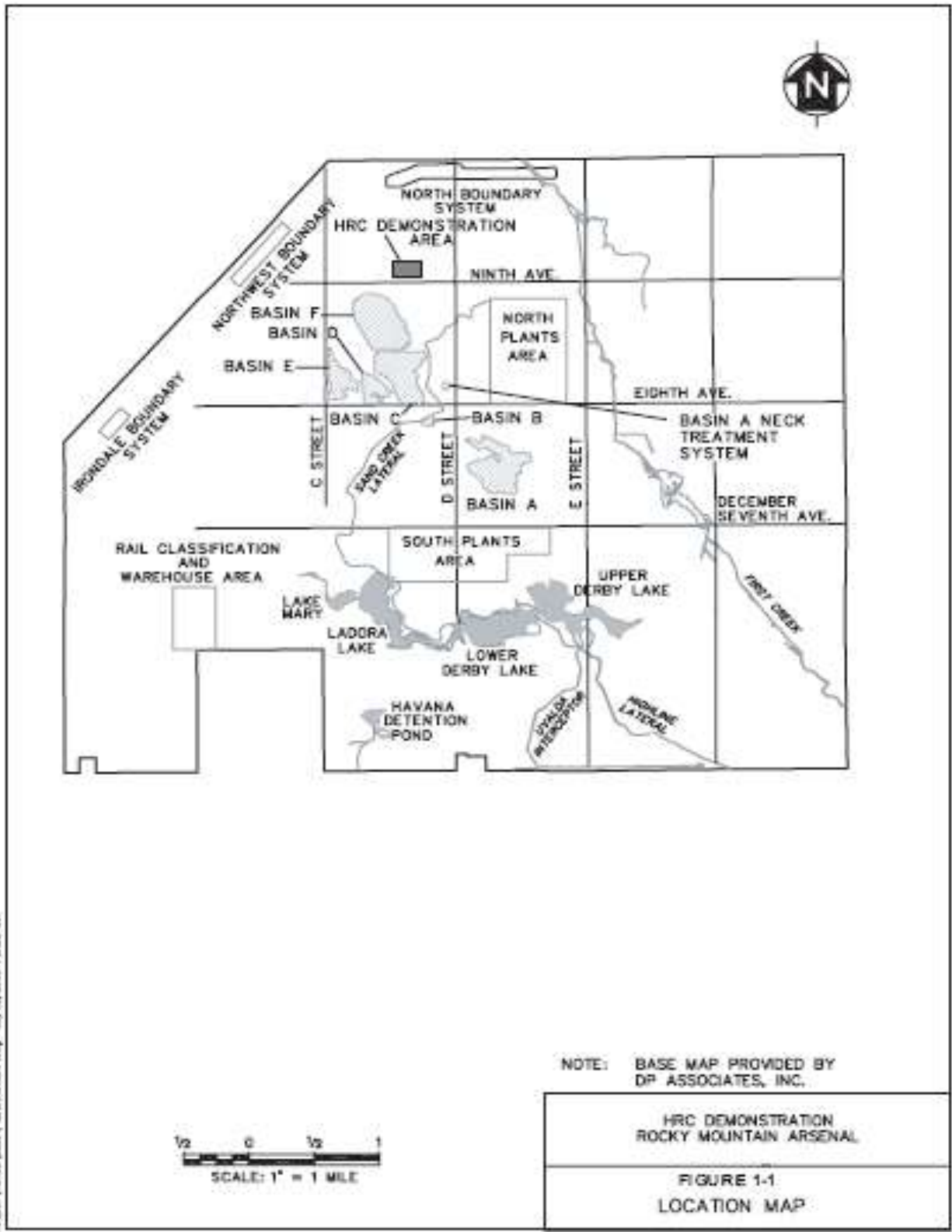


Figure 1-1

### **1.2.1 Site Location and History**

RMA occupies more than 17,000 acres (approximately 27 square miles) in southern Adams County, Colorado. It is located approximately 10 miles northeast of downtown Denver, Colorado.

The U.S. Government purchased the property in 1942 for use in World War II to manufacture and assemble chemical warfare materials, such as mustard and lewisite, and incendiary munitions. The nerve agent GB (isopropyl methylphosphonofluoridate) was produced during the 1950s. The facility was also used for chemical warfare materials destruction during the 1950s and 1960s. In addition to these military activities, major portions of the facility were leased to private industry, primarily for pesticide manufacturing. Pesticides were produced from 1947 to 1982 while portions of the arsenal were leased to Shell Oil Company.

During the 1940s and 1950s, the North Plants Area and the South Plants Area were accumulation areas for aqueous industrial wastes. These wastes were typically discharged into several unlined evaporation ponds. During the mid-1950s, groundwater contamination was suspected when minor crop damage occurred on land located north and northwest of the RMA. The discovery of this contamination led to the placement of an asphalt liner in Basin F. During this time, aqueous wastes from Basin A and aqueous wastes produced thereafter were transferred directly to Basin F. Figure 1-1 shows the location of these features at RMA, and highlights the location of the evaluation site, which is located just north of Basin F.

### **1.2.2 Site Geology/Hydrogeology**

The geological and hydrostratigraphic units of interest at RMA include surficial, unconsolidated alluvial and eolian sediments, collectively referred to as the alluvium. The alluvium in the area north of Basin F is approximately 40 to 50 feet thick. The material consists primarily of sand and silt with minor amounts of gravel and clay. The bedrock underlying the alluvium is the Denver Formation, which consists of sandstones, siltstones, lignites, and claystones (EPA and U.S. Army 2000).

The North of Basin F site is located within an alluvial paleochannel, surficial aquifer consisting of an upper 1 to 3 foot interval of well-graded sand/gravel and a lower 7 to 8 foot interval of unconsolidated sand to poorly cemented sandstone; the aquifer overlays the claystone of the Denver Formation. Groundwater in the area of Basin F generally flows north-northeast to east (EPA and U.S. Army 2000). The hydraulic gradient and conductivity are on the order of 0.001 foot per foot and 250 feet per day (ft/day), respectively (Foster Wheeler Environmental Corporation 1999).

### **1.2.3 Existing Remediation Systems and Contaminant Concentrations**

Investigations evaluating the presence or absence of contamination in the flora and fauna at the RMA have been conducted since the early 1950s (EPA and U.S. Army 2000). These investigations were initiated as a result of observations of wildlife mortality and agricultural damage. In 1974, CDPHE detected di-isopropylmethylphosphonate (DIMP) in the groundwater north of RMA (EPA and U.S. Army 2000).

Additional investigations were completed by the U.S. Army Toxic Hazardous Materials Agency in the 1970s and 1980s (EPA and U.S. Army 2000). Results of these investigations indicated that

contamination exists primarily in the alluvial sediments and groundwater. Minor amounts of contamination were observed in the Denver Formation.

The RMA site selected for the HRC<sup>®</sup> evaluation program is located just north of Basin F. Aqueous industrial wastes containing various chemical warfare agents and pesticides were discharged into Basin F at RMA and resulted in groundwater contamination at this site. As a result, a pump-and-treat system was installed north of Basin F to remediate contaminated groundwater. The extraction wells for the pump-and-treat system are located within and along the boundary of RMA. The pump-and-treat system handled over 1 billion gallons of water in 1996 (EPA 1999).

Groundwater is extracted from Well 23311 at the North of Basin F site (EPA 1999). The groundwater is pumped to the Basin A Neck System water treatment plant, located approximately 1.7 miles from Basin F, where it is treated through the use of granular activated carbon (GAC) and an air stripper prior to injection back into the subsurface. The influent to the Basin A Neck System water treatment plant is analyzed on a periodic basis; historical results of the analyses of organic contaminants are presented in Table 1-1.

### **1.3 DESCRIPTION OF THE HRC<sup>®</sup> TECHNOLOGY**

This section describes the Regenesis HRC<sup>®</sup> technology, as well as the site-specific design that was implemented for the evaluation at the RMA North of Basin F site.

#### **1.3.1 Principles of the Technology**

HRC<sup>®</sup> is a proprietary, food-quality polylactate ester used to enhance in situ biodegradation rates by slowly releasing lactic acid into the subsurface. The lactic acid is metabolized by naturally occurring microorganisms, thereby creating anaerobic aquifer conditions and the production of hydrogen. The microorganisms use the hydrogen to enhance their anaerobic degradation of organic contaminants through reductive dechlorination of chlorinated organic contaminants in groundwater. Reductive dechlorination results in the step-by-step biological degradation of chlorinated contaminants. Figure 1-2 illustrates these chemical processes using tetrachloroethene (PCE) as an example of a chlorinated organic compound that is reductively dechlorinated as hydrogen is released from the anaerobic degradation of lactic acid. According to Regenesis, HRC<sup>®</sup> can be used to degrade a range of chlorinated and other oxidized organic compounds, including: chlorinated degreasing solvents (PCE, trichloroethene [TCE], trichloroethane, and their breakdown products), carbon tetrachloride, chloroform, methylene chloride, certain pesticides and herbicides, perchlorate, nitrate, nitroaromatic explosives and dyes, and chlorofluorocarbons (Regenesis 2000).

HRC<sup>®</sup> is supplied as a viscous (20,000 centipoise), honey-like mixture of tripolylactate and glycerol that can be directly injected into contaminated groundwater and saturated soils. HRC<sup>®</sup> is specifically designed to slowly release lactic acid when it contacts water. For the HRC<sup>®</sup> process to function efficiently, however, microbial colonies must be present in the soil that (1) are suitable to perform the remediation, and (2) respond to an increase in both the biochemical energy and the hydrogen generated from HRC<sup>®</sup> (Applied Power Concepts, Inc. [APC] 2000).

**Table 1-1**  
**Historical Analytical Results, Basin A Neck System Influent**

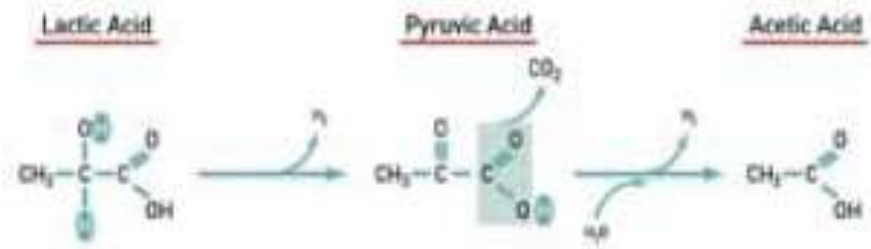
<b>Parameter</b>	<b>Year</b>	<b>Range of Concentration micrograms per liter (µg/L)</b>	<b>Average Concentration µg/L</b>	<b>Trends</b>	<b>Comments</b>
Atrazine	1996 - 1999	< 0.346 - 22.5	22.5	No Trend	Detected in one of 32 samples
Benzene	1996 - 1999	< 3.08 - < 500	10	No trend	Not detected when detection limits greater than 50 µg/L
Chloroform	1996 - 2000	590 - 18900	10209	Decreasing	Detected in 29 of 29 samples
Di-isopropyl methyl phosphonate	1996 - 1999	490 - 1000	837	Decreasing	Detected in 23 of 23 samples
Chlorophenylmethyl sulfide	1996 - 1999	68.6 - 230	152	Decreasing	Detected in 28 of 28 samples
Chlorophenylmethyl sulfone	1996 - 1999	86.3 - 380	225	Decreasing	Detected in 28 of 28 samples
Dibromochloro-propane	1996 - 2000	< 44 - < 0.27	4	No trend	Detected in 6 of 23 samples
Dicyclopentadiene	1996 - 2000	130 - 1000 (estimated)	256	No trend, but one anomalous high	Detected in 36 of 36 samples
Dieldrin	1996 - 1999	< 10 - 0.025	1.5	No trend	Detected in 14 of 30 samples

**Table 1-1 (continued)**

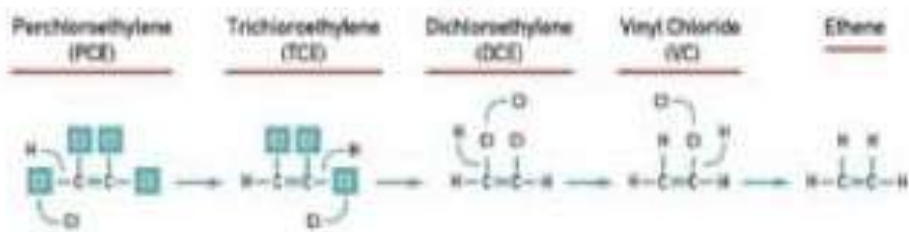
**Historical Analytical Results, Basin A Neck System Influent**

<b>Parameter</b>	<b>Year</b>	<b>Range of Concentration µg/L</b>	<b>Average Concentration µg/L</b>	<b>Trends</b>	<b>Comments</b>
Methylene chloride	1996 - 2000	< 3.28 - < 500	49	No trend	Detected in 14 of 29 samples
Trichloroethene	1996 - 2000	40.8 - 93	62	Increasing	Detected in 29 of 29 samples
Tetrachloroethene	1996 - 2000	50 - 200	140	Decreasing	Detected in 29 of 29 samples
N-Nitrosodimethyl-amine	1996 - 2000	0.89 - < 10	2.2	No trend	Detected in 15 of 20 samples

BREAKDOWN OF LACTIC ACID FROM HRC YIELDS HYDROGEN (H<sub>2</sub>)



INCREASED HYDROGEN ENHANCES REDUCTIVE DECHLORINATION



**FIGURE 1-2  
BREAKDOWN OF LACTIC ACID AND RELEASE OF HYDROGEN**

Figure 1-2



HRC<sup>®</sup> is typically applied using direct injection techniques. This process enables HRC<sup>®</sup> to be pressure-injected into the zone of contamination and forced into the aquifer. Once in the subsurface, HRC<sup>®</sup> will reside within the soil matrix and continue to provide a slow release of lactic acid for up to 18 months. The HRC<sup>®</sup> is typically injected into the aquifer matrix in a series of closely spaced rows to form a “permeable barrier” or “treatment wall” that cuts off an advancing contaminant plume.

### **1.3.2 Previous Evaluations and Treatability Studies**

An initial SITE Program evaluation, which was conducted from 1990 to 1993, involved a sequential anaerobic/aerobic biodegradation bench-scale test using various electron donors. Results of the bench-scale test indicated that lactic acid (HRC<sup>®</sup> as lactate source) was the most effective electron donor. The SITE Program conducted a second evaluation that involved isolating a small circulating groundwater cell, using a series of extraction and injection wells, in the central area of a chlorinated solvent plume at a site in Watertown, Massachusetts from 1997 to 1998. Results of the test indicated a 97 percent reduction in total mass for chlorinated volatile organic compounds (VOC) in groundwater using HRC<sup>®</sup>.

The RMA site that was selected for the HRC<sup>®</sup> evaluation program is located just north of the source zone, referred to as Basin F (see Figure 1-1). Aqueous industrial wastes consisting of various chemical warfare agents were discharged into Basin F at RMA and resulted in groundwater contamination. To investigate alternatives to the existing pump-and-treat system for the remediation of contaminated groundwater at this site, a series of bench-scale studies involving three in situ treatment technologies was proposed. The three alternatives included HRC<sup>®</sup>, Oxygen Release Compound, and Zero Valent Iron. Following the bench-scale studies, an in situ field evaluation of the HRC<sup>®</sup> technology was proposed at the North of Basin F site. Regensis was contracted to initiate the evaluation at the North of Basin F site. Prior to the evaluation, APC conducted a series of treatability studies for Regensis to determine the suitability of natural microbial populations to (1) remediate contaminated groundwater at the RMA North of Basin F site, and (2) understand how the colonies would respond to an increase of biochemical energy and hydrogen generated from HRC<sup>®</sup>. Results of the treatability studies indicated that the soil at RMA contains appropriate microbial colonies for application of HRC<sup>®</sup> (APC 2000).

## **1.4 FIELD CONSTRUCTION ACTIVITIES FOR THE EVALUATION**

Field construction activities for the evaluation at the RMA North of Basin F site included the installation of a series of monitoring wells upgradient and downgradient of the intended HRC<sup>®</sup> barrier location, followed by the construction of the barrier itself. Figure 1-3 is a schematic depicting the barrier and monitoring well layout.

### **1.4.1 Installation of Groundwater Monitoring Wells**

A location along the alluvial aquifer was identified as the location for installation of the HRC<sup>®</sup> barrier wall for the evaluation. To characterize the contaminated groundwater upgradient and downgradient from the barrier wall, 12 monitoring wells were installed upgradient and downgradient from the planned barrier location. One set of downgradient wells was installed along the central axis of the barrier parallel to the

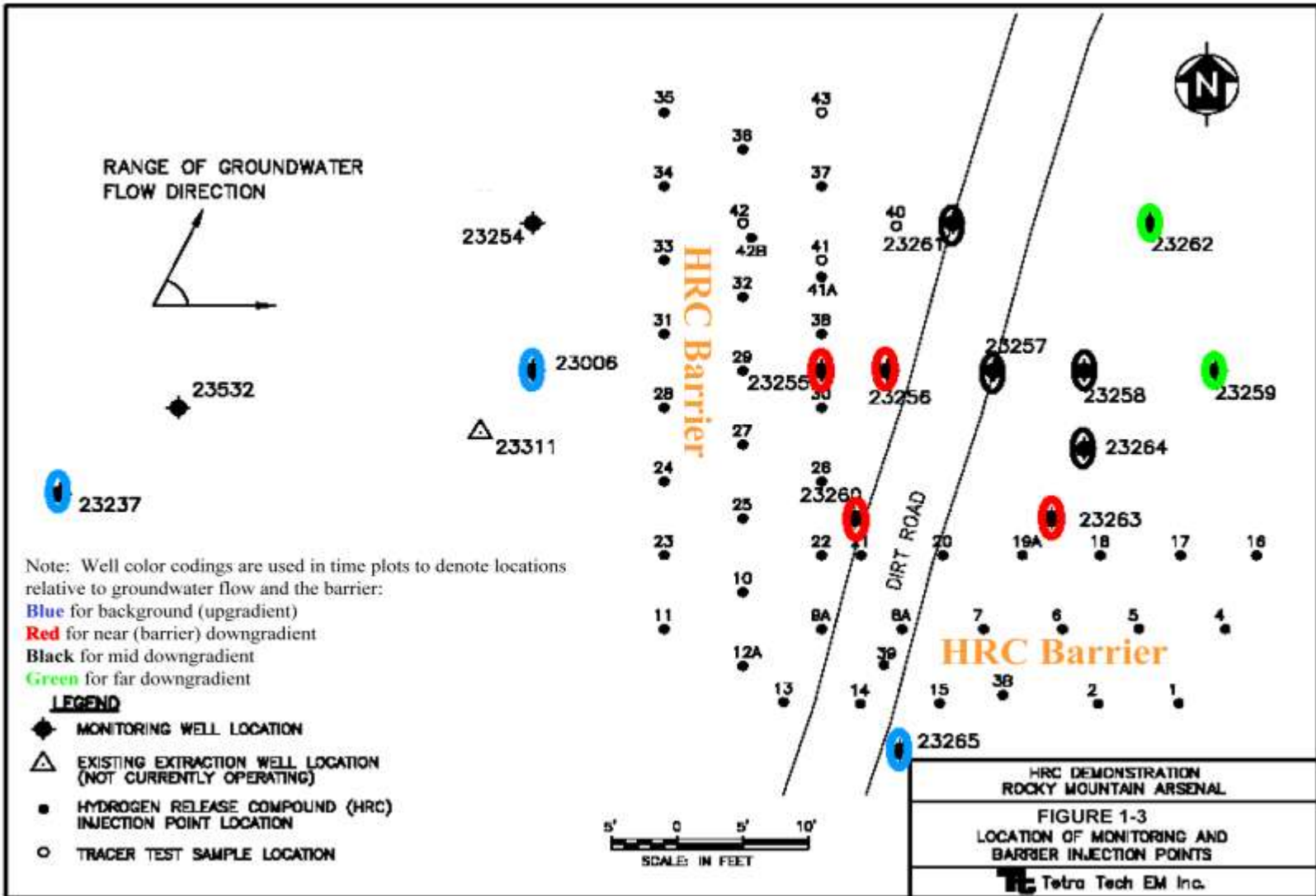


Figure 1-3

assumed easterly groundwater flow direction (wells 23255 through 23259). Existing well 23006 served as the upgradient, on-axis well. For groundwater potentially flowing north-northeast, a similar axial arrangement was used with well 23265 serving as the upgradient, on-axis well. The series of wells oriented along the north-northeast groundwater flow axis, including 23263, 23264, 23258, and 23262; served as the downgradient wells along this axis of the barrier. Figure 1-3 shows the locations of the monitoring wells in relation to the HRC<sup>®</sup> barrier.

The wells were constructed of 2-inch-diameter, flush-threaded, Schedule 40 polyvinyl chloride pipe and were screened at the base of the alluvial channel (approximately a 10-foot interval from about 43 to 53 feet below ground surface [bgs]). A sand pack with a 10/20 nominal sieve size was installed around and up to a minimum of 2 feet above the top of the screened interval, and a bentonite seal of minimum 2-foot thickness was installed above the sand pack. Wells were located from 45 feet upgradient to about 30 feet downgradient from the 12-foot-wide barrier.

#### **1.4.2 Construction of the HRC<sup>®</sup> Permeable Barrier**

Based on historical groundwater elevation data, groundwater flow directions at this site vary from north-northeast to east, depending on the time of year and other factors. A tracer study conducted at the site prior to the evaluation indicated that the primary groundwater velocity vector was northeast at the time of the study.

Due to the variability of the groundwater flow direction at this site, the barrier was installed in an “L” shape to ensure that groundwater flowing to any of the downgradient wells would pass through the treatment wall. To satisfy this arrangement, a 50-foot by 30-foot L-shaped HRC<sup>®</sup> permeable barrier was installed across the alluvial aquifer north of Basin F, as shown in Figure 1-3. HRC<sup>®</sup> was injected from the bottom up into each direct-push borehole at a dose rate of about 10 pounds per foot over a 10-foot interval from about 44 to 54 feet bgs. A total of about 4,200 pounds of HRC<sup>®</sup> was injected in these 42 points.

The constructed HRC<sup>®</sup> barrier was 12 feet in width with a 6-foot spacing between each of three rows of injection points. Injection of the HRC<sup>®</sup> barrier took about 1 week. The injections started at the upgradient row and progressed to the downgradient row so that a complete treatment effect would be observed in the first element of groundwater that passed through the barrier.

#### **1.5 EVALUATION OBJECTIVES**

The evaluation was initially designed to achieve five specific objectives, including one primary (P) objective and four secondary (S) objectives, as listed below:

- P1 Determine the ability of the Regenesis in situ groundwater treatment technology to significantly reduce the concentrations of each of the contaminants of concern (COC) in the North of Basin F plume.
- S1 Qualitatively evaluate the potential for the technology to achieve state and federal regulatory clean-up goals for the site.
- S2 Qualitatively evaluate the presence or absence of treatment-derived products and indications of anaerobic conditions in groundwater samples.
- S3 Qualitatively evaluate the COC concentrations in the peripheral monitoring wells located along the string of downgradient wells.
- S4 Obtain and evaluate data associated with the cost of implementation of the Regenesis HRC<sup>®</sup> technology for the destruction or removal of COCs as encountered at RMA.

For purposes of implementing the evaluation objectives, the list of COCs and their associated remediation goals included two components. First, the list included COCs identified in the 1996 Record of Decision (ROD) for the North Boundary Containment System at the RMA. These eight COCs are listed in Table 1-2, along with the site-specific remediation goals listed in the ROD.

**Table 1-2  
Contaminants of Concern and Groundwater Remediation Goals**

<b>Contaminant of Concern</b>	<b>Contaminant System Remediation Goal<sup>1</sup> (µg/L)</b>
Di-isopropylmethyl phosphonate <sup>2</sup>	8
Chlorophenylmethyl sulfide <sup>3</sup>	30
Chlorophenylmethyl sulfone <sup>3</sup>	36
Dieldrin <sup>2,3</sup>	0.05
Dicyclopentadiene <sup>3</sup>	46
Chloroform <sup>2,3</sup>	6
Methylene Chloride	5
Tetrachloroethene <sup>3</sup>	5

Notes:

- <sup>1</sup> North Boundary Containment System Remediation Goal
- <sup>2</sup> Also a Northwest Boundary Containment System COC
- <sup>3</sup> Also a Basin A Neck Treatment System COC

Second, the list included four additional compounds of regulatory interest, which are identified as follows, along with their corresponding remediation goals:

- Benzene, 3.0 g/L
- TCE, 3.0 g/L
- 1,2-Dibromo-3-chloropropane (DBCP), 0.20 g/L
- N-nitroso-dimethylamine, 0.007 g/L

The complete list of COCs for the evaluation included 12 compounds of direct regulatory interest at the site.

## 1.6 KEY CONTACTS

Additional information on the HRC<sup>®</sup> technology, the North of Basin F site, and the SITE Program is available from the following sources:

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U.S. Environmental Protection Agency  
National Risk Management Research Laboratory  
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Cincinnati, Ohio 45268  
Telephone: (513) 569-7271  
Fax: (513) 569-7676  
E-mail: [parker.randy@epa.gov](mailto:parker.randy@epa.gov)

## **2.0 TREATMENT EFFECTIVENESS**

This section presents the results of the evaluation of the Regenesis HRC<sup>®</sup> barrier at the North of Basin F site at RMA.

### **2.1 EVALUATION APPROACH AND METHODS**

The following sections describe the evaluation approach, including the experimental design, sampling frequency, and sampling and analytical methods. Each of these elements of the overall approach was designed to address the evaluation objectives.

#### **2.1.1 Experimental Design**

The HRC<sup>®</sup> barrier was installed to intercept groundwater flowing through the alluvial paleochannel in the study area. Groundwater monitoring wells were installed parallel to the paleochannel axis, both upgradient and downgradient from the barrier, to monitor the technology's effectiveness during the evaluation. The experimental design for the technology evaluation incorporated the analysis of groundwater samples from both the upgradient and downgradient monitoring wells to determine the impact of the HRC<sup>®</sup> barrier on groundwater quality.

#### **2.1.2 Sampling Frequency**

The evaluation sampling was conducted from February 2001 to October 2002. Three background groundwater sampling events were conducted from February to May 2001, prior to barrier installation, to establish background concentrations. Following injection of the HRC<sup>®</sup> barrier in mid-May 2001, eight groundwater sampling events were conducted over an 18-month period to determine the effectiveness of the technology in reducing contaminant concentrations in groundwater downgradient from the barrier.

Based on an estimated groundwater flow velocity of 0.8 ft/day, the impacts of the barrier in the furthest downgradient well were estimated to manifest within 6 weeks of barrier installation. Over the anticipated 1-year post-injection test period, and based on an estimated groundwater flow velocity of 0.8 ft/day, more than three pore volumes of groundwater were expected to pass through the aquifer from the mid-point of the barrier to the furthest downgradient well. Therefore results obtained toward the end of the 1-year period were expected to reflect a complete displacement of the initial groundwater with groundwater that had passed through the barrier.

#### **2.1.3 Sampling and Analytical Methods**

Groundwater levels in each well were measured during each sampling event, and groundwater samples were collected for a series of field and laboratory analyses. Groundwater samples were collected using low-flow sample collection techniques to limit inclusion of otherwise immobile colloids and target compounds that are sorbed to these particles. To facilitate sample collection, each monitoring well was equipped with a dedicated submersible bladder pump positioned in the middle, or slightly above the middle, of the saturated zone. Each well was purged at a pumping rate of 0.1 liter per minute (L/min) to flush formation water through the dedicated pump, sample tubing, and an in-line flow meter and water quality meter (flow-through cell) connected to the tubing. Purge rates were then increased step-wise to a maximum rate of 0.5 L/min, and the water level in the well casing was periodically monitored to ensure that draw-down did not exceed 0.1 meter (0.3 foot).

Temperature, conductivity, oxidation-reduction potential (ORP), dissolved oxygen (DO), pH, and turbidity were monitored every 5 minutes while purging with an in-line water quality meter. Purging was continued until these parameters stabilize to within  $\pm 1.0$  °F for temperature,  $\pm 3$  percent for conductivity,  $\pm 20$  millivolts (mV) for ORP,  $\pm 10$  percent for DO,  $\pm 0.1$  units for pH over three consecutive readings, and a 20 percent range in readings for turbidity over three consecutive measurements. Purging was continued until these parameters stabilized or three casing volumes had been removed. Sample collection began immediately following purging.

Several laboratory tests were conducted on each groundwater sample to characterize the general chemical properties, as well as to measure the specific target compounds of interest. The parameters that were analyzed in each groundwater sample included the target COCs, degradation parameters such as the organic acids that are released from the HRC<sup>®</sup>, and general groundwater chemistry parameters. The methods used to analyze each of these parameters are listed in Table 2-1.

## **2.2 EVALUATION RESULTS**

The results of the evaluation are described in the following sections, with respect to the impact of the HRC<sup>®</sup> on groundwater chemistry, non-direct indicators of degradation rates and pathways, and the observed trends in COC concentrations.

### **2.2.1 Impact of HRC<sup>®</sup> Injection on Groundwater Chemistry**

Once injected into the subsurface, HRC<sup>®</sup> rapidly hydrolyzes to yield lactic acid. Anaerobic degradation of lactic acid generates acetic acid and hydrogen, which facilitates the formation of other volatile fatty acids, including propionic acid and butyric acid. As a result, the measurement of these volatile fatty acids provides an indicator of HRC<sup>®</sup> activity in the subsurface.

Groundwater concentrations of lactic, propionic, butyric, and acetic acids over the entire period of the evaluation are plotted in Figures 2-1 through 2-4, respectively. These time-series plots show the concentration in each well, both upgradient and downgradient from the HRC<sup>®</sup> barrier, and both before and after the HRC<sup>®</sup> injection. As shown in Figure 2-1, lactic acid concentrations rose dramatically immediately following HRC<sup>®</sup> injection, but declined rapidly over the next several months. Propionic, butyric, and acetic acid concentrations also rose immediately following HRC<sup>®</sup> injection, but exhibited a slower initial rise and a slower decline as compared with lactic acid. It should be noted that significant concentrations of these volatile fatty acids remained even 18 months after injection of the HRC<sup>®</sup>. The

**Table 2-1  
Analytical Methods**

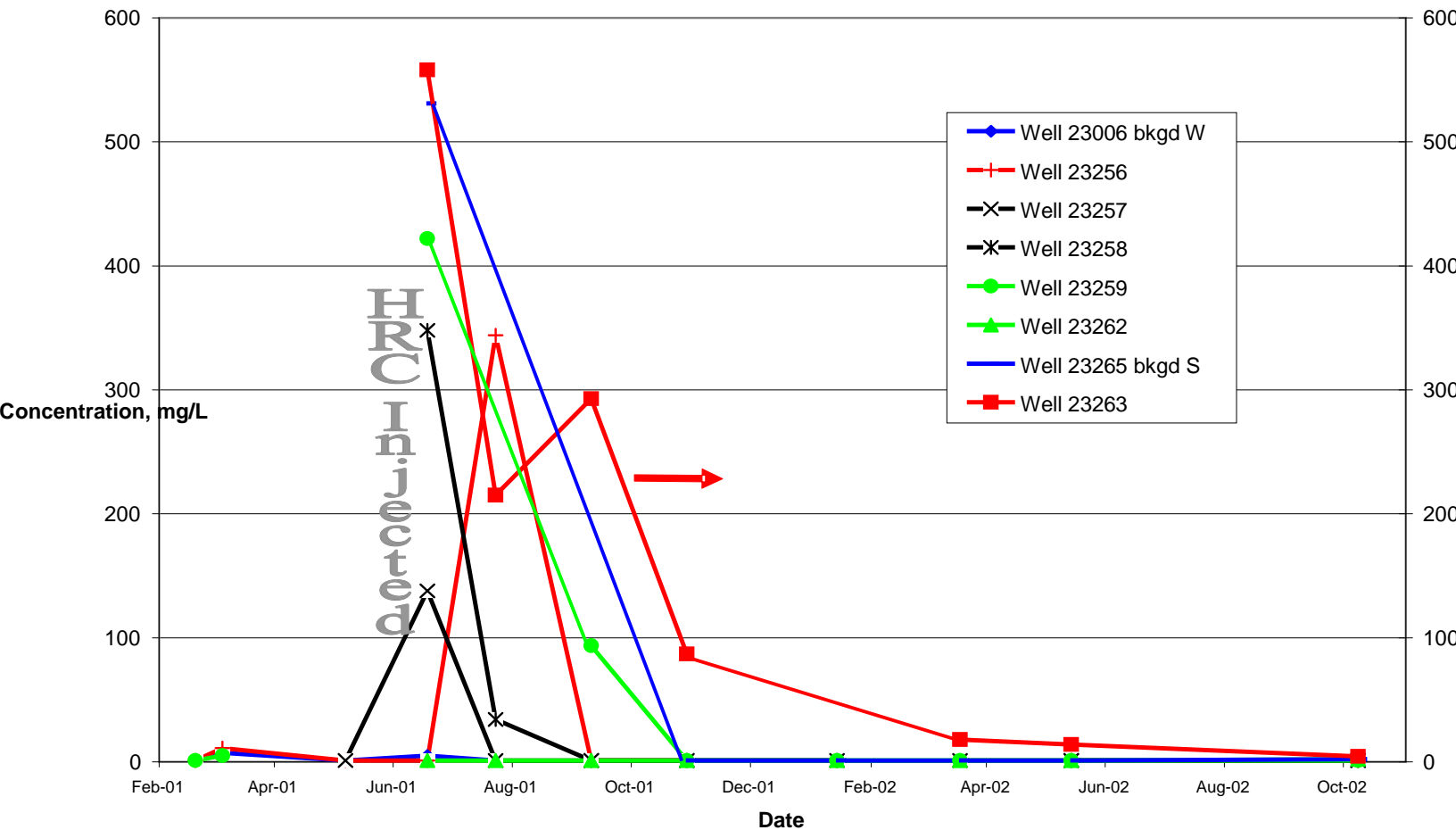
Parameter	Method	Reporting Units	Reference
<b>Target COCs</b>			
Semivolatile Organics <sup>a</sup>	EPA Method 3510C <sup>b</sup> /8270C <sup>c</sup>	µg/L	SW-846 <sup>d</sup>
Volatile Organics <sup>e</sup>	EPA Method 5030B/8260B <sup>f</sup>	µg/L	SW-846
Dieldrin	EPA Method 3510C/8081A	µg/L	SW-846
<b>Degradation Indicators</b>			
Volatile Fatty Acids	Laboratory Standard Operating Procedure (SOP) <sup>m</sup>	mg/L	Laboratory SOP
Dissolved Gases <sup>j</sup>	ASTM D-1945	mg/L	ASTM <sup>k</sup>
Total Heterotrophs	SM 9215	cfu/mL <sup>n</sup>	SMEWW <sup>i</sup>
<b>General Chemistry</b>			
Total Organic Carbon	EPA Method 9060	mg/L	SW-846
Total & Dissolved Metals <sup>g</sup>	EPA Method 3010/6010	mg/L	SW-846
Nitrite/Nitrate	EPA Method 353.2	mg/L	MCAWW <sup>h</sup>
Total Kjeldahl Nitrogen	SM 4500-N ORG	mg/L	SMEWW <sup>i</sup>
Sulfate	EPA Method 300.0	mg/L	MCAWW
Sulfide	EPA Method 376.2	mg/L	MCAWW
Chloride	EPA Method 300.0	mg/L	MCAWW

Notes:

- <sup>a</sup> Semivolatile organics include di-isopropylmethyl phosphonate, chlorophenylmethyl sulfide, chlorophenylmethyl sulfone, dicyclopentadiene, n-nitrosodimethyl amine.
- <sup>b</sup> 3510C was modified by performing the extraction at base/neutral pH conditions.
- <sup>c</sup> Modified according to Rocky mountain Arsenal (RMA) Method UM-58. The analyte list of 8270C was modified to include the semivolatile critical contaminants. Di-isopropylmethyl phosphonate and chlorophenylmethyl sulfone will be included in one blank and matrix spike.
- <sup>d</sup> *Test Methods for Evaluating Solid Waste, Physical/Chemical Methods*, U.S. Environmental Protection Agency, SW-846, Third Edition, 1986 with 12/96 Updates.
- <sup>e</sup> Volatile organics include benzene, chloroform, 1,2-dibromo-3-chloropropane, methylene chloride, tetrachloroethene, trichloroethene, and vinyl chloride.
- <sup>f</sup> Modified according to RMA Method UM-57.
- <sup>g</sup> Metals include iron and manganese.
- <sup>h</sup> *Methods for the Chemical Analysis of Water and Wastes*, U.S. Environmental Protection Agency, EPA 600/4-79-020, 1979, Revised March 1983.
- <sup>i</sup> *Standard Methods for the Examination of Water and Wastewater*, American Public Health Association, American Water Works Association, and Water Environment Federation, 20<sup>th</sup> Edition, 1998.
- <sup>j</sup> Carbon dioxide, methane, ethane, and ethene.
- <sup>k</sup> American Society of Testing and Materials.
- <sup>m</sup> Laboratory method using high performance liquid chromatography with an ultraviolet absorption detector.
- <sup>n</sup> cfu/mL : colony forming units per milliliter.



Figure 2-1 Lactic Acid



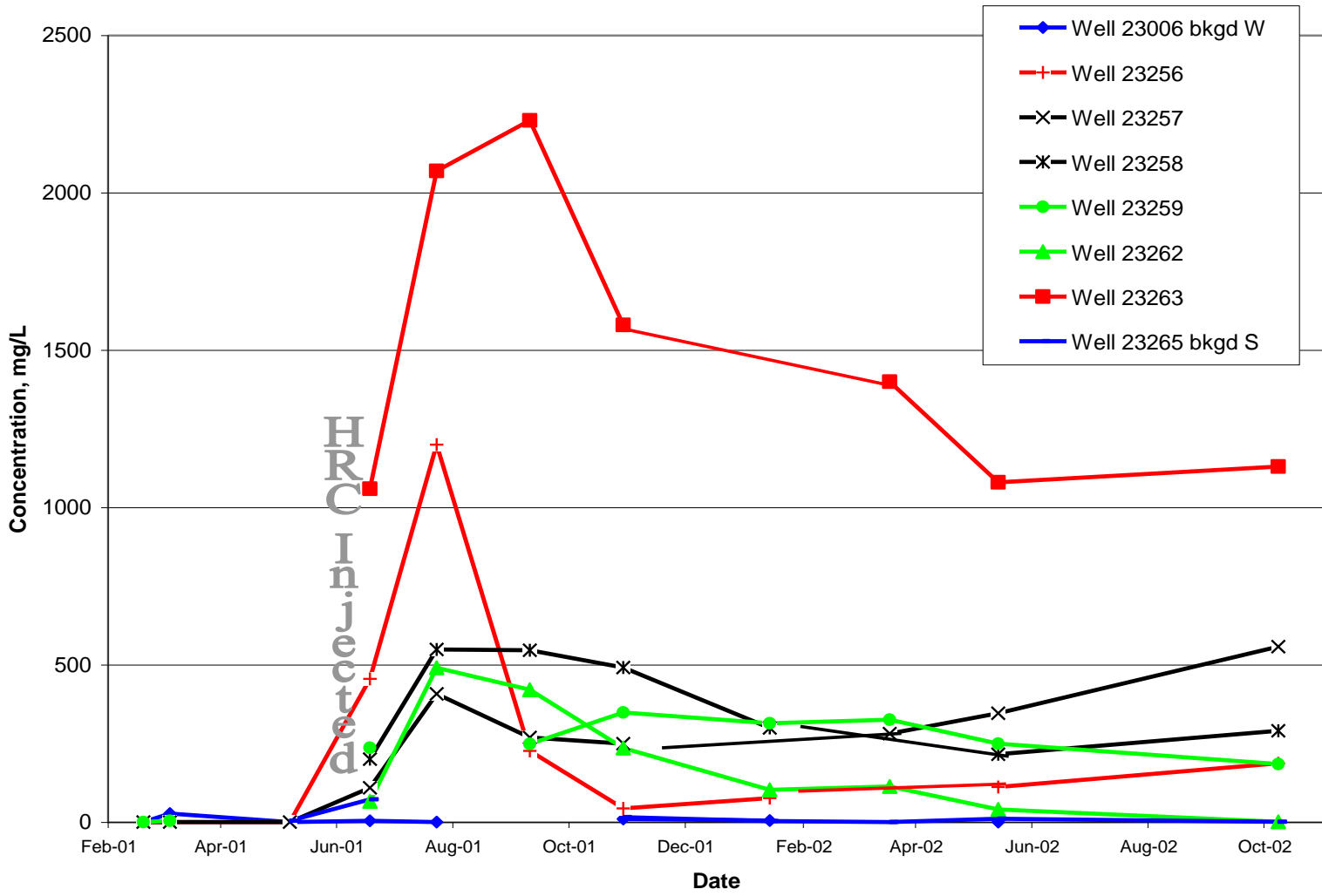


Figure 2-2 Propionic Acid

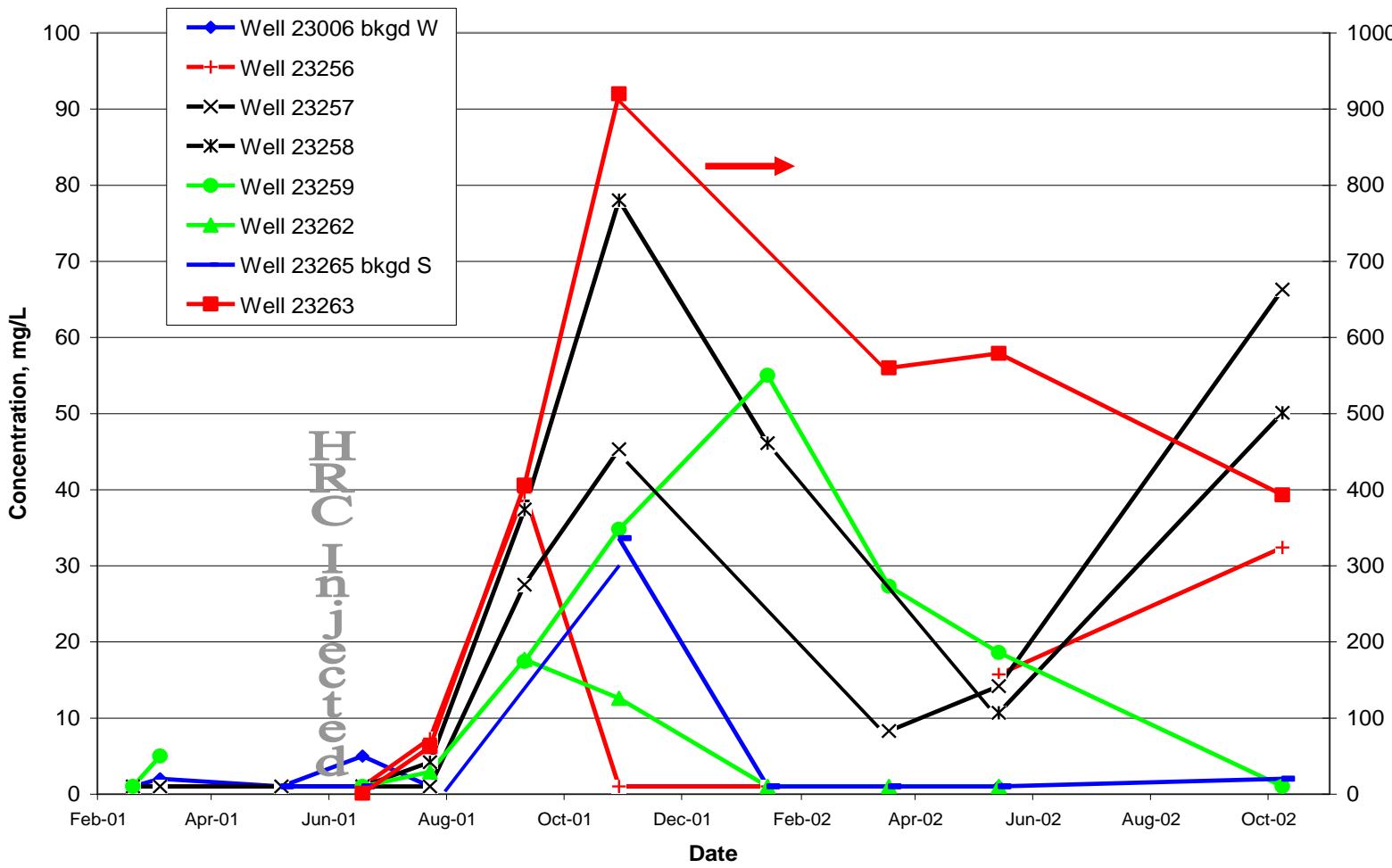


Figure 2-3 Butyric Acid

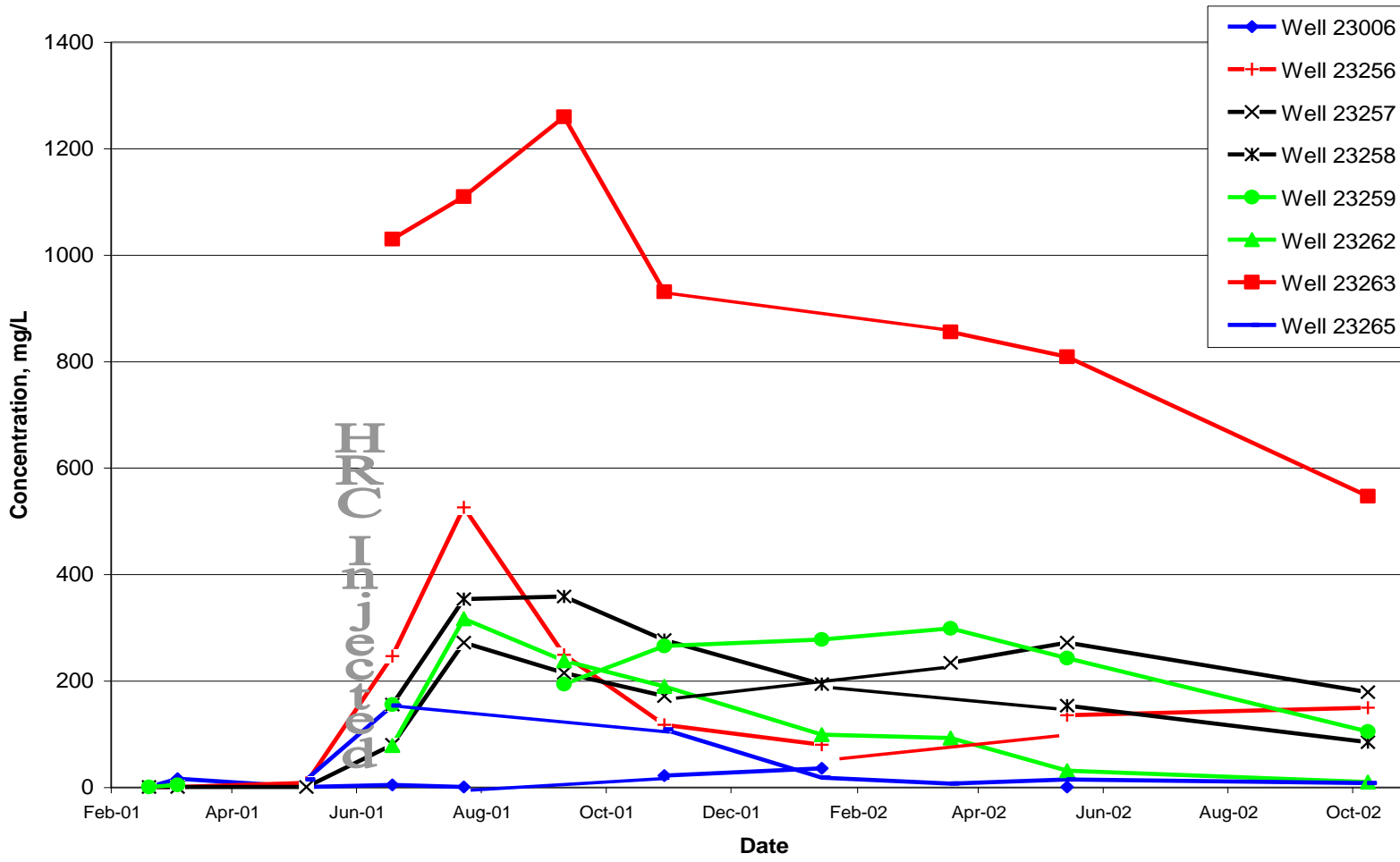


Figure 2-4 Acetic Acid

effect of HRC<sup>®</sup> injection on ORP and pH are shown in the time-series plots in Figures 2-5 and 2-6. As shown in the figures, ORP was reduced to less than 0 millivolts immediately following HRC<sup>®</sup> injection, and remained negative in downgradient wells throughout the 18 months of post-injection monitoring. The range of ORP values shown in the downgradient wells following HRC<sup>®</sup> injection was consistent with anaerobic biodegradation. The pH of the groundwater was also reduced in downgradient wells following HRC<sup>®</sup> injection due to the release of volatile fatty acids, which act as weak acids, from the injected HRC<sup>®</sup>.

Although initial aquifer conditions were only mildly aerobic, a high HRC<sup>®</sup> dose rate was used during the evaluation to overcome competing electron acceptors, including ferric iron and sulfate. Hydrogen from HRC<sup>®</sup> is used to reduce these competing electron acceptors to create redox conditions that are conducive to reductive dechlorination. Time-series plots for iron and sulfate are shown in Figures 2-7 and 2-8, respectively. As shown in Figure 2-7, baseline ferric iron concentrations in groundwater were low, but high levels of ferric iron on soil particles yielded dissolved (ferrous) iron levels following injection of from 50 mg/L to more than 200 mg/L. The ferrous iron concentrations reached maximum levels about 4 to 5 months after injection and then began to decline gradually at most wells. As shown in Figure 2-8, sulfate concentrations fell from an average baseline concentration of 550 mg/L to typically less than 100 mg/L. Despite the high hydrogen demand presented by these competing electron acceptors, sufficient volatile fatty acids (hydrogen source) remained, and ORP levels remained negative 18 months following HRC<sup>®</sup> injection, and dechlorination appeared to continue throughout the evaluation period.

Total heterotrophic plate counts in the downgradient wells increased from an average of 537 colony-forming units per milliliter (cfu/mL) of groundwater before HRC<sup>®</sup> injection to 2,090 cfu/mL following HRC<sup>®</sup> injection. This increase reflects the growth of respiring microorganisms as a result of HRC<sup>®</sup> injection. However, the total heterotrophic plate count data showed substantial variability from sampling event to sampling event, and did not reveal any other clear trends. Further, heterotrophic plate counts based on groundwater samples may not be reflective of changes in the total microbial mass in the subsurface because a large fraction of that microbial mass is in the form of attached growth.

### **2.2.2 COC Degradation Trends**

Only 10 of the 12 identified COCs including DIMP, chlorophenylmethyl sulfide (CPMS), chlorophenylmethyl sulfone (CPMSO<sub>2</sub>), dieldrin, dicyclopentadiene (DCPD), chloroform, methylene chloride, PCE, benzene, and TCE were consistently detected in the monitoring wells before injection of HRC<sup>®</sup>. Trends for n-nitrosodimethyl amine and 1,2-dibromo-3-chloropropane could not be evaluated due to lack of baseline data for comparison with post-injection concentrations. The measured average background concentrations of these 10 COCs are presented in Table 2-2. Groundwater concentrations of these 10 COCs, along with the TCE degradation product cis-1,2-dichloroethene (DCE), over the entire period of the evaluation, are plotted in Figures 2-9 through 2-19, respectively. These time-series plots show the COC concentration in select wells, both upgradient and downgradient from the HRC<sup>®</sup> barrier, and both before and after the HRC<sup>®</sup> injection, and compare these concentrations to the site-specific remediation goals, where applicable.

Trends in COC concentrations were assessed using linear regression analysis, the Kendall Tau Test, and nonlinear decay modeling. A description of the detailed statistical evaluation of the groundwater analytical data using these models is provided in the TER. The overall trends shown in each of the time-series plots is discussed below for each COC.

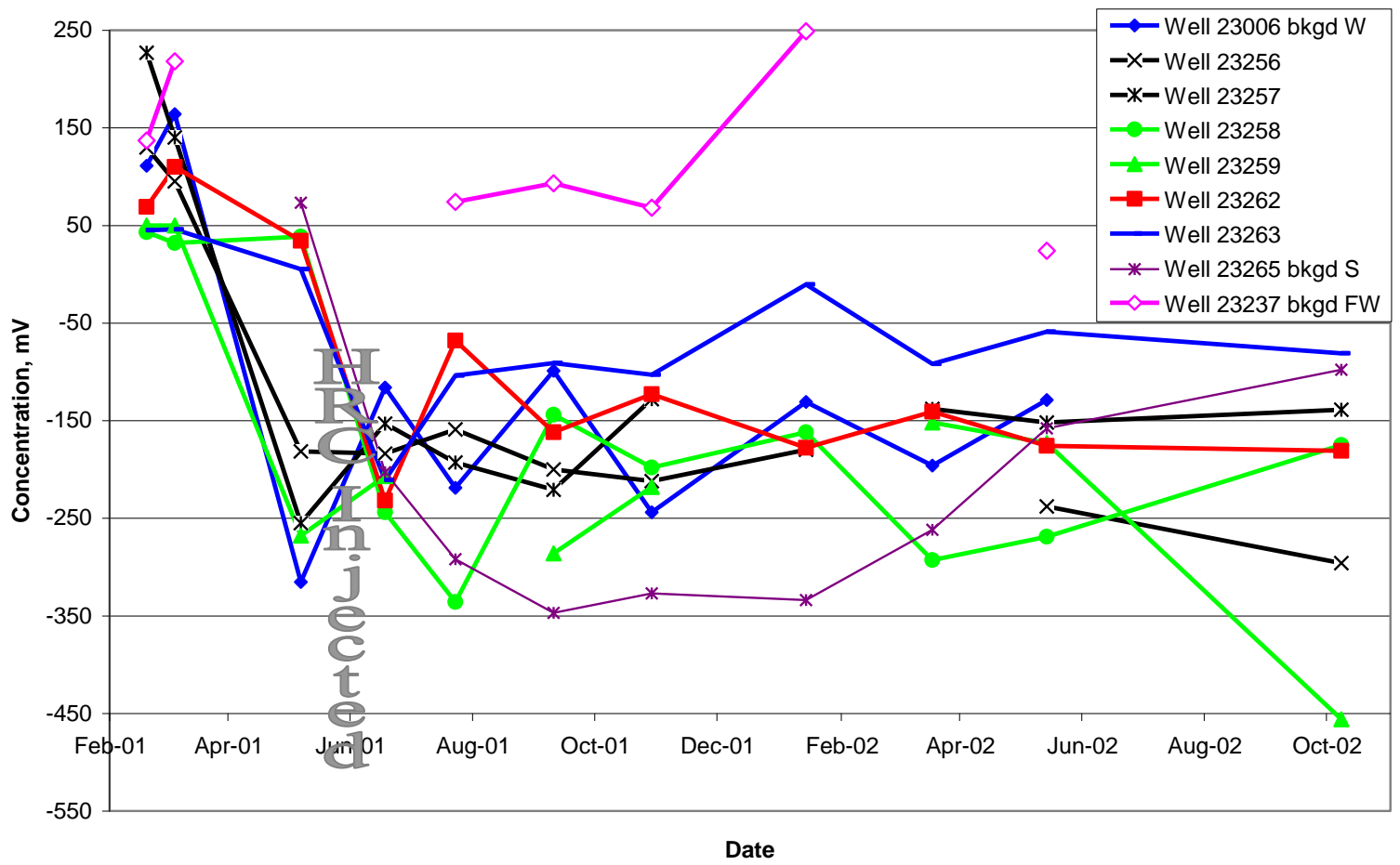


Figure 2-5 ORP

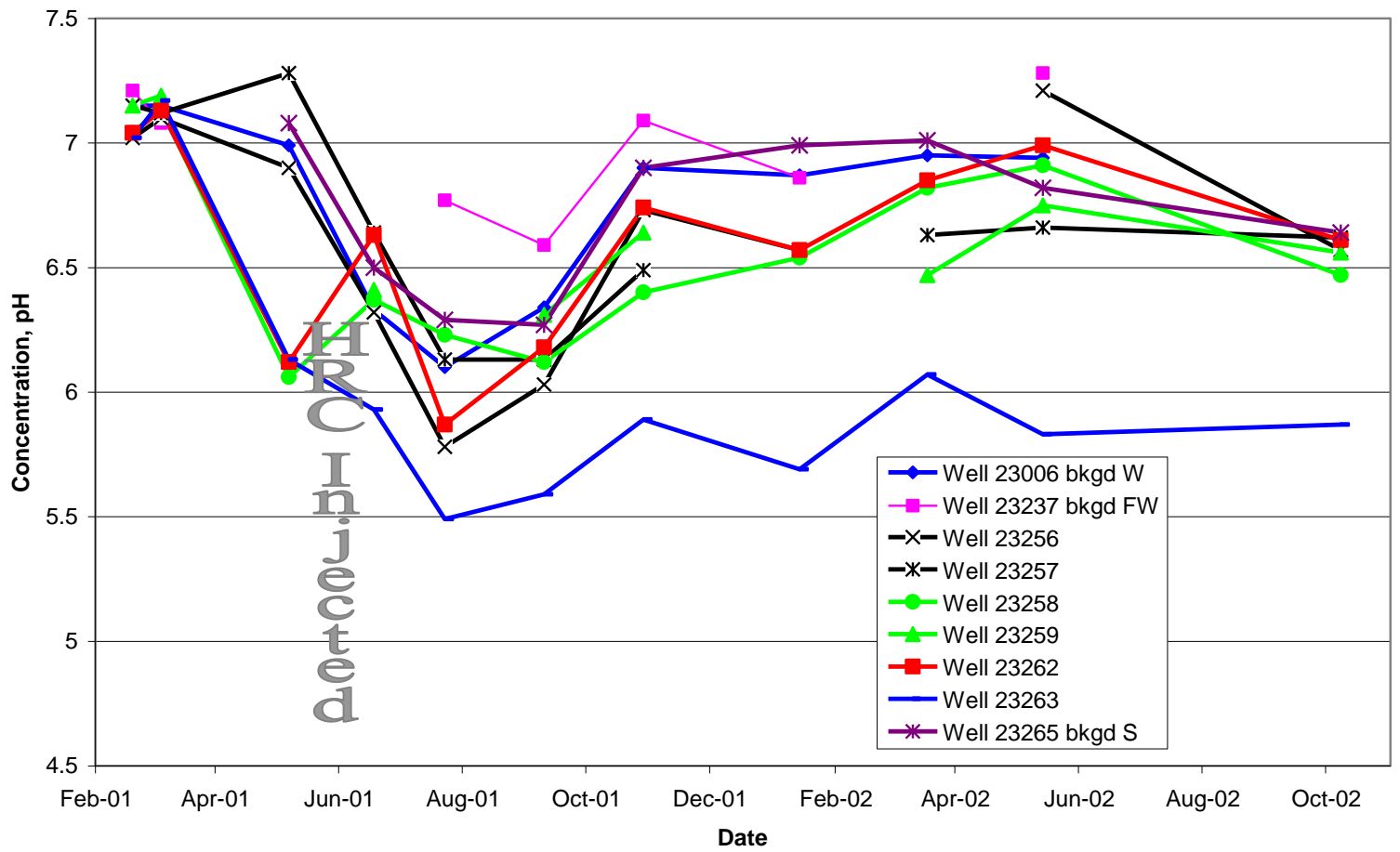


Figure 2-6 pH

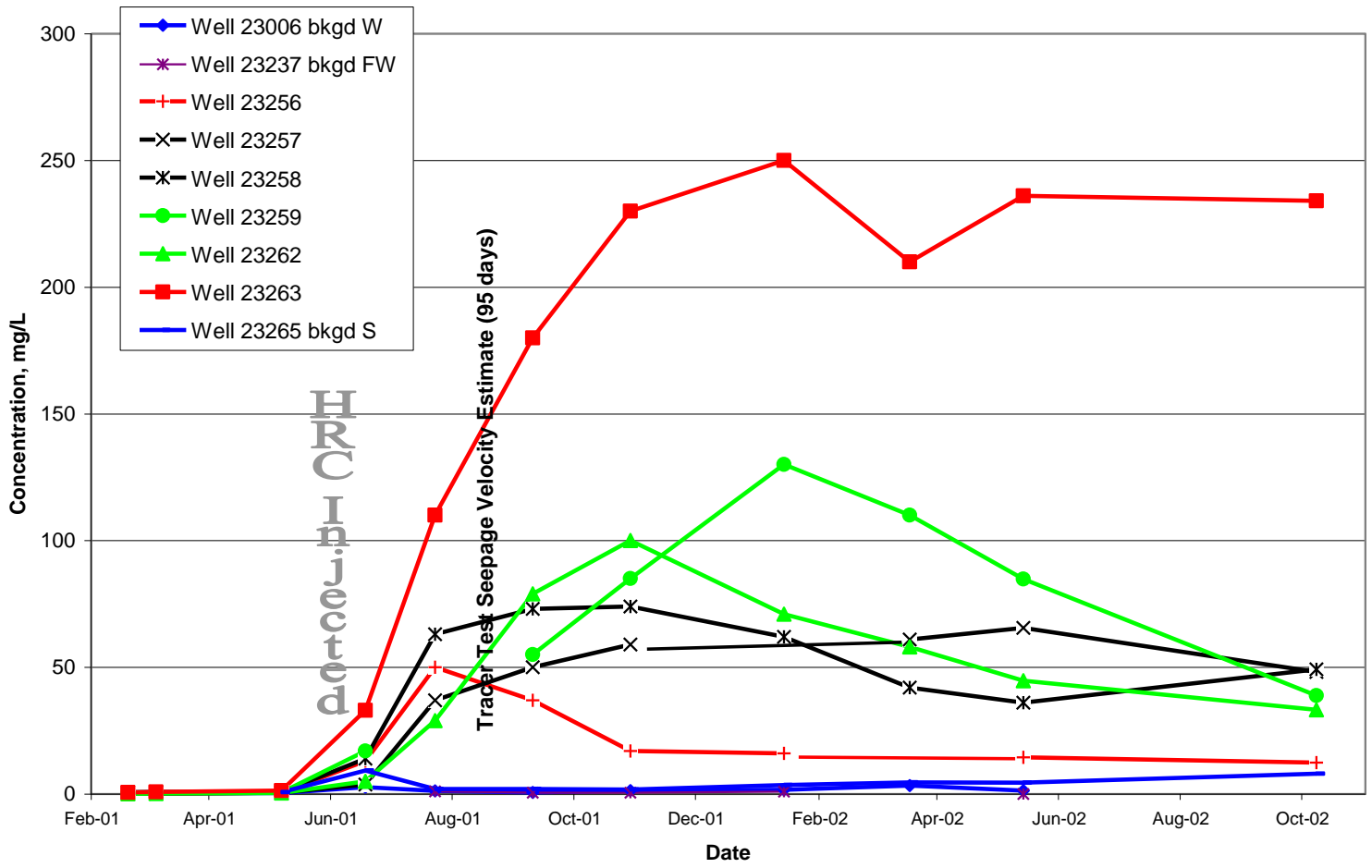


Figure 2-7 Iron



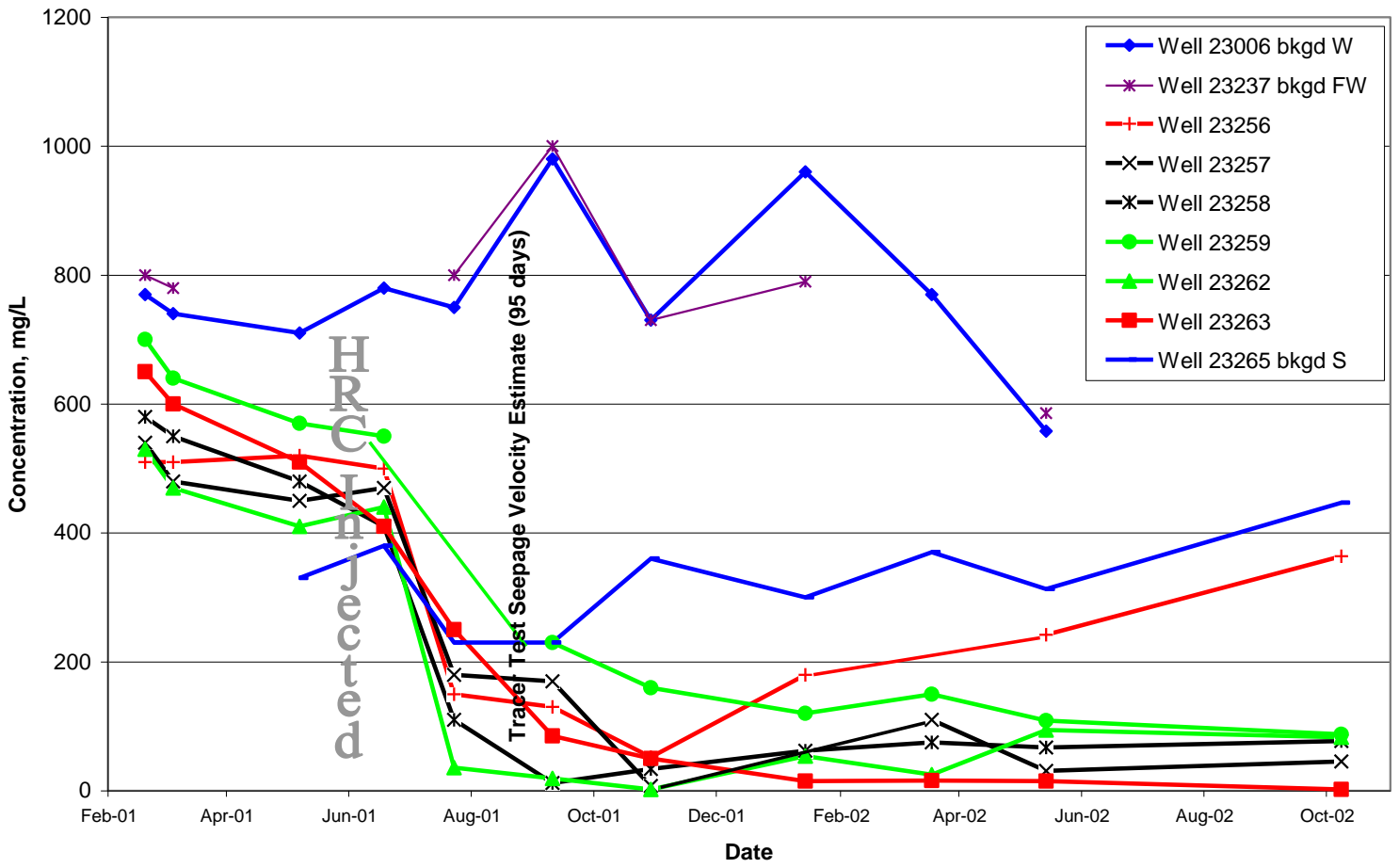


Figure 2-8 Sulfate

**Table 2-2  
Contaminants of Concern and Average Baseline Concentrations**

<b>Contaminant of Concern</b>	<b>Average Baseline<sup>1</sup> Concentration milligrams per liter (mg/L)</b>
Di-isopropylmethyl phosphonate	0.520 (0.306)
Chlorophenylmethyl sulfide	0.0032 (0.0071)
Chlorophenylmethyl sulfone	0.048 (0.021)
Dieldrin	0.00060 (0.00087)
Dicyclopentadiene	0.039 (0.072)
Chloroform	0.131 (0.280)
Methylene Chloride	0.0033 <sup>2</sup>
Tetrachloroethene	0.014 (0.019)
Trichloroethene <sup>3</sup>	0.057 (0.048)
Benzene <sup>3</sup>	0.0028 (0.00076)

Notes:

<sup>1</sup> Calculated for all wells; average for background (upgradient) wells only in parentheses.

<sup>2</sup> Not detected, value listed is the laboratory reporting limit.

<sup>3</sup> Secondary COC.

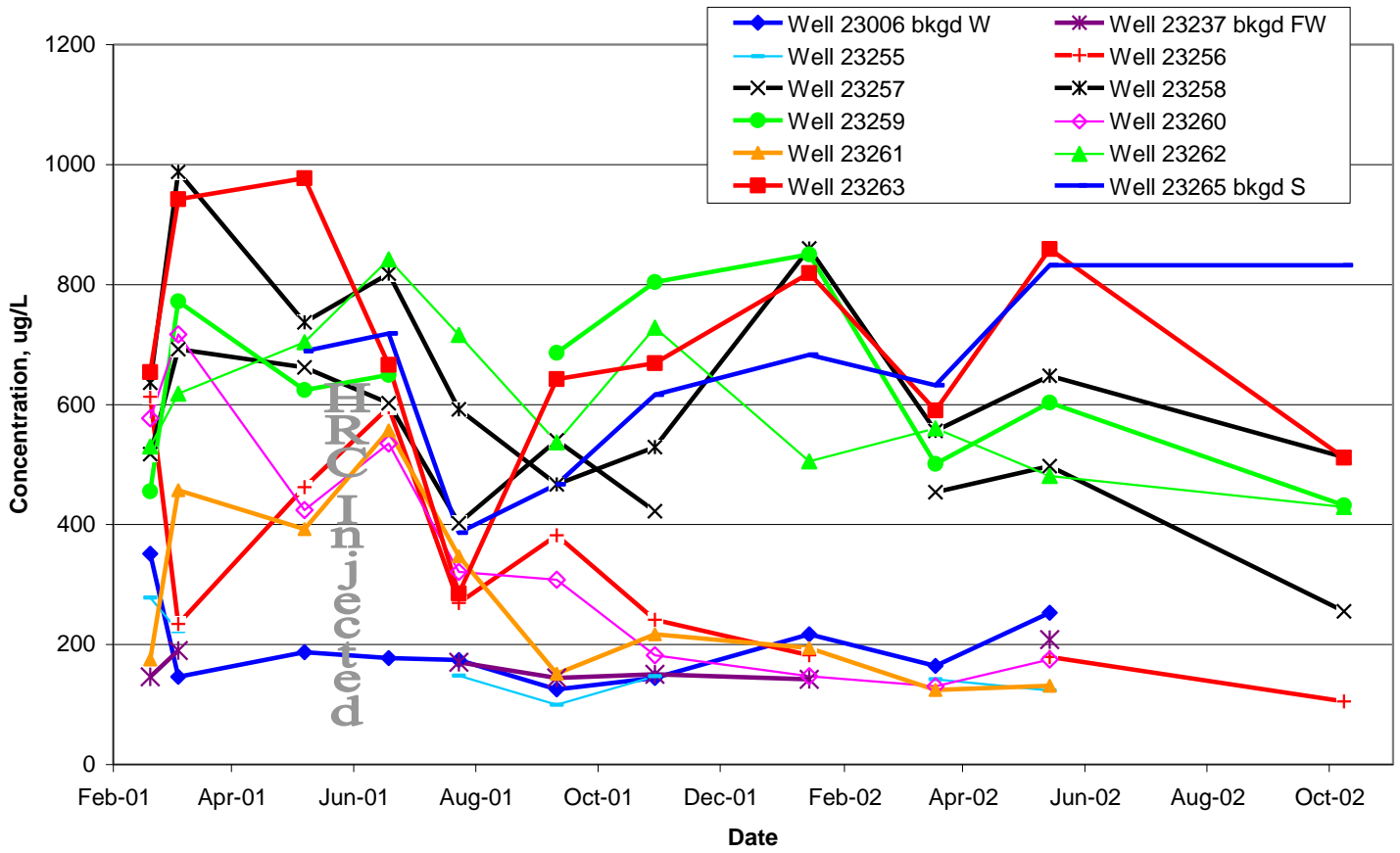
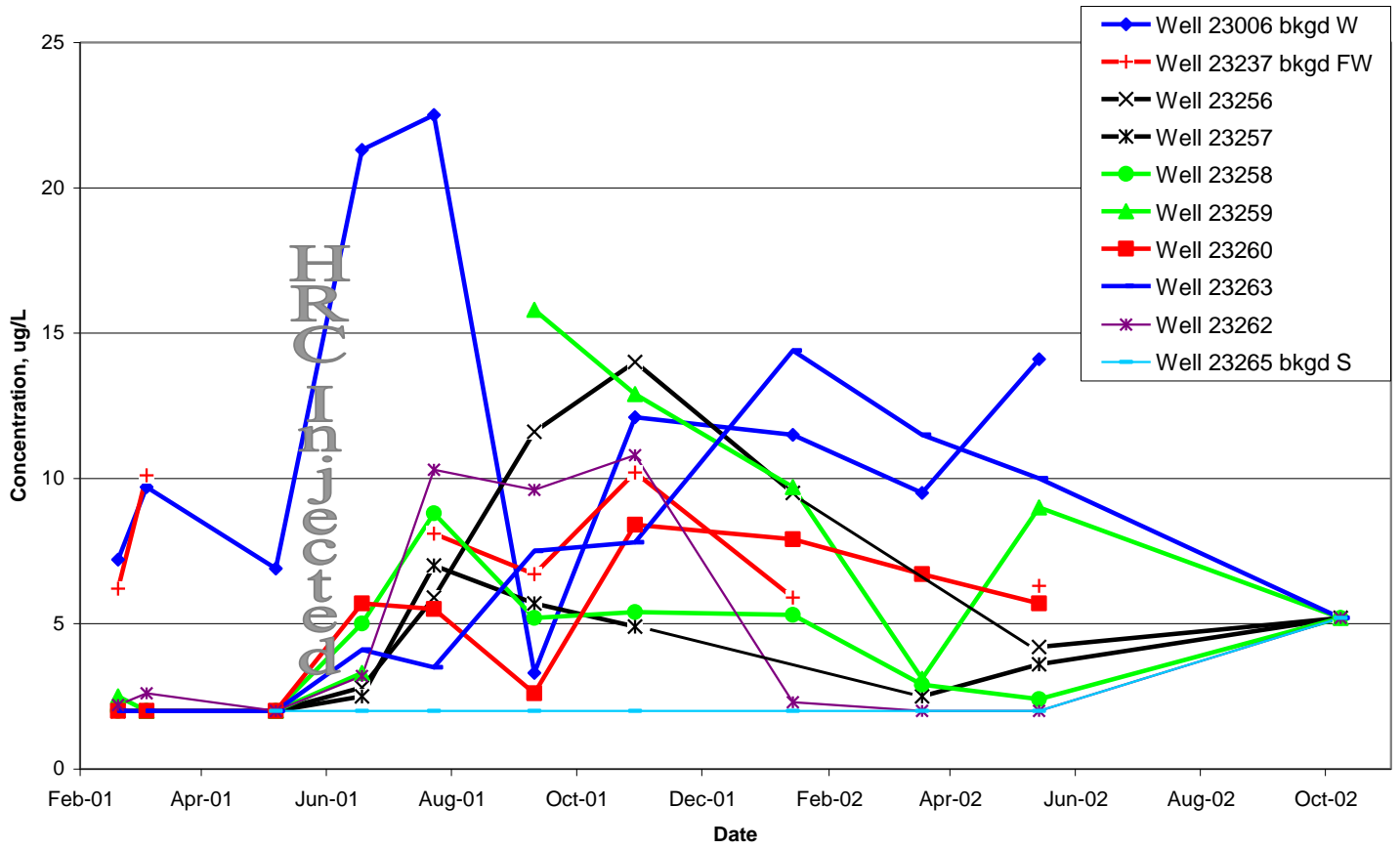


Figure 2-9 DIMP

Figure 2-10 CPMS



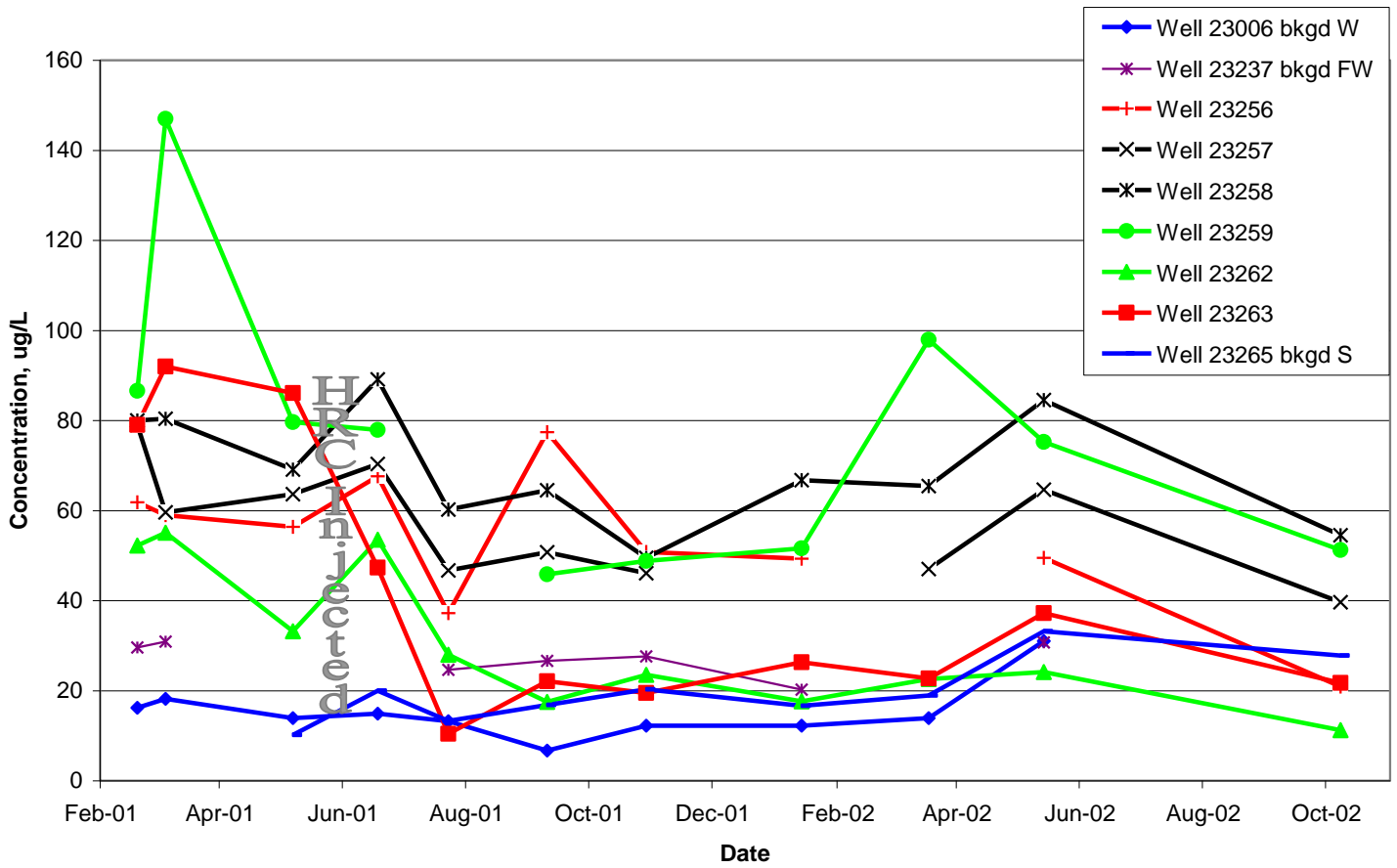


Figure 2-11 CPMSO2

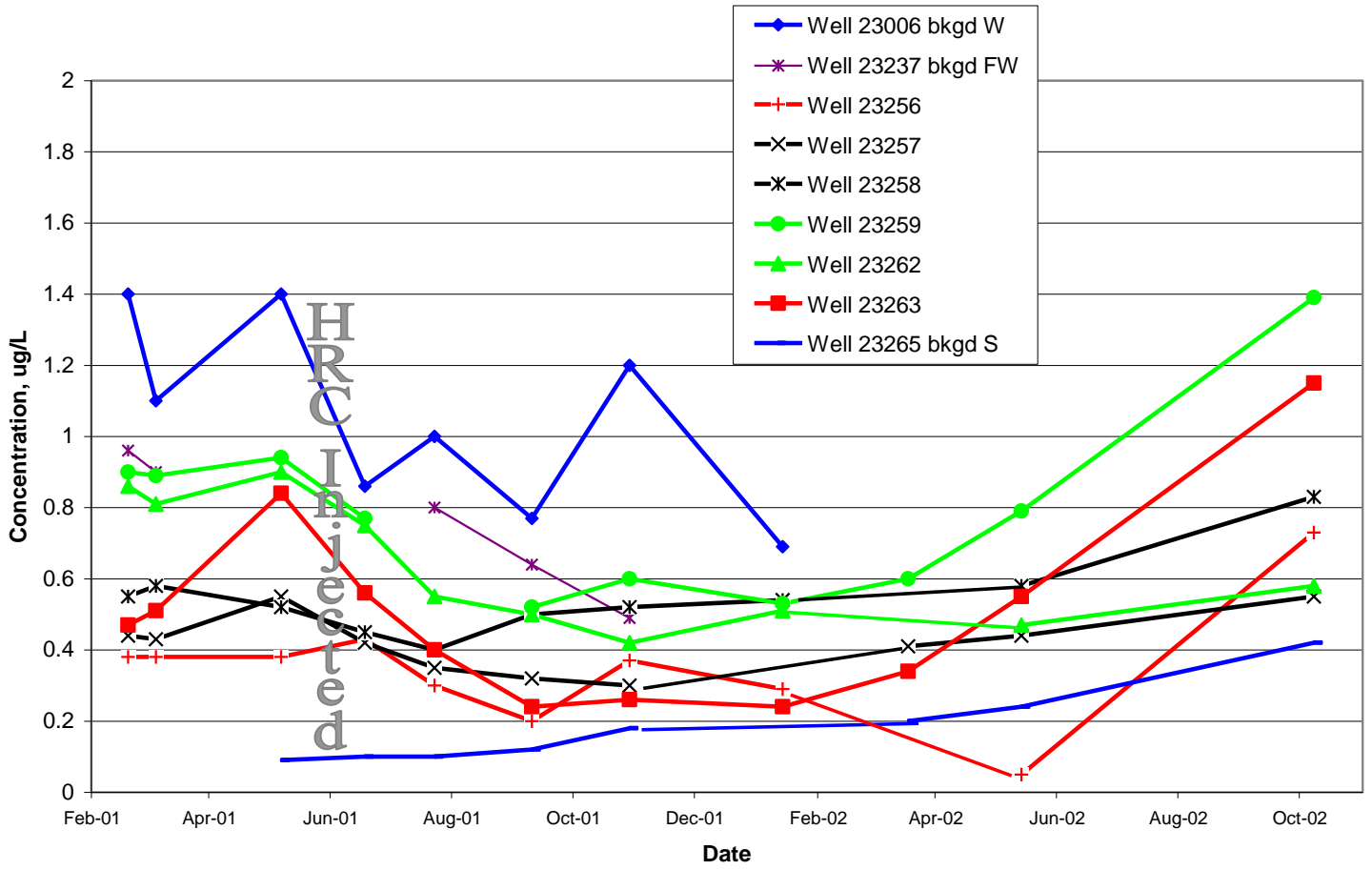


Figure 2-12 Dieldrin

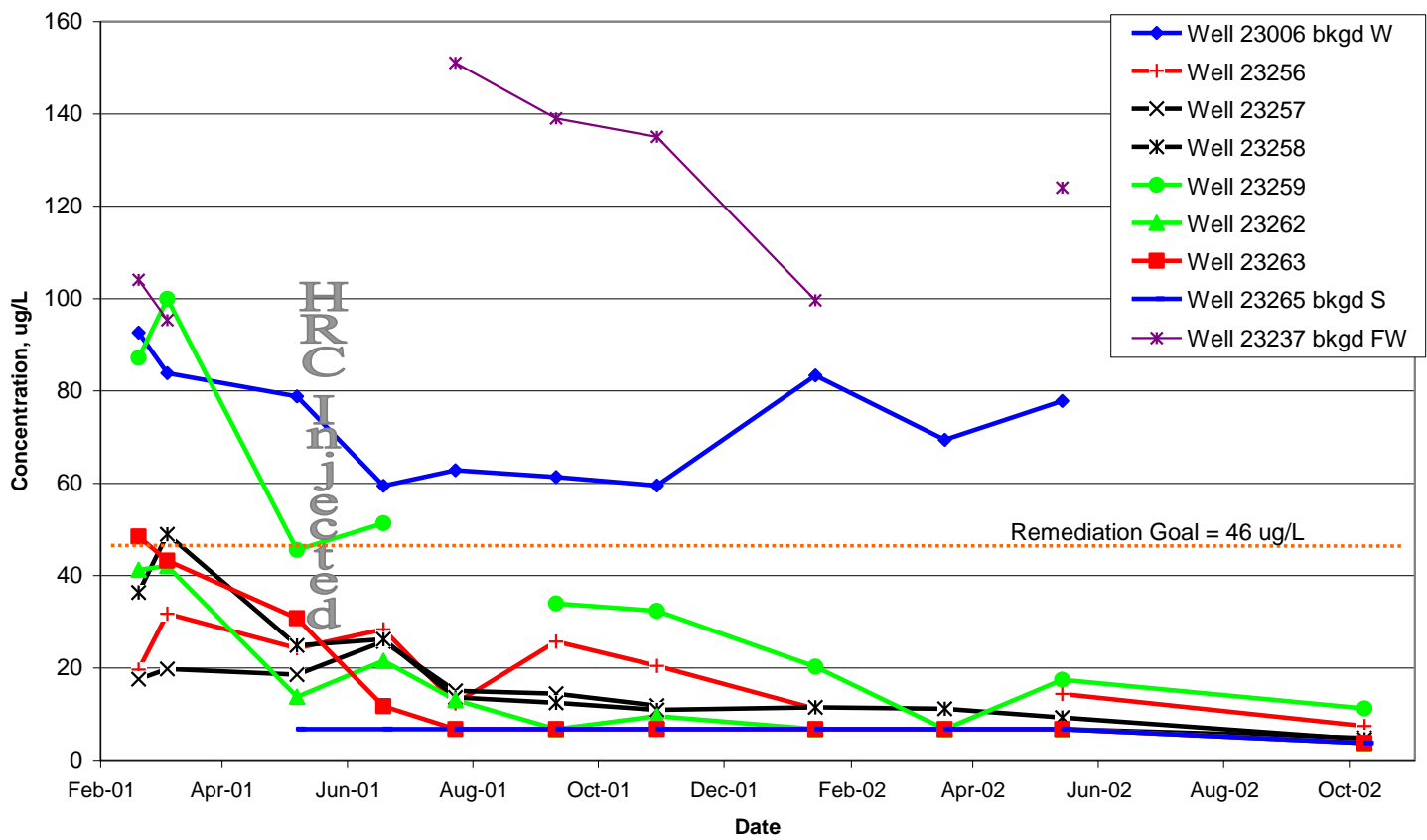


Figure 2-13 DCPD

Figure 2-14 Benzene

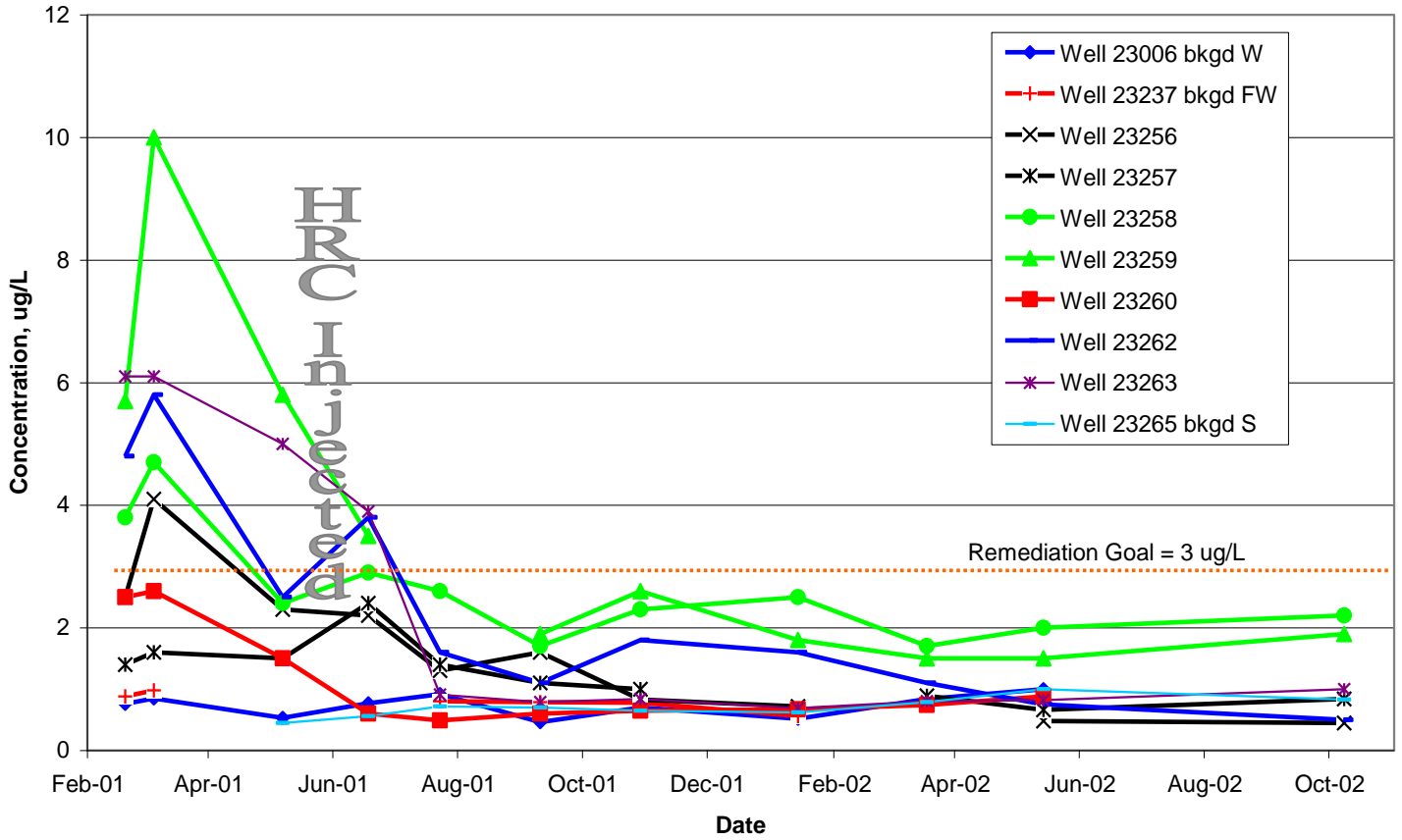
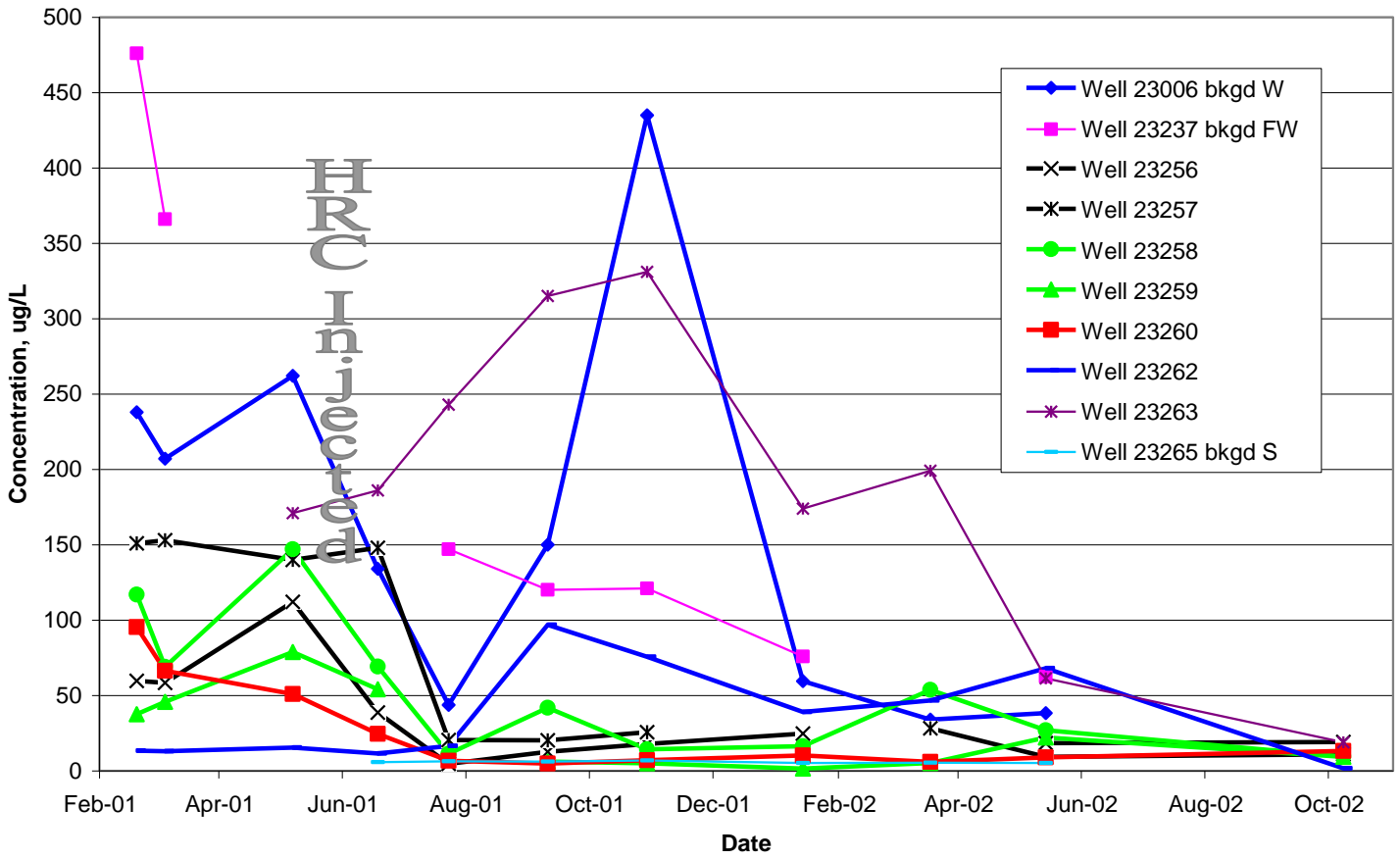




Figure 2-15 Chloroform



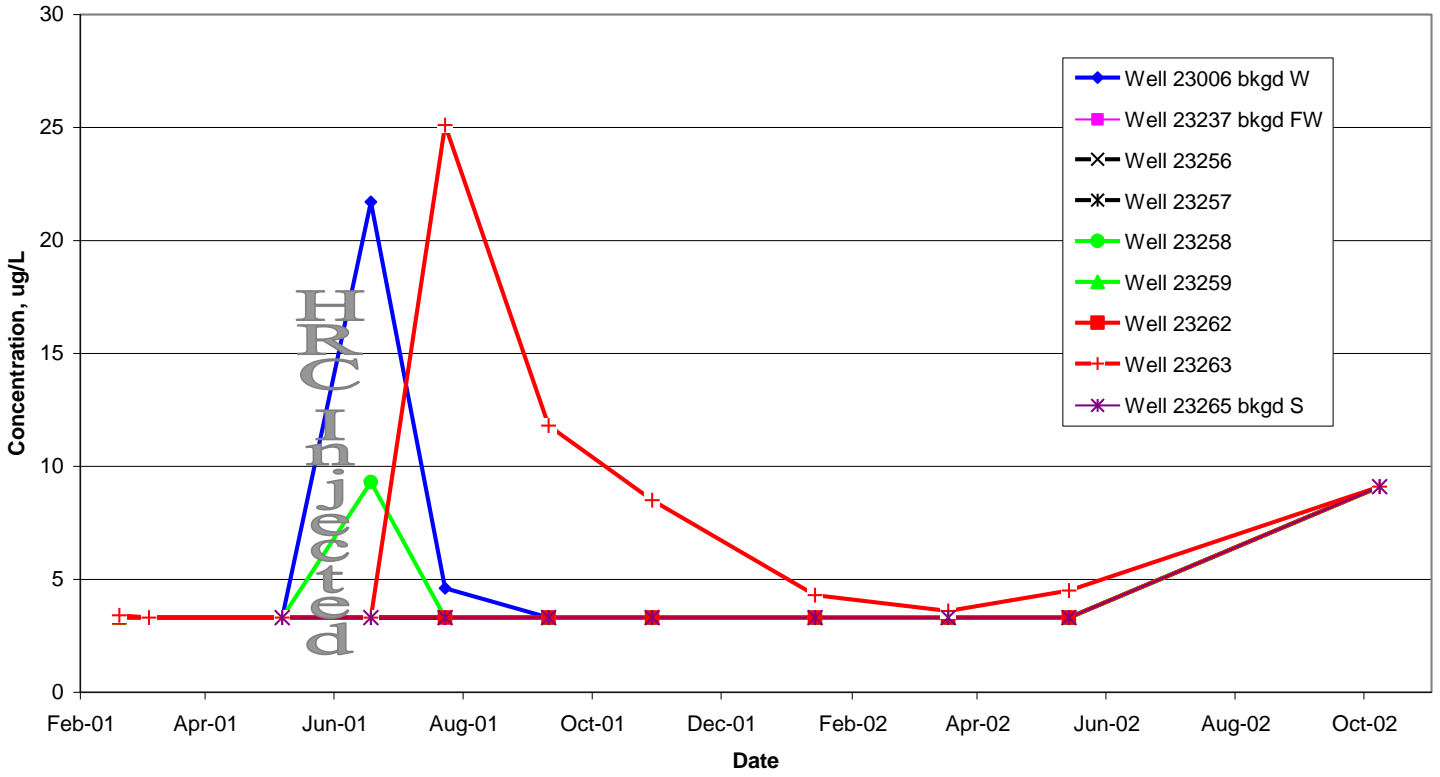


Figure 2-16 Methylene Chloride

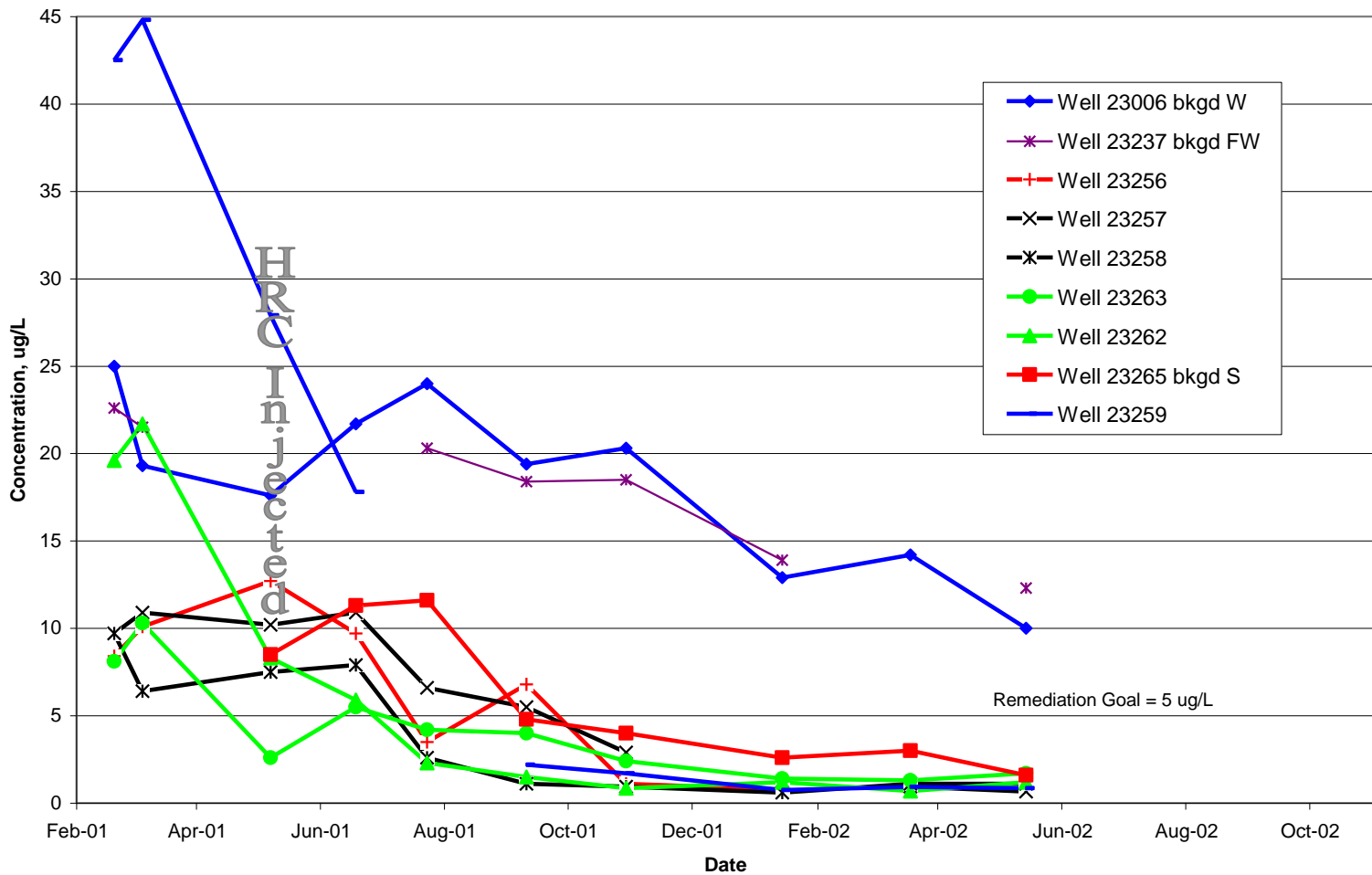


Figure 2-17 PCE

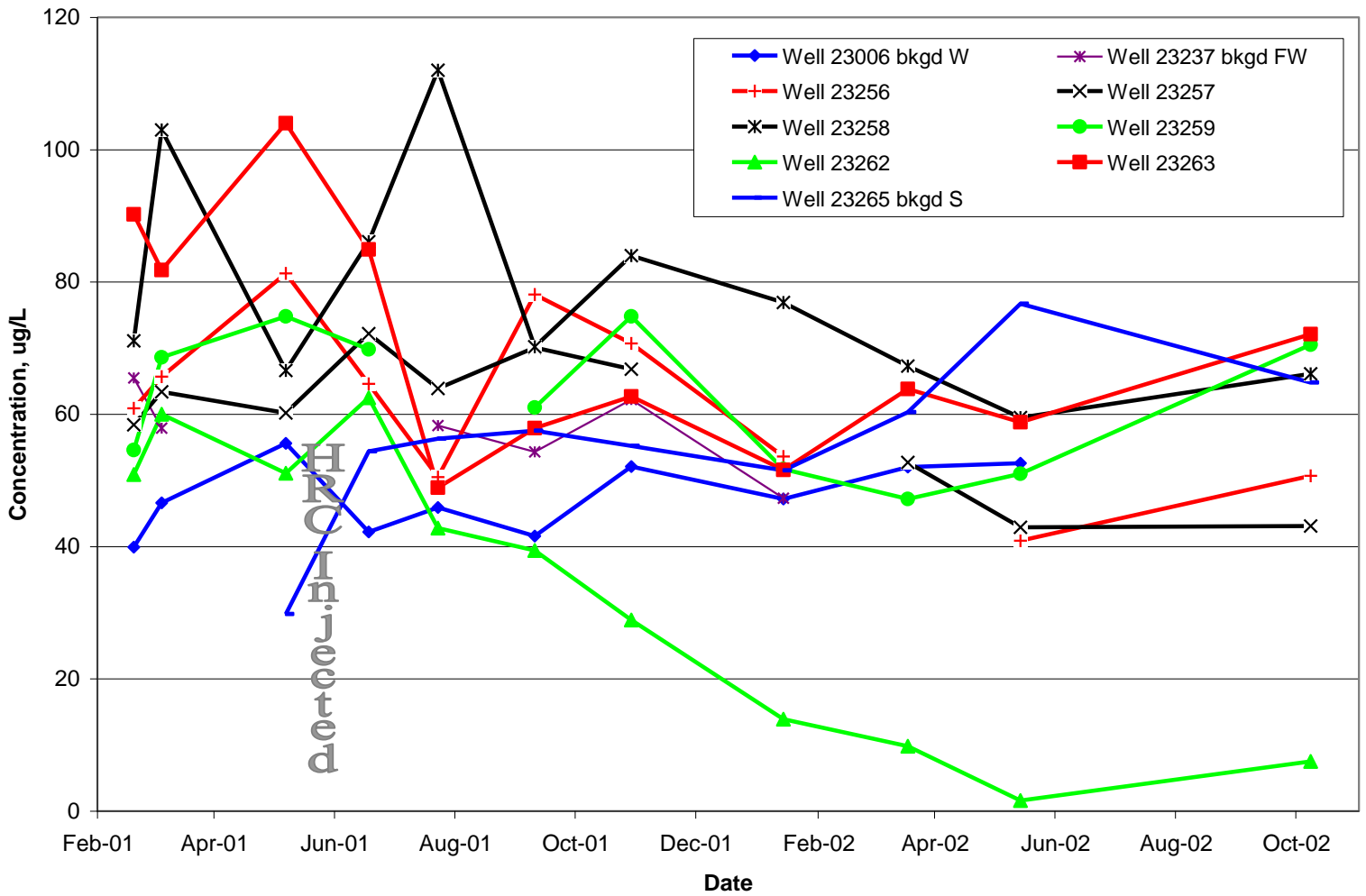


Figure 2-18 TCE

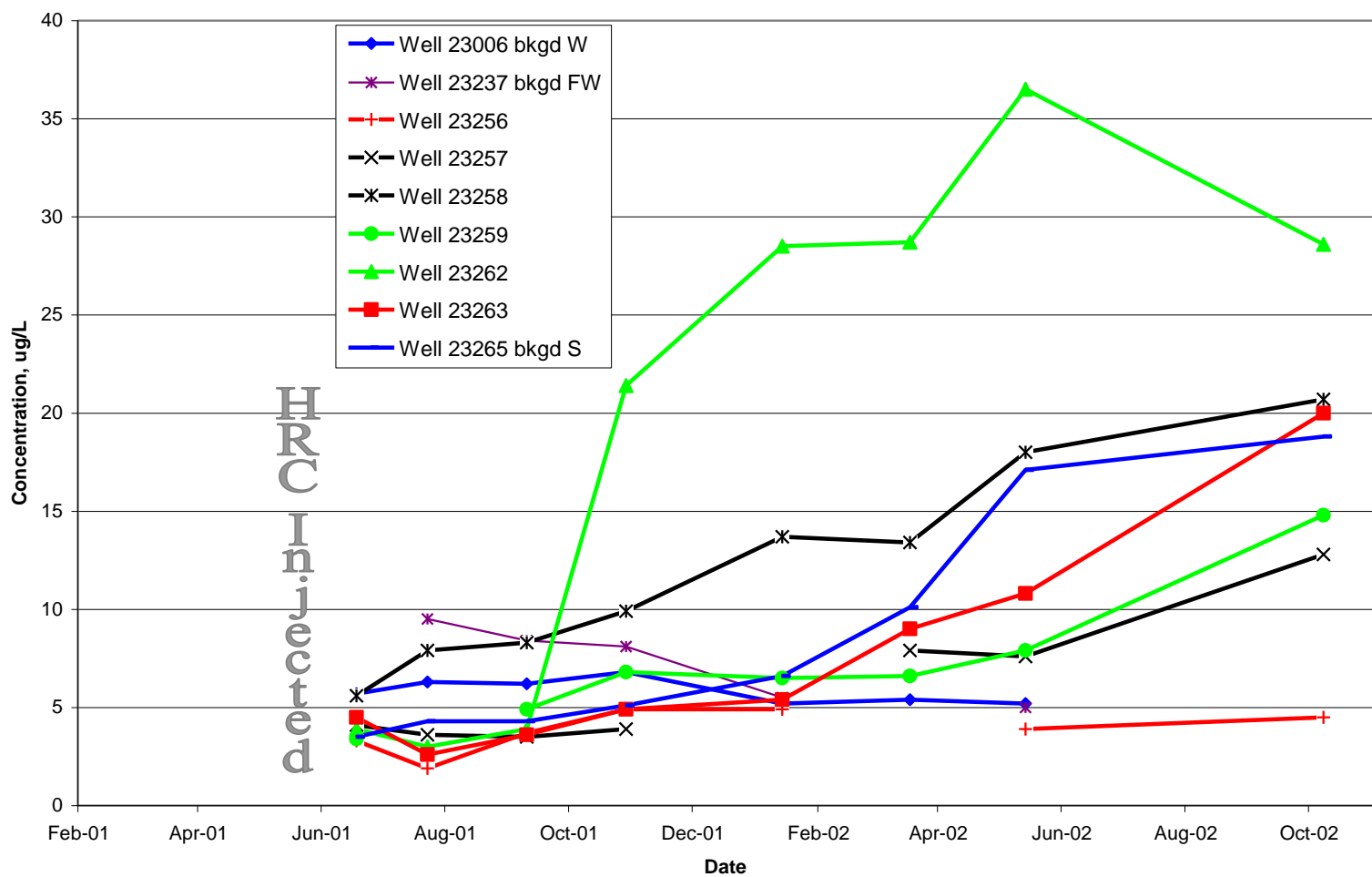


Figure 2-19 DCE

## DIMP

The time-series plot for DIMP (Figure 2-9) shows a distinct decreasing trend for five wells immediately downgradient from the HRC<sup>®</sup> barrier (wells 23255, 23256, 23257, 23260, and 23261). For all these wells, the decreasing trend was statistically significant by the Kendall Tau Test. Overall declines in DIMP concentrations at these wells over the course of the evaluation ranged from 50 to 80 percent, based on maximum pre-injection concentrations between 280 and 720 µg/L. However, the post-injection concentrations for DIMP remained well above the site-specific remediation goal of 8 µg/L.

DIMP concentrations in other downgradient wells were more variable, but tended to show slight declines, whereas concentrations in upgradient wells were variable or increasing throughout all sampling events. Wells further downgradient showed apparent decreases in concentrations of 15 to 20 percent. After about 5 to 6 months, DIMP concentrations appeared to stabilize.

## CPMS

The time-series plot for CPMS (Figure 2-10) shows the lack of clear trends in CPMS concentrations in the downgradient wells following installation of the HRC<sup>®</sup> barrier. This lack of trends suggests that degradation of CPMS was not accelerated by injection of the HRC<sup>®</sup> barrier. Concentrations appeared to increase to a maximum of between 6 and 24 µg/L in the middle of the evaluation (sampling events five through eight), and then declined. No CPMS concentrations were reported above the remediation goal of 30 µg/L during the evaluation.

## CPMSO<sub>2</sub>

The time-series plot for CPMSO<sub>2</sub> (Figure 2-11) also shows no clear trends in CPMSO<sub>2</sub> concentrations in the downgradient wells following installation of the HRC<sup>®</sup> barrier. This lack of clear trends suggests that degradation of CPMSO<sub>2</sub> was not accelerated by the injection of HRC<sup>®</sup>.

## Dieldrin

The time-series plot for dieldrin (Figure 2-12) does not show any well-defined or consistent trends for this COC in the downgradient wells. However, only two wells (upgradient well 23006 and downgradient well 23259) exhibited dieldrin concentrations greater than 1 µg/L during the evaluation period. Given the overall low concentration levels observed, sampling and analytical imprecision may have affected the results for this COC, and it is impractical to conclude whether any increased degradation of this COC occurred as a result of the HRC<sup>®</sup> injection.

## DCPD

The time-series plot for DCPD (Figure 2-13) shows a decreasing trend for most of the downgradient wells. The largest overall decline was observed at well 23259, where the DCPD concentration dropped almost 90 percent by the end of the evaluation from a maximum pre-injection concentration of 100 µg/L. Other wells displaying overall DCPD reductions in the 90 percent range include wells 23258, 23262, and 23263. Post-injection concentrations at these wells were consistently below the remediation goal of 46 µg/L. Compared with the downgradient wells, no significant trend was observed for DCPD in the single upgradient well in which it was detected, indicating that degradation was occurring in the HRC<sup>®</sup> barrier.

## **Benzene**

The time-series plot for benzene (Figure 2-14) shows decreasing concentrations at most downgradient wells following HRC<sup>®</sup> injection, indicating that degradation was occurring in the HRC<sup>®</sup> barrier. The decreasing trend was greatest at well 23259, where the concentration was reduced from a pre-injection maximum of 10 µg/L to post-injection concentrations just below 2 µg/L (greater than 80 percent reduction). Post-injection concentrations were also reduced at several other downgradient wells to the 1 to 2 µg/L range, but from lower initial (pre-injection) concentrations (2 to 6 µg/L). The post-injection concentrations of benzene in the downgradient wells declined to concentrations below the remediation goal of 3 µg/L.

## **Chlorinated Methanes (Chloroform and Methylene Chloride)**

The time-series plot for chloroform in Figure 2-15 shows that concentrations of chloroform were highly variable in upgradient and downgradient wells, with few definitive trends. The general variability of the chloroform results and the declining trend prior to HRC<sup>®</sup> injection complicated the evaluation of contaminant reduction by the HRC<sup>®</sup> technology; therefore, no percent reductions were estimated. Moreover, none of the downgradient wells displayed post-injection concentrations that were consistently below the remediation goal of 6 µg/L.

Methylene chloride was identified as a COC not only based on its historical occurrence at RMA, but also because it can be produced by reductive dechlorination of chloroform. However, this COC was detected only in one upgradient and four downgradient wells during the HRC<sup>®</sup> evaluation, and concentrations were generally below 10 µg/L. The time-series plot for methylene chloride (Figure 2-16) shows that post-injection concentrations of methylene chloride were consistently below the remediation goal of 5 µg/L in wells 23256, 23257, and 23259.

## **Chlorinated Ethenes (PCE, TCE, DCE, vinyl chloride)**

The time-series plot for PCE (Figure 2-17) shows a decline in concentration over the course of the HRC<sup>®</sup> evaluation for wells upgradient and downgradient from the HRC<sup>®</sup> barrier. Except for upgradient well 23006, the post-injection concentrations in the well network stabilized below the remediation goal of 5 µg/L, and were generally closer to the method reporting limit of 0.73 µg/L. The largest percent reduction in PCE during the evaluation was observed at downgradient well 23259, where the concentration declined from a pre-injection maximum of 45 µg/L to between 0.75 and 1.9 µg/L over the last five post-injection sampling events (greater than a 95 percent reduction). The declines observed in the upgradient wells were consistent with the recent overall declines in PCE concentration observed in this area of RMA due to the operation of an extraction well (well location 23311). This extraction well operated from 1996 to 2000, and produced notable declines in PCE and chloroform concentrations beginning in 1998.

TCE is the initial daughter product from reductive dechlorination of PCE. The time-series plot for TCE (Figure 2-18) shows few overall trends. No wells attained the remediation goal of 3 µg/L for TCE by the end of the evaluation. The lack of any overall significant reductions in TCE concentrations following HRC<sup>®</sup> injection may reflect a relative balance between creation of TCE as a daughter product and anaerobic degradation of PCE.

Though not a COC, cis-1,2-DCE is formed through the reductive dechlorination of TCE. The time-series plot for cis-1,2-DCE (Figure 2-19) shows increases in concentration during the evaluation for one upgradient and eight downgradient wells. Specifically, cis-1,2-DCE concentrations increased from pre-injection values below 5 µg/L to post-injection concentrations

between 10 and 40 µg/L at the end of the evaluation, with the largest increases observed at wells 23258, 23262, and 23263. For some wells, the magnitude of the cis-1,2-DCE concentration increase showed an approximate correlation with TCE degradation. For example, well 23263 displayed a decline of approximately 50 µg/L in TCE concentration over the course of the evaluation, along with an increase of approximately 35 µg/L in cis-1,2-DCE concentration. This decline amounts to a decrease of 0.38 micromoles of TCE that corresponds with an essentially equivalent increase of 0.36 µmol of cis-1,2-DCE. However, such correlations were not apparent for all wells. Overall, these results appear to reflect the creation of cis-1,2-DCE as a daughter product of TCE degradation and the lack of any significant degradation of cis-1,2-DCE.

Upon further dechlorination, cis-1,2-DCE degrades to vinyl chloride. In turn, vinyl chloride can be dechlorinated through either aerobic or anaerobic processes to form the fully hydrogenated compound ethylene. Because no detections were reported for either vinyl chloride or ethylene during the evaluation, trends for these compounds could not be assessed. It should be noted, however, that the sample reporting limits obtained for ethylene (5 to 12 µg/L) may have generally been too high to detect ethylene formation given the levels of TCE and cis-1,2-DCE reported in the well network during the evaluation period.

### **2.2.3 Quality Control Program**

A quality assurance project plan (QAPP) outlining the evaluation activities and planned quality control procedures was completed and approved by project participants (Tetra Tech EM Inc. [Tetra Tech] 2001a; 2001b). As required by the QAPP, various field and laboratory quality control (QC) checks were implemented during the evaluation.

A full data quality review was also conducted to evaluate all field and laboratory results, document data use limitations for data users, and remove unusable values from the evaluation data sets. This effort included reviews of sample chains-of-custody, holding times, and critical parameter identification and quantification. The results of this review were used to produce the final data sets used to assess the HRC<sup>®</sup> technology.

Field QC samples included field blanks, field duplicates, equipment blanks, and trip blanks. Field QC checks were also conducted to determine the quality of field activities, including sample collection, handling, and shipment.

Laboratory QC samples, including laboratory control samples and laboratory control sample duplicates (LCS/LCSD) and matrix spike/matrix spike duplicates (MS/MSD), were also processed according to the reference methods identified in Table 2-1 and the QAPP. Laboratory QC checks were designed to determine analytical precision and accuracy, demonstrate the absence of interferences and contamination from glassware and reagents, and ensure the comparability of data.

A review of the QC sample results did not indicate any broad QC issues or overall limitations on the data. Some results were flagged as estimated because the precision and accuracy objectives were exceeded in the MS/MSD results, but the number of estimated results was small, and none of these results impacted the overall assessment of data trends. The TER contains a detailed assessment of QC sample results and other QC checks for each sampling event.



## 2.3 EVALUATION OF RESULTS AGAINST THE OBJECTIVES

The evaluation was designed to achieve five specific objectives, including one primary (P) objective and four secondary (S) objectives. The results of the evaluation, described in the previous section, are evaluated against each of these objectives in the following sections. In each section, the objective is listed first, followed by a discussion of whether the results met this objective.

### 2.3.1 Objective P1

P1 Determine the ability of the Regenesi HRC<sup>®</sup> treatment technology to significantly reduce the concentrations of each of the primary COCs in the North of Basin F plume.

The objective was evaluated by comparing upgradient and downgradient COC concentrations in groundwater to determine reductions in the COCs. After initial distribution testing using the Shapiro-Wilk Test and the generation of summary statistics and plots for the pre- and post-injection data sets, statistical evaluation of the analytical data from the HRC<sup>®</sup> evaluation focused on the identification of general and significant trends in results for the 10 COCs and selected degradation products. As described in Section 2.2.2, this evaluation involved the preparation of time-series plots, linear and nonlinear regression analysis, and application of the Kendal Tau Test for trends. Statistical evaluation of the data is discussed further in the TER.

The evaluation found decreasing trends for the following COCs: PCE, TCE (after an initial increase in concentration at some wells), DIMP, DCPD, and benzene. Percent reductions for these COCs were generally in the 50 to 80 percent range at multiple downgradient wells, although higher percent reductions were observed for PCE and DCPD (90 to 95 percent). Except for TCE and DIMP, downgradient concentrations of these COCs were reduced over the course of the evaluation to below applicable site-specific remediation goals. Based on the evaluation results, the HRC<sup>®</sup> barrier appears to have facilitated the degradation of these five COCs at RMA.

Increasing trends in concentrations were observed in the evaluation data for cis-1,2-DCE, a daughter product from the reductive dechlorination of TCE. However, further degradation of cis-1,2-DCE to vinyl chloride and ethylene was not observed.

CPMS increased in many wells as the evaluation progressed, but then declined in the later sampling events. Conditions created by HRC<sup>®</sup> may have produced CPMS from CPMSO<sub>2</sub>, which then further degraded. The analytical data for the remaining COCs, including chloroform, methylene chloride, CPMSO<sub>2</sub>, and dieldrin, were variable and did not show significant or consistent trends for the set of wells sampled over the 18-month post-injection period.

### 2.3.2 Objective S1

S1 *Qualitatively evaluate the potential for the technology to achieve state and federal regulatory clean-up goals for the site.*

This objective evaluated the technology's ability to achieve state or federal clean-up or remediation goals as specified in the ROD for this site. Evaluation of this objective focused on wells 23259 and 23262, located furthest downgradient from the HRC<sup>®</sup> injection wall. The qualitative analysis for this objective consisted of generating concentration versus time plots for the COCs and comparing the data graphically to remediation goals. As described in Section 2.2.2, the post-injection concentrations of DCPD, PCE, and benzene at wells 23259 and 23262

were the only COCs that showed post-injection concentrations consistently below the corresponding remediation goals of 46 µg/L, 5 µg/L, and 3 µg/L, respectively.

The concentrations of CPMSO<sub>2</sub> and chloroform were also below the remediation goals for the furthest downgradient wells (23259 and 23262) during post-injection sampling events. However, the time series plots did not show any well-defined or consistent trends for the two downgradient wells, which suggested that this achievement was the result of HRC<sup>®</sup> injection. Methylene chloride was consistently detected below the remediation goal of 5 µg/L in other downgradient wells, but not in the furthest downgradient wells selected for this objective.

### 2.3.3 Objective S2

*S2 Qualitatively evaluate the presence or absence of treatment-derived products and indications of anaerobic conditions in groundwater samples.*

This objective was evaluated by comparing pre- and post-injection data for groundwater chemistry with treatment-derived products, including volatile fatty acids, degradation by-products, and certain inorganic constituents in groundwater. The qualitative analysis for this objective consisted of generating concentration versus time plots for these parameters.

As described in Section 2.2.1, lactic acid concentrations increased dramatically following HRC<sup>®</sup> injection. Propionic, butyric, and acetic acid concentrations also increased dramatically following HRC<sup>®</sup> injection, but exhibited a slower initial increase and slower decline compared with lactic acid.

A high HRC<sup>®</sup> dose rate was used during the evaluation to overcome competing electron acceptors, including ferric iron and sulfate. Despite the high hydrogen demand presented by these competing electron acceptors, the following data indicate that active anaerobic biodegradation was sustained throughout the evaluation period: (1) sufficient volatile fatty acids remained throughout the 18 months of post-injection monitoring; (2) ORP levels were reduced to less than 0 mV and remained negative during the 18 month period; and (3) the pH of groundwater in all downgradient wells was reduced following HRC<sup>®</sup> injection due to the release of volatile fatty acids.

The lack of overall significant reductions in TCE concentrations following HRC<sup>®</sup> injection may reflect a relative balance between creation of TCE as a daughter product and anaerobic degradation of TCE. This correlation was also apparent in the data for cis-1,2-DCE, which is a degradation product of TCE. For some wells, cis-1,2-DCE concentrations increased, which showed an approximate correlation with TCE degradation. Cis-1,2-DCE further degrades to vinyl chloride, which can be dechlorinated to form the fully hydrogenated compound ethylene. Although no detections were reported for vinyl chloride or ethylene during the evaluation, the limited ability of the analytical methods to detect these compounds may have been the cause.

### 2.3.4 Objective S3

*S3 Qualitatively evaluate the COC concentrations in the peripheral monitoring wells located along the string of downgradient wells.*

The planned HRC<sup>®</sup> permeable barrier was enlarged and changed to an L-shape, as described in Section 1.4.2, following formation of the evaluation objectives. The design was changed to ensure interception of all groundwater flowing to the downgradient wells regardless of minor

changes in groundwater flow direction. Thus, all downgradient wells were considered collectively in the data analysis, and Objective S3 ceased to be a separate objective.

#### **2.3.5 Objective S4**

*S4 Obtain and evaluate data associated with the cost of implementation of the Regenesis HRC<sup>®</sup> technology for the destruction or removal of COCs as encountered at RMA.*

A detailed discussion of costs associated with implementation of the HRC<sup>®</sup> technology is included in Section 3.0 of this report.

### **3.0 ECONOMIC ANALYSIS**

This economic analysis presents estimated costs for commercial application of the HRC<sup>®</sup> technology to enhance natural anaerobic degradation of chlorinated organic compounds in groundwater. The cost data provided in this section are for a barrier-based design, as was demonstrated at the RMA North of Basin F site. The estimates are based on the assumptions and costs provided by Regensis; data compiled during the SITE technology evaluation; information provided by the site engineering and operations contractors; and additional information obtained from current construction cost estimating guidance, as well as SITE Program experience. For comparability, these costs have been placed into the 12 categories applicable to typical clean-up activities at Superfund and Resource Conservation and Recovery Act (RCRA) sites (Evans 1990). The costs presented in this section are considered to be order-of-magnitude estimates.

#### **3.1 GENERAL ISSUES AND ASSUMPTIONS**

Prior to presenting the cost estimate for the selected application, it is important to describe how costs associated with the HRC<sup>®</sup> application can vary based on numerous factors, such as the type and scale of the application, contaminant types and levels, regulatory criteria, and site-specific factors. Sections 3.1.1 through 3.1.4 discuss some of the primary factors that affect the cost of an HRC<sup>®</sup> system. Section 3.1.5 discusses general assumptions used in the subsequent cost analysis provided in Section 3.1.5.

##### **3.1.1 Type and Scale of Application**

The HRC<sup>®</sup> technology would typically be used as an in situ treatment of groundwater contaminated with chlorinated organic compounds. In a remedial application, HRC<sup>®</sup> may be used at a RCRA corrective action or Superfund site. There are two basic conceptual designs of the HRC<sup>®</sup> system:

- Grid-based design
- Barrier-based design

A grid-based design is generally applicable to relatively small contaminant plumes where it is cost effective to inject HRC<sup>®</sup> at closely spaced intervals (approximately 5 to 10 feet) throughout the plume. The plume may be remediated with a single treatment event. The shape of the grid and number of injection points is determined from the shape and areal extent of the plume. The injection intervals are based on the saturated thickness and vertical extent of contamination.

For larger contaminant plumes, where the grid-based design is not cost effective, a barrier-based design may be applicable. The barrier design is essentially a containment strategy. HRC<sup>®</sup> injection points are aligned in a row or a few rows across the axis of the plume and perpendicular to the direction of contaminant migration. This type of design requires fewer injection points, but will likely require repeat treatments on an approximate annual basis. The time required to achieve remedial objectives may range from years to decades.

##### **3.1.2 Contaminant Types and Levels**

Factors affecting the mass of HRC<sup>®</sup> required to remediate a contaminant plume include the following:

- Characteristics of the individual contaminants

- Concentration or mass of the contaminants
- Naturally occurring chemicals that may inhibit HRC<sup>®</sup> chemical reactions

In dechlorination chemistry, HRC<sup>®</sup> acts as the electron donor while the chlorinated organic compounds act as electron acceptors. Essentially, the chlorine atoms of the chlorinated organic compounds are replaced with the hydrogen of the HRC<sup>®</sup> and the compound is thereby dechlorinated. Thus, the mass of HRC<sup>®</sup> required for remediation is proportional to the type and mass of the contaminants. However, some naturally occurring chemical species, such as oxygen and iron, are competing electron acceptors and will inhibit the HRC<sup>®</sup> remediation process. The mass of HRC<sup>®</sup> may have to be increased to compensate for the additional electron demand.

### **3.1.3 Regulatory Criteria**

Permitting requirements for this type of application would typically include an underground injection permit. Some regulatory entities may also require permits for boring/well installation. Benchmark concentrations established in the remedial action objectives must be considered when determining the mass of HRC<sup>®</sup> required and the period of remediation.

Regulatory agencies will generally require a monitoring program to assess the performance of the remedial system over time. This program will likely consist of periodic groundwater sampling until the remedial action is complete. More stringent regulatory criteria for the treated groundwater can affect the HRC<sup>®</sup> dose rate and the effluent monitoring costs.

### **3.1.4 Site-Specific Features**

Site-specific issues include aquifer characteristics, site access, existing structures, and underground utilities. Depending on the nature of the site, these factors may considerably affect costs.

The density of naturally occurring microorganisms that are capable of degrading chlorinated organic compounds is also a consideration. For HRC<sup>®</sup> to work, native anaerobic biota must be present in the subsurface soil or bedrock. If an aquifer has a high microbial population, it will metabolize a given mass of HRC<sup>®</sup> at a faster rate and achieve faster contaminant reductions. It is likely that a treatability study will be required to determine the presence of a sufficient native microbial population to support the remediation scenario and to assist with the overall design.

### **3.1.5 General Assumptions**

Certain assumptions were made to simplify the cost estimating. Real-world situations would require complex engineering and financial considerations. The following general assumptions were made for the cost analysis:

- Costs are rounded to the nearest \$10
- Seventeen percent was added to unit costs and labor rates to account for general and administrative costs. An additional 15 percent was added to labor rates for field work to account for health and safety monitoring and equipment
- A treatability study will be conducted to determine initial contaminant concentrations, competing electron acceptors, and microbial population
- Aquifer characteristics are similar to those presented on Table 3-1

- Initial contaminant concentrations are similar to those presented on Table 3-2
- Competing electron acceptors are similar to those presented on Table 3-3
- A barrier-based design application is used
- Drilling locations are readily accessible
- Costs were calculated for 1 year only; other factors are noted, besides inflation, that may affect the costs in subsequent years.

### **3.2 HRC<sup>®</sup> REMEDIAL APPLICATION**

The estimated costs for the HRC<sup>®</sup> remedial application are presented on Table 3-4. The following sections provide the bases for the cost calculations associated with each of the following 12 cost categories: (1) site preparation, (2) permitting and regulatory, (3) mobilization and startup, (4) equipment, (5) labor, (6) supplies, (7) utilities, (8) effluent treatment and disposal, (9) residual waste shipping and handling, (10) analytical services, (11) equipment maintenance, and (12) site demobilization.

#### **3.2.1 Site Preparation Costs**

Site preparation can vary considerably. These costs typically include preliminary costs necessary to physically prepare the site for access by a direct-push drill rig, treatability studies, site-specific design of the remedial system, and project-related administration and management. For this application, it was assumed that drilling locations were accessible by a truck-mounted drilling rig, and that the property owner's permitted access and demolition of existing structures was not required. It was assumed that physical preparation of the site consisted of an underground utility survey at a cost of \$1,000.

It was assumed that a treatability study would be conducted at the site and a hydrogeologic investigation was already completed and therefore not included as part of the study. For this scenario, it was assumed that eight soil and eight water samples would be collected from three 45-foot borings with a direct-push rig. Total cost of the drilling, field supplies, shipping, and labor for sample collection is estimated to be \$7,880. The cost for laboratory analysis of the samples was assumed to be \$10,000. The samples would be analyzed for the COCs, volatile fatty acids, dissolved gases, filtered and total inorganics, microbial population, and field parameters. It should be noted that treatability study costs can vary considerably and are highly dependent on the site, COCs, and amount of site characterization data already available.

Once the treatability study has been conducted, the design of the remedial system can be readily accomplished. Information can be entered into a spreadsheet where the amount of HRC<sup>®</sup> is automatically calculated. This service is typically provided at no charge by Regensis.

Project management and administrative expenses were estimated to be \$1,890. Total site preparation costs were estimated to be \$20,770.

**Table 3-1**  
**Aquifer Characteristics**

<b>Parameter</b>	<b>Value</b>	<b>Units</b>	<b>Notes</b>
Soil Type	Unconsolidated sand and gravel	–	
Depth to groundwater	44	feet	
Hydraulic conductivity <sup>1</sup>	89	feet per day	
Hydraulic gradient <sup>2</sup>	0.0009	unitless	
Saturated thickness	10	feet	
Length of barrier	250	feet	
Area <sup>3</sup>	2,500	square feet	Saturated thickness x length of barrier
Volumetric flow rate <sup>4</sup>	200	cubic feet per day	From Darcy's Law ( $Q=KAI$ )
Volumetric flow rate	1,496	gallons per day	

Notes:

<sup>1</sup>Identified as K in Darcy's Law.

<sup>2</sup>Identified as I in Darcy's Law

<sup>3</sup>Identified as A in Darcy's Law

<sup>4</sup>Identified as Q in Darcy's Law, where  $Q = KAI$

**Table 3-2  
Initial Contaminant Concentrations**

<b>Parameter</b>	<b>Baseline Concentration (µg/L)</b>	<b>Mass Flux<sup>1</sup> (gallons/year)</b>
Diisopropylmethylphosphonate	800	61,660
Chlorophenylmethyl sulfide	not applicable <sup>2</sup>	-
Chlorophenylmethyl sulfone	80	166
Dieldrin	1	2.1
Dicyclopentadiene	100	207
Chloroform	200	414
Methylene Chloride	NA	
Tetrachloroethene	20	41.4
Trichloroethene	80	166
Benzene	10	20.7
<b>Total</b>	21,291	2,677

Notes:

<sup>1</sup>Based on volumetric flow rate of 1,496 gallons per day or 546,000 gallons per year.

<sup>2</sup>Compound concentration was below detection limit or remedial goal.

**Table 3-3  
Geochemical Parameters**

<b>Parameter</b>	<b>Effective Concentration (µg/L)</b>
Oxygen (O <sub>2</sub> )	2,000
Nitrate (NO <sub>3</sub> )	500
Manganese (Mn)	20,000
Iron (Fe)	100
Sulfate (SO <sub>4</sub> )	400



**Table 3-4  
2003 Estimated Costs by Category**

<b>Category</b>	<b>Task</b>	<b>Item</b>	<b>Item Cost</b>	<b>Category Total</b>
Site Preparation	Utility Survey	Subcontractor	\$1,000.00	<b>\$20,770</b>
	Treatability Study	Labor	\$3,280.00	
		Drilling Subcontractor	\$4,000.00	
		Laboratory	\$10,000	
		Field Supplies	\$600.00	
	Vendor Design		\$0.00	
	Project Management	Labor	\$1,890.00	
Permitting and Regulatory	UIC Permit	Labor	\$1,590.00	<b>\$16,170</b>
	Work Plan	Labor	\$13,200.00	
	Project Management	Labor	\$1,380.00	
Mobilization and Startup	HRC <sup>®</sup> Injection	HRC <sup>®</sup> Material	\$81,750.00	<b>\$169,920</b>
		Labor	\$18,040.00	
		Drilling Subcontractor	\$32,500.00	
	Install 7 Monitoring Wells	Drilling Subcontractor	\$24,700.00	
		Labor	\$9,560.00	
	Project Management	Labor	\$1,870.00	
	Survey 7 Wells	Subcontractor	\$1,500.00	
Equipment	Dedicated Sampling Pumps	Pumps	\$4,100.00	<b>\$5,140</b>
	Pump Installation	Labor	\$1,040.00	
Labor	Performance Sampling	Labor	\$20,120.00	<b>\$26,790</b>
	Manage Data	Labor	\$6,670.00	
Supplies	Rental Equipment and Expendables	-	\$5,670.00	<b>\$5,670</b>
Utilities	Not Applicable for this Scenario	-	\$0.00	<b>\$0</b>
Effluent Treatment and Disposal	Not Applicable for this Scenario	-	\$0.00	<b>\$0</b>
Residual Waste Shipping and Handling	Not Applicable for this Scenario	-	\$0.00	<b>\$0</b>
Analytical Services	Laboratory Analysis	See Section 3.2.10 for Specific Analyses	\$46,500.00	<b>\$47,500</b>
	Shipping	-	\$1,000.00	
Equipment Maintenance	Not Applicable	-	\$0.00	<b>\$0</b>
Site Demobilization	Decommission Wells	Drilling Subcontractor	\$8,600.00	

		Labor	\$1,800.00	<b>\$10,400</b>
Total Estimated Cost				<b>\$302,360</b>

### **3.2.2 Permitting and Regulatory Costs**

Permitting and regulatory costs are highly dependent on site-specific factors, site regulatory status (such as whether treatment is performed at a Superfund or RCRA corrective action site), and how any wastes are disposed of. Superfund site remedial actions must be consistent with applicable and relevant or appropriate requirements (ARAR) that include environmental laws, ordinances, regulations, and statutes, including federal, state, and local standards and criteria. Remediation at RCRA corrective action sites requires additional monitoring and recordkeeping, which can increase base regulatory costs. In general, ARARs must be determined on a site-specific basis. For this application, it was assumed that a permit for underground injection control (UIC) would be required. Costs for obtaining the permit were estimated to be \$1,590.

Regulatory agencies typically require a work plan and health and safety plan for implementing this type of remedial action. Costs for labor associated with preparation of the plans are estimated to be \$13,200. Project management and administrative costs are estimated to be \$1,380. Total permitting and regulatory costs are estimated to be \$16,170.

### **3.2.3 Mobilization and Startup Costs**

The remedial design for this scenario assumed a 250-foot barrier application, 150 HRC<sup>®</sup> injection points to a depth of 54 feet, with an estimated 10 feet of saturated thickness at each location. HRC<sup>®</sup> would be injected at a rate of 9.1 pounds per foot of saturated thickness, or 91 pounds per location. The remedial system would be installed with a direct-push drill rig that averaged eight injection points, or 432 feet per day.

At a cost of \$5.50 per pound of HRC<sup>®</sup> and accounting for shipping and tax, the cost of the HRC<sup>®</sup> material is estimated at \$81,750. The cost of the drilling subcontractor is estimated at \$32,500. The labor cost for a geologist to conduct oversight during HRC<sup>®</sup> injection is estimated at \$18,040.

In addition to the HRC<sup>®</sup> injection, it was assumed that seven monitoring wells would be installed to a depth of 55 feet for system performance monitoring. Investigation-derived waste (IDW) is assumed to be disposed of at the site's treatment, storage, and disposal facility. It is estimated to require 9 days to complete the task. The cost of the drilling subcontractor to drill, install, and develop the wells is estimated at \$24,700. The labor for a geologist to conduct oversight during monitoring well installation activities is estimated at \$9,560. The cost of surveying the wells is estimated at \$1,500.

Project management and administrative costs are estimated to be \$1,870. Total mobilization and startup costs are estimated at \$169,920.

### **3.2.4 Equipment Costs**

The HRC<sup>®</sup> remedial system is passive; therefore, equipment required for this remedial scenario is primarily that used to inject the HRC<sup>®</sup> material. These costs are included under Mobilization and Startup Costs (Section 3.2.3). For this application, it was assumed that operational equipment would consist of dedicated bladder pumps installed in the seven performance monitoring wells discussed in Section 3.2.3. The cost of seven pumps, including tubing, fittings, and freeze protection, is estimated to be \$4,100. Installation of the pumps is estimated to cost \$1,040. Total equipment costs are estimated to be \$5,140.

### **3.2.5 Labor Costs**

Once the HRC<sup>®</sup> is injected, no further field activity is required except for performance monitoring until the HRC<sup>®</sup> material is expended and re-application is warranted. According to Regenesys, re-application generally occurs on an approximately annual basis. For this remedial scenario, it was assumed that the seven performance monitoring wells would be sampled five times during 1 year of treatment. The monitoring events would be conducted at 2 months, 4 months, 6 months, 9 months and 12 months following the first HRC<sup>®</sup> treatment event. It is assumed that IDW can be disposed of at the site's treatment, storage, and disposal facility. It was estimated that each sampling event would require 2 days of field work. It is estimated that the labor cost for the five sampling events would be \$20,120. It is assumed that some data management will also be required. The labor cost for this task is estimated at \$6,670. Total cost for this category is \$26,790.

Performance monitoring is typically conducted frequently during the initial stages of a remedial action and is reduced during subsequent years as more site-specific knowledge is gained. This monitoring may include a reduction in the number of wells that are sampled. It is likely that performance monitoring would also be reduced for this remedial scenario; thus, the labor costs in subsequent years may be significantly reduced.

### **3.2.6 Supply Costs**

Supplies for this remedial scenario consist of those materials required to conduct the performance sampling. These supplies include rental equipment such as a pump controller, compressed gas for pump operation, air monitoring equipment, water level indicator, and water quality meters for DO, ORP, pH, and temperature. Expendable supplies include water filters, field calibration solutions, personal protective equipment, buckets for purge water, sample bottles, shipping containers, ice, duct tape, and other miscellaneous supplies. The supply costs are estimated to be \$5,670 for five sampling events during the first year. As with Labor Costs (Section 3.2.5), these costs may be reduced in subsequent years due to reduced monitoring frequency.

### **3.2.7 Utility Costs**

The HRC<sup>®</sup> remedial system is passive and requires no field operations other than performance monitoring. Utilities associated with performance monitoring would consist primarily of batteries for the water quality meters and water for decontamination. The estimated costs assume that the batteries will be included with the rental equipment and that water is readily available at the site. For this reason, this cost estimate assumes no utility costs.

### **3.2.8 Effluent Treatment and Disposal Costs**

The waste generated during routine operations would consist only of purge water and IDW. It is assumed that this material requires no treatment and can be disposed of on site. For this reason, this cost estimate assumes no effluent treatment and disposal costs.

### **3.2.9 Residual Waste Shipping and Handling Costs**

Residual waste would be expected to consist of a relatively small volume of purge water and IDW. It is assumed that this waste can be disposed of on site. Costs associated with transport and handling of the residual waste would be primarily labor. The labor costs for this item are included in the cost estimate for the Labor category provided in Section 3.2.5.

### **3.2.10 Analytical Services Costs**

Analytical services include costs for laboratory analyses, data reduction, and QC. It is assumed that groundwater samples collected during the five performance sampling events will be analyzed for VOCs, semivolatile organic compounds (SVOC), pesticides, major anions, filtered metals, total metals, volatile fatty acids, dissolved gases, and heterotrophic plate counts. These analyses are assumed to be analyzed in accordance with RMA methodologies and encumber RMA costs. The cost estimate also includes analysis of all associated QC samples. The estimated analytical cost for five sampling events, including shipping, is estimated to be \$47,500. As discussed in previous sections, these costs will likely decrease as a result of reduced sampling frequency in subsequent years.

### **3.2.11 Equipment Maintenance Costs**

The dedicated bladder pumps are the only equipment required for this remediation scenario. The estimate assumes that bladder pumps would not require maintenance during the first year of use. For this scenario, HRC<sup>®</sup> treatment is expected to last only 1 year; therefore, this cost estimate assumes no maintenance costs.

### **3.2.12 Site Demobilization Costs**

Site demobilization includes decommissioning of the seven performance monitoring wells when the remedial objectives are attained. It is assumed that the services of a driller will be required for an estimated 2 days to decommission the wells. The cost of drilling services is estimated at \$8,600. The labor cost for a geologist to conduct oversight during well decommissioning is estimated at \$1,800. Total demobilization costs are therefore estimated at \$10,400.

## **3.3 CONCLUSIONS OF THE ECONOMIC ANALYSIS**

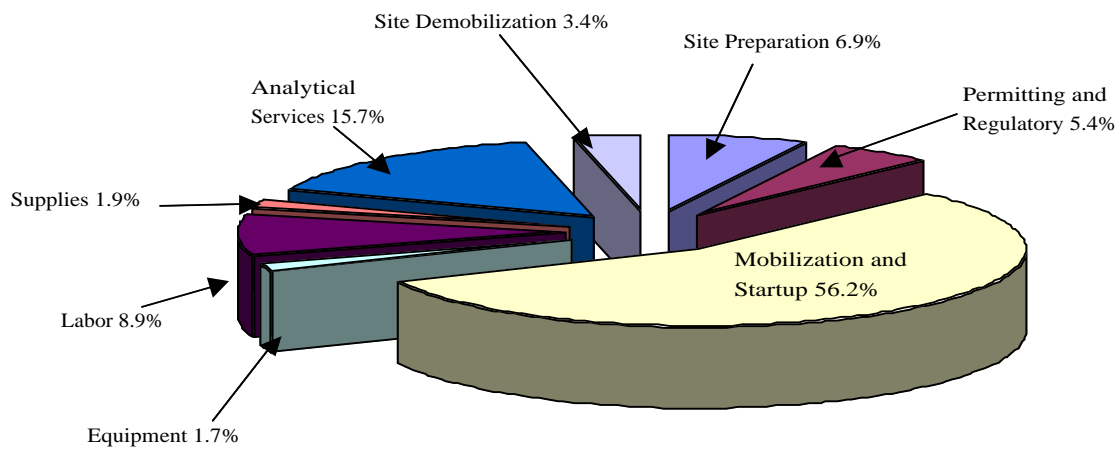
This analysis presents costs for treating groundwater contamination using an HRC<sup>®</sup> barrier. The estimate is based on actual costs experienced at RMA for 1 year. The treatment event is expected to last approximately 1 year at a cost of approximately \$302,360. The aquifer characteristics described in Table 3-1 indicate that approximately 546,040 gallons of contaminated groundwater would migrate through the treatment barrier per year. This treated volume translates to a cost of approximately \$0.55 per gallon of water. A breakdown of the relative costs by category is provided on Figure 3-1.

The unit cost provided in the preceding paragraph reflects expenses relative to the first year of remediation. It must be recognized that some first-year expenses are likely one-time expenses. Examples of likely one-time expenses are as follows:

- Site preparation costs
- Permitting and regulatory costs
- Equipment costs, although over a period of years there may be some minimal costs associated with maintenance of the bladder pumps
- Installation of performance monitoring wells in the mobilization and startup category

In addition to one-time expenses, the frequency of monitoring would likely decrease in subsequent years. This decrease would reduce costs in the labor, supply, and analytical services categories proportionately; thus, the unit cost of treated water would likely decrease if HRC<sup>®</sup> treatment is considered for a longer period of time.

**Figure 3-1**  
**HRC<sup>®</sup> Estimated Cost Breakdown**



**Notes:**

Utilities, effluent treatment and disposal, residual waste sampling, and equipment maintenance categories were not included, because they do not appear to be applicable to this remedial application.

## **4.0 TECHNOLOGY APPLICATIONS ANALYSIS**

This section of the report discusses the following topics regarding general applicability of the Regenesi HRC<sup>®</sup> technology: factors affecting technology performance, site characteristics and support requirements, material handling requirements, technology limitations, potential regulatory requirements, and state and community acceptance. This analysis is based primarily on the evaluation results at the RMA site; however, the evaluation results are supplemented by data provided by Regenesi and other applications of the HRC<sup>®</sup> technology. Vendor's claims regarding the effectiveness and applicability of the HRC<sup>®</sup> technology are included in Appendix A.

### **4.1 FACTORS AFFECTING PERFORMANCE**

Factors potentially affecting the performance of the HRC<sup>®</sup> technology include the following:

- Waste contaminant types and characteristics
- Site hydrogeologic characteristics, which affect how HRC<sup>®</sup> is introduced into the aquifer
- Operating parameters, including HRC<sup>®</sup> physical and chemical properties and the aquifer's geochemistry and microbiology, all of which affect the type and amount of HRC<sup>®</sup> needed to effectively treat contaminated groundwater
- Maintenance requirements, which are a function of the hydrogeologic and operating parameters, will be a factor at sites requiring multiple injections of HRC<sup>®</sup>

The following sections further discuss how these factors can potentially affect the HRC<sup>®</sup> technology's performance.

#### **4.1.1 Applicable Wastes**

Release and fermentation of the lactic acid in HRC<sup>®</sup> yields hydrogen and produces a reductive, anaerobic environment. As such, those contaminants most applicable to the technology are typically electron acceptors and those susceptible to anaerobic, biotic, or abiotic reductive degradation or transformation. According to Regenesi, HRC<sup>®</sup> can treat several of these types of contaminants, including chlorinated solvents, nitroaromatics, inorganics, and heavy metals (see Table 4-1). Most of these contaminants, especially organics, are treated through enhanced biodegradation processes. However, abiotic processes aided by a conducive geochemistry can serve as a secondary mechanism. According to Regenesi, the technology is most effective for passive in situ treatment of dissolved-phase contaminants, but it can also be used for sorbed and free-phase applications under proper conditions. In addition, the technology can be incorporated into an active in situ bioremediation system employing extraction and reinjection of groundwater. Such an approach can be used where surface features limit access to the aquifer, when hydraulic control is needed or variable groundwater flow directions are encountered, or when the contaminant concentrations necessitate longer treatment times.

**Table 4-1  
Summary of Treatable Contaminants According to Regensis**

Contaminant Group	HRC®
<b>Chlorinated Ethenes</b>	
Perchloroethene	XXX
Trichloroethene	XXX
Dichloroethene	XXX
Vinyl Chloride	XXX
<b>Chlorinated Ethanes</b>	
Trichloroethane	XXX
Dichloroethane	XXX
Chloroethane	XXX
<b>Chlorinated Methanes</b>	
Carbon Tetrachloride	XX
Chloroform	XX
Dichloromethane	XX
Chloromethane	XX
Chlorofluorocarbons	XXX
<b>Chlorinated Aromatics</b>	
Pesticides	XXX
Chlorobenzenes	XXX
Pentachlorophenol	XX to XXX
Furans	XXX
<b>Nitroaromatics</b>	
Explosives	XXX
Dyes	XXX
<b>Inorganics</b>	
Nitrate	XXX
Perchlorate	XXX
<b>Heavy Metals</b>	
Chromium	XXX
Arsenic	XXX

RATING SCALE: XXX = Highly Effective, XX = Effective, and X= Partially Effective

NOTE: Relative effectiveness can vary based on site conditions.



#### 4.1.2 Hydrogeologic Characteristics

Site hydrogeology significantly affects the performance of the HRC<sup>®</sup> technology by controlling the following: (1) the implementability of the technology; (2) the selection of the type of HRC<sup>®</sup> application (treating the entire groundwater plume or source [grid-based design], creating a permeable hydrogen barrier to intercept a plume [barrier-based design], or treating the source area after excavation); and (3) the HRC<sup>®</sup> injection technique (soils or bedrock setting). Hydrogeologic characteristics that affect performance of the HRC<sup>®</sup> technology application are discussed further in the following paragraphs.

##### **Implementability**

Implementation of the HRC<sup>®</sup> technology is directly affected by several hydrogeologic factors, including the depth to the saturated zone, the types of soil or bedrock and their permeability, the groundwater seepage velocity, and the saturated thickness of the contaminated aquifer.

The depth to the saturated zone can be a factor in determining the appropriate method for emplacing HRC<sup>®</sup> into the subsurface. The most common method used to emplace HRC<sup>®</sup> into the saturated zone is by direct-push technology. This method allows for direct contact with soils to ensure that HRC<sup>®</sup> is injected into the formation. HRC<sup>®</sup> is typically injected from the bottom up using commercially available high-pressure pumps (see Section 4.2.1). Injecting from the bottom up is time-efficient and allows for monitoring of injection dose rates (pounds of HRC<sup>®</sup> injected per foot of aquifer). However, most direct-push methods have depth-of-application limits and typically cannot extend past 100 to 150 feet bgs, thereby limiting HRC<sup>®</sup> injection depths. Another limiting factor of direct-push methods is refusal by subsurface materials containing large gravel or cemented sediments. Relocation of injection points may be necessary when refusal occurs.

Soil permeability can affect the type of injection method and the density of injection locations. Tight, less permeable soils will require higher injection pressures. Low permeability conditions may require a greater density of injection points due to the limited penetration of HRC<sup>®</sup> into the formation. Higher penetration pressures for all soil types will also be encountered in deeper applications as a result of greater overburden and hydrostatic heads.

Groundwater seepage velocity does not affect the injection method but can affect (1) the density of injection points in a grid, or (2) the location and number of barriers needed to intercept groundwater flow. Seepage velocity is also a design parameter that will affect HRC<sup>®</sup> dose rates and longevity, and will need to be assessed prior to HRC<sup>®</sup> application. HRC<sup>®</sup> dose rates and longevity are discussed further in Section 4.1.3.

Another critical factor to consider is the thickness of the saturated zone. Many chlorinated VOCs are denser than water. When released in sufficient quantity, these dense nonaqueous-phase liquids (DNAPL) will migrate down through the unsaturated and saturated zones under the influence of gravity. If sufficient volumes of DNAPL have been released to the environment, they will continue to migrate downward in an aquifer until an impermeable barrier stops further downward migration. This process can result in dissolved contaminant being present several tens to hundreds of feet bgs. For effective treatment, HRC<sup>®</sup> will need to be injected to ensure that flow throughout the entire contaminated interval of the saturated zone is intercepted.

## **Application to Treat an Entire Groundwater Plume: Grid-Based Design**

In this application, HRC<sup>®</sup> is injected directly into the aquifer matrix in a grid pattern over the horizontal extent and across the vertical zone of the contaminant plume or source area. The shape of the area to be treated is determined primarily by the shape of the contaminant plume or source, or by the accessible area within the plume or source. According to Regenesis, the technology is most applicable to dissolved contaminants, but it can treat adsorbed and free-phase contaminants.

For source treatment application, the period of remediation will typically be extended to account for the added mass transfer limitations imposed by the location or phase of the contaminants (such as adsorbed or free-phase nonaqueous-phase liquids [NAPL]). Dissolved contaminants are more readily available for the microbes to use. Adsorbed contaminants must desorb first or, by chance, be adsorbed near active microbes. As dissolved contaminants are degraded, additional contaminant will desorb from the soil surface to maintain equilibrium or diffuse from high concentration areas to lower concentration areas as a result of increased concentration gradients. This process can be slow and impeded further by diffusion limitations imposed not just near the soil surface but also through the soil pores. An additional phenomenon that can aid degradation of adsorbed contaminants is the secretion of bio-surfactants by microbes. These surfactants will also aid the dissolution or solubilization of contaminants from soils.

Large pools of NAPL can limit HRC<sup>®</sup> application and can have toxic effects on microbes, which can impede the biological degradation of NAPL. However, DNAPL often exists as dispersed pockets of narrow ganglia, stringers, or small blobs resulting from residual free product that has been trapped within the soil pores. Therefore, through phenomena similar to those described above for adsorbed contaminants (shifts in surface-water partitioning, enhanced diffusion gradients, and bio-surfactants), enhanced degradation will also occur in free product source areas. When adsorbed or free-phase contamination exists, water concentrations of total VOCs may actually increase after injection. This evidence for potential degradation of adsorbed and free-phase contaminants has been observed in the field for chlorinated ethenes. Chlorinated ethenes degrade through a sequential dechlorination process in which a parent contaminant such as PCE degrades to TCE, cis-DCE, and vinyl chloride. The rate of anaerobic degradation decreases as the ethene is dechlorinated. Therefore, concentrations of certain daughter products, cis-DCE in particular, will increase and take longer to decay. Concentrations of cis-DCE have been observed that exceed the original parent concentrations in groundwater, indicating that an additional source of the parent compound exists as a separate phase.

The type of soils can further complicate the use of HRC<sup>®</sup> in source zones. Soils with a high organic carbon content will adsorb more contaminant. However, these same soils already contain a carbon food source that may make the use of other substrates unnecessary to achieve anaerobic conditions. Highly porous, low permeability soils can retain more adsorbed-phase contaminants and are typically regions where NAPL will collect. Consideration must be given to this phenomenon both in terms of effects on injection pressures, dose rates, and remediation times.

## **Permeable Hydrogen Barrier Application: Barrier-Based Design**

When a groundwater plume is large and an HRC<sup>®</sup> injection grid is not cost-effective, an alternative approach is to use one or more HRC<sup>®</sup> barriers. HRC<sup>®</sup> barriers are installed

perpendicular to the groundwater flow direction at one or more intervals throughout the length of the plume. In this design approach, a unit volume of contaminated water moving in the plume is subject to single or sequential doses of hydrogen to enhance or stimulate the reductive reactions as the plume migrates.

As was demonstrated at the RMA site, HRC<sup>®</sup> is emplaced in one or more rows of injection points to form an HRC<sup>®</sup> barrier, thereby creating an anaerobic treatment zone oriented to intercept the downgradient migration of contaminants. In this application, the HRC<sup>®</sup> hydrogen barrier does not form a solid wall or true “barrier”, but rather a series of discrete HRC<sup>®</sup> injections that produce the desired levels of dissolved hydrogen. The location of injection points in each row is staggered with respect to points in other rows to minimize the effective spacing perpendicular to groundwater flow. The HRC<sup>®</sup> technology under this application would be termed a permeable reactive barrier; however, this approach does not require slurry walls or sheet piles to channel groundwater through the reactive material. It is also not a barrier in which treatment is completed once groundwater passes through. An anaerobic plume is generated downgradient from the barrier; the size of which will be dependent on factors such as seepage velocity, microbial population, and hydrogen demand (see Section 4.1.3). Degradation begins at the barrier and continues to progress as groundwater and contaminants move downgradient. Therefore, the barrier must be placed sufficiently upgradient from receptors or point-of-compliance wells.

As described above, the HRC<sup>®</sup> hydrogen barrier application involves placing a row of HRC<sup>®</sup> injection points perpendicular to the plume flow direction. In areas of high groundwater velocity or contaminant loading, multiple rows of injection points may be required to provide sufficient contact time for the microbes to degrade the contaminants. HRC<sup>®</sup> barriers may also be constructed in an iterative fashion so that injection point arrays are installed over time to satisfy regulatory criteria, remediation budgets, and the overall environmental strategy for a given site.

HRC<sup>®</sup> barriers are typically directed toward containment of a contaminant or point of compliance strategy and do not provide for source area remediation. If the contaminant source area is not remediated, the HRC<sup>®</sup> barrier will need to be maintained over time through re-injection events or combined with other treatment technologies.

### **Source Area Excavation Application**

The HRC<sup>®</sup> excavation application provides for a hydrogen source across a large treatment area in the bottom of an open excavation. This approach can be used in conjunction with source removal actions where contaminated soil in a source area is excavated. This application is only effective when excavation extends into the saturated zone. HRC<sup>®</sup> is emplaced directly into the bottom of the excavation prior to backfilling to enhance or stimulate biodegradation of the remaining bound and dissolved-phase contaminants in soil. However, this application will not treat dissolved-phase contaminants that have migrated away from the source area.

### **Injection in Soils Setting**

For soils, the most effective method to emplace HRC<sup>®</sup> into the subsurface is to inject the material through direct-push rods using hydraulic equipment. This approach allows for relatively quick distribution of HRC<sup>®</sup> throughout the aquifer. Soils with moderate to high permeability characteristics (gravels and sands) and bounded by lower permeable soils (clays and silts) present

the fewest obstacles and complications to HRC<sup>®</sup> application. The RMA site evaluation involved treating a groundwater plume in unconsolidated soils with a lower boundary of claystone. However, the penetration depths that can be achieved by direct-push technology limit this method of product delivery.

### **Injection in Bedrock Setting**

HRC<sup>®</sup> emplacement techniques in bedrock aquifers are dictated by the characteristics of the aquifer and the bedrock. HRC<sup>®</sup> can be injected into cased or open-hole completed groundwater wells using down-hole packers to isolate the injection interval or by backfilling the borehole with a tremie pipe. The HRC<sup>®</sup> installation method should be a function of the bedrock aquifer material type, the nature and distribution of fractures, and the potential radius of influence for the HRC<sup>®</sup> away from the borehole.

The best emplacement conduit in a fractured bedrock aquifer is typically an open-hole groundwater well. An open-hole well application allows HRC<sup>®</sup> to come into direct contact with the bedrock fractures. This direct contact can be by tremie-backfill or packer-assisted emplacement methods. If the bedrock matrix is sufficiently competent to support a packer, HRC<sup>®</sup> can be injected into the treatment zone under pressure. To place HRC<sup>®</sup> into direct contact with the fracture system under pressure, the operator must apply HRC<sup>®</sup> at a pressure that does not exceed the inflation pressure of the down-hole packers. This method allows for application of HRC<sup>®</sup> into defined sections of the aquifer; however, distribution of the HRC<sup>®</sup> is controlled in part by the distribution, orientation, and interconnectedness of the fractures in the treatment zone.

When packers cannot be used, HRC<sup>®</sup> can be delivered by tremie backfill into an open-hole completed groundwater well. This approach requires that the entire saturated section of the borehole be backfilled with HRC<sup>®</sup> material. HRC<sup>®</sup> distribution is accomplished by gravity flow of the material into the aquifer matrix. However, the viscous nature of the HRC<sup>®</sup> may limit distribution of the material into some portions of the aquifer pore space.

In bedrock aquifers where open-hole completions are impossible or impractical, HRC<sup>®</sup> can be applied through small diameter injection wells (2-inch). These injection wells are typically completed at the surface to allow connection to a pump so HRC<sup>®</sup> can be injected under pressure. Numerous wells may need to be installed to adequately distribute HRC<sup>®</sup> throughout the treatment zone. This application could result in substantially higher remediation costs compared to the other bedrock application techniques due to the number of wells that would be required to adequately distribute the HRC<sup>®</sup> material.

#### **4.1.3 Operating Parameters**

Since HRC<sup>®</sup> is a time-released product, the required dose rate and longevity is a function of the product chemistry and transport properties and certain biological and geochemical features of the aquifer. According to Regenesys, HRC<sup>®</sup> has been shown to have a direct effect on microbial populations through the release of lactic acid and subsequent production of secondary organic acids. The physical and chemical characteristics of HRC<sup>®</sup>, and the effects of aquifer geochemistry and microbiology on HRC<sup>®</sup> longevity and dose rates, are discussed in more detail in the following paragraphs

## **HRC<sup>®</sup> Physical and Chemical Characteristics**

The “active ingredient” of HRC<sup>®</sup>, glycerol (tri) polylactate (GPL), is one of a family of polylactate esters, defined by patent, that upon hydration break down to release lactic acid. Structurally, an ester is the product of a reaction between an organic acid (COOH group) and an alcohol (OH group). In this reaction, the two groups react, water drops out, and the ester link is formed. Polylactate esters are formed from the combination of certain alcohols with a unique lactic acid complex serving as the organic acid group. The alcohols are compounds such as glycerol (3 OH groups), xylitol (5 OH groups), and sorbitol (6 OH groups). These “foundation” molecules are then esterified with a polylactic acid complex. The unique feature of the polylactic acid complex is that lactic acid is esterified to itself. This is possible because lactic acid has both an OH and a COOH group. This reaction produces trimers or tetramers of lactic acid and creates a “polylactic acid complex” or “polylactate complex,” which is in turn esterified to the foundation OH donor.

The exact chemical nature of a specific polylactate ester, such as GPL, is a major factor in product longevity. The degree of complexity and esterification of the molecule control its viscosity, which is a critical factor in reactivity. This in turn controls product longevity under a given set of conditions. For example, the (tri)polylactate form of GPL would be more viscous than the (di)polylactate form, and a molecule built with tetramers of lactic acid would be more viscous than one made with trimers. Esters produced with longer chain alcohols such as sorbitol will be more viscous than a glycerol polylactate ester because it is based on 6 carbons rather than 3 carbons. Viscosity becomes a dominant issue in longevity because it is a measurement of resistance to flow. As a result, viscosity controls the speed at which HRC<sup>®</sup> becomes soluble in water. Therefore, as a polylactate formulation breaks down it becomes less viscous, thus exposing more of the compound to chemical and microbiological attack. Groundwater seepage velocity is another physical design parameter affecting HRC<sup>®</sup> dissolution. The more pore volumes that pass through the injected HRC<sup>®</sup> over a given time frame, the more HRC<sup>®</sup> will dissolve.

## **Aquifer Microbiology**

The nature and extent of microbial populations has a significant effect on the longevity of HRC<sup>®</sup> (Farone, W.A., S.S. Koenigsberg and J. Hughes 1999). Most microbes, and not just the kinds that ferment lactic acid into hydrogen or those that promote reductive dechlorination, will produce esterases and lipases that degrade HRC<sup>®</sup> and release lactic acid. Therefore, if an aquifer has a high microbial population, it will metabolize a given mass of HRC<sup>®</sup> at a faster rate than if the microbial counts are moderate to low.

According to Regeneration, HRC<sup>®</sup> degrades slowly, on average, over about a 9-month period (as modulated by certain features in the contaminated aquifer). Residual hydrogen will remain present in the aquifer after the HRC<sup>®</sup> degrades. Biomass should continue to accumulate and be available as fermentable carbon. Regeneration estimates the standard formulation of HRC<sup>®</sup> will stimulate reductive dechlorination within the aquifer for at least 12 months following injection.

## **Aquifer Geochemistry**

Biodegradation is fundamentally an electron transfer process in which electrons are removed from reduced compounds (electron donors) and transferred to more oxidized compounds (electron acceptors); the energy released in the process is used by microbes to sustain metabolism and growth. Like humans, microbes eat electron donors and breath electron acceptors. The most energetically favorable electron acceptor is oxygen.

The concentrations of competing electron acceptors such as dissolved oxygen, nitrate, ferric iron, and sulfate can have an effect on the dose rate and longevity of HRC<sup>®</sup> for enhancing in-situ bioremediation. Hydrogen from HRC<sup>®</sup> is used to reduce these electron acceptors to create redox conditions that are conducive to reductive dechlorination. As a result, the demand of these various electron acceptors for hydrogen (and consequently HRC<sup>®</sup>) must be considered in the specification of the amount of HRC<sup>®</sup> required for a project. Groundwater data indicating the actual site values for these parameters are important in determining an accurate final design for HRC<sup>®</sup> application.

### **4.1.4 Maintenance Requirements**

Maintenance requirements for in situ HRC<sup>®</sup> treatment are minimal. After HRC<sup>®</sup> is injected into the subsurface, there are no active maintenance requirements. Additional HRC<sup>®</sup> may need to be injected to replace HRC<sup>®</sup> that has been used in the treatment reactions. The frequency at which HRC<sup>®</sup> may need to be replaced is highly site-specific.

## **4.2 SITE CHARACTERISTICS AND SUPPORT REQUIREMENTS**

Site-specific factors can affect application of the in situ HRC<sup>®</sup> technology, and these factors should be considered before selecting the technology for remediation of a specific site. Site-specific factors addressed in this section include site access, area, and preparation requirements; climate; utility and peripheral supply requirements; support systems; and personnel requirements.

### **4.2.1 Site Access, Area, and Preparation Requirements**

In addition to the hydrogeologic conditions that determine the HRC<sup>®</sup> technology's applicability and design, other site characteristics affect implementation of this technology. The actual amount of space required for an in situ system depends on the required depth to the contamination and the number of HRC<sup>®</sup> injection points required for coverage of the treatment area.

The site must be accessible to and have sufficient operating and storage space for light- to medium-duty construction equipment. Underground utilities crossing the path of the proposed system may force modification of the HRC<sup>®</sup> injection field. Overhead space should be clear of utility lines for direct-push technology and drilling equipment to operate. The HRC<sup>®</sup> injection field may also need to be constructed around existing aboveground structures on site.

A positive displacement pump (such as a piston pump) that can meet the recommended minimum pressure, displacement, and discharge requirements needed to successfully inject HRC<sup>®</sup> into the subsurface will be required. According to Regensis, the R.E. RUPE Company Model ORC/HRC 9-1500 and the recently developed Geoprobe GS-2000 pumps meet the pressure and volume requirements needed for HRC<sup>®</sup> injection. When injecting measured volumes of HRC<sup>®</sup>

through probe boreholes, the installer should have a means to measure the HRC<sup>®</sup> as it is pumped into the subsurface.

Internal pump mechanisms and injection hoses should be cleaned by circulating hot water and a biodegradable cleaner such as Simple Green<sup>®</sup>. As a result, the installer must have a supply of water and equipment to heat the water. In order to maintain optimal pumping conditions, pure glycerin should be circulated through the pump after the pump has been thoroughly cleaned. A small volume of glycerin should be left in the pump works and hopper during storage or shipping. Further cleaning and decontamination (if necessary due to subsurface conditions) should be performed according to the equipment supplier's standard procedures and any local regulatory requirements.

#### **4.2.2 Climate Requirements**

The viscosity of HRC<sup>®</sup> is affected by temperature; as a result, the product must be warmed to a working temperature (95 °F recommended) prior to pumping it into the ground. At RMA, the product was stored inside a building overnight until it was used. The installation contractor used a portable steam cleaner and a galvanized trough to heat the HRC<sup>®</sup> to the required temperature. Extreme cold temperatures may necessitate additional handling, storage, emplacement requirements, and equipment.

Aboveground equipment associated with sampling programs to monitor the effectiveness of the HRC<sup>®</sup> injection may be affected by below freezing temperatures. At RMA, water samples were collected from groundwater monitoring wells installed at the site. The samples were collected with dedicated bladder pumps. Each pump was outfitted with a freeze protection device to prevent sample water from freezing in the discharge tube.

#### **4.2.3 Utility and Peripheral Supply Requirements**

Existing on-site sources of power and water may facilitate construction activities. During installation, water will be required to clean the injection system; however, this water can be transported to the site if an on-site source does not exist. Portable electrical generators can be used to supply electrical needs, if no power source exists on site. After the initial construction phase, the HRC<sup>®</sup> system installed at the RMA site required no electrical power or other utility support. For most applications, the wash water from the injection equipment is normally disposed of through a municipal publicly owned treatment works after appropriate permits are obtained.

Supply requirements specific to the technology may include additional HRC<sup>®</sup> for subsequent injections. The frequency at which HRC<sup>®</sup> may need to be replaced is highly site-specific. Other supplies indirectly related to the technology include typical groundwater sampling supplies and equipment for use during system monitoring activities.

#### **4.2.4 Required Support Systems**

No pretreatment of groundwater is necessary for HRC<sup>®</sup> applications. The application of HRC<sup>®</sup> to aquifers containing chlorinated ethene compounds may lead to the formation of vinyl chloride; however, only as a transitional state as the dechlorination process proceeds the vinyl chloride will eventually degrade to ethene. In cases where site conditions do not allow the vinyl chloride to have an adequate residence time in contact with HRC<sup>®</sup>, it is possible that vinyl chloride could move off-site without conversion to ethene. A second HRC<sup>®</sup> treatment application or other

secondary treatment may need to be installed downgradient of the original HRC<sup>®</sup> injection area if it is determined that further treatment is necessary.

#### **4.2.5 Personnel Requirements**

Personnel requirements for monitoring the HRC<sup>®</sup> system are minimal. Site personnel will be required to collect periodic groundwater samples to evaluate system performance. Groundwater should be analyzed at the site during sample collection for redox conditions, dissolved oxygen, and pH. Some laboratory analyses require specialized sample preparation and handling techniques. Field personnel should have skills and experience to prepare and handle these samples and to generate these types of field data.

Personnel requirements for long-term maintenance will depend on the type of maintenance activities. Personnel working with the system at a hazardous waste site may be required to complete the training requirements under the Occupational Safety and Health Act (OSHA) outlined in Title 29 of the Code of Federal Regulations 1910.120, which covers hazardous waste operations and emergency response. Personnel may also be required to participate in a medical monitoring program as specified under OSHA.

### **4.3 MATERIAL HANDLING REQUIREMENTS**

HRC<sup>®</sup> has no special handling requirements from a health and safety standpoint. HRC<sup>®</sup> is a polylactate ester that is a food-grade substance. In the subsurface environment, lactic acid products are eventually completely removed either as methane or carbon dioxide and water, leaving no residue.

HRC<sup>®</sup> is shipped in 4.25-gallon buckets and each bucket has a gross weight of approximately 32 pounds (net weight of HRC<sup>®</sup> is 30 pounds). At room temperature, HRC<sup>®</sup> is a sticky gel with a viscosity of approximately 20,000 centipoises (roughly equivalent to cold honey). The HRC<sup>®</sup> material has a nominal density of 1.3 grams per cubic centimeter or approximately 10.8 pounds per gallon. The viscosity of HRC<sup>®</sup> is temperature sensitive, and it becomes viscous below the manufacturer-recommended operating temperature. The temperature/viscosity relationship is non-linear.

Regenesis recommends the following handling procedures:

- HRC<sup>®</sup> should be stored in a warm, dry place that is protected from direct sunlight
- HRC<sup>®</sup> should be mixed into a relatively uniform fluid prior to injection
- Product uniformity is most easily achieved by pre-heating the HRC<sup>®</sup> material before pouring it into the pump hopper
- Scrape any separated HRC<sup>®</sup> material from the bottom of each bucket

Field personnel should take the following precautions while handling and applying HRC<sup>®</sup>: (1) use appropriate safety equipment, including eye and splash protection; (2) gloves should be used as appropriate based on the exposure duration and field conditions; (3) field staff should review the Material Safety Data Sheet that is provided with the shipment; and (4) personnel who operate field equipment during the installation process should have appropriate training, supervision, and experience with pressurized mechanical pump systems.



#### **4.4 TECHNOLOGY LIMITATIONS**

Recent studies by Regensis and others indicate that a broad range of contaminants may be reduced by the HRC<sup>®</sup> technology in addition to chlorinated VOCs (see Table 4-1). Past studies have shown that HRC<sup>®</sup> has been effective in reducing concentrations of petroleum hydrocarbons (aliphatic and aromatic hydrocarbons), simple aromatics (benzene, toluene, ethylbenzene, and xylene), polyaromatic hydrocarbons, certain classes of solvents (aldehydes, ketones, and alcohols/phenols), and ethers (methyl tertiary butyl ether, and 1,4-dioxane) in groundwater. Sites involving multiple types of groundwater contaminants may not be ideally suited for this technology alone; however, it can be effective at sites where a treatment train approach is used (such as sequential anaerobic/aerobic degradation barriers, air sparging, or soil vapor extraction).

#### **4.5 POTENTIAL REGULATORY REQUIREMENTS**

This section discusses regulatory requirements pertinent to using the HRC<sup>®</sup> technology at Superfund, RCRA corrective action, and other cleanup sites. The regulations applicable to implementation of this technology depend on site-specific remediation logistics and the type of contaminant being treated; therefore, this section presents a general overview of the types of federal regulations that may apply under various conditions. State and local requirements should also be considered; because these requirements vary from state to state, they are not presented in detail in this section. Table 4-2 summarizes the environmental laws and associated regulations discussed in this section.

During the SITE evaluation of the HRC<sup>®</sup> technology at RMA, no groundwater was pumped to the ground surface as a part of the installation or operation of the system. Groundwater was pumped to the surface for sample collection as part of the evaluation, and the purge water was handled and disposed of as waste. Purge water was handled and disposed of in accordance with federal and state laws.

**Table 4-2  
Summary of Environmental Regulations**

Act/Authority	Applicability	Application to the HRC® Technology	Citation
Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)	Cleanups at Superfund sites	This program authorizes and regulates the cleanup of releases of hazardous substances. It applies to all CERCLA site cleanups and requires that other environmental laws be considered as appropriate to protect human health and the environment.	Title 40 of the Code of Federal Regulations (CFR) part 300
Resource Conservation and Recovery Act (RCRA)	Cleanups at Superfund and RCRA sites	RCRA regulates the transportation, treatment, storage, and disposal of hazardous wastes. RCRA also regulates corrective actions at treatment, storage, and disposal facilities.	40 CFR parts 260 to 270
Clean Water Act (CWA)	Discharges to surface water bodies	National Pollutant Discharge Elimination System requirements of CWA apply to both Superfund and RCRA sites where treated water is discharged to surface water bodies. Pretreatment standards apply to discharges to publicly owned treatment works. These regulations do not typically apply to in situ technologies.	40 CFR parts 122 to 125, part 403
Safe Drinking Water Act	Water discharges, water reinjection, and sole-source aquifer and wellhead protection	Maximum contaminant levels and contaminant level goals should be considered when setting water cleanup levels at RCRA corrective action and Superfund sites. Sole sources and protected wellhead water sources would be subject to their respective control programs.	40 CFR parts 141 to 149
Clean Air Act	Air emissions from stationary and mobile sources	If volatile organic compound emissions occur or hazardous air pollutants are of concern, these standards may be applicable to ensure that use of this technology does not degrade air quality. State air program requirements also should be considered.	40 CFR parts 50, 60, 61, and 70
Atomic Energy Act (AEA) and RCRA	Mixed wastes	AEA and RCRA requirements apply to the treatment, storage, and disposal of mixed waste containing both hazardous and radioactive components. Office of Solid Waste and Emergency Response and Department of Energy directives provide guidance for addressing mixed waste.	AEA (10 CFR part 60) and RCRA (see above)
Occupational Safety and Health Administration (OSHA)	All remedial actions	OSHA regulates on-site construction activities and the health and safety of workers at hazardous waste sites. Installation and operation of the technology at Superfund or RCRA clean-up sites must meet OSHA requirements.	29 CFR parts 1900 to 1926
Underground Injection Control	Underground Injections	These regulations govern injection of substances into groundwater.	40 CFR part 144

#### 4.5.1 Comprehensive Environmental Response, Compensation, and Liability Act

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), as amended by the Superfund Amendment and Reauthorization Act (SARA), authorizes the federal government to respond to releases of hazardous substances, pollutants, or contaminants that may present an imminent and substantial danger to public health or welfare. CERCLA pertains to the HRC<sup>®</sup> technology by governing the selection and application of remedial technologies at Superfund sites. Remedial alternatives that significantly reduce the volume, toxicity, or mobility of hazardous substances and provide long-term protection are preferred. Selected remedies must also be cost effective, protective of human health and the environment, and must comply with environmental regulations to protect human health and the environment during and after remediation.

CERCLA requires identification and consideration of environmental requirements that are ARARs for site remediation before implementation of a remedial technology at a Superfund site. Subject to specific conditions, EPA allows ARARs to be waived in accordance with Section 121 of CERCLA. The conditions under which an ARAR may be waived are as follows:

- An activity that does not achieve compliance with an ARAR, but is part of a total remedial action that will achieve compliance (such as a removal action)
- An equivalent standard of performance can be achieved without complying with an ARAR
- Compliance with an ARAR will result in a greater risk to health and the environment than will noncompliance
- Compliance with an ARAR is technically impracticable
- A state ARAR that has not been applied consistently
- For fund-lead remedial actions, compliance with the ARAR will result in expenditures that are not justifiable in terms of protecting public health or welfare, given the needs for funds at other sites

The justification for a waiver must be clearly demonstrated (EPA 1988b). Off-site remediations are ineligible for ARAR waivers, and all applicable substantive and administrative requirements must be met.

Depending on the treatment application, post-treatment (secondary treatment) such as air sparging or soil- vapor extraction may be used in conjunction with the HRC<sup>®</sup> technology. This particular method of secondary treatment system would require air emissions and effluent discharge either on or off site. CERCLA requires on-site discharges to meet all substantive state and federal ARARs, such as effluent standards. Off-site discharges must comply not only with substantive ARARs, but also state and federal administrative ARARs, such as permitting, designed to facilitate implementation of the substantive requirements.

#### 4.5.2 Resource Conservation and Recovery Act

RCRA, as amended by the Hazardous and Solid Waste Amendments of 1984, regulates management and disposal of municipal and industrial solid wastes. EPA and the states implement and enforce RCRA and state regulations. Some of the RCRA Subtitle C (hazardous waste) requirements under 40 CFR parts 264 and 265 may apply at CERCLA sites because remedial actions generally involve treatment, storage, or disposal of hazardous waste. However, RCRA requirements may be waived for CERCLA remediation sites, provided equivalent or more stringent ARARs are followed.

Use of the HRC<sup>®</sup> technology may constitute a treatment as defined under RCRA regulations in 40 CFR part 260.10. Because treatment of a hazardous waste usually requires a permit under RCRA, permitting requirements may apply if the HRC<sup>®</sup> technology is used to treat a listed or characteristic hazardous waste. Regulations in 40 CFR part 264, subpart X, which regulate hazardous waste treatment, storage, and disposal in miscellaneous units, may be relevant to the HRC<sup>®</sup> process. Subpart X requires that in order to obtain a permit for treatment in miscellaneous units, an environmental assessment must be conducted to demonstrate that the unit is designed, operated, and closed in a manner that protects human health and the environment. Requirements in 40 CFR part 265, subpart Q (Chemical, Physical, and Biological Treatment), could also apply. Subpart Q includes requirements for waste analysis and trial tests. RCRA also contains special standards for ignitable or reactive wastes, incompatible wastes, and special categories of waste (40 CFR parts 264 and 265, subpart B). These standards may apply to the HRC<sup>®</sup> technology, depending on the waste to be treated.

In the event the HRC<sup>®</sup> technology is used to treat contaminated liquids at a hazardous waste treatment, storage, and disposal facility as part of a RCRA corrective action, regulations in 40 CFR part 264, subparts F and S may apply. These regulations include requirements for initiating and conducting RCRA corrective actions, remediating groundwater, and operating corrective action management units and temporary units associated with remediation operations. In states authorized to implement RCRA, additional state regulations more stringent or broader in scope than federal requirements must also be addressed.

Although not typically required, if secondary treatment is used in conjunction with the HRC<sup>®</sup> technology, additional RCRA regulations may apply. If secondary treatment involves extraction and treatment of groundwater, and the groundwater is classified as hazardous waste, the treated groundwater must meet Land Disposal Restriction treatment standards (40 CFR part 268) before reinjection or placement on the land (for example, in a surface impoundment).

RCRA parts 264 and 265, subparts AA, BB, and CC address air emissions from hazardous waste treatment, storage, and disposal facilities. These regulations would not apply directly to the HRC<sup>®</sup> technology, but may apply to the overall process if it incorporates secondary treatment, such as air sparging or soil-vapor extraction. Subpart AA regulations apply to organic emissions from process vents on certain types of hazardous waste treatment units. Subpart BB regulations apply to fugitive emissions (equipment leaks) from hazardous waste treatment, storage, and disposal facilities that treat waste containing organic concentrations of at least 10 percent by weight. Many organic air emissions from hazardous waste tank systems, surface impoundments, or containers will eventually be subject to the air emission regulations in 40 CFR parts 264 and 265, Subpart CC. Presently, EPA is deferring application of the Subpart CC standards to waste

management units used solely to treat or store hazardous waste generated on site from remedial activities required under RCRA corrective action or CERCLA response authorities (or similar state remediation authorities). Therefore, Subpart CC regulations may not immediately affect implementation of a secondary treatment technology associated with the HRC<sup>®</sup> technology used in remedial applications. EPA may remove this deferral in the future.

### **4.5.3 Clean Water Act**

The Clean Water Act (CWA) governs discharge of pollutants to navigable surface water bodies or publicly owned treatment works (POTW) by providing for the establishment of federal, state, and local discharge standards. On-site discharges to surface water bodies must meet substantive National Pollutant Discharge Elimination System (NPDES) requirements, but do not require an NPDES permit. A direct discharge of CERCLA wastewater qualifies as “on site” if the receiving water body is in the area of contamination or in close proximity to the site, and if the discharge is necessary to implement the response action. Off-site discharges to a surface water body require a NPDES permit and must meet NPDES permit limits. Discharge to a POTW is considered an off-site activity, even if an on-site sewer is used. Therefore, compliance with the substantive and administrative requirements of the national pretreatment program is required. General pretreatment regulations are included in 40 CFR Part 403. Any local or state requirements, such as state anti-degradation requirements, must also be identified and satisfied.

Any applicable local or state requirements, such as local or state pretreatment requirements or water quality standards (WQS), must also be identified and satisfied. State WQS are designed to protect existing and attainable surface water uses (for example, recreational and public water supply). WQSs include surface water use classifications and numerical or narrative standards (including effluent toxicity standards, chemical-specific requirements, and bioassay requirements to demonstrate no observable effect level from a discharge) (EPA 1988b). These standards should be reviewed on a state- and location-specific basis before discharges are made to surface water bodies.

Because the HRC<sup>®</sup> technology is deployed in situ and treats groundwater within the aquifer and does not require groundwater extraction or discharge of effluent to surface water bodies or POTWs, the CWA would not typically apply to the normal operation and use of this technology.

#### **4.5.4 Safe Drinking Water Act**

The Safe Drinking Water Act (SDWA), as amended in 1986, required EPA to establish regulations to protect human health from contaminants in drinking water. EPA has developed the following programs to achieve this objective: (1) a drinking water standards program, (2) a UIC program, and (3) sole-source aquifer and wellhead protection programs.

SDWA primary (health-based) and secondary (aesthetic) maximum contaminant levels generally apply as clean-up standards for water that is, or may be, used as drinking water. In some cases, such as when multiple contaminants are present, more stringent maximum contaminant level goals may be appropriate. In other cases, alternate concentration limits (ACL) based on site-specific conditions may be applied. CERCLA and RCRA standards and guidance should be used in establishing ACLs (EPA 1987a).

The underground injection control program regulates water discharge through injection wells. Injection wells are categorized as Classes I through V, depending on their construction and use. Reinjection of treated water involves Class IV (reinjection) or Class V (recharge) wells and should meet SDWA requirements for well construction, operation, and closure. The EPA or states with approved UIC programs require a UIC permit to inject HRC<sup>®</sup> into an aquifer. At RMA, a Class V UIC permit was required by EPA Region VIII for injection of HRC<sup>®</sup> during the evaluation program and two tracer dyes (Uranine and Phloxine B) that were used to confirm groundwater flow direction in the treatment area. Since HRC<sup>®</sup> is a food-grade substance that is degraded by naturally occurring microorganisms and the two tracer dyes are considered non-toxic, application for the injection permit presented no significant additional technical or administrative requirements at the test site.

The sole-source aquifer and wellhead protection programs are designed to protect specific drinking water supply sources. If such a source is to be remediated using the HRC<sup>®</sup> technology, appropriate program officials should be notified, and any potential regulatory requirements should be identified. State groundwater anti-degradation requirements and WQs may also apply.

#### **4.5.5 Clean Air Act**

The Clean Air Act (CAA), as amended in 1990, regulates stationary and mobile sources of air emissions. CAA regulations are generally implemented through combined federal, state, and local programs. The CAA includes pollutant-specific standards for major stationary sources that would not be ARARs for the HRC<sup>®</sup> process, and would apply only if secondary treatment (such as air sparging or soil-vapor extraction) were employed. State and local air programs have been delegated significant air quality regulatory responsibilities, and some have developed programs to regulate toxic air pollutants (EPA 1989). Therefore, state air programs should be consulted regarding secondary treatment if used in conjunction with the HRC<sup>®</sup> technology.

#### **4.5.6 Mixed Waste Regulations**

Use of the HRC<sup>®</sup> technology at sites with radioactive contamination might involve treatment of mixed waste. As defined by the Atomic Energy Act (AEA) and RCRA, mixed waste contains both radioactive and hazardous waste components. Such waste is subject to the requirements of

both acts. However, when application of both AEA and RCRA regulations results in a situation that is inconsistent with the AEA (for example, an increased likelihood of radioactive exposure) AEA requirements supersede RCRA requirements (EPA 1988a).

Office of Solid Waste and Emergency Response (OSWER), in conjunction with the Nuclear Regulatory Commission (NRC), has issued several directives to assist in identification, treatment, and disposal of low-level radioactive, mixed waste. Various OSWER directives include guidance on defining, identifying, and disposing of commercial, mixed, low-level radioactive and hazardous waste (EPA 1987b). If the HRC<sup>®</sup> technology is used to treat groundwater containing low-level mixed waste, OSWER/NRC directives should be considered. If high-level mixed waste or transuranic mixed waste is treated, internal DOE orders should be considered when developing a protective remedy (DOE 1988). The SDWA and CWA also contain standards for maximum allowable radioactivity levels in water supplies.

#### **4.5.7 Occupational Safety and Health Act**

OSHA regulations in 29 CFR Parts 1900 through 1926 are designed to protect worker health and safety. Both Superfund and RCRA corrective actions must meet OSHA requirements, particularly §1910.120, Hazardous Waste Operations and Emergency Response. Part 1926, Safety and Health Regulations for Construction, applies to any on-site construction activities. Any more stringent state or local requirements must also be met. In addition, health and safety plans for site remediation projects should address chemicals of concern and include monitoring practices to ensure that worker health and safety are maintained.

The HRC<sup>®</sup> technology does not require active operation by on-site personnel once installed. Work activities involved with operating this technology are limited to peripheral activities such as performance monitoring or periodic maintenance. All personnel involved in such activities are required to complete an OSHA training course and must be familiar with all OSHA requirements relevant to hazardous waste sites.

#### **4.6 STATE AND COMMUNITY ACCEPTANCE**

State regulatory agencies will likely be involved in most applications of the HRC<sup>®</sup> process at hazardous waste sites. Local community agencies and citizen groups are often also actively involved in decisions regarding remedial alternatives.

Because few long-term applications of the HRC<sup>®</sup> technology have been completed, limited information is available to assess long-term state and community acceptance. However, state and community acceptance of this technology is generally expected to be high, for several reasons: (1) relative absence of intrusive surface structures that restrict use of the treatment area; (2) absence of noise and air emissions; (3) the system is capable of significantly reducing concentrations of hazardous substances in groundwater; and (4) the system generates no residual wastes requiring off-site management and does not transfer waste to other media.

## 5.0 TECHNOLOGY STATUS

The HRC<sup>®</sup> technology, developed by Regenesis, was first introduced in 1999 and is specifically designed to supply a controlled release of hydrogen into the subsurface. Hydrogen in groundwater is essential to a naturally occurring, microbially driven, anaerobic process known as reductive dechlorination. The HRC<sup>®</sup> technology is currently available commercially and Regenesis was granted a U.S. Patent for the product on July 16, 2002.

Regenesis will design HRC<sup>®</sup> systems to suit specific site needs and has developed a software to provide assistance in estimating appropriate HRC<sup>®</sup> volumes and determining the proper design for a bioremediation project. Designs for bioremediation projects focus on delivering HRC<sup>®</sup> into contaminated groundwater plumes in grid-based or barrier-based configurations or a combination of both. Design selection depends primarily on the size and shape of the plume, groundwater velocity, site accessibility for injection equipment, and time frame for remediation.

Regenesi's HRC<sup>®</sup> technology has been applied to over 350 sites worldwide and makes up about 75 percent of all electron donor applications performed in the U.S. The technology's capabilities with regard to removal of chlorinated contaminants have been demonstrated through bench-, pilot-, and full-scale testing. According to Regenesis, the HRC<sup>®</sup> technology can also treat some nitroaromatics (explosives and dyes), inorganics (nitrate and perchlorate), and heavy metals (chromium and arsenic).

HRC<sup>®</sup> was recently proven as a low cost and effective remediation technology for the cleanup of dry cleaner sites. The EPA sponsored state coalition for remediation of dry cleaner sites recently published an article prepared by Florida's Department of Environmental Protection (FDEP) that reports the cost effectiveness of using HRC<sup>®</sup> to treat groundwater contaminated with PCE as a result of dry cleaning operations. The data presented in this article shows that a 96 percent decrease in PCE contaminant mass was achieved at one site for approximately \$28,000, which is reportedly a fraction of the cost compared to other treatment options. FDEP's Bureau of Petroleum Storage Systems subsequently deemed the HRC<sup>®</sup> technology as an environmentally acceptable product for accelerated in situ bioremediation of groundwater at contaminated sites in Florida.

The New Jersey Department of Environmental Protection (NJDEP) recently announced that HRC<sup>®</sup> was the first innovative technology to be approved under a new state program designed to promote brownfields development. An integral part of this endorsement was the evaluation of HRC<sup>®</sup> as an effective, energy efficient and secondary pollution reducing site remediation technology. An analysis prepared by NJDEP concluded that the use of HRC<sup>®</sup> as it relates to energy issues is beneficial as its application only requires that it be injected into groundwater. NJDEP reported that there is no permanent above-ground machinery, piping or equipment needed and the absence of these elements precludes any major capital and energy expenditures beyond the initial injection.



The HRC<sup>®</sup> process is currently in operation at a Department of Energy environmental management project in Ashtabula, Ohio. The site groundwater is contaminated with radionuclides and other hazardous chemicals, including TCE. The installation consisted of injecting HRC<sup>®</sup> into the saturated zone to speed the natural biodegradation of TCE into non-hazardous end products. Recent studies completed by Argonne National Laboratories and Northwestern University have shown that HRC<sup>®</sup> also facilitated biological reduction and immobilization of radionuclides migrating out of the remediation zone at the Department of Energy site.

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## APPENDIX A VENDOR'S CLAIMS FOR THE TECHNOLOGY

**Note: information in this Appendix was obtained from Regenesi s Bioremediation Products, Inc. (Regenesi s) website, <http://www.regenesi s.com>, May 2003.**

### **A.1 Introduction**

The HRC<sup>®</sup> technology can be used to degrade a range of chlorinated compounds in groundwater including degreasing agents (PCE, TCE, TCA and their breakdown products) carbon tetrachloride, chloroform, methylene chloride, certain pesticides/herbicides, perchlorate, nitrate, nitroaromatic explosives and dyes, chlorofluorocarbons, certain metals, and radionuclides. The technology, developed by Regenesi s, has been successfully implemented at over 350 sites and makes up about 75 percent of all electron donor applications performed in the U.S.

### **A.2 Technology Description**

Regenesi s' patented HRC<sup>®</sup> process is designed specifically for the treatment of chlorinated solvent based contamination or any anaerobically degradable substance in the groundwater environment. HRC<sup>®</sup> is a viscous liquid that is pressure injected directly into the subsurface. Upon contact with water, HRC<sup>®</sup> slowly hydrolyzes and is broken down by microbial action. During this process, lactic acid is released and utilized by microbes to produce hydrogen. The resulting hydrogen is then used in a microbial mediated process known as reductive dechlorination. This step-by-step biodegradation process (reductive dechlorination) reduces harmful contaminants into harmless compounds, such as ethene and ethane. Under the influence of HRC<sup>®</sup>, this process may continue at an accelerated rate for up to 18 months.

### **A.3 Advantages of the Technology**

The HRC<sup>®</sup> process has a number of advantages that make it uniquely suitable for use as a treatment process for chlorinated compounds in groundwater. These advantages are briefly described below.

- Slow-release of lactic acid to support anaerobic microbial activity and produce hydrogen in a range which is optimal for reductive dechlorination
- Long-term source of lactic acid/hydrogen to the subsurface (up to 18 months)
- Clean, low-cost, non-disruptive application
- Not limited by presence of surface structures
- No operations and maintenance following injection
- Faster and often lower cost than drawn out natural attenuation
- Complimentary product application design and site analysis from Regenesi s

#### **A.4 HRC<sup>®</sup> System Applications**

There are two general designs (grid- or barrier-based configuration) for delivering HRC<sup>®</sup> into contaminated groundwater plumes and selection is generally based on the size of the contaminated plume, groundwater velocity, and required time frame for remediation. A third application that is also sometimes used involves the emplacement of HRC<sup>®</sup> directly into the bottom of an excavated area. This is typically applied to an area that has undergone a source removal action and heavily contaminated soil has been removed via excavation and hauling. HRC<sup>®</sup> will degrade any lingering source material and prevent recharge of groundwater contaminants into the aquifer.

Grid-based designs are typically used for small- to medium-sized contaminant plumes where a relatively short remediation period is desired. For this application, HRC<sup>®</sup> is injected into the aquifer matrix in a grid pattern over the areal extent and across the vertical zone of the contaminant plume. The shape of the area to be treated is determined primarily by the shape and accessibility of the contaminant plume.

For very large plumes where a grid-based design is not cost effective, a barrier-based design is typically applied. HRC<sup>®</sup> barriers are installed perpendicular to groundwater flow direction at regular intervals throughout the length of the contaminant plume. In this approach, a unit volume of water moving in the contaminant plume is subject to sequential doses of hydrogen to promote reductive dechlorination reactions.

#### **A.5 HRC<sup>®</sup> Design Considerations**

There are a number of factors that need to be determined prior to implementing a grid- or barrier-based design for a specific project. Regensis has developed an HRC<sup>®</sup> design software to assist experienced environmental professionals in the proper design of accelerated attenuation/bioremediation projects. As with any remediation design, the first step is to gather relevant site assessment data including lithologic data, contaminant concentrations, extent of impacted groundwater, aquifer redox conditions, and groundwater velocity to determine which design is more appropriate for the project. The next step is to determine the scope of the remediation. After evaluating site-specific remediation strategies including health risks, groundwater quality thresholds, and regulatory criteria, the remediation design is developed and constructed.

The quantity of HRC<sup>®</sup> needed to fuel the reductive dechlorination process is estimated using the site assessment data and general design guidelines. The HRC<sup>®</sup> design process is simplified by using the HRC<sup>®</sup> Grid or Barrier Design Worksheets found on the HRC<sup>®</sup> Application Software (available from Regensis) and consists of specifying the following design variables:

- 1) Site Information: plume dimensions, aquifer transport parameters, and contaminant and competing electron acceptor concentrations.
- 2) Demand Factors: microbial demand factor required for remediation of a source area or plume cutoff (3x is typically used for treating a contaminant source with one application of HRC<sup>®</sup>; a demand factor of 3x and an additional 2x is typically selected for a barrier application since the

majority of contaminant load comes from flow into the barrier as opposed to potential sorbed or residual phase in a source area).

3) HRC<sup>®</sup> Delivery Point Spacing: a delivery point spacing of 5 to 15 feet-on-center is typically used to provide a reasonable distribution of HRC<sup>®</sup> into the contaminant plume. Spacing specification depends primarily on groundwater velocity, sediment permeability, amount of HRC<sup>®</sup> required, and HRC<sup>®</sup> grid or barrier size.

4) HRC Injection Rate: the HRC<sup>®</sup> injection rate for each point typically ranges from 4 to 10 pounds/foot, and its specification depends on the contaminant and competing electron acceptor loading rate, competing microbial demand, and soil type.

#### **A.6 Recommended Groundwater Monitoring Program for HRC<sup>®</sup> Pilot/Full Scale Application**

Monitoring of selected wells should be conducted to validate the HRC<sup>®</sup>-based enhancement of reductive dechlorination processes. The monitoring well network would ideally include wells from the following locations:

1) Inside Treatment Area: provides information on geochemical conditions and contaminant trends induced by the HRC<sup>®</sup> process.

2) Downgradient of Treatment Area: provides information on residence time effects. Since the contaminant has to be in contact with the electron donor for a given length of time, the actual performance may be evident at downgradient locations for sites with moderate to high groundwater velocities.

3) Upgradient of Treatment Area: provides a measure of contaminant mass and competing electron acceptor load entering treatment area.

4) Background: allows comparison of geochemical changes induced by addition of HRC<sup>®</sup>. An initial or "baseline" round of sampling should be performed to determine pre-treatment groundwater conditions. After application of HRC<sup>®</sup>, samples should be collected every other month for a six to eight month period. After the initial biodegradation and geochemical trends have been determined, the monitoring frequency can be decreased to a quarterly, semiannual, or annual program.

Groundwater monitoring should be conducted using standard low flow groundwater sampling techniques and include the measurement of the following field/chemical parameters:

- All Relevant Contaminants
- Field Parameters: DO, ORP, pH, temperature, and ferrous iron (optional field measurement)
- Natural Attenuation/Inorganic Parameters: dissolved iron and manganese, nitrate, sulfate, sulfide, chloride, and alkalinity
- HRC-Based Electron Donor: total organic carbon and metabolic acids (lactic, pyruvic, acetic, propionic, and butyric)
- End-Product Dissolved Gases: carbon dioxide, methane, ethane and ethene

A qualified laboratory should conduct the analytical testing for metabolic acids, otherwise most laboratories can provide testing for the remaining parameters. A typical cost for the above testing program is approximately \$300 per sample.